The mechanism and countermeasures of inclined wellbore instability in Dibei deep coal seam

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Abstract

The wellbore instability of the deep coal seam has always been a difficult problem limiting drilling engineering in Dibei area of Tarim basin, China. Therefore, the mechanisms of wellbore instability and anticollapse countermeasures in the Dibei deep coal seam are investigated in this study. Firstly, the microstructure and physical and chemical properties of coal and rock are studied to analyze instability mechanism. In addition, orthogonal cleat model and 3 Dimension Distinct Element Code (3DEC) model were proposed to calculate the collapse pressure of the coal seam. And we propose a method for optimizing well trajectory based on wellbore stability. Finally, by optimizing plugging material, an anti-collapse drilling fluid for coal seams is designed and applied in the field. The results indicate that there are many cleats and no montmorillonites in the clay minerals present in coal rocks, indicating that the deep coal seam in Dibei is mainly mechanically unstable. 3DEC model is more accurate, and the orthogonal cleat model can reflect the collapse pressure distribution more intuitively. The reliability of these two models is demonstrated by the actual drilling fluid density of the DB-X01. Furthermore, this study confirms that the blocking-material system of the wellbore stabilization strategy in a coal seam is 3% sulfonated asphalt, 3% emulsified asphalt, and 3% calcium carbonate based on microstructure characteristics. The results of rolling recovery rate and rheology experiments show that the new anti-collapse drilling fluid has better sealing and inhibiting properties on coal seams. Field testing in DT2 well demonstrated the reliability of the collapse pressure prediction model and anticollapse countermeasures proposed in this study. The findings of this study can help for better understanding of wellbore instability mechanism and countermeasures in coal seam. The study is useful for the safe and efficient development of the coal seams in the Dibei area.

Keywords Deep coal seam · Wellbore stability · Orthogonal cleat model · 3DEC model · Anticollapse drilling fluid

List of symbols

\( P_i \) Drilling fluid pressure in wellbore (MPa)
\( P_p \) Pore pressure (MPa)
\( \alpha \) Effective stress factor (dimensionless)
\( \nu \) Poisson’s ratio (dimensionless)
\( \theta \) Circumferential angle (°)
\( \sigma_{xx}^e, \sigma_{yy}^e, \sigma_{zz}^e, \tau_{xy}^e, \tau_{xz}^e, \tau_{yz}^e \) Normal and shear stresses in geodetic coordinate system (MPa)
\( \sigma_{xx}^b, \sigma_{yy}^b, \sigma_{zz}^b, \tau_{xy}^b, \tau_{xz}^b, \tau_{yz}^b \) Normal and shear stresses in borehole cartesian coordinate system (MPa)
\( \sigma_1^e, \sigma_2^e, \sigma_3^e, \tau_{\theta \phi}, \tau_{rz}, \tau_{\theta z} \) Normal and shear stresses in borehole cylindrical coordinate system (MPa)
\( \sigma_1, \sigma_2, \sigma_3, \tau_w, \tau_{w}, S_w \) Normal and shear stresses in cleated weak surface coordinate system (MPa)
\( \sigma_w^e, \sigma_w^b, \sigma_w^c, \phi_w \) Normal and shear stresses in cleated weak surface coordinate system (MPa)
\( \phi_w \) Internal friction angle of weak surface (°)
\( S_i \) Cohesion of rock (MPa)

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The internal friction coefficient of the rock body (dimensionless)

Internal friction angle of rock body (°)

Maximum horizontal in-situ stress (MPa)

Minimum horizontal in-situ stress (MPa)

Vertical in-situ stress (MPa)

Introduction

Coal seams are abundant in China’s Tarim Basin, Sichuan Basin, and Ordos Basin (Carpenter 2018; Cui et al. 2013; Chang et al. 2018). The Dibei area is located in the Northern Kuqa structural belt of the Tarim Basin, China, and there are multiple coal seams in the Jurassic. The coal has a high degree of discontinuity owing to the typical development of end cleats and faces cleats (Hongtao et al. 2021; Li et al. 2015; Ai et al. 2017; Zhigang et al. 2000; Ping and Ping 2004). Researchers, such as Liu et al. (2002) and Jin and Chen (1999a; b), have shown that cracks and cleats can considerably reduce the stability of a coal well. Based on this feature, many scholars have used various methods to study wellbore stability in coal seams. Deisman et al. (2010) proposed two methods to characterize the geomechanical properties of coal seams: geological strength index and synthetic rock mass. In addition, Jin and Chen (1999a; b) deduced the mathematical equation of collapse pressure containing weak surface parameters based on discontinuous medium mechanics. Kai et al. (2013) and Ai et al. (2014) established the cleat characteristic wellbore stability model using fracture mechanics and weak surface theories. Masoudian et al. (2014) proved that both the compressive strength and Young’s modulus of coal increased with the increase of confining pressure through experiments. However, Perera et al. (2013) and Ranathunga et al. (2016a; b) studies show that the change in coal rock stiffness is relatively smaller. Some scholars (Liu and Harpalani 2014, 2013; Fan and Liu 2018, 2019) proposed that the coal does not follow the traditional poroelasticity constitutive relationship.

