Hindawi
Geofluids
Volume 2022, Article ID 1731254, 12 pages
https://doi.org/10.1155/2022/1731254

Research Article

The Damage Constitutive Model of Sandstone under Water-Rock Coupling

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Received 1 December 2021; Revised 20 March 2022; Accepted 14 April 2022; Published 26 May 2022

Academic Editor: Qingzhi Wang

A constitutive model based on damage mechanics and statistical strength theory for sandstone under water-rock coupling is proposed and verified by laboratory tests and numerical tests. The damage mechanism of sandstone under the coupling action of water and force is clarified based on the microscopic test of sandstone under the coupling action of water and rock in this paper. The stress state of sandstone is determined by analyzing the results of laboratory tests. Based on the energy theory method, the strength criterion of sandstone under the interaction of water and rock is obtained, which is introduced into the statistical damage constitutive model of sandstone considering the interaction of water and rock; thus, a relatively perfect damage constitutive model of sandstone considering the interaction of water and rock is established. Finally, the influence of the number of cycles on the model parameters was further analyzed by analyzing the model parameters and the water-rock coupling test. Compared with the existing test results, the model established in this paper can perfectly reflect the deterioration characteristics of sandstone under the coupling action of water and rock.

1. Introduction

As a geological body widely existing in nature, rock often exists in a two-phase medium, that is, solid mineral crystal particles and pore (crack) water between crystals. The interaction between the granular crystal and crack water often leads to the destruction of rock mass materials. The coupling relationship between them is the key factor restricting the strength of rock mass. In the seepage field of rock mass, on the one hand, the distribution of the internal stress field of the rock mass is changed due to the load applied on the rock mass, thus resulting in the change of the action intensity, action range, and action form of water in the rock mass. On the other hand, due to the external hydraulic conditions, the percolation field of disturbed water in turn acts on the rock mass and ultimately affects the stability of the rock mass. It can be seen that there is an obvious interaction between the rock mass and fissure water, that is, water-rock coupling. The water-rock under the coupling action of the rock mass deformation and failure regularity study involved resource mining, underground cavern excavation, nuclear waste storage, and a series of key areas; therefore, clear water-rock under the action of coupling of the degradation mechanism of the rock mass proposes that the corresponding constitutive model of rock under the action of water-rock is the key problem that needs to be urgently solved in the rock mechanics field (Rutqvist and Stephansson [1]; Rahman et al. [2]; Li et al. [3]; Wu [4]; and Chen and Li [5]).

The mechanical properties of rock have been studied by scholars (Healy et al. [6]; Hossain and Rahman [7]; Sukumar et al. [8]; and Karami and Stead [9]). Dougill [10] was the first to take the damage theory as the theoretical basis for exploring rock, thus laying a foundation for the development of rock mechanics. In order to study the effect of water-rock coupling on rock strength degradation mechanism, some scholars carried out laboratory experimental research. Liu et al. [11] used laboratory tests to simulate the strength characteristics of dry-wet rock at the edge of a reservoir affected by the fluctuation of the reservoir water and obtained the strength-weakening law of sandstone soaked by the reservoir water cycle, which became a beneficial basis for analyzing the stability of the rock mass around water conservancy projects. You et al. [12] determined the water-rock coupling mechanism of sandstone through laboratory tests with the confining pressure and pore pressure as research factors. Deng et al. [13] conducted a cyclic loading and unloading damage test to discuss the strength law of damaged sandstone. Jeng et al. [14] studied the wetting degradation mechanism (strength and deformation characteristics) of sandstone (Tertiary in Taiwan, with quartz content greater than 75%) and obtained that uniaxial compressive strength decreased by 40%~60% and deformation modulus decreased by about 50% in the saturated state. Among clay minerals contained in sandstone (illite, kaolinite, and chlorite), chlorite is the most easily soluble in water and leached, which leads to a significant increase in porosity, and the strength of MS1 sandstone decreases after 60 cycles of wetting and drying. Sumner and Loubser [15] studied the mass loss and differences in mechanical properties of four groups of sandstone specimens with differing moisture content and studied the weathering mechanism and controlling factors of sandstone. Xue and Zhang [16] conducted compressional wave velocity and uniaxial compression tests on sandstones with two different mineral compositions with the number of dry-wet cycles $n = 0, 1, 2, 4, 6, 8$, and 10. The results show that the p-wave velocity and peak strength of the no. I sandstone (the cements are hydromica and calcite) decrease nonlinearly with the number of cycles, and the no. II rock sample (the cements are sericite and chlorite) is stable due to the chemical properties of crystalline sericite. Therefore, the change of p-wave velocity and peak intensity is not obvious with the number of cycles. The above studies mainly analyze the strength and deformation of rock under the action of hydraulic coupling through the form of tests, which is conducive to better clarify the mechanism of water-rock coupling, but in practical engineering, an appropriate constitutive model is needed to determine the rock deformation under the action of water-rock coupling more simply and effectively. Based on this, some scholars established a rock constitutive model considering water-rock coupling on the basis of statistical theory. Fu [17] deduced and established a statistical damage model of sandstone under the dry-wet cycle through a dry-wet cycle test of complete sandstone. Zhu [18] established a statistical model considering the initial damage of cyclic loading and unloading and the coupling damage effect of the air-dry-soaking cycle. Gao et al. [19] divided the fractured rock mass into numerous microelement cubes. The strength of the microelement cube is related to the degree of rock fracture, and the strength of each cube is randomly distributed. Therefore, the strength can reflect the degree of fracture of the fractured rock mass. In addition, it is assumed that the strength distribution of the cube obeys the Weibull distribution and the stress level satisfies the Hoek-Brown criterion. The constitutive model of the fractured rock mass of argillaceous sandstone is established based on the test result. Based on the damage mechanics/probability statistics method and the effective stress principle, Wang et al. [20] assumed that the microelement strength followed the lognormal distribution by using the M-C strength criterion, revised the relationship expression between the parameters of the model and the pore water pressure, and established a constitutive model that could reflect the damage state of saturated fine-grained sandstone more objectively. Zhou et al. [21] proposed an isotropic coupled model for hydraulic damage evolution analysis of brittle rocks based on the fine macromethod. Du et al. [22] took the internal stress as a variable to describe the deformation evolution mechanism of rock structure during the creep process and concluded that the creep deformation was affected by both strain hardening and recovery strain after analyzing the creep test results of salt rock. Li et al. [23] summarized the progress of the study on the mechanism of rock seepage, deformation, and failure and summarized the analysis model and numerical calculation of the process of water-rock coupling. The above proposed constitutive models greatly promote the development of water-rock coupling constitutive models, but most of the above models are calculated based on the existing rock strength criteria. It is well known that rocks exhibit significantly weaker strength than normal rocks under the influence of long-term water action. Therefore, the influence of hydraulic coupling must be considered in the strength criterion used in the constitutive model of sandstone.

