Wellbore stability analysis for arbitrary inclined well in anisotropic formations

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Abstract. Wellbore instability is a classic rock mechanics problem encountered during drilling and completing. The traditional model for wellbore stability analysis assumes that formation rocks are homogenous, continuous, and isotropic. However, most of the deep formation rocks are naturally anisotropic. Therefore, this study proposes an anisotropic wellbore stability model for an arbitrary inclined well, considering the anisotropic elastic properties, shear strength, and in-situ stress. This model was compared to the traditional model. The equivalent mud weight of collapse pressure (EMWCP) was predicted for three types of typical in-situ stress states, such as normal faulting (NF), strike-slip faulting (SSF), and reverse faulting (RF). The results show that rock anisotropy significantly influenced EMWCP compared to the traditional model. The anisotropy of in-situ stress and shear strength increase the EMWCP, whereas the anisotropy of rock elastic properties decreases the EMWCP. The optimal well path is in the ranges of the attack angle (the angle between the borehole axis and the normal of weak planes) lower than 45°. In other words, the anisotropy shear strength is harmful to keeping wellbore stability, whereas the anisotropy of rock elastic properties is conducive. Thus, the influence of anisotropic shear strength cannot be ignored for wellbore stability analysis, whereas the influence of anisotropic elasticity can be ignored. This model provides theoretical guidance for drilling mud density optimization, well trajectory optimization, and well drilling and completion safety.

1. Introduction
Wellbore instability is a classic rock mechanics problem encountered during drilling and completing, costing the drilling industry more than $100 million per year worldwide [1–3]. The wellbore collapse could lead to serious down-hole accidents such as pack-off, over-pulls, high torque, reaming operations, and stuck pipe [4]. To predict wellbore stability, several analytical, semi-analytical, and numerical methods have been used to solve this problem [4–5]. Wellbore stability can be defined quantitatively by using analytical or semi-analytical methods where the related research of wellbore stability includes the stress distribution model and failure criterion [1–6]. The stress distribution model includes linear elastic, poro-elastic, thermo-poro-elastic, chemo-poro-elastic, and chemo-thermo-poro-elastic models [4]. The failure criterion includes the Mohr-Coulomb, Drucker-Prager, Hoek-Brown, Mogi-Coulomb, and Wiebols-Cook criteria [6]. The poro-elastic model combined with the Mohr-Coulomb criterion is still the most common used for wellbore stability analysis. However, these models and criteria only apply to isotropic formations.

For anisotropic formations, both rock elasticity and strength are anisotropic; therefore, the anisotropic elastic model and strength criterion should be used for wellbore stability analysis [2, 7–15].
Aadnøy (1988) proposed the wellbore stability model for transversely isotropic formation by involving anisotropic elasticity [16]. The author highlighted that the magnitudes and locations of hoop stresses are affected by elastic anisotropy, leading to the much easier collapse of the wellbore. Ong and Roegiers (1993) also investigated the influence of anisotropic elasticity on wellbore stability and showed that the influence of anisotropic elasticity on fracture pressure is much higher than that of the collapse pressure [17]. Chen et al. (2011) [3], Aadnøy and Looyeh (2011) [2], Lee et al. (2012) [12], Ma and Chen (2015) [13], and Ma et al. (2016) [14] studied the influence of anisotropic strength on wellbore stability by suggesting using a single plane of weakness (SPW) criterion. Kanfar et al. (2015) [18] investigated the wellbore stability for anisotropic formations by combining both the anisotropic elastic model and anisotropic strength criterion. Setiawan and Zimmerman (2018) [19] investigated the wellbore stability for anisotropic formations by combining both the anisotropic elastic model, the SPW criterion, and Mogi-Coulomb criterion. Ma et al. (2017, 2019) [7, 8, 20] investigated the influence of anisotropic tensile strength and on fracture pressure.

