

Article

Effects of Hydro-Softening and Confining Pressure on the Mechanical Response and Energy-Damage Mechanisms of Argillaceous Sandstone

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Abstract

To investigate the mechanical response and energy-damage evolution of argillaceous sandstone under coupled hydro-softening and confining pressure effects, triaxial compression tests were conducted under different water contents (0%, 3.1%, 6.2%, and 9.3%) and confining pressures (0, 3, 6, 10, and 15 MPa). The stress–strain characteristics, failure modes, strength criteria, and energy evolution laws were systematically analyzed. The results show that argillaceous sandstone exhibits a pronounced hydro-softening effect. When the water content increased from 0% to 9.3%, the peak strength decreased by 28.5–50.3% under different confining pressures, with more significant deterioration at the low-water-content stage. Increasing the confining pressure from 0 to 15 MPa increased the peak strength by 180–240% and enhanced the plastic deformation capacity, partly offsetting the weakening induced by hydro-softening. Regression analyses indicate that the exponential strength criterion provides the best applicability for the triaxial strength of argillaceous sandstone. The proposed water-content-modified exponential strength criterion can characterize both hydro-softening and confining pressure effects, with an average relative error of 2.11% and a maximum relative error of 4.70%. Energy analysis shows that increasing water content reduced the elastic energy storage capacity; under uniaxial compression, the peak elastic strain energy at 9.3% water content was 64.4% lower than that in the dry state. The energy-based damage model can describe the pre-peak damage evolution and stress response of argillaceous sandstone. The results can provide a theoretical basis for the stability evaluation of surrounding rock in water-rich soft rock underground engineering.

Keywords: argillaceous sandstone; hydro-softening; triaxial compression test; energy evolution; damage characterization model



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1. Introduction

In underground engineering, such as deep-buried tunnels, mining roadways, and underground caverns, engineering rock masses are commonly subjected to the combined effects of groundwater infiltration and high confining pressure [1,2]. Under hydro-softening, the cementation structure inside the rock mass deteriorates and crack propagation is intensified, while confining pressure significantly changes its mechanical response and failure mode [3]. The combined action of these two factors introduces considerable uncertainty

into the mechanical behavior and energy-damage evolution of surrounding rocks. This phenomenon is particularly pronounced in argillaceous sandstone, a typical weakly cemented sedimentary rock, posing serious safety risks to the construction and operation of deep underground engineering [4,5]. Therefore, investigating the mechanical response and damage evolution of argillaceous sandstone under hydro-softening and confining pressure effects is of great significance for guiding surrounding rock stability control in water-rich soft rock underground engineering, and has become a key issue in deep surrounding rock stability control and disaster prevention.

Regarding the influence of groundwater on rock mechanical properties, many studies have examined macroscopic strength, deformation parameters, crack evolution, and microstructural deterioration. Ma et al. [6] found that repeated drying–wetting cycles promoted damage accumulation, crack development, and deterioration of sandstone mechanical properties. Li et al. [7] investigated sandstone failure under different water contents using acoustic emission and multifractal analysis, and reported that increasing water content changed crack evolution and energy release during loading. Huang et al. [8] further showed that the uniaxial and triaxial compressive strengths of clay-bearing red sandstone decreased significantly with increasing water content, mainly due to swelling of water-sensitive clay minerals and weakening of cementation. Similar water-weakening effects, including strength reduction, structural deterioration, and failure-mode transformation, have also been reported for swelling mudstone and mudstone [9,10].

Engineering rock masses are often subjected to three-dimensional stress conditions, and confining pressure has a coupled regulating effect on hydro-softening. Pore and crack compaction under confining pressure can inhibit crack propagation and coalescence, thereby improving rock bearing capacity [11]. Recent studies on soft rocks and fissured sandstones have shown that water–rock interaction promotes pore development, microcrack coalescence, and macroscopic strength deterioration, whereas confining pressure or stress state changes the evolution of this deterioration [12–14]. Liang et al. [15] found that water content significantly affected sandstone strength, deformation, and failure mode under triaxial compression, while increasing confining pressure promoted the transition from tensile-dominated to shear-dominated failure and enhanced post-peak deformation capacity. Ren et al. [16] showed that confining pressure strengthening and pore water pressure weakening jointly controlled the response of saturated sandstone. Zhou et al. [5] further reported that the peak strength, residual strength, and elastic modulus of argillaceous sandstone decreased with wetting degree, whereas confining pressure partly weakened the water-softening effect on elastic modulus.

Rock strength criteria are important for surrounding rock stability evaluation and support design. Under conventional triaxial stress conditions, rock strength is strongly affected by confining pressure, and the failure envelope usually exhibits nonlinear characteristics [17,18]. Carter et al. [19] compared several intact rock strength criteria and pointed out that different functional forms show different applicability under low- and high-confining-pressure conditions. In addition, under hydro-mechanical coupling, water content further alters cementation, pore structure, and the effective load-bearing skeleton, making strength envelope evolution more complex [20,21]. Accordingly, some studies have evaluated or modified rock strength criteria by considering hydro-mechanical coupling or complex occurrence conditions. For example, Chen et al. [22] investigated the effective stress coefficient of sandstone based on the effective stress principle and the Mohr–Coulomb criterion, while Yun et al. [23] analyzed commonly used strength criteria for softened mudstone and established a strength prediction model considering water content.

Using stress–strain relationships, mechanical parameters, and strength criteria to describe the mechanical characteristics and damage evolution of rocks is relatively intuitive.

However, from the perspective of thermodynamics, rock failure is essentially a process of energy transformation [24,25]. Therefore, investigating energy evolution during rock damage helps reveal the mechanism of instability and failure. Xie et al. [26] discussed rock damage and catastrophic failure from an energy perspective and noted that energy dissipation can describe damage development. Liu et al. [27] found that increasing water content changed the energy distribution of sandstone during uniaxial compression. Related studies have also shown that energy analysis can be used for rock instability identification, energy storage and release evaluation, and rockburst proneness characterization, while the water-bearing state further affects energy storage, dissipation, and release characteristics [28,29].

In summary, existing studies have revealed the effects of water–rock interaction on rock mechanical behavior from various perspectives. However, most existing hydro-softening models are developed by matching or modifying a specific strength criterion and mainly focus on water-induced weakening, while the combined effects of confining-pressure-induced nonlinear strengthening and water-induced deterioration have not been fully incorporated. Therefore, conventional triaxial compression tests were conducted on argillaceous sandstone under different water contents and confining pressures. The mechanical parameters, deformation characteristics, failure modes, and energy evolution laws were systematically analyzed. The applicability of different strength criteria was evaluated, and a water-content-modified exponential strength criterion was established. By introducing both a water-content deterioration term and a confining-pressure strengthening term, this criterion describes the downward shift in the strength envelope caused by hydro-softening and the nonlinear strength increase induced by confining pressure within a unified framework. Furthermore, an energy-based damage characterization model considering hydro-softening and confining-pressure effects was constructed based on dissipated energy and peak total strain energy. The results are expected to provide a theoretical reference for underground engineering practice in water-rich soft rock.

2. Experimental Preparation and Testing Program

The rock samples used in this study were collected from Dazhou, Sichuan Province, China, located at the northeastern margin of the Sichuan Basin. This region is characterized by the widespread development of clastic sedimentary strata of the Jurassic and Triassic systems, in which sandstone, mudstone, siltstone, and transitional lithologies are commonly found. Argillaceous sandstone commonly constitutes the primary surrounding rock in tunnels and mine roadways, with engineering burial depths generally ranging from 100 to 700 m. In addition, the study area is characterized by a typical subtropical humid monsoon climate, abundant precipitation, and well-developed river systems. Therefore, argillaceous sandstone in this region is frequently subjected to the combined effects of groundwater infiltration, rainfall recharge, and in situ stress confinement in underground engineering.

To ensure the reliability of the experimental results, intact rock blocks with relatively good homogeneity were selected for specimen preparation. Following the recommendations of the International Society for Rock Mechanics (ISRM) and the Standard for Test Methods of Engineering Rock Masses (GB/T 50266-2013), the rock blocks were cored and machined into standard cylindrical specimens with a diameter of 50 mm and a height of 100 mm. Prior to water-conditioning treatment, all specimens were dried in an oven at 105 °C for 24 h, cooled to room temperature in a desiccator, and then weighed. Based on the target moisture condition, the specimens were divided into four groups with water contents of 0% (dry), 3.1%, 6.2%, and 9.3% (saturated), respectively. For each test condition, three replicate specimens were prepared and tested. The saturated group was prepared by the free-immersion method. Specifically, the specimens were immersed in water for 48 h, after which the surface water was gently removed and the specimens were weighed.