The above research work has laid a good experimental and theoretical foundation for correctly understanding the mechanical properties of rock mass under the action of water-rock coupling. However, the research on the degradation mechanism and constitutive model of the rock mass under the action of water-rock coupling is not perfect yet. Therefore, based on the microscopic test of sandstone, the damage mechanism of sandstone is clarified in this paper. The stress state of sandstone is determined by analyzing the results of laboratory tests. The strength criterion of sandstone under the interaction of water and rock is obtained, which is introduced into the statistical damage model of sandstone considering the interaction of water and rock; thus, a relatively perfect damage constitutive model of sandstone considering the interaction of water and rock is established. The strength criterion proposed in this paper, compared with the common strength criterion, can better reflect the influence of water-rock coupling on the strength of sandstone, and only one parameter is added, which is more convenient for engineering application. Finally, the influence of the number of cycles on the model parameters was further analyzed. Compared with the existing test results, the model established can perfectly reflect the deterioration characteristics of sandstone under the water-rock coupling.

2. Analysis of Rock Degradation Mechanism under Water-Rock Coupling

Rocks are rich in fissures and pores that are usually filled with fluids, including liquid and gas phases such as water, oil, air, and natural gas. The rock (body) will deform under external loading and internal fluid pore pressure changes, as shown in Figure 1. In order to describe the mechanism

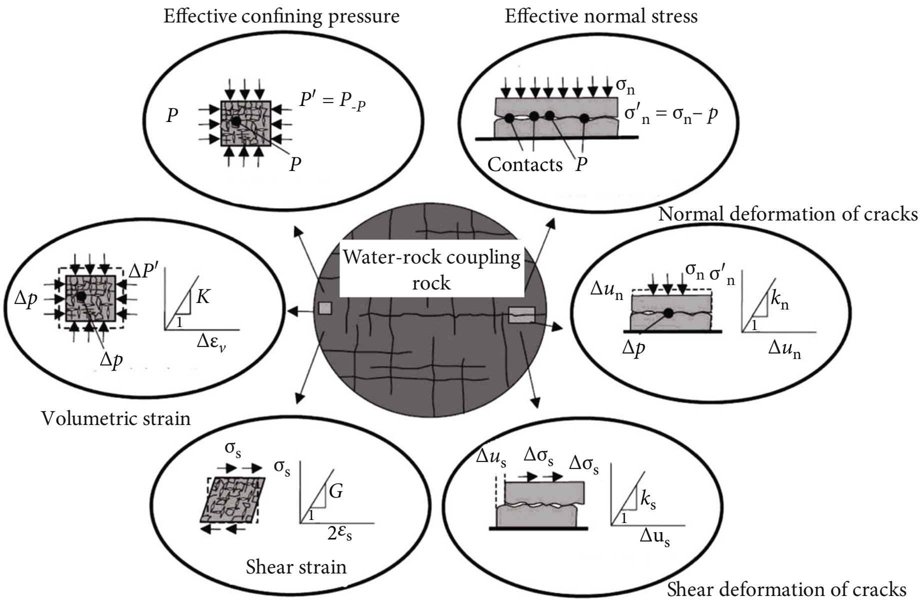
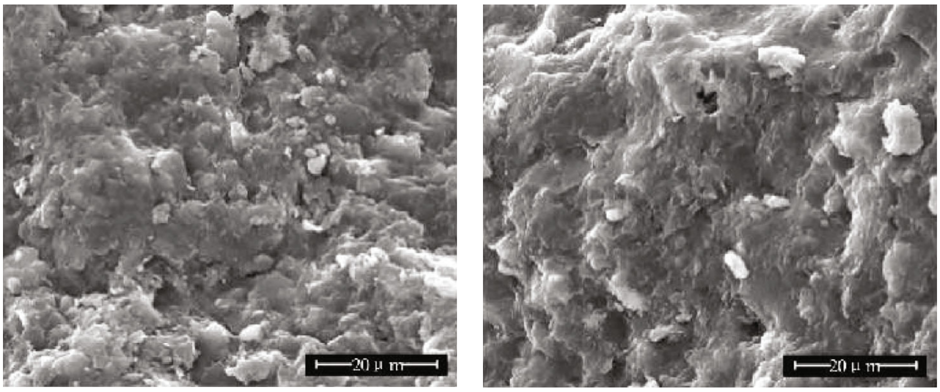


Figure 1: Deformation characteristics of rock mass under hydraulic coupling.

