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Study on Prediction of Wellbore Collapse Pressure of the Coal Seam Considering a Weak Structure Plane

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Abstract: To investigate the influence of weakly structured formations on wellbore stability in deep coal seams within the Lufeng Block, this study establishes an innovative predictive model for coal seam wellbore collapse pressure. The model integrates mechanical parameter variations along weak structural planes with the Mohr–Coulomb criterion, leveraging experimental correlations between mechanical properties and bedding angle. Key findings reveal that the coal sample demonstrates enhanced compressive strength and elastic modulus under elevated confining pressures. A distinctive asymmetric "V" pattern emerges in mechanical parameter evolution: compressive strength, elastic modulus, cohesion, and internal friction angle initially decrease before recovering with increasing bedding angle, reaching minimum values at a 60° bedding angle. Comparative analysis demonstrates that the proposed model predicts a higher collapse pressure equivalent density than conventional Mohr–Coulomb approaches, particularly when accounting for mechanical parameter alterations along weak structural planes. Field validation through coal seam data from the operational well confirms the model's effectiveness for stability analysis in weakly structured coal formations within the Lufeng Block. These findings provide critical theoretical support for wellbore stability management in deep coal seam engineering applications.

Keywords: Lufeng block; bedding angle; collapse pressure; wellbore stability; Mohr–Coulomb criterion

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1. Introduction

The deep geological conditions in the Lufeng area of China are complicated; the coal strata are widely distributed, and the stability of the coal seam is poor. When the coal seam is drilled in the drilling operation, borehole collapse and instability accidents often occur. The study on the case of wellbore instability in the Lufeng deep formation shows that the coal seam with a weak structural plane is especially prone to borehole collapse, which causes the borehole drilling project to be abandoned and seriously restricts the rapid development of drilling technology in the Lufeng area. In order to ensure the safety of drilling in the Lufeng area, it is necessary to clarify the influence mechanism of a weak structure plane on the mechanical properties of the coal seam and establish a correct prediction model of the coal seam collapse pressure.

At present, domestic and foreign scholars have carried out a lot of experimental research to study the effect of weak structure on rock mechanical properties. Holt [1], Heng Shuai [2], Yan [3] et al. studied the anisotropic mechanical strength of all kinds of rocks with a weak structural plane and obtained the mechanical strength anisotropy and

strength anisotropy degree of rocks with a weak structural plane under different confining pressures. Ong [4], Roegiers [4], Wang [5] et al. pointed out that the elastic modulus of rocks with a weak structural plane has obvious anisotropy, and the difference between the angle of the weak structure plane and the loading direction of the rock will lead to a huge difference in its elastic modulus, and the difference of elastic parameters is one of the necessary factors for building a wellbore stability model. Jaeger [6] proposed the classical strength criterion of a single weak structure plane of rock, pointing out that the weak structure plane of rock and the rock body have different mechanical parameters such as cohesion and internal friction angle, and the rock will have shear failure along the weak structure plane under certain loading directions, while the rock will fail through the rock mass in some loading directions.

Based on the experimental study of rock mechanics parameters changing with the weak structure plane, scholars have established a large number of collapse pressure prediction models to analyze wellbore stability. Considering the influence of hydration reaction on rock strength, Qi [7] et al. established a safe density window for shale drilling. Han [8] et al. studied the rock mechanical properties and wellbore stability mechanism of well 201 in the Sichuan Basin. Larki, E [9] considered the yield area under different mud weights and obtained the ideal and optimal pressure range by investigating and analyzing the output plasticity chart of the FLAC 3D software while applying UBD conditions to ensure wellbore stability. Jin et al. [10,11] established a mechanical model of drilling fluid density safety window in formation with high bedding angle and analyzed the influence of inclination and strike of inclined formation on wellbore stability. Ma et al. [12] established a mechanical analysis model for wellbore stability of shale with a weak structural plane to analyze the effects of weak structure plane inclination and wellbore trajectory on wellbore stability. In order to reflect the anisotropy of rock mechanical parameters such as elastic modulus and Poisson's ratio in wellbore stability, Amadei [13], Aadony [14], Pei [15], Li [16] et al., based on the linear elastic anisotropy theory, established a solution model for borehole collapse pressure and fracture pressure considering rock elastic parameters. Gao [17] et al. used the discrete element method to analyze wellbore stability in fractured formation and proposed a new method for fracture modeling by using formation microscanner images and image processing technology. Li [18] integrated the Monte-Carlo method and BP neural network methods to analyze wellbore stability and instability probability and evaluated the influencing factors of wellbore stability. Ma et al. [19], considering the influence of pore pressure propagation, ground stress, and wellbore pressure, put forward the Hoek–Brown criterion to predict wellbore stability of fractured formation.

In summary, scholars have comprehensively analyzed the influence mechanism of wellbore stability in strata with a weak structural plane through experimental research and elastic parameter theoretical model establishment [20–39], as shown in Table 1. On the one hand, most of the models only consider the influence of anisotropy of rock elastic modulus with a structural plane on wellbore stability, ignoring the influence of mechanical parameters such as cohesion and internal friction angle. On the other hand, there are few studies on the stability of coal's weak structural plane due to factors such as brittleness, low hardness, difficulty in coring, and complex structure.

The main purpose of this paper is to provide theoretical support for the stability analysis of a deep coal seam with a weak structural plane. In Section 2, an experimental analysis of the microstructure and mechanics of the coal block in the target area is carried out to study the effect of bedding on the mechanical properties of the coal rock. In Section 3, the experimental results and the Mohr–Coulomb criterion are combined to construct the coal seam wellbore collapse pressure prediction model considering a weak structure plane. In Section 4, the established model is applied to the calculation of the collapse pressure

under the condition of coal seam drilling on site, and the correctness and rationality of this model are verified.

Table 1. Research status of wellbore stability with a weak plane.

Research Category	Researcher	Research Content	Inadequate Research
Experimental study on mechanical properties of rock with weak structure plane	Holt [1], Yan [3], Ong [4], Roegiers [6], Wang [5] et al.	The influence of weak structure plane on elastic modulus and failure form of rock was studied.	In particular, the characteristics of coal and rock cohesion and internal friction angle change with a weak structural plane are lacking.
Research on the prediction model of isotropic borehole collapse pressure	Qi [7], Han [8], Larki, E [9] et al.	Based on rock mechanics parameters and empirical formulas, calculation models of isotropic formation collapse pressure were established.	The influence of rock anisotropy on formation collapse pressure is not considered.
Study on formation collapse pressure model considering rock anisotropy	Jin [10,11], Ma [12], Amadei [13], Aadony [14], Pei [15], Li [16] et al.	Prediction models of formation collapse pressure considering rock elastic modulus, Poisson ratio, and other mechanical parameters were established.	In particular, the coal seam collapse pressure calculation model that fully considers the characteristics of cohesion, internal friction angle, and elastic modulus with a weak plane is lacking.

2. Experimental Content

2.1. Coal Sample Microstructure

The coal was taken from the well in the Lufeng area, and the coal quality analysis shows that the carbon content of the coal sample is 60.45%, the total moisture is 17.2%, and it is low volatile lignite. The surface microstructure of the coal sample at 100 and 250 times magnification was obtained by scanning electron microscopy. As shown in Figure 1, it can be observed from the image at 100 times magnification that the surface of the coal and rock samples is rough, and the fracture structure is obvious. More cracks exist alone, the development has a single direction, and there are few fork structures in the image at 100 times magnification. As shown in Figure 2, it can be observed from the image at 250 times magnification that the surface microstructure of the coal and rock has obvious changes, and there are more gravels on the surface. Intergranular skeleton pores of different sizes are formed by the mutual support and overlap of mineral particles. Figure 2 shows that the pore size is 0.44 μm, the pore shape is basically irregular, the pore size is different, and there are few granular minerals in the pores, providing a large amount of storage space for coal and rock. In addition, the pores are connected with each other, and the connectivity of the internal structure is good. In summary, the fracture structure of the coal and rock samples is obvious and well-developed. The pores are irregular in shape and have a certain connectivity among them. The good development of pores improves the connectivity and permeability of coal and rock samples.