The relationship between immersion duration and water content is shown in Figure 1. As indicated in the figure, the water content remained nearly unchanged with further increases in immersion duration after approximately 30 h of immersion. For the intermediate water-content groups (3.1% and 6.2%), the required water absorption mass ($m_w - m_d$) was calculated based on the target water content and the initial dry mass of each specimen according to the water-content equation: $w = (m_w - m_d) / m_d \times 100\%$. During immersion, the surface moisture of each specimen was removed at 5 min intervals, and the specimen was weighed until the target mass was reached. After preparation, all conditioned specimens were sealed with plastic wrap and stored for 48 h to prevent moisture loss or gain due to air exposure and to allow the water to redistribute uniformly within the rock. To verify the internal moisture uniformity of the specimens after 48 h of sealed conditioning, additional specimens with different water contents were prepared using the same procedure. Each specimen was evenly divided into upper, middle, and lower segments along the height direction. The mass of each segment was measured, and the water content of each segment was determined using the oven-drying method. The water contents of the different segments were close to the target values, with only minor differences among the upper, middle, and lower segments, indicating that the moisture distribution was generally uniform. The final prepared specimens are shown in Figure 2. The mineralogical composition of the argillaceous sandstone was determined by X-ray diffraction (XRD), and the results are shown in Figure 3. The rock is mainly composed of quartz, plagioclase, potassium feldspar, calcite, chlorite, and kaolinite. Among these minerals, quartz, plagioclase, and potassium feldspar account for 75.3% in total and form the main load-bearing framework of the rock. In contrast, chlorite and kaolinite together account for 18.8% and belong to water-sensitive clay minerals. These clay minerals are susceptible to swelling and softening upon water absorption, which is considered a key factor responsible for the degradation of the mechanical properties of argillaceous sandstone under wet conditions [30].

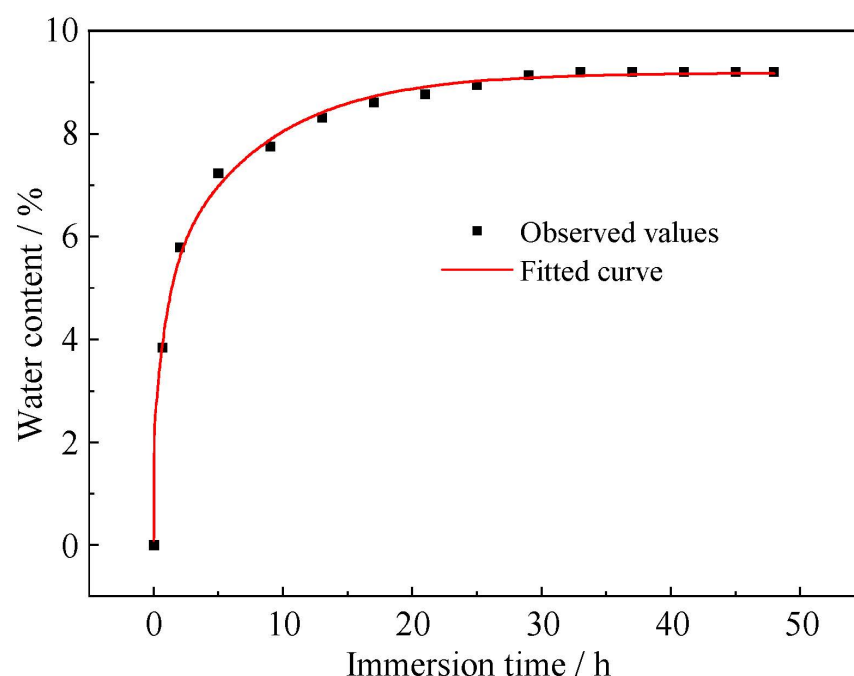


Figure 1. Relationship between water content and soaking time.



Figure 2. Argillaceous sandstone specimens.

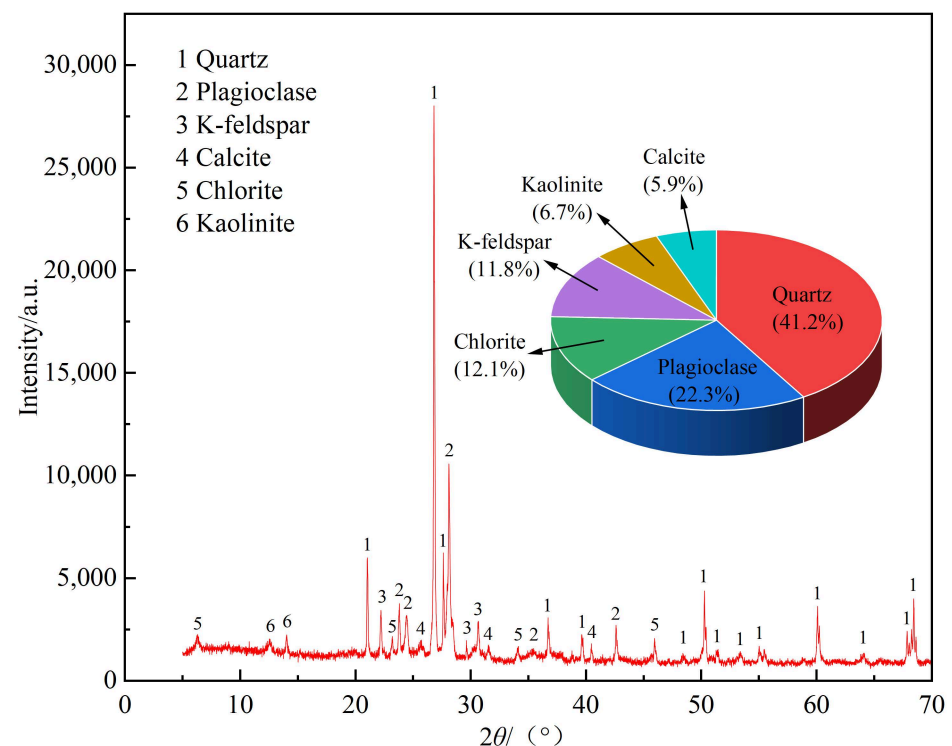


Figure 3. XRD and mineral composition of argillaceous sandstone.

The experiments were conducted using a ZYSS2000 rock triaxial high-pressure creep testing system (Figure 4). The apparatus consists mainly of four components: a triaxial testing machine, a hydraulic servo controller, an operation control system, and a hydraulic oil cylinder. It provides a maximum axial load of 2000 kN ($<\pm 1\%$ F.S.) and a maximum confining pressure of 60 MPa ($<\pm 2\%$ F.S.), and is equipped with high-precision axial and circumferential deformation measurement systems. Considering the typical burial-depth range of underground soft-rock engineering in the Dazhou area, the confining pressure levels adopted in the tests were 0, 3, 6, 10, and 15 MPa. Before testing, each specimen was wrapped with a heat-shrink tube, placed on the base of the pressure chamber, covered with the spherical loading seat, and sealed using a hot-air gun. The axial extensometer was fixed parallel to the specimen axis, while the circumferential extensometer was installed around

the middle height of the specimen. Each extensometer was carefully adjusted to ensure firm contact with the specimen surface and stable initial readings. After installation in the testing system, an axial preload of 1 kN was first applied to ensure good contact between the specimen ends and the loading platens. The confining pressure was then applied at a rate of 0.05 MPa/s to the target value and maintained constant. Subsequently, axial loading was applied at a rate of 0.5 mm/min until specimen failure.

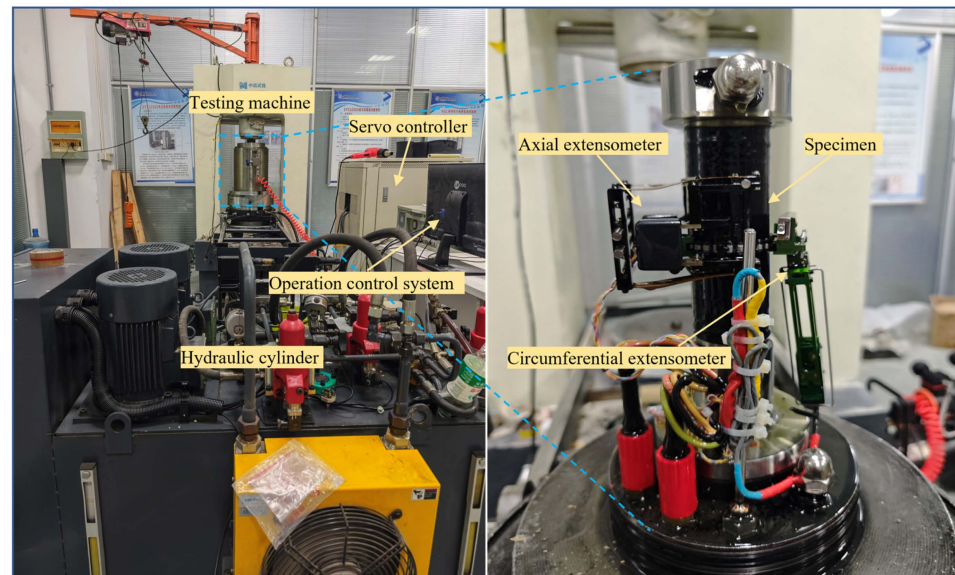


Figure 4. ZYSS2000 Rock Triaxial High-Pressure Creep Testing System.

3. Experimental Results and Analysis

3.1. Stress–Strain Curve Characteristics

Figure 5 illustrates the stress–strain characteristics of argillaceous sandstone under different test conditions. For each test condition, the stress–strain curve was obtained by extracting the stress values at identical axial strain levels from the valid replicate curves and then averaging the stress values at each strain level. Overall, under the same confining pressure, the peak strength of argillaceous sandstone decreases with increasing water content, indicating a pronounced hydro-softening effect. In contrast, an increase in confining pressure significantly enhances the rock strength, and this strengthening effect becomes more evident at higher water contents. When the water content is 0–3.1%, increasing the confining pressure from 0 MPa to 15 MPa results in an average increase of 180% in peak strength; when the water content is 6.2–9.3%, the average increase rises to 240%. Conversely, the strength deterioration induced by increasing water content is alleviated under higher confining pressures. Under low confining pressures (0–6 MPa), when the water content increases from 0% to 9.3%, the average reduction in peak strength is 40%; under high confining pressures (10–15 MPa), the average reduction decreases to 29%. This indicates that the mechanical response of argillaceous sandstone is significantly governed by the coupled effect between water content and confining pressure. In addition, with increasing confining pressure, the peak strain of the specimens increases accordingly, the pre-peak plastic deformation stage is prolonged, and the post-peak stress-softening rate decreases. These results indicate that confining pressure suppresses the propagation of microcracks through lateral confinement, thereby enhancing both the strength and plastic deformation capacity of the argillaceous sandstone.

