

Article

Study on the Instability Process of Coal Seam Wellbores Based on the Coupling of Weakness Plane Strength Criterion and Wellbore Stress

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Abstract

Coal is inherently soft, characterized by well-developed cleat systems, low strength, and significant anisotropy. Existing models that treat coal as a continuous medium or consider only a single plane of weakness fail to capture the synergistic effects of multiple weaknesses on wellbore instability. This study addresses this gap by integrating the strength criteria of weakness planes with wellbore stress theory. First, in situ stresses were transformed into the coordinate system of the weakness planes to derive the acting stress components. A strength criterion incorporating multiple structural planes—accounting for the coal matrix, bedding, face cleats, and butt cleats—was then applied to establish a coupled wellbore stability criterion. A corresponding collapse pressure program was developed using Visual Basic to analyze the effects of stress state, wellbore trajectory, and weakness orientation. The results show that the presence of multiple weakness planes significantly increases the sensitivity of wellbore stability to trajectory. Drilling parallel to the direction of minimum horizontal stress minimizes shear stress and collapse pressure, whereas drilling at high angles or parallel to the maximum horizontal stress activates the weakness planes, leading to a sharp increase in collapse pressure. The presence of these weaknesses results in a highly non-uniform and direction-dependent collapse pressure distribution, with their synergistic interactions further exacerbating the risk of localized failure.

Keywords: coal seam; wellbore stability; wellbore instability process; strength criterion; wellbore stress; collapse process



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1. Introduction

As a significant unconventional natural gas resource, coalbed methane plays a pivotal role in the world's energy structure, especially China. According to statistics, China's CBM resources buried within 2000 m depth are estimated to be as high as 3×10^{13} to 3.5×10^{13} m³, which is comparable to the country's conventional natural gas reserves. The effective development and utilization of coalbed methane (CBM) are crucial not only for optimizing the energy mix and alleviating energy supply pressures, but also for ensuring production safety and environmental protection [1,2]. Coal mine gas accidents have long posed a major threat to the safety of coal production. Extracting CBM can significantly

reduce underground gas concentrations, thereby fundamentally mitigating the occurrence of catastrophic incidents such as gas explosions. Meanwhile, methane—the primary component of CBM—is a potent greenhouse gas with a global warming potential approximately 25 times that of carbon dioxide. In China, coal mining activities release substantial amounts of methane into the atmosphere each year [3–5]. Therefore, large-scale and efficient CBM extraction that enables its utilization as a resource is essential for reducing greenhouse gas emissions and addressing climate change. Nevertheless, the efficient development of CBM faces numerous engineering and technological challenges, among which, wellbore instability is particularly prominent. As a special type of unconventional reservoir, coal reservoirs exhibit distinct mechanical characteristics, including softness, highly developed cleats and fractures, low mechanical strength, low elastic modulus, high Poisson's ratio, and a tendency to be friable and compressible. These properties make coal rock highly susceptible to downhole complications during drilling, such as wellbore collapse, spalling, and stuck pipe. This severely restricts drilling efficiency, increases operational costs, and can even lead to project failure. Particularly in regions with high exploitation potential, such as the WW Basin, frequent occurrences of coal spalling and stuck pipe during drilling have become one of the critical bottlenecks restricting the large-scale and efficient development of CBM in the area [6].

The wellbore instability process of coal rock is a complex problem involving the intersection of multiple disciplines, including geomechanics, rock mechanics, fluid mechanics, and chemistry. Its instability mechanism differs significantly from that of conventional sandstone or shale formations [7]. The core reason lies in the extensively developed cleat system within coal rock. Cleats, including face cleats and butt cleats, form a natural and dense network of weak structural planes that dissect the intact coal mass into discontinuous blocks, significantly reducing its overall strength and stiffness and introducing strong mechanical anisotropy [8–10]. During drilling, the stress around the borehole is redistributed, and these weak planes often become preferential sites for stress concentration and failure initiation. Furthermore, factors such as in situ stress state, wellbore trajectory, drilling fluid properties, and their physicochemical interactions with the coal rock collectively and synergistically influence the wellbore collapse process [11–15]. Considerable research has been conducted by scholars worldwide to address wellbore stability in coal seams, yielding fruitful results. Early studies were largely based on continuum mechanics theory, treating coal rock as a homogeneous, isotropic elastic or elastoplastic material. Classic strength criteria, such as the Mohr–Coulomb and Drucker–Prager criteria, were employed for wellbore stress analysis and collapse pressure prediction. However, these approaches struggle to accurately capture the fundamental controlling role of discontinuities such as cleats in the mechanical behavior and failure modes of coal rock [16–18]. In the analysis of borehole wall stability, the discrete fracture network (DFN), Mogi–Coulomb criterion, and modified Mohr–Coulomb model produce significantly different prediction results due to different scales and mechanical assumptions. The DFN model starts from geological structures and explicitly characterizes the spatial distribution, connectivity, and permeability of natural fractures in rock masses. It is for highly heterogeneous media and can effectively simulate borehole instability induced by fracture propagation under fluid–stress coupling. However, it has high computational costs and relies on detailed field fracture data [19]. In contrast, the Mogi–Coulomb criterion, as a continuum constitutive model, incorporates the relationship between octahedral shear stress and mean normal stress, naturally accounting for the enhancing effect of the intermediate principal stress on rock strength. Under multiaxial compression conditions (e.g., deep drilling), it predicts peak strength and failure envelopes more accurately than the traditional two-dimensional MC criterion [20]. Meanwhile, the modified Mohr–Coulomb model typically embeds the σ_2 effect into its original framework