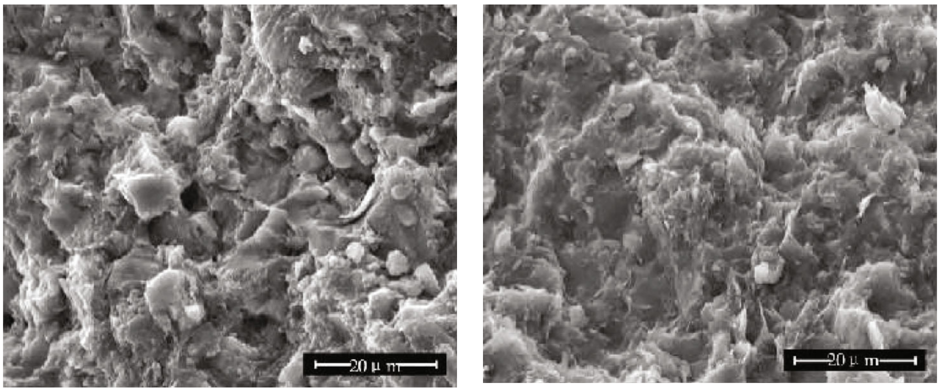
of rock strength deterioration under the coupling action of water and rock, it has become a new way to proceed from the microscopical view. To study the deterioration characteristics of mudstone and sandstone under water-rock interaction in the Jianghuai area, Tang et al. [24] conducted shear and compressive strength tests and scanning electron microscopy tests on mudstone and sandstone samples taken from shallow buried strata of the Hexu Expressway. The corresponding relationship between the pore structure and strength softening of rock under different water-loss cycles and their mutual reflection law are revealed from the macroscopic and microscopic perspectives. The microscopic experimental results are shown in Figure 2. For mudstone (Figures 2(a)–2(c)), when the number of cycles is 1, the section of the rock sample in the delineated area is not smooth, and layered peeling is found locally. There are large pores with a diameter of about 20 μm and a certain number of small pores with a diameter of less than 10 μm. Fractures are not developed, and the overall connectivity of the pores is poor. The size and shape of granular aggregates are different, and the intergranular cements are dense and have strong mechanical properties. When the number of cycles is 3, the microstructure of the rock changes significantly, the aggregate of particles gradually dissolves, and a large number of new cracks are formed, which are mostly formed on the contact surface of different mineral particles. The particles fall off obviously, the overall structure is very loose, the cementation deteriorates seriously, and some small pores are formed. After 8 cycles of saturation and water loss, the degree of cementation between mudstone particles is quite poor, the fullness of particles is very high, and the particles are arranged in a turbulent shape. The initial microcracks are fully developed, and many tiny pores run through to form microcracks, forming a quite loose mesostructure. For sandstone, by comparing the microstructure picture of sandstone with 8 cycles (Figure 2(f)) and that of sandstone with 1 cycle (Figure 2(d)), it can be found that the water-saturation cycle has a very important influence on the microstructure of sandstone. After 8 cycles, the fractures of sandstone are obviously developed, the degree of cementation between grains is quite poor, the particles are obviously detached, the number of pores is obviously increased, the overall structure is very loose, and the mechanical properties of sandstone are sharply reduced. The long-term water-rock coupling will have a significant negative impact on rock strength.

In general, the mechanism of rock under water-rock coupling is shown as follows. When a rock encounters water, the water first slowly seeps into the rock's initial cracks and pores. Because different components of rock have different expansion coefficients, under the action of water, the rock will produce uneven stress due to the uneven expansion of material, so that the state of internal stress balance of the rock is broken. The initial fissures of the rock will continue to expand under the action of uneven stress, and new fissures will be generated, resulting in the increase of the number and total area of rock fissures. With the increase of cycle indexes, water continues to flow in the rock, and the initial fracture pores are connected with the new pore fractures, so that the area and diameter of the maximum pore also show an upward trend. Furthermore, the change of pore structure in the rock caused by the water-loss cycle allows water to further penetrate into the rock and interact with it. The seepage of water in the rock will weaken the relationship between rock particles, resulting in reduced friction resistance on the joint surface inside the rock. At the same time, complex physical and chemical reactions occur between the water and rock, which further aggravates the damage and deterioration of the rock caused by the water-loss cycle. The deterioration of the rock caused by the water saturation-water loss cycle will directly affect the strength of the rock and the stability of engineering.



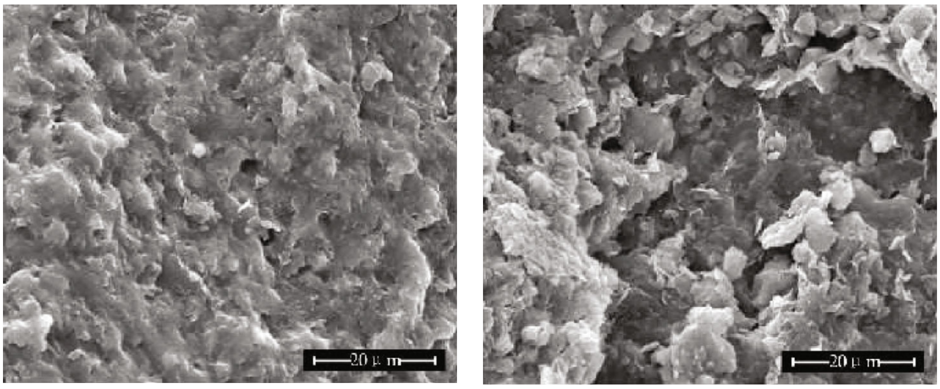
(a) The 1 cycle

(b) The 3 cycles



(c) The 8 cycles

(d) The 1 cycle



(e) The 3 cycles

(f) The 8 cycles

Figure 2: SEM test results of mudstone and sandstone under different water-rock coupling degrees (Tang et al. [24]).

3. Sandstone Failure Criterion Based on Energy Principle

3.1. Strength Criterion. According to the study of Liu et al. [25] and Xie et al. [26] under the condition of the triaxial compression of rock, the energy release is proportional to the releasable elastic strain energy stored in the rock element when the overall failure occurs. In addition, it is distributed according to the size of the minimum compressive stress difference, and the maximum rock energy release rate is along the direction of the minimum principal stress, namely, the maximum rock energy release rate G_3 is

$$G_3 = K_3(\sigma_1 - \sigma_3)U^e, \quad (1)$$

where K_3 is the material parameters of rock mass, U^e is the elastic energy, namely (Liu et al. [25]),

$$U^e = \frac{1}{2E}\left[\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\nu(\sigma_1\sigma_2 + \sigma_1\sigma_3 + \sigma_2\sigma_3)\right], \quad (2)$$

where E is the elastic modulus; ν is Poisson's ratio; and σ_1, σ_2, and σ_3 are the maximum principal stress, intermediate principal stress, and minimum principal stress, respectively.

Table 1: The parameter λ under different water and force conditions.