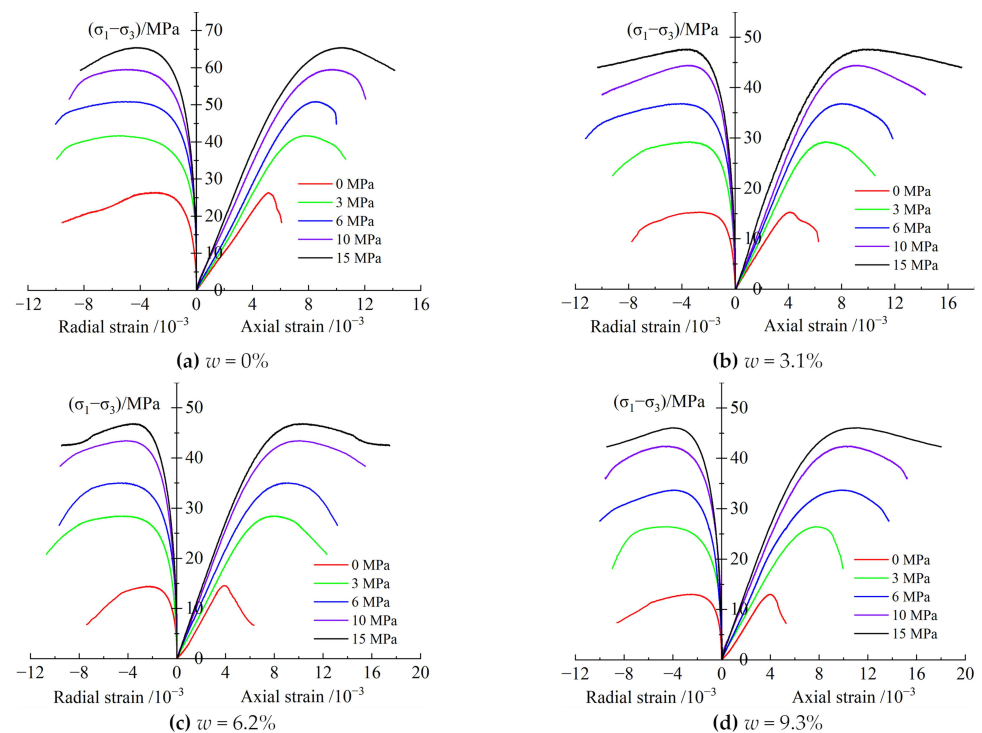


Figure 5. Stress–strain curves of argillaceous sandstone under different conditions.

3.2. Coupling Effects and Correlation Analysis

As shown in Figure 6, the relationship between water content and peak strength exhibits an exponential decay pattern, characterized by a rapid initial decrease followed by a gradual flattening ($a + b \exp(-kw)$). When the water content increases from 0% to 9.3%, the peak strength of the specimens under all confining pressure levels decreases significantly, with a reduction ranging from 28.5% to 50.3%, indicating that water content has a substantial influence on rock strength and that the argillaceous sandstone is highly water-sensitive. Taking the confining pressure of 6 MPa as an example, when the water content increases from 0% to 3.1%, the peak strength decreases by 27.5%; when it further increases from 3.1% to 6.2% and from 6.2% to 9.3%, the reductions are only 5.0% and 3.6%, respectively. This suggests that the hydrological strength degradation of argillaceous sandstone mainly occurs during the initial stage of water immersion, whereas the deterioration effect decreases markedly during the later stage.

As shown in Figure 7, the relationship between the softening coefficient and water content follows a power-law decay trend, with a steep decrease at low water content and a slower decline at higher water content. This phenomenon is related to the hydration swelling of clay minerals, the enhanced lubricating effect of water films between particles, and the reduction in cementation strength in argillaceous sandstone. However, with further increase in water content, the structural weakening space caused by hydration becomes limited, and the strength attenuation therefore tends to level off. Previous studies [31] have pointed out that, in practical engineering, the water-bearing conditions of rock masses are often complex and do not necessarily correspond to a fully saturated state. Therefore, the concept of the softening coefficient under different water contents ($k = f_w / f_d$) is introduced. Here, k is the softening coefficient, f_w is the compressive strength of the rock specimen at a given water content, and f_d is the compressive strength of the specimen in the dry state. As shown in Figures 8 and 9, at the same water content, the elastic modulus is positively correlated with confining pressure, whereas Poisson's ratio is negatively correlated with confining pressure. At the same confining pressure, the elastic modulus is negatively correlated with water content, whereas Poisson's ratio is positively correlated with water

content. These results indicate that confining pressure can improve the overall stiffness of the rock specimen and reduce its Poisson's ratio; however, it is insufficient to prevent the occurrence of structural damage caused by hydro-softening. This suggests that hydrological weakening is the dominant and irreversible controlling factor, while confining pressure can suppress such deterioration to some extent by compressing and closing part of the pores and cracks generated by hydrological weakening and by increasing the interfacial bonding strength.

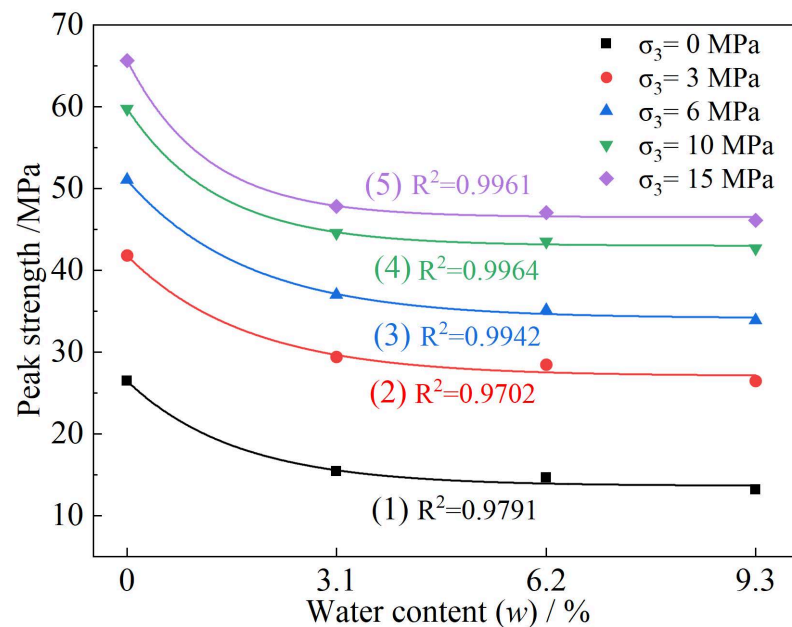


Figure 6. Peak strength-water content relationship under different confining pressures. The fitting equations corresponding to curves (1)–(5) are: (1) $y = 13.647 + 12.811\exp(-0.613w)$; (2) $y = 27.077 + 14.702\exp(-0.562w)$; (3) $y = 34.140 + 16.880\exp(-0.560w)$; (4) $y = 43.004 + 16.753\exp(-0.746w)$; (5) $y = 46.494 + 19.144\exp(-0.848w)$.

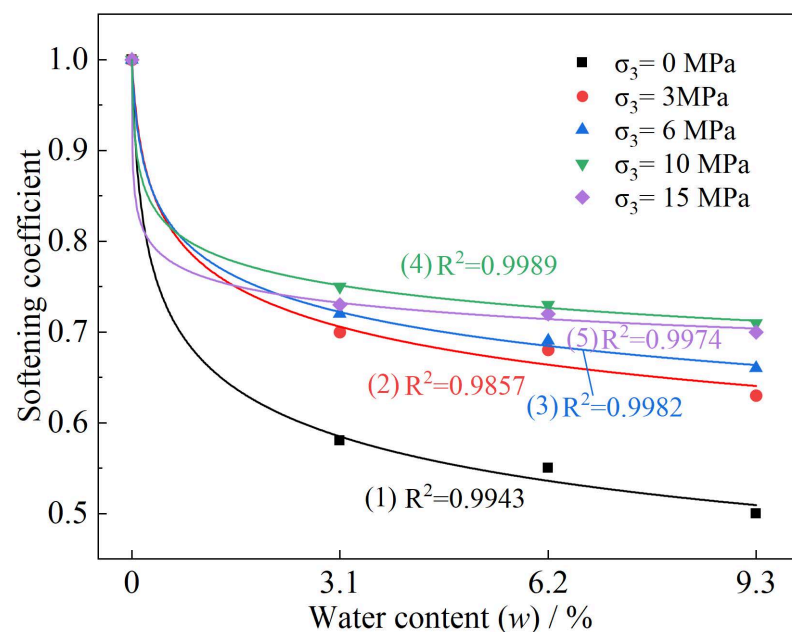


Figure 7. Softening coefficient-water content relationship under different confining pressures. The fitting equations corresponding to curves (1)–(5) are: (1) $y = 0.677(w + 0.046)^{-0.127}$; (2) $y = 0.782(w + 0.065)^{-0.090}$; (3) $y = 0.789(w + 0.047)^{-0.078}$; (4) $y = 0.794(w + 0.009)^{-0.049}$; (5) $y = 0.763(w + 0.0005)^{-0.036}$.

