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Strength Calculation Method of Bedding Rock Based on Improved Hoek-Brown Criterion Considering the Effect of Critical Confining Pressure

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Abstract

Rock is a commonly used building material. Studying rock properties can reduce production time and cost, improve production efficiency and construction safety. Therefore, rock mechanics characteristics, especially strength, have always been a hot field of rock mechanics. Classical strength criteria such as the Mohr-Coulomb (M-C) criterion and Hoek-Brown (H-B) criterion are based on rock strength homogeneity and cannot reflect the characteristics of layered rock strength changing with azimuth. Therefore, it is necessary to modify the classic strength criterion to reflect layered rock anisotropy. Based on existing triaxial test results and rock anisotropic strength properties, an improved H-B criterion for rock anisotropy considering the effect of critical confining pressure is proposed in this paper, which can be used to calculate the strength of layered rocks. Taking slate as an example, the calculation results of the improved H-B criterion show that: 1. the improved H-B criterion can mostly control the mean absolute percentage error (MAPE) of McLamore slate test results within 30%, which is obviously better than the classical H-B criterion and has good extrapolation ability; 2. the material parameters *m*, *n* are determined by test results and inversion analysis, which avoids the arbitrariness. The proposed method can be used as a supplementary and alternative method to estimate or calculate the strength of layered rock.

Keywords

strength criterion, Hoek-Brown criterion, strength anisotropy, critical confining pressure, slate, inverse analysis

1 Introduction

Rock is a commonly used construction and decorative material, it has excellent resistance to environmental influences, hardness and aesthetic properties [1, 2]. The study of rock properties can reduce production time and cost and increase production efficiency [3, 4]. Therefore, rock mechanics characteristics, especially the strength, have always been a hot field of rock mechanics [5–7]. The study of the rock strength is often carried out through tests, and the theory obtained through the summary of the test results guides the actual engineering [8], such as the classic Hoek-Brown (H-B) criterion [9].

Many rock mechanics test results show that the rock strength not only has a robust discrete type, but the strength is also related to the azimuth angle (the angle between the bedding plane and the maximum principal stress is denoted as β). In recent years, the anisotropy of rock strength has been widely recognized [10–12]. The anisotropy of layered rocks with significant bedding planes mainly depends on the mineral composition and genesis of the rock, such as the minerals of the rock are oriented in sheets or strips, the interlayer schistosity of metamorphic rock, the interlayer bedding planes of sedimentary rocks, and the weak plane of the interlayer in other rocks will cause anisotropic characteristics. The anisotropic characteristics of layered rocks have a significant impact on the safety and stability of geotechnical engineering.

Many rocks anisotropic mechanical tests have been performed out. A slate uniaxial compression test with different bedding angles as the object was carried out; the strength characteristics, deformation parameters, and failure mechanism of slate were studied, and a new empirical formula was given to describe the anisotropy of P-wave velocity and thermal parameters of the slate [13]. Different types of rock samples were used as test objects, and the strength characteristics of rock anisotropy under different conditions were obtained [14–16]. Simultaneously, some empirical

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prediction formulas have also been proposed [16–18]. The methods of empirical formulas and experiments complemented each other, and they were also widely cited by subsequent researchers, such as recent work done on the prediction of anisotropic uniaxial compressive strength of rocks [19–21]. The triaxial strength prediction is an extension of uniaxial compressive strength prediction. Whereby, the Mohr-Coulomb (M-C) criterion and the H-B criterion are used to calculate the anisotropic triaxial strength of rocks. The main idea is to establish the mapping relationship between model parameters and the azimuth angle by modifying model parameters [21, 22]. However, the disadvantage is that some mapping relationships are complex and difficult to be practical, and some parameters are chosen at random and lack specific standards. Therefore, the application of the triaxial strength anisotropy criterion in practical engineering is subject to many restrictions.

In order to reflect the anisotropy characteristics of rocks, methods that only consider the strength of bedding planes or modify model parameters are introduced into the H-B strength criterion. The single-weakness plane theory was used to calculate the strength of anisotropic rocks [23]. A method assuming that rocks and bedding planes meet the H-B and Barton-Bandis strength criteria respectively was used to study the impact of rock strength and bedding density on anisotropy [24]. Some methods have been developed by improving the material parameters (m and s) in the H-B strength criterion, and the impact of m and s on the strength of anisotropic rocks has been studied [25–28]. However, the failure strength of anisotropic rock cannot be strictly predicted through a specific bedding plane, and it often has a large error with the actual condition. In addition, the failure mode of rock under a specific confining pressure changes from brittle failure to plastic failure. The specific confining pressure is called the critical confining pressure, which is an actual law summed up based on tests. Therefore, the critical confining pressure effect should not be ignored when establishing the rock anisotropic strength criterion [29, 30]. The critical confining pressure effect was used in the H-B strength criterion, and a satisfactory result is obtained for predicting rock strength [31, 32]. It is worth noting that because the critical confining pressure effect varies with different rocks, the rock types should be distinguished in specific research.

The objective of this paper is to develop a layered rock anisotropic strength prediction method based on the H-B strength criterion, and to reflect the impact of the critical confining pressure effect on the rock failure mode. In Section 2, the introduction of the Hoek-Brown strength criterion and the derivation process of the improvement method are given; in Section 3, the method proposed in this paper is verified by the existing triaxial strength test data of slate; the rationality of parameter selection and error analysis is discussed in Section 4; the conclusions are drawn at the end.

