Study on failure models and fractal characteristics of shale under seepage-stress coupling

Yili Lou¹ | Zhonghu Wu¹,⁎ | Wenjibin Sun² | Shuai Yin³,⁴ | Anli Wang⁵ | Hao Liu² | Yujun Zuo²

¹College of Civil Engineering, Guizhou University, Guiyang, China
²Mining College, Guizhou University, Guiyang, China
³Shandong Provincial Key Laboratory of Depositional Mineralization & Sedimentary Minerals, Shandong University of Science and Technology, Qingdao, China
⁴School of Earth Science and Engineering, Xi’an Shiyou University, Xi’an, China
⁵Guizhou Province Quality and Safety Traffic Engineering Monitoring and Inspection Center CO., LTD, Guiyang, China

Correspondence
Zhonghu Wu, College of Civil Engineering, Guizhou University, Guiyang, China. Email: wuzhonghugzu@163.com

Funding information
Talent Introduction Project of Guizhou University, Grant/Award Number: [2017]63; Cultivation Project of Guizhou University, Grant/Award Number: 2, 0, 7, 1, 0, 0, 9 and 2; Guizhou Science and Technology Fund, Grant/Award Number: 2 and 2; Guizhou Postgraduate Research Fund, Grant/Award Number: 2; Project of Special Fund for Science and Technology of Water Resources Department of Guizhou Province, Grant/Award Number: KT201804; First-class Discipline Construction Project in Guizhou Province, Grant/Award Number: 1; National Natural Science Foundation of China, Grant/ Award Number: 51964007, 51574093 and 51774101; High-Level Innovative Talents Training Project in Guizhou Province, Grant/Award Number: 2016-4011

Abstract
The existence of bedding in shale plays an important role in the physical properties and destruction processes of shale. In order to study the failure mechanism of shale with different dip angles under the coupling of seepage and stress, the study uses RFPA2D-Flow software to advance the seepage-stress coupling numerical simulation for seven groups of different bedding direction shale. Research shows that (1) the compressive strength and elastic modulus of shale are significantly affected by the bedding directions. The compressive strength can be observed with the apparent anisotropy of the shale compressive strength with the change of the bedding angle α; the elastic modulus increase with the increase in α as a whole. (2) The ultimate failure mode of shale under different bedding angles can be divided into V type (0°), inverted V type (15°), multi-line type (30°), oblique type I (45°, 90°), and oblique N type (60°, 75°); the failure of shale in each group direction is mainly tensile failure with a small amount of shear failure. It can be found that the spatial distribution of acoustic emission (AE) reflected the macroscopic failure mode of shale. (3) The fractal dimension can well reflect the failure mode of the sample. From the trend of the dip-fractal dimension curve, the fractal dimension of the multi-line type reach to maximum, which is 1.41 699, and the D value of the oblique type I is the smallest, between 1.28 191 and 1.28 181. And the values of the inverted V type, V type and oblique N type, between 1.28 181 and 1.41 699. Therefore, the larger the value is, the more complex the shale failure mode is.

KEYWORDS
acoustic emission, failure mode, fractal dimension, numerical simulation, seepage-stress coupling, shale
1 | INTRODUCTION

In recent years, with the gradual reduction of conventional energy resources such as oil and natural gas, the exploration and development of shale gas have become a hot spot in current energy research. Shale gas is a kind of unconventional natural gas resource with large storage, wide and clean distribution. It has the advantages of long life and long production cycle, and has a broad prospect of progress. Exploration has found that China’s shale gas reserve is abundant and its development potential is huge, which has a strategic position in China's future oil and gas exploration and development.\(^\text{1,11,17,42,44,48,49}\) Because of the poor physical properties of shale gas reservoir and the extremely low porosity and permeability, hydraulic fracturing technology is the main method to increase production of shale gas reservoir at present.\(^\text{4,28-30,33,50,6,18,31,46,16,43,45}\) In the exploration and development of shale gas, the mechanical characteristics and failure mode of shale are important indexes to evaluate the geo-mechanical failure mode of shale. Niandou et al.\(^\text{20}\) studied the mechanical properties through uniaxial and triaxial compression test, analyzed the plastic deformation and failure modes of shale in detail, and obtained the relationship between elastic parameters and failure modes and confining pressure and dip angle. Valès et al.\(^\text{27}\) studied the mechanical properties of Tournemire shale through hydrostatic pressure and triaxial compression test, analyzed the plastic deformation and failure modes of shale in detail, and obtained the relationship between elastic parameters and failure modes and confining pressure and dip angle. The test showed that the deformation behavior of the sample from brittle to semi-brittle changed with the increase in pressure and temperature. Wu et al.\(^\text{11}\) used RFPA2D-DIP numerical simulation software to study the impact of microstructure on shale compressive strength and failure mode under different loading directions. The results showed that the mechanical properties of shale have an important influence on the compressive strength and failure mode of shale under different loading directions.

