Acoustic and fractal analyses of the mechanical properties and fracture modes of bedding-containing shale under different seepage pressures

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Abstract
The mechanical properties and failure modes of shale that contains bedding were analyzed under coupled seepage pressure and stress. In the numerical model, seven sets of shale samples with different dip-bedding values were considered, and a seepage-stress coupling numerical simulation was carried out. The results showed that the compressive strength of shale exhibited obvious anisotropy with increase in the bedding angle, and the compressive strength decreased with an increase in the osmotic pressure. The elastic modulus of shale showed an increasing trend with increase in the bedding angle, while the osmotic pressure had little effect on the elastic modulus of shale. The results also showed that weak bedding had a significant impact on the shale failure mode. When the osmotic pressure was 4 MPa, the shale fracture mode showed five failure modes. When the osmotic pressure was 8 MPa, the shale fracture mode exhibited four failure modes. When the osmotic pressure was 12 MPa, the shale fracture mode showed four failure modes. As the osmotic pressure increased, the osmotic pressure played a leading role in the shale rupture process. The spatial distribution of the acoustic emission demonstrated some self-similarity patterns, and its fractal characteristics were analyzed. It was found that the fractal dimension better reflects the rupture damage to the shale. The larger the fractal dimension is, the more severe the rupture of shale.

KEYWORDS
failure mode, fractal dimension, osmotic pressure, shale
1 | INTRODUCTION

In recent years, with the advancement of science and technology and the in-depth development of oil and gas exploration and development, unconventional oil and gas resources, such as tight sandstone gas and shale gas, have not only completely changed energy patterns in the United States but have also profoundly affected the global energy landscape.\textsuperscript{1-11} Among these resources, shale gas is an unconventional natural gas present in shale mainly in the form of adsorption or in a free state. It is characterized by its capacity for large storage, wide distribution, a long mining period, a long service life, and huge mining potential. It is considered to be an ideal replacement for conventional oil and natural gas. Currently, the exploration and development of shale gas have become a global focus. Exploration found that China's shale gas resources are rich, and the development prospects are broad, which aligns with the strategic goals of China's future oil and gas development.\textsuperscript{12-17} However, shale gas reservoir formation conditions, storage space, seepage laws, and exploitation mode all have their own characteristics, especially the poor physical properties of shale gas reservoirs, low porosity, and permeability, which bring great difficulties and challenges to its development and utilization. At present, the method of shale gas mining is based mainly on hydraulic fracturing.\textsuperscript{18-21} As a storage carrier of shale gas, it is very important to study the physical properties and fracture modes of shale for the exploration and development of shale gas.

At present, many scholars domestically and abroad have conducted further studies on the mechanical characteristics and fracture modes of shale and have obtained fruitful results. Zhang et al\textsuperscript{22} revealed the microscopic mechanism, control factors, and fracture modes of shale macroscopic cracks by studying the structural characteristics, mechanical characteristics, cracks, and microstructure characteristics of shale. Arora et al\textsuperscript{23} studied the failure modes of shale under biaxial and triaxial stress conditions. It was found that black shale exhibited extreme brittle failure under biaxial stress conditions. The layered shale was destroyed along multiple shear planes under pseudo triaxial stress conditions. Through numerical simulation of the shale, Li et al\textsuperscript{24} found that brittle shale was more likely to rupture on the multi-cross failure surface, and the tough shale was more likely to rupture on the fracture surface. It was also concluded that brittle shale was more likely to form natural fractures than ductile shale. Niandou et al\textsuperscript{25} conducted a triaxial compression test on Tournemire shale to study the anisotropy, plastic deformation, and failure modes of the shale. It was found that the shale exhibited a nonlinear elastic behavior and its plastic deformation and failure modes exhibited significant anisotropy. Valès et al\textsuperscript{26} studied the relationship between the mechanical properties of Tournemire shale and its saturation, using uniaxial and triaxial compression tests. It was concluded that the mechanical properties of shale had a strong sensitivity to saturation. Gudmundsson et al\textsuperscript{27} analyzed the law of fracture propagation and evolution through numerical model. In addition, shale usually contains flaky joints, which causes shale to have different mechanical properties and fracture modes in different directions.\textsuperscript{28-30} Wu et al\textsuperscript{11} used the RFPA2D-DIP numerical software to simulate shale filled with calcite. The shale final failure modes were different under different loading conditions, and the compressive strength showed obvious anisotropy.

In recent years, with the deepening of research, studies on shale permeability characteristics have made great progress, providing important theoretical support for promoting the mining process of shale gas. AJ et al\textsuperscript{31} used numerical methods to estimate the effective permeability of sand shale under uniform steady-state conditions. It was found that the volume fraction of shale, the spatial covariance structure, and the dimension of the flow system were important factors affecting the effective permeability. Kwon et al\textsuperscript{33} measured the permeability of the Wilcox group shale and found that the permeability of the Wilcox shale was inversely proportional to the effective compressive stress. Gareth et al\textsuperscript{33} studied the substrate permeability control of Canadian Horn shale. It was found that the source and distribution of minerals, pore size, and fabric were important factors affecting shale permeability, and the permeability of anisotropic samples was more sensitive to changes in effective stress than isotropic samples. Gutierrez et al\textsuperscript{35} conducted a direct shear test on shale and studied the hydraulic properties of shale extensible fractures. It was found that under certain high normal stress, the fracture permeability decreased with the increase of contact normal stress. Wu et al\textsuperscript{36} conducted a rock mechanics test on Lower Cambrian shale in the northern part of China. It was found that the porosity and permeability of the shale decreased with the increase of effective stress, and the mineral composition of the shale had an important influence on the shale stress sensitivity.

From the above, although many studies have been conducted on the mechanical properties and seepage of shale, they were more focused on either the mechanical properties, failure mode, or permeability characteristics as a single factor. There are few studies on the failure mode and mechanical properties of shale under seepage-stress coupling, which is the process by which shale failure in hydraulic fracturing of shale gas occurs. Therefore, the study of fracture modes of shale under the coupling of seepage stress will provide an important scientific basis for shale gas exploration and development and horizontal well placement and evaluation. In this paper, seven numerical models of different shale bedding angles were established, and the model simulated seepage-stress coupling. The mechanical properties and failure modes of shale with different bedding angles under different osmotic pressures were analyzed, and the spatial distribution of shale acoustic emissions and the relationship between
fractal characteristics and bedding angle were analyzed. The research results will provide important theoretical support for shale gas exploration and development.

2 | **FINITE ELEMENT METHOD FOR SHALE SEEPAGE STRESS COUPLED FRACTURE SIMULATION**

2.1 | **Basic equation of seepage-stress coupling model**

In the process of studying the fluid-solid coupling problem in seepage, Biot also added the change in pore fluid pressure $P$ and water capacity $\Delta n$ as a state variable and deduced the first mechanical theory of the fluid-solid coupling effect. The basic equation of seepage coupling is:

**Balance equation:**

$$\frac{\partial \sigma_{ij}}{\partial x_{ij}} + p X_j = 0 \quad (i, j = 1, 2, 3)$$

**Geometric equation:**

$$\epsilon_{ij} = \frac{1}{2} (u_{ij} + u_{ji})$$

**Constitutive equation:**

$$\sigma'_{ij} = \sigma_{ij} - \theta p \delta_{ij} = \lambda \delta_{ij} \epsilon_{v} + 2G \epsilon_{ij}$$

**Seepage equation:**

$$K'_{ij} \nabla^2 p = \frac{1}{Q} \frac{dp}{dt} - \theta \frac{\partial \Delta s}{\partial t}$$

In Equations (1)-(4), $P$ is the pore water pressure; $Q$ is the Biot coefficient; $\sigma_{ij}$ is the sum of the normal stresses; $\epsilon_{ij}$ is the body strain; $\delta_{ij}$ is the Kronecker constant; $\nabla^2$ is the pull operator; $\sigma'_{ij}$, $\sigma_{ij}$, $\epsilon_{ij}$ are the effective stress, the total stress, and the total strain, respectively; and $G$, $\lambda$ are the shear modulus and the Lame coefficient, respectively.