through empirical functions or corrections involving stress invariants. Although it retains the advantage of the MC model's concise form, its physical mechanism is less clear than that of the Mogi-Coulomb criterion, and its parameter calibration relies on lithology-specific experiments [21]. Recent studies further indicate that in scenarios involving anisotropic in situ stress coupled with pore pressure, such as underground gas storage, the traditional MC model, which only considers σ_1 and σ_3 , significantly underestimates the extent of the plastic zone around the borehole. In contrast, the Mogi-Coulomb criterion and new three-dimensional criteria (e.g., the TMNS model) more reasonably reflect the influence of σ_2 on caprock integrity [19]. Therefore, under conditions of deep wells or complex stress fields, the Mogi-Coulomb criterion, which balances physical rationality and engineering practicality, becomes a preferred choice over the classical MC model. Meanwhile, the DFN model is indispensable when a detailed characterization of fracture-controlled instability mechanisms is required. The applicable scenarios of these three approaches are clearly distinct. With growing insight, discontinuous mechanics methods, such as the discrete element method, have been introduced into the analysis of wellbore stability in coal seams. By constructing discrete fracture networks to explicitly characterize cleat systems, researchers have been able to more realistically simulate failure behaviors of coal rock, including sliding and opening along weak planes. For instance, Chen Mian et al. [9,10] established a wellbore stability analysis model incorporating parameters like cleat spacing and dip angle based on a discontinuous medium model. Zhang Guangfu et al. [22], using 3DEC 7.0 software and discrete element numerical simulations, revealed the significant influence of cleat orientation and density on the wellbore instability process. These studies mark a profound shift in the understanding of the mechanisms underlying coal rock wellbore instability, moving from a "continuum" perspective to a "discontinuum" one [23–26]. Meanwhile, a substantial body of research has focused on drilling fluid technology as a direct means of stabilizing the wellbore. It is generally accepted that the influence of drilling fluid on wellbore stability in coal rock results from the coupling of mechanical and chemical effects. Mechanically, the hydrostatic pressure of the drilling fluid column provides support to the wellbore; however, the invasion of filtrate into the pore and cleat networks of the coal seam can increase pore pressure and reduce effective stress, thereby inducing instability during drilling fluid–coal interactions. Chemically, hydration of clay minerals within the coal rock by drilling fluid filtrate can diminish the bonding strength and friction coefficient of the structural planes [27]. Therefore, the core focus of current anti-sloughing drilling fluid technology lies in "plugging" and "inhibition." By incorporating multi-scale plugging materials—such as nanomaterials, asphalt-based products, and polymeric film-forming agents—micron- to nano-scale fractures are effectively sealed, impeding pressure transmission and filtrate invasion [28]. Furthermore, inhibitors like K^+ , NH_4^+ , and polyamines are used to suppress the hydration and swelling of clay minerals. Ranging from traditional polysulfonate systems and potassium salt polymer systems to more recent innovations like fuzzy-ball drilling fluids, dual-energy synergistic drilling fluids, and solids-free drilling fluids, a series of drilling fluid systems tailored to coal seam characteristics have been successfully developed and applied in the field, achieving good anti-sloughing effects [29–32].

Although significant progress has been made in existing research, several aspects still require further deepening and breakthroughs [33–35]. First, regarding the quantitative characterization of wellbore instability processes, many studies remain at a qualitative or semi-quantitative stage. Current wellbore stress models—whether based on continuum methods or discrete element approaches—continue to face challenges in stress analysis and strength evaluation under conditions involving complex, multi-set weakness planes [36,37]. Second, research on the applicability of weakness plane strength criteria to actual coal rock

systems containing multiple weakness planes, as well as the mechanisms of interaction and competition among different weakness planes, remains insufficient [38,39]. Third, the fully coupled process of drilling fluid seepage and stress in coal rock is highly complex. Existing models often involve considerable simplifications, making it difficult to accurately characterize the dynamic changes in pore pressure around the wellbore caused by filtrate invasion and the associated time-dependent weakening effect on the mechanical parameters of the weakness planes. Finally, integrating the results of multi-factor coupling analyses to effectively guide wellbore trajectory optimization and real-time design of drilling fluid parameters remains a challenge in field practice [40,41].

In view of this, this study aims to deepen the understanding of the wellbore instability process during coal seam drilling and to develop a set of wellbore stability analysis methods that better align with the discontinuous and anisotropic characteristics of coal rock. This research adopts a core framework that integrates a wellbore stress model with weakness plane strength criteria, which focuses on introducing strength criteria applicable to rock masses containing multiple sets of weak structural planes. It quantitatively analyzes the conditions under which the coal rock mass around the wellbore undergoes shear slip or tensile failure along critical weakness planes under different in situ stress states and various wellbore trajectories. Through parametric analysis, the influence patterns of key factors—such as cleat orientation and wellbore trajectory—on wellbore collapse processes are systematically elucidated, thereby establishing a quantitative understanding of the factors affecting wellbore instability in coal seams. The anticipated outcomes of this research will provide a more reliable theoretical foundation and computational tools for the optimization of wellbore trajectory design, particularly for complex structural wells such as horizontal and multilateral wells, as well as for the rational determination of safe drilling fluid density windows in CBM wells. This holds significant theoretical importance and engineering application value for advancing safe and efficient drilling technology for coalbed methane in China.

2. Model for Calculating Coal Seam Collapse Pressure

2.1. Stress Components Acting on Coal Seam Weakness Planes

This study investigates the stress distribution on multiple weakness planes in coal seams using five stress coordinate systems: the In situ Principal Stress Coordinate System (PCS), the Geodetic Coordinate System (GCS), the Borehole Cartesian Coordinate System (BCS), the Borehole Cylindrical Coordinate System (CCS), and the Weakness Plane Coordinate System (WCS). Through coordinate transformation methods, the in situ stress is converted to derive the stress components acting on the Weakness Plane Coordinate System. Figures 1 and 2 illustrate the spatial relationships between these different coordinate systems.

In Figures 1 and 2, α_s represents the azimuth of the maximum horizontal principal stress; β_s denotes the deviation angle between the overburden pressure direction and the gravitational direction, which is taken as 0 here; α_b is the azimuth of the wellbore high side projected onto the horizontal plane, measured from the geographic north direction X_e ; β_b is the wellbore inclination angle; θ is the wellbore circumferential angle, measured counterclockwise from the positive direction of the x_b -axis in the cylindrical coordinate system; α_w is the dip direction of the weakness plane; and β_w is the dip angle of the weakness plane.

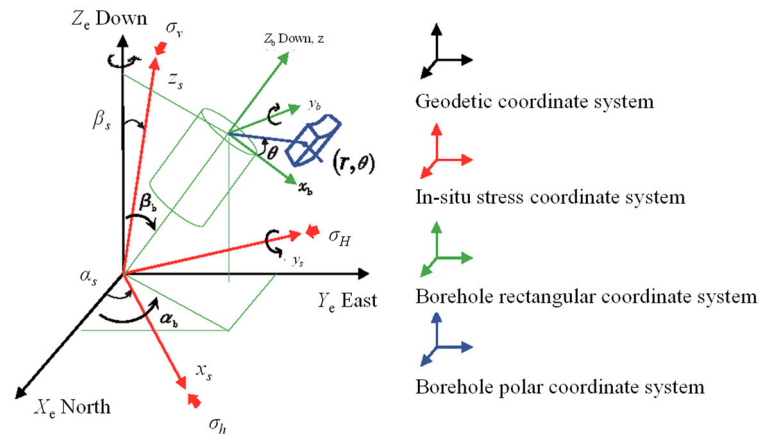


Figure 1. Spatial relationship between different system coordinates.