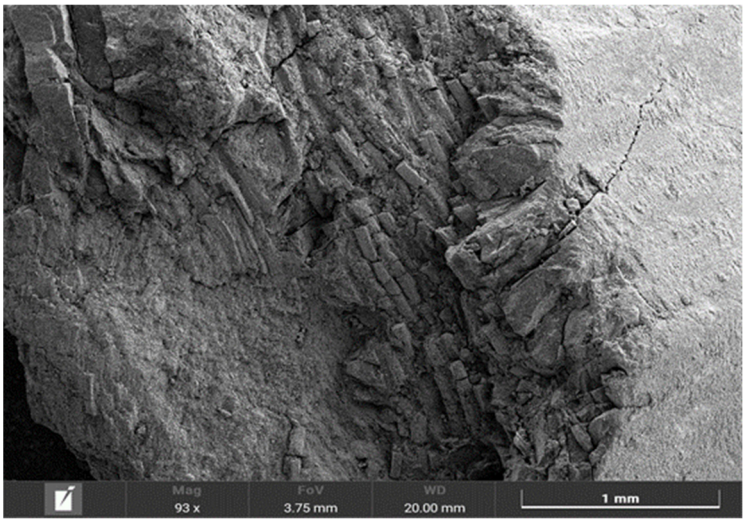


Figure 1. 100× scanning electron microscope.

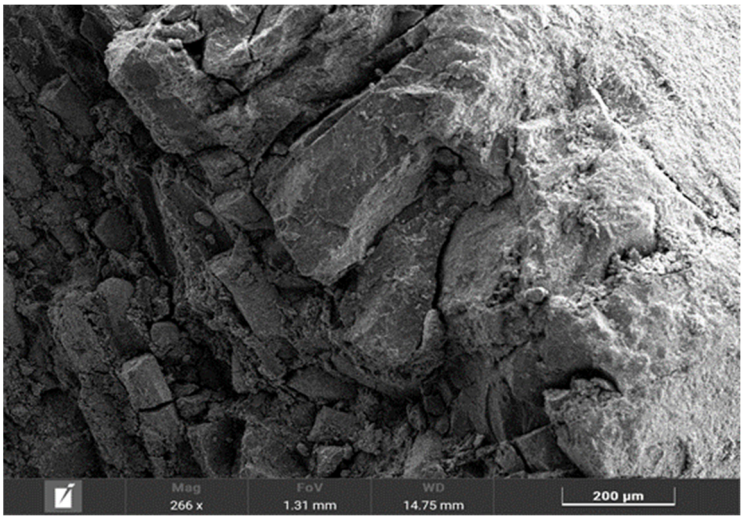


Figure 2. 250× scanning electron microscope.

2.2. Coal Sample Preparation

The coal blocks used in the mechanical experiments were obtained from the surface mine because coring coal blocks while drilling is extremely difficult. Then, the microcomposition analysis and nanoindentation experiment were carried out to verify the similarity between the coal samples used in the experiment and the coal seam. On the one hand, through the comparative analysis of the surface mine coal and the Lufeng coal mine at the target formation under the same layer, it is found that the content of the main component (silica) affecting the strength of the two coal rocks is basically the same. Among them, No. 2 coal dust contains some coal gangue, the content of silica is relatively high, and the content of carbon is relatively low, as shown in Figure 3. On the other hand, the mechanical parameters of the two coal samples under the same peak load were obtained through the nanoindentation experiment, as shown in Table 2. The results show that the minimum elastic modulus, robustness coefficient, and fracture toughness values of the two coal samples are similar, and the deviation is less than 5%. Comprehensive analysis shows that the coal samples used in the experiment can be replaced by surface mine coal samples.

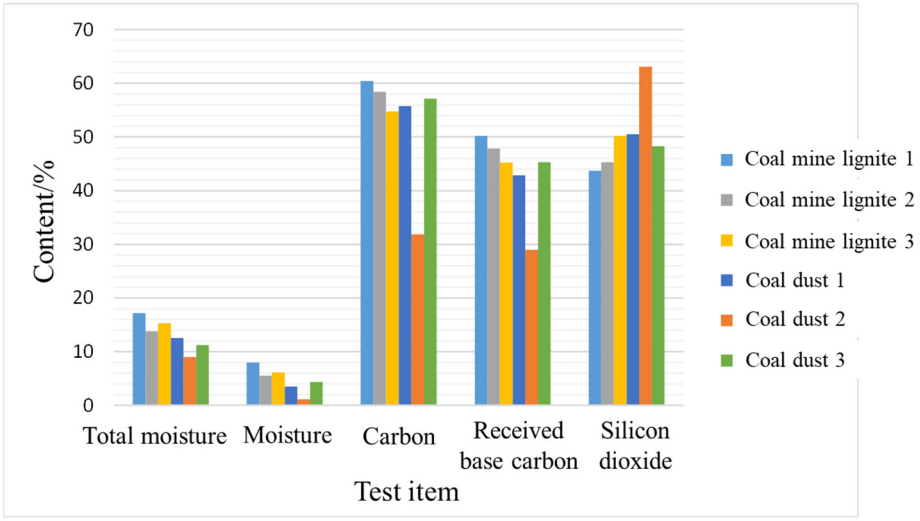
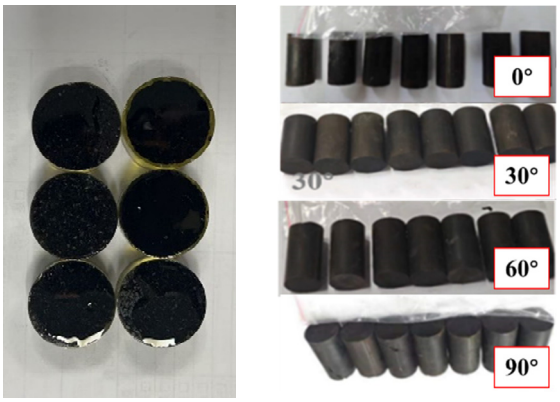


Figure 3. Comparison of elemental components in coal samples.

Table 2. Experiment results.

Core Label	Peak Load/mN	Minimum Elastic Modulus/GPa	Robustness Coefficient/GPa	Fracture Toughness/MPa·m$^{0.5}$
Coal mine lignite 1	50	1.26	0.121	0.072
Coal mine lignite 2	50	1.34	0.132	0.081
Coal mine lignite 3	50	1.24	0.118	0.072
Coal dust 1	50	1.17	0.112	0.069
Coal dust 2	50	1.29	0.120	0.072
Coal dust 3	50	1.31	0.126	0.075

In the process of preparing the standard sample of the coal rock, firstly, a 25 mm diameter drill bit is used for the coring operation, and the obtained coal rock is cut into a cylinder of 50 mm length. Finally, the machine tool is used for the meticulous grinding treatment to ensure that the upper and lower surfaces of the standard sample are parallel and smooth, and the size is accurately controlled to meet the preparation requirements of the standard sample. During the coring process, in order to clearly distinguish the size of the delamination bedding angle, the coal samples with different bedding angles of 0 °C, 30 °C, 60 °C, and 90 °C were obtained by adjusting the bedding angle between the drill rig and the coal block, as shown in Figure 4b.



(**a**) (**b**)

Figure 4. Coal sample for experiments. (**a**) Coal sample for nanoindentation experiment. (**b**) Standard cylindrical core.