Equations (1)-(4) are expressions based on Biot’s classical seepage theory. However, this theory does not consider the change in permeability caused by stress and cannot satisfy the conservation of momentum. When considering the effect of stress on seepage, the coupling equation for seepage stress is as follows:

$$K(\sigma, p) = K_0 e^{-\beta (\frac{\Delta s}{n} - \frac{\epsilon_{ij}}{\epsilon_{ij}^0})}$$

When the stress of the unit reaches the tensile strength, the elastic modulus of the unit undergoes stiffness degradation treatment. At the same time, the permeability coefficient increases correspondingly, according to the following formula, and the permeability coefficient decreases correspondingly when the unit makes contact:

$$K(\sigma, p) = \xi K_0 e^{-\beta (\frac{\Delta s}{n} - \frac{\epsilon_{ij}}{\epsilon_{ij}^0})}$$

In Equation (6), $K$ is instantaneous permeability coefficient, $K_0$ is the initial value of the permeability coefficient, $\beta$ is the coupling coefficient, $\xi$ is the permeability jump coefficient, and $\theta$ is the pore water pressure coefficient and is determined by the test.

2.2 | **Rock seepage damage coupling model**

Considering that the tensile strength of shale is much smaller than the compressive strength, the modified Mohr-Coulomb criterion (molar Coulomb strength theory with a tensile criterion) is used as the strength criterion for unit failure. When the stress state or strain state of a unit meets a given damage threshold, the unit begins to damage. That is, when the maximum tensile stress of the unit reaches its tensile strength, tensile failure begins to occur; when the stress state of the unit satisfies the Mohr-Coulomb criterion, the unit undergoes shear damage. At the same time, the stretching criteria have priority. If the mesoscopic unit satisfies the stretching criterion, then it is not necessary to judge whether it satisfies the Mohr-Coulomb criterion. Only the unit that does not meet the tensile criterion determines whether it satisfies the Mohr-Coulomb criterion, and the elastic modulus expression of the damaged element is:

$$E = (1 - \omega)E_0$$

In Equation (7), $E$ and $E_0$ are the average elastic moduli of the damage and the elastic modulus without damage, respectively, $\omega = 0$ corresponds to the nondamage state, $\omega = 1$ corresponds to the complete deformation (fracture or failure) state, and $0 < \omega < 1$ corresponds to different degrees of damage. Based on the elastic damage constitutive relation of uniaxial tension and compression, the seepage-stress coupling equation of the unit in the elastic damage evolution process under a general stress state is given. According to the general practice in rock mechanics, the compressive stress (strain) is always considered positive and the tensile stress (strain) is considered negative.

2.2.1 | **Mesoscopic unit tensile damage evolution seepage-stress coupling equation**

In the uniaxial tensile stress state, the elastic damage constitutive relationship of the mesoscopic unit is shown in Figure 1.
For the constitutive curve given in Figure 1, the expression of the damage variable is

\[
\omega = \begin{cases} 
0, & \varepsilon_{\text{t0}} \leq \varepsilon < 0 \\
1 - \frac{f_{\text{tr}}}{f_{\text{t0}}} \varepsilon, & \varepsilon_{\text{mu}} \leq \varepsilon < \varepsilon_{\text{t0}} \\
1, & \varepsilon \leq \varepsilon_{\text{mu}} 
\end{cases} (8)
\]

In Equation (8), \( f_{\text{tr}} \) is the residual strength of the element; \( \varepsilon_{\text{t0}} \) is the tensile strain corresponding to the elastic limit, the strain is called the tensile damage strain threshold; \( \varepsilon_{\text{mu}} \) is the ultimate tensile strain, when the unit uniaxial tensile strain reaches the limit When tensile strain is applied, the unit will be completely damaged in the tensile fracture (destruction) state, that is, \( \omega = 1 \).

The ultimate strain coefficient \( \eta = \varepsilon_{\text{mu}}/\varepsilon_{\text{t0}} \) is defined and then the residual strength coefficient \( \lambda = f_{\text{tr}}/f_{\text{t0}} \) is introduced, so Equation (8) can be simplified to

\[
\omega = \begin{cases} 
0, & \varepsilon_{\text{t0}} \leq \varepsilon < 0 \\
\frac{\lambda \varepsilon_{\text{t0}}}{\varepsilon}, & \varepsilon_{\text{mu}} \leq \varepsilon < \varepsilon_{\text{t0}} \\
1, & \varepsilon \leq \varepsilon_{\text{mu}} 
\end{cases} (9)
\]

It is known from the experiment\(^{45-47} \) that the damage will cause the penetration coefficient \( \xi \) of the specimen to increase, and the magnitude of \( \xi \) is given by the experiment. Therefore, the expression of the permeability coefficient \( K \) of the unit is as follows:

\[
K = \begin{cases} 
K_0 e^{-\frac{\varepsilon_{\text{c0}} - \varepsilon_{\text{tr}}}{\mu}}, & \omega = 0 \\
K_0 e^{-\frac{\varepsilon_{\text{c0}} - \varepsilon_{\text{tr}}}{\mu}}, & 0 < \omega < 1 \\
\xi K_0 e^{-\frac{\varepsilon_{\text{c0}} - \varepsilon_{\text{tr}}}{\mu}}, & \omega = 1 
\end{cases} (10)
\]

### 2.2.2 Mesoscopic unit compression shear damage evolution seepage-stress coupling equation

The above gives the elastic damage constitutive relationship when the mesoscopic unit produces tensile failure. Vonk et al\(^{48} \) believed that under the action of uniaxial compression or shear stress, softening or damage of concrete and rock materials also existed. Therefore, this paper assumes that meso-level shear damage also exists. To reflect the damage of the mesoscopic unit under compression or shear stress, the Mohr-Coulomb criterion is chosen here as the second damage threshold criterion:

\[
F = \sigma_1 - \frac{1 + \sin \varphi}{1 - \sin \varphi} \sigma_3 \geq f_c (11)
\]

In Equation (11), \( \varphi \) is the internal friction angle, \( f_c \) is the uniaxial compressive strength, and \( \sigma_1 \) and \( \sigma_3 \) are the maximum and minimum principal stresses, respectively.

A similar constitutive relationship can also be given in the uniaxial compressive stress state, as shown in Figure 2.

