



Influence of relation between stress field and bedding space on wellbore stability in shale formation

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Received: 28 February 2019 / Accepted: 27 August 2019 / Published online: 14 October 2019
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Abstract

The shale gas reservoir in Jiaoshiba area is well developed with bedding and shows strong anisotropy, which leads to the problems of wellbore instability in the drilling process. At present, for the shale rich in bedding, the conventional calculation model of shale wellbore collapse pressure cannot meet the needs of shale wellbore stability analysis. In this paper, the analytical method considering the influence of bedding is more accurate. Therefore, in this paper direct shear tests and tri-axial mechanic experiments were conducted on the down-hole core rocks of LongMaxi reservoir shale formation, and the obtained experimental results were combined with single discontinuity theory to establish the characterization method of shale strength anisotropy. Then, combining the characterization method of shale strength anisotropy with the sidewall stress distribution model, the calculation method of borehole collapse pressure is established. Finally, the JY1HF well is taken as an example for calculation and comparative analysis. The results show that the LongMaxi reservoir shale strength deteriorating after drilling fluid immersion is not the main control factor of borehole instability; the shear slip along the weak bedding plane is the main mechanical mechanism of borehole instability. The collapse pressure calculated by the conventional model decreases with the increase of the well inclination, and the collapse pressure calculated by the model in this paper shows a trend of increasing first and then decreasing with the increase of the well inclination, and the results calculated by the model in this paper are in good agreement with the actual working conditions. The research results of this paper can provide theoretical basis and reference for drilling design and borehole trajectory optimization of shale gas wells in Jiaoshiba area or other areas.

Keyword Shale gas · Weak bedding planes · Anisotropy characterization method · Collapse pressure calculation model · Wellbore stability

Highlights

- The anisotropy characterization method of shale strength and the calculation method of shale borehole collapse pressure are established.
- The shear slip along the weak bedding plane is the main mechanical mechanism of borehole instability, but the shale strength deteriorating after drilling fluid immersion is not the main control factor of borehole instability.
- The collapse pressure calculated by the model in this paper is more accurate than that by the conventional model and more consistent with the actual working condition.

Responsible Editor: Zeynal Abiddin Erguler

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s12517-019-4727-z>) contains supplementary material, which is available to authorized users.

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Introduction

China is rich in shale gas resources, which are mainly distributed in southern China, Xinjiang Tarim basin and other areas where marine shale is developed (Chen, Zhu, Wang, et al. 2010; Zhao, Qiao, Cao, et al. 2017; Qiao, Zhao, Shao, et al. 2018). On the basis of learning from the successful experience of shale gas development in North America (Sun et al., 2019a, b, c), Sinopec has made a major breakthrough in Fuling shale gas field and obtained shale gas reserves of $2500 \times 10^8 \text{m}^3$ (Wang 2015). The commercial development of Fuling shale gas field is of landmark significance for China's shale gas development and will lay a foundation for the large-scale development of shale gas in the future. According to the results of shale gas drilling and trial production in Fuling Jiaoshiba area at present, horizontal well drilling technology and volume fracturing reconstruction technology are the main technologies for shale gas development.

However, due to the characteristics of shale gas reservoirs such as old age, deep burial, strong tectonic transformation, and abnormal formation pressure (Chen, Zhu, Wang, et al. 2010; Wang 2015), many challenges are faced in the horizontal drilling process of shale gas reservoirs. In the horizontal well drilling process of shale gas reservoir, once the borehole wall instability occurs, it will lead to frequent bit sticking, bit burying, and other downhole complex accidents (Sun et al., 2018a, b, d, g; Zeng, Wei, Liu, et al. 2018). Taking JY1HF well in the area of Jiaoshiba as an example, wellbore collapse occurred frequently in the drilling process. After completion, it was found by wireline logging test that the diameter enlargement rate of the inclined section of the well reached up to 50~100%, which resulted in nine accidents caused by stuck drilling. In addition, the wellbore instability of shale gas wells also indirectly affects the drilling cycle, cementing quality and fracturing construction effect, and even leads to well abandonment in severe cases, causing huge economic losses and directly affecting the effectiveness of shale gas development (Ma, Chen 2014; Chen et al. 2014; Ma, Chen 2015).

For the mechanism of wellbore instability in shale formation, domestic and foreign scholars have carried out a large number of studies and obtained rich research results (Chen 2008; Chen et al. 2014; Chen, Zhu, Wang, et al. 2010; Jin, Chen 2012; Ma, Chen 2014; Wang 2015). In the past, most studies have focused on the complex stratum where shale is liable to collapse. In the drilling process, vertical wells are often used to quickly drill through and run casing to isolate such complex stratum, and the research focus on the mechanism of shale wellbore instability is the physicochemical coupling between drilling fluid and shale (Chen 2008; Jin, Chen 2012). However, with the development of shale gas development technology, the research on the mechanism of shale gas reservoir wellbore instability has attracted much attention. It is generally believed that the special layered structure of shale

results in significant anisotropy of its mechanical strength, which is the main mechanical mechanism leading to shale wellbore instability (Ma, Chen 2014; Chen, Ma, Xia 2014; Chen 2008; Jin, Chen 2012; Aadnoy 1989; Ong and Roegiers 1993; Okland and Cook 1998; Liu, Ye, Chen 2002; Al-Bazali et al. 2009; Lee et al. 2012; Yuan, Deng, Wei, et al. 2012; Lu et al. 2013; Liu, Chen, Jin et al. 2014; Wen, Chen, Jin et al. 2014; Ma, Chen 2015).

Aadnoy (1989) was the first to carry out relevant studies on strength anisotropy and its influence on borehole instability. A semi-analytical method for predicting the borehole stability of anisotropic formation was established by using the weak surface strength criterion proposed by Jaeger and Cook and combining with the wellbore stress distribution model proposed by Bradely (1979). Subsequently, more researchers carried out further studies on this basis (Ma, Chen 2014; Chen, Ma, Xia 2014; Chen 2008; Jin, Chen 2012; Aadnoy 1989; Ong and Roegiers 1993; Okland and Cook 1998; Liu, Ye, Chen 2002; Al-Bazali et al. 2009; Lee et al. 2012; Yuan, Deng, Wei, et al. 2012; Lu et al. 2013; Liu, Chen, Jin et al. 2014; Wen, Chen, Jin et al. 2014; Ma, Chen 2015). Various factors such as modulus anisotropy, strength degradation, pressure transfer around well, and mechanical-chemical coupling were considered. However, in these studies, the anisotropy of shale strength is often assumed or only experimental results are given. Even if the experimental results are used for fitting, it is difficult to accurately give anisotropy characteristic parameters of shale strength. Few studies have been conducted on the method to accurately obtain the anisotropic characteristic parameters of shale strength. Most of the literatures used outcrop samples to study the strength characteristics of shale. Few literatures reported the systematic study on the mechanical characteristics of shale downhole core. In addition, most of these studies do not consider the hydration of drilling fluid or only consider the influence of water-based drilling fluid, and there are few studies on the influence of oil-based drilling fluid on borehole instability.

To this end, combined with the actual field conditions of JY1HF well in the area of Jiaoshiba, the anisotropic strength parameters of shale were simply obtained by conducting direct shear test on the underground core, and then compared with the measured triaxial rock mechanics test results, a set of methods for characterizing shale body and bedding strength through direct shear test was formed. In combination with the weak surface strength criterion and the analytical solution of the stress distribution around the well, the calculation method of the collapse pressure of shale wellbore is established. Finally, the collapse pressure of JY1HF well is calculated by the conventional method and the method in this paper respectively, and compared with the actual working conditions, so as to reveal the mechanism of wellbore collapse of shale gas reservoir in the area of Jiaoshiba.

Shale strength anisotropy and characterization

In Jiaoshiba block, numerous horizontal beddings are developed in shale gas reservoir, and these weak beddings would affect the shale strength. The effect of weak beddings on strength is often called the rock strength anisotropy, and the extent of such effect depends on the relative weakness of bedding plane and its angle to stress (Sun et al., 2018b, c, e f). In order to enable better representation of the shale strength anisotropy, downhole cores from well JY1HF in LongMaxi formation are adopted to conduct direct shear tests to measure the shear strength of shale's weak beddings and mass, and then make comparison with triaxial rock mechanics test results.

Direct shear test

Direct shear test principles: when rock is sheared by increasing shear force Q in horizontal direction with a fixed normal force N , the peak shear force Q_{\max} refers to the shear strength; by applying a different normal stress N_i , the corresponding shear strength Q_{\max} can be measured; as a result, the converted normal stress and shear stress are fitted in Mohr-Coulomb criteria to acquire shear strength parameters: cohesion and friction angle. Therefore, the strength under direct shear force can be described as follows,

$$\tau = C + \sigma_n \tan \varphi \quad (1)$$

where

$$\begin{cases} \sigma_n = \frac{N}{A_1} \\ \tau = \frac{Q}{A_2} \end{cases} \quad (2)$$

N is the normal force, N; Q is shear force, N; τ is shear stress, Pa; σ_n is normal stress, Pa; C is cohesion, Pa; φ is friction angle, °; A_1 is the action area of normal force, m²; A_2 is the action area of shear force, m².