Numerous studies have shown that the wellbore stability of coal seams is also affected by many other factors. Hawkes (2007) analyzed in detail the effects of rock strength and burial depth based on elasticity theory. Thomas et al. (2009) tested the effect of different drilling fluids on the stability of coal seam wellbore through experiments. Other scholars have obtained the similar result through simulation: Fluid invasion has an important influence on the wellbore stability of coal rock (Perera et al. 2011; Ranathunga et al. 2016a; Wang et al. 2012). Zhao et al. (2012) analyzed borehole size and cleat intervals effect on wellbore stability. Shi et al. (2019) adopted mixed metal hydroxide (MMH) to inhibit hydration to improve coal seam wellbore stability. Reisabadi et al. (2020) discussed effect of coal matrix shrinkage on wellbore stresses.

However, the current discontinuous medium theory, single-weak surface theory, and fracture mechanics theory have considerable limitations: they cannot comprehensively evaluate the wellbore stability of a coal seam under the dual effects of cleats and bedding. The discrete element method has been widely used in geotechnical engineering to simulate the excavation and support of jointed rock tunnels (Huanchun et al. 2004; Yongtao et al. 2015). Therefore, many scholars have gradually applied the discrete element method to the petroleum industry to study coal seam wellbore stability: Li et al. (2002) and Yin et al. (2012) used UDEC software to evaluate coal seam wellbore stability. Qu et al. (2011) firstly used the 3DEC to investigate the stability of a coal seam. Compared to UDEC, 3DEC more intuitively reflects the block displacement and collapse process under the three-dimensional model.

Thus far, the cleat model adopted by local and global scholars does not fully represent real scenarios. Previous research only considered a single-weak surface and failed to comprehensively evaluate the law of collapse and failure of coal and rock under orthogonal cleats. Furthermore, the difference between the 3DEC method and the elasticity continuous medium is not quantified. In addition, the depth of the coal seam in Dibei is over 3500 m, which is much deeper than in other areas. Deviation points are designed in the coal seam to efficiently utilize horizontal wells to develop the oil and gas in Dibei. Because these phenomena differ considerably from previous studies, it is critical to research deep coal seam instability mechanisms and countermeasures for wellbore stability.

This paper is organized as follows: Sect. 2 analyzes the chemical properties and microstructure of coal rock through optical microscopy and X-ray diffraction experiments. In Sect. 3, orthogonal cleat model and 3DEC model are established to predict the collapse pressure of a deep coal seam in the Dibei area based on combining rock mechanics and elastic mechanics theory. The borehole trajectory is optimized on this basis. The coal seam section’s drilling fluid plugging material is selected through particle size analysis based on the microstructure of coal and rock, and the stability countermeasures for the coal seam horizontal well are formed. In Sect. 4, countermeasures are applied in the DT2 well. In a nutshell, this research novelty conducted a systematic study on deep coal seam wellbore stability from three perspectives: drilling fluid density, well trajectory, and drilling fluid system, which can serve as a framework for deep coal seam drilling and coalbed methane development in other areas.
Wellbore instability mechanism

The microstructure and chemical properties of coal rock in the Dibei area are studied using a microscope and an X-ray diffraction instrument (35 samples in total). Based on this, the mechanism of coal rock instability can be discovered.

Coal rock microstructure

Optical microscope

Mesh cleats, microfracture, face cleats, end cleats, and broken zones in the coal can be clearly seen under an optical microscope, as shown in Fig. 1. Coal rock has different properties than other rocks due to the presence of these cleats (such as carbonate, shale, etc.).

The optical microscope reveals that the rock sample has orthogonally end cleats and face cleats, as well as visible wide fractures and broken zones.

Environmental scanning electron microscope

The environmental scanning electron microscope was used to scan coal rock cuttings and core samples to obtain cleat sizes, which can visually observe the surface mineral adhesion and fracture size of the sample. Figure 2 depicts an environmental scanning electron microscope examination of a rock sample from the J1y layer outcrop.

Environmental scanning electron microscope images of rock samples in J1y reveal the presence of cleats and pores with no fillers. The geometric parameters and distribution of microfractures are calculated statistically. A total of 52 fractures were observed, and crack width and length distribution rules were drawn, as shown in Figs. 3 and 4, respectively.

Figures 3 and 4 depict the distribution of the width and length of microscopic fractures in coal, respectively. The width of the microscopic fractures can be intuitively: there are 43 groups of rock samples in the range of 0.52–3.32 μm, and three groups are in the range of 0.52–3.32 μm. There are two groups in the 3.32–6.12,
Fig. 2 The development of fractures in the J₁ layer
6.12–8.92, and 8.92–11.72-μm ranges, and one group in the 11.72–14.52 and 14.52–17.32-μm ranges. There are 41 groups with microfracture lengths ranging from 20 to 150 μm, five groups with microfracture lengths ranging from 150 to 280 μm, one group with microfracture lengths ranging from 280 to 410 μm, three groups with microfracture lengths ranging from 410 to 540 μm, and two groups with microfracture lengths ranging from 540 to 670 μm.