For Figure 2, the damage variable can be found according to the following formula

\[
\omega = \begin{cases} 
0, & \varepsilon < \varepsilon_{\text{c0}} \\
1 - \frac{\lambda \varepsilon_{\text{c0}}}{\varepsilon}, & \varepsilon \geq \varepsilon_{\text{c0}} 
\end{cases} (12)
\]

In Equation (12), \( \lambda \) is the residual strength coefficient, and its value is assumed to be the same as that under the uniaxial tension condition, that is, the relationship \( \lambda = f_{\text{c}}/f_{\text{cr}} = f_{\text{c}}/f_{\text{tr}} \) is satisfied; \( \varepsilon_{\text{c0}} \) is the maximum of the unit, and the maximum compressive principal stress of the unit reaches its uniaxial compressive strength. Corresponding to the maximum is the compressive primary strain.
The permeability coefficient \( K \) can be obtained from the following formula:

\[
K = \begin{cases} 
K_0 e^{-\frac{\sigma_{1\omega}}{S}} & \omega = 0 \\
\xi K_0 e^{-\frac{\sigma_{\omega}}{S}} & \omega > 0
\end{cases} \quad (13)
\]

Available under uniaxial compressive stress conditions as described above,

\[
\varepsilon_{c0} = f_c / E_0 \quad (14)
\]

When the unit uniaxial compression strain reaches \( \varepsilon_{c0} \), the unit begins to exhibit failure, \( \omega \) decreases continuously, and the permeability coefficient \( K \) is calculated according to Equation (13). When the unit is in a multiaxial stress state and meets the Mohr-Coulomb criterion, the maximum compressive principal strain \( \varepsilon_1 \) can be used instead of the uniaxial compressive strain in Equation (12), and the average principal stress \( \sigma_{1m}/3 \) can be used instead of \( \sigma_1 \) so that the one-dimensional expression expressed above can be used. The constitutive relationship under compressive stress is extended to three dimensions.

### 3 | NUMERICAL MODEL OF SHALE

The numerical model takes into account the mesoscopic nonuniformity of the rock. The nonuniformity parameters of the rock are introduced into the unit, and macroscopic nonlinearities are achieved with mesoscopic nonuniformities. The macroscopic process of rupture entails the accumulation of mesoscopic unit rupture. Due to the drilling conditions and the nonuniformity of the rock mass, in typical laboratory physical rock mechanics experiments, it is difficult to obtain a transversely isotropic core with different orientations and different angles. However, in numerical models, the mechanical parameters of the unit can be set to create various numerical models. Moreover, the system of analysis can perform seepage analysis, stress analysis, failure analysis, and coupling analysis on the rock failure process and can realize the simulation of the entire process of rock fracture under the coupling of seepage and stress. Figure 3 shows a shale test piece with different bedding angles set in the numerical models. The color brightness of the unit in the shale test piece characterizes the elastic modulus, whereby the brighter unit has a larger elastic modulus. The brighter unit in Figure 3 is the shale matrix. The darker color of the unit indicates a smaller modulus of elasticity, and the darker color in Figure 3 is the bedding plane.

In this paper, the shale of FC-1 well in Fenggang block 3 of northern Guizhou area is selected, which belongs to the black shale of Niutitang formation of Lower Cambrian. In this area, the joints of shale gas reservoir are obvious, and microfractures and pores are developed. In this test, 7 sets of shale test pieces with bedding angles of 0°, 15°, 30°, 45°, 60°, 75°, and 90° were established. The specimen had a height of 100 mm and a diameter of 50 mm, and the model was divided into 200 × 100 units. The loading diagram is shown in Figure 2. The entire loading process was loaded by displacement control. The initial displacement was 0.001 mm, the displacement increment \( \Delta S = 0.0002 \) mm, the fixed confining pressure \( P_2 = 10 \) MPa, and the osmotic pressure difference \( \Delta P = P_3 - P_4 \). The osmotic pressures were 4 MPa, 8 MPa, and 12 MPa, respectively. In RFPA2D-Flow, water is used as the fluid, and the seepage boundary conditions are set in the numerical model to form the seepage pressure difference between the upper and lower boundaries of the model, so as to control the distribution of fluid in shale. The elastic modulus \( E_0 \) of the unit, the uniaxial compressive strength \( \sigma_c \), Poisson's ratio \( \nu \), the pore water pressure coefficient \( \delta \), and the permeability coefficient \( K \) obey the Weibull random distribution.

\[
\phi = \frac{m}{s_0} \left( \frac{s}{s_0} \right)^{m-1} \exp \left[ - \left( \frac{s}{s_0} \right)^{m} \right] \quad (15)
\]

In Equation (15), \( S \) is \( E_0 \), \( \sigma_c \), and \( K \); \( S_0 \) is the average value corresponding thereto; and the specific values of the mechanical properties of the sample are shown in Table 1.

### 4 | RESULTS AND ANALYSIS

#### 4.1 | Seepage-stress coupling numerical simulation

Table 2 shows the shale compressive strength obtained by the test. The inclination angle \( \alpha \) is the angle between the bedding plane and the horizontal direction. In the table, \( \alpha \), \( \sigma \), and \( \Delta P \) represent the bedding angle, compressive strength, and osmotic pressure, respectively. When the osmotic pressure is 4 MPa, the compressive strength of the sample with \( \alpha = 60^\circ \) is the largest, which is 47.09 MPa; the compressive strength of the sample with \( \alpha = 45^\circ \) is the lowest, which is 42.83 MPa. The difference between the maximum and minimum compressive strength values is 4.26 MPa, which is 9% of the maximum. When the osmotic pressure is 8 MPa, the compressive strength of the sample with \( \alpha = 0^\circ \) is the largest, which is 40.14 MPa; the compressive strength of the sample with \( \alpha = 45^\circ \) is the lowest, which is 34.63 MPa. The difference between the maximum and minimum compressive strength values is 5.51 MPa, which is 13.726% of...
the maximum value. When the osmotic pressure is 12 MPa, the compressive strength of the sample with \( \alpha = 75^\circ \) is the largest, which is 30.79 MPa; the compressive strength of the sample with \( \alpha = 15^\circ \) is the lowest, which is 27.13 MPa. The difference between the maximum and minimum compressive strength values is 3.49 MPa, which is 11.335% of the maximum value. Figure 4 shows the compressive strength curves of different types of bedding shale under different osmotic pressures. It can be seen that when the osmotic pressure is 4 MPa, the compressive strength curves of different bedding shale are M-shaped. When the osmotic pressure is 8 MPa, the compressive strength curve of the shale is V-shaped. Although the shale model is considered to be isotropic, the presence of the bedding plane changes the mechanical properties of the shale. From the change in shale compressive strength, it can be found that the shale exhibits significant anisotropy. It can be seen from Figure 4 that as the osmotic pressure increases, the compressive strength of the shale is significantly reduced. This occurs because the osmotic pressure and the nonuniformity of the mesostructure result in a decrease in the compressive strength of the shale, and the greater the osmotic pressure, the more obvious the effect.

Table 3 shows the elastic modulus of the shale obtained by the test. In the table, \( \alpha \), \( E \), and \( \Delta P \) represent the lamination

| Material     | Elastic modulus E/MPa | Compressive strength/MPa | Poisson ratio \( v \) | Internal friction angle (°) | Compression/tension ratio | Permeability coefficient (m/d) | Pore pressure coefficient |
|--------------|-----------------------|--------------------------|----------------------|-----------------------------|---------------------------|-----------------------------|--------------------------|
| Shale substrate | 51 600                | 145                      | 0.22                 | 35                          | 14                        | 0.14486                     | 0.7                      |
| Bedding      | 30 960                | 116                      | 0.31                 | 30                          | 13                        | 0.104876                    | 0.73                     |
angle, the elastic modulus, and the osmotic pressure, respectively. When the osmotic pressure is 4 MPa, the maximum elastic modulus of the shale appears at $\alpha = 90^\circ$, which is 42.00 GPa; the $\alpha = 15^\circ$ sample shale has the lowest elastic modulus of 38.27 GPa. The difference between the maximum and minimum values of the elastic modulus is 3.73 GPa, which is 8.8% of the maximum value. When the osmotic pressure is 8 MPa, the elastic modulus increases sharply at $\alpha = 45^\circ$ and $60^\circ$. However, as a whole, the shale elastic modulus increases with the increase of the bedding angle, and the osmotic pressure has less of an influence.

