A new analysis model for borehole stability in gas drilling

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Abstract. Gas drilling is one of the main underbalanced drilling techniques, which has a significant effect on the ROP (rate of penetration) improvement in hard formation. However, because the circulating medium in drilling process is gas instead of liquid, the fluid column pressure of gas drilling cannot provide enough support force for the rock around borehole as that of conventional overbalanced drilling. Due to the combination influence of engineering and geological factors, the borehole rock is prone to instability during gas drilling, which can lead to rock blocks falling from the well wall and the formation of irregular borehole shape. To avoid the occurrence of complex underground accidents caused by too many falling rock blocks, such as the borehole instability and pipe-sticking, it is necessary for gas drilling to take into consideration the true triaxial stress state of the rock in the deep formation and the possibility of the borehole breakout. Based on the permitted breakout angle of borehole and true triaxial strength theory of rock, an analysis model of borehole stability has been developed for the engineering of gas drilling. The theory of linear elasticity, involved in this analysis model, is used to analyse the stress state of rock around a cylindrical hole under lower wellbore pressure. The failure of the rock around borehole is determined by the Mogi-Coulomb criterion, which considers the intermediate principal stress effect on rock material. The results show that the model is as simple and practical as the traditional model, which takes no account the effect of the intermediate principal stress or the permitted borehole breakout, and it can provide an accurate analysis for the borehole stability of gas drilling. Therefore, the results of this study, combined with the related work such as the prediction of water formation, can guide the adaptability evaluation for the engineering design of gas drilling.

1. Introduction

Gas drilling technology uses compressed gas (air, nitrogen, natural gas, or exhaust) as the circulation medium, instead of the mud used in conventional drilling, to carry cuttings to the surface that are generated by the drilling of bit at the well bottom [1]. The column pressure of compressed gas within the borehole is almost negligible, which brings two unique advantages for gas drilling: drilling speed-up and reservoir protection. It has been proved that gas drilling can greatly enhance ROP in hard formation of the Amoroso Oilfield, Texas, USA [2]. Similar cases exist in the extremely abrasive and hard formations of the Junggar, Tarim and Sichuan basins in China [3-5]. With the development and application of this technology, it has occupied an important role in oil and gas drilling operations.

Due to the lack of effective fluid pressure, there is a higher risk of borehole collapse during gas drilling [6]. The borehole instability of gas drilling, affected by drilling operation and geological factors, has become a challenge that limits the development and application of this technology [7]. In order to avoid the occurrence of various drilling accidents caused by a large number of rock blocks, it is necessary for gas drilling to have an accurate borehole stability analysis. When the borehole is formed by gas drilling, the stress concentration occurs around the well wall. The redistributed stresses
around well can usually be solved by the linear elastic theory. Then, these solutions of stress need to be inserted into a failure criterion to analyse the stability of the well wall. The Mohr-Coulomb criterion, used in many analysis models for gas drilling, ignores the effect of intermediate principal stress and cannot accurately predict the failure of rock. Whereas another failure criterion commonly used in gas drilling, the Drucker-Prager criterion, do not take the stress angle effect into consideration. Therefore, there is a need to select an appropriate strength criterion for the borehole stability analysis of gas drilling.

In the borehole stability analysis of gas drilling, it is generally considered that the mechanical characteristics of formation rock must reach a critical value to avoid any shear failure on well wall [3,8,9]. In fact, the borehole, generated by conventional drilling or gas drilling, is not circular but irregular. For example, the elliptic borehole drilled by gas drilling exists in the well Bozi 101, and there are great differences for the cross-sectional borehole shapes at different depths [10]. Engineering practice proves that the minor borehole breakout cannot cause the collapse accidents. The breakout width model, developed from Zoback et al.’s work on borehole breakout [11], therefore has been applied to wellbore stability analysis in conventional drilling [12,13]. Based on this model and the true triaxial strength theory, this paper improves the borehole stability analysis model for gas drilling.

2. Permitted breakout of borehole

In general, the failure of the rock around borehole occurs since the redistributed stresses exceed the rock strength. Once the borehole breakout happens, the stress concentration around borehole makes the breakout continue to deepen [12]. Therefore, the traditional borehole stability analysis requires that each point around the well wall should be stable for the borehole integrity. For the safety of gas drilling, it is necessary to ensure that the entire open hole section is not affected by the stress concentration. Obviously, such an ideal situation is impossible for the engineering practice.