At present, many domestic and foreign scholars have been done many researches about the mechanical properties and failure mode of shale. Niandou et al.\(^\text{20}\) studied the mechanical anisotropy of Tournemire shale through hydrostatic pressure and triaxial compression test, analyzed the plastic deformation and failure modes of shale in detail, and obtained the relationship between elastic parameters and failure modes and confining pressure and dip angle. Valès et al.\(^\text{27}\) studied the effects of the saturation of Tournemire gas-bearing shale on mechanical properties through uniaxial and triaxial compression tests. The results showed that the shale mechanical properties were particularly sensitive to shale saturation. Mokhtari et al.\(^\text{19}\) discussed the characteristics before and after the shale failure through triaxial and acoustic testing, obtained the relationship between residual stress and confining pressure and dip angle after peak failure. Sone & Zoback\(^\text{24}\) studied the relationship between elastic modulus, toughness creep behavior, and brittle strength of Barnett, Haynesville, Eagle Ford, and Fort St. John’s shale gas reservoirs through series of triaxial tests. The tests showed that the viscoplastic creep strain was approximately linear with the applied differential stress, and the creep tendency was also correlated with the static Young’s modulus. Chen et al.\(^\text{5,8}\) quantitatively analyzed the mechanical properties of shale through the microindentation test of shale. The results showed that the distribution of meso-elastic modulus and indentation hardness was uniform, and the meso-elastic modulus and indentation hardness increase nonlinearly with the increase in filler density. Based on the shear stress concentration coefficient, the shear mechanism, the mechanical properties of the bedding plane were studied, and the test results of shear strength anisotropy under different bedding angles were obtained. Gao et al.\(^\text{10}\) used energy dispersive X-ray scanning electron microscopy (SEM) to analyze the microstructure and material composition of gas-bearing shale in Ohio, and through the ultrasonic test analysis, the shale showed obvious anisotropy. Rybacki et al.\(^\text{23}\) studied the brittleness of black shale with different mineral composition, porosity, and maturity in Europe. The test showed that the deformation behavior of the sample from brittle to semi-brittle changed with the increase in pressure and temperature. Wu et al.\(^\text{11}\) used RFPA2D-DIP numerical simulation software to study the impact of microstructure on shale compressive strength and failure mode under different loading directions. The results showed that the mechanical properties of shale have an important influence on the compressive strength and failure mode of shale under different loading directions.

With the deepening of shale research, several scholars have been done various researches on the shale permeability characteristics. For example, Dong et al.\(^\text{9}\) compared the permeability and porosity of shale and sandstone. The results show that the permeability of shale is more sensitive to effective confining pressure than sandstone, and the permeability and porosity follow a power relationship under effective stress. Chen et al.\(^\text{5,8}\) established a model of the relationship between crack permeability and effective stress of gas shale through theoretical derivation, and studied the influence of permeability on model coefficient and crack compressibility. Carey et al.\(^\text{3}\) used three-axis torus and X-ray tomography technique, combined with finite-discrete element model (FDEM) analysis to study the crack permeability of Utica shale. It is found that the new crack may be the source of permeability when the bedding plane is perpendicular and parallel to the direct shear loading. Wu et al.\(^\text{10}\) studied the relationship between shale porosity and permeability and effective stress through experiments. The results show that the porosity and permeability of the shale decrease with the increase in effective stress. From the above studies, we can see that the current research on shale mainly focuses on the mechanical properties, failure mode, and permeability characteristics, the research on the fracture mechanism of shale with different bedding dip angle under the coupling of permeability and stress is lacking. But research in this area has had a significant influence on the hydraulic fracturing design of shale production and the deployment of horizontal wells. Therefore, it is necessary to do in-depth research in this area.

The establishment of fractal dimension theory provides a new theoretical basis for rock fracturing and damage analysis. Xie.\(^\text{38}\) applied fractal geometry to rock damage mechanics and made breakthroughs, and found that the fracture and damage processes of rock have fractal characteristics. Kusunose et al.\(^\text{13}\) conducted triaxial compression tests on two different granitic granodiorite, Inada and Oshima, and discussed the
fractal dimension of the acoustic emission spatial distribution. It was found that the rock particles can affect the spatial distribution and expansion of microcrack. Xie et al.\textsuperscript{37} analyzed the fractal characteristics of the spatial distribution of acoustic emission during rock damage and failure, and obtained the fractal dimension value to reflect the failure state of the rock. Zhang et al.\textsuperscript{47} analyzed the fractal dimension of the acoustic emission time series generated by the shale formation micro-crack by the Brazilian splitting test. It was found that the fractal dimension can reflect the formation and expansion of the microcrack. From the above research, fractal theory plays an important role in the study of rock failure and damage.

In this paper, the shale core of Niutitang formation of Lower Cambrian in Fenggang block is taken as the research object. The numerical model of shale with different bedding angles is established by using RFPA2D-Flow, and to conduct numerical simulation of shale percolation-stress coupling under fixed osmotic pressure. The change of elastic modulus, compressive strength, and failure mode of shale with different bedding angles under fixed osmotic pressure were studied. In addition, we also carried out the fractal dimension calculation and analysis of the acoustic hair color image and analyzed the relationship between the shale failure mode and the fractal dimension. The research results will provide an important reference for the optimization of fracturing design schemes in shale hydraulic fracturing.

2 | GEOMORPHOLOGICAL AND GEOLOGICAL SETTING OF FENGGANG NO. 3 BLOCK

The shale gas exploration area in northern Guizhou is the most abundant shale gas reserves in Yunnan-Guizhou-Guangxi Delta and the Fenggang No. 3 block is the main component of shale gas exploration area in northern Guizhou. The study area of Fenggang No. 3 block is located in Fenggang and Meitan counties in the central part of the northern Guizhou region. It covers an area of 1167 square kilometers and has a thicker shale gas reservoir. As shown in Figure 1, the study area is located in the southern section of Wuling structural belt, where SN-, NNE-, and NE-trending faults and folds are developed and superimposed. The compressive structural planes along SN-, NE-, and NNE-trending fold axes and thrust sections constitute the main structural framework of the study area. The folds and faults are generally developed in the study area. The folds are dominated by NE-trending and NNE-trending “trough-like” structures, and a series of NE-trending composite anticlines and synclines are developed. The main faults are torsional faults in NNE-trending and NE-trending, and several strike faults interlace each other. Among these tectonic tracks, the SN-trending tectonic belts were formed the earliest, the NE-trending tectonic belts were formed the latest, and the formation time of the NNE-trending tectonic belts was between the two.

