Research Article

Research on the Strength Prediction Model of Softened Mudstone Based on Triaxial Compressive Test of Rock

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Mudstone is highly sensitive to water. When it comes into contact with water, the softening phenomena such as the decrease of strength and the increase of deformation are prominent. It is of great significance to clarify its related mechanical properties. For the tertiary mudstone, a triaxial compression test and a Brazilian splitting test are carried out under the conditions of four kinds of water content (0, 10.1%, 12.5%, and 14.1%) and four kinds of confining pressures (0 MPa, 2 MPa, 5 Mpa, and 10 MPa). The test results show that (1) with the increase of confining pressure and water content, the mudstone changes from brittle failure to ductile failure. The higher the confining pressure, the greater the strength and elastic modulus. The higher the water content, the significantly lower the strength and elastic modulus, and the higher the strain. (2) With the increase of water content, the influence of confining pressure on strength is more prominent. High confining pressure can effectively inhibit the trend of strength attenuation. (3) When the water content is low (0–10.1%), the strength of the mudstone is mainly related to its own water content. When the water content increases to 10.1%–14.1%, both the confining pressure and the water content are important factors affecting the strength of the mudstone. Then, the applicability of five commonly used strength criteria to the strength prediction of softened mudstone is compared and analyzed. The results show that the Rocker strength criterion can more accurately and conveniently predict the strength of mudstone under different water content. Finally, based on this strength criterion, a nonlinear strength prediction model of softened mudstone considering water content and confining pressure effect is proposed and its good applicability is verified.

1. Introduction

China is one of the countries with the widest distribution of mudstones in the world. Mudstone exists in more than 20 provinces. With the acceleration of China's infrastructure construction, a large number of structural stability and disease problems caused by mudstone have appeared in the construction of tunnels in railway engineering, highway engineering, subway engineering, oil and gas transportation engineering, and inter-basin water transfer engineering. The main reason is that the mechanical properties of mudstone are unstable, and softening phenomena such as strength reduction and the increase of deformation are easy to occur when it comes into contact with water. It will cause huge

potential safety hazards to the construction and operation of the project. Therefore, it is necessary to study the mechanical properties of softened mudstone.

At present, many scholars have made a lot of valuable research on the mechanical properties of mudstone after long-term research. Zhang et al. [1] obtained the constitutive equation of four stages of the stress-strain curve of purplish red mudstone of the Badong Formation through the triaxial compression test. Wang and Li [2] took the soft rock in Western China as an example and obtained the variation law of strength and deformation with confining pressure under different water content. Xu et al. [3] established the fitting curve and fitting function of the four stages of the stress-strain curve through the strength and deformation

characteristics of mudstone under different confining pressures. Luo [4] obtained the stress-strain curve of strongly weathered mudstone after multiple drying and wetting cycles. Luo et al. [5] summarized the influence of water content of mudstone on its mechanical properties and Duncan-Zhang model parameters. Liu et al. [6] made the energy explanation of the water-saturated softening mechanism of mudstone and revealed the energy evolution mechanism of mudstone. Fu et al. [7] studied the functional relationship equation between shear strength and vertical deformation of pre-disintegrating carbonaceous mudstone.

The strength criterion is to study the yield condition and failure rule of rock under the real complex stress environment. The research and selection of appropriate strength criteria is of great significance to the judgment of rock strength and engineering design. Yuan et al. [8] estimated the mechanical parameters of rock mass based on the Hoek–Brown strength criterion. Zhu et al. [9] expounded the research progress and research results of the Hoek–Brown strength criterion and introduced related research work at present. Zou et al. [10] compared the Bieniawski criterion and the Balmar criterion and analyzed their advantages and disadvantages. You [11] summed up the variation characteristics of bonding force and friction force in the Mohr stress space based on the exponential strength criterion. Zhang et al. [12] constructed the exponential strength criterion through triaxial compression tests and verified its applicability. Shi et al. [13] compared and analyzed five strength criteria and evaluated the applicability of each strength criterion. Zhang and Liu [14] explored the prediction effect of different strength criteria on rock tensile strength.

At present, the applicability of many existing strength criteria to softened mudstone is seldom studied, and the scope of application is not very clear. In view of this, this paper takes the tertiary mudstone as the research object and carries out the triaxial compression test and Brazilian splitting test under different water content to reveal the influence law of water content and confining pressure on mechanical properties of mudstone. Then, based on the triaxial test data, the accuracy and applicability of the Mohr–Coulomb strength criterion, Hoek–Brown strength criterion, generalized Hoek–Brown strength criterion, Bieniawski strength criterion, and Rocker strength criterion for the prediction of mudstone strength under different water content and confining pressures are compared and analyzed. Finally, a nonlinear strength prediction model of softened mudstone considering water content and confining pressure effect is proposed.

2. Sample Preparation and Test Scheme

2.1. Field Sampling.
The tertiary mudstone block in this test is taken from Xiangshan tunnel in Zhongwei City, Ningxia, China. By the mineral composition analysis, the mineral composition of the mudstone is mainly quartz, illite, and calcite, accounting for more than 70%. The rest contains a small amount of plagioclase, chlorite, and palygorskite. The pore type of the rock sample is mainly interlayer micropores of clay minerals, and the pore level is mainly micropores. The crack is highly developed and evenly distributed. According to the field measured data, the vertical in situ stress in this section is 4.21 Mpa, and the average horizontal in situ stress is 5.03 MPa. The rock block sampling location is at the top of the tunnel, and the location has the advantages of wide distribution of test rocks, prominent rock characteristics, litter disturbance, and easy collection.

After the collection, in order to prevent the weathering and water loss of the rock blocks, which is caused by the long transportation time or the long test period, the sealing wax method is used for sealing and preservation (as shown in Figure 1) so as to ensure the accuracy of the test data.

2.2. Sample Preparation.
After the rock is sampled on-site and transported to the laboratory, the rock block shall be unpacked and processed. Since the mudstone is very sensitive to water, it is easy to become cracked and even disintegrate blocks when it comes into contact with water, which not only makes the sample formation rate low but also has a great impact on the test results. Therefore, in the process of the rock block drilling and coring, we do not cool down the rock block with water. Instead, we retrofit the original coring machine by connecting the high-pressure air pump (as shown in Figure 2). The high-pressure air can replace water to cool down the rock block (as shown in Figure 3). In this way, it will not only affect the water content of mudstone but also avoid the sticking of coring machine and rock sample damage caused by overheating. The result shows that this method works well and the size of the mudstone sample meets the test requirements. The mudstone sample is shown in Figure 4.