Porewater pressure p_w (MPa)	The parameter λ Confining pressure 10 MPa	Confining pressure 20 MPa	Confining pressure 30 MPa	Confining pressure 40 MPa
2	3.05	2.33	1.90	1.65
4	2.91	2.25	1.86	1.63
6	2.79	2.09	1.79	1.6
8	2.7	1.99	1.73	1.56

Since pore water pressure under the coupling action of water and rock weakens various mechanical parameters of the rock, compression tests of the rock under different pore water pressures and confining pressures are carried out. Therefore, a parameter about pore water pressure λ is introduced to modify Equation (1). Thus, the maximum energy release rate of rock under water and rock coupling of G_3 is

$$G_3 = \lambda K_3(\sigma_1 - \sigma_3)U^e. \tag{3}$$

Under uniaxial compression ($\lambda = 1$), the critical release rate G_c and the maximum energy release rate reached by rock unit failure G_3 are the same. Further, the critical release rate of rock can be expressed as (Liu et al. [25])

$$G_c = K_3 \frac{\sigma_c^3}{2E_0}, \tag{4}$$

where σ_c is the triaxial compressive strength of rock and E_0 is the critical elastic modulus of rock unit failure.

Combined with Equations (3) and (4), the rock failure criterion under the triaxial compression stress can be obtained:

$$(\sigma_1 - \sigma_3)\left[\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\nu(\sigma_1\sigma_2 + \sigma_1\sigma_3 + \sigma_2\sigma_3)\right] = \frac{\sigma_c^3}{\lambda}. \tag{5}$$

3.2. Hydraulic Parameter λ Evolution Law. You et al. [12] carried out the mechanical property test of sandstone under water-rock coupling. Through the analysis of the test results, it is found that the effect of water-rock coupling on Poisson's ratio of sandstone is not obvious, so it can be considered that the water-rock coupling has no effect on Poisson's ratio. Due to the introduction of parameter λ reflecting the pore pressure in the above derivation process, it is the premise to establish the strength criterion to clarify the evolution law of different confining pressures and pore pressure p_w. Since the research object in this paper is the saturated rock mass, equation (5) can be further expressed as follows according to the effective stress principle of Terzaghi:

$$\left(\sigma_1' - \sigma_3'\right)\left[\sigma_1'^2 + \sigma_2'^2 + \sigma_3'^2 - 2\nu\left(\sigma_1'\sigma_2' + \sigma_1'\sigma_3' + \sigma_2'\sigma_3'\right)\right] = \frac{\sigma_c^3}{\lambda}. \tag{6}$$

By integrating the test results and referring to Equation (6), the constant parameters can be determined as $\sigma_c = 38.02$ MPa and $\nu = 0.235$. As a macroscopic description of the rock under the water-rock coupling, hydraulic parameters λ can reasonably describe the strength evolution of the rock under the action of water-rock. Therefore, by further sorting out the test results in the literature, surrounding rock parameters under different water and force conditions can be obtained, as shown in Table 1. Under triaxial stress, the influence factors of rock strength under water-rock coupling are mainly reflected in confining pressure and pore pressure. Therefore, the influence of water-rock coupling on rock strength can be better reflected only by establishing the quantitative relationship among the three. It is found that the relation among the three can approximate satisfy the relation of the binary polynomial by analyzing the experimental results of You et al. [12], that is,

$$\lambda = a + bp_w + c\sigma_3' + dp_w^2 + e\sigma_3'^2, \tag{7}$$

where a, b, c, d, and e are the fitting parameters. Figure 3 shows the fitting results of parameters under different water and force conditions. As can be seen from the figure, the fitting results are highly close to the experimental data, so it can be considered that the binary polynomial fitting can more greatly reflect the relationship between pore pressure, confining pressure, and hydraulic parameters.

4. Rock Damage Constitutive Model

According to the theory of statistical damage mechanics, the damage variable is defined as the ratio of broken microelements N_b in rock to the total number of microelements N, and the formula is as follows (Xie [27]):

$$D = \frac{N_b}{N}. \tag{8}$$

The internal microelement failure distribution of rock under the action of external forces is random. The microelement failure probability of the test rock is related to the stress and strain state of rock, so the random variation distribution variable of rock microelement strength based on the theory of statistical damage mechanics can better reflect the change of the stress state. The distribution variable of the rock strength was selected, and the distribution function of the microelement failure probability density was set, so

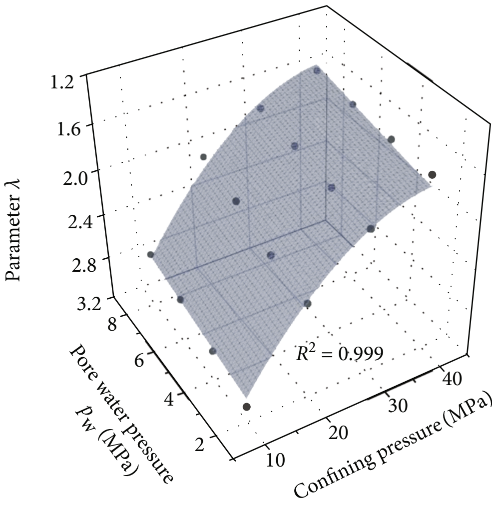


Figure 3: Fitting results of parameters under different water and force conditions.

the damage variable was expressed as

$$D = \int_0^F P(x)\mathrm{d}x. \tag{9}$$

Rock is a heterogeneous and incomplete continuous multiphase structure. Its internal structure is relatively complex, containing a large number of irregular cracks, joints, or faults, so the mechanical characteristics of each element in the rock are also different. Under normal conditions, rocks obey the generalized Hooke's law before failure; that is, they have linear elastic properties. The strength obeys Weibull random distribution, and its probability density distribution function can be expressed as

$$P(F) = \frac{m}{F_0}\left(\frac{F}{F_0}\right)^{m-1} \exp\left(-\left(\frac{F}{F_0}\right)^m\right), \tag{10}$$

where m and F_0 are distribution parameters related to mechanical properties of rock materials.

Combining Equations (8)–(10), the expression of the damage variable is as follows:

$$D = \frac{N[1 - \exp(-(F/F_0)^m)]}{N} = 1 - \exp\left(-\left(\frac{F}{F_0}\right)^m\right). \tag{11}$$

According to the strain equivalence hypothesis, if the strain before and after deformation is equivalent, the damage constitutive relation of the rock is

$$[\sigma^*] = \frac{[\sigma]}{1 - D} = \frac{[C][\varepsilon]}{1 - D}, \tag{12}$$

where $[\sigma^*]$ is the effective stress matrix of rock, $[\sigma]$ is the nominal stress matrix of rock, D is the damage variable of rock, $[C]$ is the elastic matrix, and $[\varepsilon]$ is the strain matrix of rock (Lemaitre and Chaboche [28]).