The wellbore stability of anisotropic formations has been widely investigated, especially for anisotropic elasticity and strength. However, the combined influence of both anisotropic elasticity and strength on wellbore stability of an arbitrary inclined well is seldom investigated. Therefore, this study proposes an anisotropic wellbore stability model for an arbitrary inclined well, where the anisotropic elastic properties, shear strength, and in-situ stress were considered. This model was compared to the traditional model. The equivalent mud weight of collapse pressure (EMWCP) was predicted for three types of typical in-situ stress states, such as normal faulting (NF), strike-slip faulting (SSF), and reverse faulting (RF). This model can provide theoretical guidance for drilling mud density optimization, well trajectory optimization, and well drilling and completion safety.

2. Modeling for wellbore stability analysis

2.1. Stress distribution model

For anisotropic formations, four assumptions are made to simplify this model [20]. (1) The formation is continuous, homogeneous, and transversely isotropic. (2) The elastic deformation of the rock is small. (3) The stress-strain around the wellbore satisfies the generalized plane strain condition. (4) Seepage, heat transfer, and chemical reactions are neglected.

2.1.1. Coordinate transformation

Figure 1 shows that coordinate transformations between different coordinate systems must obtain the stress distribution around the inclined borehole. Five coordinate systems exist, namely the global coordinate system (GCS) \((x, y, z)\) or \((N, E, Z)\), local coordinate system of in-situ stress (ISCS) \((x_s, y_s, z_s)\), local coordinate system of the borehole (BCS) \((x_b, y_b, z_b)\), cylindrical coordinate system of the borehole (BCCS) \((r_b, \theta, z_b)\), and local coordinate system of the transverse isotropic plane (TIPCS) \((x_w, y_w, z_w)\).

![Figure 1. Stress distribution model around an inclined borehole](image)

The inclined wellbore with an inclination angle \(\alpha\) and azimuth angle \(\beta\) is defined to express the relationship between the BCCS and GCS. The transverse isotropic plane with a dip angle \(\alpha_w\) and dip direction \(\beta_w\) is defined to express the relationship between the TIPCS and GCS. Furthermore, the azimuth angle \(\beta\) is defined as the angle between the maximum horizontal stress \(\sigma_H\) and the x-
axis (or N-axis). Therefore, coordinate transformations between different coordinate systems can be obtained using Bond transformation and rotation matrices.

2.1.2. Compliance matrix for anisotropic formations

Because of the anisotropic elasticity of anisotropic formations, the constitutive equation of the transversely isotropic rock can be expressed as

\[ [\varepsilon]_w = [A][\sigma]_w, \]

where

\[
[A] = \begin{bmatrix}
\frac{1}{E} & -\frac{v}{E} & -\frac{v'}{E'} & 0 & 0 & 0 \\
-\frac{v}{E} & \frac{1}{E} & -\frac{v'}{E'} & 0 & 0 & 0 \\
-\frac{v'}{E'} & -\frac{v'}{E'} & \frac{1}{E'} & 0 & 0 & 0 \\
0 & 0 & 0 & 1/G' & 0 & 0 \\
0 & 0 & 0 & 0 & 1/G' & 0 \\
0 & 0 & 0 & 0 & 0 & 1/G'
\end{bmatrix},
\]

where \([\varepsilon]_w = \{\varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{zz}, 2\gamma_{xy}, 2\gamma_{yx}, 2\gamma_{yz}, 2\gamma_{zy}\}^T\) is the strain vector in the TIPCS, \([\sigma]_w = \{\sigma_{xx}, \sigma_{yy}, \sigma_{zz}, \tau_{xy}, \tau_{yx}, \tau_{yz}, \tau_{zy}\}^T\) is the stress vector in the TIPCS, \([A]\) is the compliance matrix in the TIPCS, \(E, v, G\) represent the elastic modulus, Poisson’s ratio, and shear modulus perpendicular to the bedding plane, respectively, and \(E', v', G'\) represent the elastic modulus, Poisson’s ratio, and shear modulus parallel to the bedding plane, respectively.

Thus, using the Bond transformation matrix, the compliance matrix in the BCS can be obtained using

\[
[A'] = [P]_s [M_s] M_g^T [A] M_g [P]_s^T,
\]

where \([P]_s\) represents the Bond transformation matrix between BCS and GCS and \([M_s]\) represents the Bond transformation matrix between TIPCS and GCS.