2.3. Test Scheme.
This test mainly includes the triaxial compression test and Brazilian splitting test of mudstone with different water content. The sample for the triaxial compression test is a cylinder with a diameter of $D = 50$ mm and a height of $h = 100$ mm. The test equipment is a large-rigidity rock triaxial testing machine, as shown in Figure 5. The sample for the Brazilian splitting test is also a cylinder with a diameter of $D = 50$ mm and a height of $h = 50$ mm. The test equipment is a universal material testing machine, as shown in Figure 6. The tensile strength of rock is calculated according to the following formula:

$$\sigma_t = \frac{2P}{\pi Dh}. \tag{1}$$

In the equation, σ_t is the tensile strength of the rock, P is the failure load, D is the diameter of the sample, and h is the height of the sample.

In order to explore the strength and deformation characteristics of mudstone under different water content and different confining pressures, the triaxial compression test and Brazilian splitting test are carried out for four kinds of water content: dry state, natural state, saturated state, and state between the natural state and saturated state. Mudstone samples in the dry state, the saturated state, and the state between the natural state and saturated state can be prepared

FIGURE 1: Sealing and preservation of the rock block with wax.

FIGURE 2: High-pressure air pump.

FIGURE 3: Automatic coring machine sampling.

FIGURE 4: Mudstone sample.

by the drying method, vacuum saturation method, and free immersion method, respectively. According to the water content test, when the rock sample is immersed for 1-2 hours, its water content only increases slightly, which is not very different from the water content in the natural state. When it is immersed for 3 hours, its water content will increase significantly. When it is immersed for 4 hours, the water content will reach the saturated stable state. Therefore, the free immersion time of rock samples with water content between the natural water content and saturated water content in this test will be 3 hours. The water content of mudstone samples under four water content states is 0 (dry state), 10.1% (natural state), 12.5% (water content state between the natural state and saturated state), and 14.1% (saturated state). According to the actual stress environment of the rock, four groups of confining pressures are selected for the triaxial compression test, which are 0 MPa, 2 MPa, 5 Mpa, and 10 MPa.

According to the principle of the parallel test, in order to eliminate the test error caused by individual differences of samples, the number of samples for each group of test should be 5 under the same water content state and the same loading direction. Therefore, under the same water content and the same confining pressure, take five groups of samples to repeat the triaxial compression test, and the total number of rock samples for the triaxial compression test under four water content and four groups of confining pressures is 80. Under the same water content, take five groups of samples to

FIGURE 5: Rock triaxial testing machine.

FIGURE 6: Universal material testing machine.

repeat the Brazilian splitting test, and the total number of Brazilian splitting test samples under four water content conditions is 20.

3. Analysis of Test Results

3.1. Analysis of Deformation Characteristics. According to the triaxial compression test results, the stress-strain curves of mudstone in four water content states under different confining pressures can be drawn, as shown in Figure 7.

It can be seen from Figure 7 that (1) when the water content of mudstone is low (0–10.1%), at low confining pressure (0 MPa–2 MPa), the stress-strain curve can be

obviously divided into four stages: compaction stage, linear elasticity stage, yield stage, and failure stage. With the increase of water content, the compaction stage and linear elastic stage of the stress-strain curve become significantly shorter. The rock sample begins the yield stage relatively quickly, and there is no obvious yield point. The strain of the rock sample will continue to increase at a certain stress level and eventually lead to failure. The failure mode changes from brittle failure to ductile failure. The reason may be that with the increase of water content of mudstone, the argillization phenomenon is prominent and it is similar to the properties of general sand. The strength is reduced, and the rock samples are mostly ductile failure. (2) Under the same water content, with the increase of confining pressure, the compressive strength, residual strength, and elastic modulus of mudstone increase, and the value of axial strain is also increased. (3) Under the same confining pressure, the compressive strength, residual strength, and elastic modulus of mudstone decrease significantly with the increase of water content, and the value of strain when reaching the peak compressive strength is increased with the increase of water content. After the rock sample failure, the residual strength remains unchanged and the amount of plastic deformation continues to increase.

3.2. Analysis of Strength Characteristics. Through the triaxial compression test and Brazilian splitting test, the compressive strength under different confining pressures in different water content states and the tensile strength under different water content are obtained. The results are shown in Table 1.

Through the analysis of the data in Table 1, the characteristics of the compressive strength and tensile strength of mudstone are obtained: (1) When the water content is only increased from 0 to 14.1%, the uniaxial compressive strength of mudstone decreases from 9.2 MPa to 2.0 MPa and the tensile strength is reduced from 3.1 Mpa to 0.66 MPa. The decline rate is nearly 80%. It can be seen that this kind of mudstone is very sensitive to water, and the water content has a significant impact on the strength of mudstone. Under the same confining pressure, the compressive strength and tensile strength will decrease significantly with the increase of water content; (2) under the same water content, the compressive strength and tensile strength of mudstone increase with the increase of confining pressure; (3) when the mudstone is in the state of low water content (0–10.1%), with the increase of confining pressure from 0 MPa to 10 MPa, the strength increases by about 350%–400%. When the water content increases to 12.5%–14.1%, the strength increases by 600%–700%, which is about 1.5–2 times of the low water content state. It shows that the higher the water content of mudstone, the greater the influence of confining pressure on its strength; (4) when the mudstone is in a high confining pressure (5 MPa–10 MPa) environment, as the water content increases from 0 to 14.1%, its strength decreases by about 60%. When the confining pressure decreases (0 MPa–2 MPa), the decrease rate increases to about 70%, which indicates that the strength reduction of mudstone in the low confining pressure environment is more obvious.
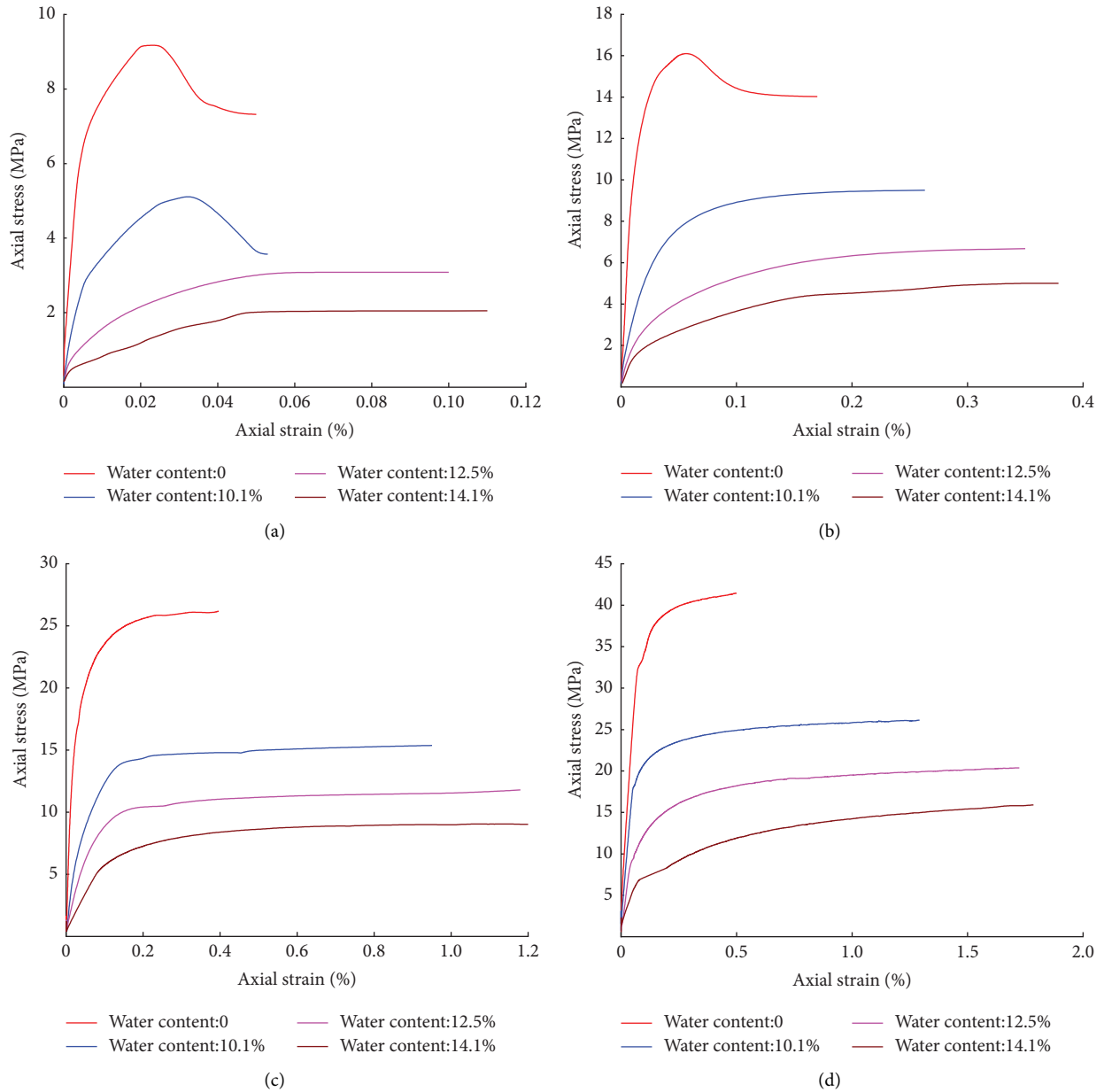
FIGURE 7: Stress-strain curves of mudstone under four water content under different confining pressures. (a) Confining pressure: 0 MPa. (b) Confining pressure: 2 MPa. (c) Confining pressure: 5 MPa. (d) Confining pressure: 10 MPa.