In order to test the shear resistance characteristics of the weak beddings and rock mass, the square rock samples (with a size of 1.97 in. × 1.97 in. × 0.98 in.) were prepared along the direction of parallel bedding and the direction of vertical bedding respectively. As shown in Fig. 1, in order to save downhole core, the thickness is controlled as 0.98 in. and tested by a direct shear tester. During test the normal stresses are controlled as 0 MPa, 5 MPa, and 10 MPa, respectively, and the results are listed in Table 1. It is clearly shown that the shear strength and mechanical strength parameters of shale in the direction of parallel bedding are lower than those in the vertical direction; that is, the strength of weak bedding is lower than that of shale rock mass.

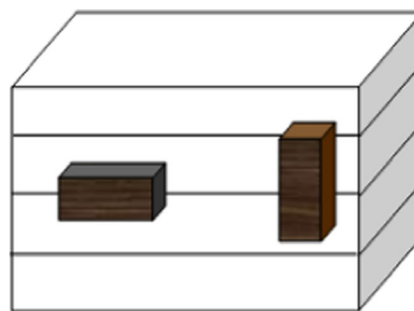


Fig. 1 Shale samples for direct shear test

Triaxial rock mechanics experiment

In order to study the mechanical parameters and anisotropic distribution of shale rock, considering the difficulty in obtaining downhole core, so the standard $\Phi 0.98$ in. cylindrical cores are drilled respectively along the three directions as vertical bedding, parallel bedding, bedding, and angle of 30° (bedding normal angle 60°) from the downhole core (Fig. 2). Considering that shale is brittle, easy to hydrate and break, the core is strengthened by cement to avoid breakage during core drilling. Firstly, a layer of paraffin wax was wrapped around the full-size downhole core cylinder to avoid hydration during the cement solidification process. Then, the wax-coated core cylinder was placed in a box and poured with cement for solidification. Finally, dry air suction drilling is used to drill the core. After successful drilling, the core column with a length of 1.97 in. and a length-diameter ratio of about 2~3 was cut with a stone cutter, and the end faces were ground flat. The parallelism error of the two end faces was required to be no more than 0.02 in. After the completion of sample preparation, a triaxial mechanics experiment is carried out with a GCTS-1000 type high-temperature and high-pressure triaxial rock mechanics testing unit; the test environment temperature is 25~27 °C, and the loading rate 0.0018 in./s. The core at each sampling angle is required to be tested under two different confining pressures (0 and 25 MPa); the test results are as shown in Table 2. It is clear that the sample's compressive strength is the lowest at an angle of 30° to the bedding plane, and vertical bedding direction sample has the highest strength. In addition, post-failure rock sample photos are shown in Fig. 3, in which the sample is subjected to shear failure along the vertical direction to the bedding plane, shear slip failure along the bedding plane at a bedding angle of 30°, and parallel bedding direction sample split and damage happened, indicating that the shear slip failure along the weak bedding plane is the key mechanic mechanism to shale strength reduction.

Yan et al. conducted conventional triaxial and direct shear tests on shale samples soaked by drilling fluids, and pointed out that, in the case of soaking in water-based or oil-based drilling fluids, both the cohesion and friction angle of shale rock mass and beddings decrease with the increase of soaking

Table 1 Results of shale direct shear test

No.	Shear direction	Normal stress (MPa)	Peak shear stress (MPa)	Cohesion (MPa)	Friction angle (°)
P-1	Parallel to bedding	0.00	4.01	3.57	36.37
P-2	Parallel to bedding	5.00	6.36		
P-3	Parallel to bedding	10.00	11.37		
C-1	Vertical to bedding	1.03	8.25	7.77	47.50
C-2	Vertical to bedding	5.33	14.74		
C-3	Vertical to bedding	10.45	18.60		

time, and it can be roughly divided into slowly reduce, fast and smooth to reduce three stages (Yan, Deng, Wei, et al. 2013). In order to identify the strength change laws of LongMaxi shale in Jiaoshiba area of Fuling after soaking in drilling fluids, the downhole cores from well JY1HF in LongMaxi formation are used for triaxial tests, and the drilling fluid used for soaking is the same as used in the second spud of well JY1HF; the soaking time is set to 30 days. The test results are shown in Table 3. Figure 4 shows the comparison between the results of the triaxial experiment with the shale before soaking. On the whole, the compressive strength of the shale decreased slightly after soaking, which can be called the shale strength degradation effect, indicating that the physical and chemical reaction after the contact between shale and drilling fluid resulted in the shale strength degradation. The experimental results were basically consistent with the results reported in the literature, which may also be one of the

important reasons for the shale wellbore instability. However, the shale strength degradation effect is not very significant in the case of soaking for 30 days, and there are individual differences in the degradation phenomenon after soaking; for example, the shale sample at an angle of 90° to the bedding plane under the condition of confining pressure 25 MPa compressive strength is higher than the dry shale strength.

Shale strength anisotropy characterization methods

Both direct shear and triaxial mechanical experiments of shale have confirmed that, due to the existence of bedding, shale presents significant anisotropy of strength. The ways to characterize the anisotropic strength of bedded rock include Jaeger model and McClamore models. Many studies have confirmed that, using Jaeger model, the strength parameters could be

Fig. 2 Shale samples for triaxial rock mechanics test: (a) vertical to bedding; (b) angle of 30° to the plane; (c) parallel to bedding

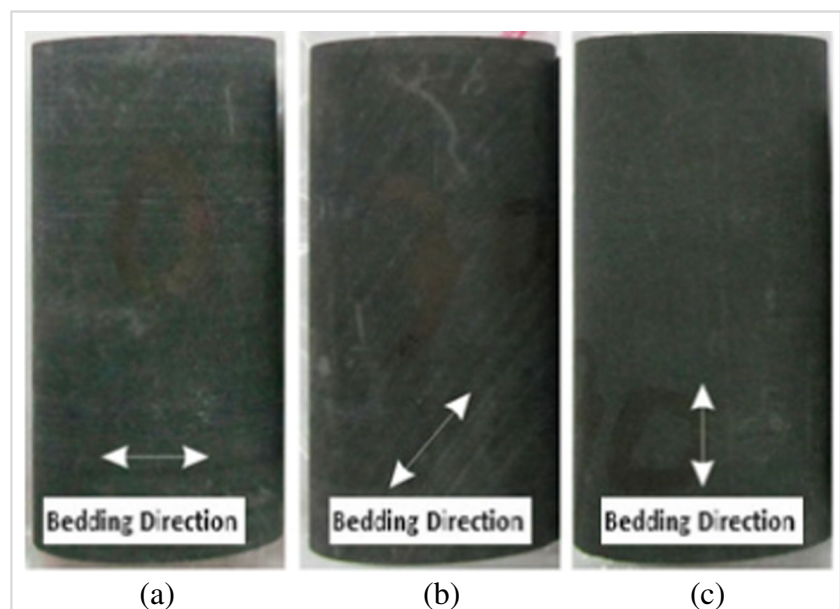


Table 2 Triaxial rock mechanics test results

No.	Sampling angle (°)	Confining pressure (MPa)	Poisson ratio	Elastic modulus (MPa)	Compressive strength (MPa)	Cohesion (MPa)	Friction angle (°)
0-1	0	0	0.191	24,527.0	169.7	55.95	23.20
0-2	0	25	0.231	24,143.6	202.5		
30-1	30	0	0.117	7048.3	45.5	20.14	6.97
30-2	30	25	0.154	18,747.4	52.4		
90-1	90	0	0.155	25,274.2	115.1	/	/
90-2	90	25	0.202	22,095.8	128.7		

acquired through conventional rock mechanics experiments, while Mclamore model is a strength criterion with continuously varying of cohesion and internal friction angle. Comparatively, Jaeger model is more simple to use and it can represent the anisotropy of rock strength more accurately (Ma, Chen 2014; Chen, Ma, Xia 2014; Chen 2008; Jin, Chen 2012; Ma, Chen 2015). Therefore, Jaeger model is adopted to characterize shale strength anisotropy in this paper. This model describes the shear failure of rock mass with one or a group of parallel weak surface conditions, which is usually called single weak plane strength theory model; the criterion of weak surface failure in this model is as follows (Ma, Chen 2014; Chen, Ma, Xia 2014; Chen 2008; Jin, Chen 2012; Ma, Chen 2015):

$$\sigma_1 = \sigma_3 + \frac{2(C_w + \sigma_3 \tan \varphi_w)}{(1 - \tan \varphi_w \cot \beta) \sin 2\beta} \quad (\beta_1 \leq \beta \leq \beta_2) \quad (3)$$

where

$$\begin{cases} \beta_1 = \frac{\varphi_w}{2} + \frac{1}{2} \arcsin \left[\frac{(\sigma_1 + \sigma_3 + 2C_w \cot \varphi_w) \sin \varphi_w}{\sigma_1 - \sigma_3} \right] \\ \beta_2 = \frac{\pi}{2} + \frac{\varphi_w}{2} - \beta_1 \end{cases} \quad (4)$$

