Study on the unloading damage constitutive model of sandstone based on hydro-pressure cycle

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Abstract. The periodic rise and fall of reservoir water level under hydro-pressure cycle leads to the deterioration of physical and mechanical properties of rock and seriously triggers the instability of the reservoir slope. From the laboratory data and characteristics of the stress–strain curve under different hydraulic cycles, combined with the generalized Hooke’s law, the Weibull distribution theory, and the Hoek–Brown strength criterion, the energy dissipation in the unloading process is assumed as the damage variable, and the unloading damage constitutive model of saturated sandstone under hydro-pressure cycle is established. Under hydro-pressure cycle, the parameters m and F of the constitutive model are gradually decreasing, and the sandstone brittleness and macroscopic strength are gradually weakened. In addition, the scattered energy increases, while plastic deformation slowly plays a dominant role. The comparative analysis shows that the constitutive model fits well with the experimental curves. The damage constitutive equation can be expressed under hydro-pressure cycle. This research can help in the stability analysis of rock slope under the reservoir water in the field.

Key words. Rock, Hydro-pressure cycle, Unloading, Damage, Constitutive model

1 Introduction

The long-term fluctuation of reservoir water level leads to deterioration of the physical and mechanical properties of rock and soil along the rock slope due to hydro-pressure cycle and seriously affects the safety of the reservoir slope. Therefore, people take great importance of the slope stability under hydro-pressure cycle. Brace [1] et al. studied the effect of pore water pressure on granite under...
high confining pressure, obtained the variation law of pore water pressure inside granite, and facilitated the study of the mechanical properties of rock mass in pore water. Lu [2-3] et al. discussed the basic physical and mechanical properties of rock using experimental research and proposed a new method for determining the yield limit of rock mass through the water–rock coupling test results. Li [4] et al. studied the deformation characteristics of sandstone under cyclic pore water pressure using rock mechanics test system and concluded that water pressure circulation has a great influence on sandstone strain. Zhou [5] et al. proposed a secondary loading surface model suitable for cyclic loading and unloading of rock, considering the different strength characteristics of rock under triaxial compression and tension. Chen [6] et al. set up the constitutive relationship of fractured and jointed rock masses based on the principle of energy equivalence and analyzed the stability of rock mass in the Three Gorges Reservoir Area. Zhao [7] et al. studied the mechanical properties of sandstone under different hydraulic cycles and established a damage statistical constitutive model of sandstone. Qin [8] et al. established a constitutive equation that can characterize the initial damage to the mechanical behavior under the limitation of the traditional constitutive model and discussed the damage during the full stress–strain process of the rock evolutionary mechanism based on the statistical damage mechanics theory of the Weibull distribution. Ye [9] set up a damage deterioration constitutive equation applied to rock under triaxial compression with microelement strength and damage mechanics theory. Song [10] et al. established a macroscopic and mesoscopic damage composite constitutive model of nonpersistent jointed rock mass based on the Drucker–Prager criterion. Wen [11] et al. assumed that the mesoelement elastic modulus of rock obeys the Weibull distribution and the combined theory of strain energy density to establish a rock damage constitutive model. Ma [12] et al. set up a damage model associated with equivalent plastic strain by performing conventional triaxial loading and unloading tests on sandstones and combined with the Drucker–Prager model.

More researchers focus on the analysis of the change of the mechanical parameter during the rock damage failure process and set up the rock damage constitutive model with the statistical analysis of the rock mechanical parameter degradation law, which has built a good foundation for understanding the rock damage law. However, it is difficult to study the law of energy evolution in the rock damage process. This paper applies the principle of minimum energy consumption to set up a damage constitutive model of sandstone under hydro-pressure cycle. The damage constitutive equation was derived based on the principle of energy consumption, combined with the Hoek–Brown strength criterion. Finally, the rationality of the damage constitutive model is verified in this paper.