Because the high confining pressure can inhibit the development of cracks in mudstone, hinder the penetration of cracks, and delay the occurrence of the critical failure state. Hence, the macro-performance is the improvement of compressive strength and the strength decline is relatively small.

3.3. Analysis of Softening Characteristics.

The property that the strength of rock changes after immersion in water is called softening. The softening coefficient is usually used to characterize the softening characteristics of rocks. In order to facilitate the analysis of the softening characteristics of mudstone under different water content and different confining pressure conditions, a triaxial softening coefficient is introduced. Under the same confining pressure, the calculation method of the triaxial softening coefficient is the ratio of the compressive strength of mudstone under different water content states to the compressive strength of mudstone in the dry state. The triaxial softening coefficient ξ' can be expressed as

$$\xi' = \frac{R_{cb}}{R_c}. \tag{2}$$

In the equation, R_{cb} is the compressive strength of mudstone in different water content states and R_c is the compressive strength of mudstone in the dry state.

TABLE 1: Summary of mudstone strength test results.

Water content (%)	Confining pressure (MPa)	Compressive strength (MPa)	Tensile strength (MPa)
0	0	9.2	3.10
	2	16.1	
	5	26.2	
	10	41.5	
10.1	0	5.2	1.75
	2	9.5	
	5	15.4	
	10	26.1	
12.5	0	3.0	1.05
	2	6.7	
	5	11.8	
	10	20.4	
14.1	0	2.0	0.66
	2	5.0	
	5	9.0	
	10	15.9	

Taking the compressive strength of mudstone in Table 1 into equation (2), the variation curve of the triaxial softening coefficient of mudstone with confining pressure under different water content conditions can be drawn, as shown in Figure 8.

It can be seen from Figure 8 that under different confining pressures, the variation law of the triaxial softening coefficient of mudstone with water content is roughly the same, showing a downward trend with the increase of water content. When the water content changes from 0 to 10.1%, there is little difference in the reduction range of the mudstone softening coefficient under the confining pressure state of the four groups. When the water content is 10.1%, the triaxial softening coefficients are all around 0.6, which means that when the water content is low, the strength is mainly related to its own water content. As the water content continues to increase, from 10.1% to 14.1%, the variation range of the softening coefficient is different. The higher the confining pressure is, the smaller the reduction range of the triaxial softening coefficient is, and the greater the strength is. It shows that when the water content increases to a certain range, not only the mudstone strength is related to its own water content but also the size of the confining pressure will become an important influencing factor. Confining pressure can weaken the downward trend of strength due to the increase of water content. Therefore, in practical engineering application, when considering the softening phenomenon of mudstone, the water content state and the actual stress environment should be comprehensively analyzed. In this way, the strength of the mudstone can be accurately determined.

4. Applicability Study of Strength Criterion

The strength criterion can truly and objectively reflect and describe the strength characteristics and failure characteristics of rock, which is widely used in bridge, tunnel, water conservancy, mining, and other engineering fields. As the
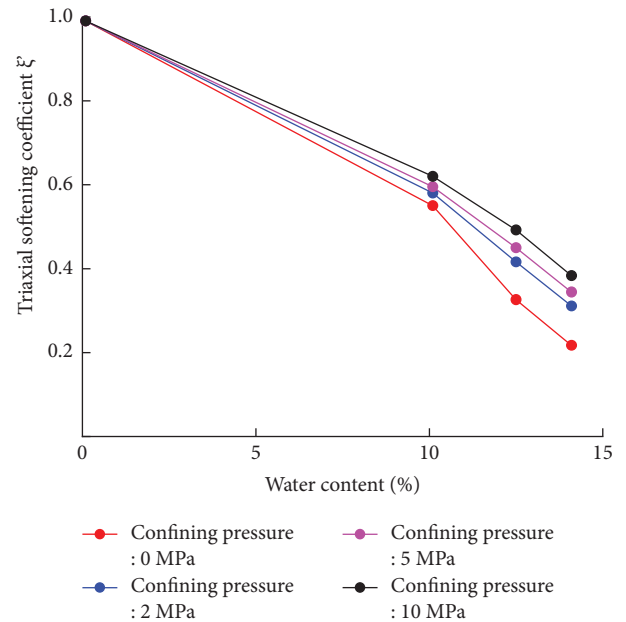

FIGURE 8: Triaxial softening coefficient curve of mudstone.

basic theory of rock mechanics, the strength criterion can also be used to predict and check the strength of rocks.