As a result, it is possible to conclude that the fracture width of coal rock samples is primarily in the range of 0.52–3.32 μm, and the length is primarily within 280 μm. There are very few microfractures that are longer than 500 μm and can form during the geological structure or sampling process. During the drilling process, the large fracture provides a good seepage channel for the drilling fluid to invade the formation, resulting in a decrease in the mechanical properties of the coal rock and wellbore instability.

**Chemical properties**

The clay minerals in the samples were extracted using the clay settlement extraction method, and the main types and contents of the clay minerals were examined using an X-ray diffraction instrument (as shown in Table 1). Numbers 1–5 are cutting test results, while numbers 6–9 are outcrop test results.

According to Table 1, the content of clay minerals accounts for 30.32% of the total content in the cuttings test results. Based on this, it is hypothesized that chemical stability factors may exist in coal rock instability. However,
outcrop test results show that the clay mineral content accounts for only 12.8% of the total contents, which is considerably lower than that of cuttings. There are two possible explanations. One is that drilling fluid additives such as asphalt or polymers that mix with coal cuttings cannot be removed. Another factor is that the coal seam section is mixed with mudstone and sandstone, increasing the clay mineral content. Because the outcrop coal of the J1y stratum is uncontaminated and has a relatively pure texture, the outcrop content test result is low.

XRD tests are conducted to detect the clay mineral composition of coal rock to further analyze whether there exists a relationship between the wellbore instability of the coal seam section and the clay minerals. Table 2 shows the types and relative contents of clay minerals in the J1kz and J1y intervals.

As shown in Table 2, clay minerals in these strata are mostly illite and kaolinite, with a trace of chlorite but no montmorillonite. Because illite and kaolinite are clay minerals with low hydration ability, the coal in this section has a low hydration ability.

As a result, the influence of hydration stress can be ignored when analyzing the mechanism of wellbore instability. Therefore, it is possible to conclude that the shaft wall instability mechanism is primarily mechanical.

**Countermeasures**

Wellbore stability countermeasures primarily include developing a collapse pressure prediction model to obtain a suitable drilling fluid density, optimizing the well trajectory, and optimizing the drilling fluid ideal for coal seams.

| Number | Well | Stratum | Depth (m) | Illite (I) | Illite/montmorillonite (I/S) | Montmorillonite (S) | Kaolinite (K) | Chlorite (C) | Interlayer ratio %S |
|--------|------|---------|-----------|------------|-------------------------------|--------------------|---------------|--------------|---------------------|
| 1      | DBX01| J1kz    | 4216      | 42.7       | 5.0                           | 0.0                | 44.8          | 7.5          | 15.0                |
| 2      | DBX01| J1y     | 4696      | 54.4       | 3.5                           | 0.0                | 36.0          | 6.0          | 15.0                |
| 3      | DBX04| J1y     | 4614      | 53.0       | 9.2                           | 0.0                | 32.3          | 5.4          | 15.0                |
| 4      | DBX04| J1y     | 4629      | 47.3       | 3.7                           | 0.0                | 42.0          | 7.0          | 15.0                |
| 5      | DBX04| J1y     | 4630      | 34.1       | 16.4                          | 0.0                | 42.4          | 7.1          | 15.0                |
| 6      | DBX  | J1y     | 4709      | 15.2       | 10.9                          | 0.0                | 73.9          | 9.8          | 20.0                |
| Average|      |         |           | 41.8       | 10.3                          | 0.0                | 42.65         | 6.7          | 15.8                |
Collapse pressure prediction model

Orthogonal cleat model

According to the Fairhurst equation, the stress equation around the well can be expressed by Eq. (1):

\[
\begin{align*}
\sigma_r &= \frac{p_i}{r} + \frac{\sigma^w_{xx} + \sigma^w_{yy}}{2} \left( 1 - \frac{p_i}{r} \right) + \frac{\sigma^w_{xy}}{2} \left( 1 + \frac{3p_i}{r} - \frac{4p_i^2}{r^2} \right) \cos 2\theta + \frac{\sigma^w_{xz}}{2} \left( 1 + \frac{3p_i}{r} - \frac{4p_i^2}{r^2} \right) \sin 2\theta \\
\sigma_\theta &= -\frac{p_i}{r} + \frac{\sigma^w_{xx} + \sigma^w_{yy}}{2} \left( 1 + \frac{p_i}{r} \right) - \frac{\sigma^w_{xy}}{2} \left( 1 + \frac{3p_i}{r} - \frac{4p_i^2}{r^2} \right) \cos 2\theta - \frac{\sigma^w_{xz}}{2} \left( 1 + \frac{3p_i}{r} - \frac{4p_i^2}{r^2} \right) \sin 2\theta \\
\sigma_z &= \frac{1}{2} (\sigma^w_{xx} - \sigma^w_{yy}) + \frac{\sigma^w_{xy}}{2} \left( 1 - \frac{3p_i}{r} + \frac{2p_i^2}{r^2} \right) \cos 2\theta + \frac{\sigma^w_{xz}}{2} \left( 1 - \frac{3p_i}{r} + \frac{2p_i^2}{r^2} \right) \sin 2\theta \\
\tau_\theta &= \frac{1}{2} \left( \sigma^w_{xy} \sin 2\theta + \sigma^w_{xz} \sin 2\theta \right) \\
\tau_\phi &= 2 \sigma^w_{xz} \cos \theta - 2 \sigma^w_{xy} \sin \theta \\
\tau_\phi &= 0
\end{align*}
\]