2.3. Mechanical Experimental Scheme

In order to study the influence of different bedding angles on the mechanical properties of the coal cores, the TAW-1000 multifunctional rock triaxial test system was used to carry out triaxial compression experiments of the cores with different bedding angles under different confining pressure conditions. In order to characterize the effective stress of the actual coal seam in the target block, the confining pressure selected in this experiment is 30 MPa, 40 MPa, and 50 MPa. Due to the thin thickness of the target coal seam, the effective stress in the coal seam area can be considered as a certain average value. According to the pore pressure and ground stress measured on site, the effective stress of the target coal seam is about 38 MPa. Therefore, the triaxial mechanical experiment of the samples under the confining pressure of 40 MPa was carried out to obtain the elastic modulus and Poisson's ratio of the target coal seam. In order to obtain the cohesion and internal friction angle of the target coal seam, it is necessary to carry out the triaxial mechanical experiments of the coal samples under at least three sets of the confining pressure, so the triaxial mechanical experimental of the coal samples under confining pressure of 30 MPa and 50 MPa are added. During the experiment, the loading and unloading rate of confining pressure is 50 kPa/s, and the core is axially loaded in displacement loading mode, and the loading rate is 0.1 mm/min. The specific experimental scheme is displayed in Table 3.

Table 3. Experiment scheme.

Core Label	Bedding Angle/°	Diameter/mm	Height/mm	Quantity/g	Confining Pressure/MPa
M-1	0	24.61	49.97	29.16	30
M-2	30	24.58	48.97	28.23	30
M-3	60	24.70	49.60	29.07	30
M-4	90	24.60	49.60	29.43	30
M-5	0	24.62	49.91	29.37	40
M-6	30	24.71	50.00	29.17	40
M-7	60	24.70	49.54	29.09	40
M-8	90	24.70	50.08	29.25	40
M-9	0	24.69	50.32	29.28	50
M-10	30	24.68	50.72	29.19	50
M-11	60	24.52	50.20	28.95	50
M-12	90	24.96	49.67	29.35	50

2.4. Mechanical Experiment Results

2.4.1. Stress–Strain Curve Characteristics

The stress–strain curves of cores with different bedding angles are obtained by triaxial mechanics experiments. As shown in Figures 5–8, the stress–strain curves of the core are all parabolic, and the curves can be divided into the initial compaction stage, elastic deformation stage, plastic yield stage, and failure stage. The compaction stage of the coal sample core in the initial loading stage is not obvious because the micro-fractures and pores in the core have been fully compacted when high confining pressure is applied. The elastic deformation stage is immediately followed by the compaction stage, and the stress and strain of the curve in this stage are linear and obey Hooke's law. The elastic modulus and Poisson's ratio of the core can be obtained by fitting the linear slope at this stage. With the continuous increase of stress, micro-cracks and pores in the core continue to increase, and macro-cracks begin to appear. At this time, irreversible damage occurs and accumulates inside the core, and the core enters the plastic yield stage. When the core reaches the

bearing limit, the core is destroyed along the fracture surface, the stress begins to decrease gradually, and the core is in the failure stage.

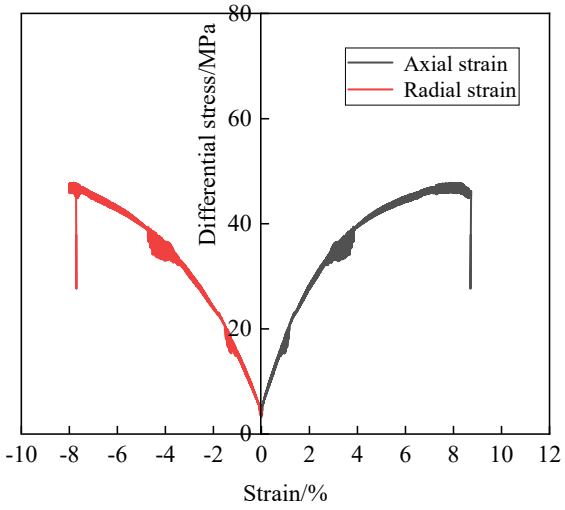


Figure 5. Core stress-strain curve of 50 MPa confining pressure and bedding angle of 90°.

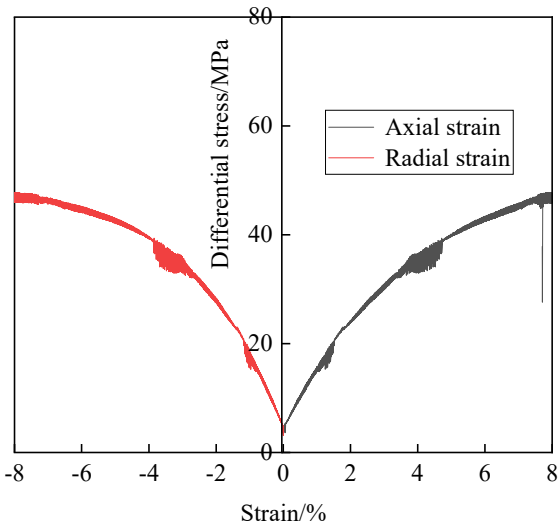


Figure 6. Core stress-strain curve of 50 MPa confining pressure and bedding angle of 30°.

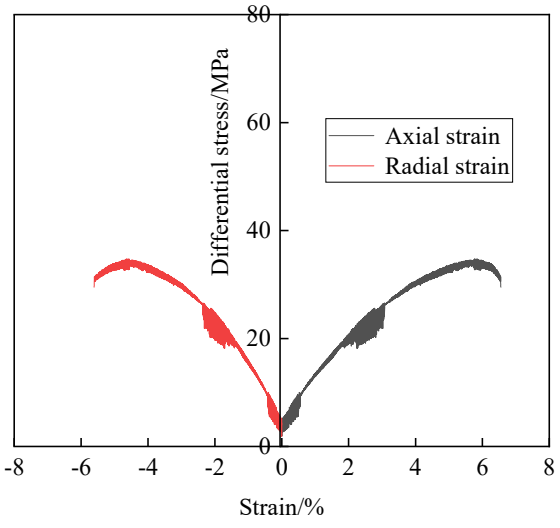


Figure 7. Core stress-strain curve of 50 MPa confining pressure and bedding angle of 60°.

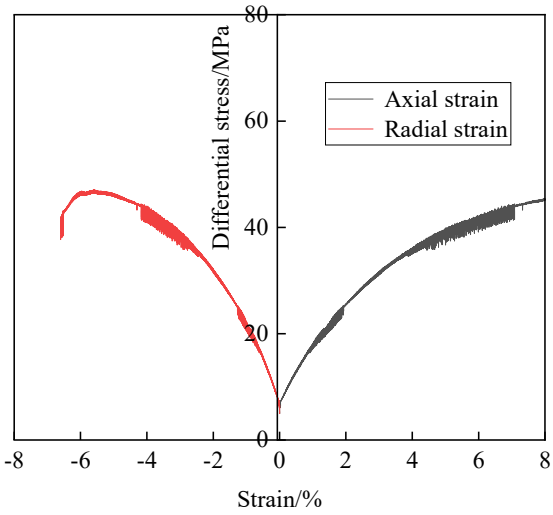


Figure 8. Core stress-strain curve of 50 MPa confining pressure and bedding angle of 0°.

The characteristic of the coal rock stress–strain curve is closely related to the microfracture-cavity structures in the coal rock. On the one hand, a large number of microfracture-cavity structures result in the coal rock's low overall strength, so the peak strength of the stress–strain curve is low. On the other hand, a large number of microfracture-cavity structures in the coal lead to sufficient fracture development in the plastic yield stage of coal rock, so the plastic yield stage of coal rock is long.

