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Mechanical Properties and Wellbore Stability Analysis of Beipiao Oil Shale

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Abstract: ***This study analyzes the wellbore stability of Beipiao oil shale in Liaoning Province. XRD analysis and triaxial compression tests, conducted at bedding inclination intervals of 30° (0°, 30°, 60°, and 90°), characterize the samples as hard-brittle shale with significant mechanical anisotropy. Specifically, the cohesion and internal friction angle of the rock matrix are 17.15 MPa and 36.21°, respectively, while those of the bedding weak planes are significantly lower at 8.95 MPa and 25.85°. By coupling a transversely isotropic model with Jaeger's criterion, the collapse pressure equivalent density was calculated under various in-situ stress regimes. The results indicate that the optimal drilling trajectory varies with the stress regime: under strike-slip and reverse faulting conditions, the optimal trajectory aligns with the maximum horizontal in-situ stress (σ_H), whereas under normal faulting conditions, it aligns with the minimum horizontal in-situ stress (σ_h). These findings provide a theoretical basis for trajectory optimization in hard-brittle laminated formations.***

Keywords: Oil shale, Wellbore stability, Transverse isotropy, Shale reservoir, Collapse pressure.

1. Introduction

In recent years, as the exploitation of conventional oil and gas resources increasingly fails to meet the demands of modern industrial development, the development of unconventional resources, such as shale oil, has emerged as a research hotspot [1]. However, wellbore instability in shale formations severely restricts the efficient development of these resources [2]. In shale oil development, rock strength degradation is driven by complex in-situ stresses, pronounced bedding, and drilling fluid invasion. This degradation significantly exacerbates the risk of wellbore collapse and instability.

To understand the mechanisms of wellbore instability in shale formations and mitigate incidents such as sidewall collapse and lost circulation, extensive research has been conducted by petroleum engineers worldwide [3-7]. Aadnoy et al. developed a mechanical analysis model for anisotropic media, incorporating anisotropic elastic parameters and directional shear/tensile strength parameters; they demonstrated that ignoring rock anisotropy introduces significant errors into instability analyses [8]. Ong and Roegiers introduced a triaxial stress analysis model that accounts for wellbore fluid column pressure, fluid flow, and thermal stress, finding that wellbore stability in directional wells is primarily governed by rock anisotropy, in-situ stress heterogeneity, and thermal effects [9]. Sardar et al. argued that deviated wells in shale with anisotropic mechanical properties and strength pose a higher risk of instability than vertical wells [10]. Lee et al. established a model considering anisotropic rock strength and provided a method for determining the failure zone around the wellbore, noting that both the failure zone size and the safe mud weight are controlled by wellbore orientation, bedding planes, and the in-situ stress field [11].

However, quantitative analyses regarding the impact of shale anisotropy on near-wellbore stress and the safe mud weight window (SMWW) remain rarely reported, and the understanding of the mechanical mechanisms governing wellbore instability in shale formations remains insufficient.

Therefore, focusing on the laminated oil shale horizontal wells in Beipiao, Liaoning, this study establishes a transversely isotropic wellbore stability model to analyze the variation laws of collapse pressure. The findings of this study reveal the mechanical mechanisms of instability in anisotropic shale wellbores, providing guidance for safe and efficient drilling design in shale oil horizontal wells and reducing economic and time losses caused by wellbore collapse.

2. Mineral Composition and Mechanical Properties

2.1 Mineral Composition Analysis

Three blocks of natural oil shale outcrop were collected from a single site in the Beipiao area of Liaoning Province and processed into standard rock specimens. X-ray diffraction (XRD) analysis was conducted to determine their mineralogical compositions, as presented in Table 1.

