Study on Rock Mechanical Properties and Wellbore Stability of Fractured Carbonate Formation Based on Fractal Geometry

Houbin Liu, Shuai Cui,* Yingfeng Meng,* Zhengbo Han, and Mou Yang

ABSTRACT: To mitigate borehole wall instability in fractured carbonate formations in an oilfield, the main factors affecting borehole wall instability were determined by combining the characteristics of underground cores, logging data, and a series of laboratory mechanics experiments. The geometric morphology characteristics of a carbonate rock fracture surface were studied together with an artificial rock fracture surface formed by triaxial mechanics experiments. A relationship between the geometric morphology characteristics of a fracture surface and rock mechanical properties was established based on fractal geometry. Using the Mohr–Coulomb failure and weak plane failure criteria, a rock strength criterion based on the fractal characteristics of a rock fracture surface was established. Finally, the mechanical rock properties characterized by fractal geometry were imported into the established borehole stability evaluation model. The results show that a collapse formation is mainly limestone with relatively developed microfractures, and some fractures are filled with expansive clay. The anisotropy of mechanical properties of bedrocks and microfractured rocks is obvious, whereas drilling-fluid immersion has little effect on the mechanical properties of a rock. 3D scanning experiments of artificial fracture surfaces formed after a triaxial mechanical test of a bedrock and fracture surfaces of a rock with microfractures show that the geometric characteristics of fracture surfaces after bedrock failure were more complex than those of fractured rocks. The geometric characteristics of rock fracture surfaces were numerically expressed through a statistical analysis and fractal geometry. Function relationships among cohesion, an internal friction angle, and fractal dimensions of bedrocks and microfracture rocks were fitted. A numerical simulation of borehole stability based on the fractal model of a carbonate fracture surface shows that different fracture inclinations and borehole trajectories significantly influence the collapse pressure equivalent density of a borehole wall. On drilling a horizontal well along the inclination of a fracture, the collapse pressure equivalent density of the borehole wall is relatively low when the fracture inclination is along the direction of the minimum horizontal principal stress. Unlike that from a conventional borehole stability model, the collapse pressure equivalent density calculated from the fractal model will increase by 0.1–0.2 g/cm³. The study results provide a theoretical basis for safe and efficient drilling in fractured carbonate formations.

1. INTRODUCTION

Carbonate reservoirs play an important role in the development of global oil and gas resources. According to Information Handling Services (HIS) statistics, carbonate rock oil and gas resources account for about 70% of the global oil and gas resources, their proven recoverable reserves account for about 50%, and their production accounts for about 60%.1 Carbonate formations with relatively developed fractures are easy to break and have low mechanical strength, and the existence of fractures improves the seepage performance in carbonate rocks. The seepage capacity of a borehole wall, a fracture angle, and a weak plane effect of fractures all have an obvious influence on the borehole stability in a carbonate formation.2–5 These factors have a great influence on the three formation pressures, thus increasing the difficulty of predicting the three formation pressures and failing to form an effective evaluation method.6,7 At present, there is no definite conclusion on how fractures affect the wellbore stability of carbonate formations. Therefore, it is necessary to carry out research on wellbore stability of carbonate formations with relatively developed fractures and seek a method to evaluate the wellbore stability of fractured carbonate formations, so as to provide a theoretical basis for predicting the wellbore instability of carbonate formations.

Many scholars have conducted various studies on wellbore stability in fractured carbonate strata. Sun et al.8 established a borehole stability model for deviated wells in fractured carbonate formations based on a porous elastic model of borehole stability and the strength theory of weak surfaces. The influence of a fracture orientation on borehole collapse

Received: August 16, 2022
Accepted: November 4, 2022
Published: November 15, 2022
pressure was quantitatively analyzed, and a variation law of borehole collapse pressure with weak plane occurrence characteristics under different borehole trajectories was studied, which provided a basis for wellbore stability during drilling operations. To study the elastic properties of fractured carbonate rocks, Tan et al. used media filtering and threshold segmentation technology to establish carbonate digital cores by X-ray CT scanning. Then digital carbonate cores of different fracture types were constructed by inserting fractures into scanned slices. Based on the theory of elasticity, the finite element method was used to calculate the elastic properties of carbonate rock cores with fractures, and the influence of microscopic factors on the elastic properties of rock was studied in detail. The effects of a fracture density, opening, and length on a stiffness matrix element and wave velocity were studied through pore-scale simulation. He et al. studied multiple oil and gas reservoir wells inside a buried hill. By analyzing geological engineering data, they discovered that pores and fractures in a carbonate reservoir inside the buried hill were extremely well developed. A fracture zone formed by faults and buried hill weathering crusts significantly influences the wellbore stability. The essence of a carbonate formation with relatively developed fractures is to strengthen fracture plugging, and a drilling fluid density is the control factor of leakage prevention. A low density oil-water emulsion drilling fluid with a close balance with formation pressure has a good leakage prevention effect. Jin et al. summarized the research on wellbore stability technologies in deep fracture carbonate formations from two aspects of wellbore instability mechanisms and wellbore stability control methods. The critical factors affecting the wellbore instability in deep carbonate formations are a complex in situ stress environment and mechanical strength deterioration of rock mass caused by natural fracture development. Reasonable optimization of a drilling fluid density and engineering parameters can significantly stabilize borehole walls by improving the drilling-fluid plugging and chemical wall fixing ability. Liu et al. conducted systematic experimental tests on the microstructure characteristics and physicochemical properties of fractured limestone, revealing the influence of fractures on the mechanical properties of limestone and establishing a relationship model between formation collapse pressure and fracture strikes. Their results showed that fractures significantly influenced a rock’s mechanical strength and different fracture strikes influenced borehole stability differently. A fracture strike has the greatest impact on borehole stability at 40°–60°. Kidambi et al. used a comprehensive geomechanical analysis method to transform available logging dynamic data into mechanical properties using correlation coefficients. The static data obtained from their core samples were then correlated with the properties obtained from logging analysis to analyze the borehole stability comprehensively. The stress concentration around a wellbore was studied with the fracture and natural fracture information obtained from image logging. A safe mud density window was designed to ensure wellbore stability. To facilitate the analysis of fracture development in carbonate formations, Liu et al. introduced the concept of a formation integrity coefficient commonly used in rock engineering. The empirical formulas of the integrity coefficient and cohesion of a carbonate formation were proposed with mechanical and acoustic experiments, establishing a calculation model for a collapse density considering the formation integrity. The results can guide the borehole stability research.

Figure 1. Distribution of collapsed strata and falling blocks in Well X: (a) logging data of the deviated section; (b) downhole fall-blocks; (c, d) downhole cores.
in carbonate rocks, especially in a fractured carbonate rock formation.