4.1. Strength Criterion and Its Expression

4.1.1. Mohr–Coulomb Strength Criterion. Since its establishment, the Mohr–Coulomb strength criterion has been widely used for its concise expression and clear physical concept. So far, the Mohr–Coulomb strength criterion is still one of the most classical strength theories in the field of rock mechanics. According to the criterion, the failure of rock is mainly the shear failure that occurs on a certain surface of the rock. The expression is

$$\sigma_1 = \sigma_c + k\sigma_3. \qquad (3)$$

In the equation, σ_1 is the maximum principal stress (the same below), σ_3 is the minimum principal stress (the same below), σ_c is the uniaxial compressive strength (the same below), and k is the influence coefficient of different confining pressures on strength.

4.1.2. Hoek–Brown Strength Criterion. In 1980, Hoek and Brown [15, 16] first proposed the Hoek–Brown strength criterion by summarizing and analyzing a large number of triaxial test data and results. It can describe the nonlinear relationship between the internal ultimate principal stress of rock when failure occurs. The expression is

$$\sigma_1 = \sigma_3 + \sigma_c \left(m_i \frac{\sigma_3}{\sigma_c} + 1 \right)^{0.5}. \tag{4}$$

In the equation, m_i is the empirical parameter of rock dimension (the same below), which can reflect the degree of softness and hardness of rock. Its value ranges from 0.001 to 25. The value of m_i can be obtained by looking up the table. In order to avoid the error of human subjectivity and make the calculation more accurate, in this paper, the value of m_i is determined by the uniaxial compressive strength and tensile strength. The calculation method is as follows:

$$m_i = 16 \frac{\sigma_t}{\sigma_c} - \frac{\sigma_c}{\sigma_t}. \tag{5}$$

In the equation, σ_t is the tensile strength (the same below).

4.1.3. Generalized Hoek–Brown Strength Criterion. Hoek et al. [17] improved the Hoek–Brown strength criterion in 1992, which is called the generalized Hoek–Brown strength criterion. Its expression is

$$\sigma_1 = \sigma_3 + \sigma_c \left(m_b \frac{\sigma_3}{\sigma_c} + s \right)^a. \tag{6}$$

In the equation, m_b and a are dimensional empirical parameters for different rock masses and s is a parameter reflecting the degree of rock fragmentation. Hoek et al. [18, 19] proposed a method for obtaining rock mass parameters m_b, s, and a based on the geological strength index (GSI). The GSI can be obtained by looking up the table [20],

$$\left. \begin{aligned} m_b &= \exp\left(\frac{GSI - 100}{28}\right) m_i \\ s &= \exp\left(\frac{GSI - 100}{9}\right) \\ a &= 0.5 \end{aligned} \right\}. \tag{7}$$

4.1.4. Bieniawski Strength Criterion. The Bieniawski criterion is a two-dimensional rock empirical strength criterion summarized and proposed by Bieniawski [21] in 1974 on the basis of a large number of rock strength tests. It belongs to one of the power function strength criterion. Bieniawski believed that in general, the strength curve is not a straight line. Its expression is

$$\frac{\sigma_1}{\sigma_c} = 1 + e \left(\frac{\sigma_3}{\sigma_c} \right)^f. \tag{8}$$

In the equation, e and f are the relevant parameters determined by the triaxial compression test. Bieniawski determined the parameter f as a constant 0.75 after fitting the test results through the experimental analysis of five types of rocks. At this time, the above formula only contains one unknown parameter, which is called the single-parameter Bieniawski strength criterion.

Converting equation (8) into equation (9), there are two unknown parameters e and f, which is called the two-parameter Bieniawski strength criterion,

$$\ln \frac{\sigma_1 - \sigma_c}{\sigma_c} = \ln e + f \ln \left(\frac{\sigma_3}{\sigma_c} \right). \tag{9}$$

If equation (8) is modified into equation (10), it contains three unknown parameters e, f, and g, which is called three-parameter Bieniawski strength criterion,

$$\frac{\sigma_1}{\sigma_c} = g + e \left(\frac{\sigma_3}{\sigma_c} \right)^f. \tag{10}$$

The single-parameter Bieniawski strength criterion is based on the strength test data of five types of rocks. After fitting analysis, the value of parameter f in the expression is determined to be 0.75, and the value of e depends on the rock type, and its value ranges from 3 to 5. The expression of the two-parameter Bieniawski strength criterion is based on the single-parameter expression and obtained by taking logarithms on both sides of the formula. At this time, the value of parameter f is no longer fixed at 0.75. For other types of rocks except for the five types of rocks, the two-parameter expression is more applicable. The three-parameter Bieniawski strength criterion is also obtained by further modifying the parameters based on the single-parameter Bieniawski strength criterion. To sum up, the parameters in the Bieniawski strength criterion are all obtained by fitting the rock strength test data. The two-parameter and three-parameter Bieniawski strength criteria are evolved from the single-parameter Bieniawski strength criterion, which is applicable to all kinds of rocks with significant nonlinear or linear characteristics of strength curves.

4.1.5. Rocker Strength Criterion. The Rocker strength criterion was proposed by Carter et al. [22]. Its expression is

$$\sigma_1 = \sigma_c \left(\frac{\sigma_3}{\sigma_t} + 1 \right)^m. \tag{11}$$

In the equation, the value of index m can be obtained by fitting and regression analysis of the triaxial compression test data, and its value range is 0.3–1.

The Rocker strength criterion is an empirical power function strength criterion. Its biggest feature is that the

expression includes the tensile strength parameter. Compared with other empirical strength criteria, the Rocker strength criterion considers not only the influence of uniaxial compressive strength but also the influence of rock tensile strength in the prediction of rock triaxial compressive strength, which makes the strength analysis of rock more complete.

In this paper, five widely used strength criteria are selected to predict the strength of mudstone under different water content states and different confining pressures. The purpose is to discuss and study the applicability of different kinds of strength criteria. Based on the strength test data (as shown in Table 1), through regression analysis, the relevant constants included in the five strength criteria are obtained, and in this way, the complete calculation expression of each strength criterion is obtained. The calculation expressions of the five strength criteria for mudstone under different water contents are shown in Table 2:

According to the calculation expressions listed in Table 2, five strength criterion prediction curves of mudstone under different water content can be obtained. In order to study the deviation between each strength criterion and the test value of strength more intuitively, the triaxial compression test data are marked. The curve is shown in Figure 9.