2 Hydro-pressure cycle experiment of sandstone

2.1 Test plan
Sandstone samples having good quality and strength uniformity were obtained from the Three Gorges Reservoir Area (Figure 1). The samples were 50 mm in diameter and 100 mm in length according to the specification requirements. The triaxial experiment of saturated sandstone was conducted. Then, the unloading triaxial experiment under hydro-pressure cycle was performed using rock triaxial rheometer (Top Industrie, France), as shown in Figure 2. The specific test operation steps were as follows: (1) The sandstone samples were completely saturated using the vacuum immersion saturation method in accordance with the “Specifications for rock tests in water conservancy and hydroelectric
(2) During the triaxial test, the confining pressure was increased to a preset value of 20 MPa at a rate of 0.12 MPa/min, the axial pressure was gradually applied to destroy the sample, and the triaxial compressive strength was obtained. (3) The rate control method was used in the unloading test under hydro-pressure cycle. (4) The water pressure was increased from 0 to 0.3 MPa at a rate of 0.01 MPa/min and was maintained for 30 min. Then, the water pressure was reduced to 0 at a rate of 0.01 MPa/min. (5) The axial pressure was increased to 80% of the triaxial compressive strength and was maintained. Subsequently, the confining pressure was released at a rate of 0.12 MPa/min until the sandstone samples were destroyed.

2.2 Stress–strain curve analysis

Unloading tests under triaxial compression and hydro-pressure cycle were performed. The stress–strain curve during the unloading failure process under different hydro-pressure cycles is shown in Figure 3. A statistical analysis was performed to analyze the influence of the number of hydro-pressure cycles on mechanical parameters, such as compressive strength and elastic modulus of rock specimens (see Figures 4–6). In this study, the elastic modulus took the slope of the straight section of the stress–strain.

As shown in Figures 3–6, we observe the following:

(1) From the lateral strain and the axial strain of sandstone, cracks were observed simultaneously with an increase in the number of hydro-pressure cycles. For the stress peak under 24 hydro-pressure cycles, the lateral strain is 1.37×10−3, and axial strain is 12.51×10−3, which are increased by 153.77% and 14.16%, respectively, in comparison with 0 cycle. The lateral strain increases faster than the axial strain, which is mainly due to the circulating water pressure, reducing the inside cementation of sandstone. Furthermore, it weakens the constraint on the lateral deformation to a certain extent. Generally, both the lateral strain and axial strain increase with the number of hydro-pressure cycles.
Figure 3. Stress–strain curve of sandstone at different hydro-pressure cycles.

Figure 4. Peak stress and the corresponding axial strain of sandstone.

Figure 5. Tangent elastic modulus of sandstone at different hydro-pressure cycles.
(2) The stress–strain curve shape of the rock sample during the loading process is the same under different hydraulic pressure cycles. Furthermore, all have gone through the compaction phase, elastic phase, yield phase, and failure phase, corresponding to OA, AB, BC and CD (see in Figure 3), respectively. With an increase in the number of hydro-pressure cycles, the compressive strength of the sample gradually decreases, and the corresponding axial strain increases. The curves are scissorlike (as shown in Figure 4); that is, after hydro-pressure cycle, the accumulation effect of the internal structure damage is observable.

(3) The tangential elastic modulus shows a decreasing–increasing–decreasing trend under each cycle number, which is consistent with the characteristics of the stress–strain curve. A decrease in the elastic modulus indicates that the irreversible progressive sandstone damage is caused by hydro-pressure cycle. If the damage process is assumed to change continuously with an increase in the number of hydro-pressure cycles, the damage evolution equation can be set up as follows:

$$E = -0.227x + 26.03$$

where $E$ is the elastic modulus and $x$ is the number of hydro-pressure cycles.

3 Analysis of sandstone energy evolution under hydro-pressure cycle

We can assume that there is no heat exchange with the outside since the rock is unloaded and destroyed in the test instrument in a completely closed environment and the test temperature is normal. According to the second law of thermodynamics, we can consider that the rock absorbs the work done by the instrument, denoted as the total energy $U$. The total energy is the sum of the stored elastic strain energy $U_1$ and the dissipative energy $U_2$. It is caused by the damage and plastic deformation of the material inside the rock [14]. The relation is as follows:

$$U = U_1 + U_2$$

The work done by the testing machine on the sample under the load $U$ is the area under the loading curve, and the elastic strain energy released by the sample during the unloading process is the area
under the unloading curve, which is $U_1$ in Figure 7. The dissipation energy is the area between the loading and unloading curves, which is $U_2$ in Figure 7.

\[
U_1 = \frac{1}{2E} \left( \sigma_1^2 - 4\nu \sigma_1 \sigma_3 \right)
\]

(3)

\[
U = \int \sigma_i d\varepsilon_i - 2\nu \sigma_3 \int d\varepsilon_i
\]

(4)