Figures 6-8 show the stress-strain curves of different bedding shale types under different osmotic pressures. The curve shows that the shale peak stress shows significant anisotropy. When the osmotic pressure is 4 MPa, the peak stress of the sample with $\alpha$ of $60^\circ$ is the largest, and the sample with $\alpha$ of $45^\circ$ is the lowest. When the osmotic pressure is 8 MPa, the peak stress of the sample with $\alpha$ of $0^\circ$ is the largest, and the sample with $\alpha$ of $45^\circ$ is the lowest. When the osmotic pressure is 12 MPa, the peak stress of the sample with $\alpha$ of $75^\circ$ is the largest, and the sample with $\alpha$ of $15^\circ$ is the lowest. Under the same osmotic pressure, the difference in the stress drop of

![Table 2](image)

**Table 2** Compressive strength of different bedding shale under different osmotic pressures

| $\alpha$ (°) | $\Delta P$ (MPa) | σ (MPa) | $\Delta E$ (GPa) |
|--------------|-----------------|---------|-----------------|
| 4            | 8               | 12      |
| 0            | 44.92           | 40.14   | 29.65           |
| 15           | 46.31           | 39.87   | 27.13           |
| 30           | 45.27           | 38.56   | 29.49           |
| 45           | 42.83           | 34.63   | 29.38           |
| 60           | 47.09           | 36.31   | 27.78           |
| 75           | 46.20           | 39.55   | 30.79           |
| 90           | 44.77           | 39.35   | 29.15           |

![Graph 1](image)

**Figure 4** Relationship between bedding angle and compressive strength under different osmotic pressures

![Table 3](image)

**Table 3** Elastic modulus of different bedding shale under different osmotic pressures

| $\alpha$ (°) | $\Delta P$ (MPa) | E (GPa) | $\Delta E$ (GPa) |
|--------------|-----------------|---------|-----------------|
| 4            | 8               | 12      |
| 0            | 39.13           | 38.97   | 39.64           |
| 15           | 38.27           | 38.56   | 39.66           |
| 30           | 40.42           | 38.59   | 39.21           |
| 45           | 40.48           | 41.32   | 40.47           |
| 60           | 40.80           | 41.27   | 40.74           |
| 75           | 41.55           | 40.11   | 39.99           |
| 90           | 42.00           | 41.08   | 41.17           |

![Graph 2](image)

**Figure 5** Relationship between the bedding angle and the elastic modulus under different osmotic pressures

Figure 5 is a graph showing the elastic modulus of different bedding shale types under different osmotic pressures. When the osmotic pressure is 4 MPa and 12 MPa, the shale elastic modulus increases as a whole. When the osmotic pressure is 8 MPa, the elastic modulus increases sharply at $\alpha = 45^\circ$ and $60^\circ$. However, as a whole, the shale elastic modulus increases with the increase of the bedding angle, and the osmotic pressure has less of an influence.
different stratified bedding shale types is obvious—the larger the stress drop is, the more significant the brittle failure characteristics. Therefore, when the osmotic pressure is 4 MPa, the brittleness characteristic of the 0° sample is most remarkable. When the osmotic pressure is 8 MPa, the brittle fracture characteristics of the 45° sample are most significant. When the osmotic pressure is 12 MPa, the brittleness characteristics of the 75° sample are most significant. It can be seen from the above description that the presence of bedding in shale has a significant effect on the mechanical properties of the shale.

Figure 9 is a stress-strain curve of seven sets of samples having a bedding angle of 0° to 90°. The curve shows that as the osmotic pressure increases from 4 MPa to 12 MPa, the peak stress of the seven groups of samples shows a significant decreasing trend. When the osmotic pressure is 4 MPa or 8 MPa, the residual stress of the sample is higher, and the residual stresses of the sample of α = 0° and α = 75° are relatively close. When the osmotic pressure is 12 MPa, the residual stress of the remaining samples is almost 0 MPa, except for the 60° sample. This indicates that the mechanical properties of shale are relatively stable at lower osmotic pressures. Under higher osmotic pressure, the mechanical properties of shale are seriously damaged, resulting in a sharp decrease in the residual stress of the shale and its complete destruction.

According to the above analysis, under the fluid-solid coupling, the mechanical properties of shale are significantly affected by the bedding plane, showing obvious anisotropy. Through the test results, it can be found that the osmotic pressure also significantly affects the mechanical properties of shale. Under low osmotic pressure (4 MPa and 8 MPa), the internal structure of shale is less affected by the softening of seepage, and the bedding plane plays a leading role in its mechanical properties. With the increase of osmotic pressure, when the osmotic pressure reaches 12 MPa, the internal structure of shale is significantly affected by the softening of seepage. At this time, the osmotic pressure is the key factor affecting the mechanical properties of shale.

Figures 10-12 show the failure modes of shale with different bedding angles under seepage-stress coupling. It can be clearly seen that bedding and osmotic pressure have an important influence on the shale failure mode. The shale destruction patterns vary. Figure 10 shows the failure mode of shale under seepage-stress coupling, when the osmotic pressure is 4 MPa. When α = 0°, initial cracks are formed in the upper left and upper right corners of the sample. As the load increases, the initial crack extends toward the middle and along the bedding plane at an angle of approximately 45°, then penetrates the bedding plane until a V-shaped failure mode is formed. When α = 15°, the initial crack is formed in the middle of the shale, and as the load increases, it extends from the inside to the outside until an
inverted V-shaped failure mode is formed. When $\alpha = 30^\circ$, initial cracks are formed at the edges of the two bedding faces in the middle of the shale and are then extended along the edge of the bedding face to penetrate the matrix until a multi-line failure mode is formed. When $\alpha = 45^\circ$, initial cracks appear on the bedding plane and then break along the bedding plane and the matrix until the oblique I shape is formed. When $\alpha = 60^\circ$, since the initial crack is distributed on the two bedding planes, the cracks are broken along the two bedding planes, and finally through the matrix connecting the two fracture planes until the oblique N-shape is formed. When $\alpha = 75^\circ$, an initial crack is formed on the lower left corner of the shale. The crack extension direction is at an angle of approximately $30^\circ$ to the bedding plane until an oblique N-type failure mode is formed. In summary, due to the existence of osmotic pressure and bedding characteristics, shale eventually forms five failure modes, namely V-type ($0^\circ$), inverted V-type ($15^\circ$), multi-line-type ($30^\circ$), oblique I-type ($45^\circ$, $90^\circ$), and oblique N-type ($60^\circ$, $75^\circ$).