Generally, the calculation of formation collapse pressure is based on the Mohr–Coulomb criterion or Drucker–Prager criterion. It is necessary to get the cohesion and internal friction angle of formation rock before the calculation of formation collapse pressure. For fractured carbonate formations, due to the development of fractures and low formation strength, the complete standard core cannot be taken out; thus, it is difficult to obtain the internal friction angle and cohesion, and the cohesion and internal friction angle will be different for formations with different integrities. According to the above research on wellbore stability of fractured carbonate formation, the internal friction angle and cohesion of the core obtained from a conventional triaxial confining pressure test are mainly used to calculate the collapse pressure of the whole formation, which makes the calculated results inaccurate.

Thus, the collapse of a borehole wall in a fractured carbonate formation in an oilfield block was studied. First, the mechanical properties of rock in this block were analyzed from the macroscopic and microscopic perspectives based on an analysis of mineral component content. Second, a relationship between the fractal characteristics of a carbonate fracture surface and the mechanical properties (the cohesion and internal friction angle) of rock was established based on the basis of fractal tectonic movement generates large-scale communication fractures in a later period, resulting in a high degree of rock fragmentation and a decrease in rock mechanical properties. According to the above research on wellbore stability of fractured carbonate formation, the internal friction angle and cohesion of the core obtained from a conventional triaxial confining pressure test are mainly used to calculate the collapse pressure of the whole formation, which makes the calculated results inaccurate.

As shown in Figure 2 a), the microfractures in downhole carbonate rocks are relatively well developed, forming a crisscross fracture network structure. Additionally, the violent tectonic movement generates large-scale communication fractures in a later period, resulting in a high degree of rock fragmentation and a decrease in rock mechanical properties. Figure 2b shows that honeycomb and petal-like montmorillonites can be seen in the mudstone filled between the fractures. When a drilling fluid enters the formation in a drilling environment, the gray-green mudstone will produce hydration expansion due to the presence of montmorillonite, resulting in an expansion pressure difference around the nonexpansive quartz, calcite, and other minerals, which will lead to the macroscopic collapse of a borehole wall and blockage. The results also indicate that the acoustic time difference and natural γ value are higher, and the mud content is higher in the areas with a higher expansion rate on a logging curve.

3. EXPERIMENTS

3.1. Experimental Methods. Triaxial mechanical experiments of a dry carbonate rock bedrock, a drilling-fluid-soaked carbonate rock bedrock, a dry carbonate rock sample with microcracks, and a drilling-fluid-soaked carbonate rock sample with microcracks were conducted to evaluate the mechanical properties of carbonate rocks under different conditions, and the confining pressures were 20 and 40 MPa, respectively. All the tests of the rock samples in these experiments mainly follow the national standard GB/T 50266-99 (engineering rock mass test method standard) and the ASTM test standard.
ASTM D2664-04 (triaxial tests), and the ISRM-recommended methods for rock mechanics tests (part 1) will be used as a reference. The triaxial rock mechanics test equipment is an RTR-1000 static (dynamic) triaxial rock mechanics servo-controlled test system manufactured by GCTS Company in the United States. The device consists of four parts: a high-temperature and high-pressure triaxial chamber, a confining pressure pressurization system, an axial pressurization system, and an automatic data acquisition and control system.

Various studies on fracture formation, classification, measurement, and control factors have been conducted using the traditional fracture research method and recognized the complexity of formation fractures. However, a numerical representation of a fracture plane formed by fractures is rarely studied through traditional methods. Fractal geometry and statistical analysis were used to numerically study the irregularity of rock fracture surfaces through a "self-similarity" law of irregular nature and 3D laser scanning technology. A relationship between the fractal characteristics of a rock fracture surface and rock mechanical properties was established. In the experiments, a 3D scanner (Figure 3) is used to scan the geometric characteristics of a rock fracture surface by a raster. This equipment is a method in which the radiation emitted by a grating is reflected on the surface of an object and received by a detector, thus accurately describing the shape of the object. There is a developed scanner of a Shining3D series.

According to different settings, the Eascan-D structured light scanning system has three different sizes of single scan area, which are 100 mm × 75 mm, 200 mm × 150 mm, and 400 mm × 300 mm. Scanning of larger objects can also be done by splicing. Each scan will produce 1.3 million point clouds, and the distance between the point clouds and the scanning accuracy will be different depending on the size of the scanning area and the distance between the scanning system and the scanned object. Cloud spacing represents the richness of fracture morphology data obtained by scanning, which ranges from 80 to 320 μm, and scanning accuracy represents the deviation between point cloud data and scanned object size, which ranges from 10 to 20 μm. The roughness and undulation of the rock end surface studied are about a few millimeters. Therefore, the Eascan-D structured light scanning system can obtain enough point cloud data to identify the undulation of the core surface and can meet the needs of spatial reconstruction. Its measurement system is mainly composed of three parts, namely: the central projector, the industrial CCD cameras on both sides, and the calibration boards of three sizes. The Eascan-D structured light scanning system adopts optical phase measurement profilometry, which measures the phase of the deformed fringe image projected on the object and obtains the three-dimensional topography of the object through the mapping relationship between phase and height. The Eascan-D structured light scanning system projects a set of structured scanning light and then analyzes the degree of deformation, which is essentially a process of modulation and demodulation in signal processing. The Eascan-D structured light scanning system uses industrial CCD camera to detect grating fringe distortion to measure the surface fluctuation of objects. The Eascan-D structured light scanning system uses two industrial CCD cameras mounted on either side of the projector to improve the field of view, measurement range, and efficiency of the system. At the same time, the fields of view of the two CCD cameras are complementary to each other, which greatly reduces the blind area of the scanning system, especially suitable for natural objects with irregular shapes such as rock cracks.

### 3.2. Experimental Results and Discussion

#### 3.2.1. Test Results of Mechanical Parameters of Rock Samples before and after Drilling-Fluid Soaking

The mechanical experimental results obtained from the triaxial mechanical tests are shown in Table 1.