To consider the mechanical characteristics under the water-rock coupling, the original stress state is changed to effective stress. The axial stress σ_1' and axial strain ξ_1 under equal confining pressure can be expressed as

$$\sigma_1' = E\xi_1(1 - D) + 2\nu\sigma_3' = E\xi_1 \exp\left(-\left(\frac{F}{F_0}\right)^m\right) + 2\nu\sigma_3'. \tag{13}$$

Further adjusting Equation (12), it can be obtained as

$$\xi_1 = \frac{1}{E}\left(\sigma_1' - 2\nu\sigma_3'\right) = \frac{\sigma_1' - 2\nu\sigma_3'}{E\exp(-(F/F_0)^m)}. \tag{14}$$

The strength criterion shown in Equation (7) is put into Equation (11), and the expression of the damage variable of sandstone considering water-rock coupling under constant confining stress is as follows:

$$D = 1 - \exp\left(-\left(\frac{\left(\sigma_1' - \sigma_3'\right)\left[{\sigma'}_1^2 + 2{\sigma'}_3^2 - 2\nu\left(2\sigma_1'\sigma_3' + {\sigma'^2}_3\right)\right] - \sigma_c^3/\lambda^3}{F_0}\right)^m\right). \tag{15}$$

The above equation is the damage evolution of rock, and the rock constitutive equation based on statistical damage mechanics can be obtained by combining Equations (7) and (14):

$$\xi_1 = \frac{\sigma_1' - 2\nu\sigma_3'}{E\exp\left(-\left(\left(\left(\sigma_1' - \sigma_3'\right)\left[{\sigma'}_1^2 + 2{\sigma'}_3^2 - 2\nu\left(2\sigma_1'\sigma_3' + {\sigma'^2}_3\right)\right] - \sigma_c^3/\lambda^3\right)/F_0\right)^m\right)}. \tag{16}$$

5. Determination of Parameters of Model for Sandstone

The key to the establishment of the above constitutive relation is to determine the Weibull distribution parameters. At present, there are mainly two ways to solve the above parameters using the statistical model: one is to use the data fitting method to solve the parameters and the other is to determine the derivative characteristics of the peak point of the rock stress-strain curve. Although the direct solution method has strict significance, the solution process is complicated, the fitting solution method is simple, and the fitting effect is better but cannot strictly meet the solution conditions. Therefore, this paper proposes the idea of a model solution for the above solution methods.

Transposition of Equation (14) can be obtained:

$$\ln\left(\frac{\sigma_1' - 2\nu\sigma_3'}{E\xi_1}\right) = -\left(\frac{F}{F_0}\right)^m. \tag{17}$$

Taking the logarithm of both sides of Equation (16), it can be obtained:

$$\ln\left[-\ln\left(\frac{\sigma_1' - 2\nu\sigma_3'}{E\xi_1}\right)\right] = m\ln F - m\ln F_0. \tag{18}$$

For Equation (18), assume the following:

$$\left.\begin{aligned} y &= \ln\left[-\ln\left(\frac{\sigma_1' - 2\nu\sigma_3'}{E\xi_1}\right)\right] \\ x &= \ln F \\ t &= m \\ n &= -m\ln F_0 \end{aligned}\right\}, \tag{19}$$

where t is the slope and n is the intercept.

Equation (18) is equivalent to the linear equation, which is

$$y = tx + n. \tag{20}$$

The data of the water-rock coupling sandstone stress-strain test are substituted into the first two equations of Equation (18) to obtain a set of data of (x,y). The slope t and intercept n of the linear fitting line are obtained, and then, the parameters m and F_0 are obtained by backward derivation according to the last two equations of Equation (19).

The above is the specific idea of the first fitting to solve the Weibull distribution function, and the second numerical method will be described below. Assuming that the stress and strain at the peak point of rock are, respectively,σ_{p} andξ_{p}, according to the derivative characteristics of the rock stress-strain curve at the extreme point, the geometric conditions of the sandstone stress-strain model curve are as follows:

$$\left.\begin{aligned} \sigma_{\mathrm{p}}' &= \sigma_1' \\ \frac{\mathrm{d}\sigma}{\mathrm{d}\xi_{\mathrm{p}}} &= 0 \end{aligned}\right\}. \tag{21}$$

In combination with Equations (14) and (21), the parameters m and F_0 of the constitutive model under the water-rock coupling strength criterion can be obtained.

6. Model Validation

When calculating rock failure strength, the Mohr-Coulomb (M-C) failure criterion, Drucker-Prager (D-P) failure criterion, or Hoek-Brown (H-B) failure criterion derived from engineering experience are generally used to judge whether the rock has been destroyed. To better reflect the failure mechanism of rock water-rock coupling and reflect the failure criterion related to rock material and stress state, a failure criterion suitable for sandstone under the action of water-rock coupling is deduced. Equation (6) is an energy failure criterion applicable to sandstone under water-rock coupling, as well as a parameter related to rock material and stress state. To verify the correctness of the criterion, the theoretical failure strength of sandstone under different water-rock coupling conditions is calculated by Equation (6) and compared with the test results. The accuracy of this criterion is compared with that of Mohr-Coulomb equal area circle D-P criterion in reflecting the water-rock coupling strength criterion. The revised D-P criterion expression is