According to the experimental data, the total energy is absorbed. Furthermore, the elastic strain and dissipated energies in the saturated sandstone failure process under hydro-pressure cycle are calculated. Moreover, the change in the number of hydro-pressure cycles is shown in Figure 8.

\[\text{Figure 7. Energy calculation diagram.}\]

\[\text{Figure 8. Relationship curve of the total, elastic, and dissipated energies versus the number of hydro-pressure cycles in sandstone failure process.}\]
As shown in Figure 8, the relationship curve of the total and dissipated energies versus the number of hydro-pressure cycles during the sandstone failure process can be divided as follows: (1) initial stage, exacerbation stage, and saturation stage. The dissipated energy is only less than 60 kJ for hydro-pressure cycle from 1 to 6, accounting for 3.92% of the total energy. Furthermore, the energy variation is small. The water pressure at this stage does not significantly degrade the internal structure of the sample, and the failure form is brittle failure, so it is defined as the initial stage. With an increase in the number of hydro-pressure cycles, the internal cementation of sandstone weakens. Furthermore, there is a large amount of plastic deformation in addition to elastic deformation before failure. Therefore, the total, elastic strain, and dissipated energies of the sample show a growth rate compared with the initial stage uptrend, defined as the stage of increasing impact. After 16 hydro-pressure cycles, the growth rate of the total and elastic energies decreased significantly, while that of the dissipated energy continued to increase. The reason is that hydro-pressure cycle has severely damaged the internal structure of sandstone, while plastic deformation has gradually played a leading role. Furthermore, the hydro-pressure cycle deterioration tends to be saturated.

4 Sandstone damage constitutive model

4.1 Deduction of damage constitutive equation

The principle of energy dissipation is based on the theory that damage and deformation of rock are essentially due to the energy conversion inside the rock. Energy dissipation is an essential attribute of rock damage [15]. We define a hydro-pressure cycle of 0 as the nondestructive state of sandstone. The energy changes of sandstone under hydro-pressure cycle are defined as the difference between the energy of sandstone unloading failure under a hydro-pressure cycle and that at 0 hydro-pressure cycle. Therefore, the energy difference \( \Delta U_{ij} \) generated by the ith cycle can be expressed as follows:

\[
\Delta U_{ij} = U_{ij} - U_{0j}
\]

where i represents the ith hydro-pressure cycle, \( j = 1, 2, 3 \) (1 is the total energy, 2 is the elastic strain energy, and 3 is the dissipated energy), and \( U_{0j} \) is the energy value of the sandstone unloading failure under a hydro-pressure cycle of 0.

The internal damage process of sandstone results to the development and expansion of internal cracks under the influence of external load. The damage process has the most direct relationship with the number of microelements that cause damage in sandstone. Hence, the damage variable DHZ of sandstone can be defined as the total ratio of the number of damaged microelements, \( N_f \), to the total number of sandstone microelements, \( N \), which is as follows:

\[
D_{HZ} = \frac{N_f}{N} = \frac{\iint \int f(k) dk \, dx \, dy \, dz}{N} = \int_0^k f(k) \, dk
\]

Equation (6) combined with the Weibull distribution probability density function is given as follows:
\[ D_{HZ} = \int_0^I f(k) dk = 1 - \exp \left[ -\left( \frac{k}{F} \right)^m \right] \] (7)

The sandstone damage variable \( D_w \) based on the principle of energy dissipation is defined as the ratio of the dissipated energy released during sandstone unloading failure to the total energy absorbed, which is as follows:

\[ D_w = \frac{\Delta U^D}{\Delta U^U} = 1 - \frac{\Delta U^E}{\Delta U^U} = 1 - \zeta \] (8)

Furthermore, the elastic energy ratio coefficient \( \zeta \) can be defined as the ratio of the elastic strain energy to the total energy during the unloading process.

The damage process of sandstone under the action of water pressure is not simply the superimposition of the damage caused by the hydraulic pressure cycle and the stress damage. It is necessary to derive the comprehensive damage variable \( D \) during the unloading process of sandstone under hydro-pressure cycle according to the equivalent principle [15]:

\[ D = D_{HZ} + D_w - D_{HZ} D_w \] (9)

Based on the above equations, the comprehensive damage variable of sandstone during the unloading process under hydro-pressure cycle is as follows:

\[ D_{w} = 1 - \zeta \exp \left[ -\left( \frac{k}{F} \right)^m \right] \] (10)