Figure 11 shows the failure mode of shale under seepage-stress coupling with an osmotic pressure of 8 MPa. It can be seen that when $\alpha = 15^\circ$ and $\alpha = 75^\circ$, the failure mode is simpler. When $\alpha = 15^\circ$, an initial crack is formed on the right side of the shale, and there is an indication of crack initiation at the lower left. The crack extension direction is at an angle of approximately $45^\circ$ to the bedding plane until two parallel oblique I-shaped cracks are formed, and there are fewer crack branches. When $\alpha = 75^\circ$, an initial crack is formed on
the upper right side of the shale, and the crack extends to both sides until an oblique I-type failure mode is formed, and the crack distribution is concentrated. When $\alpha = 60^\circ$, initial cracks are formed on the bedding plane on the right side of the shale, and the cracks are broken along the bedding plane until the oblique I-type failure mode is formed. However, many microcracks extend to the lower right of the crack, and the damage is intensified. When $\alpha = 90^\circ$, an initial crack is formed in the matrix on the right side of the shale, and the crack extending direction is at an angle of approximately $30^\circ$ to the bedding plane, until an oblique I-type failure mode is formed. Many microcracks are formed around the main crack, and the distribution is complicated. When $\alpha = 0^\circ$, an initial crack is formed on the lower right side of the shale, and the crack extension direction forms an angle of approximately $45^\circ$ with the bedding plane, until a V-shaped failure mode is formed. When $\alpha = 30^\circ$, the shale failure mode is more complicated. Microcracks are formed in a large area in the lower part of the shale, and the crack penetrates the bedding plane until a flame-type failure mode is formed. When $\alpha = 45^\circ$, the shale forms an initial crack at the edge of the right bedding surface, and the crack extends along the edge.
of the bedding surface, eventually forming a W-type failure mode. Due to the combined action of the bedding plane and the osmotic pressure, the shale eventually forms four failure modes, namely V-type (0°), oblique I-type (15°, 60°, 75°, 90°), flame-type (30°), and W-type (45°).

Figure 12 shows the failure mode of shale under seepage-stress coupling with an osmotic pressure of 12 MPa. It can be seen that when \( \alpha = 0° \), an initial crack is formed in the matrix on the left side of the shale, and the crack extending direction is at an angle of approximately 60° to the bedding plane until an oblique I-type failure mode is formed. When \( \alpha = 15° \), an initial crack is formed on the right side of the shale, and the crack extending direction is at an angle of approximately 75° to the bedding plane, until an oblique I-type failure mode is formed. When \( \alpha = 30° \), the initial crack occurs in the middle and upper parts of the shale, and the crack extends upwards and downwards until a crescent-shaped failure mode is formed. When \( \alpha = 45° \), an initial crack is formed on the left side of the shale, and there are signs of crack initiation in the middle and lower parts, extending along the edge of the bedding plane until a V-shaped failure mode is formed. When \( \alpha = 60° \), initial cracks are formed in the lower bedding plane of the shale, extending along the bedding plane until an oblique I-type failure mode is formed. When \( \alpha = 75° \), an initial crack is formed in the lower part of the shale, and the crack extending direction is at an angle of approximately 30° to the bedding plane, until a V-shaped failure mode is formed. When \( \alpha = 90° \), initial cracks are formed in the upper part of the shale, extending parallel along the bedding plane until a broom-type failure mode is formed. In summary, due to the combination of layer characteristics and osmotic pressure of 12 MPa, namely oblique I-type (0°, 15°, 60°), crescent-type (30°), V-type (45°, 75°), and broom-type (90°).

Figures 10-12 show the acoustic emission spatial distribution of shale under three osmotic pressures. Among them, red indicates tensile failure, white indicates shear failure, and black indicates complete destruction. It is found that the shale failure under the three osmotic pressures is mainly tensile failure, accompanied by shear failure. This is because the shale has a greater compressive capacity than tensile capacity. Under the coupling of seepage stress, a tensile stress concentration zone appears inside the shale. As the loading progresses, the tensile stress will first reach the tensile strength of the shale and damage will occur. In Figures 9-11, it can be seen that the spatial distribution of acoustic emissions is a good reflection of the macroscopic failure mode of shale.

4.2 | Fractal characteristics of the shale fracture process

In this paper, the coverage method is used to determine the fractal dimension in the process of shale failure, which is the most common method of measurement at present. The basic parameters in describing fractal theory are the fractal dimension \( D \), the spectral density index \( \gamma \), parameter \( \beta \), etc, where the fractal dimension \( D \) is the core parameter, and the calculation formula is\(^51,52\)

\[
D = \lim_{\mu \to 0} \frac{\log N(\mu)}{\log \frac{1}{\mu}}
\]  

(16)
In Equation (16), $D$ is the self-similar fractal dimension of the damaged region, $\mu$ is the square box side length, and $N(\mu)$ is the number of boxes required to cover the entire broken area with a square box with side length $\mu$.

A unit microrupture in the RFPA2D-Flow numerical model is an acoustic emission event, and the amount of acoustic emission energy is the energy released when the unit is destroyed. The spatial distribution of acoustic emissions can well reflect the damage of rock, which has a certain self-similarity. Therefore, the fractal geometry method can be used to quantitatively analyze the spatial distribution of acoustic emission points and then analyze the damage of the rock, as shown in Figure 13.

The shale loading process is actually the cumulative development process of damage. If the fractal dimension of the rupture damage in this process is counted, the variation of the fractal dimension of the shale during the rupture damage evolution process can be obtained. The acoustic emissions energy values and fractal dimensions of the different stress levels of the shale under the seepage-stress coupling are shown in Tables 4-6.

Figure 14 is a graph showing the relationship between the stress level and the acoustic emission energy at different inclination angles when the osmotic pressure is 4 MPa. It can be seen that in each set of samples, the initial acoustic emission energy value was 0, and no damage occurred in each group of samples until the stress level reached 50%. After this, the 15° sample showed a very low acoustic emission energy value. As the stress level increased, the acoustic emission energy values appeared in the shale of different bedding angles. However, the 90° sample showed a very low acoustic emission energy value when the stress level reached 70%, and each group of samples rapidly increased to the maximum value. The 15° sample had the highest acoustic emission energy value of 2.54443. The 90° sample had the lowest acoustic emission energy value of 0.8622. Figure 15 shows the relationship between stress level and energy at different inclination angles when the osmotic pressure is 8 MPa. It can be seen that when the stress level reached 40%, the acoustic emission energy value began to appear at the 15° sample. After the stress level reached 60%, the acoustic emission energy values appeared in all the samples. Then, with the increase in the stress level, the acoustic emission energy values of each group gradually increased to the maximum. Among them, the 30° sample was the largest, with a value of 1.4072; the 45° sample was the smallest, with a value of 0.37301. Figure 16 shows stress levels vs energy at different inclination angles at an osmotic pressure of 12 MPa. When the stress level reached 40%, the 15°, 30°, and 45° samples all showed extremely low acoustic emission energy values. After the stress level reached 50%, the acoustic emission energy values appeared in all the samples. Finally, the acoustic emission energy values of the samples in each group surged to a maximum, with the 75° sample being the largest, at a value of 0.44462; the 15° sample was the lowest, with a value of 0.15357. The above description shows that osmotic pressure and bedding have a significant effect on shale damage evolution. Due to the influence of the confining pressure, osmotic pressure, and mechanical properties of shale, the acoustic emission energy and the shale failure phenomenon appear later, and the final acoustic emission energy exhibits anisotropy.