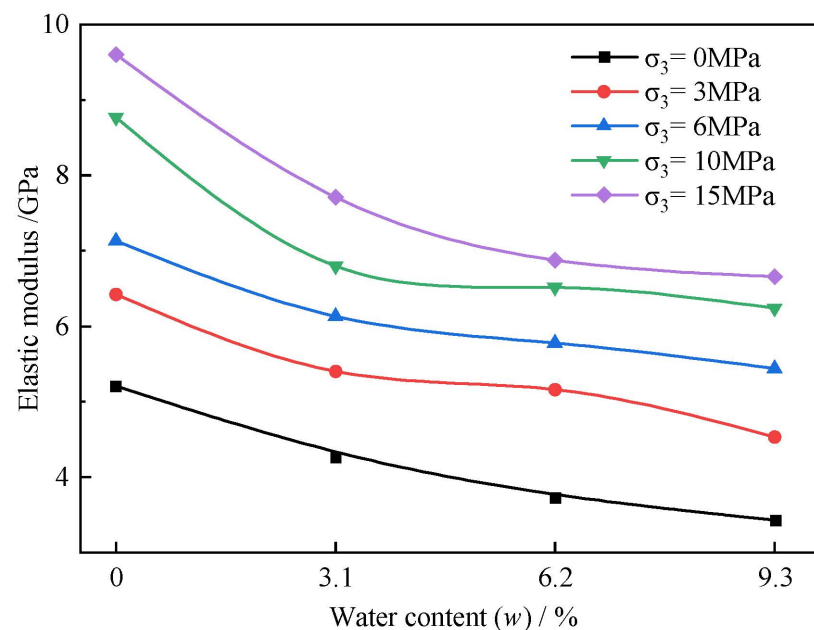


Figure 8. Water content-elastic modulus relationship under different confining pressures.

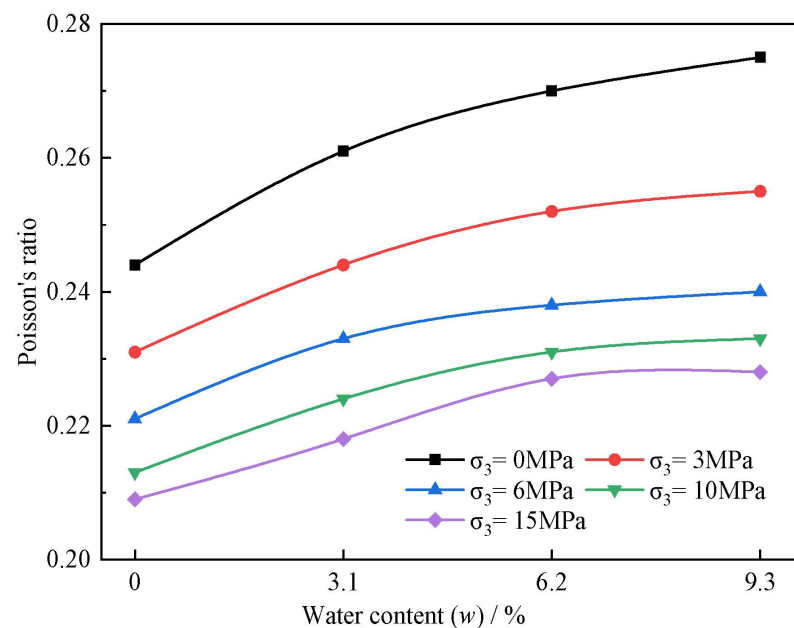


Figure 9. Poisson's ratio-water content relationship under different confining pressures.

3.3. Specimen Failure Characteristics

As shown in Figure 10, the failure mode of argillaceous sandstone changes markedly with increasing water content. Under uniaxial compression, the specimens exhibit a transition from splitting tensile failure to tensile–shear composite failure and finally to predominantly shear failure, accompanied by local spalling of rock blocks, showing an evident transformation from brittle to ductile behavior. This indicates that hydro-softening reduces the cementation strength and frictional resistance between particles, while localized fragmentation occurs at both ends of the shear failure surface. At a confining pressure of 6 MPa, the specimens are dominated by shear failure, but the continuity of the principal shear band is lower than that under uniaxial compression. Under high water-content conditions, slab-like shear failure is observed, indicating that hydro-softening promotes local sliding in high-stress regions and layered peeling under eccentric loading effects. When the confining pressure increases to 15 MPa, crack propagation is subjected to stronger lateral

confinement, and macroscopic shear cracks can no longer fully penetrate the specimen. As a result, the shear band becomes less distinct, and the overall failure pattern is characterized by shear-expansion failure. In summary, water content and confining pressure jointly affect the failure mode of argillaceous sandstone. Water content mainly influences the degree of damage and the width of the failure zone, whereas confining pressure primarily controls the crack propagation pattern.

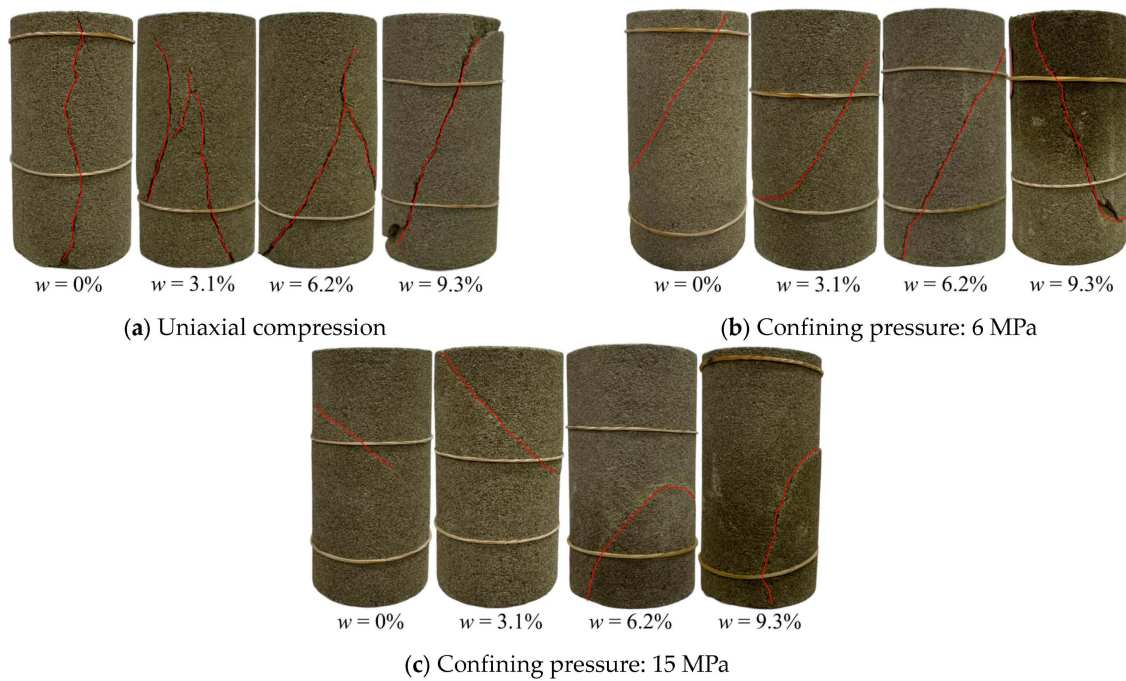


Figure 10. Failure patterns of argillaceous sandstone under different confining pressures and water contents. (Red lines indicate the main crack paths.)

4. Strength Criteria Under Coupled Water Content and Confining Pressure Effects

4.1. Regression Analysis of Strength Criteria

The peak strength of argillaceous sandstone is jointly influenced by hydro-softening and confining pressure. Therefore, based on the experimental data, regression analyses were performed to evaluate the applicability of the Mohr–Coulomb ($\sigma_1 = a + b\sigma_3$), Hoek–Brown ($\sigma_1 = \sigma_3 + a(b\sigma_3 + 1)^{0.5}$), generalized Hoek–Brown ($\sigma_1 = \sigma_3 + a(b\sigma_3 + 1)^c$), exponential ($\sigma_1 = \sigma_3 + a - b \exp(-c\sigma_3)$), and Rocker ($\sigma_1 = a(\sigma_3/b + 1)^c$) strength criteria to the triaxial strength of argillaceous sandstone. The analysis results are presented in Figure 11, where σ_1 is the major principal stress, MPa; σ_3 is the minor principal stress, MPa; and a , b , and c are fitting coefficients.

To quantitatively evaluate the deviation between the calculated results of each strength criterion and the experimental data, the coefficient of determination (R^2) and the normalized root mean square error (NRMSE) were adopted as comprehensive indicators of fitting accuracy. The expression for NRMSE is as follows:

$$\text{NRMSE} = \beta = \sqrt{\frac{1}{n} \sum_{i=1}^n (\sigma_{1,i}^{\text{test}} - \sigma_{1,i}^{\text{cal}})^2} / \bar{\sigma}_1^{\text{test}} \times 100\% \quad (1)$$

where $\sigma_{1,i}^{\text{test}}$ and $\sigma_{1,i}^{\text{cal}}$ denote the experimental and calculated values of the major principal stress under the i -th confining pressure condition, respectively, MPa; $\bar{\sigma}_1^{\text{test}}$ is the mean peak

strength under different confining pressure conditions; n is the number of test groups, which is 5 in this study.