If the above conditions are not met, rock mass failure follows the Mohr-Coulomb criteria,

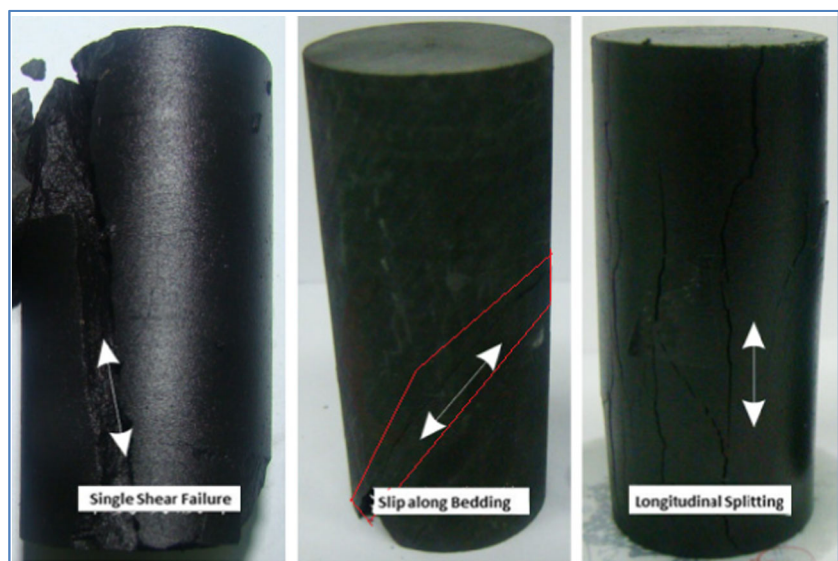
$$\sigma_1 = \sigma_3 \cot^2 \left(\frac{\pi}{2} - \frac{\varphi_0}{2} \right) + 2C_0 \cot \left(\frac{\pi}{2} - \frac{\varphi_0}{2} \right) \quad (\beta_2 \leq \beta \leq \beta_1) \quad (5)$$

where σ_1 is the maximum principal stress, Pa; σ_3 is the minimum principal stress, Pa; C_0 is the cohesion of rock mass, Pa; C_w is weak-plane cohesion, Pa; φ_0 is the friction angle, °; φ_w is the friction angle of weak plane, °; and β is the angle between weak-plane normal and maximum principal stress, °.

It is clear that, only when the conditions and stress states described in equations (3) and (4) are satisfied at the same time, can the failure occur along the bedding weak surface; that is, the rock mass strength is controlled by the weak surface strength. If this condition is not met, a mass failure occurs in the rock mass with a failure angle of $(\pi/4 + \varphi_0/2)$.

In order to clarify the shortcomings or defects in acquiring the strength parameters of shale weak bedding plane by triaxial rock mechanics experiments, and confirm that the single weak plane strength theory model

Fig. 3 Post-failure shale samples after triaxial rock mechanics test: (a) vertical to bedding; (b) angle of 30° to the bedding; (c) parallel to bedding



(a) Vertical to bedding (b) angle of 30° to the bedding (c) Parallel to bedding

Table 3 Results of triaxial rock mechanics test for soaked shale

No.	Sampling angle (°)	Confining pressure (MPa)	Poisson ratio	Elastic modulus (MPa)	Compressive strength (MPa)	Cohesion (MPa)	Friction angle (°)
0-3	0	0	0.150	19,945.7	134.2	38.64	30.13
0-4	0	25	0.283	25,554.7	184.6		
30-3	30	0	0.228	9732.7	30.8	/	/
30-4	30	25	0.106	31,862.8	46.0		
90-3	90	0	0.276	16,192.3	70.2	20.26	30.00
90-4	90	25	0.213	33,643.3	145.2		

can be used to characterize shale strength anisotropy, the single weak plane strength theory is used here to calculate the theoretical strength in a triaxial test on the basis of rock mass and bedding strength parameters (cohesion and internal friction angle) acquired from direct shear tests, and compared with the strength tested by triaxial experiment. The results are shown in Fig. 5. It was found that the calculated theoretical strength is roughly identical to the strength data from triaxial tests, indicating that direct-shear test results can be used to characterize shale body and bedding strength. This method can avoid the inadequacy of the triaxial rock mechanics experimental parameters in calculating the strength parameters of shale body and bedding respectively.

Shale wellbore collapse pressure calculation model

Under the influences of in situ stress field, wellbore trajectory (deviation and azimuth), bedding occurrence (trend and dip angle), and other factors, wellbore stability laws in shale formations are different from that in common sandstone formations. Therefore, above factors should be comprehensively considered during the establishment of the wellbore stability mechanics model.

Wellbore stress distribution model

Considering that shale is hard and brittle, with strong elasticity presented in stress-strain curve, therefore, shale can be assumed as pore elastic medium. According to Bradely’s wellbore stress distribution model, the radial distance is taken as the wellbore radius, and then, the wellbore stress distribution model of any inclined well can be obtained (Chen 2008; Jin, Chen 2012):

$$\begin{cases} \sigma_r = p_w - \alpha p_p \\ \sigma_\theta = \sigma_x(1 - 2\cos 2\theta) + \sigma_y(1 + 2\cos 2\theta) - 4\tau_{xy}\sin 2\theta - p_w - \alpha p_p \\ \sigma_z = \sigma_z - \alpha p_p \\ \tau_{\theta z} = 2(-\tau_{xz}\sin\theta + \tau_{yz}\cos\theta) \end{cases} \quad (6)$$

where

$$\begin{bmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{xy} & \sigma_y & \tau_{yz} \\ \tau_{xz} & \tau_{yz} & \sigma_z \end{bmatrix} = [L] \begin{bmatrix} \sigma_H & & \\ & \sigma_h & \\ & & \sigma_v \end{bmatrix} [L]^T \quad (7)$$

$$[L] = \begin{bmatrix} \cos\omega\cos\psi & \sin\omega\cos\psi & -\sin\psi \\ -\sin\omega & \cos\omega & 0 \\ \cos\omega\sin\psi & \sin\omega\sin\psi & \cos\psi \end{bmatrix} \quad (8)$$

σ_r is the effective radial stress, Pa; σ_θ is the effective tangential stress, Pa; σ_z is the effective axial stress, Pa; $\tau_{\theta z}$ is the

Fig. 4 Comparison of triaxial test results before and after Soaking

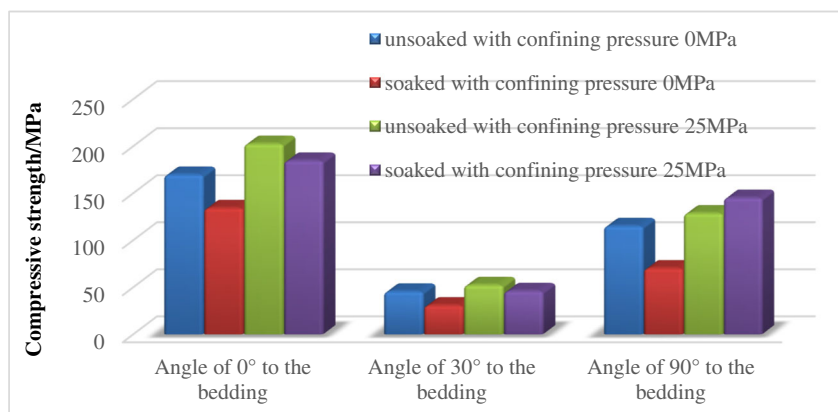
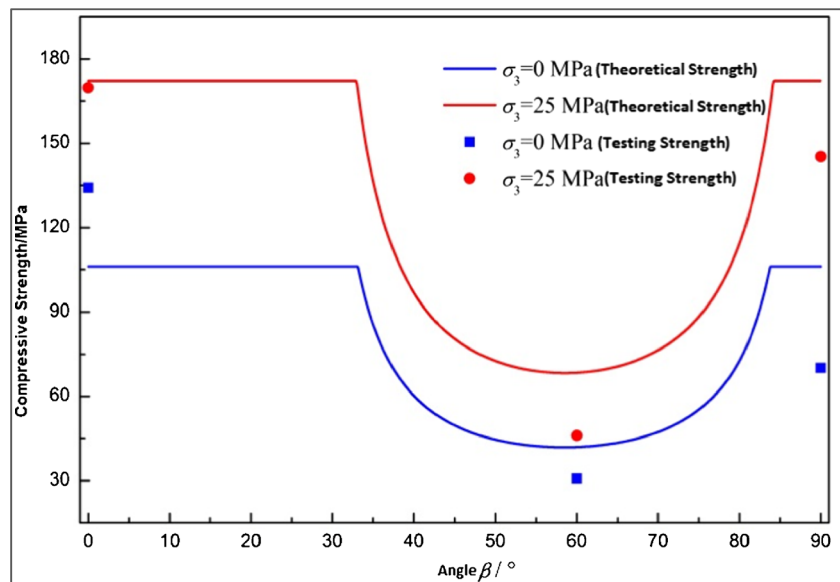


Fig. 5 Shale strength vs loading angle



component of shear stress at wellbore wall, Pa; p_w is drilling fluid column pressure, Pa; p_p is formation pore pressure, Pa; α is effective stress coefficient, dimensionless; σ_H is the maximum horizontal stress, Pa; σ_h is the minimum horizontal stress, Pa; σ_v is vertical stress, Pa; θ is circumferential angle, °; ψ is deviation angle, °; ω is azimuth angle, °.