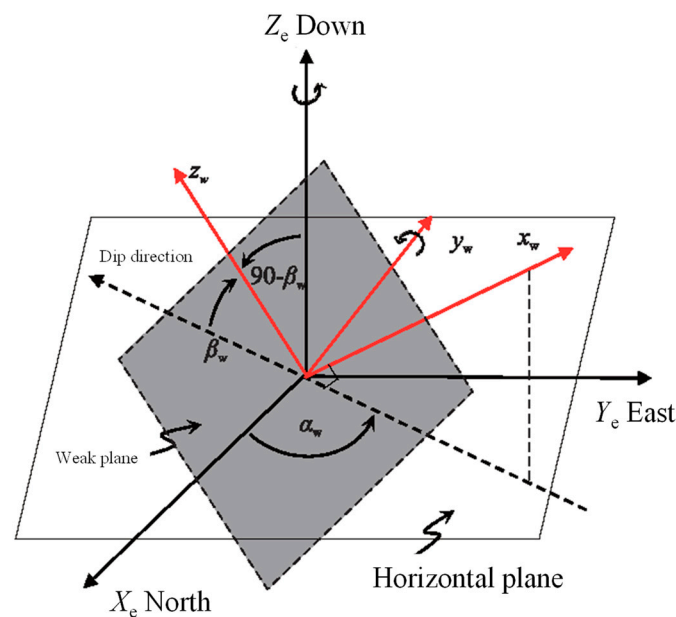


Figure 2. Spatial relationship between the geodetic coordinate system and the weak plane coordinate system.

The stress components σ_e of the in situ stress in the Geodetic Coordinate System (GCS) can be obtained using Equation (1),

$$\sigma_e = M_1^T \begin{bmatrix} \sigma_H & 0 & 0 \\ 0 & \sigma_h & 0 \\ 0 & 0 & \sigma_v \end{bmatrix} M_1 \quad (1)$$

Subsequently, the stress components σ_b of σ_e in the Borehole Cartesian Coordinate System (BCS) can be derived through Equation (2),

$$\sigma_b = M_2 \sigma_e M_2^T = \begin{bmatrix} \sigma_{xx}^b & \tau_{xy}^b & \tau_{xz}^b \\ \tau_{yx}^b & \sigma_{yy}^b & \tau_{yz}^b \\ \tau_{zx}^b & \tau_{zy}^b & \sigma_{zz}^b \end{bmatrix} \quad (2)$$

$$M_1 = \begin{bmatrix} \cos \alpha_s \cos \beta_s & \sin \alpha_s \cos \beta_s & \sin \beta_s \\ -\sin \alpha_s & \cos \alpha_s & 0 \\ -\cos \alpha_s \cos \beta_s & -\sin \alpha_s \sin \beta_s & \cos \beta_s \end{bmatrix} \quad (3)$$

$$M_2 = \begin{bmatrix} \cos \alpha_b \cos \beta_b & \sin \alpha_b \cos \beta_b & \sin \beta_b \\ -\sin \alpha_b & \cos \alpha_b & 0 \\ -\cos \alpha_b \cos \beta_b & -\sin \alpha_b \sin \beta_b & \cos \beta_b \end{bmatrix} \quad (4)$$

In the equations, M_1 is the transformation matrix from transforming the In situ stress Coordinate System (ICS) to the Geodetic Coordinate System (GCS); M_2 is the transformation matrix from transforming GCS to BCS; σ_H , σ_h , σ_v are the maximum horizontal principal stress, minimum horizontal principal stress, and vertical principal stress in MPa, respectively; and σ_{xx} , σ_{yy} , σ_{zz} , τ_{xy} , τ_{xz} and τ_{yz} are the normal and shear stress components in different directions within the Borehole Cartesian Coordinate System in MPa. By performing a coordinate transformation on the effective stresses σ_{ccs}^{eff} in the Borehole Cylindrical Coordinate System (CCS), the stress components σ_w on the weakness plane can be obtained:

$$\sigma_w = M_4 M_2^T M_3^T \sigma_{ccs}^{eff} M_3 M_2 M_4^T = \begin{bmatrix} \sigma_{xx}^w & \tau_{xy}^w & \tau_{xz}^w \\ \tau_{yx}^w & \sigma_{yy}^w & \tau_{yz}^w \\ \tau_{zx}^w & \tau_{zy}^w & \sigma_{zz}^w \end{bmatrix} \quad (5)$$

$$M_3 = \begin{bmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (6)$$

$$M_4 = \begin{bmatrix} \cos \alpha_w \cos \beta_w & \sin \alpha_w \cos \beta_w & \sin \beta_w \\ -\sin \alpha_w & \cos \alpha_w & 0 \\ -\cos \alpha_w \cos \beta_w & -\sin \alpha_w \sin \beta_w & \cos \beta_w \end{bmatrix} \quad (7)$$

In the equations, M_3 is the transformation matrix from transforming the Geodetic Coordinate System (GCS) to the Borehole Cartesian Coordinate System (BCS), and M_4 is the transformation matrix from transforming the Borehole Cartesian Coordinate System (BCS) to the Weakness Plane Coordinate System (WCS).

2.2. Analysis of Principal Stresses Around the Wellbore in Coal Seams

According to the Fairhurst equation, the effective stresses σ_{ccs}^{eff} at the wellbore wall, derived from the stress components in the Borehole Cylindrical Coordinate System (CCS) when transformed from the Borehole Cartesian Coordinate System (BCS), can be expressed as shown in Equation (8):

$$\sigma_{ccs}^{eff} = \begin{bmatrix} \sigma_r & \tau_{r\theta} & \tau_{rz} \\ \tau_{r\theta} & \sigma_\theta & \tau_{\theta z} \\ \tau_{rz} & \tau_{\theta z} & \sigma_z \end{bmatrix} \quad (8)$$

In the equation, σ_r , σ_θ , σ_z are the radial stress, circumferential stress, and axial stress in the borehole cylindrical coordinate system, respectively (MPa), and $\tau_{r\theta}$, $\tau_{\theta z}$, τ_{rz} are the shear stresses in different directions within the borehole cylindrical coordinate system (MPa).