(1)

Equation (1) transforms the stress component of the cylindrical coordinate system into the cleat weak-plane coordinate system. The normal and maximum shear stresses on the weak surface are then as follows:

\[
\begin{align*}
\sigma_w &= \sigma^w_{xx} \\
|\tau| &= \sqrt{(\tau_\theta \cos 2\theta)^2 + (\tau_\phi \sin 2\theta)^2}. \\
\end{align*}
\]

(2)

When \( r = R \) (wellbore radius), the effective stresses around the well are:

\[
\begin{align*}
\sigma_r &= p_i - \sigma_p \\
\sigma_\theta &= -\sigma_p + \sigma^w_{xx} (1 - 2 \cos \theta) + \sigma^w_{yy} (1 + 2 \cos 2\theta) - 4 \sigma^w_{xy} \sin 2\theta - \sigma_p \\
\sigma_z &= \sigma^w_{zz} - \frac{1}{2} (\sigma^w_{xx} - \sigma^w_{yy}) \sin 2\theta + 4 \sigma^w_{xy} \cos 2\theta - \sigma_p \\
\tau_\theta &= 0 \\
\tau_\phi &= 2 \sigma^w_{xz} \cos \theta - 2 \sigma^w_{xy} \sin \theta \\
\tau_\phi &= 0
\end{align*}
\]

(3)

\( \sigma_p \) is one of the principal stresses, and the other two principal stresses \( \sigma_1 \) and \( \sigma_3 \) are:

\[
\begin{align*}
\sigma_1 &= \frac{\sigma_a + \sigma_\theta}{2} + \sqrt{\left( \frac{\sigma_a - \sigma_\theta}{2} \right)^2 + \tau_\phi^2} \\
\sigma_3 &= \frac{\sigma_a + \sigma_\theta}{2} - \sqrt{\left( \frac{\sigma_a - \sigma_\theta}{2} \right)^2 + \tau_\phi^2}
\end{align*}
\]

(4)

The maximum and minimum principal stresses of the coal rock formation can be calculated using the above model, and the collapse pressure can be obtained by combining the coal rock failure criterion.

According to Jaeger’s single-weak surface strength theory and coal rock microstructure analysis results, coal rock failure can be classified into two types: the bedding strength determines the strength of the coal rock mass when it is broken along the bedding plane. However, unlike conventional bedding rational rocks, coal has both weak bedding planes and cleats. As a result, the failure judgment of bedding and cleats should be made concurrently \((i = 1, 2, 3)\).

\[
\tau^{(i)}_w = \sigma^{(i)}_w + \sigma_p \tan \phi^{(i)}_w.
\]

(6)

When the rock is not broken along the bedding plane, the strength of the coal rock equals the strength of the coal rock matrix, and coal rock failure can be expressed as Eq. (7):

\[
\begin{align*}
\sigma_1 &= \sigma_3 + 2(S_i + u_i\sigma_3)(\sqrt{1 + u_i^2} + u_i) \\
u_i &= \tan \phi_i
\end{align*}
\]

(7)

When the cleats and rock matrix strengths are compared, the lowest value is considered as the ultimate shear strength, which is then combined with Eq. (3) to calculate the collapse pressure.

Table 3 shows an example calculation of the basic calculation parameters of the J2Kz and J1y seams.

| Parameter | \( \sigma_1 \) (MPa) | \( \sigma_3 \) (MPa) | \( \sigma_p \) (MPa) | \( S_i \) (MPa) | \( \psi_i \) (°) | \( u_i \) | \( S_d \) (MPa) | \( \psi_d \) (°) | \( \alpha \) | \( R \) (m) |
|-----------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| \( \sigma_1 \) (MPa) | 26.5 | 21.0 | 23.5 | 17.8 | | | | | | |
| \( \sigma_3 \) (MPa) | | | | | | | | | | |
| \( \sigma_p \) (MPa) | | | | | | | | | | |
| \( S_i \) (MPa) | | | | | | | | | | |
| \( \psi_i \) (°) | | | | | | | | | | |
| \( u_i \) | | | | | | | | | | |
| \( S_d \) (MPa) | | | | | | | | | | |
| \( \psi_d \) (°) | | | | | | | | | | |
| \( \alpha \) | | | | | | | | | | |
| \( R \) (m) | | | | | | | | | | |
The collapse density is obtained by substituting the basic parameters into the orthogonal cleat model, which changes with the inclination and azimuth angles.

