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Optimization of wellbore trajectory using the initial collapse volume

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A B S T R A C T

During an actual drilling process, the wellbore pressure might be below the critical pressure under which the rock surrounding the wellbore begins to fail. Therefore, optimizing the wellbore trajectory based on the critical pressure to improve wellbore stability may be unreasonable, because the critical pressure can only reflect the degree of difficulty for the initial damage to occur at the wellbore rather than the extent of the wellbore damage. In accordance with the linear poroelastic rock mechanics theory, combined with the Mogi–Coulomb criterion, the shape of the initial shear failure zone of arbitrary wellbores is simulated. In order to predict the degree of the wellbore damage, the initial shear failure location, failure width, and failure depth of arbitrary wellbores are determined, and then a new model for calculating the initial collapse volume of a directional wellbore is derived in this paper. With the help of computer programming, the failure position, critical pressure, failure depth, failure width, and the initial collapse volume of arbitrary wellbores under different in-situ stresses are analysed. The results show that the wellbore trajectory optimized according to the critical pressure is significantly different to that optimized according to the degree of wellbore damage, and these trajectories can be completely opposite. A case from southwest Sichuan shows that, when the wellbore pressure has to be below the critical pressure during a drilling process, the new model provided in this paper can be used for optimizing the wellbore trajectory to ensure the safety of the drilling operation.

1. Introduction

The drilling process experiences wellbore shear failure when the wellbore pressure is lower than a value known as the critical or collapse pressure. Avoiding any degree of shear failure requires excessively high wellbore pressure, which may result in drilling fluid leakage. A certain degree of wellbore damage will not cause wellbore instability, and thus the wellbore pressure is allowed to be below the critical pressure during the actual drilling process (Zoback, 2007). However, serious wellbore enlargement will affect the safety of the drilling operation and completion quality. In order to improve wellbore stability during the drilling process, the critical pressure or its equivalent density is generally used as a basis for optimizing wellbore trajectory (Awal et al., 2001; Kadyrov and Tutuncu, 2012; Lee et al., 2012; Al-Shaaibi et al., 2013; Fang et al., 2013; Gao et al., 2014; He et al., 2015). However, it may be no longer be reasonable to use the critical pressure as the basis for optimizing when the wellbore pressure is below the critical pressure, since the critical pressure can only reflect the degree of difficulty of wellbore failure, and cannot reflect the degree of damage of the wellbore.

The technique of determining the magnitudes and orientations of in-situ stress using wellbore failures has been widely applied in the literature (Zoback et al., 1985; Peška and Zoback., 1995; Pei et al., 2009; Zoback et al., 2003; Vernik and Zoback, 1992; Ramirez and Frydman, 2006). Conversely, it is also feasible to predict the degree of damage of the wellbore and optimize the wellbore trajectory based on the degree of wellbore damage if the in-situ stress and rock mechanical properties are known. Aadnoy and Kaarstad (2010) established a model to calculate the collapse volume of a directional wellbore, but this model is based on the assumption that the wellbore is a standard ellipse after shear failure and the failure width maintains a constant 180°. However, the specific value of failure width should change in accordance with parameters such as stress magnitude and rock mechanical properties (Moos et al., 2007). The failure width of 180° means that all the rock surrounding the wellbore will fail, which may lead to washouts due to the lack of insufficient intact material around the wellbore wall to support the applied stresses (Zoback, 2007).

According to the linear poroelastic rock mechanics theory, combined with the Mogi–Coulomb criterion, the initial shear

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failure of a directional wellbore at different wellbore pressures is simulated, and a new calculation model for the initial collapse volume is derived. Then, the paper demonstrates how to use this model to analyse the wellbore stability under different in-situ stresses, and finally, the wellbore trajectory for a directional wellbore from the southwest Sichuan is optimized.

1.1. Stresses around the wellbore

When a well is drilled, the rock surrounding the wellbore must support the stress that was previously supported by the removed rock, which leads to a stress concentration around the wellbore (Bradley, 1979). If this stress concentration exceeds the rock strength, shear failure will occur at the wellbore. The severity of the wellbore stress concentration depends on both the magnitudes and orientations of the in-situ stresses and the wellbore inclination and azimuth. Once the magnitudes and orientations of the three principal stresses (vertical, minimum horizontal and maximum horizontal) are known, the stress distribution near the wellbore can be determined. Assuming that the rock is a linear poroelastic material with isotropic properties, the stress near the wellbore as a function of radial distance away from a wellbore is given by the well-known Kirsch equations (Bradley, 1979; Aadnoy and Chenevert, 1987; Li and Purdy, 2010):