To determine the location where failure occurs in the coal matrix, the three principal stresses in the cylindrical coordinate system are calculated using Equation (9). By comparing the magnitudes of the principal stresses σ_1 , σ_2 , and σ_3 , the maximum principal stress, minimum principal stress, and intermediate principal stress can be obtained,

$$\begin{aligned} \sigma_1 &= \frac{\sigma_z + \sigma_\theta}{2} + \sqrt{\left(\frac{\sigma_z - \sigma_\theta}{2}\right)^2 + \tau_{\theta z}^2} \\ \sigma_2 &= \frac{\sigma_z + \sigma_\theta}{2} - \sqrt{\left(\frac{\sigma_z - \sigma_\theta}{2}\right)^2 + \tau_{\theta z}^2} \\ \sigma_3 &= \sigma_r \end{aligned} \quad (9)$$

2.3. Failure Criterion for Multiple Weakness Planes in Coal Seams

Coal seams are characterized by highly developed fractures, exhibiting distinct orthogonal development features of bedding planes and cleat planes. Specifically, cleat planes are divided into face cleats and butt cleats, which can be considered two sets of weakness planes intersecting at different angles. To facilitate analysis, an assumption is made that the face cleats and butt cleats are mutually perpendicular, as illustrated in Figure 3. In this model, the dip direction of the face cleat α_{fc} is consistent with the dip direction of the bedding plane α_w . The dip direction of the butt cleat α_{bc} intersects the bedding plane dip direction at 90° . The dip angle of the bedding plane is β_w . The dip angle of the face cleat β_{fc} is $90^\circ - \beta_w$, and the dip angle of the butt cleat β_{bc} is the same as that of the face cleat. Therefore, when evaluating the strength of coal seams, three sets of weakness planes—namely the bedding plane, butt cleat, and face cleat—must be considered simultaneously, in addition to the strength of the coal matrix itself.

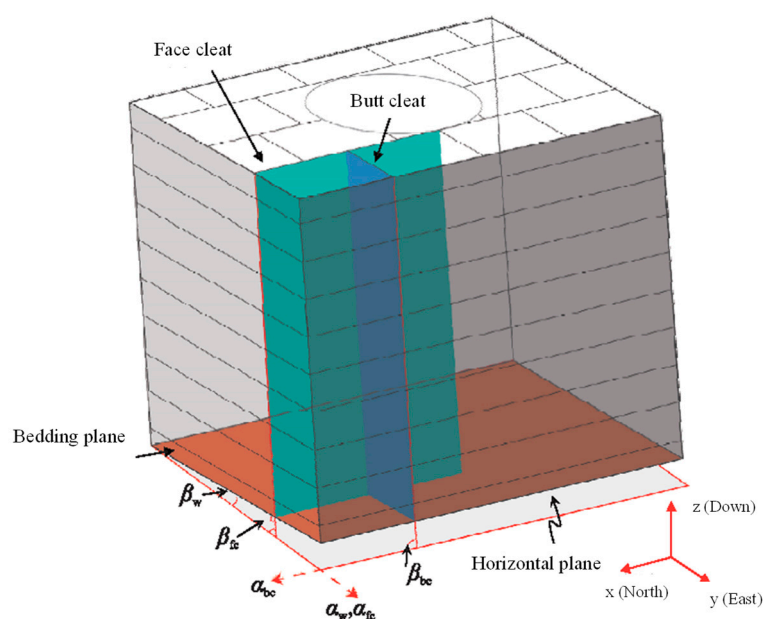


Figure 3. Simplified schematic diagram of the weak plane system in the coal seam of the borehole wall.

After obtaining the effective stress components on the weakness plane using Equation (5), the normal stress δ_w and shear stress τ_w acting on the weakness plane can be calculated through Equation (10):

$$\begin{cases} \delta_w = \sigma_{xx}^w \\ |\tau_w| = \sqrt{(\tau_{xy}^w)^2 + (\tau_{xz}^w)^2} \end{cases} \quad (10)$$

The stability judgment for multiple weakness planes in coal seams is obtained by superposing multiple weakness plane criteria, as shown in Equation (11):

$$\tau_w^{(i)} = C_w^{(i)} + \delta_w \tan \varphi_w^{(i)} \quad (11)$$

When the rock does not fail along the weakness planes, i.e., matrix failure occurs, the failure criterion for the coal matrix itself should be adopted as the judgment basis.

In the equation, δ_w is the resultant normal stress acting on the weakness plane in MPa; τ_w is the resultant shear stress acting on the weakness plane in MPa; $C_w^{(i)}$ is the cohesion of the weakness plane in MPa; and $\varphi_w^{(i)}$ is the internal friction angle of the weakness plane in $^\circ$, where $i = 1, 2, 3$ represent the bedding plane, face cleat, and butt cleat, respectively.

In the model established in this study, the following simplifications are made: the rock mass is regarded as a continuous elastic medium, weakness planes are assumed to be orthogonally developed with simplified geometries, the seepage effect of drilling fluid is not considered in a coupled manner, and the linear Mohr–Coulomb strength criterion is adopted for failure evaluation.

The model establishment and detailed solution steps are as follows,

- ① Based on the borehole stress equation, input parameters are in situ stress, pore pressure, and rock strength parameters of the block;
- ② Set the borehole azimuth angle to vary within the range of 0° to 360° at intervals of 10° , and the borehole inclination angle to vary within the range of 0° to 90° at intervals of 10° ;
- ③ Increase the borehole circumferential angle within the range of 0° to 360° at intervals of 2° ; set the bottomhole pressure to increase from 0 to x at intervals of 0.001 MPa, calculate the borehole stress at each point around the borehole, and convert it into the principal stress around the borehole;
- ④ Substitute the three principal stresses around the borehole into the rock strength criterion, and repeat step ③ until the critical condition for maintaining rock stability at that point is reached. The bottomhole pressure at this time is the critical value for maintaining the stability of the borehole wall at that point;
- ⑤ At the borehole wall, i.e., at $r = r_w$, take the maximum value of the critical values for maintaining the stability of the formation rock at points ranging from 0° to 360° around the borehole as the borehole wall collapse pressure under specific borehole azimuth and inclination conditions. Repeat step ④ to obtain the collapse pressure for any wellbore trajectory.

3. Results and Discussions

3.1. Input Parameters

A calculation model for coalbed methane wellbore collapse pressure was developed using Visual Basic to investigate the influence of factors such as cleat structure and in situ stress on coal seam collapse pressure. The input parameters [32] for the model are set as shown in Tables 1 and 2. The strength parameters of the structural planes (e.g., cohesion and internal friction angle) were obtained through laboratory rock mechanics tests. The testing equipment included the MTS rock mechanics testing system, and the test procedures followed the recommended standards of the International Society for Rock Mechanics (ISRM). The samples were taken from core specimens collected from the target coal seam block. The orientation parameters of the weakness planes were determined based on field core observations and interpretation results from imaging logging.