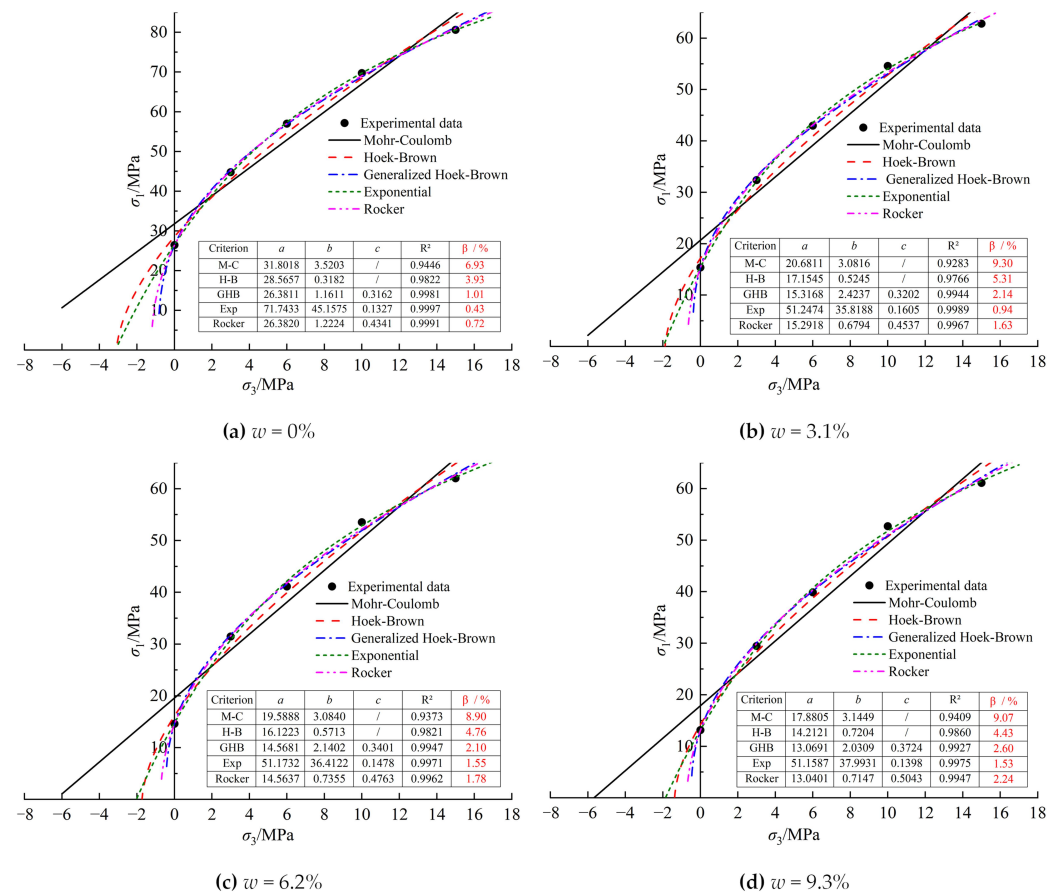


Figure 11. Regression analysis of strength criteria for argillaceous sandstone under different water contents.

Under the four water-content conditions, the β values of the Mohr–Coulomb criterion range from 6.93% to 9.30%, indicating poor applicability. Although it can reflect the trend of strength increasing with confining pressure, it is difficult for this criterion to capture the nonlinear characteristics of the confining-pressure effect. For the Hoek–Brown criterion, β decreases to 3.93–5.31%, suggesting that it is better suited to representing the nonlinear characteristics of rock strength. However, because its exponential form is relatively fixed, its ability to adjust to changes in the curvature of the strength envelope under different water-content conditions remains limited. By introducing an exponent parameter, the generalized Hoek–Brown criterion further reduces β to 1.01–2.60%, and its fitting performance is improved compared with that of the Hoek–Brown criterion. This indicates that the introduction of the exponent parameter enhances the criterion’s ability to regulate the curvature of the strength envelope, enabling it to better accommodate the nonlinear variation in strength growth of argillaceous sandstone under different water-content conditions. In contrast, the exponential strength criterion yields β values of 0.43–1.53%, all of which are lower than those of the other strength criteria. In this criterion, σ_3 can reflect the direct contribution of confining pressure to the major principal stress, while the exponential term can characterize the nonlinear feature that the strengthening effect of confining pressure gradually weakens as confining pressure increases. The β values of the Rocker strength criterion range from 0.72% to 2.24%, and its regression performance is also relatively good, but overall it is slightly inferior to that of the exponential strength criterion. In particular, as

water content increases, the Rocker criterion is less adaptable than the exponential criterion in describing the overall downward shift in the strength envelope. Combined with the coefficient of determination R^2 shown in the figure, it can be concluded that the exponential criterion exhibits the best applicability under all water-content conditions.

4.2. An Exponential Strength Criterion Considering Water-Induced Softening

Based on the exponential strength criterion and considering the effect of hydro-softening, function relationships between the parameters a , b , and c and water content were established. A modified exponential strength criterion was then proposed to capture the nonlinear characteristics of both hydro-softening and the confining-pressure effect in an integrated manner. When $\sigma_3 = 0$ MPa, the major principal stress is equal to the uniaxial compressive strength σ_c . In this case, the exponential strength criterion can be simplified as: $\sigma_c = a - b$. According to the fitting results of the exponential strength criterion under different water-content conditions, regression analysis was conducted on the relationship between parameter a and water content w (Figure 12). The results show that parameter a decrease exponentially with increasing water content w , characterized by a rapid initial decline followed by a gradual stabilization; this relationship is expressed in Equation (2). As shown in Figure 6, the uniaxial compressive strength of the specimens at $\sigma_3 = 0$ MPa also exhibits an exponential decay trend with increasing water content, and can therefore be described by Equation (3). Since parameters a and b are related to σ_c , substitution leads to Equation (4).

$$a(w) = 51.166 + 20.578 \exp(-1.784w) \quad (2)$$

$$\sigma_c(w) = 13.647 + 12.811 \exp(-0.613w) \quad (3)$$

$$b(w) = a(w) - \sigma_c(w) \quad (4)$$

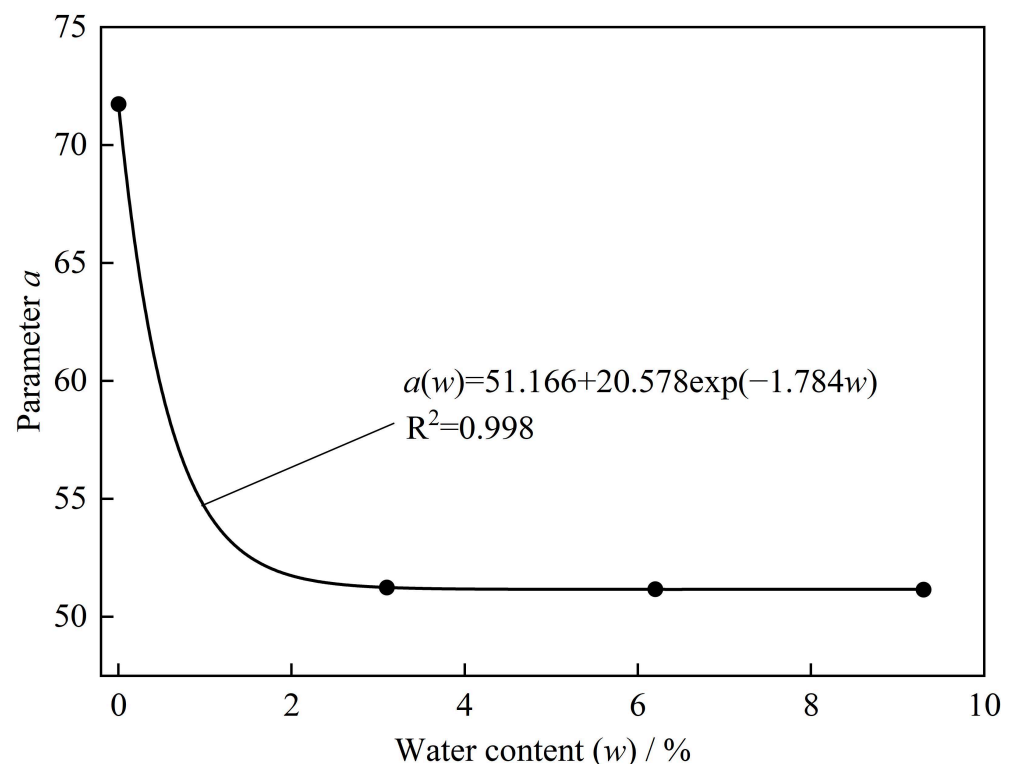


Figure 12. Fitting curve of parameter a versus water content.

As shown in Figure 11, parameter c mainly controls the curvature of the strength envelope. The fitting results of the exponential strength criterion under different water-

content conditions give the values of parameter c for the four water-content levels as 0.133, 0.161, 0.148, and 0.140, respectively. The dispersion of this parameter is relatively small, and no obvious variation pattern is observed. Therefore, its mean value is adopted here, yielding $\bar{c} = 0.146$. Substituting Equations (2)–(4) and $\bar{c}$ into the exponential strength criterion gives the modified exponential strength criterion:

$$\sigma_1 = \sigma_3 + a(w)[1 - \exp(-0.146\sigma_3)] + \sigma_c(w) \exp(-0.146\sigma_3) \quad (5)$$

Equation (5) includes both a hydro-softening term and a confining-pressure strengthening term. When $\sigma_3 = 0$ MPa, Equation (5) can be simplified to $\sigma_1 = \sigma_c(w)$, indicating that it remains consistent with the experimental strength relationship under uniaxial compression conditions.