2.1.3. Stress component around a borehole

Lekhnitskij (1981) [21] and Amadei (1983) [22] divided the stress distribution into three parts, namely the component induced by the (1) far-field in-situ stress, (2) drilling the borehole, and (3) the wellbore pressure. The stress distribution around the inclined wellbore can be obtained by superimposing these three components [16],

\[
[\sigma]_b = [O_b] [R_b] [\sigma],
\]

where

\[
\phi(z) = 0.5 \gamma \left[ (\mu_{i} \lambda_{i} \lambda_{i} - \mu_{i}) (\sigma_{ii} - i\tau_{ii} - p_{i}) + (\lambda_{i} \lambda_{i} \lambda_{i} - 1)(\tau_{ii} - i\tau_{ii} + i\tau_{ii} + i\tau_{ii}) + \lambda_{ii} (\mu_{i} - \mu_{i})(\tau_{ii} - i\tau_{ii}) \right]
\]

\[
\phi'(z) = 0.5 \gamma \left[ (\mu_{i} - \mu_{i} \lambda_{i} \lambda_{i} \lambda_{i})(\sigma_{ii} - i\tau_{ii} - p_{i}) + (1 - \lambda_{i} \lambda_{i} \lambda_{i})(\tau_{ii} - i\tau_{ii} + i\tau_{ii} + i\tau_{ii}) + \lambda_{ii} (\mu_{i} - \mu_{i})(\tau_{ii} - i\tau_{ii}) \right]
\]

\[
\phi''(z) = 0.5 \gamma \left[ (\mu_{i} \lambda_{i} - \mu_{i}) (\sigma_{ii} - i\tau_{ii} - p_{i}) + (\lambda_{ii} - \lambda_{ii})(\tau_{ii} - i\tau_{ii} + i\tau_{ii} + i\tau_{ii}) + (\mu_{ii} - \mu_{ii})(\tau_{ii} - i\tau_{ii}) \right]
\]
\[
\gamma_i = -\frac{1}{\Delta z_i} \sqrt{(z_i/R)^2 - 1 - \mu_i^2} \\
\xi_i = \frac{z_i/R + \sqrt{(z_i/R)^2 - 1 - \mu_i^2}}{1 - i \mu_i},
\]
(7)

where \( \{\sigma\} = \{\sigma_{xx}^0, \sigma_{yy}^0, \sigma_{zz}^0, \tau_{xx}^0, \tau_{yy}^0, \tau_{zz}^0\}^T \) represents the stress component induced by the far-field in-situ stress. \( \{\sigma\} = \{\sigma_e, \sigma_u, \sigma_h, 0, 0, 0\}^T \) represents the far-field in-situ stress in ISGS. \( \sigma_e, \sigma_u, \) and \( \sigma_h \) represent the in-situ stresses. \( [R_a] \) represents the Bond transformation matrix between BCS and GCS. \( a_{ij} \) is the compliance matrix in the BCS \( [A'] \). \( \phi_1(z_1), \phi_2(z_2), \) and \( \phi_3(z_3) \) represent the analytic functions. \( \mu_i \) are the roots of the sixth order polynomial equation for strain compatibility. \( \lambda_i, \gamma_i, \xi_i, \) and \( \Delta \) represent the complex variables related to \( \mu_i, \) and \( p_w \) is the wellbore pressure.

2.2. Anisotropic strength criterion

For anisotropic formations, rock strength can be calculated using the SPW theory. As shown in Figure 2, assuming that there is a group of planes of weakness \( AB \) in the rock mass, the angle between the \( AB \) plane (normal) and direction of the maximum principal stress is \( \beta. \) From the experimental observations, two types of typical failure modes exist, namely (1) failure across the intact rock matrix, and (2) slippage along the weak planes. Thus, the anisotropic strength criterion can be written as

\[
\begin{cases}
\tau_0 = c_0 + \sigma_{00} \tan \phi_0 & \text{(Failure across the intact rock matrix)} \\
\tau_w = c_w + \sigma_{ww} \tan \phi_w & \text{(Slippage along the weak planes)}
\end{cases}
\]
(8)

where \( \tau_0 \) is the shear stress acting on the body failure plane, \( \sigma_{00} \) is the normal stress acting on the body failure plane, \( c_0 \) is the cohesion of the rock body, and \( \phi_0 \) is the internal friction angle of the rock body. \( \tau_w \) is the shear stress acting on the weak planes, \( \sigma_{ww} \) is the normal stress acting on the weak planes, \( c_w \) is the cohesion of the rock plane of weakness, and \( \phi_w \) is the internal friction angle of the rock plane of weakness.