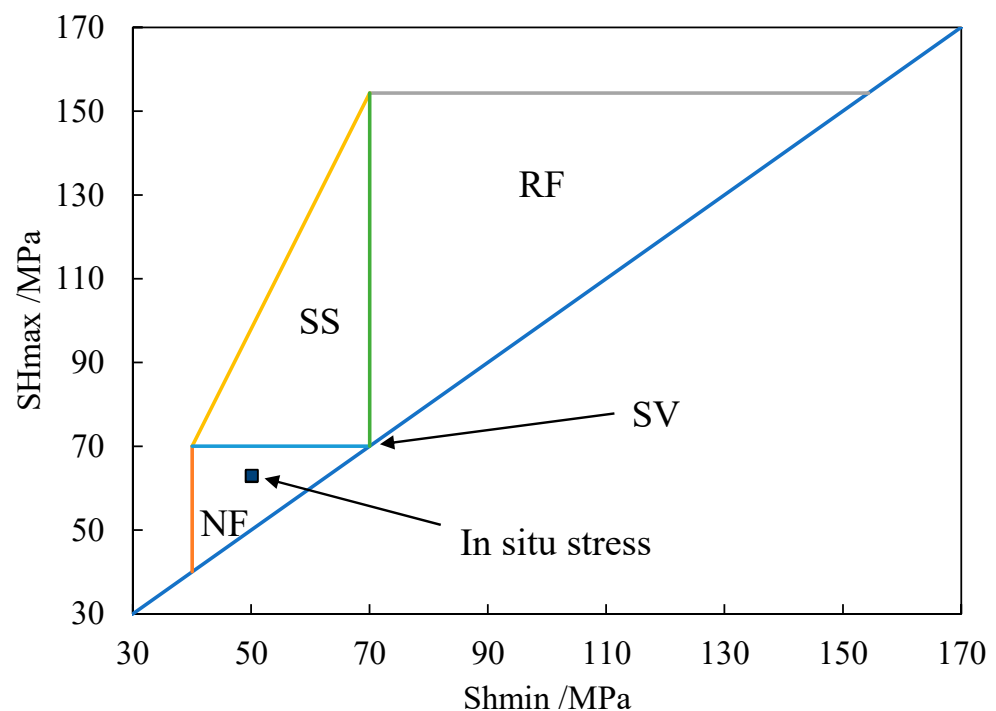
Table 1. Input Geo-mechanical Parameters for the Model.

Parameter	Value	Parameter	Value
Vertical depth	3850 m	Poisson's ratio	0.16
Maximum horizontal stress	62.89 MPa	Effective stress coefficient	0.9
Minimum horizontal stress	50.06 MPa	Coal seam thickness	8 m
Vertical stress	70.04 MPa	Pressure conductivity coefficient of coal rock	$8 \times 10^4 \text{ cm}^2/\text{s}$
Pore pressure	29.89 MPa	Porosity	0.02
Matrix cohesion	20.84 MPa	Filtration loss	$1 \text{ cm}^3/\text{d}$
Matrix internal friction angle	27.81°	Elastic storage ratio	0.8
Drilling fluid viscosity	50 mPa·s	Seepage time	3600 s

Table 2. Input strength parameters of rock structural planes in the model.

Parameter	Value
Bedding cohesion	13.11 MPa
Bedding internal friction angle	18.66°
Face cleat cohesion	11.12 MPa
Face cleat internal friction angle	15.61°
Butt cleat cohesion	11.16 MPa
Butt cleat internal friction angle	15.62°
Bedding dip angle	0°
Bedding dip direction	180°
Face cleat dip angle	90°
Face cleat dip direction	180°
Butt cleat dip angle	90°
Butt cleat dip direction	90°

Based on the fault activity theory derived from the Coulomb friction criterion, the friction coefficient between faults is set as $\mu = 0.6$. The in situ stress polygon is constructed and presented in Figure 4, with the input in situ stress parameters plotted within it. In the figure, NF denotes the normal faulting regime, SS the strike-slip faulting regime, and RF the reverse faulting regime. SV represents the input vertical stress magnitude, while the green square indicates the input values for the minimum and maximum horizontal stresses. The in situ stress corresponds to a normal faulting regime, where the vertical stress significantly exceeds both the minimum and maximum horizontal stresses.

**Figure 4.** In situ stress regime.

3.2. Influence of Coal Rock Structure on Wellbore Instability

To systematically evaluate the influence of coal rock structure—including bedding planes, face cleats, and butt cleats—on wellbore stability, this study conducts parametric numerical simulations based on the multi-weakness-plane strength criterion and the wellbore stress coupling model established in Section 2. The input parameters are listed in Tables 1 and 2. The analysis focuses on the variation patterns of the equivalent col-

lapse pressure (drilling fluid density) with wellbore trajectory, specifically the wellbore inclination angle and azimuth angle, under different in situ stress directions.

Figure 5 illustrates the variation in equivalent collapse pressure drilling fluid density with wellbore inclination when drilling in the direction of the minimum horizontal principal stress. Based on coordinate transformation of the wellbore stress field, as the inclination angle increases, the principal stress components around the wellbore are redistributed. Notably, the ratio of normal to shear stress acting on weak planes (e.g., face cleats and butt cleats) changes significantly. When the inclination angle is less than 30° , the normal stress on the weak planes dominates and the shear component is relatively small, resulting in a gradual increase in collapse pressure. Once the inclination exceeds 45° , the angle between the weak planes and the principal stress direction enters the most unfavorable range (approximately 50° – 70°). According to weak-plane failure criteria (e.g., the Jaeger criterion), the shear stress on the weak planes increases markedly while the effective normal stress decreases, promoting shear sliding along the weak planes and leading to a sharp rise in collapse pressure, with the peak occurring between 60° and 75° . This indicates that when drilling in the σ_h direction, a high inclination angle significantly activates the mechanical response of the weak planes, requiring a higher drilling fluid density to maintain wellbore mechanical equilibrium.

Figure 6 shows the variation in collapse pressure with wellbore inclination when drilling in the direction of the maximum horizontal principal stress. Compared with drilling in the σ_h direction, the stress distribution around the wellbore is more favorable in this case. Stress tensor transformation analysis reveals that when the wellbore azimuth aligns with the σ_H direction, the normal stress acting on the weak planes is higher while the shear stress component is relatively low, making the weak planes less prone to shear failure. At low to moderate inclination angles ($<45^\circ$), the weak planes remain in a stable region and the increase in collapse pressure is limited. As the inclination angle increases further, although the shear stress on the weak planes rises, the “anchoring” effect of the normal stress remains strong; therefore, the increase in collapse pressure is significantly lower than that in the σ_h direction. These results indicate that drilling in the σ_H direction effectively suppresses slip along weak planes and is beneficial for wellbore stability.