As shown in Table 1, a dry bedrock has high mechanical strength; the compressive strength is mostly above 200 MPa, and the cohesion is up to 39.77 MPa. Drilling immersion has little influence on the mechanical properties of the bedrock rock, and its maximum compressive strength can reach 283.94 MPa. Fractures have obvious effects on the mechanical properties of the rock; the highest compressive strength of the rock samples with fractures is only 133.213 MPa, followed by fractures on the cohesion of the rock samples, which is less than 15 MPa. Unlike the dry fractured rock samples, drilling-fluid soaking has fewer effects on the mechanical properties of rock.

| core no. | sample description | diameter (mm) | length (mm) | confining pressure (MPa) | compressive strength (MPa) | elastic modulus (MPa) | Poisson ratio | cohesion (MPa) | internal friction angle (deg) |
|----------|-------------------|---------------|-------------|--------------------------|---------------------------|-----------------------|---------------|---------------|-------------------------------|
| 1        | dry without fracture | 25            | 50          | 20                       | 235.56                    | 25935.92              | 0.20          | 37.34         | 39.77                         |
| 2        | dry with fracture | 25            | 50          | 40                       | 318.78                    | 29383.93              | 0.17          | 14.74         | 29.01                         |
| 3        | dry with fracture | 25            | 50          | 20                       | 104.054                   | 12587.71              | 0.16          | 14.74         | 29.01                         |
| 4        | dry with fracture | 25            | 50          | 40                       | 133.213                   | 15669.79              | 0.15          | 32.21         | 33.38                         |
| 5        | soaked without crack | 25            | 50          | 20                       | 192.81                    | 23462.83              | 0.21          | 32.21         | 33.38                         |
| 6        | soaked with crack | 25            | 50          | 40                       | 283.94                    | 27896.01              | 0.19          | 12.20         | 25.34                         |
| 7        | soaked with crack | 25            | 50          | 20                       | 96.83                     | 9039.92               | 0.18          | 12.20         | 25.34                         |
| 8        | soaked with crack | 25            | 50          | 40                       | 118.00                    | 10425.11              | 0.17          | 12.20         | 25.34                         |

As shown in Table 1, a dry bedrock has high mechanical strength; the compressive strength is mostly above 200 MPa, and the cohesion is up to 39.77 MPa. Drilling immersion has little influence on the mechanical properties of the bedrock rock, and its maximum compressive strength can reach 283.94 MPa. Fractures have obvious effects on the mechanical properties of the rock; the highest compressive strength of the rock samples with fractures is only 133.213 MPa, followed by fractures on the cohesion of the rock samples, which is less than 15 MPa. Unlike the dry fractured rock samples, drilling-fluid soaking has fewer effects on the mechanical properties of rock.
the fractured rock samples. The maximum compressive strength of the fractured rock sample soaked by the drilling fluid is only 118.00 MPa, and its maximum cohesion is 12.2 MPa. The key factors affecting the compressive strength of the rock samples are different occurrences of fractures and the degree of fracture penetration. The photos of some of the rock samples before and after the experiments are shown in Figure 4.

3.2.2. Experimental Test Results of Fracture Surface Geometry in Carbonate Rock. A 3D scanning technology can be used to accurately locate the position of each point on a fracture surface in a rock in a spatial coordinate system. A 3D scanner scans a rock sample’s fracture plane with fracture development and a bedrock fracture plane destroyed by a triaxial mechanics experiment. Figure 5 shows the frequency histogram of a distribution of the roughness height of a fracture surface after fracture sample and bedrock failure. In this figure, max and min respectively represent the maximum and minimum values of the roughness height of the fracture surface, mean is the average value of the roughness height of the fracture surface, ΔX is the intergroup width of the distribution frequency statistics, and Std is the standard deviation of the fracture surface height.

Figure 4. Photos of rock samples before and after the triaxial mechanics experiments: (a) dry fractured carbonate rock samples; (b) dry fractured carbonate rock samples after the experiment; (c) drilling-fluid-soaked fractured carbonate rock samples; (d) drilling-fluid-soaked fractured carbonate rock samples after the experiment.

Figure 5. Frequency histograms of rough height distributions of a rock fracture surface: (a) fractured rock sample; (b) bedrock sample.

4. CALCULATIONS

4.1. Study on Fractal Characteristics of Rock Fracture Surface. 4.1.1. Calculations of Fractal Dimension of a Rock Sample. Due to the complexity of rock fracture surfaces, many scholars have numerically modeled the morphological characteristics of rock fracture surfaces and proposed combining a fractal dimension with the geometric parameters of rock fracture surfaces, obtaining the fractal dimension. However, when the fractal dimension is obtained using a classical Koch curve, the average height \( h \) and average base length \( l \) of the Koch curve generator are difficult to calculate, and it is difficult to describe the geometric characteristics of a rock fracture surface. Like many objects with fractal characteristics, the geometry of rock fracture surfaces also has fractal characteristics. Therefore, a fractal model for a rock fracture surface can be established by applying the relevant theories of fractal geometry and combining them with the results of the 3D scanning experiments. The fractal dimension of a rock surface formed after the failure of the bedrock rock sample is rougher than that of a fractured rock sample. Its spatial layering is also stronger, and there is a significant difference between them. The average height of fracture surfaces of fractured rock and bedrock samples shows that the morphological characteristics of the bedrock samples after failure are also complicated. The fracture plane in the microfracture-developed rock samples and that in the bedrock formed after the triaxial mechanical tests were scanned, and the results are shown in Table 2.
Table 2. 3D Scanning Fracture Plane Distribution of Fractured Rock Samples and Bedrock after Triaxial Mechanical Tests

| Core No. | Microfractured cores | Bedrock cores |
|----------|----------------------|---------------|
| 1        | ![Image](image1.png)  | ![Image](image2.png) |
| 2        | ![Image](image3.png)  | ![Image](image4.png) |
| 3        | ![Image](image5.png)  | ![Image](image6.png) |
| 4        | ![Image](image7.png)  | ![Image](image8.png) |
| 5        | ![Image](image9.png)  | ![Image](image10.png) |
| 6        | ![Image](image11.png) | ![Image](image12.png) |
| 7        | ![Image](image13.png) | ![Image](image14.png) |
| 8        | ![Image](image15.png) | ![Image](image16.png) |
| 9        | ![Image](image17.png) | ![Image](image18.png) |

The fractal characteristic model for a rock fracture surface was established on the basis of statistical theory and fractal
geometry. Variance is an important indicator of a dispersion degree of data volume in statistics; thus, a relationship between variance and a fractal dimension can be considered. Assume that \( z(x) \) is a univariate function of a rock fracture surface and \( h \) and \( N \) represent the distance (mm) between two adjacent points and the number of sampling points on the fracture surface of a swept surface, respectively; \( j \) is an iteration variable, and \( z(x_j) \) is the rough height at a point. According to geostatistics, the average variance increment method is used to define variance \( V(h) \) as follows:

\[
V(h) = \frac{1}{N - j} \sum_{i=1}^{N-j} [z(x_i + h) - z(x_i)]^2
\]

(1)

Based on the variable graph method in fractal geometry theory, the variance can be expressed in the following form:

\[
V(h) = Ah^{(2-D)}
\]

(2)

In the logarithmic coordinates of variance \( V(h) \) and \( h \), \( A \) is the intercept of the \( \log V(h) \) axis, \( 2(2 - D) \) is the slope of a fitted curve in the logarithmic coordinates of variance \( V(h) \) and the measured adjacent point \( h \), and \( D \) is a fractal dimension. After scanning a rock fracture surface, the data are processed by statistical methods, obtaining a relationship between different measurement scales \( H \) and variance \( V(h) \). Figure 6 shows the processing results of the scanned data of one rock sample.