To verify the applicability of the modified exponential strength criterion, $\sigma_3 = 0, 3, 6, 10$, and 15 MPa were substituted into Equation (5), respectively, to obtain the predicted curves of the modified exponential strength criterion for argillaceous sandstone under different confining pressures while accounting for the effect of water content. These predicted curves were then compared with the experimental results, as shown in Figure 13. It can be seen from the figure that the predicted curves of the modified exponential strength criterion agree well overall with the experimental data points. Under different water-content conditions, the mean relative error between the calculated strength values and the experimental values of argillaceous sandstone is 2.11%, and the maximum relative error is 4.70%. These results indicate that the modified exponential strength criterion considering the effect of water content can simultaneously capture the softening effect of water content and the strengthening effect of confining pressure, and it has good predictive capability for the strength characteristics of argillaceous sandstone under different combinations of water content and confining pressure.

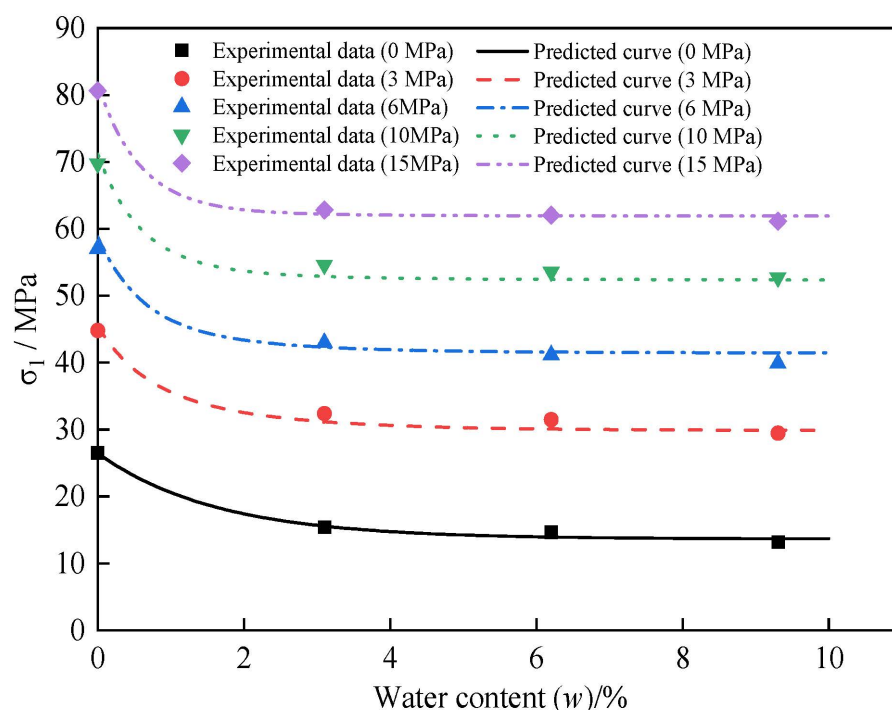


Figure 13. Predicted curves of the modified exponential strength criterion considering the water content effect.

5. Energy Damage Evolution Analysis

5.1. Principles of Energy Calculation

During the loading process of argillaceous sandstone, its deformation and failure are accompanied by four stages of energy input, accumulation, dissipation, and release. Investigating the loading failure behavior of argillaceous sandstone from an energy perspective is helpful for revealing the intrinsic mechanism by which hydro-softening affects its damage evolution and failure process, and can provide a basis for evaluating the stability of water-bearing argillaceous sandstone under complex stress conditions. Assuming that no heat exchange occurs between the specimen and the external environment during the test, the specimen can be regarded as a closed system. The total input energy of the rock is denoted as (U). According to the first law of thermodynamics:

$$U = U^e + U^d \quad (6)$$

where U^e is the elastic strain energy, $\text{kJ}\cdot\text{m}^{-3}$; and U^d is the dissipated energy, $\text{kJ}\cdot\text{m}^{-3}$.

In the principal stress space, the energy components of the rock can be expressed as:

$$U = \int_0^{\varepsilon_1} \sigma_1 d\varepsilon_1 + \int_0^{\varepsilon_2} \sigma_2 d\varepsilon_2 + \int_0^{\varepsilon_3} \sigma_3 d\varepsilon_3 \quad (7)$$

$$U^e = \frac{1}{2}\sigma_1\varepsilon_1^e + \frac{1}{2}\sigma_2\varepsilon_2^e + \frac{1}{2}\sigma_3\varepsilon_3^e \quad (8)$$

$$\varepsilon_i^e = \frac{1}{E_i}[\sigma_i - \nu_i(\sigma_j + \sigma_k)] \quad (9)$$

Substituting Equation (9) into Equation (8) gives:

$$U^e = \frac{1}{2E}[\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\nu(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_3\sigma_1)] \quad (10)$$

where $\sigma_1, \sigma_2, \sigma_3$ are the principal stresses; $\varepsilon_1, \varepsilon_2, \varepsilon_3$ are the principal strains; ε_i^e is the elastic strain in each principal stress direction; E is the elastic modulus, GPa; and ν is Poisson's ratio.

Under uniaxial compression, since $\sigma_2 = \sigma_3 = 0$, Equations (7) and (10) can be simplified as:

$$U = \int_0^{\varepsilon_1} \sigma_1 d\varepsilon \quad (11)$$

$$U^e = \frac{\sigma_1^2}{2E} \quad (12)$$

Under conventional triaxial compression, since $\sigma_2 = \sigma_3 = 0$, Equations (7) and (10) can be simplified as:

$$U = \int_0^{\varepsilon_1} \sigma_1 d\varepsilon_1 + 2 \int_0^{\varepsilon_3} \sigma_3 d\varepsilon_3 \quad (13)$$

$$U^e = \frac{1}{2E}[\sigma_1^2 + 2\sigma_3^2 - 2\nu(\sigma_3^2 + 2\sigma_3\sigma_1)] \quad (14)$$

5.2. Energy Evolution Analysis

Based on the above energy calculation formulas, the energy evolution curves under different water contents were obtained by taking confining pressures of 0, 6, and 15 MPa as examples, as shown in Figures 14–16. Overall, the total strain energy and dissipated energy continuously increase with axial strain, whereas the elastic strain energy exhibits pre-peak accumulation and post-peak release characteristics. (1) At the initial loading stage, the input energy is mainly converted into dissipated energy, which is used for the compaction and

closure of initial cracks in the rock, while only a small portion is transformed into elastic strain energy and stored inside the rock. (2) As loading continues, the growth rates of the total strain energy and elastic strain energy increase significantly, whereas the increase in dissipated energy remains relatively small, indicating that the input energy at this stage is mainly stored in the form of elastic strain energy. (3) When the specimen approaches the peak strength point, the elastic strain energy reaches its storage limit and is rapidly released with the formation of macroscopic cracks. Meanwhile, the dissipated energy increases sharply and gradually becomes dominant, indicating that the specimen begins to undergo macroscopic failure.

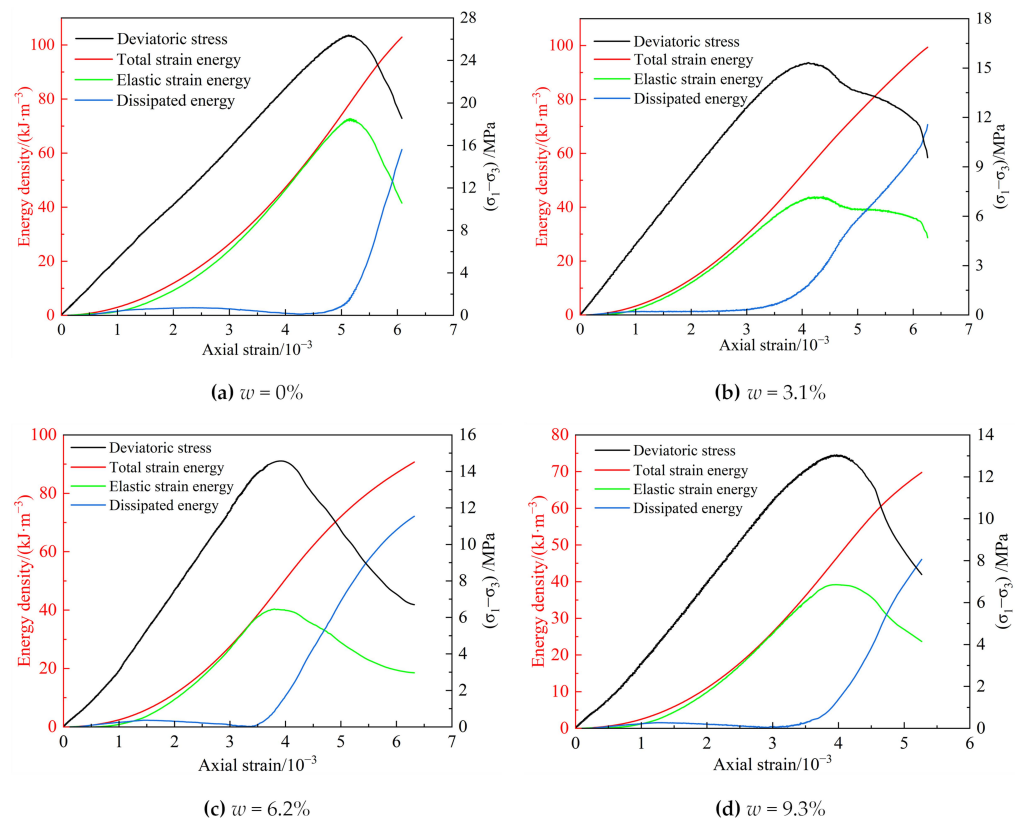


Figure 14. Energy evolution of argillaceous sandstone under uniaxial compression at different water contents.