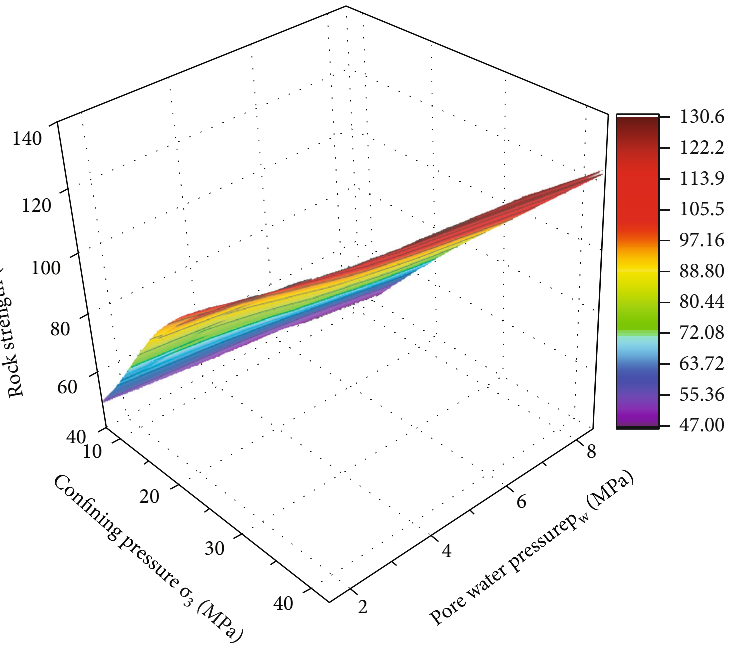
$$\begin{cases} F = \alpha I_1 + \sqrt{J_2} = k, \\ I_1 = \sigma_1' + \sigma_2' + \sigma_3', \\ \sqrt{J_2} = \sqrt{\dfrac{1}{6}\left[\left(\sigma_1' - \sigma_2'\right)^2 + \left(\sigma_2' - \sigma_3'\right)^2 + \left(\sigma_1' - \sigma_3'\right)^2\right]}, \\ \alpha = \dfrac{2\sqrt{3}\sin\varphi}{\sqrt{2\sqrt{3}\pi(9-\sin^2\varphi)}}, \\ k = \dfrac{6\sqrt{3}c\cos\varphi}{\sqrt{2\sqrt{3}\pi(9-\sin^2\varphi)}}. \end{cases} \tag{22}$$

The strength parameters c and φ required by the D-P failure criterion are calculated, $c = 11.86\mathrm{MPa}$ and $\varphi = 33.94^\circ$, respectively. The comparison results are shown in Figure 4. The results show that under the action of different confining pressures and pore water pressures, the peak strength test value and theoretical calculation value of rock in the triaxial compression test are compared and analyzed. The results show that the theoretical calculated failure strength of the rock failure criterion and the D-P and H-B failure criteria under water-rock coupling are all smaller than the experimental failure strength.

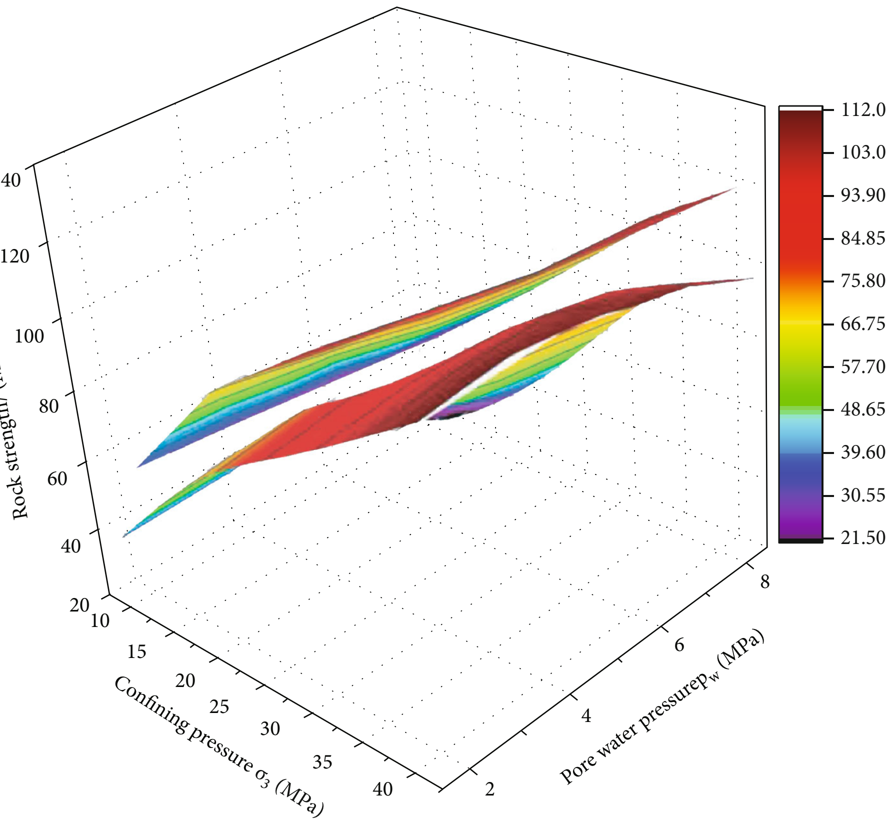
To specifically analyze the calculation effect of the model, the model deviation is analyzed here, and the calculation formula is as follows:

$$\delta = \frac{\sum_{i=1}^{n'}\left|\sigma_i^{th} - \sigma_i^{te}\right|}{n'}, \tag{23}$$

where δ is the relative error,σ_i^{th} is the theoretical stress under the same strain, σ_i^{te} is the laboratory test stress, and n' is the number of data points. For simplicity, only pore water pressure p_{w} of 2 MPa is taken as an example here, and the results are shown in Table 2. Comparatively speaking, the error of the failure criterion used in this paper is within 5% compared with the actual test value. The other two failure criteria are far less than the test values, and the maximum error values are 35.34% and 37.11%, respectively, while the minimum error of the failure criteria in this paper is 0.35%. Therefore, the failure criterion based on the energy principle can basically reflect the real situation of rock as the failure criterion of rock under water coupling.

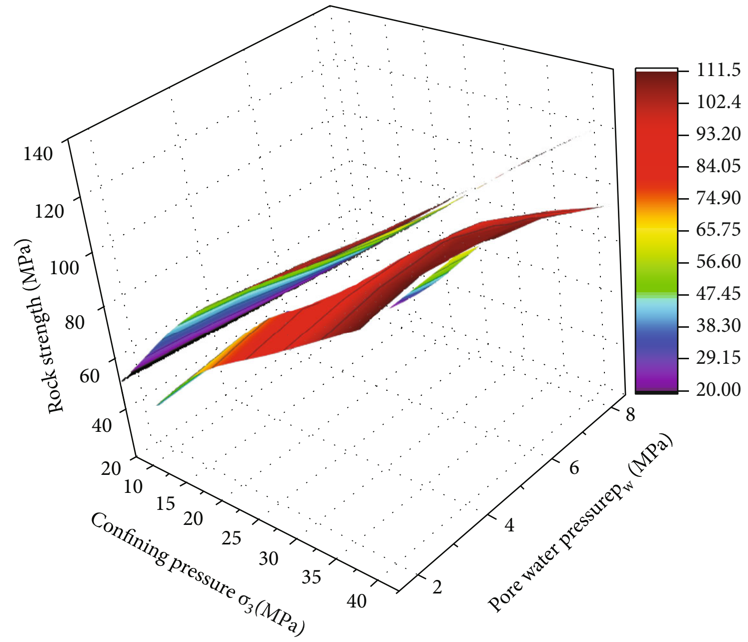


(a) The failure criterion of this paper



(b) The H-B failure criterion

Figure 4: Continued.