![Figure 2. Theoretical analysis diagram of rock strength with a single plane of weakness [23]](image)

Equation (8) can also be expressed using the principal stresses [23]

\[
\begin{cases}
\sigma_1 = \sigma_3 + \frac{2(c_0 + \sigma_3 \tan \phi_0)}{(1 - \tan \phi_0 \cot \beta_0 \sin 2\beta_0)} \beta < \beta_1 \text{ or } \beta > \beta_2 \\
\sigma_1 = \sigma_3 + \frac{2(c_w + \sigma_3 \tan \phi_w)}{(1 - \tan \phi_w \cot \beta \sin 2\beta)} \beta_1 \leq \beta \leq \beta_2
\end{cases}
\]
(9)

where \( \sigma_1 \) is the maximum principal stress, \( \sigma_3 \) is the minimum principal stress, \( \beta \) is the angle between the weak plane normal and the maximum principal stress, and \( \beta_0 \) is the angle between the body failure
plane and the maximum principal stress, and $\beta_0 = \pi/4 + \varphi_0$, and $\beta_1$ and $\beta_2$ are the angle limitations when failed along the weak planes [23].

Given this, combining Equations (4) and (8) or (9), the critical collapse pressure can be obtained by solving this nonlinear equation by first calculating the angle between the weak plane normal and the maximum principal stress. In this study, we used a much simpler way than introduced by Lee et al. (2012) [12] to solve this nonlinear equation. In this simplified method, the second formula of Equation (8) and the first formula of Equation (9) are combined to characterize the anisotropic strength. The solution for the failure across the intact rock matrix (the first formula of Equation (9)) is like the traditional method, whereas the solution for slippage along the weak planes (the second formula of Equation (8)) is different from the traditional method. The stress component in the BCS was transformed into TIPCS. The shear and normal stresses acting on the weak planes can be expressed as [12]

$$
\begin{align*}
\sigma_{\text{ss}} &= \sigma_{\text{ss}}^w \\
\tau_{\text{ss}} &= \sqrt{(\tau_{\text{ss}}^w)^2 + (\tau_{\text{ss}}^w)^2},
\end{align*}
$$

where $\sigma_{\text{ss}}^w$, $\tau_{\text{ss}}^w$, and $\tau_{\text{ss}}^w$ represent the stress component acting on the weak planes.

Once the shear and normal stresses acting on the weak planes are calculated, the critical collapse pressure for slippage along the weak planes can be calculated by substituting these stress components into the second formula of Equation (8). Two critical collapse pressures corresponding to these two types of typical failure modes exist. We must compare these two critical collapse pressures and obtain the bigger one as the real critical collapse pressure. The collapse pressure can be further calculated as the EMWCP [24].

3. Results and discussion

3.1. Basic parameters

To compare the isotropic model (isotropic elasticity and strength), anisotropic elasticity model (anisotropic elasticity and isotropic strength), and fully anisotropic model (anisotropic elasticity and strength), they were used to predict the collapse pressure for arbitrary inclined well in anisotropic formations. The basic parameters are as follows: \(TVD = 3,000\) m, \(R = 216\) mm, \(\alpha_p = 0.8\), \(p_p = 42\) MPa, \(E = 16.48\) GPa, \(E' = 23.50\) GPa, \(\nu = 0.20\), \(\nu' = 0.25\), \(c_0 = 25\) MPa, \(\varphi_0 = 35^\circ\), \(c_0 = 5\) MPa, \(\varphi_e = 25^\circ\), \(\alpha_s = 0^\circ\), and \(\beta_0 = 0^\circ\). Table 1 lists the in-situ stress components, where three types of typical in-situ stress states were used, such as NF, SS, and RF. The predicted EMWCP can be displayed using the hemispherical projection plot, and the principle of the hemispherical projection plot can be found in references [24, 25].