From Fig. 5, the highest collapse pressure equivalent density in the J<sub>2k</sub>z stratum is 1.72 g/cm<sup>3</sup>, while the lowest collapse pressure equivalent density is 1.20 g/cm<sup>3</sup>. The vertical wellbore stability is the worst in this interval. The highest collapse pressure equivalent density in the J<sub>1y</sub> stratum is 2.0 g/cm<sup>3</sup>, and the lowest collapse pressure equivalent density is 1.81 g/cm<sup>3</sup>. The best trajectory has an azimuth of 110° or 250° and an inclination angle of 45°–75°.

3DEC mode

As shown in Fig. 6, the overall model size is 2 m × 2 m × 2 m, the wellbore direction is along the Z-axis, the wellbore radius is 0.108 m, and the inner model size is 0.8 m × 0.8 m × 2 m. The degree of fragmentation is relatively greater in the inner...
To generate discrete cleats, discrete fracture network (DFN) technology is used. The face cleats in the outer model are parallel to the $X$ direction, with a cleat spacing of 0.1 m, and the end cleats are parallel to the $Y$ direction, with a cleat spacing of 0.2 m.

The inner model in this study employs DFN to generate discrete cleats, and the randomly generated cleat groups consist of a set of discrete, planar, and disc-shaped cleats. Given that many small cleats will increase the model’s complexity and calculation time, the author suggests that small cleats be ignored to improve calculation efficiency, as shown in Fig. 7.

Model boundary condition configuration: $X = 1$ plane is set as a stress boundary, $X = -1$ plane is set as a fixed displacement boundary; $Y = 1$ plane is set as a stress boundary, $Y = -1$ plane is set as a fixed displacement boundary; $Z = 1$ plane is set as a stress boundary.
plane is set the stress boundary, and the $Z = -1$ surface is set as the fixed displacement boundary.

Model initial conditions: in situ stress conditions, the overburden pressure coefficient is 2.35, the maximum horizontal principal stress pressure coefficient is 2.65, the direction is along the negative $X$-axis, the minimum horizontal principal stress pressure coefficient is 2.10, and the direction is negative along the $Y$-axis direction.

The wellbore radius of the DB-X01 well is 0.108 m, the well depth is 4000 m, and the liquid column pressure is 65 MPa. As determined by laboratory tests, the mechanical parameters of coal and cleats are as follows: coal has an initial Poisson's ratio of 0.38, a cohesion of 10.3 MPa, an internal friction angle of 17.5°, and a density of 2467 kg/m³. Cleat cohesion is 4.5 MPa, and the internal friction angle is 4.2°.

Four observation points were set on the well's circumference, including $A_1 (0, 0.108, 0)$, $A_2 (0, -0.108, 0)$, $B_1 (0.108, 0, 0)$, and $B_2 (-0.108, 0, 0)$, as shown in Fig. 8. During the simulation, the displacement of the four observation points is recorded as the basis for determining whether the model reaches a steady state.

After a finite number of calculations, the displacement of each observation point no longer changes, and the model is said to be steady. Figure 9 depicts the displacement of the observation point.

After the model has reached a steady state, the data are recorded, and the simulation results and model state are saved. Then, the displacement of each block in the model can be displayed intuitively using the displacement contour, as shown in Fig. 10.

The displacement of the observation point stabilized after a finite number of iterations, and the model reached equilibrium. According to the displacement contour (Fig. 10 (right)), the maximum radial displacement is 3.76 cm, and the wellbore radius is 0.108 m, indicating that wellbore wall failure has occurred at 17.2% of the wellbore diameter. Therefore, the position where the block fell first, as affected by the cleat surface, does not strictly correspond to the maximum horizontal principal stress position, but rather the smaller block cut by the cleat falls first.

However, the displacement is still greater along the maximum horizontal principal stress direction, which is consistent with the classic rock mechanics theory. In addition, based on the displacement contour, it is possible to conclude that the cleats cause the displacement of coal blocks to be discontinuous.

According to Fig. 8, because $B_1$ and $B_2$ are both in the maximum horizontal principal stress direction, their displacements are greater than those of $A_1$ and $A_2$. However, even though $B_1$ and $B_2$ are in symmetrical stress positions, $B_1$'s displacement is greater than $B_2$'s. This is because the cleats at these two positions are different, resulting in the displacement difference, demonstrating that cleats are extremely important when analyzing wellbore stability in coal formations.

**Models comparison and discussion**

The two models are compared and analyzed by combining the actual drilling fluid density of the DB-X01 well. The orthogonal cleat model and the 3DEC model are used to
predict collapse pressure at various depths, and the results of the calculations are compared to the actual drilling fluid density, as shown in Figs. 11 and 12, respectively.

The actual drilling fluid density in the J2Kz is quite different from the model-predicted value, as shown in Fig. 11, and the average well diameter expansion rate reached 17.9%. Conversely, Fig. 12 indicates that the actual drilling fluid density in the J1y is very close to the model-predicted value, and the average well diameter expansion rate is only 7%. As a result, this study opines that both models are of reference significance.