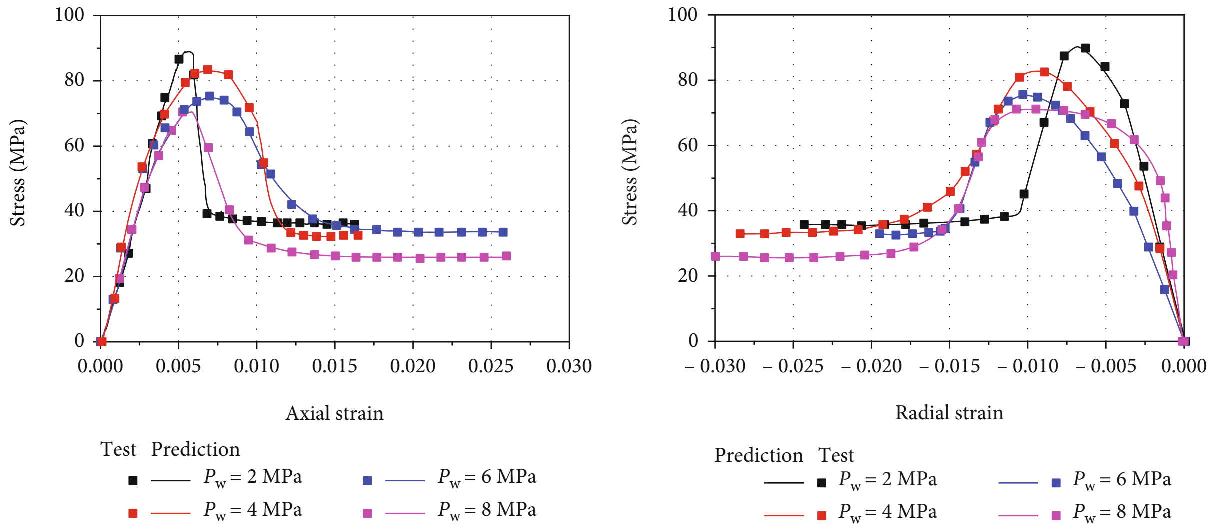


(c) The D-P failure criterion

Figure 4: Comparison between different failure criteria and test results.

Table 2: Model-relative error results.

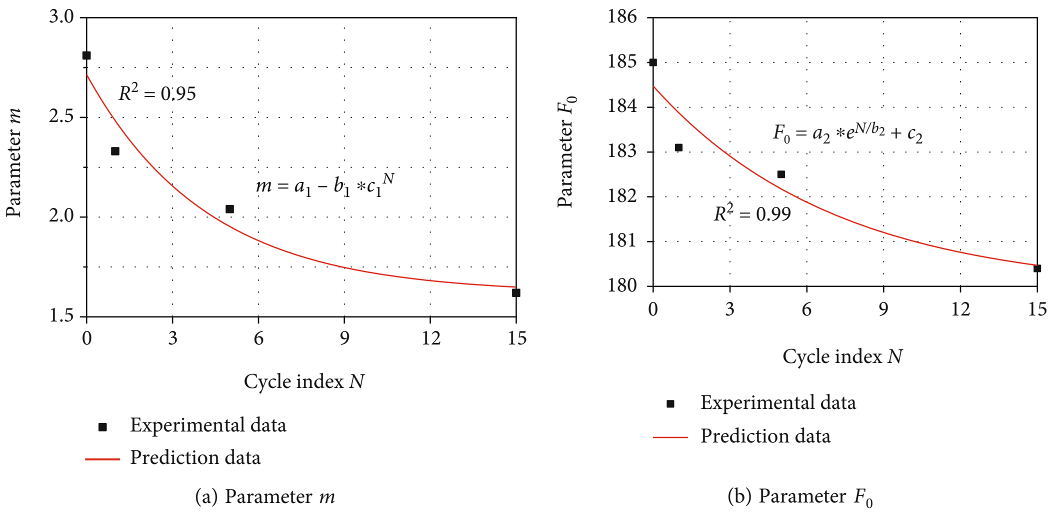
Failure criterion	The parameterλ Confining pressure 10 MPa	Confining pressure 20 MPa	Confining pressure 30 MPa	Confining pressure 40 MPa
Water-rock coupling	0.95	-2.5	-0.53	0.77
D-P	17.14	18.82	22.49	22.79
H-B	16.32	17.92	21.42	21.7



(a) Axial strain prediction

(b) Radial strain prediction

Figure 5: Comparison of preexperimental results of model-predicted values.



(a) Parameter m

(b) Parameter F_0

Figure 6: The change of constitutive equation parameters under different conditions of wetting and drying cycles.

The stress-strain curves of sandstone samples under the water-rock coupling action are fitted and solved according to the above process method, and the corresponding m and F_0 of the curves can be obtained. Combined with Equation (16), the stress-strain relationship of sandstone is predicted. As seen from Figure 5, the constitutive equation of the fractured rock mass of argillaceous sandstone proposed in this paper can well reflect the actual mechanical behaviour of the fractured rock mass of argillaceous sandstone. The initial deformation modulus and peak strength of the fractured rock mass are roughly the same as those of the test, and the model curve is basically consistent with the test results. When the confining pressure is low, the difference between the theoretical strain value of the model and the actual strain value of the same stress value is large, but with the increase of the confining pressure, the difference becomes smaller, and the simulation accuracy of the model curve to the test results increases with the increase of the confining pressure.