Figures 17-19 are graphs of stress levels and fractal dimensions for different bedding angles during loading. It can be seen that under the three osmotic pressures, the shale of all bedding angles increases with the internal fracture damage evolution, and the fractal dimension increases with an increase of the stress level. When the osmotic pressure is 4 MPa, the fractal dimension appears after the stress level is 40%. When the peak stress is reached, the fractal dimension of the 15° sample is the largest, with a value of 1.23215; the fractal dimension of the 15° sample is the lowest, with a value of 1.06592. When the osmotic pressure is 8 MPa, the fractal dimension appears after the stress level is 40%. When the peak stress is reached, the fractal dimension of the 15° sample is the largest, with a value of 1.24476; the 45° sample has the lowest fractal dimension, which is 1.06592. When the
**TABLE 4**  Acoustic emission energy and fractal dimension of shale at different stress levels when the osmotic pressure is 4 MPa

| Stress level | α | 10% | 20% | 30% | 40% | 50% | 60% | 70% | 80% | 90% | 100% |
|--------------|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| 0°           |   | 0   | 0   | 0   | 0   | 0   | 0.00104 | 0.00589 | 0.02724 | 0.15382 | 1.19158 |
|              | D | 0   | 0   | 0   | 0   | 0   | 0.47945 | 0.57983 | 0.49511 | 0.76519 | 1.08641 |
| 15°          |   | 0   | 0   | 0   | 0   | 0   | 0.00053 | 0.00313 | 0.01176 | 0.05619 | 0.31284 | 2.54443 |
|              | D | 0   | 0   | 0   | 0   | 0   | 0.41526 | 0.45052 | 0.55289 | 0.68543 | 0.90195 | 1.23215 |
| 30°          |   | 0   | 0   | 0   | 0   | 0   | 0.00342 | 0.02334 | 0.09804 | 0.35785 | 1.3189 |
|              | D | 0   | 0   | 0   | 0   | 0   | 0.51448 | 0.61018 | 0.78897 | 0.91727 | 1.10139 |
| 45°          |   | 0   | 0   | 0   | 0   | 0   | 0.00067 | 0.00741 | 0.03764 | 0.16089 | 1.15431 |
|              | D | 0   | 0   | 0   | 0   | 0   | 0.39768 | 0.54057 | 0.65527 | 0.80671 | 1.13501 |
| 60°          |   | 0   | 0   | 0   | 0   | 0   | 0.00087 | 0.011 | 0.05944 | 0.33324 | 1.6869 |
|              | D | 0   | 0   | 0   | 0   | 0   | 0.45864 | 0.63532 | 0.82884 | 0.97876 | 1.20474 |
| 75°          |   | 0   | 0   | 0   | 0   | 0   | 0.00028 | 0.00197 | 0.0274 | 0.17968 | 1.02139 |
|              | D | 0   | 0   | 0   | 0   | 0   | 0.21428 | 0.54996 | 0.78023 | 0.94506 | 1.11912 |
| 90°          |   | 0   | 0   | 0   | 0   | 0   | 0.00028 | 0.00197 | 0.0274 | 0.17968 | 1.02139 |
|              | D | 0   | 0   | 0   | 0   | 0   | 0.34181 | 0.75511 | 0.79688 | 1.07226 |

**TABLE 5**  Acoustic emission energy and fractal dimension of shale at different stress levels when the osmotic pressure is 8 MPa

| Stress level | α | 10% | 20% | 30% | 40% | 50% | 60% | 70% | 80% | 90% | 100% |
|--------------|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| 0°           |   | 0   | 0   | 0   | 0   | 0   | 0.00135 | 0.01189 | 0.08734 | 0.38472 | 1.12977 |
|              | D | 0   | 0   | 0   | 0   | 0   | 0.46685 | 0.60843 | 0.84413 | 1.03488 | 1.21862 |
| 15°          |   | 0   | 0   | 0   | 0   | 0   | 0.00172 | 0.00557 | 0.01856 | 0.09963 | 0.33284 | 1.35232 |
|              | D | 0   | 0   | 0   | 0   | 0   | 0.2819 | 0.40481 | 0.63339 | 0.90306 | 1.03824 | 1.24476 |
| 30°          |   | 0   | 0   | 0   | 0   | 0   | 0.00067 | 0.00426 | 0.02222 | 0.1099 | 0.37888 | 1.4072 |
|              | D | 0   | 0   | 0   | 0   | 0   | 0.47962 | 0.55808 | 0.63152 | 0.87753 | 1.04361 | 1.23464 |
| 45°          |   | 0   | 0   | 0   | 0   | 0   | 0.00003 | 0.00101 | 0.00575 | 0.0259 | 0.09352 | 0.37301 |
|              | D | 0   | 0   | 0   | 0   | 0   | 0.22857 | 0.39998 | 0.60901 | 0.74185 | 0.85438 | 1.06592 |
| 60°          |   | 0   | 0   | 0   | 0   | 0   | 0.00068 | 0.00608 | 0.03575 | 0.14331 | 0.4768 |
|              | D | 0   | 0   | 0   | 0   | 0   | 0.41991 | 0.57478 | 0.80840 | 0.97331 | 1.09409 |
| 75°          |   | 0   | 0   | 0   | 0   | 0   | 0.00031 | 0.0079 | 0.0606 | 0.26737 | 1.09722 |
|              | D | 0   | 0   | 0   | 0   | 0   | 0.39285 | 0.70908 | 0.87930 | 1.02194 | 1.22055 |
| 90°          |   | 0   | 0   | 0   | 0   | 0   | 0.00007 | 0.0051 | 0.0658 | 0.25852 | 0.89834 |
|              | D | 0   | 0   | 0   | 0   | 0   | 0.16981 | 0.68513 | 0.83810 | 1.05736 | 1.23117 |
osmotic pressure is 12 MPa, the fractal dimension appears after the stress level is 30%. When the peak stress is reached, the fractal dimension of the 75° sample is the largest, at 1.20184; the 15° sample is the lowest, at 1.06559. According to the above description, it can be said that the fractal dimension is positively correlated with acoustic emission. Acoustic emission can reflect the evolution process of shale rupture damage; therefore, the fractal dimension can better reflect the shale rupture damage evolution.

### TABLE 6  Acoustic emission energy and fractal dimension of shale at different stress levels when the osmotic pressure is 12 MPa

| Stress level | α  | 10% | 20% | 30% | 40% | 50% | 60% | 70% | 80% | 90% | 100% |
|--------------|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
|              |    |     |     |     |     |     |     |     |     |     |      |
| 0°           | AE | 0   | 0   | 0   | 0   | 0.00009 | 0.00129 | 0.01066 | 0.04856 | 0.13159 | 0.25658 |
|              | D  | 0   | 0   | 0   | 0   | 0.25606 | 0.56526 | 0.72024 | 0.95288 | 1.09252 | 1.16023 |
| 15°          | AE | 0   | 0   | 0   | 0   | 0.00001 | 0.00025 | 0.00067 | 0.00309 | 0.01849 | 0.05957 | 0.15357 |
|              | D  | 0   | 0   | 0   | 0   | 0.36321 | 0.45728 | 0.6006  | 0.85779 | 0.96636 | 1.06559 |
| 30°          | AE | 0   | 0   | 0   | 0   | 0.00002 | 0.00061 | 0.00366 | 0.01321 | 0.04758 | 0.13208 | 0.39321 |
|              | D  | 0   | 0   | 0   | 0   | 0.44908 | 0.59072 | 0.75127 | 0.86787 | 1.00542 | 1.15310 |
| 45°          | AE | 0   | 0   | 0   | 0   | 0.00012 | 0.00175 | 0.01105 | 0.04615 | 0.14299 | 0.32188 |
|              | D  | 0   | 0   | 0   | 0.31213 | 0.45617 | 0.58055 | 0.78820 | 0.92040 | 1.07962 | 1.16723 |
| 60°          | AE | 0   | 0   | 0   | 0   | 0.00018 | 0.00087 | 0.00422 | 0.01963 | 0.08372 | 0.20951 |
|              | D  | 0   | 0   | 0   | 0.57952 | 0.60275 | 0.6496  | 0.89588 | 1.00161 | 1.15660 |
| 75°          | AE | 0   | 0   | 0   | 0   | 0.00005 | 0.00151 | 0.01328 | 0.06466 | 0.18909 | 0.44462 |
|              | D  | 0   | 0   | 0   | 0.35802 | 0.68439 | 0.80757 | 1.03432 | 1.12077 | 1.20184 |
| 90°          | AE | 0   | 0   | 0   | 0   | 0.00001 | 0.00042 | 0.00645 | 0.03498 | 0.12754 | 0.25957 |
|              | D  | 0   | 0   | 0   | 0   | 0.22857 | 0.49882 | 0.87888 | 0.88563 | 1.10213 | 1.14728 |