2.4.2. Variation Characteristics of Mechanical Parameters with Bedding Angle

As the confining pressure increases from 30 MPa to 50 MPa, the compressive strength of the coal core increases under the same coring angle. The analysis shows that confining pressure makes a large number of pores and fractures in the coal core tend to close, and confining pressure is one of the important external factors affecting rock mechanical properties. The greater the confining pressure, the stronger the constraint effect on the core, the more obvious the internal compaction effect of the core, and the stronger the resistance to failure of the core. With the confining pressure increasing from 30 MPa to 50 MPa, the elastic modulus of the coal core increases under the same coring angle. According to the Mohr–Coulomb strength criterion, there is a certain relationship between the shear strength of the coal core and the normal stress. When the confining pressure increases, the normal stress on the structural plane increases, and the friction on the structural plane also increases, resulting in the increase of the overall shear strength of the coal core. The elastic modulus is a measure of the material's resistance to deformation. With the increase of the shear strength, the elastic modulus of the coal core increases correspondingly.

According to the stress-strain curve, the elastic modulus and compressive strength of the core with different bedding angles under different confining pressure conditions are obtained. Based on the Mohr–Coulomb criterion, the cohesion and internal friction angles of the cores with different bedding angles are obtained. Based on the different confining pressures σ_3 and their corresponding axial stresses σ_1, the stress Mohr-circles with different diameters are plotted, the envelope of which is the shear strength curve of rock. The changing characteristics of the core mechanical parameters with bedding angles are described in Figure 9. The compressive strength, elastic modulus, cohesion, and internal friction of the coal cores with different bedding angles are different. With the increase of the bedding angle, the compressive strength, elastic modulus, cohesion, and internal friction angle of the coal core all decrease first and then increase, and the change curve presents an asymmetric "V" shape. When the bedding angle is 60°, the mechanical parameter value of the coal core is the smallest, and 60° is also called the critical point where the mechanical

parameter of the coal core changes with the bedding angle. In addition, the sample fracture mode is closely related to the angle of the weak structure plane. Although the fracture mode of the samples under triaxial confining pressure is shear failure, the fracture of the samples with the 0° and 90° angles between the weak structure plane and the loading direction is basically not affected by the weak structure plane. The shear failure of the sample with a 60° angle between the weak structure plane and the loading direction is mainly along the weak structure plane.

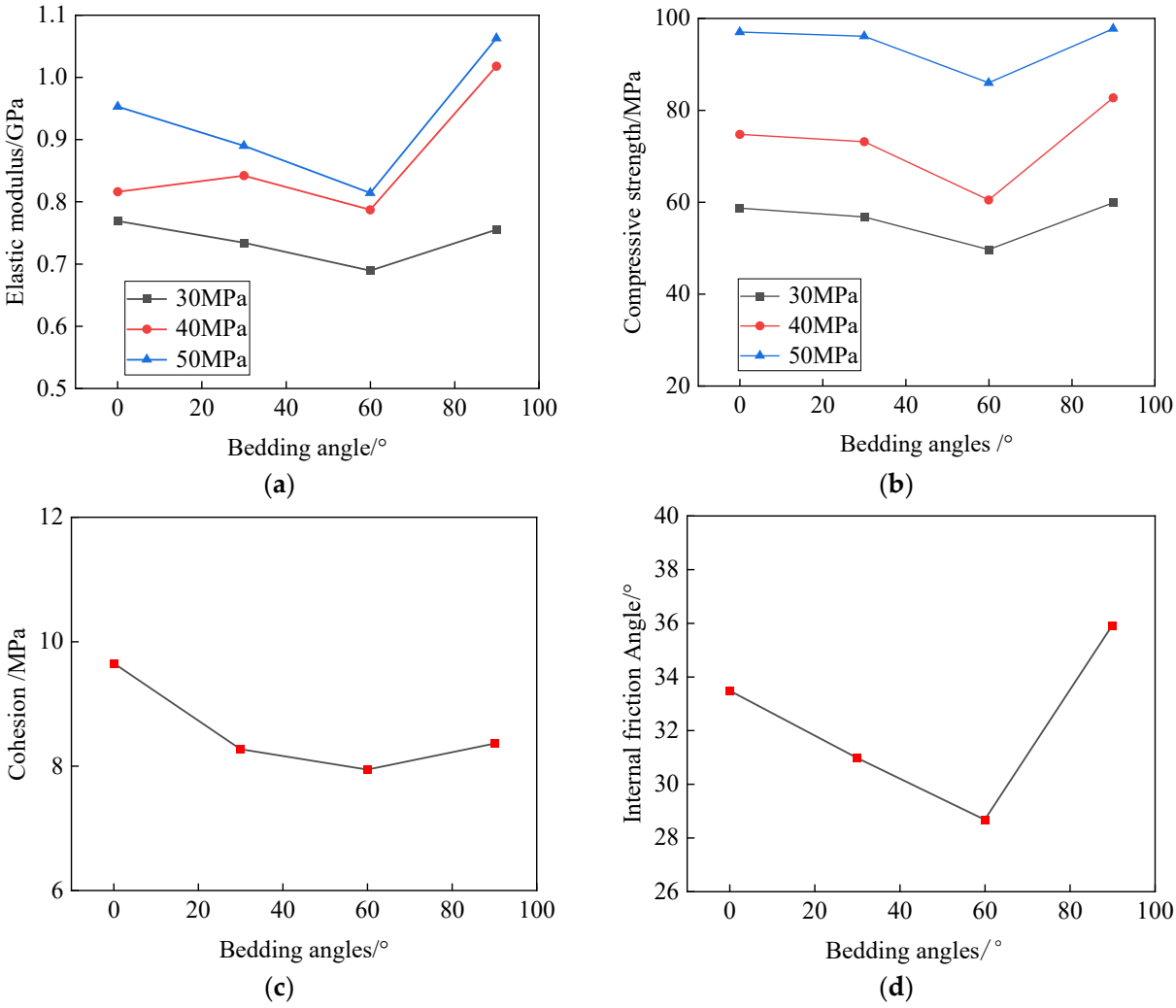


Figure 9. Variation characteristics of mechanical parameters with bedding angle. (**a**) Elastic modulus. (**b**) Compressive strength. (**c**) Cohesion. (**d**) Internal friction angle.

3. Wellbore Collapse Pressure Prediction Model Considering Weak Structure Plane

3.1. Wellbore Stress Distribution Transformation

Drilling in rock mass will cause the effect of stress concentration around the well. In this study, the rock mass is considered a uniform, linear, elastic, and isotropic medium. The principle of establishing the model is to judge whether the rock has a weak structure plane failure or body failure by judging the angle between the maximum principal stress and the weak structure plane. Therefore, it is necessary to calculate the value of principal stress and the relation between the maximum principal stress and the relative orientation of the weak structure plane. As shown in Figure 10, through the Cartesian coordinate system, the borehole coordinates are transformed to simplify the original ground stress level of the coal

seam to the three-way principal stress. In fact, when only borehole failure is considered, the distribution of the lateral stress around the wellbore is described as follows:

$$\begin{cases} \sigma_r = p_i - \delta\varphi(p_i - p_p) \\ \sigma_\theta = \sigma_{xx} + \sigma_{yy} - 2(\sigma_{xx} - \sigma_{yy})\cos 2\theta - 4\sigma_{xy}\sin 2\theta + \delta\left[\frac{\alpha_b(1-2\nu)}{1-\nu} - \varphi\right](p_i - p_p) \\ \sigma_z = \sigma_{zz} - 2\nu\left[(\sigma_{xx} - \sigma_{yy})\cos 2\theta + 2\sigma_{xy}\sin 2\theta\right] + \delta\left[\frac{\alpha_b(1-2\nu)}{1-\nu} - \varphi\right](p_i - p_p) \\ \tau_{\theta z} = 2(\sigma_{yz}\cos\theta - \sigma_{xz}\sin\theta) \\ \tau_{rz} = \tau_{r\theta} = 0 \end{cases} \quad (1)$$

where, σ_{xx}, σ_{yy}, σ_{zz} are the horizontal components of the ground stress in the X, Y, and Z axes in the Cartesian coordinate system, respectively, MPa; X*, Y*, Z* are the original three axes. $\tau_{\theta z}$, $\tau_{r\theta}$, τ_{rz} are the shear stresses in the θz, $r\theta$, and rz planes in the cylindrical coordinate system, respectively, MPa; σ_{xy}, σ_{xz}, σ_{yz} are the ground stresses in the XY, XZ, and YZ planes in the Cartesian coordinate system, respectively, MPa; σ_r, σ_θ, σ_z are the radial, circumferential, and axial normal stresses in the cylindrical coordinate system, respectively, MPa; θ is the circumferential angle, °; φ is the porosity, %; ν is the Poisson's ratio; p_i is the liquid column pressure, MPa; α_b is the Biot coefficient; p_p is the pore pressure, MPa; δ is the wellbore coal permeability coefficient. When the value of δ is 1, the borehole is permeated, and the borehole is impermeable when the value of δ is 0.