A 3D scanned rock fracture surface was statistically analyzed, and the distance between two adjacent points was calculated according to the scanning results. Then, the variance of the rock fracture surface was calculated using eqs 1 and 2 through the height difference between adjacent points, and the fractal dimension of a rock sample fracture surface can be calculated by taking the logarithms of variance \( V(h) \) and the adjacent measuring point \( H \). Table 3 shows the scanning results of the fracture plane of the microfractured rock No. 1.

Table 3. Scanning Results of Fractured Rock Sample No. 1

| calculation time | distance between adjacent measuring points \( h \) (mm) | variance \( V(h) \) |
|------------------|-----------------------------------------------|-----------------|
| 1                | 0.2291                                        | 0.0229          |
| 2                | 0.4556                                        | 0.0048          |
| 3                | 0.6794                                        | 0.0742          |
| 4                | 0.9007                                        | 0.1019          |
| 5                | 1.1195                                        | 0.1309          |

Table 4. Calculation Results of Fractal Dimensions of Different Rock Samples

| core no. | fractal dimension of microfractured rock sample | fractal dimension of bedrock rock |
|----------|-----------------------------------------------|---------------------------------|
| 1        | 1.3433                                        | 1.4659                          |
| 2        | 1.4611                                        | 1.4780                          |
| 3        | 1.4738                                        | 1.4807                          |
| 4        | 1.4827                                        | 1.4850                          |
| 5        | 1.4844                                        | 1.4525                          |
| 6        | 1.5151                                        | 1.4970                          |
| 7        | 1.4820                                        | 1.4992                          |
| 8        | 1.4904                                        | 1.4997                          |
| 9        | 1.4909                                        | 1.5501                          |

4.1.2. Functional Relationship between Fractal Characteristics of a Fracture Surface and Rock Mechanics Properties in Carbonate Rocks. The shear strength of rock refers to the ability to resist shear failure when the rock is subjected to shear failure. When the stress exerted by an external environment reaches a shear force which the rock can bear, it means that the bearing capacity of the rock reaches a limit, and then the rock will be completely destroyed in an instant, thus forming a macroscopic rock fracture surface. The rock fracture surface will slip if the stress exerted continues to increase. It can be observed that the mechanical characteristics of rock have an essential causal relationship with the characteristics of a fracture surface formed after fracturing, and the geometric morphology of the fracture surface reflects the rock’s mechanical properties. The shear strength of a rock can be expressed by cohesion and an internal friction angle. The cohesion and internal friction angle of rock calculated by triaxial mechanical experiments fit the relationship with the rough height of a fractured surface of rock with microcracks and bedrock damage, as shown in Figures 7 and 8.

Figure 7 shows that a rock’s cohesion increases exponentially with an increase in the roughness height of a fracture surface. Compared with the fractured rock, the average roughness height of a fracture surface after bedrock failure is larger, and the cohesion values of rock mechanical parameters are also larger. As shown in Figure 8, the rock’s internal friction angle increases with an increase in the roughness height of a rock fracture surface. Compared with the fractured rock, the average value of the rough height of the fractured surface of bedrock has a larger range, and the internal friction angle is mainly concentrated between 30 and 54°.

Meanwhile, the relationship between the fractal dimension of a rock fracture surface and the cohesion and internal friction angle of carbonate rock was fitted, as shown in Figures 9 and 10.

Figures 9 and 10 show the relationships between the fractal dimension of a rock fracture plane and mechanical parameters of carbonate rock. Both have good fitting correlations, and the cohesion of rock with a fracture plane and bedrock increases.
exponentially with an increase in the fractal dimension of the rock fracture plane. However, the change rate and amplitude of a curve are different. Compared with the fractured rock, the change rate and amplitude of the curve are more evident with an increase in the fractal dimension of bedrock cohesion. The internal friction angle of fractured and bedrock rocks increases with an increase in the fractal dimension of a rock fracture surface, but the curve’s change rate and amplitude are different; the increased amplitude of bedrock rock is larger than that of fractured rock. Meanwhile, it is verified that the fracture surfaces of fractured and bedrock rocks become more complex after fracturing. It is also verified that a fracture plane formed by a triaxial test of bedrock rock is more complex than that of the microfractured rock samples.

Based on the data shown in Figure 9, the exponential fitting method was adopted to obtain the regression equation between the fractal dimension of a fracture surface after rock failure and the cohesion of rock mechanical parameters. The relationship between the fractal dimension of the fracture surfaces of microfractured and bedrock rocks is given by the following equations:

\[ y = A_0 + A_1 \times \exp(-t/\tau) + \tau \]

Where:
- \( y \) is the cohesion (in MPa)
- \( A_0 \) is a constant
- \( A_1 \) is a constant
- \( \tau \) is the fractal dimension
- \( \exp \) is the exponential function

The equations are:

**For microfractured cores:**
- \( y_0 = 5.81007 \pm 0.54326 \)
- \( A_1 = 5.18646 \pm 3.25081 \)
- \( t_1 = -0.03622 \pm 0.06250 \)
- \( R^2(\text{COD}) = 0.98169 \)

**For bedrock cores:**
- \( y_0 = 6.26657 \pm 2.05880 \)
- \( A_1 = 1.36028 \pm 3.17003 \)
- \( t_1 = -0.00734 \pm 0.00109 \)
- \( R^2(\text{COD}) = 0.99448 \)

**Figure 7.** Relationship between the average roughness height of a rock fracture surface and cohesion: (a) microfractured cores; (b) bedrock cores.

**Figure 8.** Relationship between average roughness height of a rock fracture surface and internal friction angle: (a) microfractured cores; (b) bedrock cores.

**Figure 9.** Relationship between fractal dimension of rock fracture plane and rock cohesion. (a) Microfractured cores. (b) Bedrock cores.
Figure 10. Relationship between fractal dimension of rock fracture plane and the internal friction angle in rock. (a) Microfractured cores. (b) Bedrock cores.

surface and cohesion of bedrock rock after failure is given as follows:

$$C = 6.2646 + 1.8055 \times 10^{-85} e^{(D/0.0075)}$$  \hspace{1cm} (3)$$

The relationship between the fractal dimension of a fracture surface and the cohesion of fractured rock is given as

$$C_w = 5.8187 + 5.1864 \times 10^{-17} e^{(D/0.0382)}$$  \hspace{1cm} (4)$$

where $C$ and $C_w$ are the cohesion of bedrock and fractured rock, respectively (in MPa) and $D$ is the fractal dimension (dimensionless).