The stratigraphic division of Meitan-Fenggang area in which the study area is located belongs to South China stratigraphic region, Yangtze stratigraphic region, northern Guizhou-southern Sichuan region and Zunyi Nanchuan district. Figure 2 is a histogram of the Lower Cambrian lithofacies in northern Guizhou region. According to drilling data and regional outcrops, the strata developed in the study area include Cambrian, Ordovician, Lower-Middle Silurian, Permian, Triassic, Paleogene and Quaternary strata, and the strata of Upper Silurian, Devonian, Carboniferous, Jurassic, and Cretaceous are missing. According to the data, the Niutitang shale in the study area has no exposed, which is mainly composed of black carbonaceous shale, siliceous shale, and phosphorous siliceous shale, and the reservoir thickness of about 24-55 m. In early Cambrian Niutitang period, the northern part of the Yangtze platform was an active continental margin, while the southern part was a passive continental margin. At the beginning of Early Cambrian, the whole area of the study area and its surrounding areas sink, and most of them evolved into shelf sedimentary environment. At this time, the sedimentary paleogeomorphology pattern was high in NW and low in SE. From NW to SE, it was composed of ancient land, shore, shallow-water shelf, deepwater shelf, and slope facies. The deepwater continental shelf generally evolved to shallow-water continental shelf and tidal flat under the background of rapid Marine advancement and slow Marine retreat forming an inundation unconformity characterized by rapid deepening. As a result, the deepwater facies at the bottom of Niutitang formation directly overlaid the Dengying formation and deposited a set of mud shale formations. Because of sedimentation, there are structural weak planes containing quartz, calcite, and other minerals in the shale, forming carbonaceous shales with weak bedding planes.

The regional structure in the study area belongs to the Upper Yangtze platform, and the process of regional tectonic evolution has undergone several stages of tectonic movement superimposition, including the Snow Peak Movement, Early-Middle Caledonian Movement, Late Caledonian Movement, Hercynian Movement, Indosinian Movement, Yanshanian Movement, and Himalayan Movement. The structural morphology of Yangtze platform is very complicated due to the superimposition of multi-stage tectonic deformation. The Yanshanian movement is the most important period affecting the geological structure of the study area. During this period, the Asian plate was subjected to the intense subduction of the Pacific plate, and the research area was subjected to the compression stress field from northwest to southeast, forming a series of folds and fault zones. The Himalayan movement strengthened the fold belt deformation formed in the Yanshanian period. During this period, the whole area experienced the compression stress field from the near east to the west. With
FIGURE 1  Regional tectonic locations of Feng’gang No. 3 block (a) Tectonic map of northern Guizhou region. (b) Location of the study area. Maps show the elementary structural features of the Feng’gang No. 3 block. (c) Tectonic cross-section of the location shown in (b).
the formation of fold zones, shale structures in the study area are different, forming shale reservoirs with structural planes in different directions (Figure 3).

The higher the content of brittle minerals in shale, the more likely it is to produce fractures under pressure. In this paper, 19 shale samples of niutitang formation of Lower Cambrian
with different buried depths of well FC-1 are selected, and XRD whole-rock diffraction and clay mineral analysis are carried out. The test results are shown in Figure 4.

As shown in Figure 4, shale is mainly composed of quartz, potash feldspar, anorthose, calcite, ankerite, pyrite and clay, and the content of quartz ranges from 36% to 92%, with an average of 78%; the content of pyrite ranges from 2% to 25%, with an average content of 7.4%; the content of potash feldspar ranges from 3% to 23%, with an average content of 15%; the content of clay mineral is 2%-30%, with an average content of 8%. The clay mineral is mainly Illite, with an average content of 87%. It can be seen that the black shale of niutitang formation in this area is dominated by brittle minerals, which make the shale more likely to appear joints in the formation process.

In the multi-stage tectonic movement, the study area forms shale reservoirs with weak bedding planes in different directions, and the weak structure has an important impact on the mechanical properties of shale, which significantly affects the further exploitation of shale gas in the study area. Therefore, this paper uses FEM software to simulate the seepage-stress coupling test of weak shale with different bedding, and studies its mechanical properties and failure mode, providing important theoretical support for the development of shale gas exploitation in the research area.

3 | RFPA2D-FLOW TEST PRINCIPLE

RFPA2D-Flow numerical simulation software is a real fracture process analysis system based on elastic damage theory and finite element basic theory. It can simulate the permeability evolution law and the seepage-stress coupling mechanism during crack initiation and expansion, which has been described in detail elsewhere.

3.1 | Analysis of classical Biot seepage mechanics coupling equation

Biot has made a systematic study on the fluid-solid problem in seepage flow. The pore water pressure $P$ and variation $\Delta n$ are added into state variables, and the constitutive equations reflecting fluid-solid coupling are deduced and sorted out. The basic equations are expressed as follows:

\[ \frac{\partial \sigma_{ij}}{\partial X_j} + \rho X_j = 0 \quad (i,j = 1,2,3) \]  

(Figure 4) Mineral composition of shale in the study area
Geometric equation:
\[ \epsilon_i = \frac{(u_{ij} + u_{ji})}{2}, \quad \epsilon_V = \epsilon_{11} + \epsilon_{22} + \epsilon_{33} \] (2)

Constitutive equation:
\[ \sigma_{ij}' = \sigma_{ij} - \theta \rho \delta_{ij} \epsilon_V + 2G \epsilon_{ij} \] (3)
\[ \Delta n = P/Q - \theta \epsilon_V = P/H - \sigma_{ij} / 3H \] (4)

Seepage equation:
\[ K_{ij} \nabla^2 P = \frac{1}{Q} \frac{\partial P}{\partial i} - \theta \frac{\partial \epsilon_V}{\partial i} \] (5)

In the Equations 1-5, \( P \) and \( \Delta n \) are, respectively, the pore water pressure and the pore water change amount; \( \rho \) is the physical density; \( \nabla^2 \) is the pull operator; \( \delta \) is the Kronecker constant; \( K_{ij} \) is the permeability coefficient; \( \sigma_{ij}, \sigma_{ij}' \), and \( \epsilon_{ij} \) are, respectively, total stress, effective stress, and total strain; \( \alpha \) is called the pore water pressure coefficient; \( G \) and \( \lambda \) are, respectively, the shear modulus and the Lame coefficient; \( H \) and \( R(Q, \alpha) \) are the Biot constant. \( 1/R \) measures the change in water capacity due to changes in water pressure; and \( 1/H \) measures the change in the overall volume of the medium due to changes in water pressure. \( \theta \) is the pore water pressure coefficient, and it is determined by the test. \( 1/Q \) is the amount of water squeezed into the porous medium under the action of water pressure in the case where the volume of the porous medium is constant. Where \( Q, R, H, \) and \( \theta \) satisfy the following relationship

\[ \theta = \frac{3 \lambda + 2 G}{3H} = \frac{2}{3} \frac{(1 + \mu)}{(1 - 2 \mu) H} \Rightarrow \frac{E}{3 (1 - 2 \mu) H} = \frac{K'}{H} \] (6)
\[ 1/R = 1/Q + \theta / H \] (7)

In Equation (6), \( E \) and \( K' \) are, respectively, the modulus of elasticity and volume. For rock mass, pore water pressure coefficient \( \theta \) is between 0 and 1.