Furthermore, the orthogonal cleat model yields relatively high results, whereas the 3DEC method yields results that are closer to the actual drilling fluid density. Furthermore, as depth increases, the difference between the orthogonal cleat model calculation results and the actual drilling fluid density increases, whereas the difference between the 3DEC model calculation results and the actual drilling data changes only slightly. As a result, the 3DEC model calculation result is closer to the actual drilling value than the orthogonal cleat model calculation result.

The orthogonal cleat model is proposed in this study for calculating the best drilling azimuth and inclination angle, as well as the 3DEC model for calculating drilling fluid density.

**Well trajectory optimization**

As shown in Fig. 5, the orthogonal cleat model depicts the distribution of collapse pressure at various azimuth and inclination angles.

The best trajectory corresponds to the lowest collapse pressure. The best trajectory for the J2Kz interval is 120° azimuth and 60°–75° inclination angle. The best trajectory for the J1y interval is 110° or 250° azimuth and 45°–75° inclination angles.

Taking the J1y and J2Kz intervals into account, we can obtain the best drilling orientation that is beneficial to wellbore stability: the best drilling azimuth is around 115°, and the best deviation angle is around 60°.
Anticollapse drilling fluid

According to the investigation, the original drilling fluid used in well DB-X04 is 2–4.5% bentonite, 0.5–0.7% caustic soda, 3–5% sulfonated phenolic resin 2–3% sulfonated brown coal resin, 5% emulsified asphalt, 1–2% lubricant, and 3–5% potassium chloride. However, serious drilling fluid leakage occurred in the coal seam, and the well diameter expansion rate was very high. As a result, the original drilling fluid’s plugging performance needs to be improved even further.
Drilling fluid optimization

The SEM test results of the drilling fluid containing asphalt additives after hot rolling coal and rock cuttings are shown in Fig. 13. As can be seen, asphalt can effectively fill the cleats of coal rock and adhere to the coal bedrock well.

Table 4 indicates the particle size test results of the plugging materials commonly used in Tarim Oilfield.

According to Table 4, sulfonated asphalt seals the smallest cleats, followed by dry powder asphalt, and emulsified asphalt seals the largest cleats. The combination of dry powder asphalt, emulsified or sulfonated asphalt, and 2200-mesh ultrafine calcium has the highest efficiency in plugging 1–10 μm coal rock cleats; whereas the combination of dry powder asphalt, emulsified or sulfonated asphalt, and 2200-mesh ultrafine calcium can seal most of the cleats in coal rock.

Coal rock cores were used to conduct drilling fluid plugging effect tests under various compound systems and dosage conditions to determine the optimal drilling fluid plugging compound system and dosage. Figure 14 depicts the results.

Dry powder asphalt system at a 48-h maximum liquid output is approximately 12 mL; dry powder asphalt and emulsified asphalt compound system at a 48 h maximum liquid output is approximately 6.5 mL; dry powder asphalt, emulsified asphalt, and sulfonated asphalt compound system at a 48-h maximum liquid output is approximately 1.6 mL; dry powder asphalt, sulfonated asphalt, emulsified asphalt, and 2200 mesh superfine calcium compound system at a 48 h maximum liquid output is only 1.2 mL. As a result, the compound system of sulfonated asphalt, emulsified asphalt, and 2200 mesh superfine calcium is preferred, and the recommended minimum amount of plugging material for the compound system is 3% sulfonated asphalt, 3% emulsified asphalt, and 3% 2200 mesh superfine calcium.

The following is the main additive equation of the new anticollapse drilling fluid: 4–5% soil powder, 0.3–0.8% CMC-LV, 1–1.5% Redu-2, 2–3% SMP-3, 0.2–0.25% Na2CO3, 3–4% sulfonated asphalt, 3–4% emulsified asphalt, and 3% superfine calcium (2200 mesh).

Inhibition performance

The rolling recovery rate experiment was used to evaluate the new drilling fluid’s inhibition performance. Figure 15 depicts the results of the rolling recovery rate test.

Figure 15 shows that the new drilling fluid’s rolling recovery rate for outcrop coal and rock was 98.6%, and the rolling recovery rate for mudstone was 85.7%, with the overall suppression performance of the drilling fluid being excellent. The rolling recovery rate of the original drilling fluid for outcrop coal is only 85.1%, and it is only 63% for mudstone. The inhibition of the new drilling fluid on coal rock and carbonaceous mudstone is considerably greater than that of the original drilling fluid, and the inhibition on coal rock is greater than that of oil-based drilling fluid. It demonstrates that the new drilling fluid’s suppression
performance has been considerably improved and that the new drilling fluid is more conducive to wellbore stability.

**Rheology and filter loss**

A six-speed rotary viscometer was used to measure the rheological properties of the new drilling fluid. Table 5 shows the result of the rheological properties of the new drilling fluid.

The rheological properties of the new drilling fluid are similar before and after aging, indicating that the new drilling fluid has good stability after high-temperature treatment and good thermal stability.