2 Materials and method

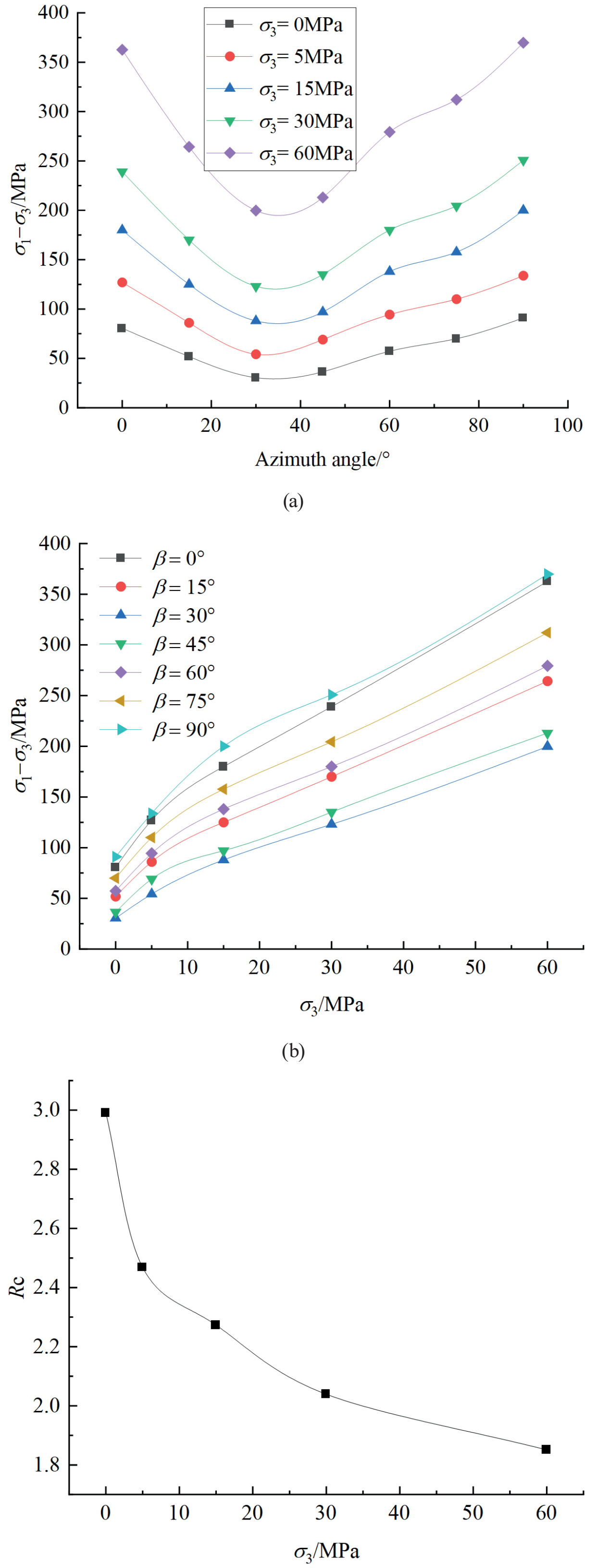
2.1 Strength characteristics of layered rock

It has been noted in Introduction that the strength of bedding rocks has anisotropic characteristics and exists in the three major rock types [33]. Slate is a typical layered rock, and it is the object of many physical tests. The anisotropic strength curve and characteristic curve of the slate are shown in Fig. 1. Furthermore, the test data is obtained from published literatures [14, 31]. It can be seen from Fig. 1 (a): the anisotropy characteristics of slate strength is obvious, and its strength changes with the azimuth angle to show a U-shaped or V-shaped tendency; the rock strength is the smallest when the azimuth angle is 30°, and the peak strength may appear at 0° or 90°. Moreover, the law is approximately satisfied under different confining pressures. It can be seen from Fig. 1 (b) that when the azimuth angle is the same, the deviator stress increases nonlinearly as the confining pressure increases. The impact of different confining pressures on the anisotropy ratio is shown in Fig. 1 (c). The anisotropy effect is characterized by the anisotropy ratio *Rc* (i.e., the ratio of the maximum and minimum rock strength under the same azimuth) [31]. It can be seen from Fig. 1 (c) that as the confining pressure increases, the anisotropy effect gradually decreases, which indicates that the confining pressure has an inhibitory effect. The smaller the *Rc*, the weaker the rock anisotropy. It should be noted that the three laws summarized above are not only applicable to slate, but can be extended to different types of rocks.

2.2 General calculation method of Hoek-Brown strength criterion

After the anisotropic strength characteristics of layered rocks are obtained from tests, corresponding methods need to be established to guide engineering practice [25]. In general, the M-C criterion and H-B criterion can be used to estimate the anisotropic strength of rocks.

The M-C criterion is the most classic strength criterion in geotechnical engineering, and the M–C criterion can be



(a)

(b)

(c)

Fig. 1 The typical rock anisotropic strength curve and its characteristics: (a) change curve of rock strength with azimuth angle, (b) the influence of confining pressure on strength, (c) the effect of confining pressure on the anisotropy ratio

used to describe the relationship between deviatoric stress and confining pressure:

$$\begin{cases} Q = \dfrac{2c\cos\varphi}{1-\sin\varphi} \\ K = \dfrac{2\sin\varphi}{1-\sin\varphi} \end{cases}, \tag{1}$$

where c and φ represents rock cohesion and internal friction angle.

Then the M–C criterion can be simplified as

$$\begin{aligned} &(\sigma_1 - \sigma_3) = Q + K\sigma_3 \\ &Q = \sigma_c, \end{aligned} \tag{2}$$

where σ_c is the uniaxial compressive strength of rock (UCS); σ_1 and σ_3 are the major and minor principal stresses, respectively.

Furthermore, considering the anisotropy of rock strength and its strength parameters, Eq. (2) can be rewritten as

$$(\sigma_1 - \sigma_3)_\beta = \sigma_{c(\beta)} + K\sigma_3, \tag{3}$$

where $(\sigma_1 - \sigma_3)_\beta$ is the strength at azimuth angle β, $\sigma_{c(\beta)}$ is the uniaxial compressive strength at azimuth angle β.

The H-B criterion is an empirical criterion established on many mechanical test results, which is widely promoted in rock engineering. When the rock anisotropy is not considered, the H-B criterion of a complete rock sample can be expressed as

$$(\sigma_1 - \sigma_3) = \sqrt{m\sigma_c\sigma_3 + s\sigma_c^2}, \tag{4}$$

where m is the material parameter, which is related to the rock type; constant s describes the rock integrity ranging from 0 to 1. In this paper, s is 1 because the rock is intact.

When considering the anisotropy of rocks, the H-B criterion has different modified methods. However, these modified methods have one thing in common: establish the mapping relationship between the parameters involved in Eq. (4) and the azimuth angle β. Since it is not meant to modify the empirical coefficient m [19], the uniaxial compressive strength can be modified. Furthermore, the H-B criterion considering anisotropy can be written as

$$(\sigma_1 - \sigma_3)_\beta = \sqrt{m\sigma_{c(\beta)}\sigma_3 + \sigma_{c(\beta)}^2}. \tag{5}$$

Besides, there are many forms of the H-B criterion considering anisotropy. But the mapping relationship between the coefficient and the azimuth angle is established, which is essentially the same, so it will not be repeated.