In order to determine whether stress on wellbore wall exceeds shale strength, the maximum and minimum principal stresses are usually needed. Based on the analysis of sidewall stress state, the maximum and minimum principal stresses can be obtained as follows (Ma, Chen 2014; Chen, Ma, Xia 2014; Chen 2008; Jin, Chen 2012; Ma, Chen 2015):

$$\begin{cases} \sigma_1 = \frac{\sigma_\theta + \sigma_z}{2} + \sqrt{\left(\frac{\sigma_\theta - \sigma_z}{2}\right)^2 + \tau_{\theta z}^2} \\ \sigma_3 = \sigma_r = p_w - \alpha p_p \end{cases} \quad (9)$$

Moreover, the angle between the intermediate principal stress of the sidewall and the borehole axis is shown below.

$$\gamma = \frac{1}{2} \arctan \frac{2\tau_{\theta z}}{\sigma_\theta - \sigma_z} \quad (10)$$

Variation rule of angle between principal stress field and normal direction of bedding

The accurate evaluation of the included angle relationship between the principal stress field and the normal direction of bedding plane is the key to evaluate the stability of horizontal drilling in bedding shale reservoirs. Ong (1993), Okland and Cook (1998), Jin and Chen (2012), Chen et al. (2008), Liu et al. (2002), Al-Bazali (2009), and Lee et al. (2012) studied the variation rule of the angle between the maximum principal stress of the sidewall and the normal direction of bedding, and

quantitatively evaluated the influence of the angle change between the maximum principal stress of the sidewall and bedding on the collapse pressure of the formation. In this paper, the angle relationship between the main stress field (maximum principal stress, minimum principal stress) and the normal direction of bedding plane is systematically studied, and the influence of the angle change between the maximum principal stress, minimum principal stress, and bedding on the collapse pressure of the borehole formation is quantitatively evaluated.

Assuming that the in situ stress field coordinate system is $(\sigma_H, \sigma_h, \sigma_v)$, the in situ stress field coordinate system $(\sigma_H, \sigma_h, \sigma_v)$ rotates α_s along the σ_v axis, and then rotates β_s along σ_h , the rectangular coordinate system (x_s, y_s, z_s) along the shale bedding plane can be obtained. The spatial coordinate transformation between in situ stress field and bedding plane is shown in Fig. 6.

Assuming that the unit matrix of in situ stress field is as shown below,

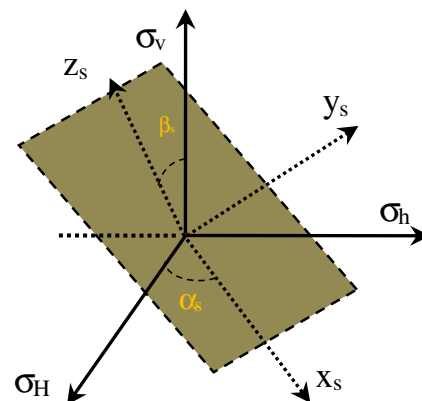


Fig. 6 Conversion of coordinates between in situ stress field and bedding surface space

$$\vec{E} = \begin{bmatrix} \vec{i} & 0 & 0 \\ 0 & \vec{j} & 0 \\ 0 & 0 & \vec{k} \end{bmatrix} \tag{11}$$

then, the unit vector of rectangular coordinates along bedding plane can be expressed as follows,

$$\begin{aligned} \vec{x}_s &= \cos\alpha_s \cos\beta_s \cdot \vec{i} + \sin\alpha_s \cos\beta_s \cdot \vec{j} - \sin\beta_s \cdot \vec{k} \\ \vec{y}_s &= -\sin\alpha_s \cdot \vec{i} + \cos\alpha_s \cdot \vec{j} \\ \vec{z}_s &= \cos\alpha_s \sin\beta_s \cdot \vec{i} + \sin\alpha_s \sin\beta_s \cdot \vec{j} + \cos\beta_s \cdot \vec{k} \end{aligned} \tag{12}$$

We can obtain the rectangular coordinates (x_a, y_a, z_a) along inclined borehole axis z_a if the in situ stress field coordinates rotate to α along σ_v axis, and then rotates to β along σ_h . The conversion between in situ stress field coordinates ($\sigma_H, \sigma_h, \sigma_v$) and rectangular coordinates along inclined borehole axis is as shown in Fig. 7.

Then, the unit vector of rectangular coordinates along inclined borehole axis can be expressed as follows:

$$\begin{aligned} \vec{x}_a &= \cos\alpha \cos\beta \cdot \vec{i} + \sin\alpha \cos\beta \cdot \vec{j} - \sin\beta \cdot \vec{k} \\ \vec{y}_a &= -\sin\alpha \cdot \vec{i} + \cos\alpha \cdot \vec{j} \\ \vec{z}_a &= \cos\alpha \sin\beta \cdot \vec{i} + \sin\alpha \sin\beta \cdot \vec{j} + \cos\beta \cdot \vec{k} \end{aligned} \tag{13}$$

In order to evaluate the stability of rock mass of inclined borehole, it is required to determine the principal stress field ($\sigma_1, \sigma_2, \sigma_3$) of sidewall rock and the included angle relation between principal stress field and bedding normal direction. Then, the conversion between principal stress field of sidewall and rectangular coordinates along borehole axis is as shown in Fig. 8.

We can obtain the coordinates ($\sigma_3, \sigma_1, \sigma_2$) of the principal stress of wellbore by rotating θ along z_a axis, and then rotates γ along x_a in the axial rectangular coordinate system of the inclined well.

Then, the unit vector of the minimum principal stress (σ_3) for inclined borehole can be expressed as:

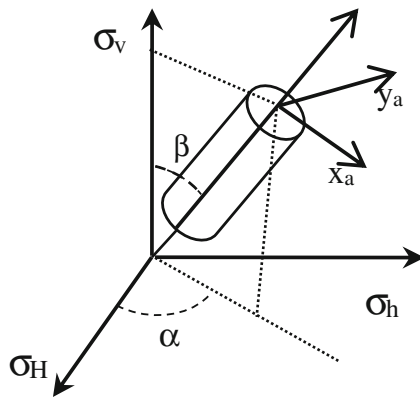


Fig. 7 Transformation of in situ stress field and spatial coordinate system of inclined borehole axis

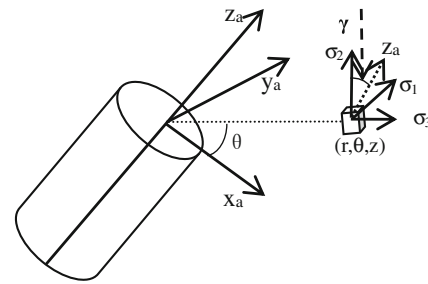


Fig. 8 Conversion of coordinates between inclined borehole axis and principal stress field space of borehole wall

$$\vec{\sigma}_3 = a_3 \vec{i} + b_3 \vec{j} + c_3 \vec{k} \tag{14}$$

where

$$\begin{aligned} a_3 &= \cos\alpha \cos\beta \cos\theta - \sin\alpha \sin\theta \\ b_3 &= \sin\alpha \cos\beta \cos\theta + \cos\alpha \sin\theta \\ c_3 &= -\sin\beta \cos\theta \end{aligned}$$

The unit vector of the middle principal stress (σ_2) for inclined borehole can be expressed as:

$$\vec{\sigma}_2 = a_2 \vec{i} + b_2 \vec{j} + c_2 \vec{k} \tag{15}$$

$$\begin{aligned} a_2 &= \cos\alpha \cos\beta \sin\theta \sin\gamma + \sin\alpha \cos\theta \sin\gamma + \cos\alpha \sin\beta \sin\gamma \\ b_2 &= \sin\alpha \cos\beta \sin\theta \sin\gamma + \cos\alpha \cos\theta \sin\gamma + \sin\alpha \sin\beta \cos\gamma \\ c_2 &= -\sin\beta \sin\theta \sin\gamma + \cos\beta \cos\gamma \end{aligned}$$

The unit vector of the maximum principal stress (σ_1) of sidewall rock can be expressed as:

$$\vec{\sigma}_1 = a_1 \vec{i} + b_1 \vec{j} + c_1 \vec{k} \tag{16}$$

$$\begin{aligned} a_1 &= -\cos\alpha \cos\beta \sin\theta \cos\gamma - \sin\alpha \cos\theta \cos\gamma + \cos\alpha \sin\beta \sin\gamma \\ b_1 &= -\cos\alpha \cos\beta \cos\gamma - \sin\alpha \cos\theta \cos\gamma + \sin\alpha \sin\beta \sin\gamma \\ c_1 &= \sin\beta \sin\theta \cos\gamma + \cos\beta \sin\gamma \end{aligned}$$

Calculation method of borehole wall collapse pressure

For the single direction bedding formation, the Jaeger single-group weak plane instability model (Eq. (3)) is adopted in this paper. In the single-group weak plane instability model, the key to the influence of the mechanical properties of the weak plane on the stability of the wellbore is the angle relationship between the main stress and the weak plane. Therefore, it is necessary to determine the included angle relationship between the main stress field and the normal direction of the weak plane before carrying out the judgment of single group of weak plane instability (Ma and Chen, 2014; Chen et al., 2014; Ma and Chen, 2015; Chen et al., 2008; Jin and Chen, 2012).