Further analysis of Figures 14–16 shows that increasing water content significantly weakens the elastic energy storage capacity of the specimens. Under uniaxial compression, the dry specimen has a higher peak elastic strain energy, a faster pre-peak energy storage rate, and a more rapid post-peak release, showing a pronounced brittle release characteristic. As water content increases, the peak elastic strain energy decreases. For example, when the water content is 9.3%, the peak elastic strain energy is $22.82 \text{ kJ} \cdot \text{m}^{-3}$, which is 64.4% lower than that under the dry condition, $64.07 \text{ kJ} \cdot \text{m}^{-3}$. Meanwhile, the proportion of dissipated energy gradually increases, indicating that hydro-softening promotes earlier propagation and sliding of internal cracks. This phenomenon is consistent with the energy-analysis results for water-bearing sandstone reported in Refs. [26,27]. Increasing confining pressure enhances the lateral confinement effect on energy storage, shifts the axial strain corresponding to the peak elastic strain energy backward, and makes the post-peak release smoother, thereby delaying crack propagation and improving the overall energy storage capacity of the rock specimen.

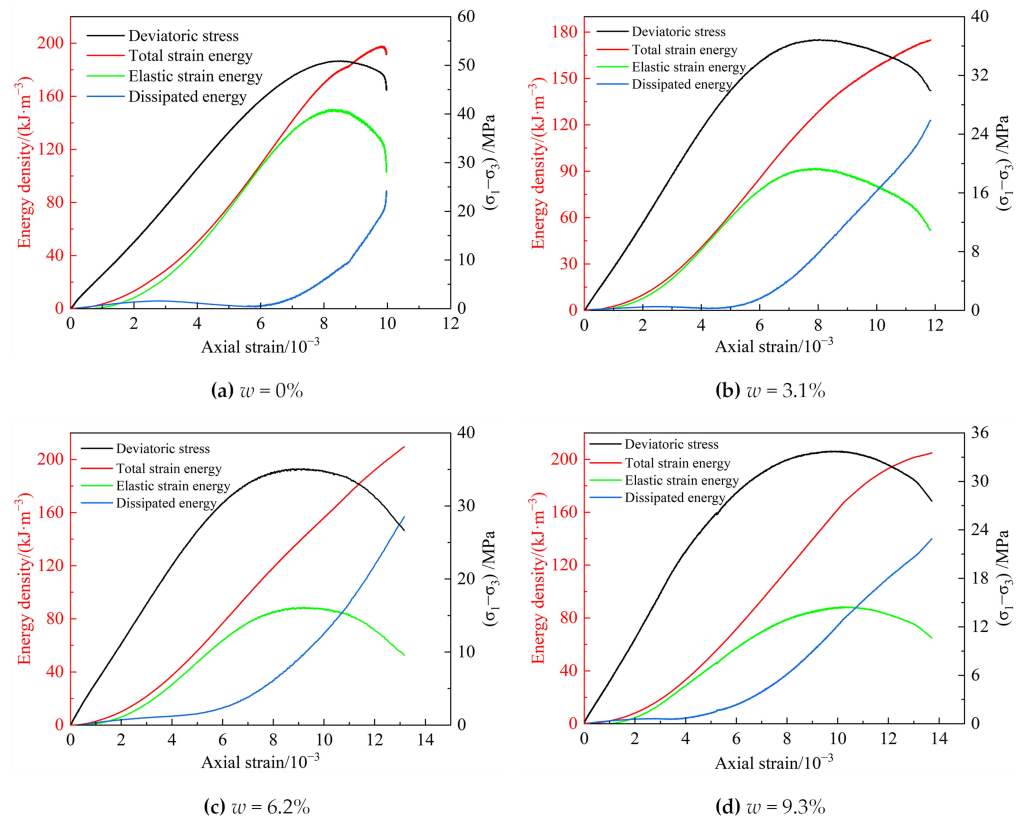


Figure 15. Energy evolution of argillaceous sandstone under 6 MPa confining pressure at different water contents.

5.3. Energy-Based Damage Evolution Model Under Water Content and Confining Pressure

The deformation and failure of argillaceous sandstone under loading are essentially a process in which internal defects gradually develop, damage continuously accumulates, and macroscopic fractures eventually form [32]. As the intrinsic driving force of rock damage, energy dissipation is mainly associated with the development of internal cracks. Its proportion in the total input energy can, to a certain extent, be used to characterize the damage degree of rock. Accordingly, the energy damage variable is defined as:

$$D = \frac{U^d}{U} \quad (15)$$

where D is the damage variable, U^d is the instantaneous dissipated energy, and U is the total strain energy.

Since the rock specimens were prepared from relatively homogeneous and intact rock blocks, the pre-peak macroscopic average degradation process of argillaceous sandstone was simplified to improve the engineering applicability of the model. Therefore, based on the strain equivalence principle proposed by Lemaitre, the internal damage of the rock was assumed to be isotropic [33,34], and the damage constitutive relationship during loading can be expressed as follows:

$$\sigma = E\varepsilon(1 - D) \quad (16)$$

where σ is the nominal stress; E and ε are the elastic modulus and axial strain of the rock under different states, respectively.

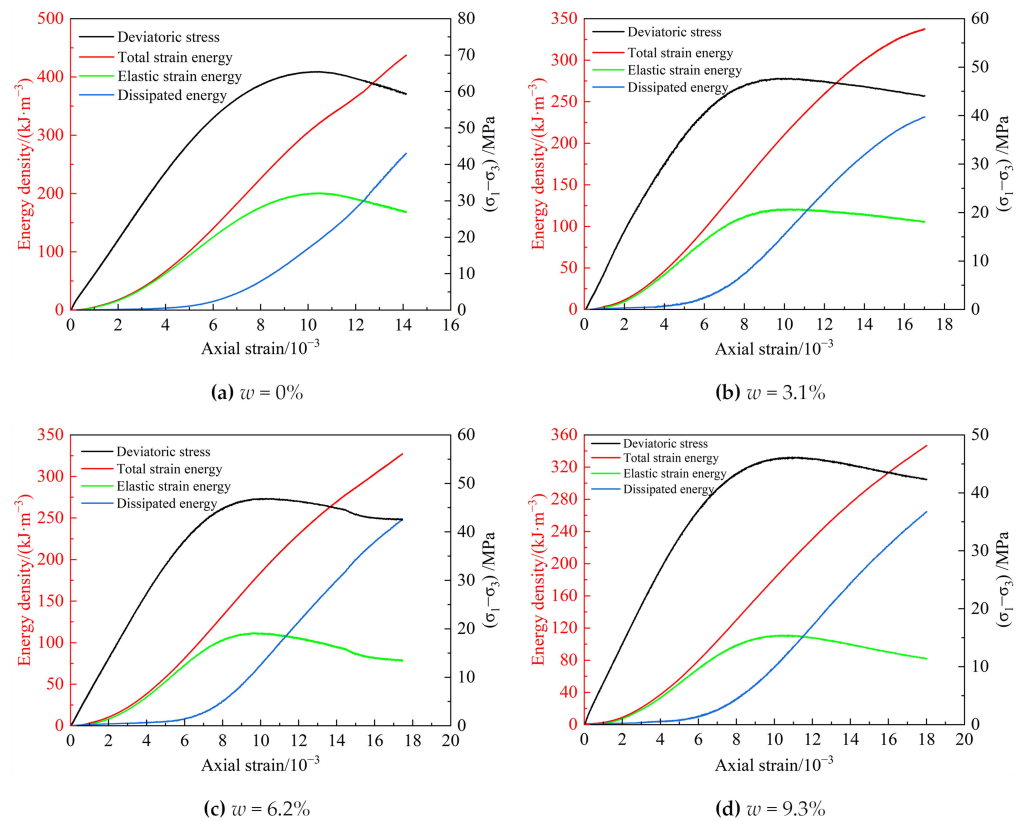


Figure 16. Energy evolution of argillaceous sandstone under 15 MPa confining pressure at different water contents.

The total strain energy U and dissipated energy U^d are obtained from the energy calculation formulas in the previous section. Based on the calculated energy results under different water contents and confining pressures, multiple nonlinear regression was used to fit the peak total strain energy U_m under the combined effects of water content and confining pressure. The composite function of U_m is established as follows:

$$U_m = \lambda \cdot U_r \cdot f(w) \cdot f(\sigma_3) \quad (17)$$

where λ is the reference correction coefficient; U_r is the reference peak total strain energy, taken as the peak total strain energy under dry and uniaxial compression conditions, with a value of $80.46 \text{ kJ} \cdot \text{m}^{-3}$; $f(w)$ is the water-weakening function; and $f(\sigma_3)$ is the confining-pressure enhancement function.