Table 1: Mineral composition of the specimens

Sample ID	Mineral Composition (wt%)					
	Qtz	Kfs	Ab	Ank	Py	Clay
B1	36.1	9.3	19.5	12.6	14.2	8.3
B2	37.2	8.5	16.5	13.5	14.7	9.6
B3	39.6	10.2	17.5	11.3	12.2	9.2

As indicated in Table 1, the mineral compositions of the oil shale in this region show high consistency, exhibiting pronounced brittle characteristics. The rock matrix is predominantly composed of quartz (36.1%–39.6%), feldspars (including K-feldspar and albite, totaling 25.0%–28.8%), and carbonate minerals (mainly ankerite, 11.3%–13.5%). Notably, the specimens contain a relatively high proportion of pyrite (12.2%–14.7%), which contributes to the increased density and hardness of the rock. In contrast, the total clay mineral content is relatively low, ranging from 8.3% to 9.6%.

Based on the classification of mineral mechanical properties, the brittleness index of these specimens is exceptionally high, suggesting that the formation mechanically behaves as a hard-brittle material. Although the absolute content of clay minerals (<10%) is insufficient to induce significant macroscopic volumetric swelling, the impact of fluid-rock interaction on wellbore stability cannot be ignored. Upon the invasion of water-based drilling fluid (WBDF) filtrate into formation micro-fractures, the surface hydration of clay minerals reduces the inter-particle surface energy, leading to a significant degradation in rock cohesion and internal friction angle. Furthermore, during drilling, the filtrate tends to penetrate along bedding planes, weakening the interlayer cementation strength and potentially inducing shear slippage or spalling along these planes.

2.2 Mechanical Properties Analysis

To characterize the mechanical anisotropy of the Beipiao oil shale, standard core specimens were drilled at varying orientations. The angles between the coring axis and the normal to the bedding plane were set to 0°, 30°, 60°, and 90°. Triaxial compression tests were conducted using a rock mechanics testing system. Figure 1 illustrates the typical failure modes observed under loading conditions parallel and perpendicular to the bedding planes.

(a) Parallel to bedding

(b) Perpendicular to bedding

Figure 1: Failure patterns of oil shale

When the loading direction was parallel to the bedding planes, the specimens underwent catastrophic delamination and slabbing disintegration. Due to the enrichment of directionally aligned illite and organic matter along the bedding planes, the interlayer cementation strength is significantly lower than that of the rock matrix. Under axial stress, these weak bedding planes were preferentially activated and dilated, causing the specimens to shatter into regular slab-like fragments along the layers. This stark contrast in failure modes demonstrates that wellbore stability is highly dependent on the relative angle between the wellbore trajectory and formation bedding. Consequently, in horizontal drilling or highly deviated sections, stress components parallel to the bedding are prone to inducing severe spalling and sloughing.

In contrast, when the loading direction was perpendicular to the bedding planes, the failure mode was primarily characterized by trans-layer tensile splitting. Fractures forcibly propagated through the rigid mineral skeleton. Although through-going fractures developed, the specimens retained their overall columnar integrity, indicating that the rock possesses higher matrix strength and shear resistance in the direction perpendicular to bedding.

The results of the triaxial compression tests are presented in Table 2.

Table 2: The results of the triaxial compression tests

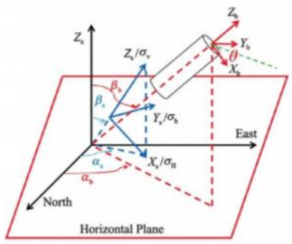
B (°)	No.	σ_3 (MPa)	E (MPa)	v	σ_1 (MPa)
	1-1	5	5204.1	0.246	86.92
0	1-2	10	5427.9	0.235	106.45
	1-3	20	6225.3	0.241	145.12
	2-1	5	6275.1	0.231	72.65
30	2-2	10	6685.9	0.226	92.18
	2-3	20	7082.3	0.224	130.44
	3-1	5	7654.3	0.198	41.25
60	3-2	10	8136.2	0.211	53.94
	3-3	20	8336.7	0.205	79.82
	4-1	5	11927.3	0.176	82.34
90	4-2	10	12013.9	0.182	101.55
	4-3	20	12119.7	0.172	139.67

3. Calculation of Collapse Pressure

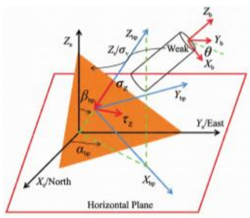
3.1 Determination of Anisotropic Parameters

To obtain the near-wellbore stress distribution, it is necessary to establish coordinate transformation relationships among the geodetic coordinate system, the in-situ stress coordinate system, the wellbore Cartesian and polar coordinate systems, and the bedding plane coordinate system. The geometric relationships among these coordinates are illustrated in Figure 2.