The included angle between the wellbore main stress and the normal direction of the bedding plane can be calculated by

combining with the unit vector of the borehole wall principal stress and the unit vector of the normal direction of the bedding plane, and combining with the calculation model of the included angle of the space vector.

The included angle relationship between the maximum principal stress (σ_1) of the wellbore wall and the normal direction of the bedding plane can be expressed as follows:

$$\beta\beta_\theta = \arccos\left(\frac{\overrightarrow{\sigma_1} \cdot \overrightarrow{z_s}}{|\overrightarrow{\sigma_1}| |\overrightarrow{z_s}|}\right) \tag{17}$$

The included angle relationship between the middle principal stress (σ_2) of the wellbore wall and the normal direction of the bedding plane can be expressed as follows:

$$\beta\beta_z = \arccos\left(\frac{\overrightarrow{\sigma_2} \cdot \overrightarrow{z_s}}{|\overrightarrow{\sigma_2}| |\overrightarrow{z_s}|}\right) \tag{18}$$

The included angle relationship between the minimum principal stress (σ_3) of the wellbore wall and the normal direction of the bedding plane can be expressed as follows:

$$\beta\beta_z = \arccos\left(\frac{\overrightarrow{\sigma_3} \cdot \overrightarrow{z_s}}{|\overrightarrow{\sigma_3}| |\overrightarrow{z_s}|}\right) \tag{19}$$

If the included angle calculated from Eq. (17) satisfies $\beta_1 \leq \beta \leq \beta_2$, then the wellbore principal stress calculated by Eq. (9) is substituted into Eq. (3) for the determination of wellbore stability, and the critical collapse pressure along the bedding failure can be obtained by solving the nonlinear equation containing p_w . If the included angle calculated by Eq. (17) does not satisfy $\beta_1 \leq \beta \leq \beta_2$, then the wellbore principal stress calculated by Eq. (9) can be substituted into Eq. (5) for borehole stability discrimination, and the critical collapse pressure of shale body failure can be obtained by solving the nonlinear equation containing p_w .

Data analysis

In combination with the above suggested theoretical mathematical model and equations (11–19), this paper has evaluated the relationship between the wellbore principal stress (σ_1, σ_2) and the normal angle ($\beta\beta_\theta, \beta\beta_z$) of the bedding plane in different stress environments, and the influence of the relationship between the main stress field and the bedding plane on the mud density required for drilling.

The change rule of the relationship between the borehole wall principal stress and the normal angle of the bedding plane

Firstly, we utilize Eq. (17) to evaluate the variation rule of angle ($\beta\beta_\theta$) between the maximum principal stress (σ_1) of borehole wall and the normal direction of bedding surface under different stress environments, as shown in Fig. 9.

Through simulation analysis, when the borehole azimuth angle (α) is consistent with bedding plane inclination (α_s), the maximum value of the angle ($\beta\beta_\theta$) between the borehole wall maximum principal stress and the normal direction of the bedding plane appeared in the $\theta = 0^\circ$ and $\theta = 180^\circ, 90^\circ$ in average; the minimum value of $\beta\beta_\theta$ appeared in the $\theta = 90^\circ$ and $\theta = 270^\circ$. The variation law of $\beta\beta_\theta$ firstly decreases and then increases, presenting a symmetrical distribution around the borehole wall. When $\beta_s = 0^\circ$, $\beta\beta_\theta$ value under different β conditions is equal to $\beta\beta_\theta$ under the conditions of $\beta_s = 90^\circ$ and $(90^\circ - \beta)$. When $\beta_s = 30^\circ$, $\beta = 0^\circ$ is equal to $\beta\beta_\theta$ under the conditions of $\beta = 60^\circ$. When $\beta_s = 60^\circ$, $\beta = 30^\circ$ is equal to $\beta\beta_\theta$ under the conditions of $\beta = 90^\circ$.

At the same time, Eq. (18) is used to evaluate the variation rule of the included angle ($\beta\beta_z$) between the middle principal stress (σ_2) and the normal direction of the bedding plane under different conditions, as shown in Fig. 10.

Figure 10 shows that when the hole azimuth angle is equal to the bedding surface direction, any point ($\theta = 0 \sim 360^\circ$) $\beta\beta_z$ around hole is equivalent to a certain value, and the angle $\beta\beta_z$ under different hole drift angle (β) conditions meets $|\beta - \beta_s|$. When $\beta_s = 0^\circ$, $\beta\beta_\theta$ value under different β conditions is equal to $\beta\beta_\theta$ under the conditions of $\beta_s = 90^\circ$ and $(90^\circ - \beta)$. When $\beta_s = 30^\circ$, $\beta = 0^\circ$ is equal to $\beta\beta_\theta$ under the conditions of $\beta = 60^\circ$. When $\beta_s = 60^\circ$, $\beta = 30^\circ$ is equal to $\beta\beta_\theta$ under the conditions of $\beta = 90^\circ$.

The influence of angle relation between principal stress and normal direction of bedding plane on borehole wall stability

Combined with the included angle relationship between the maximum principal stress obtained from Eq. (17) and the normal direction of the bedding plane, the influence of the included angle relationship between the maximum principal stress (σ_1) and the bedding plane on the equivalent density of collapse pressure of the rock mass in the wellbore wall can be evaluated by Eq. (9), as shown in Fig. 11.

Through simulation analysis, Fig. 11 shows that the angle relationship between the maximum principal stress and the bedding plane has a significant influence on the stability of the sidewall rock mass, and the influence rules are obviously different under different conditions. When the conditions meet $\sigma_v > \sigma_H > \sigma_h$ and $\alpha_s = 90^\circ$, the rock collapse pressure is different under the dip angle of different bedding surface.

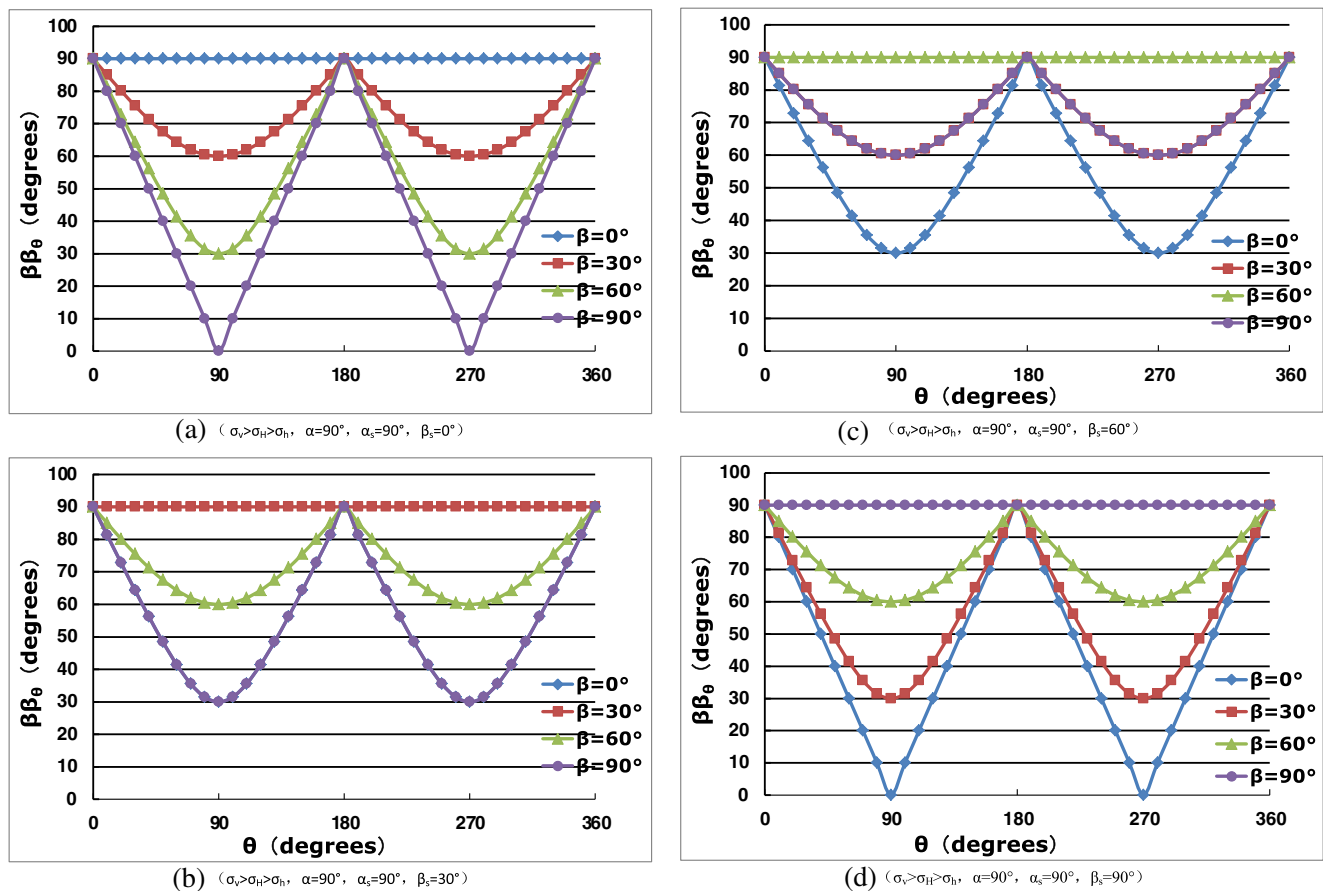


Fig. 9 The variation rule of the angle ($\beta\beta_\theta$) between maximum principal stress of the wellbore wall and the normal direction of bedding plane under different conditions