2.3 The modified Hoek-Brown strength criterion

The confining pressure will affect the strength of the rock. It is generally believed that as the confining pressure increases in the initial stage, the strength of the rock gradually increases. During the compression process, the strength growth rate of the rock will gradually decrease, and the rock strength envelope gradually becomes flat. As the confining pressure increases, the rock gradually transforms from brittleness to ductility. The transition phenomenon of rock failure mode is called the critical confining pressure effect [29]. In the σ-τ coordinate system (Fig. 2 (a)), the shear strength envelope is geometrically nonlinear. Under a specific confining pressure, the tangent gradient of the shear strength envelope is 0.

When considering the critical confining pressure, the σ-τ coordinate system can be expressed in the principal stress form, as shown in Fig. 2 (b). It can be seen from Fig. 2 (b) that M-C criterion and H-B criterion are monotonically increasing, which can be proved from Eqs. (3) and (5). However, when the confining pressure increases to the critical confining pressure, the deviator stress intensity will remain constant, which is ignored in the classic M-C criterion and H-B criterion.

In the M-C criterion and the H-B criterion, the deviator stress strength is a monotone increasing function of the confining pressure. As the confining pressure increases, the estimation errors of these two criteria will gradually increase (Fig. 2 (b)). A nonlinear term $A\sigma_3^2$ is introduced into the classic H-B criterion, and the material parameter m of the same type of rock is regarded as a fixed value [31, 32]. Therefore, the H-B criterion can be expressed as

$$\left(\sigma_1-\sigma_3\right)_\beta=\sqrt{m\sigma_{c(\beta)}\sigma_3+\sigma_{c(\beta)}^2}-A\sigma_3^2, \tag{6}$$

where A is an empirical constant, $\sigma_{c(\beta)}$ is the uniaxial compressive strength of rock with weak angle β. According to the concept of critical confining pressure, when σ_3 reaches σ_{rc}, the slope of the $\sigma_1-\sigma_3$ curve is 0.

$$\frac{\partial\left(\sigma_1-\sigma_3\right)_\beta}{\partial\sigma_3}=0 \tag{7}$$

The expression of A can be obtained by deriving Eq. (6):

$$A=\frac{m\sigma_{c(\beta)}}{4\sigma_{rc}\sqrt{m\sigma_{c(\beta)}\sigma_{rc}+\sigma_{c(\beta)}^2}}. \tag{8}$$

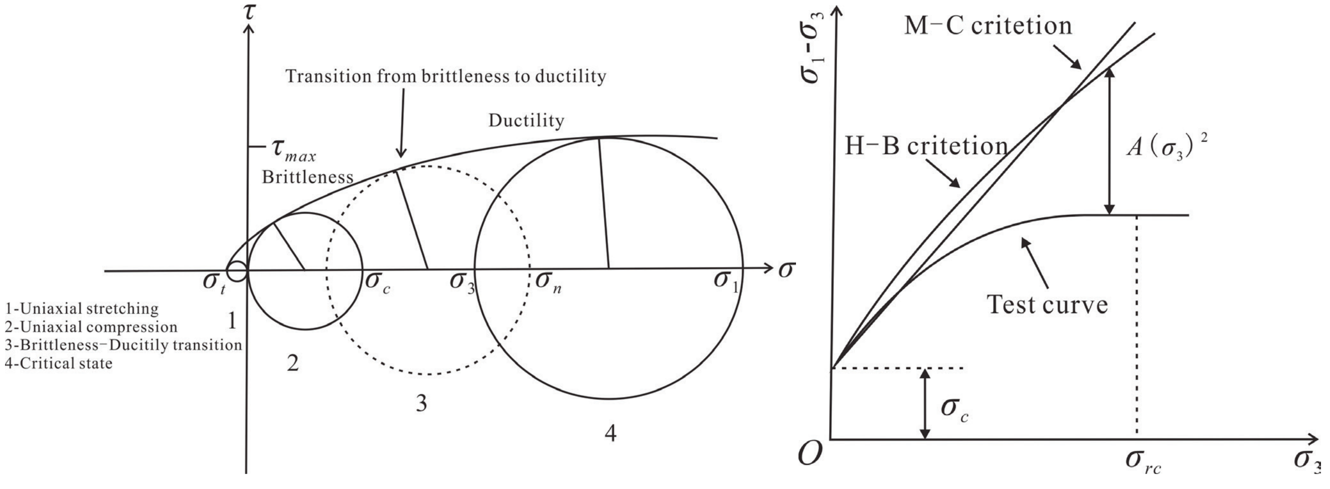
It can be seen that the A is a function of the azimuth angle. And σ_{rc} (critical confining pressure) can be expressed as

$$\sigma_{rc}=n_\beta\sigma_{c(\beta)}, \tag{9}$$

where n_β is the correction coefficient, which varies with rock type and azimuth.

Substituting Eq. (8) into Eq. (6), Eq. (10) can be obtained:

$$\begin{aligned}\left(\sigma_1-\sigma_3\right)_\beta&=\sqrt{m\sigma_{c(\beta)}\sigma_3+\sigma_{c(\beta)}^2}\\&-\frac{m\sigma_{c(\beta)}}{4n_\beta\sigma_{c(\beta)}\sqrt{m\sigma_{c(\beta)}n_\beta\sigma_{c(\beta)}+\sigma_{c(\beta)}^2}}\sigma_3^2.\end{aligned} \tag{10}$$



(a) (b)

Fig. 2 The critical confining effect of rock; (a) σ-τ coordinate system, (b) $\sigma_3-(\sigma_1-\sigma_3)$ coordinate system

Therefore, the improved anisotropic H–B criterion can be expressed as

$$\begin{cases}(\sigma_1-\sigma_3)_\beta=\sqrt{m\sigma_{c(\beta)}\sigma_3+\sigma_{c(\beta)}^2}-\dfrac{m\sigma_{c(\beta)}}{4n_\beta\sigma_{c(\beta)}\sqrt{m\sigma_{c(\beta)}n_\beta\sigma_{c(\beta)}+\sigma_{c(\beta)}^2}}\sigma_3{}^2, & \sigma_3\le\sigma_{rc}\\ (\sigma_1-\sigma_3)_\beta=\dfrac{3mn_\beta+4}{4\sqrt{mn_\beta\sigma_{c(\beta)}{}^2+\sigma_{c(\beta)}^2}}\sigma_{c(\beta)}^2, & \sigma_3>\sigma_{rc}\end{cases}. \tag{11}$$

Simplifying the Eq. (11), the following expression can be obtained:

$$\begin{cases}(\sigma_1-\sigma_3)_\beta=\sqrt{m\sigma_{c(\beta)}\sigma_3+\sigma_{c(\beta)}^2}-\dfrac{m}{4n_\beta\sigma_{c(\beta)}\sqrt{mn_\beta+1}}\sigma_3^2, & \sigma_3\le\sigma_{rc}\\ (\sigma_1-\sigma_3)_\beta=\dfrac{3mn_\beta+4}{4\sqrt{mn_\beta+1}}\sigma_{c(\beta)}, & \sigma_3>\sigma_{rc}\end{cases}. \tag{12}$$

Equation (12) is the final improved anisotropic Hoek–Brown criterion. The calculation flow chart is shown in Fig. 3. The parametric solution of the criterion will be discussed below.