Based on the data shown in Figure 10, the polynomial fitting method was adopted to obtain the regression equation between the fractal dimension of a fracture surface after rock failure and the internal friction angle of rock mechanical parameters. The relationship between the fracture surface and the internal friction angle of bedrock rock after failure is shown as follows:

$$\phi = -1950.0D^2 + 6158.4D - 4901.1$$  \hspace{1cm} (5)$$

The relationship between a fracture plane and an internal friction angle of fractured rock after failure is shown as

$$\phi_w = -0.23D^2 + 4.05D + 12.2$$  \hspace{1cm} (6)$$

where $\phi$ and $\phi_w$ are the internal friction angles of bedrock and fractured rock, respectively, (in deg).

According to the above statistical analysis, a close relationship between the fractal dimension of a fracture surface formed after rock failure and the rock mechanical parameters before rock failure can be observed. Therefore, the rock mechanical parameters before the failure of rock with fractures can be quantitatively calculated by measuring the fractal dimension of the fracture surface formed after the failure of rock with fractures. A drilling-fluid density was calculated in a drilling process using the Mohr–Coulomb failure criterion based on the fractal characteristics of the fracture surface. Therefore, the Mohr–Coulomb failure judgment criterion shows that the shear failure of rock is related to the magnitude of in situ stress and the rock’s mechanical strength. Meanwhile, the rock’s mechanical strength is related to the fractal characteristics of a fracture surface formed after rock failure. Therefore, the Mohr–Coulomb failure judgment criterion based on the fractal characteristics of the fracture surface can be considered. This is shown as

$$\tau = C(D) + \sigma \tan \phi(D)$$  \hspace{1cm} (8)$$

where $C(D)$ is a cohesion function between fracture planes and a fractal dimension, determined by eq 3 and $\phi(D)$ is a function of the internal friction angle between cracks on the fractal dimension, which is determined by eq 5.

When cracks develop in a local formation and the in situ stress is too high, the rock will slide along a weak plane and lose stability. For a fractured stratum, when the angle between a fracture surface and the maximum principal stress is within a certain range, the stratum failure follows the weak plane strength judgment criterion, which is shown as

$$\sigma_0 - \sigma_\alpha = \frac{2(C_w + \tan \phi_w(\sigma_\alpha - \sigma_p))}{(1 - \tan \phi_w \cot \zeta)\sin 2\zeta}$$  \hspace{1cm} (9)$$

where $\sigma_\alpha$ and $\sigma_\epsilon$ are the circumferential and radial stresses of a borehole wall, respectively (in MPa), $\alpha$ is an effective stress coefficient (dimensionless), $\sigma_p$ is the formation pore pressure (in MPa), $\zeta$ is the included angle between the normal direction of a fracture plane and the maximum principal stress (in deg), $C_w$ is the cohesion of the weak plane (in MPa), and $\phi_w$ is the internal friction angle of the weak plane (in deg).

It can be observed from the weak plane strength criterion that the rock’s sliding instability along a weak plane is mainly related to the stratum stress and the rock’s mechanical strength, whereas the rock’s mechanical strength is related to the fractal characteristics of a fracture plane formed after the rock’s failure. Therefore, the weak surface strength criterion can be established based on the fractal characteristics of
fracture surfaces. The strength criterion of a weak plane based on the fractal characteristics of a fracture plane is shown as

\[ \sigma_0 - \sigma_i = \frac{2[C_w(D) + \tan \varphi_w(D)(\sigma_i - \alpha \eta \sigma_p)]}{(1 - \tan \varphi_w(D) \cot \theta \sin 2\xi)} \]  

(10)

where \( \varphi_w(D) \) is a function of an internal friction angle between cracks on a fractal dimension, determined by eq 4 and \( C_w(D) \) is a cohesion function between the cracks on the fractal dimension, determined by eq 6.

A drilling fluid can easily migrate along a wellbore and formation. The migration of the drilling fluid significantly influences the pore pressure of a borehole wall, which also affects wellbore stability. When the surrounding rock of the borehole wall does not slip along a fracture surface, the equivalent density of the borehole wall collapse pressure is calculated as\(^{33,32}\)

\[ \rho_w = \left[ \eta \left( 3\sigma_H - \sigma_h - \left( \frac{1 - 2\mu}{1 - \mu} - \phi \right) \frac{\sigma_p(t)}{2} \right) \right. \\
+ \cot \left( 45^\circ - \frac{\varphi(D)}{2} \right) \phi \frac{\sigma_p(t)}{2} - 2C \cos \left( 45^\circ - \frac{\varphi(D)}{2} \right) \\
\left. \right] \left[ (1 - \alpha + \phi) \cos \frac{45^\circ - \varphi(D)}{2} \right] \\
- \mu \left( \frac{1 - 2\mu}{1 - \mu} - \phi - 1 - \alpha \right) \times \frac{\sigma_p(t)}{2} \right) \times \frac{100}{H} \]  

(11)

where \( \sigma_H \) is the maximum horizontal principal stress (in MPa), \( \sigma_h \) is the minimum horizontal principal stress (in MPa), \( \sigma_p(t) \) is the pore pressure at a borehole wall at time \( t \) (in MPa), \( \alpha \) is an effective stress coefficient (dimensionless), \( \mu \) is the Poisson ratio (dimensionless), \( \phi \) is the porosity of a formation (in %), \( C \) is the cohesion (in MPa), \( \varphi \) is an internal friction angle (in deg), and \( \eta \) is a correction coefficient (dimensionless).