When the inclination of bedding plane is $\beta_s = 0^\circ$, the equivalent density of wellbore collapse pressure increases first and then decreases. The collapse pressure will reach the maximum value when the hole drift angle $\beta = 40^\circ$. At the horizontal section ($\beta = 90^\circ$), the collapse pressure along the minimum horizontal principal stress direction is the highest. When the inclination of bedding plane is $\beta_s = 30^\circ$ or $\beta_s = 60^\circ$, if drilling along the direction of $\alpha = 0^\circ, 30^\circ, 45^\circ$, or 60° , the sidewall rock collapse pressure increases with the increase of hole angle, but if drilling along the minimum horizontal principal stress direction ($\alpha = 90^\circ$), the sidewall rock collapse pressure under the conditions of bedding surface dip ($\beta_s = 30^\circ$) will present a trend of decrease first, then increases and then decreases, and that under the conditions of bedding surface angle ($\beta_s = 60^\circ$) will present a trend of increase first, then decreases and then increases. At the horizontal section ($\beta = 90^\circ$), the collapse pressure along the minimum horizontal principal stress direction is the smallest. When the bedding plane angle is $\beta_s = 90^\circ$, drilling along the direction of $\alpha = 0^\circ, 30^\circ, 45^\circ$, or 60° , the sidewall rock collapse pressure increases with the increase of hole angle, but if drilling along the minimum

horizontal principal stress direction ($\alpha = 90^\circ$), the collapse pressure of sidewall rock will present a trend of increases first and then decreases. The stability is best along the direction of minimum horizontal principal stress.

Similarly, considering the included angle relation $\beta\beta_z$ between the intermediate principal stress (σ_2) and the bedding plane, the influence of the angle relationship between the intermediate principal stress and the bedding surface on the collapse pressure of the sidewall rock is evaluated, as shown in Fig. 12.

Through simulation analysis, Fig. 12 shows that the angle relation between the intermediate principal stress and the bedding plane has a certain influence on the collapse pressure of the sidewall rock, but the impact range is less than the angle relationship between the maximum principal stress and the bedding plane. Considering the angle relationship between the intermediate principal stress and the bedding surface, the equivalent density of the sidewall rock collapse pressure is generally lower than 1 g/cm^3 . When the bedding surface angle is $\beta_s = 0^\circ$ or 30° , with the increase of borehole angle, the sidewall rock collapse pressure shows an increasing trend.

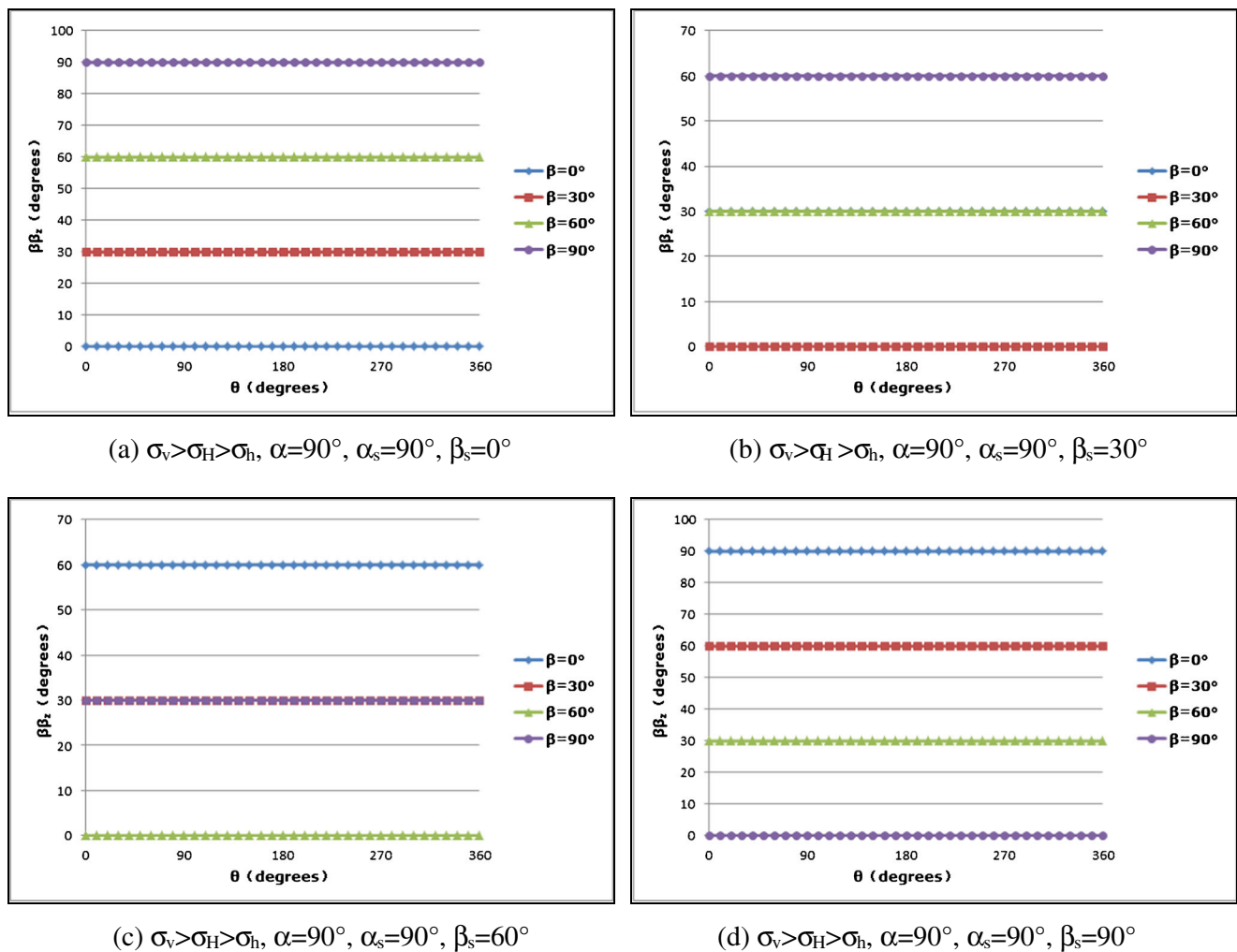


Fig. 10 The variation rule of the angle ($\beta\beta_0$) between middle principal stress of the wellbore wall and the normal direction of bedding plane under different conditions

During the drilling at the minimum horizontal principal stress direction, the stability of borehole wall at the horizontal section is the best. When the bedding surface dip is $\beta_s = 60^\circ$ or 90° , with the increase of borehole drift angle, the collapse pressure of borehole wall rock will present a trend of decrease first and then increase. During the drilling at the minimum horizontal principal stress direction, the stability of borehole wall at the horizontal section is the best.

Example analysis

In order to test the accuracy of the calculation model of shale wellbore collapse pressure, JY1HF well in Jiaoshiba area of Fuling was taken as an example for calculation and analysis, and the calculation was compared with the actual working condition on site. Well JY1HF is a horizontal shale gas well located in the

upper part of the Jiaoshiba structure in Fuling region, and its drilling target is the Lower Silurian LongMaxi shale formation, with a total depth of 11,988 ft and a vertical depth of 7932.4 ft. The relation between collapse pressure and borehole trajectory is calculated by conventional method and the method proposed in this paper.