3 Results

In this paper, the anisotropic triaxial strength estimation of slate is taken as an example to verify the proposed method. The test data is obtained from published literatures [14–16], and the original test data is shown in Fig. 4. The material parameter *m* depends on the type of rock and the level of failure before reaching the major principal stress σ_1 and minor principal stress σ_3. Generally, the *m* ranges from 0.001 to 25. For severely disturbed rocks, *m* is 0.001, and for complete hard rocks, *m* is 25. Therefore, the material parameter *m* is 22 for the slate [34]. However, it is difficult to obtain the *n* from intuitive statistics due to the limited data. Therefore, the *n* is obtained through inverse analysis.

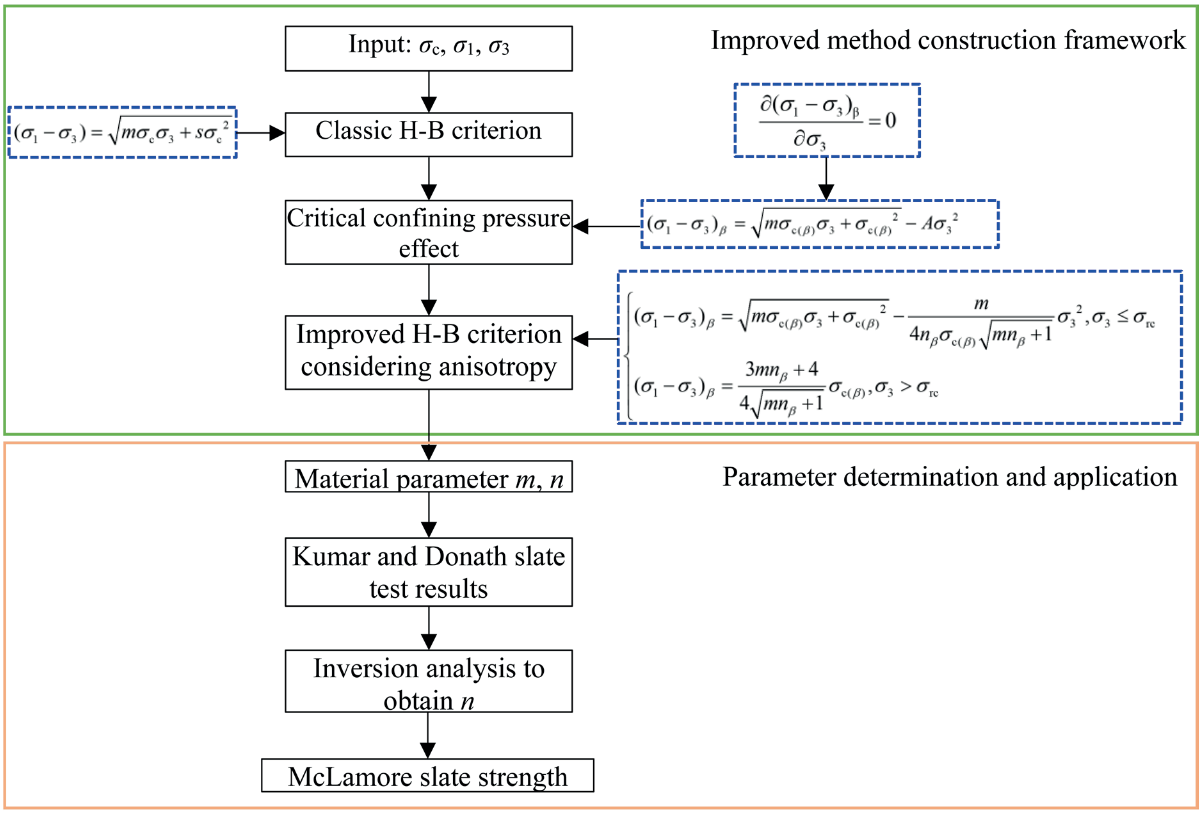
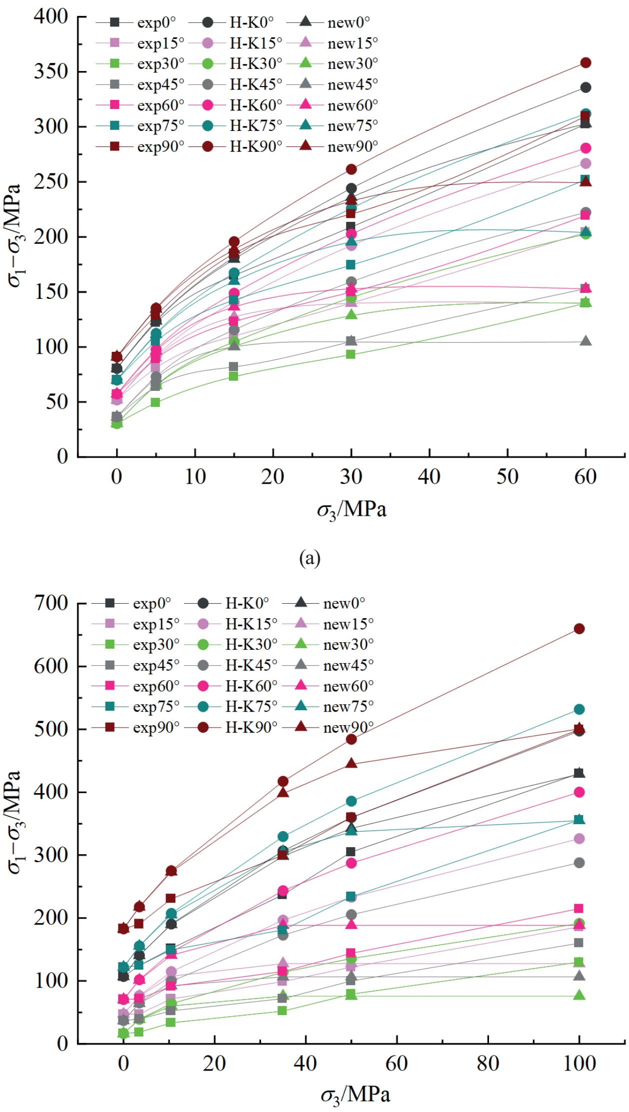