4.2. Applicability Evaluation Criteria of Strength Criteria.
To evaluate the applicability of the strength criterion, the author intends to use the method of calculating the least mean standard fitting deviations and analyzing the strength criterion prediction curves and then find the best strength criterion for predicting the strength of mudstone. The least mean standard fitting deviations represent that when the mudstone is under the same water content condition, the average deviation between the calculated value of the fitting expression and the test value of the mudstone compressive strength under the four confining pressure conditions. It reflects the accuracy of each strength criterion expression in predicting the compressive strength of mudstone under different confining pressures under a certain water content state. The smaller the value, the smaller the deviation, and the better the prediction effect of the fitting expression. The formula of the least mean standard fitting deviations is as follows:

$$\eta = \sqrt{\frac{\sum_j \left(\sigma_{1j}^{\text{cal}} - \sigma_{1j}^{\text{test}} \right)^2}{n}}. \tag{12}$$

In the equation, η is the least mean standard fitting deviation, σ_{1j}^{cal} is the calculated value of the maximum principal stress, $\sigma_{1j}^{\text{test}}$ is the test value of the maximum principal stress, j is the test point under different confining pressures, and n is the number of test data and $n = 4$.

According to equation (12), the least mean standard fitting deviations of each strength criterion of mudstone under different water content states can be obtained, as shown in Table 3.

4.3. Applicability Study of Strength Criterion.
According to the results in Figure 9 and Table 3, it is shown that the least mean standard fitting deviations of the Mohr–Coulomb strength criterion under different water content states is small and the difference is not significant. When the mudstone is in the state of low confining pressure (0 MPa–2 MPa), the Mohr–Coulomb strength criterion has a good effect on the prediction of mudstone strength. With the increase of confining pressure, the calculated value deviates from the test value, and both give a low estimation of the actual compressive strength of mudstone. It shows that the Mohr–Coulomb strength criterion is more suitable for predicting the strength of mudstone at a lower confining pressure level. At the same time, the calculated values of the tensile strength of mudstone under the four water content states have great deviations from the experimental values, and the higher the water content, the greater the deviation. The maximum deviation is about 2.5 times of the test value, indicating that when mudstone is in the state of tensile stress failure, its strength reflects the regular characteristics of nonlinearity, while the linear Mohr–Coulomb strength criterion cannot be applied.

The calculated compressive strength of mudstone under the Hoek–Brown strength criterion and generalized Hoek–Brown strength criterion is quite different from the experimental value. When the water content is low (0–10.1%), the calculated compressive strength values of the two strength criteria are significantly lower than the experimental values. In the dry state, the least mean standard fitting deviation of the generalized Hoek–Brown strength criterion reaches 11.15 MPa. The reason may be that the influence of the change of water content is not considered when determining the geological strength index (GSI), resulting in the low value of the parameters. The calculated value of compressive strength is low. With the increase of water content (12.5%–14.1%), the least mean standard fitting deviations of the two strength criteria decrease significantly, indicating that the prediction effect of the two criteria becomes better. At this time, the calculated value of compressive strength is close to the actual test value. Under the four water content states, the Hoek–Brown strength criterion has a good effect on the prediction of the tensile strength of mudstone, the calculated value is little different from the actual test value, and the calculated value of the generalized Hoek–Brown strength criterion is lower than the test value. Generally speaking, the Hoek–Brown strength criterion and generalized Hoek–Brown strength criterion have good prediction effect only when mudstone is within a certain water content range, but they are prone to large deviations in other water content states. The overall applicability is not good.

The Bieniawski strength criterion has little difference between the calculated value of compressive strength and the test value under different water content and different confining pressures, and the least mean standard fitting deviation is small, which can achieve good fitting effect. Among them, the three-parameter Bieniawski criterion is the best, followed by the two-parameter, and the single-parameter deviation is relatively the largest. However, the Bieniawski

TABLE 2: Calculation expression of the strength criterion under different water content.