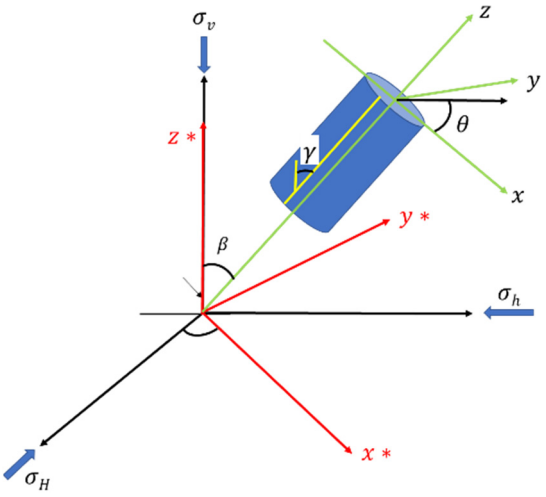


Figure 10. Diagram of conversion relationship of wellbore coordinates.

According to Formula (1), the magnitude and direction of the three principal stresses at the coal rock borehole are derived, and the principal stresses at the borehole are shown as follows:

$$\begin{cases} \sigma_i = p_i - \delta\varphi(p_i - p_p) \\ \sigma_j = \frac{\sigma_z - \sigma_\theta}{2} + \sqrt{(\sigma_\theta - \sigma_z)^2 + \tau_{\theta z}^2} \\ \sigma_k = \frac{\sigma_z - \sigma_\theta}{2} - \sqrt{(\sigma_\theta - \sigma_z)^2 + \tau_{\theta z}^2} \end{cases} \quad (2)$$

where σ_i, σ_j, σ_k are the three principal stresses at the borehole, respectively, MPa.

Among the three principal stresses, the largest value is the maximum principal stress σ_1, and the smallest value is the minimum principal stress σ_3. σ_1 and σ_3 are substituted into the failure criterion of weak plane rock to calculate the collapse pressure.

The angle c between the maximum principal stress σ_1 at the borehole and the Z axis is obtained, as shown in Equation (3):

$$c = \frac{1}{2}\arctan\frac{2\sigma_\theta}{\sigma_\theta - \sigma_Z} \tag{3}$$

Combined with Formula (3), the direction vector of the normal direction of the bedding plane and the direction vector of the maximum principal stress are derived, as shown in Formulas (4)–(8) below:

$$n = \sin a \cos b \vec{i} + \sin a \sin b \vec{j} + \cos a \vec{k} \tag{4}$$

$$N = b_1 \vec{i} + b_2 \vec{j} + b_3 \vec{k} \tag{5}$$

$$b_1 = \cos\phi \cos r \sin\theta - \sin\phi \cos\theta + \cos\phi \sin r \cos c \tag{6}$$

$$b_2 = \sin\phi \cos r \sin\theta + \cos\phi \cos\theta + \sin\phi \sin r \cos c \tag{7}$$

$$b_3 = -\sin r \sin\theta + \cos r \cos c \tag{8}$$

where ϕ is the azimuth angle, °; n is the direction vector of the normal direction of the bedding plane; N is the direction vector of the maximum principal stress; a is the bedding angle, °; b is the strike azimuth, °; r is the well inclination, °.

By connecting the vertical lines (4)–(8), the angle between the normal direction and the maximum principal stress direction of the lower layer of the polar coordinate system is derived, as shown in Equation (9) below:

$$\beta = \arccos\frac{n \cdot N}{|n| \cdot |N|} \tag{9}$$

3.2. Strength Criterion of the Coal Formation Considering the Weak Structure Plane

As shown in Figure 11, based on the internal friction angle and cohesion relationship between the rock body and the weak structure plane of bedding, the normal stress σ and shear stress τ on the weak structural plane are, respectively,

$$\begin{cases} \tau = \frac{\sigma_1 - \sigma_3}{2} \sin 2\beta \\ \sigma = \frac{\sigma_1 + \sigma_3}{2} + \frac{\sigma_1 - \sigma_3}{2} \cos 2\beta \end{cases} \tag{10}$$

where σ_1 is the maximum principal stress on the coal rock body, MPa; σ_3 is the minimum principal stress on the coal rock body, MPa; β is the angle of the bedding coal rock between the normal direction of the weak structural plane and the direction of the maximum horizontal principal stress, °.

The weak plane strength theory follows the Mohr–Coulomb criterion, then:

$$\tau = c_w + \sigma \tan \varphi_w \tag{11}$$

where c_w is the cohesion of bedding coal rock, MPa; φ_w is the angle of internal friction of bedding coal rock, °.

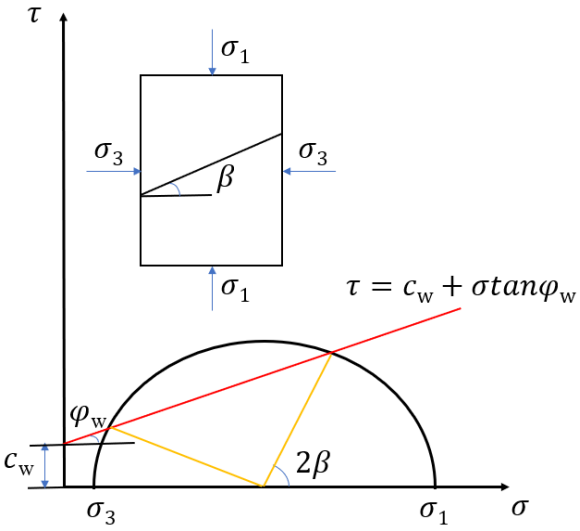


Figure 11. Mohr–Coulomb weak plane strength criterion.

By combining Formulas (1) and (2), the strength criterion of the rock weak structure plane is derived as follows:

$$\sigma_1 - \sigma_3 = \frac{2(c_w + \sigma_3 \tan \varphi_w)}{(1 - \tan \varphi_w \cot \beta) \sin 2\beta} \tag{12}$$

$$\begin{cases} \beta_1 = \frac{\varphi_w}{2} + \frac{1}{2}\arcsin\frac{(\sigma_1+\sigma_3+2c_w \cot \varphi_w) \sin \varphi_w}{\sigma_1-\sigma_3} \\ \beta_2 = \frac{\pi}{2} + \frac{\varphi_w}{2} - \frac{1}{2}\arcsin\frac{(\sigma_1+\sigma_3+2c_w \cot \varphi_w) \sin \varphi_w}{\sigma_1-\sigma_3} \end{cases} \tag{13}$$

According to the Mohr–Coulomb criterion, whether the coal rock is damaged along the main body or the weak structure plane is judged according to β, and the extreme values of the upper and lower bounds of the bedding angle are shown in Formula (4). The condition of rock failure along the weak structure plane is $\beta_1 < \beta < \beta_2$, and the relation is established after β is substituted into Formula (3). If the β is not within the angle interval of Equation (4), then the rock is damaged along the body, and the conventional Mohr–Coulomb criterion of Formula (5) is used for calculation:

$$\sigma_1 - \sigma_3 = \frac{2(c_0 + \sigma_3 \tan \varphi_0)}{(1 - \tan \varphi_0 \cot \beta_0) \sin 2\beta_0} \tag{14}$$

where c_0 is the cohesion of the coal rock body, MPa; φ_0 is the internal friction angle of the coal rock body, °; β_0 is the angle of the coal rock body between the normal direction of the structural plane and the direction of the maximum horizontal principal stress, °.