Fig. 3 The calculation flow chart of the improved H-B criterion

3.1 The impact of confining pressure on rock strength

The slate test data is divided into two categories, denoted by S1 and S2 respectively. S1 is used to obtain the value of *n* and test the fitting ability of the improved criterion; S2 is used to test the actual extrapolation effect of the improved criterion. The fitting result of S1 is shown in Fig. 4.

The calculation results of the H-B strength criterion and the improved H-B strength criterion are shown in Fig. 4. Moreover, the increasing trend of slate strength with increasing confining pressure is shown in Fig. 4. In Fig. 4 (a), the critical confining pressure effect is not obvious, and it is only reflected when the azimuth angle is small. The obvious critical confining pressure effect can be seen in Fig. 4 (b). When the confining pressure exceeds 35 MPa, the failure mode of slate transitions from brittle failure to ductile failure. When the azimuth angle is large, it is difficult to find the critical confining pressure effect. This is because when the azimuth angle is 70° or 90°, the fracture surface expands parallel to the bedding surface, which is similar to the instability of the pressure rod, and the penetrating splitting and tension failure occurs.



(a)

(b)

Fig. 4 Test results and calculation results of S1: (a) Kumar slate test results and comparison [14], (b) Donath slate test results and comparison [15]

3.2 The impact of azimuth angle on rock strength

The relationship between the strength and azimuth angle of Kumar slate when the confining pressure is 15 MPa, 15 MPa, 30 MPa and 60 MPa is shown in Fig. 5.

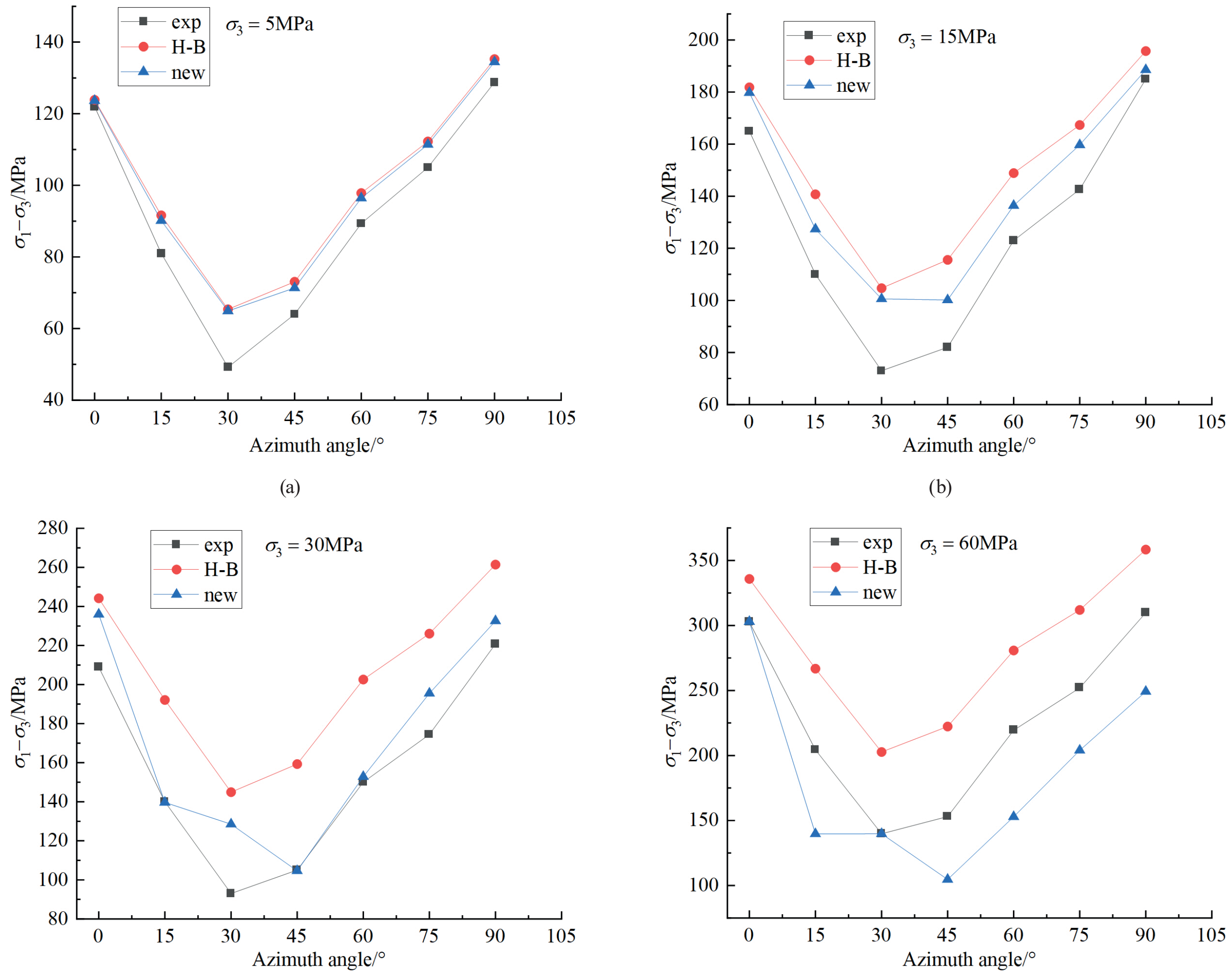
The relationship between the strength and angle of Donath slate when the confining pressure is 10.5 MPa, 35 MPa, 50 MPa and 100 MPa is shown in Fig. 6.