When the rock of a borehole wall slides along a fracture surface, the formula for calculating the equivalent density of the borehole wall collapse pressure is given as\(^{33,34}\)

\[ \rho_w = \left[ \sigma_H + \sigma_h - 2(\sigma_H - \sigma_h) \cos 2\theta \right] \left[ 1 - \tan \varphi_w \cot \xi \right] \sin 2\xi - 2C_w + 2 \tan \varphi_w \alpha \frac{\sigma_p(t)}{2} \left( 1 - \tan \varphi_w \cot \xi \sin 2\xi \right) \times \frac{100}{H} \]  

(12)

where \( \theta \) is a well’s circumference angle (in deg), \( C_w \) is the cohesion of a weak plane (in MPa), \( \varphi_w \) is the friction angle of the weak plane (in deg), and \( \xi \) is the included angle between the maximum principal stress of the borehole wall and the normal direction of the fracture plane (in deg). The expression for \( \xi \) is\(^{35}\)

\[ \xi = \frac{\theta}{2} + \arcsin \left[ \frac{\sigma_H + \sigma_3 + 2C_w \cos \varphi_w \sin \varphi_w}{\sigma_1 - \sigma_3} \right] \]  

(13)

where \( \sigma_1 \) and \( \sigma_3 \) are the maximum and minimum principal stresses, respectively (in MPa). Among them, \( \xi \) determines whether rock failure occurs in the body or along a fracture plane, and the specific law is shown as follows: According to the Mohr–Coulomb strength failure criterion (formula 8) and the weak plane strength criterion (formula 10) and based on fractal characteristics of a fracture surface, when the borehole wall rock fails to slip along the fracture surface, the equivalent density calculation formula for the borehole wall collapse pressure can be expressed as:

\[ \rho_w = \left[ \sigma_H + \sigma_h - 2(\sigma_H - \sigma_h) \cos 2\theta \right] \left[ 1 - \tan \varphi_w \cot \xi \right] \sin 2\xi - 2C_w + 2 \tan \varphi_w \alpha \frac{\sigma_p(t)}{2} \left( 1 - \tan \varphi_w \cot \xi \sin 2\xi \right) \times \frac{100}{H} \]  

According to the Mohr–Coulomb strength failure criterion (eq 8) and the weak plane strength criterion (eq 10) and based on fractal characteristics of a fracture surface, when the borehole wall rock fails to slip along the fracture surface, the equivalent density calculation formula for the borehole wall collapse pressure can be expressed as follows:

\[ \rho_w = \left[ \eta \left( 3\sigma_H - \sigma_h - \left( \frac{1 - 2\mu}{1 - \mu} - \phi \right) \frac{\sigma_p(t)}{2} \right) \right. \\
+ \cot \left( 45^\circ - \frac{\varphi(D)}{2} \right) \phi \frac{\sigma_p(t)}{2} - C(D) \cos \left( 45^\circ - \frac{\varphi(D)}{2} \right) \\
\left. \right] \left[ (1 - \alpha + \phi) \right] \left[ (1 - \frac{1 - 2\mu}{1 - \mu} - \phi - 1 - \alpha) \right] \times \frac{100}{H} \]  

(15)

Similarly, based on the above criteria, when the rock of a borehole wall slides along a fracture surface, the equivalent density calculation formula for the borehole wall collapse pressure can be expressed as follows:

\[ \rho_w = \left[ \sigma_H + \sigma_h - 2(\sigma_H - \sigma_h) \cos 2\theta \right] \left[ 1 - \tan \varphi_w \cot \xi \right] \sin 2\xi - 2C_w + 2 \tan \varphi_w \alpha \frac{\sigma_p(t)}{2} \left( 1 - \tan \varphi_w \cot \xi \sin 2\xi \right) \times \frac{100}{H} \]  

\[ \left/ \right[ (1 - \frac{1 - 2\mu}{1 - \mu} - \phi - 1 - \alpha) \right] \times \frac{100}{H} \]  

(16)

### 4.2.2. Analysis of Wellbore Stability Based on Fractal Characteristics of a Rock Fracture Surface

Taking an oilfield well in the studied block as an example, for a fractured limestone formation with a 30° dip angle, a horizontal well is
drilled along different fracture tendencies (0°, 90°, 180°, and 270°) combined with changes of different azimuth angles and well inclination angles. The equivalent density calculation formula for the borehole wall collapse pressure based on the conventional strength criterion and the fractal characteristic strength criterion of a fracture surface is used to evaluate and analyze the borehole wall stability of the collapsed stratum at 3400 m. Together with the field drilling and logging data, the specific parameters of the well are shown in Table 5. The bedrock cohesion is calculated according to the function $C(D)$, the internal friction angle is calculated using the function $\phi(D)$, the cohesion of rock samples with fractures is calculated using the function $C_w(D)$, and the internal friction angle of the rock samples with fractures is calculated using $\phi_w(D)$. Among them, the fractal dimension of a bedrock fracture surface is 1.4280, the fractal dimension of a fractured rock surface is 1.4980, and the rock’s Poisson ratio is 0.21.

For the fractured limestone stratum with a dip angle of 30°, horizontal wells are drilled along the fracture tendencies, the equivalent density of the formation collapse pressure is calculated, and the wellbore stability is evaluated in combination with the changes in different fracture tendencies, azimuth angles, and the angle of inclination. The results are shown in Figure 11.

According to the comparison in Figure 11, for the fractured limestone stratum with a 30° inclination, horizontal wells are drilled along the fracture tendencies. Considering the seepage and pressure penetration between a wellbore and the stratum, different fracture tendencies and borehole trajectories have an obvious influence on the equivalent density of borehole wall collapse pressure. In the drilling process, the seepage migration of drilling fluid occurs between wellbore and formation under the complex multipotential energy field. The seepage migration of drilling fluid changes the pore pressure and effective stress field distribution around the wellbore and affects the wellbore stability of the formation. Different fracture tendencies, azimuth angles, and angle of inclination changes lead to different angles between the radial direction of each location around the well and the microfractures developed in the formation, resulting in changes in the seepage capacity of drilling fluid between the wellbore and the formation, changes in the effective stress field near the well wall, and changes in the equivalent density of the formation collapse pressure, which finally influence the wellbore stability of the formation. When drilling a horizontal well along a fracture dip, the formation collapse pressure equivalent density is highest in an inclination angle range of 55°–80°, generally higher than 1.55 g/cm³. The collapse pressure equivalent density is still higher than 1.5 g/cm³ in a range of 110° to the left and right of a fracture dip direction. The section with severe collapse extends to 90° of an inclination angle: that is, the section of a horizontal well. The equivalent density of the collapse pressure of the horizontal well decreases along the opposite direction of the fracture tendency: that is, the direction of fracture tendency +180°. When the fractures tend to be 90 and 270°, that is, along the minimum horizontal principal stress direction, the equivalent density of the borehole wall collapse pressure is 1.58–1.59 g/cm³. The fractures tend to be 0 and
180°; along the maximum horizontal principal stress direction, the equivalent density of borehole wall collapse pressure is 1.62−1.63 g/cm³.