### 3.2 Analysis of seepage-stress coupled equations for mesoscopic unit damage evolution

Based on the constitutive relationship of uniaxial tension and compression, Yang et al\(^4\) elaborated the seepage-stress coupling equation in the elastic damage evolution process of the element under general stress state. When the stress state or strain state of the unit reaches a given deformation threshold, the unit begins to damage. Figure 5 shows the constitutive relation when the mesoscopic element is uniaxially loaded (either compression or tension). Initially, there is no deformation to the unit, and the stress-strain curve is linear or elastic. When the maximum tensile or compressive strain is reached, the unit undergoes brittle deformation.

The constitutive relation of elastic brittleness with residual strength under uniaxial tension is expressed as follows:

\[ \omega = \begin{cases} 0 & \epsilon_{\theta} \leq \epsilon, \\ 1 - f_{tr} / E_o \epsilon & \epsilon_{\theta} \leq \epsilon \leq \epsilon_{\theta}, \\ 1 & \epsilon \leq \epsilon_{\theta} \end{cases} \] (8)

The permeability coefficient \( K \) is expressed as.

\[ K = \begin{cases} K_0 e^{-\beta \sigma_{ij} / H} & \omega = 0, \\ \xi K_0 e^{-\beta \sigma_{ij} / H} & 0 < \omega < 1, \\ \xi K_0 e^{-\beta \sigma_{ij} / H} & \omega = 1 \end{cases} \] (9)

In Equations 8 and 9, \( \beta \) is the coupling coefficient; \( \omega \) is the deformation variable; and \( f_{tr} \) is the uniaxial tensile strength. \( \xi (\xi > 1) \) is the permeability jump coefficient, which characterizes the increase in the permeability coefficient before and after the unit deformation under the same stress state, it can be obtained by the stress-strain-permeability test; \( f_{tr} \) is the residual strength at the initial tensile failure; \( \epsilon_{\theta} \) is the tensile strain threshold when the uniaxial stretching criterion \( (\sigma_3 \leq -f_t) \) is employed. In the uniaxial tensile stress state, \( \epsilon_{\theta} \) is obtained by the following formula.

\[ \epsilon_{\theta} = -f_{tr} / E_o \] (10)

When the unit uniaxial tensile strain reaches \( \epsilon_{\theta} \), the unit begins to fail; meanwhile, \( \omega \) decreases continuously, and the permeability coefficient is calculated according to (Equation 9); when the maximum tensile principal stress
reaches $\varepsilon_{tu}$, it is considered that the unit has completely lost the bearing capacity, the unit is under permanent strain, that is, $\omega = 1$.

According to the Mohr-coulomb criterion, the constitutive equation under uniaxial compression stress state is

$$\omega = \begin{cases} 0, & \varepsilon < \varepsilon_{c0} \\ 1 - \lambda' \varepsilon_{c0} / \varepsilon, & \varepsilon_{c0} \leq \varepsilon \end{cases}$$  (11)

The expression of permeability coefficient $K$ is

$$K = \begin{cases} K_0 e^{-\beta \sigma_t / H}, & \omega = 0 \\ \xi K_0 e^{-\beta \sigma_t / H}, & \omega > 0 \end{cases}$$  (12)

In Equations 11 and 12, $\lambda'$ is the residual strength coefficient, which satisfies the relationship $f_{df_{tu}} = f_{df_{cr}} = \lambda'$; $\varepsilon_{c0}$ is the maximum pressure principal strain corresponding to the maximum compressive principal stress when reaching its uniaxial compressive strength. In the state of uniaxial compressive stress, $\varepsilon_{c0}$ is calculated by the following formula

$$\varepsilon_{c0} = f_{c0} / E_0$$  (13)

When the uniaxial tensile strain of the unit reaches $\varepsilon_{tu}$, the unit begins to deformation and $\omega$ decreases continuously, and the permeability coefficient is calculated according to (Equation 12); when the maximum tensile principal stress reaches $\varepsilon_{tu}$, it is considered that the unit has completely lost the bearing capacity, and the unit is in a completely damaged state.

Through the above analysis, the seepage-stress coupling constitutive equation and the unit failure evolution constitutive equation are explained in detail. Based on the above equation, RFPA2D-Flow software conducts seepage analysis, stress analysis, failure analysis, and coupling analysis of rock failure process. It simulates the entire process of rock failure under seepage-stress coupling.

4 | NUMERICAL MODEL

RFPA2D-Flow software discretizes the heterogeneous material. The mechanical properties of the discretized mesoscopic unit are subject to the Weibull statistical distribution law, and the homogeneity coefficient $m$ is used to reflect the uniformity of the material. The larger the $m$, the more homogeneous the rock; on the contrary, the smaller the $m$, the less heterogeneous the rock. The unit's elastic modulus $E_0$, the uniaxial compressive strength $\sigma_c$, the Poisson’s ratio $\nu$, the pore water pressure coefficient $\alpha$, and the permeability coefficient $K$ obey the Weibull random distribution.

$$\phi = m \left( \frac{s}{s_0} \right)^{m-1} \exp \left[ - \left( \frac{s}{s_0} \right)^{m} \right]$$  (14)

In Equation (14), $S$ is $E_0$ or $\sigma_c$ or $K$; $S_0$ is the average value corresponding to it, and the specific values of the mechanical properties of the sample are shown in Table 1.36

In order to simulate the failure of different bedding shale better, we use different dip angles to obtain different dip bedding shale to establish a numerical model, as is shown in Figure 6.