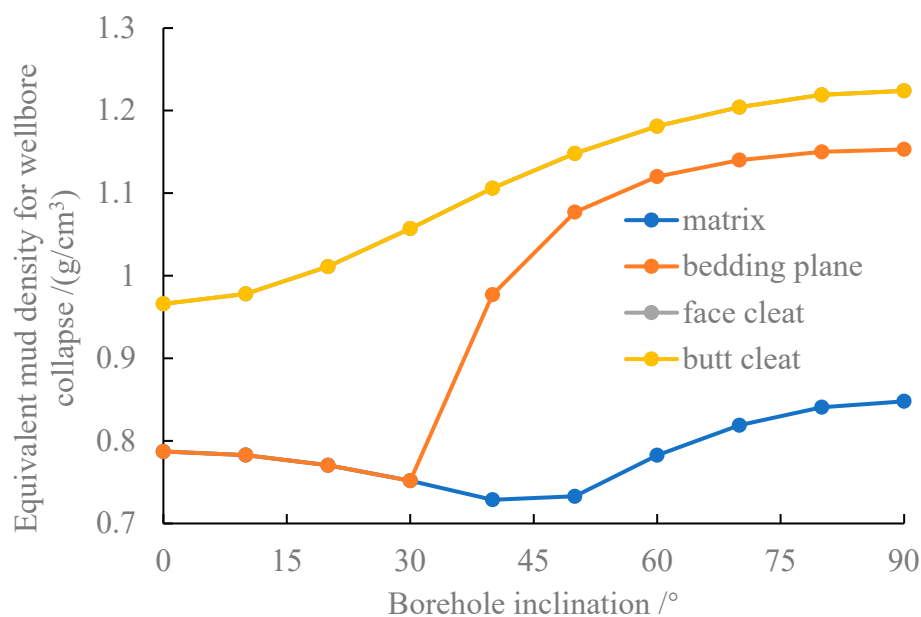


Figure 5. Variation pattern of equivalent drilling fluid density for borehole wall collapse in the direction of minimum horizontal principal stress with well inclination angle.

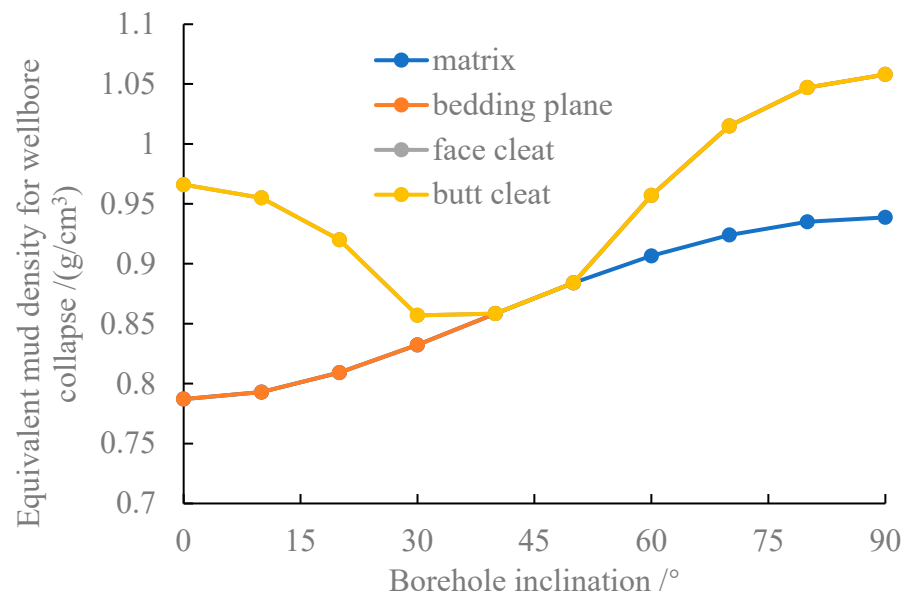


Figure 6. Variation pattern of equivalent drilling fluid density for borehole wall collapse in the direction of maximum horizontal principal stress with well inclination angle.

Figure 7 presents the variation in equivalent collapse pressure drilling fluid density with wellbore azimuth for horizontal wells. Azimuth transformation analysis of the wellbore stress field shows that when the wellbore azimuth aligns with the σ_h direction (0° or 180°), the maximum shear stress around the wellbore is minimized, and the shear stress acting on the weak planes is also lowest, resulting in the minimum collapse pressure. As the azimuth deviates from the σ_h direction, the spatial orientation of the weak planes relative to the principal stresses changes, causing the shear stress component on the weak planes to gradually increase. Consequently, wellbore stability deteriorates and collapse pressure rises. When the azimuth is perpendicular to the σ_h direction (i.e., approaching the σ_H direction), the wellbore stress state is most unfavorable for weak-plane stability, and the collapse pressure reaches a maximum. These findings, from the perspectives of stress tensor transformation and weak-plane failure mechanisms, confirm the significant controlling role of in situ stress direction on wellbore stability, and that drilling along the σ_h direction optimizes the stress distribution around the wellbore and substantially reduces the risk of slip along weak planes.

The combined analysis indicates that the multiple sets of weak planes (bedding planes, face cleats, and butt cleats) in coal rock are highly sensitive to stress field variations under complex wellbore trajectories. When drilling in the σ_H direction or at high inclination angles, the coupling between the wellbore trajectory and the spatial configuration of the weak planes significantly increases the shear stress concentration on the weak planes, thereby lowering the critical condition for weak-plane failure and raising the collapse pressure. In contrast, drilling in the σ_h direction effectively improves the stress distribution around the wellbore and controls shear sliding along weak planes, representing a key trajectory design strategy for optimizing wellbore stability.

3.3. Influence of Wellbore Trajectory on Wellbore Instability

To further reveal the spatial influence characteristics of different weakness plane structures on wellbore collapse pressure, this study conducts parametric numerical simulations based on the multi-weakness-plane strength criterion and the wellbore stress coupling model established in Section 2. The input parameters are listed in Tables 1 and 2. The analysis focuses on the variation patterns of equivalent collapse pressure (drilling fluid density) with wellbore trajectory—specifically, wellbore inclination angle and azimuth

angle—under the influence of different coal rock structures, as shown in Figures 8–11. In the contour plots, the color transition from dark blue to deep purple indicates a gradual increase in the equivalent collapse pressure drilling fluid density. The circumferential direction represents the wellbore azimuth, with 0° denoting the direction of the minimum horizontal stress and 90° denoting the direction of the maximum horizontal stress. The radial direction represents the wellbore inclination angle, where the center of the circle denotes a vertical well, and the outermost ring of the nephogram denotes a horizontal well.