As described in Section 2, the $(\sigma_1-\sigma_3)-\beta$ curve shows a U-shaped trend. It can be seen from Figs. 5 and 6 that the slate strength is the lowest when the azimuth angle is 30°, and the slate strength is the highest when the azimuth angle is 90°. Moreover, the strength estimated by the improved H-B strength criterion is closer to the test result. In addition, when the confining pressure is small, the strength estimated by the improved H-B strength criterion has a smaller error.

3.3 Slate strength estimation

Material parameters *m*, *n* are obtained from Kumar and Donath slate test data. In order to test the extrapolation prediction ability of the improved H-B criterion, another set of test data (Fig. 7) was used to verify the applicability of the improved H-B criterion using the material parameters obtained in the previous section. The McLamore slate test results [16] and prediction results are shown in Fig. 7, and the calculation results of the traditional H-B strength criterion are given for comparison.

The test data has a high degree of agreement with the improved H-B criterion, and the prediction performance of rock anisotropic strength is the best when the confining pressure exceeds 100 MPa. As the confining pressure increases, the critical confining pressure effect becomes more and more obvious. The same trend as in Fig. 6 can be obtained from Fig. 8, but it is worth noting that a smaller error has been achieved in the McLamore slate strength prediction. It can be seen that the extrapolation ability of the improved H-B criterion is also better than that of the classic H-B criterion, which shows that the improved criterion proposed in this paper is reasonable.



(a) (b)

(c) (d)

Fig. 5 The impact of azimuth angle on Kumar slate strength; (a) the confining pressure is 5 MPa, (b) the confining pressure is 15 MPa, (c) the confining pressure is 30 MPa, (d) the confining pressure is 60 MPa

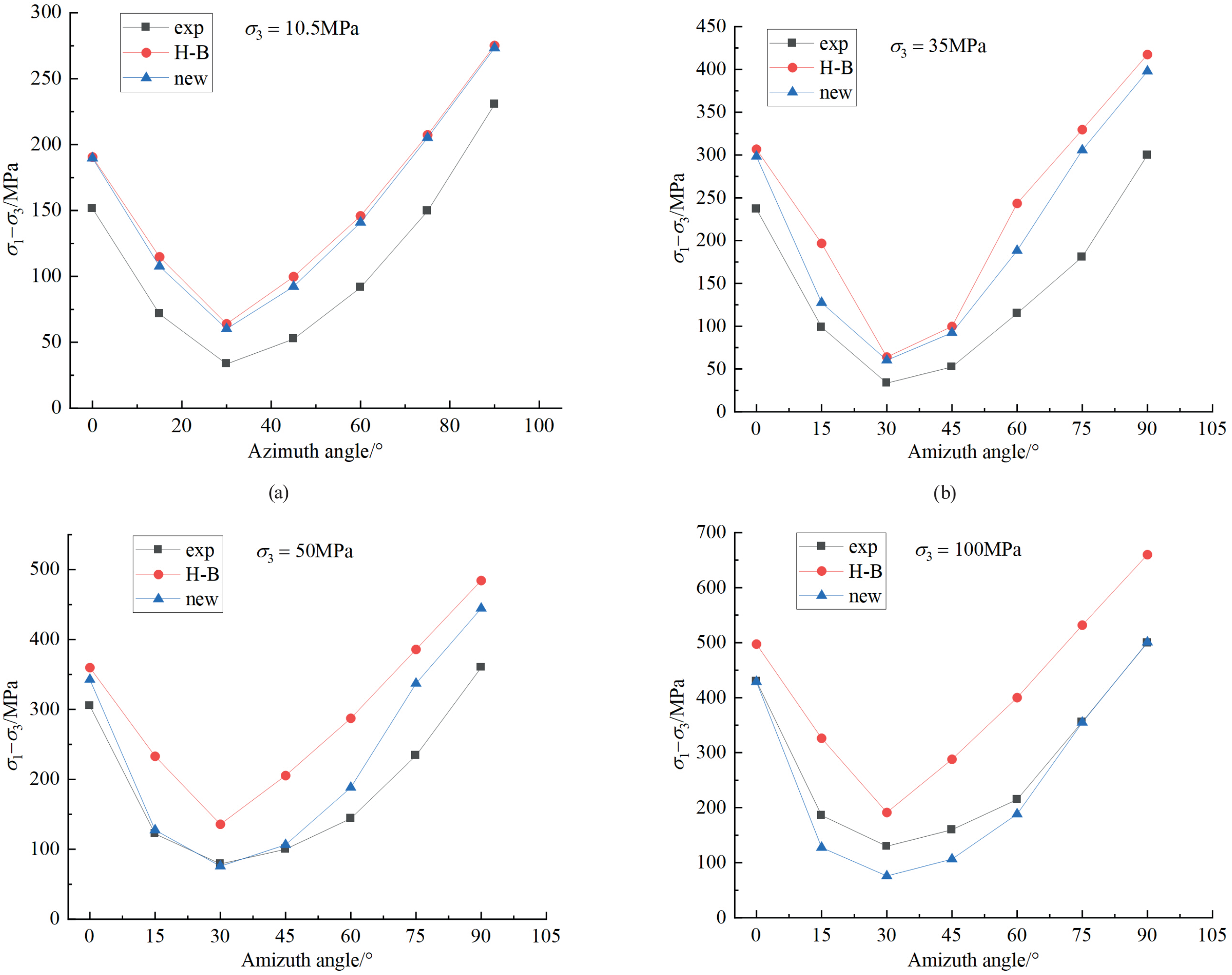
4 Discussions

4.1 The determination of material parameters

After obtaining the uniaxial compressive strength of multiple azimuth angles through experiments, the material parameters need to be solved include m, n in Eq. (12). At the same time, parameter values should be objective and accurate. The value of m can be obtained according to the results of the triaxial test and combined with the ultrasonic test, but the other fitting parameters are additionally introduced in the method of correcting the value of m [35]. It is complicated and time-consuming to modify the value method of m. Although the parameters m and n can be obtained by fitting or inverse analysis method, the general physical meaning of parameters is lost, and they are easily affected by the sample size and fitting method. Therefore, m is obtained by consulting extensive sample statistics in this paper. When the test data is sufficient, the direct deduction analysis is used to obtain the n. By drawing the curve of the deviator stress changing with the confining pressure at different azimuth angles and obtaining the n through statistics. If there is insufficient statistical data, the inversion analysis method is used to get the parameter n.