The calculation model was built-in the RFPA2D-Flow software. Model height is 100 mm, and the diameter is 50 mm. The model is divided into 200 $\times$ 100 units. It is well known that shale has a layered structure plane. Therefore, we consider the shale and its bedding plane in the model establishment, and combine the mechanical parameters in the shale and the layer to establish two media with different mechanical properties to characterize the shale matrix and the weak surface of the layer, which is shown in Figure 7.

In this experiment, we establish the shale numerical models with different dip angles of 0°, 15°, 30°, 45°, 60°, 75°, and 90°, as is showed in Figure 7. The brightness of the element in the model characterizes the element’s modulus of elasticity. The brighter the color is, the greater the modulus of elasticity. Conversely, the darker the color is, the lower the modulus of elasticity. The model satisfies the results of coring at different angles to make the research results better in line with the actual situation. In this paper, we simulate the failure mode of shale under osmotic pressure-stress coupling. The numerical model loading diagram is shown in Figure 7. And the bottom end of the sample is fixed. First, add a certain axial pressure $P_1$, the fixed confining pressure $P_2 = 10$ MPa, and set the osmotic pressure difference ($\Delta = P_3 - P_4$) at the upper and lower ends of the sample, and the osmotic pressure is 4MPa. Then, the whole process is loaded by displacement control. The initial displacement is 0.001mm, and the displacement increment $\Delta S = 0.0002$ mm.

5 | RESULTS AND ANALYSIS

5.1 | numerical simulation results of seepage-stress coupling

Under fixed osmotic pressure, the compressive strength, elastic modulus, and failure mode of different bedding shale under osmotic-stress coupling are different. Table 2 shows the compressive strength and elastic modulus values of 7 groups of shale under the osmotic-stress coupling
action at an osmotic pressure of 4 MPa, in which inclination \( \alpha \) is the angle between the weak surface of bedding and the horizontal direction. Figure 8 shows the variations in the compressive strength and the elastic modulus with the azimuth angle. In the figure, the left axis represents the compressive strength and the right axis represents the elastic modulus. It can be seen that the shale of different bedding angles exhibits significant anisotropy under the seepage-stress coupling, which is due to the weak cementation of the bedding plane. The maximum compressive strength occurs when \( \alpha = 60^\circ \), which is 47.09 MPa. When \( \alpha = 45^\circ \), the compressive strength is the lowest, at 42.83 MPa. The difference between the maximum and minimum values of the elastic modulus is 3.73 GPa, which is 8.9% of the maximum value. This indicates that the bedding direction has a significant effect on the compressive strength and elastic modulus of shale under the effect of osmotic-stress coupling. This is because the shale is affected by the weak cementation of the bedding weak surface. Bedding planes with different dip angles cause different stress concentration of the shale under loading conditions, which lead to different compressive strength of different bedding shale.

Figure 9 shows the evolution of cracks, the failure mode, and the acoustic emissions for various azimuth angles under seepage-stress coupling. We can see it clearly different bedding angles make the shale failure modes different. When \( \alpha = 0^\circ \), the initial crack is formed in the shale matrix in the upper left corner and the upper right corner, and then the left side extends along the middle of the initial crack to the middle of the bedding surface, and the angle between the plane and the bedding surface is about 45°, until the V-mode failure mode is formed; when \( \alpha = 15^\circ \), the initial crack is formed in the middle of the shale and then extends to the left and right sides until an inverted V-shaped failure mode is formed; when \( \alpha = 30^\circ \), the initial crack is formed at the edge of the two bedding planes in the middle of shale, and then the failure is extended along the edge of the bedding plane, and the matrix is broken through until the multi-broken line failure mode is formed; when \( \alpha = 45^\circ \), initial crack appears in the bedding weak surface, and then along the bedding plane and matrix extension until the oblique I form is formed; when \( \alpha = 60^\circ \), since the initial crack is distributed on the two bedding planes, the cracks are broken along the two lamination planes, and finally, the through matrix connects the two fracture planes until the oblique N shape is formed; when \( \alpha = 75^\circ \), the initial crack is formed in the lower left corner of the shale and extends at an angle of about 30° with the bedding plane until an oblique N-type failure mode is formed; when \( \alpha = 90^\circ \), an initial crack is formed in the upper right corner of the shale, extending at an angle of about 45° along the bedding plane until an oblique I-type failure mode is formed. To sum up, due to the characteristics of the bedding and the presence of osmotic pressure, the shale forms five final failure modes, namely V type (0°), inverted V type (15°), multi-line type (30°), oblique I type (45°, 90°), oblique N type (60°, 75°).

| Material       | Elastic modulus/MPa | Compressive strength/MPa | Poisson ratio \( \nu \) | Internal friction angle (°) | Compressional 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                    |

**Figure 6** Directional coring diagram of specimens with different bedding orientations (a) directional coring diagram for shale sample preparation and (b) diagram of the angles \( \alpha \) (the angle between the bedding planes and the horizontal direction)
In the AE diagram of Figure 9, red represents tensile failure, white represents shear failure, and black represents complete failure. It can be clearly seen that the failure modes of all dip bedding shale are mainly tensile failure and accompanied by shear failure. This is because the compressive strength of shale is much greater than the tensile strength. Under the effect of seepage-stress coupling, the tensile stress first reaches the limitation, and the failure mode is dominated by tensile failure. We can see from the acoustic emission diagram that the spatial distribution of acoustic emission points reflects the macroscopic failure mode of the pattern well.