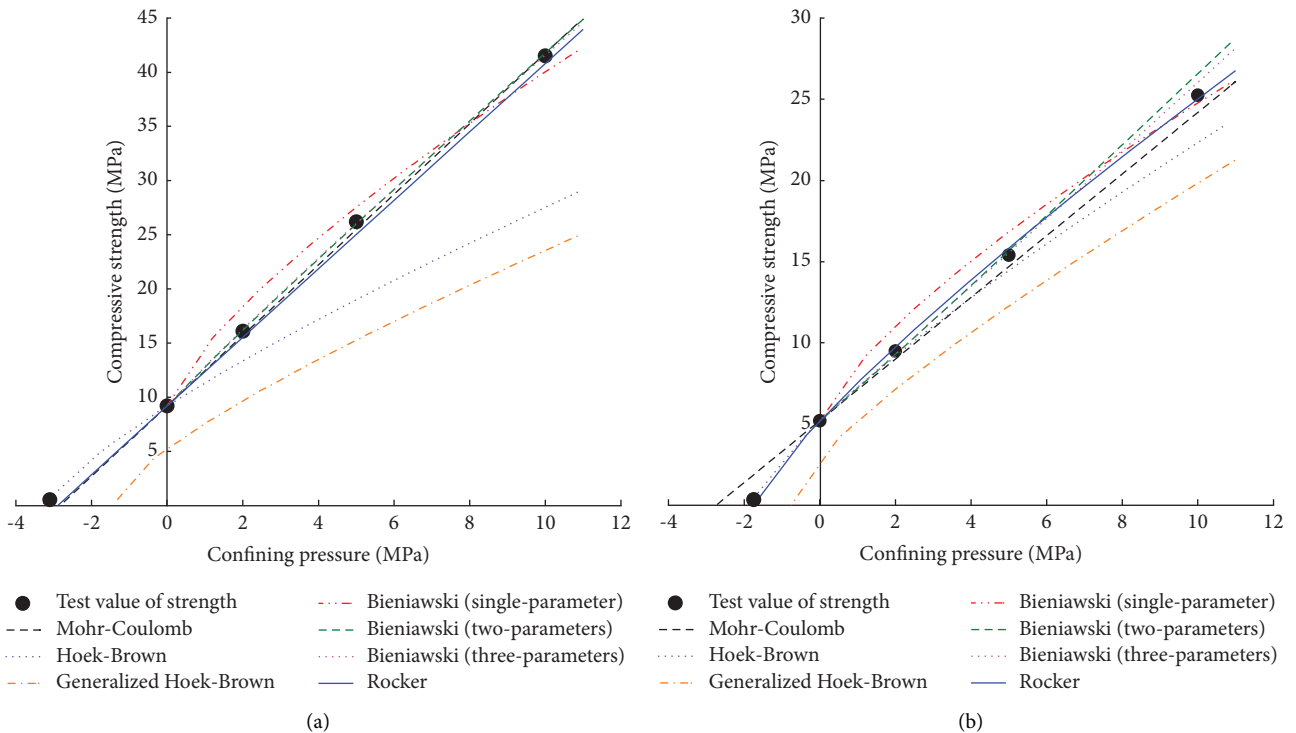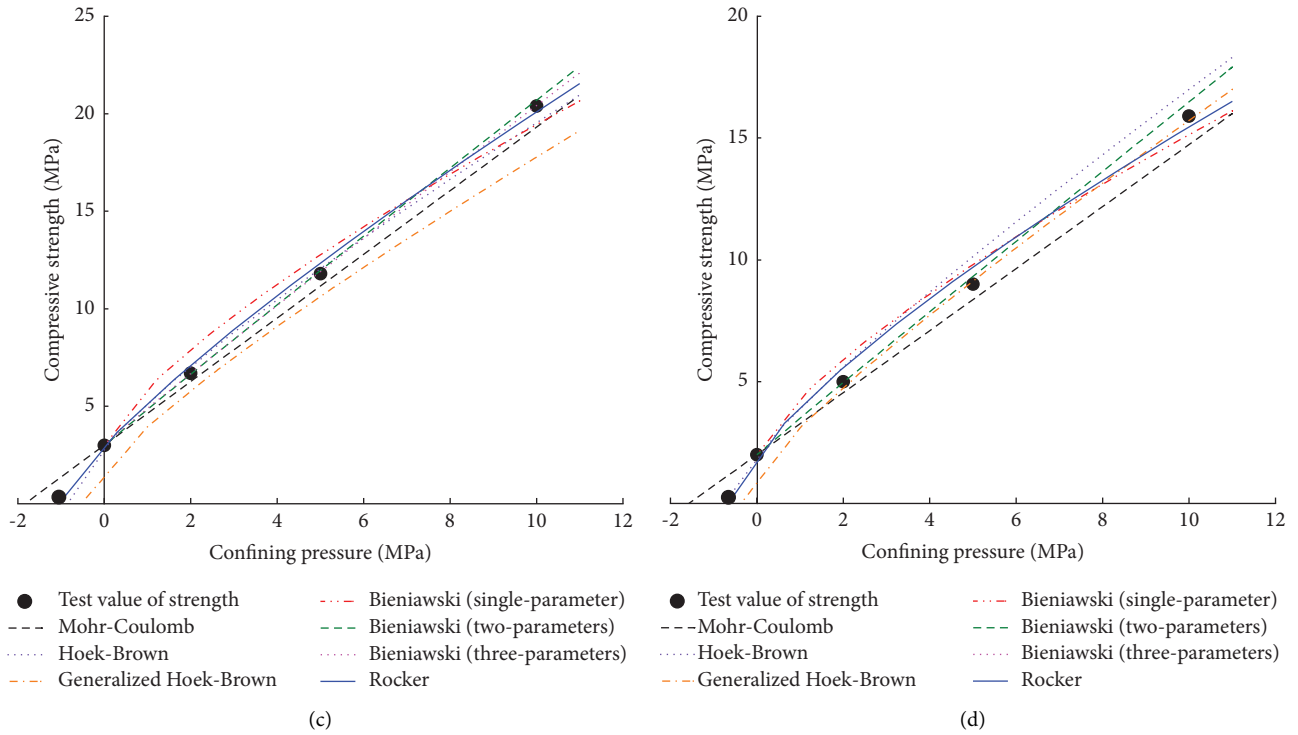| Strength criterion	Water content (%)	Evaluate expression
Mohr–Coulomb	0	$\sigma_1 = 9.2 + 3.255\sigma_3$
	10.1	$\sigma_1 = 5.2 + 1.899\sigma_3$
	12.5	$\sigma_1 = 3 + 1.632\sigma_3$
	14.1	$\sigma_1 = 2 + 1.273\sigma_3$
Hoek–Brown	0	$\sigma_1 = \sigma_3 + 9.2\,(0.263\sigma_3 + 1)^{0.5}$
	10.1	$\sigma_1 = \sigma_3 + 5.2\,(0.464\sigma_3 + 1)^{0.5}$
	12.5	$\sigma_1 = \sigma_3 + 3\,(0.914\sigma_3 + 1)^{0.5}$
	14.1	$\sigma_1 = \sigma_3 + 2\,(1.125\sigma_3 + 1)^{0.5}$
Generalized Hoek–Brown	0	$\sigma_1 = \sigma_3 + 9.2\,(0.184\sigma_3 + 0.329)^{0.5}$
	10.1	$\sigma_1 = \sigma_3 + 5.2\,(0.325\sigma_3 + 0.329)^{0.5}$
	12.5	$\sigma_1 = \sigma_3 + 3\,(0.640\sigma_3 + 0.329)^{0.5}$
	14.1	$\sigma_1 = \sigma_3 + 2\,(0.787\sigma_3 + 0.329)^{0.5}$
Bieniawski (single-parameter)	0	$\sigma_1 = 9.2 + 9.2 \times 3.147\,(\sigma_3/9.2)^{0.75}$
	10.1	$\sigma_1 = 5.2 + 5.2 \times 2.306\,(\sigma_3/5.2)^{0.75}$
	12.5	$\sigma_1 = 3 + 3 \times 2.223\,(\sigma_3/3)^{0.75}$
	14.1	$\sigma_1 = 2 + 2 \times 1.965\,(\sigma_3/2)^{0.75}$
Bieniawski (two-parameter)	0	$\sigma_1 = 9.2 + 9.2 \times 3.268\,(\sigma_3/9.2)^{0.957}$
	10.1	$\sigma_1 = 5.2 + 5.2 \times 2.100\,(\sigma_3/5.2)^{1.028}$
	12.5	$\sigma_1 = 3 + 3 \times 1.814\,(\sigma_3/3)^{0.980}$
	14.1	$\sigma_1 = 2 + 2 \times 1.487\,(\sigma_3/2)^{0.984}$
Bieniawski (three-parameter)	0	$\sigma_1 = 9.2 \times 0.994 + 9.2 \times 3.257\,(\sigma_3/9.2)^{0.941}$
	10.1	$\sigma_1 = 5.2 \times 1.011 + 5.2 \times 2.061\,(\sigma_3/5.2)^{1.014}$
	12.5	$\sigma_1 = 3 \times 1.015 + 3 \times 1.798\,(\sigma_3/3)^{0.972}$
	14.1	$\sigma_1 = 2 \times 1.021 + 2 \times 1.456\,(\sigma_3/2)^{0.970}$
Rocker	0	$\sigma_1 = 9.2\,((\sigma_3/3.1) + 1)^{0.998}$
	10.1	$\sigma_1 = 5.2\,((\sigma_3/1.75) + 1)^{0.825}$
	12.5	$\sigma_1 = 3\,((\sigma_3/1.05) + 1)^{0.808}$
	14.1	$\sigma_1 = 2\,((\sigma_3/0.66) + 1)^{0.735}$

FIGURE 9: Continued.