According to the comparative analysis shown in Figure 12, when a horizontal well is drilled along a fracture dip in limestone strata with a 30° dip angle, considering the existence of seepage and pressure penetration between a wellbore and a stratum, different fracture dips and well trajectories have a significant impact on the equivalent density of borehole collapse pressure. The equivalent density of borehole wall collapse pressure is 1.59−1.61 g/cm³ when the fractures tend to be 90 and 270°; that is, the minimum horizontal principal stress direction. The fractures tend to be 0 and 180°; along the maximum horizontal principal stress direction, the equivalent density of the borehole wall collapse pressure is 1.63−1.65 g/cm³, and the equivalent density of the formation collapse pressure reaches the maximum, 1.65 g/cm³. Considering the effect of seepage and pressure penetration between a wellbore and the formation, the equivalent density of the borehole collapse pressure calculated based on the fractal model will increase by 0.1−0.2 g/cm³. Combined with the functional relationship between rock mechanical parameters and fractal dimension, a wellbore stability analysis model based on fractal geometry is established. This model can more accurately characterize the mechanical parameters of the rock with relatively developed microcracks, especially the values of cohesion and internal friction angle, so as to more accurately evaluate the wellbore stability.

Based on the wellbore stability results evaluated using two different calculation models, it can be observed that the equivalent collapse pressure density calculated using the wellbore stability model based on the fracture surface fractal model is higher on considering the seepage migration and pressure penetration effect between a wellbore and a stratum. The conventional wellbore stability model calculations show that the equivalent density of the wellbore collapse pressure is 1.61−1.63 g/cm³. The borehole stability model based on the fractal characteristics of a rock fracture surface shows that the equivalent density of the borehole collapse pressure is 1.64−1.65 g/cm³. According to the field drilling data, a borehole wall still collapses when the drilling fluid is raised to 1.61−1.63 g/cm³. Therefore, the equivalent density of the borehole collapse pressure calculated using the borehole stability model based on the fractal characteristics of a rock fracture surface can be considered as the field’s drilling fluid density. Meanwhile, the effective plugging ability of the drilling fluid can be improved to reduce or avoid the seepage between the wellbore and the formation, and the effective support effect of the drilling fluid on a wellbore wall can be enhanced to effectively improve the wellbore stability of a horizontal well in collapsed strata.

5. CONCLUSIONS

According to the rock mechanical properties of the carbonate rocks in the collapsed section, a functional relationship between the fractal dimension of a rock fracture surface and the rock’s mechanical properties was established. The wellbore stability model based on the fractal model of a carbonate rock can more accurately evaluate the mechanical parameters of the rock with relatively developed microcracks, especially the values of cohesion and internal friction angle, so as to more accurately evaluate the wellbore stability.
The main conclusions are summarized as follows.

(1) Through studying the structural characteristics and mechanical properties of the rock in the collapsed stratum, it can be concluded that the lithology of the collapsed stratum is mainly limestone, and the rock microcracks are relatively developed. Some rock samples contain mudstone intercalation, among which the gray-green mudstone has strong hydration and expansion performance. The mechanical strength of a fractured rock sample is low, and the rock has low compressive strength. The bedrock rock has good mechanical properties, and the stability of a borehole wall is good.

(2) Based on statistical analysis and fractal geometry, a fractal model was established for the geometric features of rock fracture surfaces, obtaining the fractal dimension of the fracture surfaces formed by the triaxial mechanical tests of fractured rock and bedrock samples. Bedrock’s average fractal dimension is larger than that of rock samples with fractures, reflecting that the geometric spatial features of rocks formed after bedrock failure were complicated. Meanwhile, a relationship between a rock fracture plane and rock’s mechanical properties was established, yielding the functional relationship among rock cohesion, an internal friction angle, and the fractal dimension.

(3) Combining the functional relationship between rock mechanics parameters and the fractal dimension, a borehole stability model based on the carbonate fracture surface fractal model was established. This model can accurately characterize the mechanical parameters of rock, thus more accurately evaluating the stability of a borehole wall. Compared with the conventional wellbore stability analysis, the equivalent density of the collapse pressure calculated using the wellbore stability model based on the fractal model will increase by 0.1–0.2 g/cm³.

Notes
The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS
This research work was supported by the National Science Foundation of China (NSFC, No. 52174008).

■ REFERENCES
(1) Li, Y.; Kang, Z.; Xue, Z.; Zheng, S. Theories and practices of carbonate reservoirs development in China. Petroleum Exploration and Development 2018, 45 (4), 712–722.
(2) Chen, S.; Abousleiman, Y. N. Stress analysis of borehole subjected to fluid injection in transversely isotropic poroelastic medium. Mechanics Research Communications 2016, 73, 63–75.
(3) Wang, Y.; Zhuang, Z.; Liu, Z.; Yang, H.; Li, C. Finite element analysis for inclined wellbore stability of transversely iso-tropic rock with HMCID coupling based on weak plane strength criterion. Science China(Scientifical Technological Sciences) 2017, 60, 624–637.
(4) Wang, L.; Liu, Z.; Yang, H.; Zhuang, Z. Finite element analysis for wellbore stability of transversely isotropic rock with hydraulic-mechanical-damage coupling. Science China(Scientifical Technological Sciences) 2017, 60, 133–145.
(5) Wang, Y.; Liu, Z.; Yang, H.; Shao, Z.; Zhuang, Z. FE Analysis of Rock with Hydraulic-Mechanical Coupling Based on Continuum Damage Evolution. Mathematical Problems in Engineering 2016, 2016, 1–9.
(6) Zhang, Y.; Han, Z.; Kong, L.; Chen, Q.; Liu, H. Study on the Wellbore Stability in Fractured Carbonate Formations in North Truva Area. Special Oil & Gas Reservoirs 2021, 28 (01), 161–169.
(7) Guo, Y.; Hou, L.; Yao, Y.; Zuo, L.; Wu, Z.; Wang, L. Experimental study on influencing factors of fracture propagation in fractured carbonate rocks. Journal of Structural Geology 2020, 131, 103955.
(8) Sun, Y.; Cheng, Y.; Hao, Y.; Meng, M.; Dai, X.; Wang, Y.; Dong, S.; Peng, G. Analysis of borehole stability for inclined wells in fractured carbonate formation. Fresenius Environ. Bull. 2019, 28 (5), 3893–3899.
(9) Tan, M.; Su, M.; Liu, W.; Song, X.; Wang, S. Digital core construction of fractured carbonate rocks and pore-scale analysis of acoustic properties. J. Pet. Sci. Eng. 2021, 196, 107771.
(10) He, S.; Zhou, J.; Deng, X.; Luo, F. Countermeasures for Wellbore Stability in Drilling Procedures of Inner Buried-hill Reservoir in Jizhong Depression. Science Technology and Engineering 2016, 16 (19), 185–191.
(11) Jin, J.; Ou, B.; Zhang, D.; Wang, X.; Li, D.; Wang, Y. Research status and prospect of borehole stability technology in deep fractured carbonate reservoirs. Journal of Yangtze University (Natural Science Edition) 2021, 18 (06), 47–54.
(12) Liu, H. B.; Liu, T.; Meng, Y. F.; Han, X.; Cui, S.; Yu, A. Experimental study and evaluation for borehole stability of fractured limestone formation. J. Pet. Sci. Eng. 2019, 180, 130–137.
(13) Kidambi, T.; Kumar, G. S. Mechanical earth Modeling for a vertical well drilled in a naturally fractured tight carbonate gas reservoir in the persian gulf. J. Pet. Sci. Eng. 2016, 141, 38–51.
(14) Liu, H. B.; Cui, S.; Meng, Y.; Han, X.; Liu, T.; Fan, Y.; Tao, Y.; Yu, A. A new method for wellbore stability evaluation based on fractured carbonate reservoir rock breaking degree. Arabian Journal of Geosciences 2021, 14 (7), 647–664.
(15) Wang, Y.; Hou, B.; Wang, D.; Jia, Z. Features of fracture height propagation in cross-layer fracturing of shale oil reservoirs. Petroleum Exploration and Development 2021, 48 (2), 469–479.
(16) Yu, S.; Li, L.; Shi, G.; Cao, Z.; He, X. Fracture development and evolution characteristics of low permeability sandstone reservoirs. Chinese Journal of Geology (Scientia Geologica Sinica) 2021, 56 (01), 109–120.
(17) Liu, H.; Zhang, F.; Meng, Y.; Li, G.; Zhang, G. Influence of hydraulic flow and clay hydration on pore pressure and collapse pressure of swelling shale. J. Pet. Sci. Eng. 2017, 49, 38–43.