| No. | Anderson’s faulting | $\sigma_1$/MPa | $\sigma_2$/MPa | $\sigma_3$/MPa |
|-----|---------------------|----------------|----------------|----------------|
| 1   | NF ($\sigma_1 > \sigma_2 > \sigma_3$) | 90             | 80             | 60             |
| 2   | SS ($\sigma_2 > \sigma_1 > \sigma_3$) | 70             | 80             | 60             |
| 3   | RF ($\sigma_2 > \sigma_1 > \sigma_3$) | 55             | 80             | 60             |

3.2. Analysis results for NF stress state

Figure 3 shows the hemispherical projection plot of EMWCP for the NF stress state. The EMWCP predicted by the anisotropic elasticity model is slightly lower than that of the isotropic model, and the EMWCP variation law of collapse pressure is close between the isotropic and anisotropic elasticity models (Figures 3(a) and (b)). However, the EMWCP predicted by both isotropic and anisotropic elasticity models is significantly lower than that of the fully anisotropic model, and the EMWCP variation law of collapse pressure is different between the isotropic and fully anisotropic models (Figures 3(a)–(c)).
The wellbore stability controls the failure across the rock matrix when the attack angle exceeds 45°. The most stable well path is the inclined well along the minimum horizontal in-situ stress. The most unstable well path is the horizontal well along the maximum horizontal in-situ stress. The stability of the vertical well is much better than the highly-deviated and horizontal wells, and the optimal drilling direction is toward the vertical well. For the fully anisotropic model, the most stable well path is the inclined well, and the most unstable well path is the horizontal well along the minimum horizontal in-situ stress. The stability of the vertical well is much better than the highly-deviated and horizontal wells. Because the failure across the rock matrix when the attack angle is lower than 45° controls the wellbore stability, slippage along the weak planes when the attack angle exceeds 45° controls the wellbore stability, and the optimal drilling direction is toward the maximum horizontal in-situ stress.

Overall, the predicted EMWCP is ~1.17–1.47 g/cm³ for the isotropic model, ~1.16–1.44 g/cm³ for the anisotropic elasticity model, and ~1.24–1.98 g/cm³ for the fully anisotropic model. The EMWCP predicted by the fully anisotropic model is always the highest, followed by the isotropic and anisotropic elasticity models. Thus, the influence of anisotropy strength increases the wellbore collapse pressure, whereas the influence of elasticity anisotropy decreases the wellbore collapse pressure. Therefore, rock strength anisotropy is detrimental to wellbore collapse, whereas rock elasticity anisotropy is favorable to wellbore collapse.

3.3. Analysis results for SS stress state

Figure 4 shows the hemispherical projection plot of EMWCP for the SS stress state. The EMWCP predicted by the anisotropic elasticity model is slightly lower than that of the isotropic model, and the EMWCP variation law of collapse pressure is close between the isotropic and anisotropic elasticity models (Figures 4(a) and (b)). However, the EMWCP predicted by both isotropic and anisotropic elasticity models is significantly lower than that of the fully anisotropic model, and the EMWCP variation law of collapse pressure is different between the isotropic and fully anisotropic models (Figures 4(a)–(c)).

Figures 4(a) and (b) shows that for the isotropic and anisotropic elasticity models, the most stable well path is the horizontal well that deviated ~30° from the direction of the minimum horizontal in-situ stress. The most unstable well path is the vertical well. The stability of the vertical well is much worse than the highly-deviated and horizontal wells, and the optimal drilling direction is toward the maximum horizontal in-situ stress. Figure 4(c) shows that for the fully anisotropic model, the most stable well path is the vertical or low-angle inclined well. The most unstable well path is the horizontal well along the minimum horizontal in-situ stress. The stability of the vertical well is much better than the highly-deviated and horizontal wells. Because the failure across the rock matrix when the attack angle is lower than 45° controls the wellbore stability, slippage along the weak planes when the attack angle exceeds 45° controls the wellbore stability, and the optimal drilling direction is toward the maximum horizontal in-situ stress.
Overall, the predicted EMWCP is 1.01–1.27 g/cm³ for the isotropic model, 0.99–1.26 g/cm³ for the anisotropic elasticity model, and 1.17–1.93 g/cm³ for the fully anisotropic model. The EMWCP predicted by the fully anisotropic model is always the highest, followed by the isotropic and anisotropic elasticity models. Thus, the influence of strength anisotropy increases wellbore collapse pressure, whereas the influence of elasticity anisotropy decreases wellbore collapse pressure. Therefore, rock strength anisotropy is detrimental to wellbore collapse, whereas rock elasticity anisotropy is favorable to wellbore collapse.