7. Model Parameter Analysis

The parameters$m$andF_0in the above damage models of rock deformation are as shown in Figure 6. Thus, it can be seen that its characteristics are as follows:

1. The peak value of the stress-strain curve increases with the increase of m and F_0, but the change of m and F_0 does not change the linear deformation curve before the peak value
2. The influence of m and F_0 on the nonlinear deformation of the stress-strain curve, especially after the peak value, is obvious, and the shape of the curve can be changed

The above characteristics reflect the impact of m and F_0 on the stress-strain curve of rock. The physical significance of parameter m can be understood as an indicator of the brittleness degree of rock. The larger the value of m is, the stronger the brittleness degree is. The physical significance of parameter F_0 can be understood as an indicator of the macroscopic average strength of rock (Wu and Zhang [29]). Liu [30] carried out stress-strain characteristics under different cycling conditions through triaxial compression tests of rocks under different dry-wet cycling conditions. To vividly show the effect of the water-rock cyclic action on lithology deterioration, m and F_0 are taken as the vertical coordinates and the number of water-rock cyclic action (N) as the horizontal coordinates, as shown in Figure 6. According to the distribution characteristics of the test data points in the figure above, the relationship between $N - m$ and $N - F_0$ is fitted. Finally, the relationship between the m and F_0 values of sandstone and the number of water-rock cyclic action (N) is obtained as

$$m = a_1 - b_1 * c_1^N, \tag{24}$$

$$F_0 = a_2 * e^{N/b_2} + c_2, \tag{25}$$

where m and F_0 are the model parameters of water-saturated sandstone after N cycles.

From Equations (24) and (25), the model parameter m value of sandstone after water-rock cycling is a function of m_0 and N, namely, $m = f(m_0, N)$; F_0 is a function of F_{00} and N, that is, $F_0 = f(F_{00}, N)$.

According to Figure 6, as well as Equations (24) and (25), the shear strength of sandstone is degraded by the water-rock cycle, and the mechanical properties gradually decline with the increase of the water-rock cycle. Table 3 shows the deterioration analysis results of model parameter m of sandstone under the water-rock coupling action. In the table, the total deterioration is $D_i = (c_0 - c_i)/c_0 \times 100\%$, the stage deterioration is $\Delta D_i = (D_i - D_{i-1})$, and the single cycle deterioration within the stage is $\Delta D_i/(N_i - N_{i-1})$.

The degradation of model parameter m is nearly 17.08% after a single water-rock cycle. With the increase of the number of water-rock cycles, the degradation of model parameter M is gradually deepened; for example, it has reached 42.35%

Table 3: Analysis of the deterioration of the parameter m of sandstone under the effect of water-rock interaction.

Cycle index N	Parameter m	Test stage no. i	Total degree of degradation D_i	Stage deterioration degree Δ D_i	Degree of single cycle deterioration
0	2.81	0	0.00	0.00	0.00
1	2.33	1	17.08	17.08	17.08
5	2.04	2	27.40	10.32	2.58
15	1.62	3	42.35	14.95	1.50

Table 4: Analysis of the deterioration of the parameter F_0 of sandstone under the effect of water-rock interaction.

Cycle index N	Parameter F_0	Test stage no. i	Total degree of degradation D_i	Stage deterioration degree ΔD_i	Degree of single cycle deterioration
0	185.0	0	0	0.00	0.00
1	183.1	1	1.03	1.03	1.03
5	182.5	2	1.35	0.32	0.08
15	180.4	3	2.49	1.14	0.11

after 15 cycles. However, the degradation of the single cycle gradually decreased from 17.08%/time to 1.50%/time. It can be concluded that in the early stage of the water-rock cycle, the physical and chemical damage of sandstone caused by water-rock interaction is great, the model parameters are obviously affected, and their changes show a rapid and greatly decreasing trend. With the increase of the number of action and the extension of the action time, the physical and chemical damage effect of water-rock action on rock decreases, the influence of model parameters decreases, and the variation tends to be gentle.

According to geological knowledge, rock or rock mass in nature that is repeatedly soaked by the water-drying cycle will eventually decompose into soil or silt. At the same time, according to the stress-strain relationship of sandstone, the curve shape becomes steeper with the increase of m, and the postpeak stress-strain process and fracture velocity are relatively intensified, indicating that the brittleness of the material is enhanced. According to the fitting Equation (24), with the increase of the number of cyclic actions, m gradually decreases, which is consistent with its influence on the stress-strain curve.

Table 4 shows the deterioration analysis results of model parameter F_0 of sandstone under the water-rock coupling action. In the table, the total deterioration is $D_i = (c_0 - c_i)/c_0 \times 100\%$, the stage deterioration is $\Delta D_i = (D_i - D_{i-1})$, and the single cycle deterioration within the stage is $\Delta D_i/(N_i - N_{i-1})$. After one water-rock cycle, the model parameter F_0 decreased slightly, and the degradation of F_0 was 1.03% after a single cycle. With the increase of the number of the water-rock cycle, the degradation of the model parameter F_0 gradually deepened; for example, it reached 2.49% after 15 cycles. However, the degradation of the single cycle gradually decreased from 1.03%/time to 0.11%/time. Therefore, with the increase of the number of action and the extension of the action time, the physical and chemical damage effect of the water-rock action on rock decreases, the model parameter F_0 is less affected, and its change basically remains flat.

8. Conclusions

(1) Through the analysis of the rock microtest results, it is found that the long-term water-rock coupling leads to the obvious development of fractures in the rock mass, the poor degree of cementation between particles, the obvious detachment of particles, and the loose overall structure, which have a significant negative impact on the rock strength

(2) A strength criterion considering the influence of water-force coupling parameters was proposed and compared with the experimental results; the superiority of the strength criterion proposed in this paper compared with the H-B and D-P strength criteria in simulating sandstone hydraulic coupling was verified

(3) The damage statistical model of sandstone considering the water-rock coupling is in consistent with the test curve, indicating that the analysis idea of considering the influence of the water-rock interaction process on the rock stress strain curve is reasonable and feasible and can well reflect the deterioration damage effect of circulating water-rock interaction on sandstone

(4) By establishing the quantitative relationship between hydraulic pressure cycle times and model parameters, the deterioration mechanism of sandstone strength caused by water-rock coupling is further clarified from a macroscopic perspective. As the number of cycles increases, the model parameters m and F_0 decrease. This reflects the mechanical properties of sandstone under water-rock coupling, which is consistent with the actual deformation and failure characteristics of sandstone under water-rock coupling

Data Availability

The experimental data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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