According to laboratory experiment and field logging evaluation results, the overburden pressure gradient is 2.65 MPa/328 ft, the maximum horizontal principal stress gradient is 3.2 MPa/328 ft, the minimum horizontal principal stress gradient is 2.4 MPa/328 ft, the pore pressure gradient is 1.2 MPa/328 ft, the effective stress coefficient is 0.8, the Poisson’s ratio is 0.24, the shale body’s cohesion is 39.50 MPa, the body’s friction angle is 38.80° , the bedding plane’s cohesion is 10.23 MPa, and the bedding plane’s friction angle is 24.58° , given that the shale bedding plane in LongMaxi formation of the Jiaoshiba area is generally horizontal, bedding plane

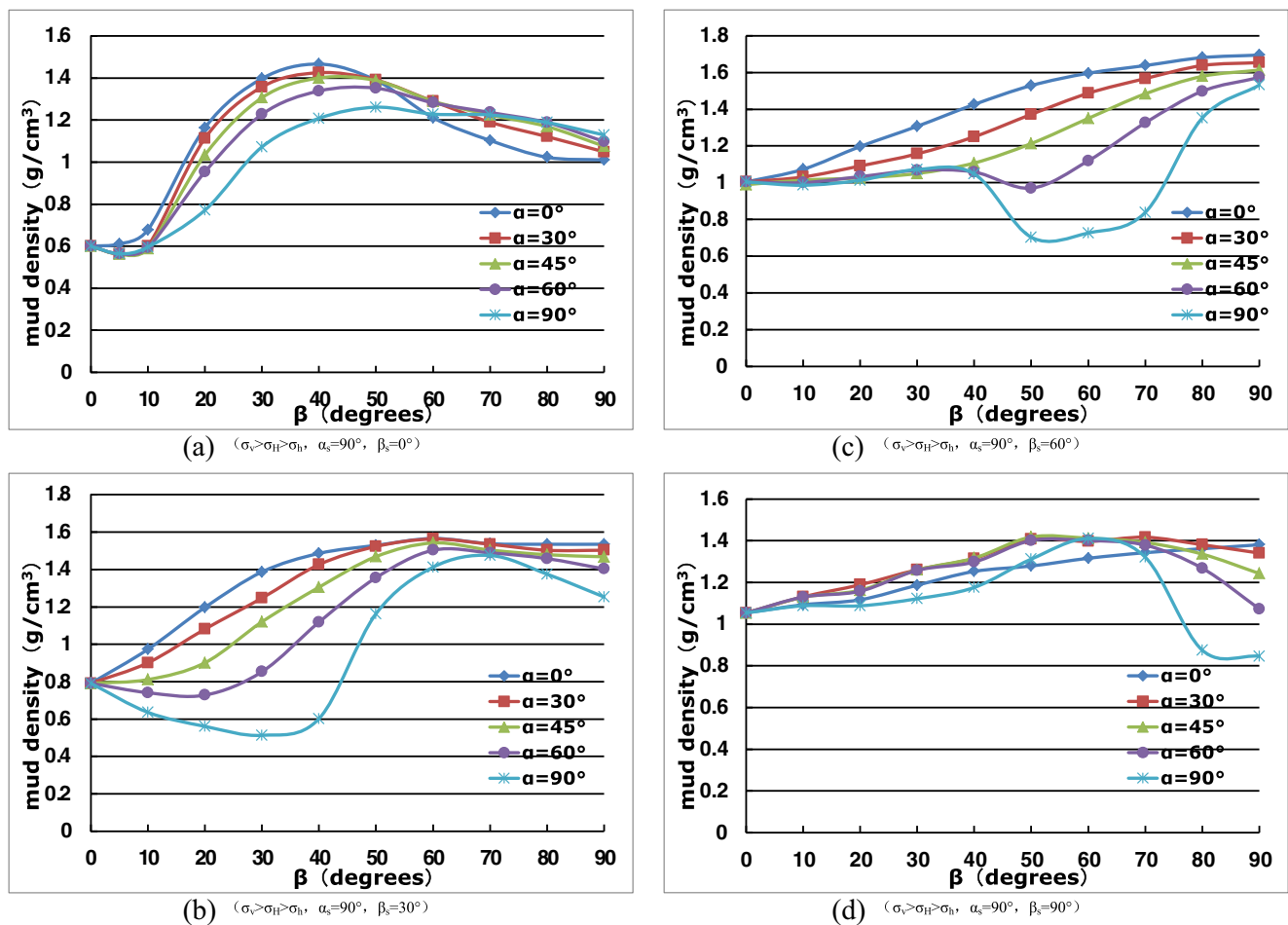


Fig. 11 The influence of angle relationship between the maximum principal stress (σ_1) and bedding plane on the equivalent density of sidewall rock collapse pressure

tendency of 0° , and dip angle of 0° . Calculations were carried out by conventional method and the method proposed in this paper, as shown in Fig. 13.

Figure 13 data shows that:

1. If the conventional model is used for calculation, overall collapse pressure decreases with the increase of deviation angle, and azimuth angle between 0° and 30° of borehole stability is better, namely drilling along the maximum horizontal in situ stress direction stability is better.
2. If the model in this paper is adopted for calculation, the relationship between collapse pressure and hole angle is more complicated because of the existence of bedding plane. Overall, regardless of the well azimuth, the collapse pressure increases first and then decreases with the increase of the hole angle; when the deviation angle is below 30° , the collapse pressure decreases gradually with the increase of the hole angle; when the deviation angle is $30^\circ\sim 60^\circ$, the collapse pressure increases rapidly and peaks appear at a deviation angle of about 60° ; when the

deviation angle is higher than 60° , the collapse pressure decreases rapidly and its minimum equivalent density appears at a deviation angle of 90° . At the same time, azimuth has obvious influence on the stability of shale gas reservoir sidewall. Drilling along the direction of minimum horizontal principal stress, the equivalent density of collapse pressure is higher than drilling along the direction of maximum horizontal principal stress; that is, drilling along the maximum horizontal stress direction is more stable.

In fact, JY1HF well is drilled along the minimum horizontal principal stress for the convenience of later fracturing reconstruction, and the density of the drilling fluid used in the second spud drilling section is 1.43 g/cm^3 . When drilling to the depth of 7762.3 ft, downhole leakage and collapse happened at the same time, which led to frequent blocking accidents; when drilling to the depth of 8201.4 ft, hole angle is 67.2° and drilling was forced to terminate, showing that the

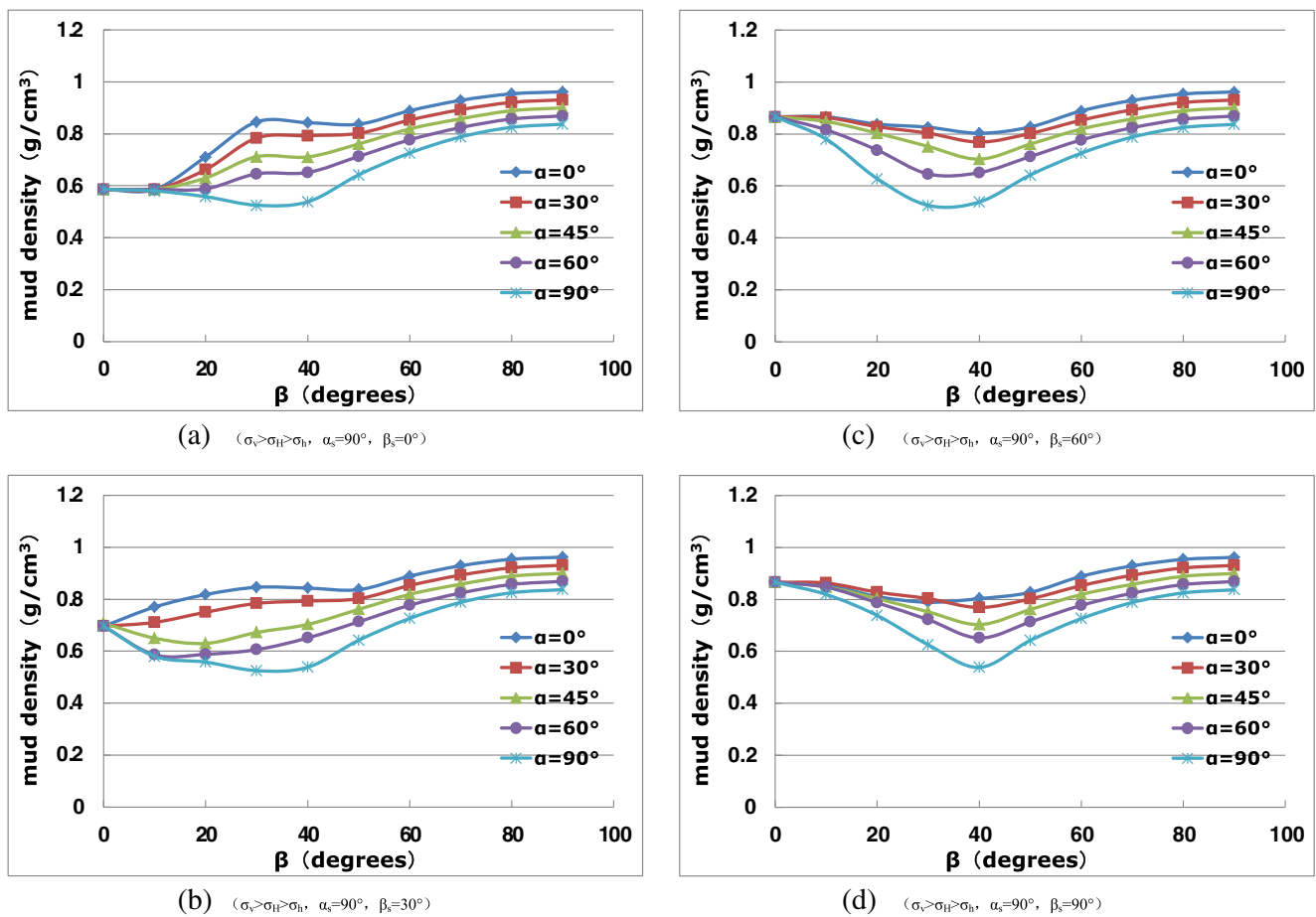


Fig. 12 The influence of angle relationship between the middle principal stress (σ_2) and bedding plane on the equivalent density of sidewall rock collapse pressure