The mathematical model of the collapse pressure prediction can be applied to strata with a weak structure plane in different rock types. For the different types of strata with the weak structure plane, it is only necessary to obtain the rock cohesion, internal friction angle, elastic modulus, and other mechanical properties and substitute their values into the collapse pressure prediction mathematical model to obtain the collapse pressure distribution characteristics in this region.

3.3. Process of Solving the Collapse Pressure Considering the Weak Structure Plane

For the deep formation of a well, it is necessary to define the basic drilling data such as the distribution state of in situ stress, well trajectory, and weak structural plane orientation. Then, the angle between the direction of the maximum principal stress at the wellbore and the borehole is obtained according to the distribution of in situ stress at the horizon.

The angle between the normal direction of the weak structural plane and the direction of the maximum principal stress is obtained based on the well trajectory, the orientation of the weak structural plane, and the angle β between the maximum principal stress and the well circumference. Finally, by comparing β with the calculated β_1 and β_2 results, the failure criterion of the weak structure plane or the discriminant criterion of the rock body is selected. The detailed analysis flow of the coal seam wellbore collapse pressure prediction model is described in Figure 12.

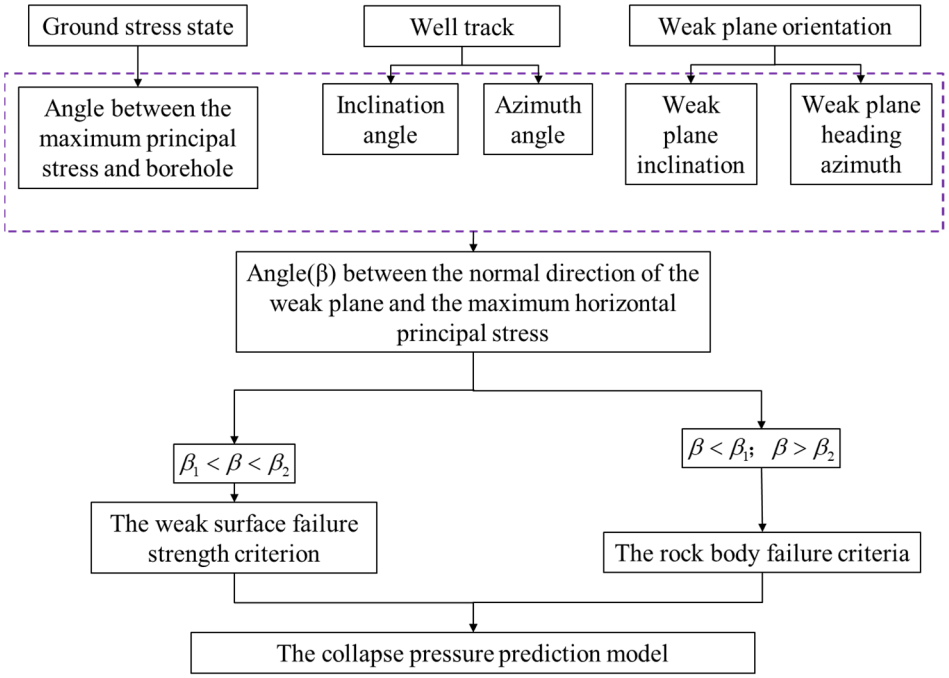


Figure 12. Coal seam wellbore stability model analysis flow.

4. Field Application of the Collapse Pressure Prediction Model

A well in the Lufeng block has been drilled into a coal seam at 3800–3900 m, and the collapse is serious during coring, and more coal dust and small coal are returned. It is determined that the coal seam section is 3840–3848 m, and the well inclination angle at the coal seam is 5°, and the angle between the weak structure plane and the borehole is 45°.

The ground stress is the basis of the coal seam collapse pressure prediction. As shown in Figure 13, strata in the Lufeng well area are controlled by normal faults, and the relative magnitude of the ground stress according to Anderson's theory is as follows: overburden pressure > maximum horizontal ground stress > minimum horizontal ground stress. According to geological exploration, the ground stress orientation in the Lufeng oilfield is about N165 °E, so the maximum horizontal ground stress orientation in this well area is determined to be about N165 °E in this study. Combined with the logging data and the inverted horizontal structural stress coefficient, the ground stress profile distribution of the formation in the well area is obtained, as shown in Figure 14.

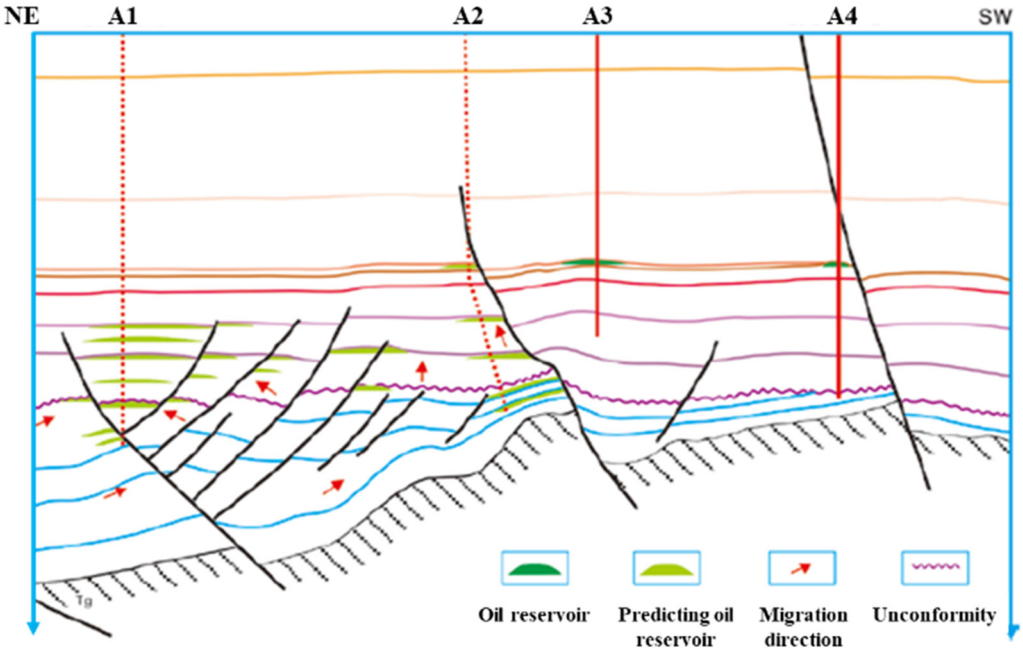


Figure 13. Structure diagram of Lufeng oilfield.