In Figure 2, α_s represents the azimuth of the maximum horizontal in-situ stress relative to the geographic North; β_s denotes the angle between the vertical in-situ stress and the vertical direction; the angle between the wellbore axis and the vertical direction is defined as the wellbore deviation angle βb; the angle between the projection of the wellbore trajectory on the horizontal plane and the geographic North is the wellbore azimuth α_b; $\alpha_{(bp)}+\pi/2$ corresponds to the strike of the bedding plane; and $\beta_{(bp)}$ represents the angle between the normal to the bedding plane and the vertical direction.



(a) Transformation of in-situ stress coordinates



(b) Transformation of bedding plane coordinates

Figure 2: Schematic diagram of coordinate transformation

Based on the in-situ stress coordinate system, the stress distribution around the wellbore in the Cartesian coordinate system is obtained through a series of coordinate transformations, which can be expressed as:

$$\begin{bmatrix}\sigma_{x,i}\\ \sigma_{y,i}\\ \sigma_{z,i}\\ \tau_{xy,i}\\ \tau_{yz,i}\\ \tau_{zx,i}\end{bmatrix}=\begin{bmatrix}cos^2\alpha_b cos^2\beta_b & sin^2\alpha_b cos^2\beta_b & sin^2\beta_b\\ sin^2\alpha_b & cos^2\alpha_b & 0\\ cos^2\alpha_b sin^2\beta_b & sin^2\alpha_b sin^2\beta_b & cos^2\beta_b\\ -0.5 sin(2\alpha_b) cos\beta_b & 0.5 sin(2\alpha_b) cos\beta_b & 0\\ -0.5 sin(2\alpha_b) sin\beta_b & 0.5 sin(2\alpha_b) sin\beta_b & 0\\ 0.5 cos^2\alpha_b sin(2\beta_b) & 0.5 sin^2\alpha_b sin(2\beta_b) & -0.5 sin(2\beta_b)\end{bmatrix}\begin{bmatrix}\sigma_H\\ \sigma_h\\ \sigma_v\end{bmatrix} \quad (1)$$

Given that the oil shale in the study area is a typical hard-brittle rock exhibiting significant elasticity, and triaxial tests have demonstrated its pronounced strength anisotropy, the formation is assumed to be a transversely isotropic poroelastic medium. Consequently, its constitutive equations can be expressed as:

$$\epsilon=A\sigma \quad (2)$$

$$A=\begin{bmatrix}1/E_h & -v_h/E_h & -v_v/E_v & 0 & 0 & 0\\ -v_h/E_h & 1/E_h & -v_v/E_v & 0 & 0 & 0\\ -v_v/E_v & -v_v/E_v & 1/E_v & 0 & 0 & 0\\ 0 & 0 & 0 & \frac{E_v(1+2v_v)+E_h}{E_hE_v} & 0 & 0\\ 0 & 0 & 0 & 0 & \frac{E_v(1+2v_v)+E_h}{E_hE_v} & 0\\ 0 & 0 & 0 & 0 & 0 & \frac{2(1+v_h)}{E_h}\end{bmatrix} \quad (3)$$

Based on Eqs. (2) and (3), in conjunction with the triaxial strength test results, the anisotropic elastic parameters of the oil shale in the study area were obtained, as listed in Table 3.