The weak cementation of sedimentary structure and bedding surface of shale is the main cause of failure mechanism anisotropy. From our analysis, the five failure modes above are mainly caused by the different failure mechanisms of bedding shale with different dip angles under different loading conditions. The failure modes of all layered dip specimens are mainly tensile failure accompanied by shear failure, which can be seen from the acoustic emission image. When \( \alpha = 45^\circ \) and \( \alpha = 60^\circ \), the failure mode of the specimen is mainly

**TABLE 2** Simulation results of shale elastic modulus and uniaxial compressive strength

| Azimuth(°) | Elastic modulus/GPa | Uniaxial compressive strength/MPa |
|-----------|---------------------|----------------------------------|
| 0         | 39.13               | 44.92                            |
| 15        | 38.27               | 46.31                            |
| 30        | 40.42               | 45.27                            |
| 45        | 40.48               | 42.83                            |
| 60        | 40.80               | 47.09                            |
| 75        | 41.55               | 46.20                            |
| 90        | 42.00               | 44.77                            |
FIGURE 8  Compressive strength and elastic modulus of shale at various azimuth angles.

FIGURE 9  Failure mode and acoustic emission (AE) diagram of shale at various azimuth angles.
dominated by the tensile failure of the bedding plane, the failure mode of the specimen at other angles is characterized by the composite failure of the matrix and the bedding plane; when \( \alpha = 90^\circ \), the failure mode of the sample does not break along the bedding plane. This is due to the confining pressure and osmotic pressure, which make the sample failure mode appear oblique I; when \( \alpha = 30^\circ \), the failure mode of the sample exhibits a multi-line shape with small crack branches, forming a complex crack network.

### 5.2 Fractal characteristics of shale damage process

At present, using the overlay method to determine the fractal dimension of an object is one of the most common methods. Fractal dimension \( D \), spectral density index \( \gamma \), parameter \( \beta \), etc are used to describe the basic parameters of fractal theory, in which fractal dimension \( D \) is the core parameter, and the calculation formula is as follows,\(^{2,14}\)

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

(15)

where \( D \) is the self-similar fractal dimension of the failure region; \( \mu \) is the square box side length; and \( N(\mu) \) is the number of boxes required to cover the entire area of the broken area with a square box with a side length of \( \mu \).

The acoustic emission energy values and fractal dimension values of different stress levels obtained by seepage-stress coupling of different layered dip shale are shown in Table 3. The fractal dimension values of the complete failure are shown in Table 4. It can be found that the fractal dimension value increases as the acoustic emission energy increases. When the stress level is 100%, the acoustic emission energy of the 15° sample is 2.54443, and the fractal dimension is 1.23215. The 90° sample has an acoustic emission energy of 0.8622 and a fractal dimension of 1.07226.
Figure 10 shows the AE energy versus the stress for various azimuth angles under seepage-stress coupling. It can be seen that the acoustic emission energy value increases with the increase in the stress level during the rupture of different dip bedding shale. When the stress level is <80%, the acoustic emission energy value of each group of samples tends to be gentle and in a quiet period. When the stress level is >40%, the AE energy value appears in the 15° sample; the 0°, 30°, 45°, 60°, and 75° samples exhibit AE energy values at stress level is >50%; the 90° sample has an AE energy value when the stress level is >60%; this is due to the combination of confining pressure and bedding structure. When the stress level exceeds 80%, the AE energy values of the 60° and 15° samples increase rapidly; when the stress level exceeds 90%, the AE energy value of the 15° sample sharply increases to the maximum, followed by 60°, and the 90° sample growth is the most gradual. This indicates that the layer has a significant effect on the release of acoustic emission energy during shale rupture. When the stress reaches the peak value, the energy released by the 15° sample is the largest, the failure is the most severe, and the internal damage is the most serious.

Figure 11 shows the fractal dimension versus the stress for various azimuth angles under seepage-stress coupling. It can be seen that the fractal dimension appears when the stress level is >40%, and as the internal failure of the shale accumulates, the fractal dimension increases with the increase in the stress. When the stress level is >40%, the fractal dimension $D$ value begins to appear in the 15° sample; when the stress level is >50%, the fractal dimension $D$ values begin to appear at 0°, 30°, 45°, 60°, and 75° samples; when the stress level is >60%, the fractal dimension $D$ value appears in the 90° sample. This is because of the difference in the damage of different layered shale due to the effect of the bedding plane and the confining pressure, resulting in the difference in fractal dimension. When the stress level is <90%, the $F$-value of the fractal dimension $D$ of the 60° sample increases the fastest; when the peak stress level, 15° sample $D$ values increase sharply to the maximum, 1.232 159; 0° and 90° samples $D$ values are the lowest, at 1.086 414 and 1.072 262, respectively. According to the above description, under the effect of seepage-stress coupling, the bedding direction has a significant effect on the generation and development of microcracks inside shale. After the bedding and the matrix are subjected to the load, the microcracks are more easily to be produced than the simple bedding or matrix. The crack development of 0° and 90° samples is slower than other angles.

Figure 12 shows the relationships of azimuth angles with the fractal dimension under different stress levels. As can be seen from Figure 10, when the stress level exceeds 50%, the value of individual points is ignored, and the curve of
the dip-fractal dimension changes in an M shape. When the stress reaches the peak value, the fractal dimension of the 15° sample is the largest, which is 1.232 159; the fractal dimension values of the 0° and 90° samples are the smallest, at 1.086 414 and 1.072 262, respectively; when the sample is completely destroyed, the fractal dimension of the 30° sample is the largest, which is 1.41 699, followed by the 0° and 15° samples, the 60° and 75° samples are smaller, and the fractal dimensions of the 45° and 90° samples are the lowest. The minimum number is 1.286 181 and 1.281 991. The reason is that under the coupling of seepage and stress, when the stress reaches its peak, although there is a crack in the shale, it is not completely through and continues to apply the load. New microcracks will continue to be produced and microcracks will be fully penetrated to form macroscopic cracks. Further analysis shows that the macroscopic cracks of the 45° and 90° specimens are inclined I, and the failure mode is single, so the fractal dimension is the smallest. The macroscopic failure crack of the 30° sample is multi-folded, forming a crack network, and the fractal dimension is the largest. For the failure modes of an inverted V, V, and oblique N, the fractal dimension is between the oblique I and the polyline. Therefore, the larger the value of D is, the more severe failure of shale and the more complicated the failure mode.