**FIGURE 14**  Relationship between the stress level and the acoustic emission energy at different dip angles when the osmotic pressure is 4 MPa

**FIGURE 15**  Relationship between the stress level and the acoustic emission energy at different dip angles when the osmotic pressure is 8 MPa
completely destroyed shale sample. Under the coupling of seepage stress, when the stress reaches the peak, the shale sample is not completely destroyed, but as the load increases, the initiating crack continues to expand and penetrate, which leads to the complete destruction of the shale pattern. It can be seen that when the osmotic pressure is 4 MPa, the bedding angle-fractal curve becomes roughly M-shaped. As the inclination angle increases, when the sample is completely destroyed, the fractal dimension of the 30° sample is the largest, with a value of 1.41699, and the corresponding failure mode is also the most complex, which is a multi-line-type. The 90° sample has the lowest fractal dimension and is 1.281991. The failure mode of the 90° specimen is the simplest, and it is oblique I-type.

When the osmotic pressure is 8 MPa, the bedding angle-fractal curve is roughly V-shaped before the peak stress as the inclination angle increases. Because of the increase of osmotic pressure, the curve of the specimen is changed when it is completely destroyed, and is W-shaped. When the specimen is completely destroyed, the fractal dimension of the 30° specimen is the largest, with a value of 1.594072. The corresponding failure mode is also the most complex, showing the flame-type. The fractal dimension of the 15° specimen is the lowest, with a value of 1.409562. The failure mode of the 15° specimen is the simplest, and it is oblique I-type.

When the osmotic pressure is 12 MPa, the distribution of the bedding angle-fractal curve becomes more complex with the
increase of bedding angle. This is because the effect of excessive osmotic pressure on rock fracture damage exceeds that of the bedding, resulting in complex changes in the fractal dimension. When the specimen is completely destroyed, the fractal dimension of the 90° specimen is the largest, with a value of 1.550602. The corresponding failure mode is also the most complex and is broom-type. The fractal dimension of the 15° specimen is the lowest, with a value of 1.316954. The failure mode of the 15° specimen is the simplest and is oblique I-type. From the above analysis, it is shown that the
fractal dimension can reflect the fracture damage of shale. The larger the value of the fractal dimension, the more complex the damage of shale is.

5 | CONCLUSIONS

Based on the experimental and theoretical analysis presented, some useful conclusions can be drawn as follows:

1. Bedding has a significant effect on the compressive strength and modulus of elasticity of the shale. The compressive strength of shale shows obvious anisotropy with the increase of the bedding angle. The shale elastic modulus increases with the increase in the bedding angle.

2. The effect of osmotic pressure on the compressive strength of shale is significant. The shale compressive strength decreases as the osmotic pressure increases. However, the osmotic pressure has a weaker influence on the shale elastic modulus.

3. The bedding plane and osmotic pressure have a significant effect on the rupture mode of shale. When the osmotic pressure is 4 MPa, the shale exhibits six modes of failure. When the osmotic pressure is 8 MPa, the shale exhibits four modes of failure. When the osmotic pressure is 12 MPa, the shale exhibits four modes of failure. Increased osmotic pressure plays a leading role in the rupture damage process of shale. Fractal characteristics during shale rupture become complicated as osmotic pressure increases. The fractal dimension can reflect the rupture damage of shale. The larger the fractal dimension, the more complicated the rupture damage of shale.

4. In this paper, numerical simulation and fractal theory are used to analyze the mechanical and fractal characteristics of shale. The results show that both the mechanical characteristics and the fractal characteristics show obvious regularity. These results will provide important theoretical support for the exploration and exploitation of shale gas.

5. Hydraulic fracturing of shale is a complicated and multifactor fracture process. Because of the influence of geological sedimentary environment and geological tectonism, shale fractures develop and then affect the extension of hydraulic fractures. This paper mainly focuses on the study of the mechanical properties and fracture of shale, especially the effect of bedding direction on failure mode is analyzed in detail. In the follow-up work, we will explore the influence of fracture, filling, confining pressure, and other factors on shale strength, deformation, and fracture toughness.

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REFERENCES

1. Qiu X, Liu C, Mao G, Deng Y, Wang F. Major, trace and platinum-group element geochemistry of the upper Triassic nonmarine hot shales in the Ordos Basin, Central China. Appl Geochem. 2015;33:42-52.

2. Wu ZH, Zuo YJ, Wang SY, Chen J. Numerical study of multi-period paleotectonic stress fields in Lower Cambrian shale reservoirs and the prediction of fractures distribution: a case study of the Niutitang Formation in Feng’gang No. 3 block, South China. Mar Pet Geol. 2017;80:369-381.

3. Wang G, Chang X, Yin W, Li Y. Impact of diagenesis on reservoir quality and heterogeneity of the upper Triassic chang 8 tight oil sandstones in the Zhenjing area, Ordos Basin, China. J Petrol Sci Eng. 2017;83:84-96.

4. Lu YY, Chen XY, Tang JR, Li HB. Relationship between pore structure and mechanical properties of shale on supercritical carbon dioxide saturation. Energy. 2019;172:270-285.

5. Wang Q, Zhan LN. Assessing the sustainability of the shale gas industry by combining DPSIRM model and RAGA-PP techniques: an empirical analysis of Sichuan and Chongqing, China. Energy. 2019;176:353-364.

6. Shi BB, Chang XC, Yin W, Li Y, Mao LX. Quantitative evaluation model of tight sandstone reservoirs based on statistical methods - a case study of the Triassic Chang 8 tight sandstones, Zhenjing area, Ordos Basin, China. J Petrol Sci Eng. 2019;173:601-616.

7. Lou Y, Wu Z, Sun W, et al. Study on failure models and fractal characteristics of shale under seepage-stress coupling. Energy Sci Eng. 2020;8(5):1634-1649. https://doi.org/10.1002/esec.6261

8. Yin S, Zhao J, Wu Z, Ding W. Strain energy density distribution of a tight gas sandstone reservoir in a low-amplitude tectonic zone and its effect on gas well productivity: a 3D FEM study. J Petrol Sci Eng. 2018;170:1-16.

9. Yin S, Lv D, Ding W. New method for assessing microfracture stress sensitivity in tight sandstone reservoirs based on acoustic experiments. Int J Geomech. 2018;18(4):1-16.

10. Yin S, Ding W. Evaluation indexes of coalbed methane accumulation in the strong deformed strike-slip fault zone considering tectonics and fractures: a 3D geomechanical simulation study. Geol Mag. 2019;156(6):1052-1068.

11. Yin S, Xie R, Wu Z, Liu J, Ding W. In situ stress heterogeneity in a highly developed strike-slip fault zone and its effect on the distribution of tight gases: a 3D finite element simulation study. Mar Pet Geol. 2019;81(1):1-17.

12. Wu Y, Yang Y. The competition situation analysis of shale gas industry in China: Applying Porter's five forces and scenario model. Renew Sustain Energy Rev. 2014;40:798-805.

13. Chang Y, Huang R, Masanet E. The energy, water, and air pollution implications of tapping China's shale gas reserves. Resour Conserv Recycl. 2014;91:100-108.