Table 3: Anisotropic elastic parameters

E_v(MPa)	E_h(MPa)	v_v	v_h
5427.9	12013.9	0.241	0.177

3.2 Wellbore Stress Model

After the formation is drilled, the secondary stress distribution resulting from stress redistribution is closely correlated with the in-situ stress and the fluid pressure around the wellbore. This secondary stress field can be decomposed into three components: the in-situ stress component, the stress component induced by wellbore excavation, and the stress component induced by the fluid pressure around the wellbore. By linearly superimposing these three components, the stress distribution model around the wellbore in shale formations is obtained.

$$\begin{cases}\sigma_r=P_w\\ \sigma_\theta=\sigma_{xx}+\sigma_{yy}-2(\sigma_{xx}-\sigma_{yy})\cos 2\theta-4\tau_{xy}\sin 2\theta-P_w\\ \sigma_z=\sigma_{zz}-v\left[2(\sigma_{xx}-\sigma_{yy})\cos 2\theta+4\tau_{xy}\sin 2\theta\right]\\ \tau_{\theta z}=2(\tau_{yz}\cos\theta-\tau_{xz}\sin\theta)\\ \tau_{r\theta}=0\\ \tau_{rz}=0\end{cases} \quad (4)$$

3.3 Anisotropic Failure Criterion

Since the majority of rock strength criteria are typically expressed in terms of principal stresses, it is necessary to transform the near-wellbore stress components into principal stresses to facilitate the calculation.

$$\begin{cases}\sigma_i=\sigma_r-P_p\\ \sigma_j=\frac{\sigma_\theta+\sigma_z}{2}-P_p+\sqrt{\left(\frac{\sigma_\theta-\sigma_z}{2}\right)^2+\tau_{\theta z}^2}\\ \sigma_k=\frac{\sigma_\theta+\sigma_z}{2}-P_p-\sqrt{\left(\frac{\sigma_\theta-\sigma_z}{2}\right)^2+\tau_{\theta z}^2}\end{cases} \quad (5)$$

Given the significant strength anisotropy exhibited by the Beipiao oil shale, Jaeger's Single Plane of Weakness criterion is employed to characterize its failure behavior. Based on the data in Table 2, the cohesion and internal friction angle of the rock matrix are determined to be 17.15 MPa and 36.21°, respectively, while those for the bedding planes are 8.95 MPa and 25.85°, respectively. The Jaeger criterion is expressed as follows:

$$\sigma_1=\sigma_3+\frac{2(c_0+\sigma_3\tan\varphi_0)}{(1-\tan\varphi_0\cot\beta_0)\sin 2\beta_0}\ (\beta<\beta_1\ or\ \beta>\beta_2) \quad (6)$$

$$\sigma_1=\sigma_3+\frac{2(c_w+\sigma_3\tan\varphi_w)}{(1-\tan\varphi_w\cot\beta)\sin 2\beta}\ (\beta_1\le\beta\le\beta_2) \quad (7)$$

By substituting the near-wellbore principal stresses into Equations (6) and (7) and solving using a cyclic iterative method, the equivalent density of the collapse pressure can be obtained. This facilitates the study of the influence of in-situ stress anisotropy on wellbore collapse pressure.

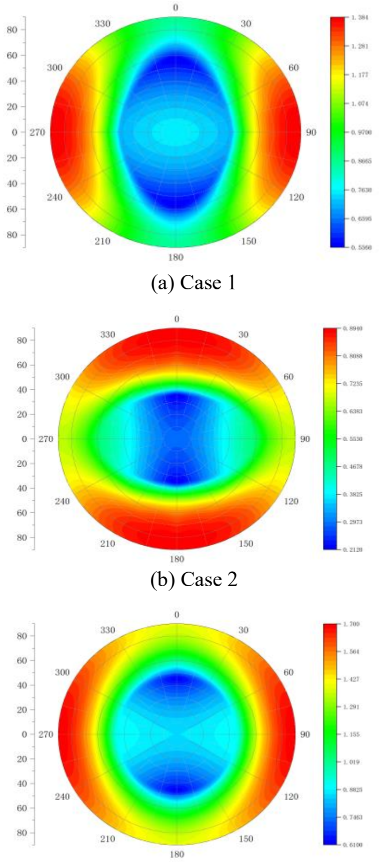
3.4 Influence of In-situ Stress Anisotropy

Laboratory-derived rock properties (Young's modulus, Poisson's ratio, and strength parameters) were input into the model. The well depth is 1200 m, and the formation possesses horizontal bedding. The vertical stress was kept constant, whereas the horizontal stress parameters varied as shown in Table 4.