FIGURE 9: Strength criterion prediction curves of mudstone under different water content. (a) Water content: 0. (b) Water content: 10.1%. (c) Water content: 12.5%. (d) Water content: 14.1%.

TABLE 3: Least mean standard fitting deviations of each strength criterion.

Strength criterion	Water content (%)	Least mean standard fitting deviations (MPa)
Mohr–Coulomb	0	0.43
	10.1	0.60
	12.5	0.66
	14.1	0.70
Hoek–Brown	0	7.97
	10.1	1.94
	12.5	0.48
	14.1	0.85
Generalized Hoek–Brown	0	11.15
	10.1	3.86
	12.5	1.63
	14.1	0.46
Bieniawski (single-parameter)	0	1.53
	10.1	1.25
	12.5	0.92
	14.1	0.73
Bieniawski (two-parameter)	0	0.18
	10.1	0.30
	12.5	0.18
	14.1	0.34
Bieniawski (three-parameter)	0	0.13
	10.1	0.12
	12.5	0.06
	14.1	0.07
Rocker	0	0.75
	10.1	0.60
	12.5	0.37
	14.1	0.51

strength criterion is an empirical model, and the correlation coefficient in the calculation expression has no specific physical meaning, which is easy to cause human error. At the same time, this criterion can only predict the compressive strength of rock but cannot obtain the tensile strength of rock. The scope of application has obvious limitations.

The Rocker strength criterion can well fit the compressive strength values of mudstone under different water content states and different confining pressures, and the least mean standard fitting deviations are all below 1 MPa. It can be seen from the figure that as the confining pressure increases gradually, the Rocker strength criterion curve has a gradual slowing trend, indicating that the growth rate of the compressive strength value decreases with the increase of the confining pressure, which is also more consistent with the actual situation. Moreover, the physical meaning of the parameters in the expression of the Rocker strength criterion is clear, and the acquisition method is simple and reliable, so the Rocker strength criterion has strong applicability.

To sum up, by comparing and analyzing the applicability of the five strength criteria, it can be seen that the Rocker strength criterion can not only be well applied to the calculation and prediction of mudstone strength under different water content and different confining pressures but also the parameters in the expression are clear, simple, and easy to get. Generally speaking, the Rocker strength criterion is more applicable.

4.4. Rocker Strength Criterion Considering Water Content and Confining Pressure Effects. Through the comparative analysis of the applicability of the five strength criteria above, it is proposed to select Rocker strength criterion to describe and predict the strength index of mudstone. From the calculation expression of the Rocker strength criterion, it can be seen that the uniaxial compressive strength, the tensile strength, and the value of exponent m will affect the calculation and prediction of mudstone strength. At the same time, they are closely related to the water content of mudstone. The purpose of this subsection is to study the function correspondence between the uniaxial compressive strength, the tensile strength, the value of exponent m, and the water content of mudstone and then obtain the calculation expression of the modified Rocker strength criterion including both water content and confining pressure. Finally, a nonlinear strength prediction model for softened mudstone can be established.

According to the analysis of the triaxial compression test results, it can be seen that the relationship between the uniaxial compressive strength and the water content approximately satisfies the quadratic polynomial function relationship. The fitting curve is shown in Figure 10, and its relational expression is

$$\sigma_c = -0.028w^2 - 0.128w + 9.207. \tag{13}$$

Its correlation coefficient is $R^2 = 0.997$, indicating that the fitting effect is good.

The relationship between the tensile strength and water content of mudstone approximately meets the exponential
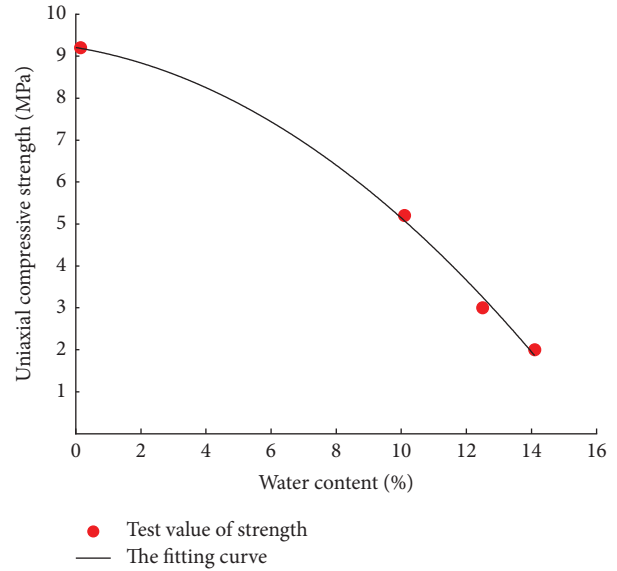

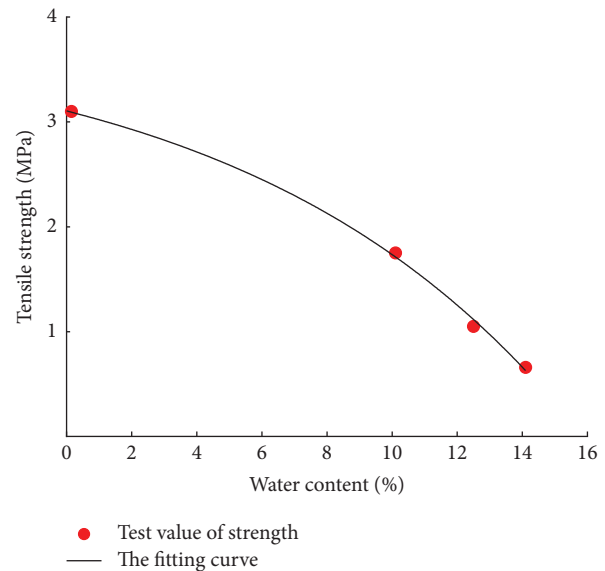FIGURE 10: Fitting curve between the uniaxial compressive strength and water content.

FIGURE 11: Fitting curve between the tensile strength and water content.

function relationship. The fitting curve is shown in Figure 11, and its relational expression is

$$\sigma_t = 3.891 - 0.787 \exp\left(\frac{w}{9.915}\right). \tag{14}$$

Its correlation coefficient is $R^2 = 0.998$, indicating that the fitting effect is good.