The damage variable \( D_{w} \) of the sandstone and the elastic energy ratio coefficient \( \zeta \) under different hydro-pressure cycles are calculated from equation (10). Furthermore, the statistical relationship is obtained. The functional relationship between the elastic energy ratio \( \zeta \) and hydro-pressure cycle, \( i \), is as follows:

\[ \zeta = -0.069\exp\left( \frac{i}{11.981} \right) + 0.959 \] (11)

Under conventional triaxial stress conditions (\( \sigma_2 = \sigma_3 \)), the microelements in the rock obey the generalized Hook’s law before failure, and the constitutive model of sandstone unloading damage under conventional stress damage can be obtained as follows:
\[ \sigma_1 = E \zeta \varepsilon_1 \exp \left[ -\left( \frac{k}{F} \right)^m \right] + 2v \sigma_3 \]  

(12)

Since the Hoek–Brown strength criterion is more applicable to the bias loading method than the Mohr–Coulomb strength criterion, this paper will use the Hoek–Brown strength criterion as the microelement strength distribution variable of the rock.

\[ Q = \sigma_1 - \sigma_3 - \sigma_\varepsilon \left( m_i \frac{\sigma_3}{\sigma_\varepsilon} + 1 \right)^{\frac{1}{2}} \]  

(13)

where Q represents the microelement statistical distribution variable of the rock, \( \sigma_\varepsilon \) represents the uniaxial compressive strength of sandstone, and \( m_i \) represents the rigidity of the rock. \( m_i \) can be calculated by uniaxial and triaxial compressive strength tests, which is as follows:

\[ m_i = \frac{\left( \sigma_1 - \sigma_3 \right)^2 - \sigma_\varepsilon^2}{\sigma_3 \sigma_\varepsilon} \]  

(14)

In the three-dimensional stress state, the constitutive relationship of the rock material satisfies Hooke’s law. Hence, from the aforementioned law, we obtain the following:

\[ Q = 2G(\varepsilon_1 - \varepsilon_3) - \sigma_\varepsilon \left( m_i \frac{\sigma_3}{\sigma_\varepsilon} + 1 \right)^{\frac{1}{2}} \]  

(15)

By substituting equation (15) into equation (14), we obtain the constitutive model expression of sandstone damage under hydro-pressure cycle as follows:

\[ \sigma_1 = E \zeta \varepsilon_1 \exp \left[ -\left( \frac{2G(\varepsilon_1 - \varepsilon_3) - \sigma_\varepsilon \left( m_i \frac{\sigma_3}{\sigma_\varepsilon} + 1 \right)^{\frac{1}{2}}}{F} \right)^m \right] + 2v \sigma_3 \]  

(16)

4.2 Derivation and determination of model parameters

Considering the unloading failure point \( p(\sigma_p, \varepsilon_p) \), the sandstone stress–strain curve has the following two rules:

(1) At point P, \( \sigma_1 = \sigma_{1p} \), \( \varepsilon_1 = \varepsilon_{1p} \), and \( \varepsilon_3 = \varepsilon_{3p} \).
(2) At point P, \( \frac{d\sigma_i}{d\varepsilon_i} = 0 \).

Combining the aforementioned rules and performing integral calculations on equation (16), we obtain the following:

\[
1 - \frac{2Gm\varepsilon_{i_{1p}}}{F} \left( \frac{2G(\varepsilon_{i_{1p}} - \varepsilon_{3_{1p}}) - \sigma_s (m_i \frac{\sigma_{3i}}{\sigma_s} + 1)^2}{F} \right)^{m-1} = 0
\]

(17)

At point P, \( \frac{\sigma_{1p} - 2v\sigma_3}{E\varepsilon_{i_{1p}}} \) and \( 2G(\varepsilon_{i_{1p}} - \varepsilon_{3_{1p}}) - \sigma_s (m_i \frac{\sigma_{3i}}{\sigma_s} + 1)^2 \) are both fixed values. Hence, can define them as follows:

\[
M = \ln \frac{\sigma_{1p} - 2v\sigma_3}{E\varepsilon_{i_{1p}}}
\]

(18)

\[
N = 2G(\varepsilon_{i_{1p}} - \varepsilon_{3_{1p}}) - \sigma_s (m_i \frac{\sigma_{3i}}{\sigma_s} + 1)^2
\]

(19)

Solving equations (16), (17), (18), and (19) simultaneously, we obtain the following expression:

\[
m = \frac{-N}{2MG\varepsilon_{i_{1p}}}
\]