AUTHOR INFORMATION

Corresponding Authors
Shuai Cui – State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu 610500, People’s Republic of China; orcid.org/0000-0003-0788-119X; Email: cuishu8@sina.com

Yingfeng Meng – State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu 610500, People’s Republic of China; orcid.org/0000-0002-1153-9664; Email: mengyf523@sina.com

Authors
Houbin Liu – State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu 610500, People’s Republic of China
Zhengbo Han – Petroleum Engineering Technology Research Institute, Northwest Oilfield Company, SINOPEC, Urumqi 830000, People’s Republic of China
Mou Yang – State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu 610500, People’s Republic of China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.2c05270
(18) Liu, J.; Yang, Z.; Sun, J.; Dai, Z.; Lv, K.; You, Q. Experimental investigation on hydration mechanism of Sichuan shale (China). *Journal of Petroleum Science & Engineering* 2021, 201, 108421.

(19) Liu, Y.; Lu, C.; Zhao, T. Research on shear-slip characteristics with different-size rectangular zigzag gouge by double-direct tests. *International Journal of Distributed Sensor Networks* 2017, 13 (4), 1–12.

(20) Cao, C.; Pu, X.; Wang, G.; Huang, T. Comparison of Shale Inhibitors for Hydration, Dispersion, and Swelling Suppression. *Chemistry and Technology of Fuels and Oils* 2018, 53 (6), 966–975.

(21) Guo, T.; Zhang, S.; Ge, H.; Wang, X.; Lei, X.; Xiao, B. A new method for evaluation of fracture network formation capacity of rock. *Fuel* 2015, 140, 778–787.

(22) Zhang, C.; Zhu, D.; Luo, Q.; Liu, L.; Liu, D.; Yan, L.; Zhang, Y. Major factors controlling fracture development in the Middle Permian Lucaogou Formation tight oil reservoir, Junggar Basin, NW China. *Journal of Geology and Geophysics* 2017, 46, 279–295.

(23) Li, C.; Zhao, L.; Liu, B.; Chen, Q.; Lu, C.; Kong, Y. Research status, significance and development trend of microfractures. *Natural Gas Geoscience* 2020, 31 (3), 402–416.

(24) Li, C.; Zhao, L.; Liu, B.; Li, J.; Chen, Y.; Zhang, Y. Research status and development trend of fractures in carbonate reservoir. *Bulletin of Geological Science and Technology* 2021, 40 (4), 31–48.

(25) Feng, W.; Yang, C.; Tao, S.; Wang, C.; Lu, Y.; Zhang, L.; Zhou, F. Experimental study on the surface feature of acid-etched fractures in carbonate rocks. *Lithologic Reservoirs* 2012, No. 4, 6–10.

(26) Gong, L.; Zeng, L.; Miao, F.; Wang, Z.; Wei, Y.; Li, J.; Zu, K. Application of fractal geometry on the description of complex fracture systems. *Journal of Human University of Science & Technology (Natural Science Edition)* 2012, No. 4, 6–10.

(27) Li, Y. *Meso-Mechanical Testing Study on Characteristics and Mechanism of Water Damage of Gypsum Breccia*; Shanghai Jiao Tong University: 2012; pp 6–10.

(28) Li, B.; Tan, X.; Wang, F.; Lian, P.; Gao, W.; Li, Y. Fracture and vug characterization and carbonate rock type automatic classification using X-ray CT images. *Bulgarian Chemical Communications* 2017, 153, 88–96.

(29) Jin, Y.; Chen, M. *Wellbore Stability Mechanics*; Science Press: 2012.

(30) Chen, M. *Petroleum Engineering Rock Mechanics*. Science Press: 2008.

(31) Chen, P.; Ma, T. S.; Fan, X. Y. Well path optimization based on wellbore stability analysis. *Natural Gas Industry* 2015, 35 (10), 84–92.

(32) Wang, Y.; Zhuang, Z.; Liu, Z.; Yang, H.; Li, C. Finite element analysis for inclined wellbore stability of transversely iso-tropic rock with HMC coupling based on weak plane strength criterion. *Science China (Technological Sciences)* 2017, 60 (4), 624–637.

(33) Chen, P.; Ma, T. S.; Xia, H. A collapse pressure prediction model of horizontal shale gas wells with multiple weak planes. *Natural Gas Industry* 2015, 2 (1), 101–107.

(34) Deng, J. *Mechanical Mechanism of borehole wall instability in drilling engineering*; Petroleum Industry Press: 1998.

(35) Ma, T.; Chen, P. Analysis of wellbore stability for horizontal wells in stratification shale. *Journal of Central South University (Science and Technology)* 2015, 46 (4), 1373–1383.

(36) Ma, D.; Duan, H.; Zhang, J.; Liu, X.; Li, Z. Numerical Simulation of Water–Silt Inrush Hazard of Fault Rock: A Three-Phase Flow Model. *Rock Mech Rock Eng.* 2022, 55, 5163–5182.

(37) Ma, D.; Duan, H.; Zhang, J. Solid grain migration on hydraulic properties of fault rocks in underground mining tunnel: Radial seepage experiments and verification of permeability prediction. *Tunnelling and Underground Space Technology* 2022, 126, 104525.