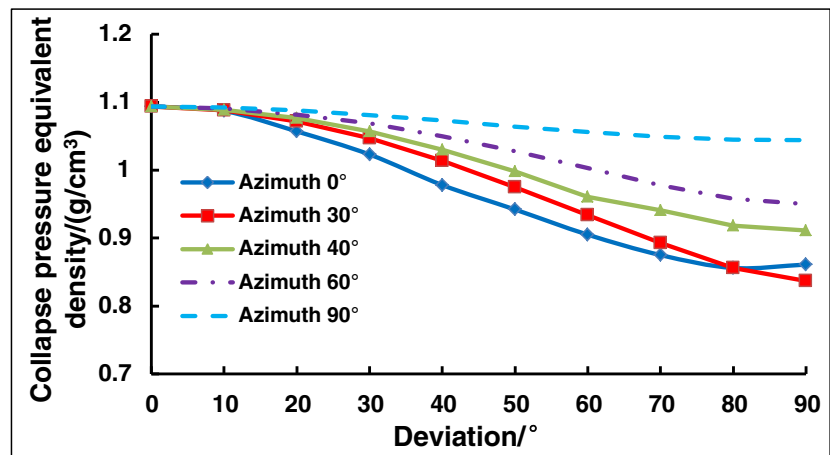
borehole wall stability is poorer. This situation had a good agreement with the calculation results; the calculation results show that when the angle is about 60° , collapse pressure is the highest. The equivalent density of collapse pressure calculated by the model in this paper is 1.65 g/cm^3 . Considering the existence of bedding, the allowable minimum density of drilling fluid is higher than the actual density of drilling fluid, which leads to the failure of the borehole wall along the bedding plane and the instability accident. Late in the process of completion, the wire line logging caliper curve also shows that when the angle is about 60° , the borehole diameter was enlarged seriously, as shown in Fig. 14 in which the maximum enlargement rate reached about 100%, showing that the results are basically identical with the actual result.

On the contrary, the calculation result of the conventional model is about 1.12 g/cm^3 , which is inconsistent with the actual situation. In addition, the strength degradation effect of shale soaked in drilling fluid is not considered in this model. If this degradation effect is taken into account in the model, the calculated critical collapse

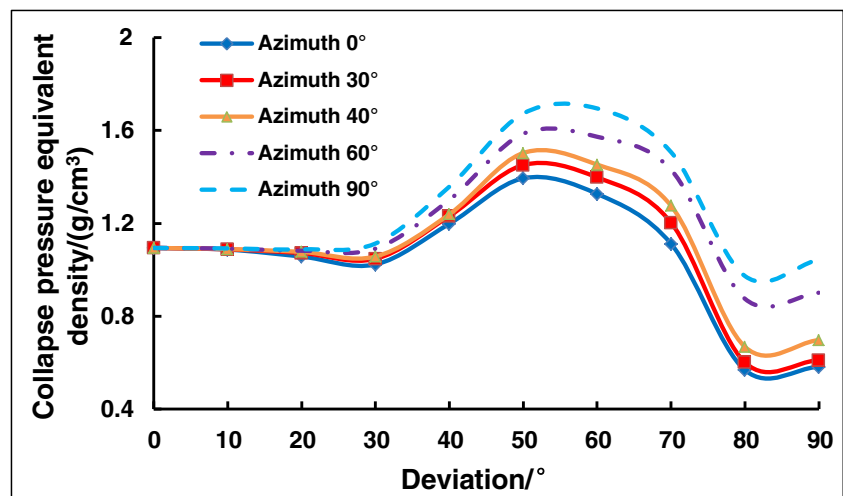
pressure will gradually increase with the drilling time, because the shale strength will decrease with the extension of drilling fluid soaking time. Therefore, for the shale rich in bedding, the conventional model cannot meet the demand of shale wellbore stability analysis. This analysis method considering the influence of bedding is more accurate in calculation. In the later construction of the well, the experience and lessons of the inclined well in the second spud drilling section were learned. Oil-based drilling fluid was used in the horizontal well section of the third spud drilling process, and the density of drilling fluid was added with a certain safety increment. The actual density of drilling fluid was 1.55 g/cm^3 , reaching the minimum density of drilling fluid allowed in the horizontal well section of the third spud drilling process. In the process of completion, the wireline logging curve indicates that the borehole in the third spud drilling section is regular, the diameter enlargement rate is generally less than 10%, and the borehole wall is stable, which further verifies the accuracy of the model in this paper.

Overall, in this paper, model calculation result tallies with the actual engineering conditions, and the wellbore collapse of

Fig. 13 The relationship between collapse pressure with azimuth angle, deviation angle



(a) Results calculated by conventional model



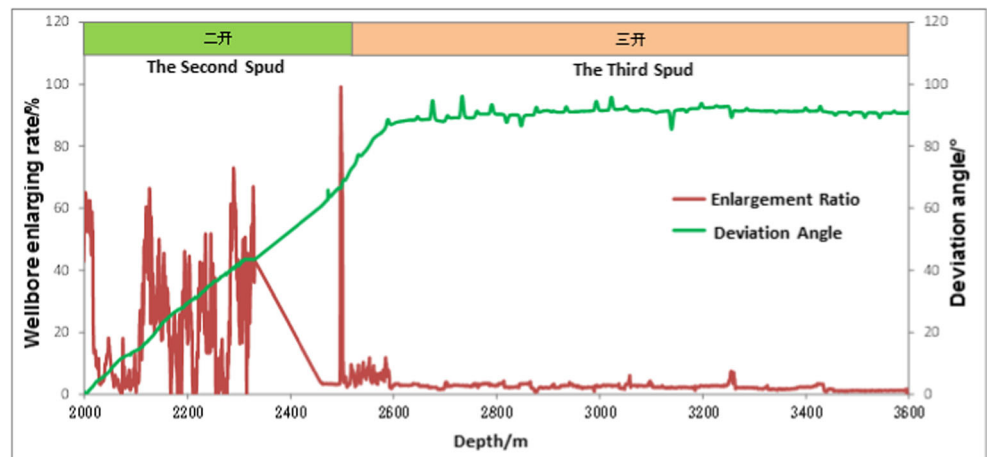
(b) The calculation results of the model in this paper

stratified shale gas reservoir mainly in the kick-off section, especially for 60° hole angle sidewall collapse problem which is more outstanding. Given all this, the density of drilling fluids shall be increased reasonably in response to wellbore stability requirements.

Conclusions

(1) Due to the development of shale bedding in LongMaxi formation, the compressive strength of weak bedding is lower than that of shale itself. In the case of an included angle of 30°

Fig. 14 Wireline logging curve in completion process of JY1HF well



with bedding, the compressive strength of the sample is the lowest, and that of the sample in the direction of vertical bedding is the highest, which indicates that LongMaxi shale shows strong strength anisotropy.

(2) The triaxial rock mechanics experiment shows that shear failure occurs in the direction of vertical bedding, with bedding angle of 30° the sample along the bedding plane shear sliding failure happened, and parallel bedding direction sample split and damage happened, which indicates that the shear slip failure along the weak bedding plane is the key mechanic mechanism of the shale strength reduction; the compressive strength degradation of the shale sample which soaked with on-site drilling fluid for 30 days is not very significant, indicating that the physical and chemical reaction between shale and drilling fluid after contact leads to the deterioration of shale strength, which may also be one of the important reasons for the shale wellbore wall instability.

(3) The collapse pressure calculated by the conventional model decreases with the increase of the hole angle, while the collapse pressure calculated by the model in this paper increases first and then decreases with the increase of the hole angle, indicating that the wellbore wall stability of stratified shale gas reservoir is closely related to the bedding occurrence and borehole trajectory. Borehole wall instability is mainly concentrated in the build-up section, i.e., the hole angle in the range of $40^\circ\sim 70^\circ$. The horizontal well section is less affected by the weak bedding planes, with better stability, and drilling along the maximum horizontal stress direction is more stable.

(4) The wellbore stability analysis results of JY1HF well show that the collapse pressure calculated by the model in this paper is more consistent with the actual situation, while the conventional model cannot accurately calculate the change of wellbore collapse pressure, which confirms the rationality and accuracy of the model in this paper. It also indicates that the failure of weak bedding may be the main mechanical mechanism for the collapse and instability of horizontal borehole wall of shale gas reservoir in Fuling Jiaoshiba block and the deterioration of shale strength is not the most important controlling factor.

Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

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