(20)

By substituting equation (20) into equation (17), we obtain the following expression of F:

\[
F = \frac{N}{(-M)^{\frac{1}{m}}}
\]

(21)

\( \sigma_e = 105.7\text{MPa} \) and \( \sigma_l = 228.94\text{MPa} \) are obtained from the uniaxial loading and triaxial compression tests of saturated sandstone, respectively. Substituting the values into equation (14), we obtain the following: \( m_i = 15.36 \). From the triaxial test of sandstone under hydro-pressure cycle, the parameters M, N, m, and F are calculated from equations (18), (19), (20), and (21), respectively. The relationship of the parameters m and F versus the number of hydro-pressure cycles is established by fitting, as shown in Figures 9 and 10, respectively.
The relationships of the constitutive model parameters $m$ and $F$ versus the number of hydro-pressure cycles, $i$, are as follows, respectively:

\begin{equation}
    m = 2.26 \exp\left(-\frac{i}{19.80}\right) + 1.14
\end{equation}

\begin{equation}
    F = 107.81 \exp\left(-\frac{i}{10.66}\right) + 5.28
\end{equation}

Substituting equations (22) and (23) into equation (16), the empirical equation of the unloading damage constitutive model of sandstone under hydro-pressure cycle is obtained as follows:

\begin{equation}
    \sigma_1 = E \zeta \epsilon_1 \exp \left[ - \frac{2G(\epsilon_1 - \epsilon_3) - \sigma_1 (m \sigma_3 / \sigma_1 + 1)^{\frac{1}{2}}}{107.81 \exp\left(-\frac{i}{10.66}\right) + 5.28} \right] + 2\nu \sigma_3
\end{equation}

**5 Damage constitutive model verification**

The constitutive model calculation curves of saturated sandstone with an initial confining pressure of 20 MPa under different hydro-pressure cycles are obtained by substituting $\sigma_1$, $\sigma_3$, $\epsilon_1$, $E$, and $\nu$, obtained from the triaxial loading and unloading test of saturated sandstone and the energy data during the experiment, into equation (24). Subsequently, the calculated curve is compared with the test curve, which is limited in space. Here, we only list the verification curves under 2, 10, and 24 hydro-pressure cycles (as shown in Figures 11–13) for analysis and explanation.
It can be observed from Figure 10 that the stress–strain test curve of the saturated sandstone specimens subjected to the triaxial loading and unloading experiment at different hydro-pressure cycles is highly consistent with the theoretical curve solved using the damage constitutive model, especially in the elastic loading stage.
In the Weibull distribution, the parameter $F$ can be defined as an index of the macroscopic average strength of the rock, and the parameter $m$ is an index of the brittleness of the rock. From the fitting curve of the relationship of $F$ and $m$ versus the number of hydro-pressure cycles, it is observed that increasing the number of cycles, both $F$ and $m$ show a decreasing trend, indicating that the brittleness and the macroscopic strength of sandstone gradually weaken due to the hydro-pressure effect, which is consistent with the actual deformation and failure characteristics of sandstone under hydro-pressure cycle.

6 Conclusion
The degradation law of elastic modulus, compressive strength, and other parameters of sandstone are obvious under hydro-pressure cycle. The damage evolution equation of the elastic modulus is established. Furthermore, the accumulation effect of internal structure damage is observable. According to the characteristics of the stress–strain curve of sandstone in the triaxial compression under the action of hydro-pressure cycle and the continuous damage theory and isotropic hypothesis, the rock damage evolution equation is derived using the principle of minimum energy dissipation, and the unloading damage constitutive model of sandstone under hydro-pressure cycle is set up. The essence of rock damage is the energy evolution. With an increase in the number hydro-pressure cycles, the more energy the rock needs to dissipate during its failure. Moreover, the growth rate of the releasable ultimate elastic energy accumulated in the rock has a significant weakening trend. Plastic deformation gradually plays a leading role, and sandstone brittleness gradually weakens. The calculation of the established statistical damage constitutive model is fit for the test curve. Furthermore, the established statistical damage constitutive equation can better reflect the sandstone damage effect under hydro-pressure cycle. Also, the parameters $m$ and $F$ of the constitutive model are gradually decreasing, indicating that the sandstone brittleness gradually weakens and the macroscopic strength gradually decreases under the cycle, which is consistent with the actual deformation and failure characteristics of the sandstone under hydro-pressure cycle.

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