API fluid loss and HTHP (high temperature and high pressure) water loss measurements were performed on the new and original drilling fluids, respectively. Figure 16 depicts the results.

The API water loss of the new drilling fluid is 2.3 mL, and the HPHT water loss is 2.4 mL, as shown in Fig. 16. The original drilling fluid's API water loss is 3.43 mL, and the HPHT water loss is 4 mL. The new drilling fluid's API water loss and HPHT water loss have decreased considerably, indicating that the new drilling fluid has better water loss control. In theory, the new drilling fluid has better sealing performance on the well-lining rock and can effectively

![Filtration loss measurement result](image1)

![Analysis results of actual drilling of inclined coal section in DT2 well](image2)
prevent coal seam well-lining collapse and drilling fluid loss during the drilling process.

Field application result and discussion

The DT2 well is an exploratory well in Dibei that is intended to be directional. This well’s actual drilling deflection point is at the bottom of J1y.

The orthogonal cleat model is used to determine the best drilling azimuth and inclination angle, and the 3DEC model is used to calculate the drilling fluid density, yielding the following results: the coal seam section's drilling azimuth is 135°–145° (S1 azimuth = 133°), the inclination angle is 35°–45°, and the drilling fluid density is 1.70–1.74 g/cm³.

To ensure the stability of the coal seam section after entering the coal seam, the centralizer size is reduced from 311 to 306 mm, the weight on the bit is reduced to 30–80 kN, the speed is reduced to 30–35 rpm, and the displacement is 18–22 L/s. Figure 17 depicts the analysis results of actual drilling in the inclined section of the DT2 well’s coal seam.

Figure 17 shows that after implementing comprehensive coal seam stabilization measures in the inclined section of the coal seam, it has good wellbore stability when drilling into the coal-measure strata. The well diameter expansion rate of most intervals is less than 20%, and the average well diameter expansion rate in the coal seam is only approximately 7%. There is no accident or complicated drilling of the coal-measure strata, indicating that this study and coal seam countermeasures can effectively ensure wellbore stability.

Summary and conclusion

This study proposes an orthogonal cleat model and a 3DEC model based on the structure and chemical properties of coal rocks to predict the collapse pressure of a coal seam, optimize the wellbore trajectory, and develop an anticollapse drilling fluid for coal seams. The following four conclusions were drawn:

1. It is clear from the analysis of microstructure and chemical properties that mechanical instability dominates coal seam instability.
2. Both the orthogonal cleat and 3DEC models achieved consistent results with the actual drilling, wherein the 3DEC method's results are closer to the actual drilling fluid density.
3. Through experimental evaluation, an anticollapse drilling fluid suitable for the Dibei area has been developed: 4–5% soil powder, 0.3–0.8% CMC-LV, 1–1.5% Reducer, 2–3% SMP-3, 0.2–0.25% Na₂CO₃, 3–4% sulfonated asphalt, 3–4% emulsified asphalt, and 3% superfine calcium (2200 mesh). The anticollapse drilling fluid has strong inhibitory properties; the coal rock recovery rate is as high as 98.6%; the water loss of the new system API and HPHT are relatively low, at only 2.3 mL and 2.4 mL, respectively.
4. The wellbore in the coal seam directional section has good stability after applying stabilization measures in the DT2 well, with no downhole accidents. This demonstrates the reliability of the mechanism and countermeasures proposed in this study.

References

Ai C, Hu C, Li Y et al (2014) Wellbore stability estimation model of horizontal well in cleat-featured coal seam.
Ai C, Li X, Li Y et al (2017) Mechanical test analysis of impact on tensile strength from weak planes in coal. Coal Geol China 29(2):53–56
Carpenter C (2018) Coalbed methane development in China: challenges and opportunities. J Pet Technol 70:67–68
Chang Z, Hou B, Wang L, Chen WG, Muhadasi Y, Li ZJ (2018) Propagation law of hydraulic fracture in coal seam based on element coils model. In: Paper presented at the 52nd U.S. rock mechanics/geomechanics symposium, Seattle, Washington, June 2018
Cui F, Lai XP, Cao JT (2013) Numerical simulation of top-coal caving in steeply dipping and thick coal seam mining. In: Paper presented at the 47th U.S. rock mechanics/geomechanics symposium, San Francisco, California, June 2013
Deisman N, Ivars DM, Darcel C et al (2010) Empirical and numerical approaches for geomechanical characterization of coal seam reservoirs. Int J Coal Geol 82(3–4):204–212
Fan L, Liu S (2018) Numerical prediction of in situ horizontal stress evolution in coalbed methane reservoirs by considering both poroelastic and sorption induced strain effects. Int J Rock Mech Min Sci 104(2018):156–164. https://doi.org/10.1016/j.ijrmms.2018.02.012
Fan L, Liu S (2019) Fluid-dependent shear slip behaviors of coal fractures and their implications on fracture frictional strength