4.2 Error analysis

The relative errors of the two criteria for calculating the strength of Kumar slate and Donath slate are given in Table 1 and Table 2, respectively. It can be seen from Table 1 and Table 2 that the overall error of the improved H-B criterion is smaller than that of the classic H-B criterion. In the classic H-B criterion, as the confining pressure increases, the error of the calculation results also increases. Moreover, in the improved H-B criterion, due to the consideration of the critical confining pressure effect, the prediction accuracy of slate strength under higher confining



(a) (b)

(c) (d)

Fig. 6 The impact of azimuth angle on Donath slate strength; (a) the confining pressure is 10.5 MPa, (b) the confining pressure is 35 MPa, (c) the confining pressure is 50 MPa, (d) the confining pressure is 100 MPa

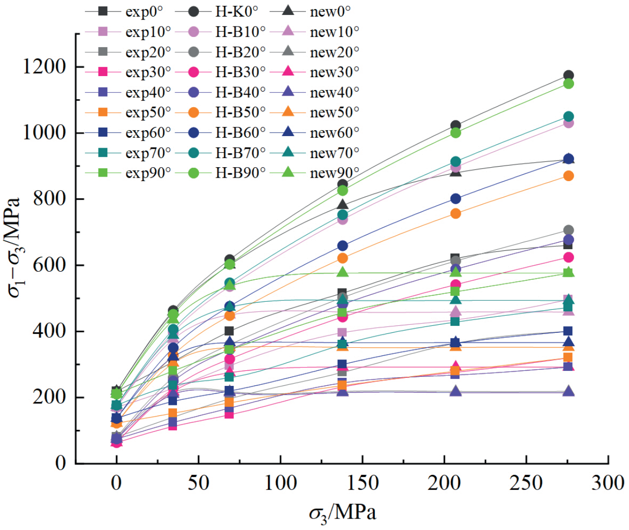
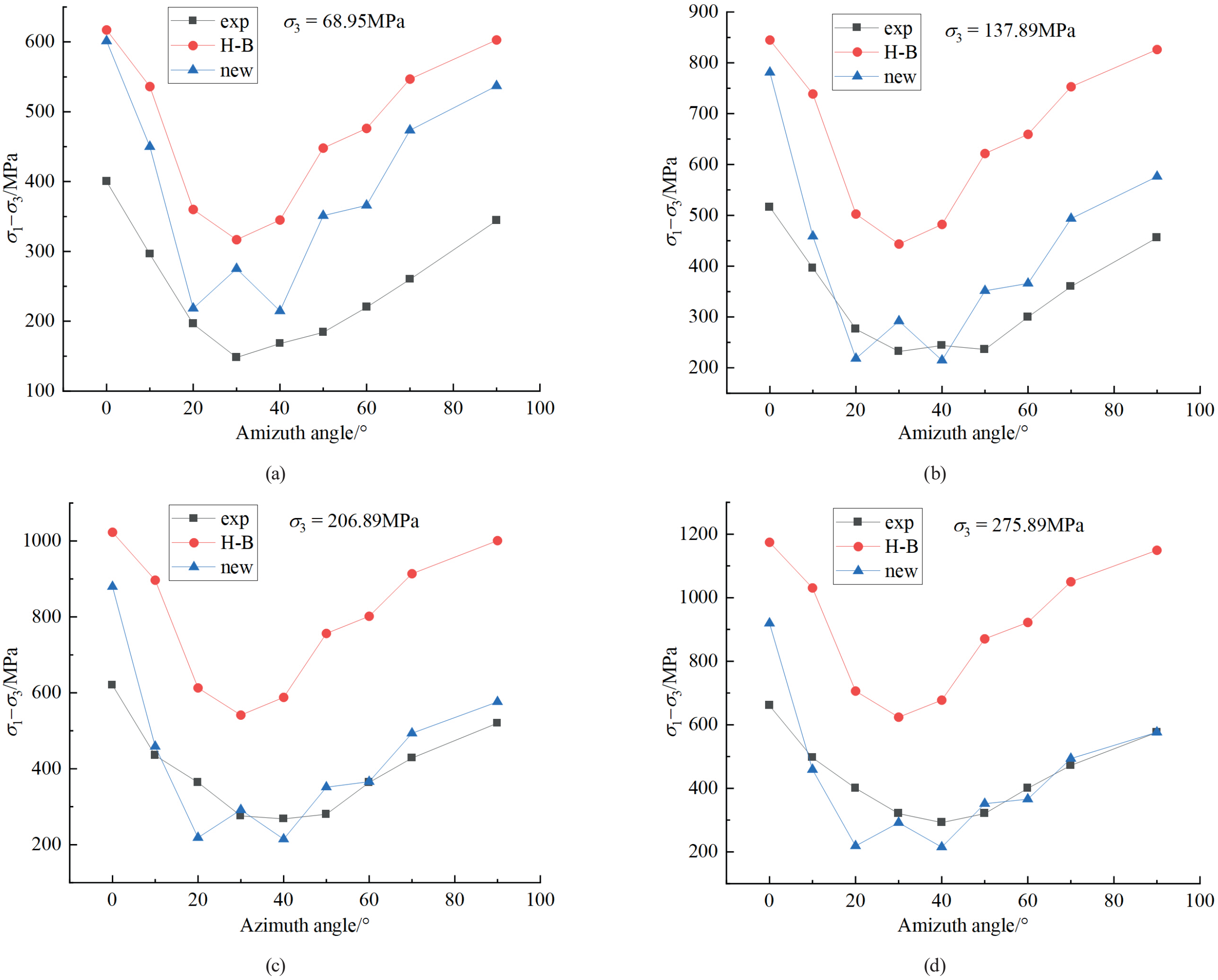


Fig. 7 Improved H-B strength criterion estimation results and comparison [18]

pressure is greatly improved. For example, in Kumar slate, when the azimuth angle $\beta = 90°$ and the confining pressure $\sigma_3 = 30$ MPa, the relative error is 5.23%; in Donath Slate, when the azimuth angle $\beta = 90°$ and the confining pressure $\sigma_3 = 100$ MPa, the relative error is 0.16%. It can also be concluded from Table 1 and Table 2 that as the azimuth angle and confining pressure increase, the smaller the relative error, the higher the prediction accuracy. Therefore, the critical confining pressure effect can be reflected in the improved H-B criterion. The relative errors of the two criteria are relatively large under individual confining pressures, but they are within the acceptable range, which may be related to the values of m and n.