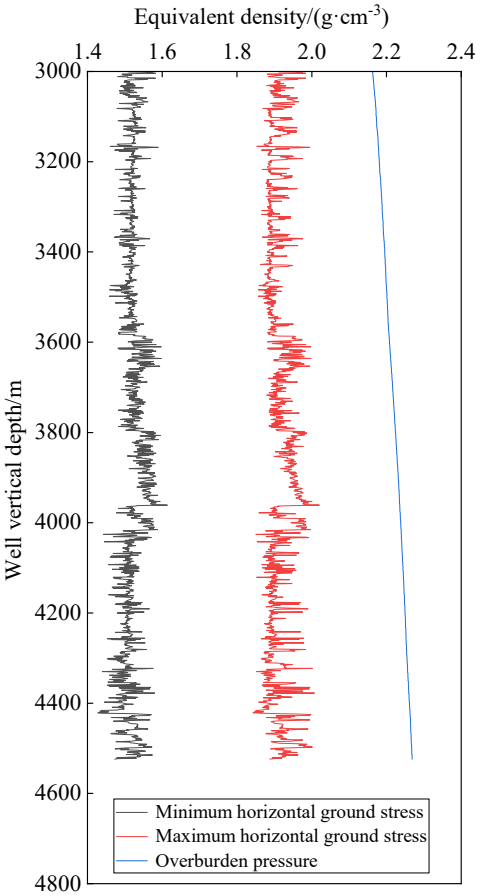


Figure 14. Ground stress vertical profile.

According to the results of the ground stress calculation, the ground stress in the well area shows a trend of increasing gradually with the increase in depth. In addition, the ground stress of the whole well section satisfies the law that the overburden pressure is the maximum principal stress, and the magnitude difference between the two horizontal ground stresses is not significant, which is conducive to maintaining the stability of

the borehole. The minimum equivalent density of horizontal principal stress is above 1.44 g/cm^3, and the maximum equivalent density of horizontal principal stress is above 1.78 g/cm^3. Then, the uniaxial compressive strength of rock is predicted by using logging data and empirical formula, and the calculated results of the coal seam are compared with the experimental results of the uniaxial compression of the coal seam, as shown in Figure 15. The analysis shows that the predicted uniaxial compressive strength of the coal seam is in good agreement with the experimental value, and the uniaxial compressive strength of the coal seam is smaller than that of the adjacent strata. In addition, the influence of the drilling fluid seepage in the wellbore is temporarily ignored during the prediction of the collapse pressure.

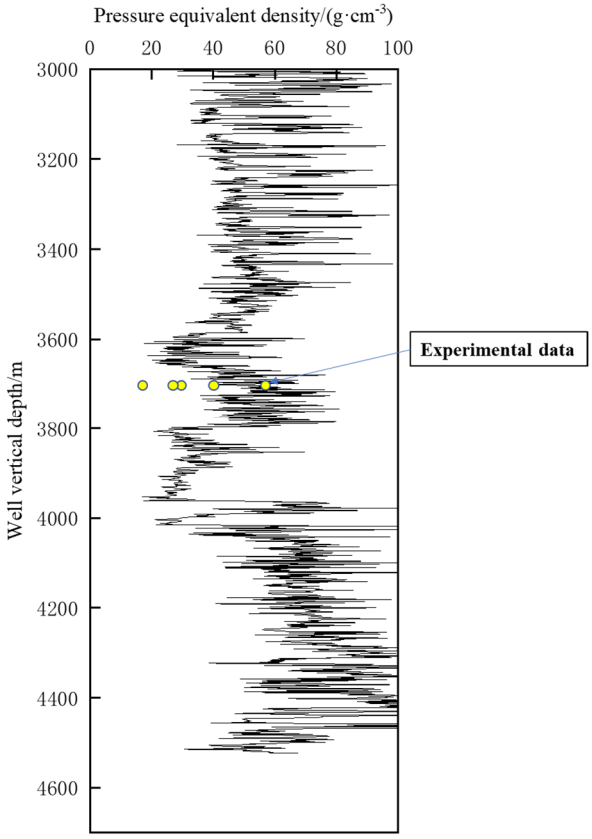


Figure 15. Vertical profile of uniaxial compressive strength.

The vertical distribution of pore pressure was obtained through the Eaton method combined with the acoustic time-lag logging data of the well in the Lufeng block. The influence of the drilling fluid seepage in the wellbore is temporarily ignored during the prediction of the collapse pressure. According to the prediction model of the coal seam collapse pressure considering the weak plane, combined with the results of the value and orientation of the ground stress, rock strength, and pore pressure, the change law of the collapse pressure equivalent density of the directional well in the target area with the inclination angle and the azimuth angle is analyzed.

The distribution of the target coal seam collapse pressure equivalent density with the inclination angle and azimuth angle are shown in Figure 16. The calculated results show that the collapse pressure equivalent density of the vertical well is 1.26 g/cm^3, and drilling in the direction of horizontal minimum principal stress is the lowest collapse pressure, which is conducive to wellbore stability. The collapse pressure equivalent density of the horizontal well in the direction of horizontal minimum principal stress is 1.36 g/cm^3, which is 0.1 g/cm^3 higher than that of the vertical well. When drilling in the horizontal

maximum principal stress orientation, the collapse pressure of the directional well is the highest, which is not conducive to wellbore stability. The collapse pressure equivalent density of horizontal wells in the maximum ground stress orientation is 1.50 g/cm^3, which is 0.24 g/cm^3 higher than that of the vertical well.

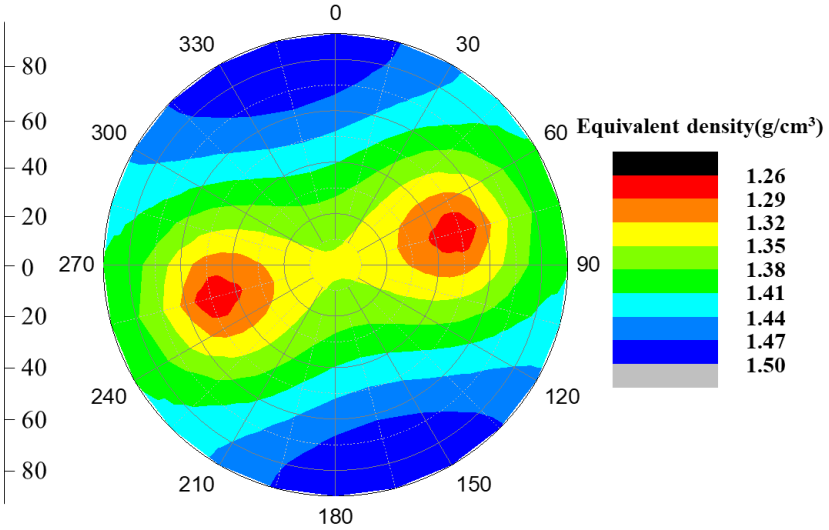


Figure 16. Map of the coal seam collapse pressure risk distribution.

The collapse pressure gradient curves of 3800–3900 m are obtained based on the basic mechanical parameters such as elastic modulus, cohesion, and internal friction angle of the coal seam obtained by logging data and the traditional Mohr–Coulomb criterion. The input parameters required for the calculation are shown in Table 4, the ground stress distribution data at the coal seam can be obtained according to Figure 14, and the pore pressure distribution data at the coal seam can be obtained according to Figure 17a. As shown in Figure 17, combined with the changes of drilling fluid density and borehole diameter during drilling, it can be seen that the borehole diameter of the coal seam section has significantly expanded, indicating that there is a large borehole collapse in this section. However, the pore pressure and collapse pressure obtained by using the traditional Mohr–Coulomb criterion are within the normal range, indicating that the reservoir is well drilled normally. It can be seen that when the coal seam with the weak structural plane is drilled, the traditional Mohr–Coulomb criterion is no longer applicable, and the collapse pressure of the coal seam cannot be accurately predicted, which leads to improper selection of drilling fluid density, and then causes the problem of borehole collapse.

Table 4. Input parameters.