14. Wang C, Wang F, Du H, Zhang X. Is China really ready for shale gas revolution—re-evaluating shale gas challenges. Environ Sci Policy. 2014;39:49-55.

15. Zhao J, Liu C, Yang H, Li Y. Strategic questions about China's shale gas development. Environ Earth Sci. 2015;73(10):6059-6068.

16. Wang R, Gu Y, Ding W, et al. Characteristics and dominant controlling factors of organic-rich marine shales with high thermal maturity: A case study of the lower Cambrian Niutitang formation in the Chen’gong block, Southern China. J Nat Gas Sci Eng. 2016;33:81-96.

17. Sun WJB, Zuo YJ, Wu ZH, Liu H. Fractal analysis of pores and the pore structure of the Lower Cambrian Niutitang shale in northern Guizhou province: investigations using NMR, SEM and image analyses. Mar Petrol Geol. 2019;99:416-428.

18. Rybacki E, Meier T, Dresen G. What controls the mechanical properties of shale rocks? - Part II: brittleness. J Petrol Sci Eng. 2016;144:39-58.

19. Liu J, Ding W, Xiao Z, Dai J. Advances in comprehensive characterization and prediction of reservoir fractures. Prog Geophys. 2019;34(6):2283-2300 (in Chinese).

20. Guo T, Zhang S, Qu Z, Zhou T, Xiao Y, Guo J. Experimental study of hydraulic fracturing for shale by stimulated reservoir volume. Fuel. 2014;128:373-380.

21. Liu LL, Cheng YM, Pan QI, Dias D. Incorporating stratigraphic boundary uncertainty into reliability analysis of slopes in spatially variable soils using one-dimensional conditional Markov chain model. Comput Geotech. 2020;118:103321.

22. Zhang JH, Liu SX, Ma YS. Macro-fracture mode and micro-fracture mechanism of shale. Petrol Explor Develop. 2015;42(2):269-276.

23. Shrey A, Bries M. Investigation of the failure mode of shale rocks in biaxial and triaxial compression tests. Int J Rock Mech Min Sci. 2015;79:109-123.

24. Li ZC, Li LC, Zhang LY, Zhang ZL. A numerical investigation on the effects of rock brittleness on the hydraulic fractures in the shale reservoir. J Nat Gas Sci Eng. 2018;50:22-32.

25. Niu H, Shao JF, Henry JP, Fourmantraux D. Laboratory investigation of the mechanical behaviour of Tournemire shale. Int J Rock Mech Min Sci. 1997;34:3-16.

26. Valès F, Minh DN, Gharbi H, Rejeb A. Experimental study of the influence of the degree of saturation on physical and mechanical properties in Tournemire shale (France). Appl Clay Sci. 2004;26(1-4):197-207.

27. Gudmundsson A, Simmenes TH, Larsen B, Philipp SL. Effects of internal structure and local stresses on fracture propagation, deflection, and arrest in fault zones. J Struct Geol. 2010;32(11):1643-1655.

28. Hou H, Diao C, Li D. An experimental investigation of geomechanical properties of deep tight gas reservoirs. J Nat Gas Sci Eng. 2017;47:22-33.

29. Meng FB, Ge HK, Yan W, Wang XQ. Effect of saturated fluid on the failure mode of brittle gas shale. J Nat Gas Sci Eng. 2016;35(A):624-636.

30. Heng S, Guo Y, Yang C, Daemen JJK, Li Z. Experimental and theoretical study of the anisotropic properties of shale. Int J Rock Mech Min Sci. 2015;74:58-68.

31. Wu ZH, Zuo YJ, Wang S, Yi T, Chen S. Numerical simulation and fractal analysis of organic rich marine shales with high thermal maturity. Mar Pet Geol. 2019;99:416-428.

32. Desbarats AJ. Numerical estimation of effective permeability in sand-shale formations. Water Resour Res. 1987;23(2):273-286.

33. Kwon O, Kronenberg AK, Gangi AF, Johnson B. Permeability of organic-rich marine shales with high thermal maturity. Environ Sci Technol. 2017;51(17):9109-9115.
34. Gareth RL, Chalmers DJ, Ross DJK, Bustin RM. Geological controls on matrix permeability of Devonian Gas Shales in the Horn River and Liard basins, northeastern British Columbia, Canada. Int J Coal Geol. 2012;103:120-131.
35. Gutierrez M, Øino LE, Nygård R. Stress-dependent permeability of a de-mineralised fracture in shale. Mar Pet Geol. 2000;17(8):895-907.
36. Wu Z, Zuo Y, Wang S, Sunwen J, Liu L. Experimental study on the stress sensitivity and influence factors of shale under varying stress. Shock Vibrat. 2018;2018:1-9.
37. Biot MA. General theory of three-dimensional consolidation. J Appl Phys. 1941;12(2):155-164.
38. Yang TH, Tang CA, Zhu WC, Feng QY. Coupling analysis of seepage and stresses in rock failure process. Chin J Geotech Eng. 2001;4:489-493 (in Chinese).
39. Brady BHG, Brown ET. Rock Mechanics for Underground Mining. Netherlands: Springer; 2006.
40. Liu HY, Kou SQ, Lindqvist PA. Numerical simulation of the fracture process in cutting heterogeneous brittle material. Int J Rock Mech Min Sci. 2002;26:1253-1278.
41. Zhu WC, Liu J, Tang CA, Zhao XD, Brady BH. Simulation of progressive fracturing processes around underground excavations under biaxial compression. Tunn Undergr Space Technol. 2005;20:231-247.
42. Wang S, Sloan S, Sheng D, Tang C. Numerical analysis of the failure process around a circular opening in rock. Comput Geotech. 2012;39:8-16.
43. Wang S, Sloan S, Tang C, Zhu W. A numerical investigation of the failure mechanism around tunnels in transversely isotropic rock masses. Tunn Undergr Space Technol. 2012;32:231-244.
44. Zuo Y, Zhang Q, Xu T, Liu Z, Qiu Y, Zhu W. Numerical tests on failure process of rock particle under impact loading. Shock Vib. 2015:2015:1-12.
45. Wang JA, Park HD. Fluid permeability of sedimentary rocks in a complete stress-strain process. Eng Geol. 2002;63:291-300.
46. Li SP, Wu DX. Effect of confining pressure, pore pressure and specimen dimension on permeability of Yinzhuang sandstone. Int J Rock Mech Min Sci. 1997;34(3/4):435-441.
47. Souley M, Homand F, Pepa S, et al. Damage induced permeability changes in granite: a case example at the URL in Canada. Int J Rock Mech Min Sci. 2001;38:297-310.
48. Vonk RA, et al. Micromechanical simulation of concrete softening. In: Proceedings of the International RILEM/ESIS Conference Fracture Processes in Concrete, Rock and Ceramics. London, UK: E. & FN; 1991.
49. Yang TH, Tang CA, QY. Numerical simulation on progressive failure of loaded rock sample under pore hydraulic pressure. Rock Soil Mech. 2001;22(4). https://doi.org/10.16285/j.rsm.2001.04.005 (in Chinese).
50. Yang TH, Tang CA, Li LC, Zhu WC. Study on permeability evolution in failure process of inhomogeneous rock. Chin J Rock Mech Eng. 2004;23(5):758-762 (in Chinese).
51. Bouboulis P, Dalla L, Drakopoulos V. Construction of recurrent bivariate fractal interpolation surfaces and computation of their box-counting dimension. J Approx Theory. 2006;141(2):99-117.
52. Li J, Du Q, Sun C. An improved box-counting method for image fractal dimension estimation. Pattern Recogn. 2009;42(11):2460-2469.

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