When the water content of mudstone is 0, 10.1%, 12.5%, and 14.1%, the value of exponent m is 0.998, 0.825, 0.808, and 0.735, respectively. According to the corresponding relationship, they approximately meet the function relationship of the quadratic polynomial. The fitting curve is shown in Figure 12, and its relational expression is
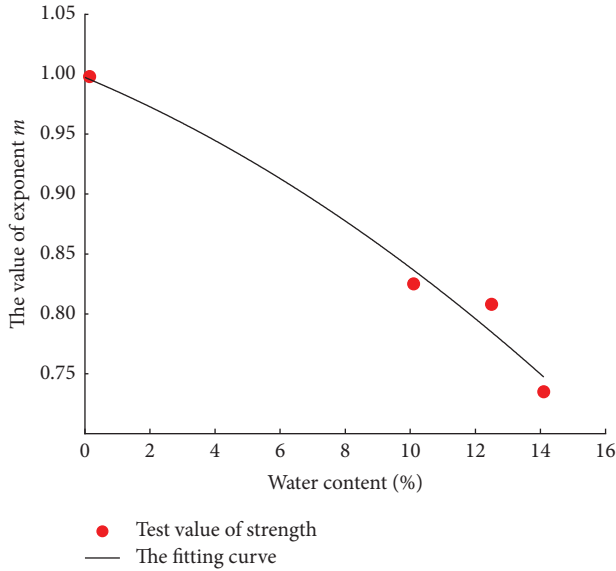
FIGURE 12: Fitting curve between the value of exponential m and water content.

$$m = -0.00045w^2 - 0.011w + 0.997. \quad (15)$$

Its correlation coefficient is $R^2 = 0.978$, indicating that the fitting effect is good.

Substituting equations (13)–(15) into (11), the following equation can be obtained:

$$\ln\left(\frac{\sigma_1}{-0.028w^2 - 0.128w + 9.207}\right)$$
$$= \left(-0.00045w^2 - 0.011w + 0.997\right) \quad (16)$$
$$\ln\left(\frac{\sigma_3}{3.891 - 0.787 \exp\left(w/9.915\right)} + 1\right).$$

Equation (16) is the Rocker strength criterion expression for softened mudstone considering both water content and confining pressure. Substituting $\sigma_3 = 0$ MPa, 2 MPa, 5 Mpa, and 10 MPa into equation (16), we can get the Rocker strength criterion prediction curve considering the water content effect under different confining pressures, as shown in Figure 13.

It can be seen from Figure 13 that (1) the four predicted curves have basically the same trend, indicating that the strength of softened mudstone varies with water content in roughly the same law under different confining pressure states and the strength decreases significantly with the increase of water content. Under the same water content state, the strength increases with the increase of confining pressure. (2) When the water content of mudstone is higher than 10%, the influence of confining pressure on strength is more significant, and the amplitude of strength change caused by the change of confining pressure is greater. (3) When the water content of mudstone increases, high confining pressure can effectively inhibit the degree of strength attenuation. (4) Under different confining pressures, when the water
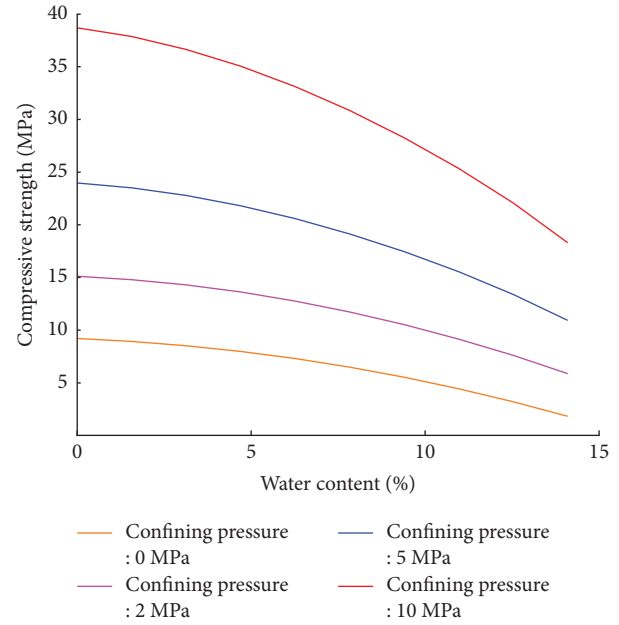

FIGURE 13: Prediction curve of the Rocker strength criterion considering the water content effect.

content of mudstone is 0, 10.1%, 12.5%, and 14.1%, the average deviations between the calculated strength and the experimental strength of mudstone are 4%, 4%, 9%, and 11%, respectively.

From the abovementioned relevant strength test results and softening characteristic law in Chapter 3, it can be seen that the results obtained by the prediction curve of the Rocker strength criterion are consistent with the actual situation. The prediction law is basically consistent with the test law, and the deviation between the calculated value and the test value is small. The prediction effect is good. The research results show that the strength prediction model considering the water content and confining pressure effect based on the Rocker strength criterion can well reflect the strength characteristics and softening characteristics of softened mudstone under different water content and different confining pressures. It has good applicability for the prediction and calculation of softened mudstone strength.

5. Conclusion

Taking the tertiary mudstone as the research object, this paper analyzes the triaxial strength characteristics and deformation law of softened mudstone through field sampling, triaxial compression strength test, and Brazilian splitting test and discusses the applicability of the strength criterion for softened mudstone. The main conclusions are as follows:

(1) In terms of deformation characteristics, with the increase of confining pressure and water content, the mudstone changes from brittle failure to ductile failure; under the same water content state, with the increase of confining pressure, the compressive strength, residual strength, and elastic modulus of mudstone increase significantly, and the amount of

deformation is also greatly increased; under the same confining pressure, the compressive strength, residual strength, and elastic modulus of mudstone decrease significantly with the increase of water content, and the value of strain will be increased when reaching the peak compressive strength.

(2) In terms of strength characteristics, the water content has a significant influence on the strength index of mudstone. The higher the water content of mudstone, the greater the effect of confining pressure on its strength, and the high confining pressure can effectively suppress the degree of strength attenuation.

(3) In terms of softening characteristics, under different confining pressures, the variation law of the triaxial softening coefficient of mudstone with water content is roughly the same, showing a downward trend with the increase of water content. When the water content is low (0–10.1%), the strength of the mudstone is mainly related to its own water content. When the water content increases to 10.1%–14.1%, both the confining pressure and the water content are important factors affecting the strength of the mudstone. Confining pressure can weaken the downward trend of strength due to the increase of water content.

(4) Five different forms of rock strength criteria are compared and analyzed from the aspects of the accuracy of the strength prediction of softened mudstone and the objectivity and convenience of expression parameter selection. The research shows that the applicability of the Rocker strength criterion is better.

(5) Based on the Rocker strength criterion, a nonlinear strength prediction model of softened mudstone considering the water content and confining pressure effect is obtained. The results show that the prediction law of the model is basically consistent with the test law, and the deviation between the calculated value and the test value is small. It can better describe the strength characteristics and softening characteristics of softened mudstone and has good applicability.

Data Availability

The data used to support the findings of this study can be obtained from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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