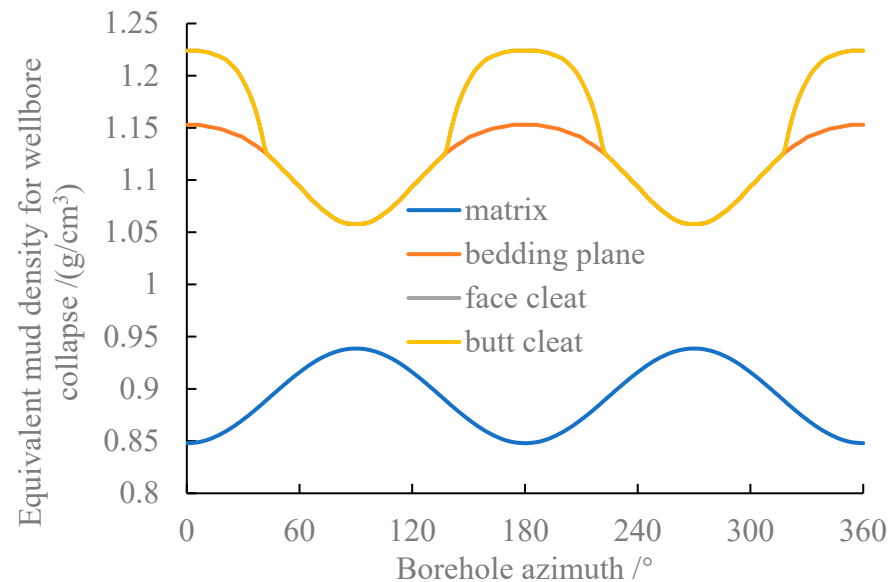


Figure 7. Variation pattern of equivalent drilling fluid density for borehole wall collapse with borehole azimuth angle.

Figure 8 shows the collapse pressure nephogram for coal rock treated as an isotropic medium, without considering the influence of weakness plane structures. It can be observed from the figure that the collapse pressure nephogram exhibits a relatively uniform concentric ring distribution. The collapse pressure primarily increases gradually with the increase in wellbore inclination, showing weak dependence on azimuth. This indicates that under the continuum assumption that ignores weakness planes, wellbore stability is mainly controlled by the inclination angle, with generally low overall risk and a relatively symmetric distribution. Figure 9 presents the collapse pressure nephogram when only the influence of bedding planes is considered. It can be seen that after considering bedding planes, the collapse pressure distribution begins to exhibit directional differences. Particularly in regions where the wellbore inclination exceeds 45° and the azimuth approaches the bedding dip direction (around 180°), the collapse pressure increases significantly. This suggests that bedding planes, as single weakness planes, are easily activated at specific orientations, leading to localized deterioration of stability.

Figure 10 displays the collapse pressure nephogram when considering the influence of bedding planes and face cleats while neglecting butt cleats. It is evident from the figure that after incorporating bedding planes and face cleats, the complexity and non-uniformity of the collapse pressure distribution become more pronounced. Multiple high collapse pressure zones appear in the nephogram, especially in areas with azimuths of $0\text{--}60^\circ$ and $120\text{--}180^\circ$ and wellbore inclinations greater than 60° . The introduction of face cleats enhances the wellbore's sensitivity to stresses from various directions. Particularly when the angle between the wellbore trajectory and the strike of the face cleats is small, shear stress concentration becomes significant, increasing the collapse risk. Figure 11 illustrates the collapse pressure nephogram when considering all structural influences, including bedding

planes, face cleats, and butt cleats. It can be observed that the collapse pressure distribution becomes most complex, exhibiting distinct multi-extremum characteristics. High-collapse-pressure zones are concentrated in areas with azimuths of $30\text{--}60^\circ$ and $150\text{--}180^\circ$, and wellbore inclinations greater than 50° . Due to the combined effect of the three sets of weakness planes, wellbore instability may occur in multiple directions. When the wellbore trajectory approaches the strike of any one of these weakness plane sets, it is prone to induce synergistic failure involving multiple weakness planes.

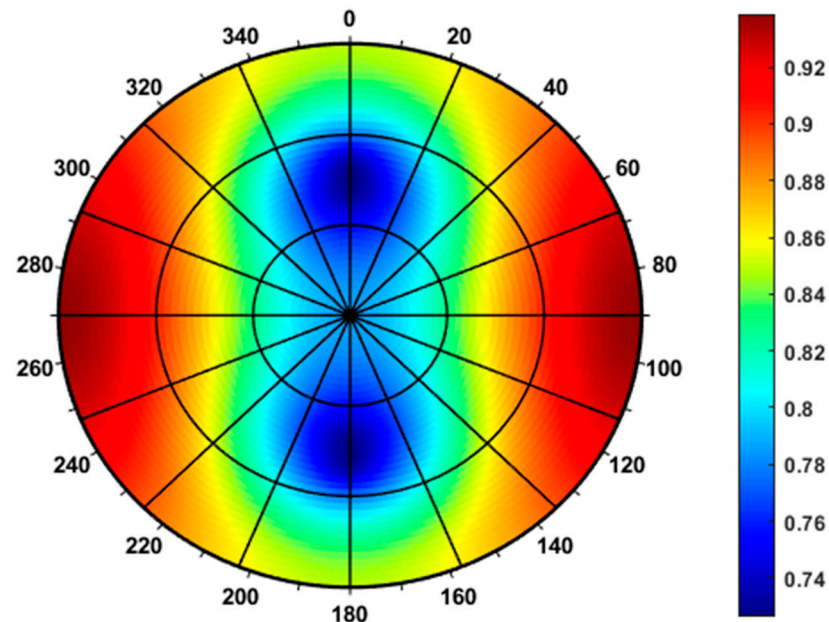


Figure 8. Cloud map of borehole wall collapse pressure without considering the influence of weak plane structure.

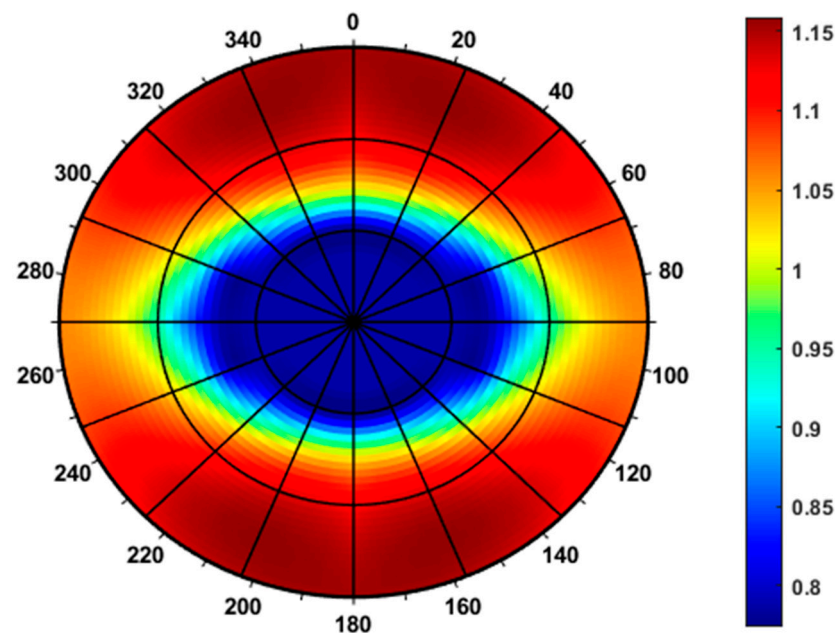


Figure 9. Cloud map of borehole wall collapse pressure considering only the influence of bedding.