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reduction and permeability evolutions. Int J Coal Geol 212:103235. https://doi.org/10.1016/j.coal.2019.103235
Hawkes C (2007) Assessing the mechanical stability of horizontal boreholes in coal. Can Geotech J 44(7):797–813
Huanchun Z, Richard B, Patrick A (2004) Numerical methods and application for jointed rock mass, part 1: approaches and discussions. Chin J Rock Mech Eng 23(20):3444–3449
Jin Y, Chen M (1999a) Wellbore stability analysis of inclined shaft in weak surface formation. J Univ Pet 23(4):46–48
Jin Y, Chen M (1999b) Wellbore stability mechanics model for weak surface formation. Drill Prod Technol 22(3):13–14
Kai Z, Jin-Gen D, Bao-Hua YU et al (2013) Wellbore stability of highly-deviated well in bedding shale. Sci Technol Eng 13(5):1147–1149
Li S, Deng J, Li M (2002) Discrete element analysis on wellbore stability in jointed broken formation. Chin J Rock Mech Eng 21(z1):2139–2143
Li X, Liang H, Yao M et al (2015) A new understanding of exploration of coalbed methane in Sha’erhu Sag. Sci Technol Eng 15(16):33–39
Liu S, Harpalani S (2013) Determination of the effective stress law for deformation in coalbed methane reservoirs. Rock Mech Rock Eng 47(5):1809–1820. https://doi.org/10.1007/s00603-013-0492-6
Liu S, Harpalani S (2014) Evaluation of in situ stress changes with gas depletion of coalbed methane reservoirs. J Geophys Res Solid Earth. https://doi.org/10.1002/2014JB011228.Received
Liu X, Zhongbin YE, Chen Y (2002) Influence of rock on weak plane texture on sidewall stability. Nat Gas Ind 22(2):41–42
Masoudian MS, Airey DW, El-Zein A (2014) Experimental investigations on the effect of CO2 on mechanics of coal. Int J Coal Geol 128–129:12–23
Perera MSA, Ranjith PG, Peter M (2011) Effects of saturation medium and pressure on strength parameters of Latrobe Valley brown coal: carbon dioxide, water and nitrogen saturations. Energy 36(12):6941–6947. https://doi.org/10.1016/j.energy.2011.09.026
Perera MSA, Ranjith PG, Viete DR (2013) Effects of gaseous and super-critical carbon dioxide saturation on the mechanical properties of bituminous coal from the Southern Sydney Basin. Appl Energy 110:73–81
Ping MZ, Ping PS (2004) Mudstone composition of coal measures and its influence on the mechanical properties. Coal Geol Explor 32(2):14–16
Qu P, Shen R, Fu L, Zhang X, Yang H (2011) Application of the 3D discrete element method in the wellbore stability of coal-bed horizontal wells. Acta Petrolei Sin 32(1):153–157
Ranathunga AS, Perera MSA, Ranjith PG (2016a) Influence of CO2 adsorption on the strength and elastic modulus of low rank Australian coal under confining pressure. Int J Coal Geol 167:148–156
Ranathunga AS, Perera MSA, Ranjith PG, Bui H (2016b) Super-critical CO2 saturation-induced mechanical property alterations in low rank coal: an experimental study. J Supercrit Fluids 109:134–140. https://doi.org/10.1016/j.supflu.2015.11.010
Reisabadi MZ, Haghighi M, Sayyafzadeh M, Khaksar A (2020) Effect of matrix shrinkage on wellbore stresses in coal seam gas: an example from Bowen Basin, east Australia. J Nat Gas Sci Eng 77:103280
Hongtao L, Haotian W, Wei Z, Junyan L, Yutao Z, Sharma MM (2021) Predicting sand production rate in high-pressure, high-temperature wells in the Tarim basin. SPE Prod & Oper 36:174–196. https://doi.org/10.2118/191406-PA
Shi Y, Chen S, Yang X, Lang Yu, Cai J (2019) Enhancing wellbore stability of coal measure strata by electrical inhibition and wetting control. J Pet Sci Eng 174:544–552
Thomas G, Nathan D, Chalaturnyk RJ (2009) Effect of drilling fluids on coal permeability: Impact on horizontal wellbore stability. Int J Coal Geol 78(3):177–191
Wang S, Elsworth D, Liu J (2012) Mechanical behavior of methane infiltrated coal: the roles of gas desorption, stress level and loading rate. Rock Mech Rock Eng 46(5):945–958. https://doi.org/10.1007/s00603-012-0324-0
Yin H, Li Q, Guo L et al (2012) Evaluation of wellbore stability in coal seams by use of the universal discrete element code (UDEC) method. Nat Gas Ind 32(11):59–63
Yongtao G, Jinfei C, Shunchuan WU et al (2015) Deformation characteristics of surrounding rock during tunnel excavation based on 3DEC. Min Res Dev
Zhao H, Chen M, Li Y, Zhang W (2012) Discrete element model for coal wellbore stability. Int J Rock Mech Min Sci 54:43–46
Zhigang L, Shengli F, Xiaoming W et al (2000) Research on mechanical property test and mechanism of hydraulic fracture of gas well in coal beds. Pet Drill Tech 28(3):10–12
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