3.4. Analysis results for RF stress state

Figure 5 shows the hemispherical projection plot of EMWCP for the RF stress state. The EMWCP predicted by the anisotropic elasticity model is slightly higher than that of the isotropic model, and the EMWCP variation law of collapse pressure is close between the isotropic and anisotropic elasticity models (Figures 5(a) and (b)). However, the EMWCP predicted by both isotropic and anisotropic elasticity models is significantly lower than that of the fully anisotropic model, and the EMWCP variation law of collapse pressure is different between the isotropic and fully anisotropic models (Figures 5(a)–(c)).

Figures 5(a) and (b) shows that for the isotropic and anisotropic elasticity models, the most stable well path is the highly-deviated and horizontal well along the maximum horizontal in-situ stress. The most unstable well path is the highly-deviated and horizontal wells along the minimum horizontal in-situ stress. The optimal drilling direction is toward the maximum horizontal in-situ stress. For the fully anisotropic model (Figure 5(c)), the most stable well path is the vertical or low-angle inclined well. The most unstable well path is the horizontal well along the minimum horizontal in-situ stress. Because the failure across the rock matrix when the attack angle is lower than 45° controls the wellbore stability, slippage along the weak planes when the attack angle exceeds 45° controls the
wellbore stability, and the optimal drilling direction is the direction of maximum horizontal in-situ stress.

Overall, the predicted EMWCP is 0.83–1.29 g/cm³ for the isotropic model, 0.99–1.26 g/cm³ for the anisotropic elasticity model, and 1.17–1.93 g/cm³ for the fully anisotropic model. The EMWCP predicted by the fully anisotropic model is always the highest, followed by the anisotropic elasticity and isotropic models. Thus, the influence of strength anisotropy increases wellbore collapse pressure, and the influence of elasticity anisotropy also slightly increases wellbore collapse pressure. Therefore, both strength anisotropy and elasticity anisotropy are detrimental to wellbore collapse, but the impact of strength anisotropy is much more significant.

4. Conclusions
(1) The traditional model for wellbore stability analysis assumes that the formation rock is homogenous, continuous, and isotropic, which is different from the real situation. Therefore, an anisotropic wellbore stability model was proposed for an arbitrary inclined well in anisotropic formations, where the anisotropic elastic properties, shear strength, and in-situ stress were considered.

(2) This model was compared to the traditional isotropic and anisotropic elasticity models. The results show that rock anisotropy significantly influences EMWCP compared to the traditional isotropic model. The EMWCP predicted by the fully anisotropic model is always the highest, followed by the anisotropic elasticity or isotropic models. The anisotropic elasticity has a slight impact on EMWCP, whereas the anisotropy of rock strength significantly influences EMWCP. The anisotropy shear strength is detrimental for keeping wellbore stability, whereas the anisotropy of rock elastic properties is conducive for wellbore stability.

(3) When the anisotropic strength is considered, the most stable well path is always the vertical or low-angle inclined well, whereas the most unstable well path is the horizontal well along the minimum horizontal in-situ stress. Because the failure across the rock matrix when the attack angle is lower than 45° controls the wellbore stability, slippage along the weak planes when the attack angle exceeds 45° controls the wellbore stability.

(4) The influence of seepage, heat transfer, and chemical reaction were ignored. Their influence on wellbore stability of an arbitrary inclined well in anisotropic formations should be further investigated in the future.

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