The analysis indicates that the introduction of weakness planes significantly alters the distribution characteristics of wellbore collapse pressure, gradually transitioning from continuous and uniform to highly non-uniform and direction-dependent. Under a multi-weakness-plane system, the sensitivity of wellbore stability to wellbore trajectory—

particularly azimuth—is significantly enhanced. Moreover, as the number of weakness planes increases, the zones of high collapse pressure gradually expand and become more dispersed, indicating that multi-weakness-plane systems exacerbate the risk of localized and anisotropic wellbore failure. In practical drilling design, wellbore trajectories that closely align with the strikes of multiple sets of weakness planes should be avoided as much as possible. Especially under conditions of high wellbore inclination, careful selection of wellbore azimuth is critical to reducing collapse risk. It is recommended to prioritize drilling along the direction of the minimum horizontal stress and optimize the combination of wellbore inclination and azimuth based on weakness plane orientations to achieve a safe and economical wellbore trajectory design.

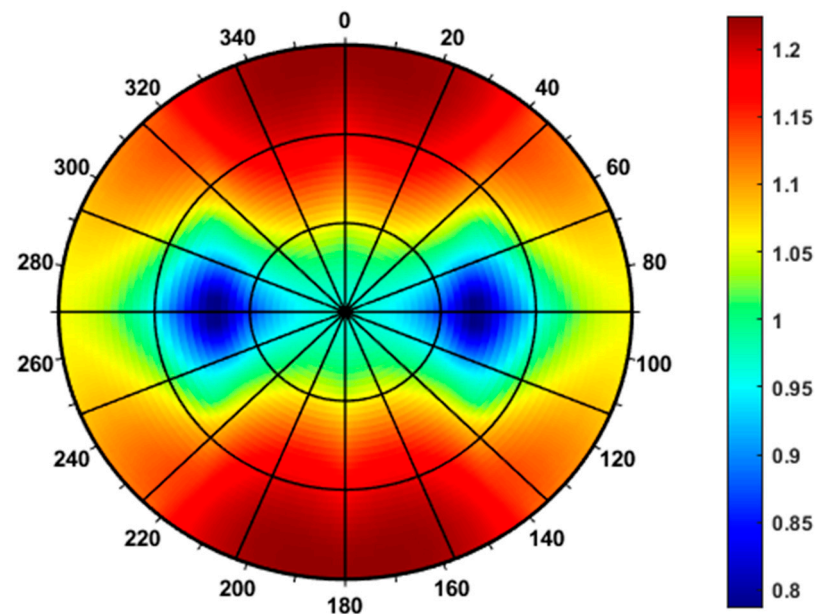


Figure 10. Cloud map of borehole wall collapse pressure considering the influence of bedding and face cleats.

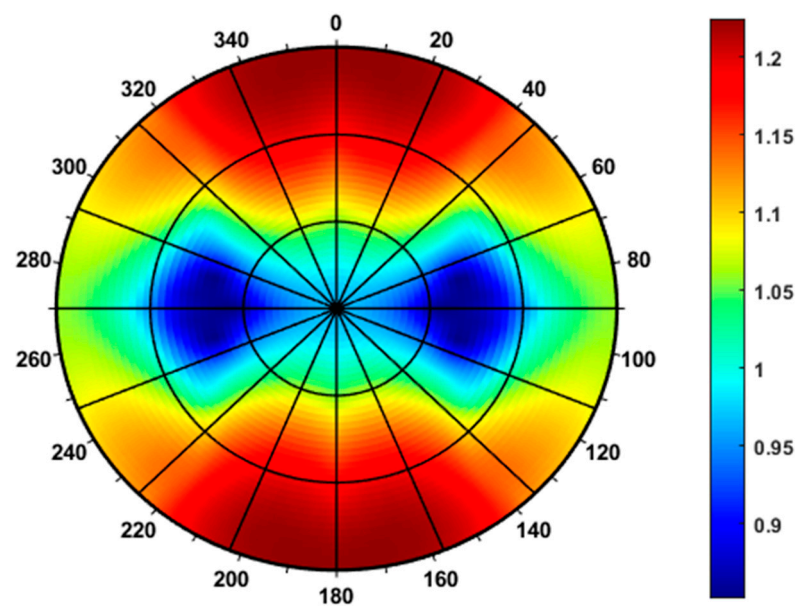


Figure 11. Cloud map of borehole wall collapse pressure considering the influence of bedding, face cleats, and butt cleats.

4. Conclusions

This study addresses the challenge of wellbore instability during coal seam drilling by establishing a stability analysis method for coal rock systems with multiple weakness planes. By integrating multi-weakness-plane strength criteria with a wellbore stress model that accounts for dual-porosity characteristics and drilling fluid seepage, the proposed approach overcomes the limitations of traditional continuum methods in characterizing the discontinuous and anisotropic nature of coal rock. The main conclusions are as follows:

(1) Wellbore trajectory significantly influences instability. Drilling along the direction of minimum horizontal stress minimizes collapse pressure by mitigating the adverse effects of weakness planes. In contrast, drilling along the maximum horizontal stress direction or at high inclination angles activates weakness planes and induces synergistic failure, leading to a sharp increase in collapse pressure.

(2) The presence of multiple weakness planes expands high collapse pressure zones and increases the risk of localized wellbore failure. In practice, wellbore trajectories aligned with the strikes of multiple weakness sets should be avoided; under high-inclination conditions, azimuth should be carefully optimized to reduce collapse risk.

(3) The findings support the rational determination of safe drilling fluid density windows and enable synergistic optimization of mechanical and chemical measures for wellbore stability.

Future work could incorporate multi-field coupled numerical simulations, experimental validation, and machine learning-based intelligent decision-making to enable real-time optimization and risk warning in coalbed methane drilling.

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