$$\begin{cases} \sigma_{rr} = \dfrac{\sigma_{11}+\sigma_{22}}{2}\left(1-\dfrac{R^2}{r^2}\right) + \dfrac{\sigma_{11}-\sigma_{22}}{2}\left(1+3\dfrac{R^4}{r^4}-4\dfrac{R^2}{r^2}\right)\cos 2\theta + \sigma_{12}\left(1+3\dfrac{R^4}{r^4}-4\dfrac{R^2}{r^2}\right)\sin 2\theta + \mathit{\Delta} P\dfrac{R^2}{r^2} \\ \sigma_{\theta\theta} = \dfrac{\sigma_{11}+\sigma_{22}}{2}\left(1+\dfrac{R^2}{r^2}\right) - \dfrac{\sigma_{11}-\sigma_{22}}{2}\left(1+3\dfrac{R^4}{r^4}\right)\cos 2\theta - \sigma_{12}\left(1+3\dfrac{R^4}{r^4}\right)\sin 2\theta - \mathit{\Delta} P\dfrac{R^2}{r^2} \\ \sigma_{zz} = \sigma_{33} - 2\nu(\sigma_{11}-\sigma_{22})\dfrac{R^2}{r^2}\cos 2\theta - 4\nu\sigma_{12}\dfrac{R^2}{r^2}\sin 2\theta \\ \tau_{\theta z} = (\sigma_{23}\cos\theta - \sigma_{13}\sin\theta)\left(1+\dfrac{R^2}{r^2}\right) \end{cases} \quad (1)$$

where θ is the well round angle, degree; R the wellbore radius, mm; r the distance between the analysis point and wellbore axis, mm; ν the Poisson's ratio; and $\mathit{\Delta} P$ the difference between wellbore pressure (P_w) and pore pressure (P_p), MPa. The symbols σ_{rr}, $\sigma_{\theta\theta}$, σ_{zz}, $\tau_{\theta z}$ are the radial, tangential, axial, and shear stress components near the wellbore as a function of radial distance away from the wellbore axis, respectively. The effective stress components of the in-situ stress near the wellbore (Aadnoy and Chenevert, 1987; Awal et al., 2001; Li and Purdy, 2010) $\sigma_{ij}(i,j=1,2,3)$ are given by Eq. (2) and they are derived from the coordinate conversion, as shown in Fig. 1.

$$\begin{cases} \sigma_{11} = \cos^2\alpha\left(\sigma_H\cos^2\beta + \sigma_h\sin^2\beta\right) + \sigma_V\sin^2\alpha \\ \sigma_{22} = \sigma_H\sin^2\beta + \sigma_h\cos^2\beta \\ \sigma_{33} = \sin^2\alpha\left(\sigma_H\cos^2\beta + \sigma_h\sin^2\beta\right) + \sigma_V\cos^2\alpha \\ \sigma_{12} = \cos\alpha\cos\beta\sin\beta(\sigma_h - \sigma_H) \\ \sigma_{13} = \left(\sigma_H\cos^2\beta + \sigma_h\sin^2\beta - \sigma_V\right)\sin\alpha\cos\alpha \\ \sigma_{23} = \sin\alpha\cos\beta\sin\beta(\sigma_h - \sigma_H) \end{cases} \quad (2)$$

where α is the inclination angle, degrees; β the azimuth angle (measured from the direction of the maximum horizontal stress), degrees; σ_H the effective stress of the maximum horizontal stress, MPa; σ_h the effective stress of the minimum horizontal stress, MPa; and σ_V the effective stress of the vertical stress, MPa.

Fig. 1 shows the stress transformation system in a directional wellbore, where the azimuth angle is taken as the rotation angle around the z_1-axis, and the inclination angle is taken as the rotation angle around the y_1-axis.

The effective stresses of the in-situ stresses are given by:

$$\begin{cases} \sigma_H = S_H - P_p \\ \sigma_h = S_h - P_p \\ \sigma_V = S_V - P_p \end{cases} \quad (3)$$

where S_H is the maximum horizontal stress, MPa; S_h the minimum horizontal stress, MPa; and S_V the vertical stress, MPa.

In order to predict the degree of damage of a directional wellbore, consideration needs to be given as to whether the principal stresses acting in the tangent plane at the wellbore wall, and its parallel plane away from the wellbore wall, will exceed the strength of the rock. The principal stresses near the wellbore (Peška and Zoback, 1995) are given by Eq. (4).

$$\begin{cases} \sigma_{tmax} = \dfrac{1}{2}\left[\sigma_{zz} + \sigma_{\theta\theta} + \sqrt{(\sigma_{zz}-\sigma_{\theta\theta})^2 + 4\tau_{\theta z}^2}\right] \\ \sigma_{tmin} = \dfrac{1}{2}\left[\sigma_{zz} + \sigma_{\theta\theta} - \sqrt{(\sigma_{zz}-\sigma_{\theta\theta})^2 + 4\tau_{\theta z}^2}\right] \end{cases} \quad (4)$$

where $\sigma_{t\,max}$, $\sigma_{t\,min}$ are the maximum and minimum principal stresses on tangential plane of a directional wellbore, respectively.

1.2. Mogi–Coulomb criterion

Rock failure criterion is used for determining whether the rock will fail under a certain stress. Among the many failure criteria, the Mohr–Coulomb criterion is the most commonly used, although it ignored the effect of intermediate principal stress on rock's failure. Through compressive, tensile and biaxial tests on different rocks, Mogi (1967) concluded that the intermediate principal stress has an influence on rock failure, but its influence is relatively small compared to the minimum principal stress. Al-Ajmi and Zimmerman (2005) developed the Mogi–Coulomb criterion for wellbore stability analysis, in which the effect of intermediate principal stress was considered, as shown in Eq. (5). Compared to the Mohr–Coulomb criterion, the result by using Mogi–Coulomb criterion is more practical (Zhang et al., 2010).

$$\sigma_{oct} = a + b\sigma_m \quad (5)$$

Rock material parameters a and b can be derived directly from the uniaxial compressive strength (C_0) and internal friction angle (ϕ):