To further clarify the influence of water content and confining pressure on peak total strain energy, the relationships between U_m and water content as well as confining pressure were plotted, as shown in Figure 17. The peak total strain energy exhibits a negative exponential relationship with water content and a linear relationship with confining pressure. Therefore, the hydro-softening function and the confining-pressure effect function are, respectively, expressed as follows:

$$f(w) = r + s \cdot \exp(-t \cdot w) \quad (18)$$

$$f(\sigma_3) = 1 + u \cdot \sigma_3 \quad (19)$$

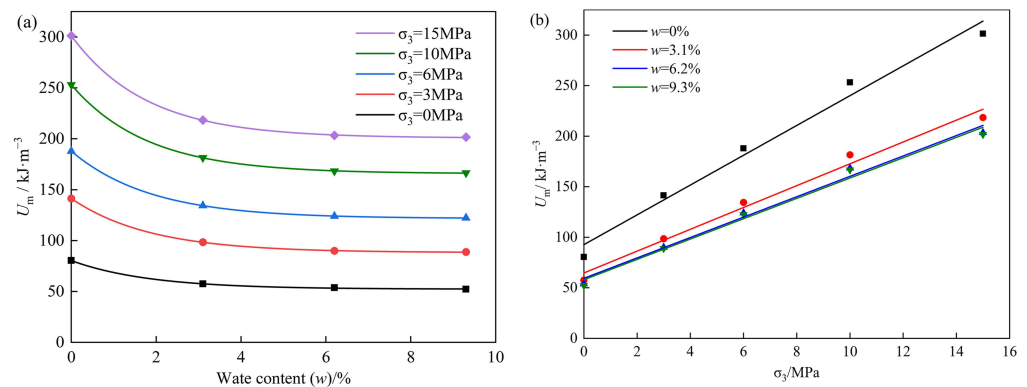


Figure 17. Relationship between peak total strain energy and water content (a) and confining pressure (b).

Substituting Equations (18) and (19) into Equation (17), the expression for the peak total strain energy of argillaceous sandstone under different water contents and confining pressures can be obtained as:

$$U_m = \lambda \cdot U_r \cdot [r + s \cdot \exp(-t \cdot w)] \cdot (1 + u \cdot \sigma_3) \quad (20)$$

Further substituting Equation (20) into Equation (16), the final characterization model can be obtained as:

$$\sigma = E\varepsilon \left(1 - \frac{U^d}{\lambda \cdot U_r \cdot [r + s \cdot \exp(-t \cdot w)] \cdot (1 + u \cdot \sigma_3)} \right) \quad (21)$$

5.4. Model Validation

To verify the reliability of the energy damage characterization model, multiple non-linear regression analysis was performed on the peak total strain energy U_m obtained from the experimental results. According to Equation (20), the model parameters were determined as follows: $r = 0.8317$, $s = 0.4356$, $t = 0.5553$, $u = 0.1655$, and the reference correction coefficient $\lambda = 0.8874$. By substituting these parameters into the model, the theoretical peak total strain energy U_m' under different combinations of water content and confining pressure was obtained and compared with the experimental value U_m , as shown in Table 1. The results show that the theoretical values agree well with the experimental values, with a maximum relative error of 14% and an average relative error of less than 5%. This indicates that the proposed peak total strain energy prediction function can reasonably reflect the energy storage capacity of argillaceous sandstone under the combined effects of water content and confining pressure.

Table 1. Comparison of actual and theoretical peak total strain energies under different conditions.

ID	U_m /kJ·m ⁻³	U_m' /kJ·m ⁻³	Relative Error/%	ID	U_m /kJ·m ⁻³	U_m' /kJ·m ⁻³	Relative Error/%
I-0	80.46	90.49	12.5	III-0	53.79	60.38	12.3
I-3	141.43	135.41	4.3	III-3	90.04	90.36	0.3
I-6	187.93	180.34	4.0	III-6	124.08	120.33	3.0
I-10	253.14	240.24	5.1	III-10	168.38	160.30	4.8
I-15	301.31	315.11	4.6	III-15	203.39	210.27	3.4
II-0	57.51	64.94	12.9	IV-0	52.24	59.56	14.0
II-3	98.47	97.19	1.3	IV-3	88.87	89.13	0.3
II-6	134.43	129.43	3.7	IV-6	122.34	118.71	3.0
II-10	181.47	172.43	5.0	IV-10	166.57	158.13	5.1
II-15	218.39	226.17	3.6	IV-15	201.67	207.42	2.9

In the table, I, II, III, and IV represent water contents from 0% to 9.3%, respectively; 0, 3, 6, 10, and 15 represent the confining pressure levels. U_m is the experimental value, and U_m' is the theoretically predicted value.

The model parameters and test conditions were further substituted into the characterization model in Equation (21) to obtain the theoretical stress–strain curves under different water contents and confining pressures. These curves were then compared with the experimental curves, as shown in Figure 18. The results show that the theoretical curves agree well with the experimental curves overall, although local deviations increase under high confining pressure. This is mainly because high confining pressure enhances the plasticity of sandstone, while the characterization model based on elastic damage theory has certain limitations in describing strong plastic yielding behavior. Nevertheless, the model can generally describe the pre-peak stress–strain response of argillaceous sandstone and the overall variation in strength with water content and confining pressure, confirming the rationality of the proposed damage characterization model.

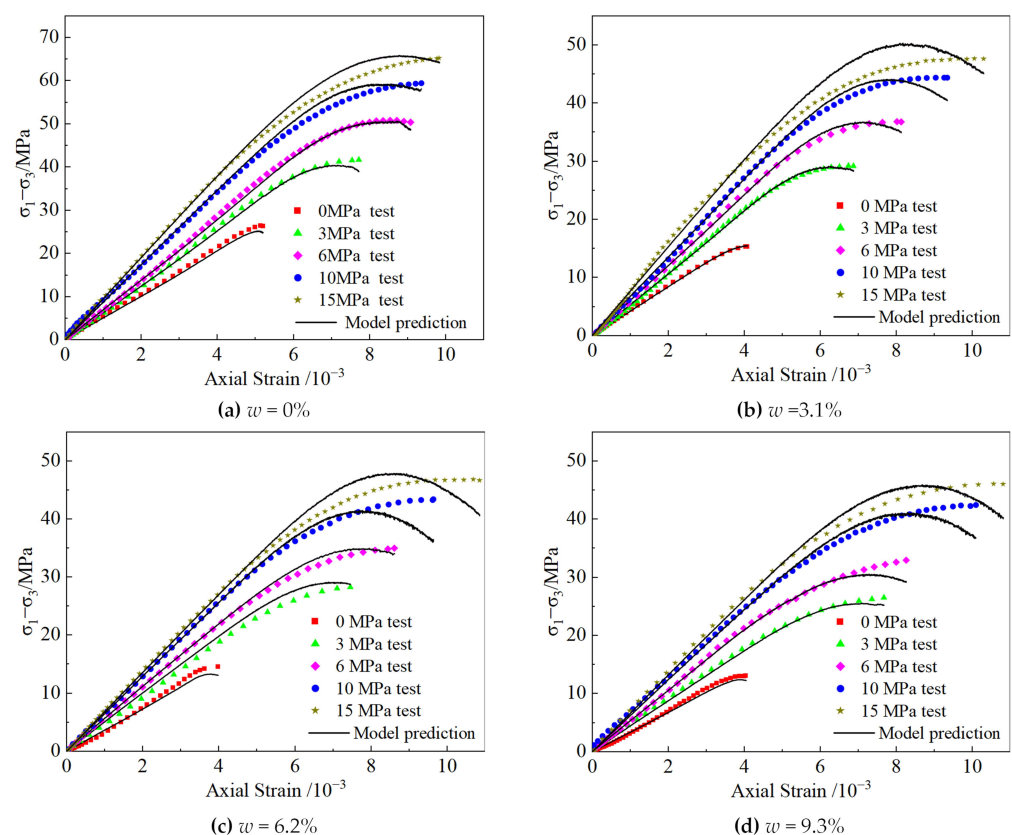


Figure 18. Comparison of theoretical and experimental stress–strain curves under different water contents and confining pressures.

6. Conclusions

The main conclusions of this study are as follows:

- (1) The argillaceous sandstone in this paper presents prominent water-induced softening behavior. As the water content increases from 0% to 9.3%, the peak strength drops by 28.5–50.3% under all confining pressures. Both its softening coefficient and elastic modulus decrease, with more severe deterioration observed at low water contents. Meanwhile, confining pressure raises peak strength and peak strain, improves plastic deformation capacity, and alleviates the water-induced softening effect to a certain degree.

- (2) The failure mode was jointly affected by water content and confining pressure. Increasing water content intensified the damage degree and widened the damaged zone, whereas increasing confining pressure restricted crack propagation and promoted the transition from tensile failure to shear-dominated failure.
- (3) Among the evaluated strength criteria, the exponential strength criterion showed the best applicability for argillaceous sandstone under different water contents. The proposed water-content-modified exponential strength criterion can describe both hydro-softening and confining-pressure strengthening effects, with an average relative error of 2.11% and a maximum relative error of 4.70%. This indicates that the proposed criterion can reasonably characterize the nonlinear strength envelope within the tested range.
- (4) Energy evolution was also jointly controlled by water content and confining pressure. Increasing water content reduced elastic strain energy storage and increased the proportion of dissipated energy, whereas increasing confining pressure enhanced peak total strain energy and delayed elastic energy release. The relative error between theoretical and experimental peak total strain energy was 0.3–14.0%, with an average error below 5%, indicating that the proposed energy-based damage model can reasonably describe the pre-peak damage evolution of intact argillaceous sandstone within the tested ranges of 0–9.3% water content and 0–15 MPa confining pressure.

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