Table 4: In-situ stress distribution

Case	σ_H (MPa)	σ_h (MPa)	σ_v (MPa)	P_p (MPa)
Case 1	36	24	30	12
Case 2	25	18	30	12
Case 3	42	36	30	12

The predicted results, calculated using the aforementioned parameters, are illustrated in Figure 3. In this figure, the radial coordinate represents the wellbore inclination (deviation angle), where 0° corresponds to a vertical well and 90° to a horizontal well. The angular coordinate represents the wellbore azimuth, with 0° (North) indicating the direction of the maximum horizontal in-situ stress.



(a) Case 1

(b) Case 2

(c) Case 3

Figure 3: Collapse pressure equivalent density distribution under different in-situ stress states

Case 1 (Strike-slip Faulting Regime): In this regime, the maximum horizontal stress σ_H becomes the dominant driver of wellbore failure. When drilling along the direction of the minimum horizontal stress, the wellbore cross-section is subjected to direct compression from σ_H, causing the collapse pressure to peak. Conversely, when drilling along the direction of σ_H, the wellbore avoids direct compression from the maximum stress. In this orientation, the lateral stress state is controlled by σ_h and σ_v; the resulting lower stress difference is conducive to maintaining wellbore stability.

Case 2 (Normal Faulting Stress Regime): When the drilling azimuth aligns with the direction of σ_H, the wellbore sidewall is primarily supported laterally by σ_h. Since σ_h has the lowest magnitude, it fails to provide sufficient confining pressure to resist the stress concentration induced by the high vertical stress σ_v. Consequently, the tangential stress at the wellbore wall easily exceeds the strength of the rock matrix, leading to severe shear failure. Optimal Drilling Azimuth (along σ_h): In contrast, drilling along the direction of σ_h allows the wellbore to be laterally supported by the larger σ_H. This effectively mitigates the stress difference caused by the vertical load, resulting in a relatively lower collapse pressure and maximum wellbore stability.

Case 3 (Reverse Faulting Regime): In this scenario, both horizontal principal stresses are high. Due to the strong horizontal tectonic stress, horizontal well sections are subjected to intense overall compression, leading to universally higher collapse pressures compared to the normal faulting regime. Similar to the strike-slip case, drilling along the σ_h azimuth exposes the wellbore to the most severe compression from σ_H, presenting the highest risk, whereas drilling along the σ_H azimuth is relatively safer.

4. Conclusions

1) The oil shale in the Beipiao area is characterized by a high content of brittle minerals (quartz, feldspar) and low clay content (mainly illite). Hydration primarily weakens the interlayer cementation, leading to shear slippage or spalling along bedding planes. Additionally, triaxial tests verify that the rock possesses significant strength and elastic anisotropy.

2) The elastic modulus of the tested oil shale specimens varies from 5204.1 to 12119.7 MPa, with values parallel and perpendicular to the bedding of 12013.9 MPa and 5427.9 MPa, respectively, yielding an anisotropy ratio of 2.21. The Poisson's ratio generally falls between 0.172 and 0.246; specifically, the Poisson's ratios parallel and perpendicular to the bedding are 0.177 and 0.241, respectively, resulting in a ratio of 0.48. In terms of strength characteristics, Jaeger's single plane of weakness theory demonstrates a good fit for the variation of strength with bedding inclination; based on triaxial test data, the cohesion and internal friction angle were calculated to be 17.15 MPa and 36.21° for the rock matrix, and 8.95 MPa and 25.85° for the weak planes.

3) A calculation model for wellbore collapse pressure was established. Based on calculations under three different in-situ stress states, the results indicate that: The influence of drilling azimuth on wellbore stability varies significantly with stress regimes. In strike-slip and reverse faulting regimes, the optimal drilling direction aligns with the maximum horizontal stress σ_H to minimize lateral compression. Conversely, in a normal faulting regime, the optimal azimuth shifts to the minimum horizontal stress σ_h direction, where the lateral support provided by σ_H effectively mitigates the instability induced by vertical stress.

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