6 | CONCLUSION

Through this experiment, the following conclusions can be drawn:

1. The bedding has a significant effect on the compressive strength and modulus of elasticity of the shale. As the bedding angle α increases, the change curve of compressive strength was M-shaped, showing obvious anisotropy. However, the elastic modulus of shale increased with the increase in bedding inclination α.

2. Due to the influence of the weak cementation of the bedding plane, the shale sedimentary structure, and loading conditions, the bedding plane of different dip angles has different effects on the failure mode of shale and finally show five failure modes, namely V type (0°), inverted V type (15°), multi-line type (30°), oblique type I (45°, 90°), and oblique N type (60°, 75°).

3. Since the spatial distribution of the acoustic emission point has fractal characteristics, the magnitude of the fractal dimension can reflect the shale failure mode. After the stress level exceeds 50%, the fractal dimension shows a M-type distribution trend with the increase in the bedding angle. When α = 30°, the maximum is 1.41 699, and the macroscopic crack is multi-line type; the minimum is α = 45° and α = 90°, the values are 1.286 181 and 1.281 991, respectively, and the macro crack is inclined I. The fractal dimension values of other samples ring from 1.286 181 to 1.41 699, and the failure modes are V type (0°), inverted V type (15°), and oblique N type (60°, 75°). Therefore, the larger the fractal dimension of the acoustic emission point is, the more complicated the corresponding failure mode is; with the stress level increasing, the fractal dimension values of each group of samples increase.

4. The different distribution and groups of shale and the different environment of exploitation will affect the exploitation efficiency of shale gas. In this paper, only the osmotic-stress coupling test of the Lower Cambrian Niutitang Formation shale in the Fenggang block provides a new idea for studying the physical properties and failure modes of shale, especially in layers with different dip angles. A detailed analysis is made in the influence of the rock failure mode. Subsequent effects of confining pressure, osmotic pressure, and other factors on the strength, failure modes, and fractal characteristics of different inclined bedding shale will be carried out.

ACKNOWLEDGMENTS

This study was supported by the Talent Introduction Project of Guizhou University (Project No. [2017]63), the Cultivation Project of Guizhou University (Project No. [2017]5788-49), the Guizhou Science and Technology Fund (Project No. [2019]1075 and [2018]1107), the Guizhou Postgraduate Research Fund (YJSCXJH [2019]033), the Project of Special Fund for Science and Technology of Water Resources Department of Guizhou Province (Project No. KT201804), the First-class Discipline Construction Project in Guizhou Province (Project No. QYNYL[2017]0013), the National Natural Science Foundation of China (Project Nos. 51964007, 51574093, and 51774101), and the High-Level Innovative Talents Training Project in Guizhou Province (Project No. 2016-4011).

ORCID
Zhonghu Wu https://orcid.org/0000-0001-7315-9109

REFERENCES

1. Biot MA. General theory of three-dimensional consolidation. J Appl Phys. 1941;12(2):155-164.
2. Bouboulis P, Dalla L, Drakopoulos V. Construction of recurrent bivariate fractal interpolation surfaces and computation of their box-counting dimension. Journal of Approximation Theory. 2006;141(2):99-117.
3. Carey JW, Zhou L, Rougier E, Mori H, Viswanathan H. Fracture-permeability behavior of shale. Journal of Unconventional Oil and Gas Resources. 2015;11:27-43.
4. 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.
5. Chen D, Pan Z, Ye Z. Dependence of gas shale fracture permeability on effective stress and reservoir pressure: model match and insights. Fuel. 2015a;139:383-392.

6. Chen J, Lan H, Maccotta R, et al. Anisotropy rather than transverse isotropy in Longmaxi shale and the potential role of tectonic stress. Eng Geol. 2018;247(2018):38-47.

7. Chen MJ, Kang YL, Zhang TS, Li XC, Lin C. Shale gas transport behavior considering dynamic changes in effective flow channels. Energy Science & Engineering. 2019;7(5):2059-2076.

8. Chen P, Han Q, Tianshou MA, Lin D. The mechanical properties of shale based on micro-indentation test. Petroleum Exploration and Development. 2015b;42(5):723–732(open access).

9. Dong Ji, Hsu JY, Wu W, Shimamoto T, Hung J, Wu Y. Stress-dependence of the permeability and porosity of sandstone and shale from TCDP Hole-A. Int J Rock Mech Min Sci. 2010;47(7):1141-1157.

10. Gao Q, Tao J, Hu J, Yu X. Laboratory study on the mechanical behaviors of an anisotropic shale rock. Journal of Rock Mechanics and Geotechnical Engineering. 2015;7(2):213-219.

11. Haddad M, Sepehrnoori K. Simulation of hydraulic fracturing in quasi-brittle shale formations using characterized cohesive layer: Stimulation controlling factors. Journal of Unconventional Oil and Gas Resources. 2015;9:65-83.

12. 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.

13. Kusunose K, Lei X, Nishizawa O, Satoh T. Effect of grain size on fractal structure of acoustic emission hypocenter distribution in granite rock. Phys Earth Planet Inter. 1991;67(1-2):194-199.

14. Li J, Du Q, Sun C. An improved box-counting method for image fractal dimension estimation. Pattern Recogn. 2009;42(11):2460-2469.

15. Li X, Shi W, Guo M, Li X, Zhao H. Characteristics of marine shale gas reservoirs in Jiaoshiba area of fuling shale gas field. Journal of Oil and Gas Technology. 2014;36(11):11-15.

16. Li Z, Zhang JC, Tang X, et al. Approaches for the evaluation of favorable shale gas areas and applications: implications for China’s exploration strategy. Energy Science & Engineering. 2019;90:1-21.