In McLamore slate strength prediction, the mean absolute percentage error (MAPE) for each azimuth angle of the improved H-B criterion is shown in Fig. 9. It can be



(a) (b) (c) (d)

Fig. 8 The impact of azimuth angle on McLamore and Gray slate strength; (a) the confining pressure is 68.95 MPa, (b) the confining pressure is 137.89 MPa, (c) the confining pressure is 206.89 MPa, (d) the confining pressure is 275.89 MPa

seen from Fig. 9, the improved H-B criterion can control most of the MAPE within 30%, which is obviously better than the classical H-B criterion, showing its good extrapolation ability.

In summary, based on the empirical criterion of nonlinear change of rock strength considering critical confining pressure proposed by M. Singh et al. (2011) [31], this paper mainly uses the concept of critical condition (when $\sigma_3 = \sigma_{rc}$) to calculate the modified H-B strength calculation formula of anisotropic rock. The material parameter n is obtained by inverse calculation of Kumar and Donath slate test data. The new method has lower error by theoretical derivation and experimental data correction. The criterion contains a small number of parameters, and the parameters are easy to obtain, so it is convenient for application and provides a reference for the calculation of anisotropic rock strength.

5 Conclusions

In this paper, an improved H-B criterion suitable for anisotropic rock is developed. And compared with McLamore test results and the classic H-B criterion. The conclusions are as follows:

1. The change of strength with azimuth angle is approximately U-shaped or V-shaped. The anisotropic strength increases nonlinearly with confining pressure, and R_c decreases with increasing the confining pressure.
2. In the classic H-B criterion, the deviator stress is a monotonically increasing function of the confining pressure. As the confining pressure increases, the theoretical calculation results and the triaxial test results have larger errors. The improved H-B criterion considers the effect of critical confining pressure, which

Table 1 Relative error of Kumar slate strength

$\beta/°$	σ_3/MPa	Relative error/%	
		H-B	Improved H-B
0	0	0.00%	0.00%
	5	1.52%	1.34%
	15	10.19%	8.94%
	30	16.84%	12.90%
	60	10.97%	0.11%
15	0	0.00%	0.00%
	5	13.11%	11.27%
	15	27.93%	15.76%
	30	37.24%	0.23%
	60	30.54%	31.64%
30	0	0.00%	0.00%
	5	32.87%	31.94%
	15	43.44%	37.81%
	30	55.83%	38.15%
	60	45.00%	0.01%
45	0	0.00%	0.00%
	5	14.14%	11.47%
	15	40.92%	22.15%
	30	51.72%	0.36%
	60	45.31%	31.62%
60	0	0.00%	0.00%
	5	9.49%	7.94%
	15	21.03%	10.88%
	30	35.07%	1.88%
	60	27.97%	30.34%
75	0	0.00%	0.00%
	5	6.90%	6.10%
	15	17.32%	11.97%
	30	29.60%	12.09%
	60	23.78%	19.06%
90	0	0.00%	0.00%
	5	5.04%	4.41%
	15	5.80%	1.90%
	30	18.39%	5.32%
	60	15.68%	19.54%

Table 2 Relative error of McLamore slate strength

$\beta/°$	σ_3/MPa	Relative error/%	
		H-B	Improved H-B
0	0	0.00%	0.00%
	3.5	12.9%	12.84%
	10.5	25.72%	25.22%
	35	29.42%	25.88%
	50	17.98%	12.36%
	100	15.69%	0.26%
15	0	0.00%	0.00%
	3.5	61.52%	59.84%
	10.5	60.54%	50.50%
	35	98.69%	28.79%
	50	91.03%	4.51%
	100	75.36%	31.45%
30	0	0.00%	0.00%
	3.5	112.39%	110.16%
	10.5	90.82%	79.74%
	35	119.14%	45.88%
	50	71.86%	3.981%
	100	47.15%	41.65%
45	0	0.00%	0.00%
	3.5	64.69%	62.60%
	10.5	89.94%	75.82%
	35	140.30%	47.90%
	50	105.36%	6.49%
	100	80.03%	33.44
60	0	0.00%	0.00%
	3.5	42.68%	41.91%
	10.5	59.39%	53.97%
	35	111.74%	63.79%
	50	99.55%	30.80%
	100	86.14%	12.39%
75	0	0.00%	0.00%
	3.5	25.00%	24.81%
	10.5	38.67%	37.24%
	35	82.10%	68.91%
	50	64.87%	44.04%
	100	49.39%	0.29%
90	0	0.00%	0.00%
	3.5	14.42%	13.32%
	10.5	19.34%	18.58%
	35	39.14%	32.62%
	50	34.53%	23.46%
	100	32.02%	0.16%

can reflect the transition from brittleness to ductility of layered rocks as the confining pressure increases.

3. The improved H-B criterion is better than the classic H-B criterion in the prediction of McLamore slate test results. When the azimuth is constant, the prediction performance under higher confining pressure is better. As the azimuth angle increases, the MAPE becomes smaller. The improved H-B criterion avoids the arbitrariness of parameter determination, takes into account anisotropy and critical confining pressure effects, and is relatively simple and easy to implement.

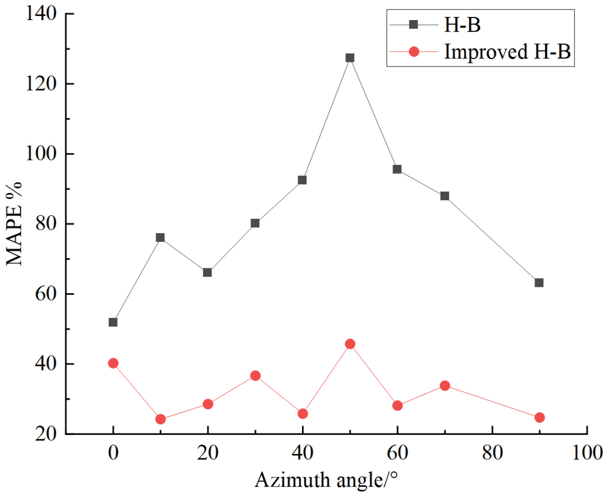


Fig. 9 McLamore slate strength prediction error

The topics presented below may be considered for further exploration:

1. The material parameter *m* can be combined with subjective evaluation to improve its accuracy on the basis of inversion analysis.
2. The correction factor *n* varies with rock type and azimuth, and more types of training samples can be used to improve its accuracy.

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Data availability

All data generated or analyzed during this study are included within the paper.

Conflict of interest

The authors declare that they have no conflict of interest.

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