Elastic Modulus/GPa	Bedding Angle/°	Cohesion/MPa	Internal Friction Angle/°
0.83	45	8.24	30.32

In order to solve the above problems, the collapse pressure of the coal seam is recalculated by using the wellbore collapse pressure prediction model, considering the weak structural plane. As shown in Figure 18, the results show that the gradient of the collapse pressure obtained by the model in this paper is higher than that obtained by the traditional Mohr–Coulomb criterion, and the result is closer to the field situation, which can better explain the problem of the coal seam wellbore collapse considering the weak structural surface. In addition, in order to ensure drilling safety when drilling into the coal seams, the

equivalent density of the drilling fluid should be appropriately increased, and the drilling fluid density at 3840–3848 m should be adjusted to 1.28 g/cm^3.

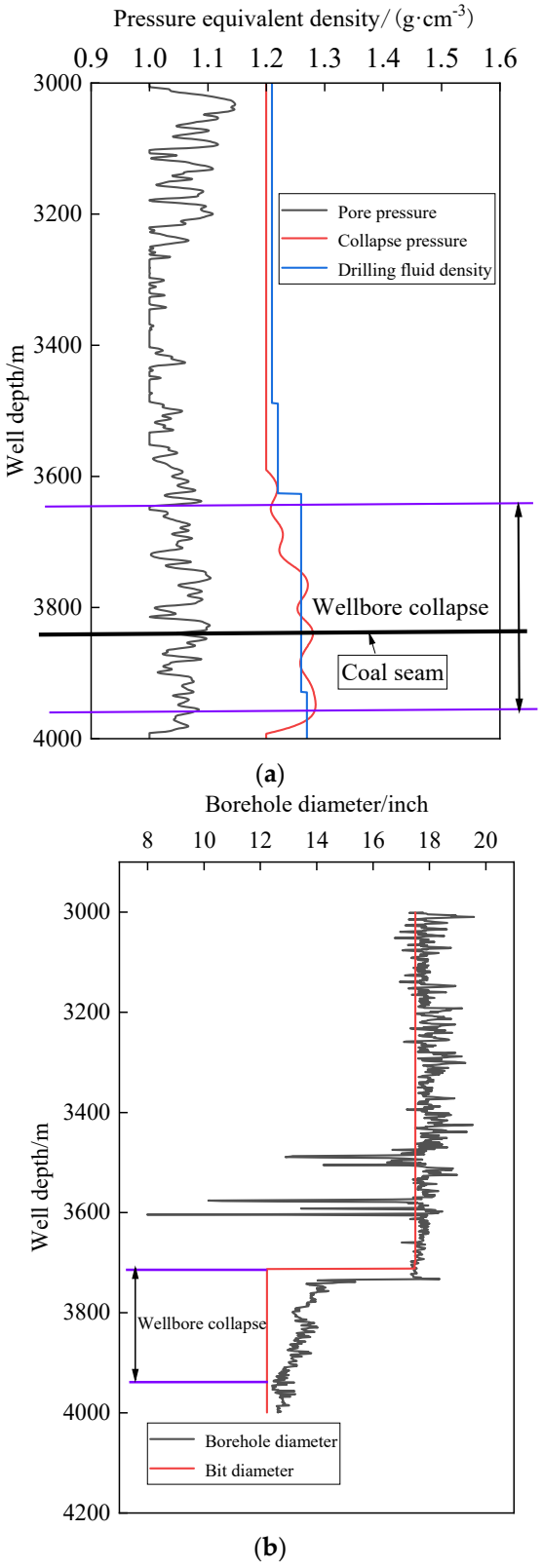


Figure 17. Traditional Mohr–Coulomb prediction result. (**a**) Pore pressure and collapse pressure equivalent density based on traditional Mohr–Coulomb prediction. (**b**) Change of wellbore diameter during drilling.

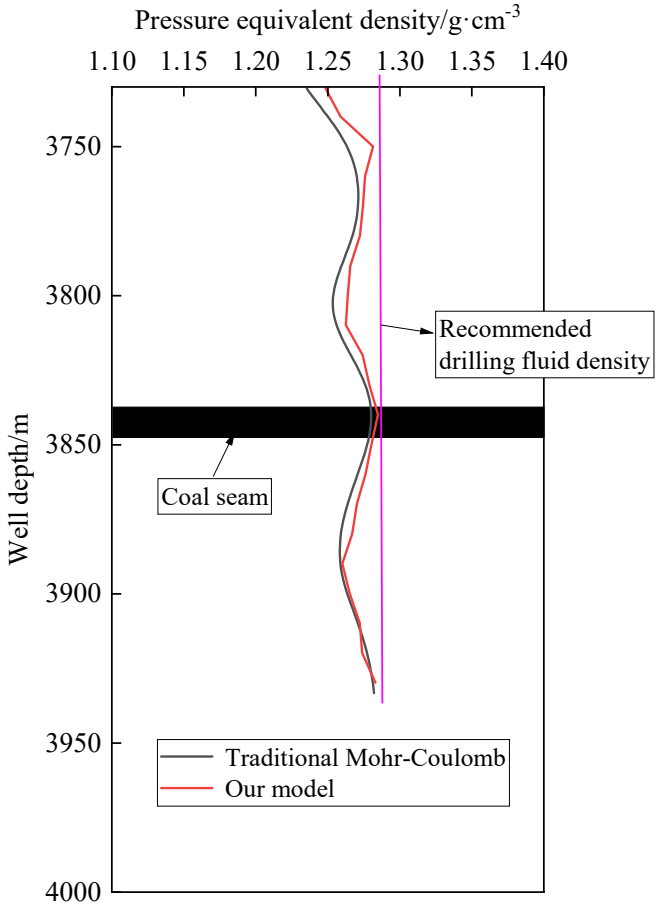


Figure 18. Prediction results of our model.

5. Conclusions

In order to reveal the influence of the weak structure in deep coal seams on wellbore stability in the Lufeng block, based on experiment and theoretical analysis, this paper established a new coal seam wellbore collapse pressure prediction model that comprehensively considered the change of mechanical properties of the weak structural plane, and carried out field application on a well in the Lufeng block. The specific conclusions are as follows:

(1) The fracture structure of coal and rock samples is obvious and well-developed. The pores are irregular in shape and have a certain connectivity among them. The good development of pores improves the connectivity and permeability of coal and rock samples but degrades the mechanical properties of the coal rock;

(2) With the increase of confining pressure, the compressive strength and elastic modulus of the coal rock show an increasing trend. With the increase of bedding angle, the compressive strength, elastic modulus, cohesion, and internal friction angle of the coal rock all decrease first and then increase, and the change curve presents an asymmetric "V" shape. When the bedding angle is 60°, the mechanical parameter value of coal and rock is the smallest, and 60° is the critical point when the mechanical parameter of the coal rock changes with the bedding angle;

(3) Compared with the traditional wellbore collapse pressure prediction model without considering the weak structural plane, the collapse pressure obtained by the new model considering the change of mechanical parameters of the weak structural plane is higher;

(4) Comparing with the coal seam data of the well drilled in the field, it is suggested that the drilling fluid density of this coal seam should be moderately increased to

1.28 g/cm^3 during actual drilling, so as to reduce the occurrence of leakage accidents while ensuring the low risk of borehole collapse and instability.

6. Research Limitations and Prospects

The mechanical properties and collapse pressure of stratified coal seams are studied in this work. Compared with previous studies, the variation of mechanical parameters such as cohesion and internal friction angle with bedding angle is considered in the proposed collapse pressure prediction model, which verifies the applicability of the proposed model in the oilfield. However, due to the large content and length of this work, this study only determined the mechanical properties and collapse pressure of the coal seam under the influence of the single weak structure plane, and the failure to establish a model of the coal seam collapse pressure under the influence of multi-weak planes will be the focus of subsequent research. At present, the prediction model of multi-weak planes borehole collapse pressure is under study, and new research on this topic will be published in a follow-up paper.

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