17. Li Z, Jia CG, Yang CH, Zeng YJ, Guo YT. Propagation of hydraulic fissures and bedding planes in hydraulic fracturing of shale. Chin J Rock Mechan Eng. 2013;34(1):12-20.

18. Mao R, Zhang J, Pei P, Xie Z, Zhou X. Adsorption characteristics of clay-organic complexes and their role in shale gas resource evaluation. Energy Science & Engineering. 2018;7(1):108-119.

19. Mokhtari M, Alqahtani AA, Tutuncu AN. Failure behavior of anisotropic shales; 2013. In: Proceedings of the 47th US Rock Mechanics/Geomechanics Symposium.

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

21. Qiao L, Long X, Ranjith PG, Tan J, Kang Y. Experimental investigation on the mechanical behaviours of a low-clay shale under water-based fluids. Eng Geol. 2018;233(2018):124-138.

22. Rutqvist J, Rinaldi AP, Cappa F, Moridis GJ. Modeling of fault reactivation and induced seismicity during hydraulic fracturing of shale-gas reservoirs. J Petrol Sci Eng. 2013;107:31-44.

23. Rybacki E, Meier T, Dresen G. What controls the mechanical properties of shale rocks? Part II: Brittleness. J Petrol Sci Eng. 2016;144:38-58.

24. Sone H, Zoback MD. Mechanical properties of shale-gas reservoir rocks-Part 2: ductile creep, brittle strength, and their relation to the elastic modulus. Geophysics. 2013;78(5):D390-D399.

25. 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 Pet Geol. 2019;99:416-428.

26. Tang CA, Tham LG, Lee PKK, Yang T, Li L. Coupled analysis of flow, stress and damage (FSD) in rock failure. Int J Rock Mech Min Sci. 2002;39(4):477-489.

27. 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.

28. 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.

29. 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 cen’gong block, southern China. Journal of Natural Gas Science and Engineering. 2016a;33:81-96.

30. 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 Cen’gong block, southern China[J]. Journal of Natural Gas Science and Engineering. 2016b;33:81-96.

31. Wang R, Hu Z, Long S, et al. Differential characteristics of the Upper Ordovician-Lower Silurian Wufeng-Longmaxi shale reservoir and its implications for exploration and development of shale gas in/around the Sichuan Basin[J]. Acta Geologica Sinica (English edition). 2019;93(3):520-535.

32. Wang R, Hu Z, Sun C, et al. Comparative analysis of shale reservoir characteristics in the Wufeng-Longmaxi (O3w–S1l) and Niutitang (C1n) formations: a case study of the Wells JY1 and TX1 in southeastern Sichuan Basin and its periphery, SW China[J]. Interpretation 2018;6(4):SN31-SN45.

33. 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.

34. Wu ZH, Zuo YJ, Wang S, Yi T, Chen S. Numerical simulation and fractal analysis of mesoscopic scale failure in shale using digital images. J Petrol Sci Eng. 2016;145:592-599.

35. Wu ZH, Zuo YJ, Wang S, et al. Numerical study of multi-period palaeotectonic 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;80:369e381.

36. Wu ZH, Zuo YJ, Wang S, Sunwen JB, Liu L. Experimental study on the stress sensitivity and influence factors of shale under varying stress. Shock and Vibration. 2018;2018:1-9. https://doi.org/10.1155/2018/3616942.

37. Xie HP, Liu JF, Ju Y, Li J, Xie LZ. Fractal property of spatial distribution of acoustic emissions during the failure process of bedded rock salt. Int J Rock Mech Min Sci. 2011;48(8):1344-1351.

38. Xie H. An Introduction to Fractal – Rock Mechanics. Beijing (in Chinese): Science Press; 1996.

39. Yang TH, Tham LG, Tang CA. Influence of heterogeneity of mechanical properties on hydraulic fracturing in permeable rocks. Rock Mech Rock Eng. 2004a;37:251-275.

40. Yang TH, Tang CA, Li LC, Zhu WC. Study on permeability evolution in failure process of inhomogeneous rock. Chin J Rock Mechan Eng. 2004b;23(5):758-762. (in Chinese).
41. Yang TH, Tang CA, Zhu WC, Feng QY. Coupling analysis of seepage and stresses in rock failure process. *Chinese Journal of Geotechnical Engineering*. 2001;4:489-493.

42. Yang X, Guo BY. Statistical analyses of reservoir and fracturing parameters for a multifractured shale oil reservoir in Mississippi. *Energy Science & Engineering*. 2019;00:1-11.

43. Yin S, Ding WL. 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*. 2019b;156(6):1052-1068.

44. Yin S, Han C, Wu ZH, Li QM. Developmental characteristics, influencing factors and prediction of fractures for a tight gas sandstone in a gentle structural area of the Ordos Basin, China. *Journal of Natural Gas Science and Engineering*. 2019c;72:103032.

45. 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*. 2019a;81(1):1-17.

46. 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(6):1-16.

47. Zhang SW, Shou KJ, Xian XF, Zhou JP, Liu GJ. Fractal characteristics and acoustic emission of anisotropic shale in Brazilian tests. *Tunn Undergr Space Technol*. 2018;71:298-308.

48. Zhang X, Jiang T, Jia C, et al. Physical simulation of hydraulic fracturing of shale gas reservoir. *Petroleum Drilling Techniques*. 2013;41(2):70-74.

49. Zhao Y, He PF, Zhang YF, Wang L. A new criterion for a toughness-dominated hydraulic fracture crossing a natural frictional interface. *Rock Mech Rock Eng*. 2019;52:2617-2629.

50. Zhao J, Liu C, Yang H, Li Y. Strategic questions about China’s shale gas development. *Environmental Earth Sciences*. 2015;73(10):6059-6068.

51. Zhou SW, Liu HL, Chen H, et al. A comparative study of the nanopore structure characteristics of coals and Longmaxi shales in China. *Energy Science & Engineering*. 2019;00:1-14.

How to cite this article: 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;8:1634–1649. [https://doi.org/10.1002/ese3.621](https://doi.org/10.1002/ese3.621)