After the initial formation, the borehole breakout eventually reaches a stable shape, which is deeper rather than wider [12]. In addition, it has been confirmed by the drilling data that the borehole breakout is unavoidable, but the minor one cannot cause the accidents of collapse and pipe-sticking [12-14]. Therefore, the permitted breakout width, which allows the borehole to breakout within a certain extent, is proposed to modify the traditional borehole stability analysis [11]. For the permissible range of borehole breakout width, the upper limit of vertical well is 90°, whereas that of horizontal well is 30° (caused by the cuttings, etc.), as shown in Figure 1. So, it can also be called as the permitted breakout angle of borehole. Based on this, Ma et al. established two simple breakout width models for the stability analysis and path optimization of conventional drilling [13]. Engineering practice has proved that the permitted borehole breakout can also be applied to vertical wells of gas drilling [14], but its modification in deviated or horizontal wells requires more practical verification and theoretical research (not discussed in this paper).

![Figure 1. The schematic diagram of the permissible breakout width [12,13]. Gray shadow part: the initial borehole breakout](image-url)
3. Rock Strength Criteria

The rock strength criterion is particularly important for determining the breakout angle of borehole. The Mohr-Coulomb criterion, generally referred to as the linear shear strength criterion, has become the most common strength criterion used in the traditional borehole stability analysis of gas drilling. This criterion assumes that the rock failure is shear fracture along a plane, where the shear stress and the normal force on this plane meet the linear relationship:

$$\tau = c + \sigma \tan \phi$$  \hspace{1cm} (1)

where, $c$ is the cohesion of rock, MPa; $\phi$ is the internal friction angle of rock, $^\circ$. The stresses $(\tau, \sigma)$ on the plane is only related to the maximum principal stress $\sigma_1$ and the minimum principal stress $\sigma_3$ of the rock:

$$\tau = \frac{1}{2}(\sigma_1 - \sigma_3)\cos \phi$$  \hspace{1cm} (2)

$$\sigma = \frac{1}{2}(\sigma_1 + \sigma_3) - \frac{1}{2}(\sigma_1 - \sigma_3)\sin \phi$$  \hspace{1cm} (2)

Due to the neglect of the intermediate principal stress, the Mohr-Coulomb criterion is gradually replaced by the true triaxial strength criteria in engineering evaluation. The Drucker-Prager criterion is also often used in the borehole stability analysis of gas drilling. Although the Drucker-Prager criterion is a three-dimensional model for rock strength, its yield surface on $\pi$-plane is a circle (see Figure 2), which is not consistent with the reality of many rocks. Currently, this criterion is not applicable to the problem of rock mechanics such as borehole stability analysis.

Figure 2. The yield surfaces of these strength criteria on $\pi$-plane.

Based on the results of the true triaxial experiment on many rocks, Al-Ajmi and Zimmerman proposed the Mogi-Coulomb criterion [15]:

$$\tau_{\text{act}} = a + b\sigma_{m,2}$$  \hspace{1cm} (3)

where, $a$ and $b$ are the material constants for rock, which are related to the cohesion and internal friction Angle:

$$a = \frac{2\sqrt{3}}{3} c \cos \phi$$  \hspace{1cm} (4)

$$b = \frac{2\sqrt{3}}{3} \sin \phi$$  \hspace{1cm} (4)

Further, the stresses in equation (3) can be expressed by the principal stresses:
Poisson applies are the Mohr-Coulomb equation of result, Analysis stability the of p stress gas 2 conventional to rock the minimum around The is the system coordinate system wellbore, petroleum drilling solution on determining wellbore Mogi-Coulomb and elasticity xy the stress w gas and of as is and the angle in drilling, used is state traditional gas conventional the 2 angle engineering redistributed. As the 2 of in breakout \( \tau_{\text{out}} = \frac{1}{3} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]^{\frac{1}{2}} \) \* MERGEFORMAT (5)

The Mogi-Coulomb criterion is widely used in the field of petroleum engineering because of its practicality and accuracy [13,16,17]. In this paper, the application results of Mohr-Coulomb and Mogi-Coulomb in borehole stability analysis of gas drilling are discussed in comparison.

4. Analysis model of borehole stability in gas drilling

The stress state of rock is another essential part in determining the breakout angle of borehole in gas drilling. The rock in formation is kept balanced by in situ stresses (including the overburden formation stress \( \sigma_\text{s} \), the maximum horizontal stress \( \sigma_{\text{H}} \), and the minimum horizontal stress \( \sigma_{\text{n}} \)). When the borehole is formed by gas drilling, the stresses around well are redistributed. The linear elasticity theory, used for the solution of the stress concentration in conventional drilling, also applies to gas drilling [8]. For a well with the inclination angle \( \beta \) and the azimuthal angle \( \alpha \), in situ stresses first need to be transformed from the geo coordinate system to the Cartesian coordinate system where the borehole axis is located, as follows [18]:

\[
\begin{align*}
\sigma^o_x &= \sigma_{\text{H}} \cos^2 \alpha \cos^2 \beta + \sigma_{\text{n}} \cos^2 \beta \sin^2 \alpha + \sigma_x \sin^2 \beta \\
\sigma^o_y &= \sigma_{\text{H}} \sin^2 \alpha + \sigma_{\text{n}} \cos^2 \alpha \\
\sigma^0_z &= \sigma_{\text{H}} \sin^2 \beta \cos^2 \alpha + \sigma_{\text{n}} \sin^2 \beta \sin^2 \alpha + \sigma_z \cos^2 \beta \\
\tau^o_{xy} &= -\sigma_{\text{H}} \cos \beta \cos \alpha \sin \alpha + \sigma_{\text{n}} \cos \beta \cos \alpha \sin \alpha \\
\tau^o_{yz} &= -\sigma_{\text{H}} \sin \beta \cos \alpha \sin \alpha + \sigma_{\text{n}} \sin \beta \cos \alpha \sin \alpha \\
\tau^0_{xz} &= \sigma_{\text{H}} \cos \beta \sin \beta \cos^2 \alpha + \sigma_{\text{n}} \cos \beta \sin \beta \sin^2 \alpha - \sigma_z \sin \beta \cos \beta
\end{align*}
\]

\* MERGEFORMAT (6)

The stresses around well in the cylindrical coordinate system where the borehole axis is located can be expressed as:

\[
\begin{align*}
\sigma_r &= \sigma^0_r + \frac{\sigma^0_\theta}{2} \left( 1 - \frac{R_w^2}{r^2} \right) + \frac{\sigma^0_z}{2} \cos 2\theta + \tau^0_{xy} \sin 2\theta \left( 1 + \frac{3R_w^2}{r^4} + \frac{4R_w^2}{r^2} \right) + \frac{R_w^2}{r^2} p_w \\
\sigma_\theta &= \sigma^0_\theta + \frac{\sigma^0_r}{2} \left( 1 - \frac{R_w^2}{r^2} \right) - \frac{\sigma^0_z}{2} \cos 2\theta + \tau^0_{xy} \sin 2\theta \left( 1 + \frac{3R_w^2}{r^4} + \frac{4R_w^2}{r^2} \right) - \frac{R_w^2}{r^2} p_w \\
\sigma_z &= \sigma^0_z - \nu \left[ 2 \left( \sigma^0_r - \sigma^0_\theta \right) \frac{R_w^2}{r^2} \cos 2\theta + 4\tau^0_{xy} \frac{R_w^2}{r^2} \sin 2\theta \right] \\
\tau_{\theta\phi} &= \frac{\sigma^0_r - \sigma^0_\theta}{2} \sin 2\theta + \tau^0_{xy} \cos 2\theta \left( 1 - \frac{3R_w^2}{r^4} + \frac{2R_w^2}{r^2} \right) \\
\tau_{r\phi} &= \left( \tau^0_{xy} \cos \theta - \tau^0_{xz} \sin \theta \right) \left( 1 + \frac{R_w^2}{r^2} \right) \\
\tau_{z\phi} &= \left( \tau^0_{xy} \cos \theta + \tau^0_{xz} \sin \theta \right) \left( 1 - \frac{R_w^2}{r^2} \right)
\end{align*}
\] \* MERGEFORMAT (7)

where, \( \nu \) is Poisson’s ratio; \( \theta \) is the circumferential angle around wellbore; \( p_w \) is the wellbore pressure. Generally, the stresses of rocks on the well wall are analysed in traditional borehole stability analysis model for conventional drilling and gas drilling. As a result, equation (7) is simplified as follows:
This simplification reduces computation but ignores the failure possibility of other rocks around borehole. In addition, gas drilling is often performed in dry formation (without any fluids) due to its sensitive to fluids. Therefore, the effective stress around the well in gas drilling can be used without considering the pore pressure [8,14]. Whereas the pore pressure changes and radial drag force, generated by the fluid output, should be considered in the formation containing fluids [19,20], which is not discussed in this study. The principal stresses at each point around the well can be obtained through the elastic theory based on the results of equation (7). Combined with the permitted breakout angle of borehole, Mogi-Coulomb criterion and stress analysis, a new analysis model of wellbore stability suitable for gas drilling is established. The analysis process of the model is shown in Figure 3.

**Figure 3.** The analysis process of wellbore stability analysis model for gas drilling. PBAB: the permitted breakout angle of borehole

5. Case study
Based on the new analysis model, the borehole stability of gas drilling was evaluated for a vertical well in Sichuan Basin. Taking the depth points of 2000m and 2500m as examples, the results of the evaluation are presented. The equivalent density of in situ stresses are \( \sigma_h = 2.67 \text{g/cm}^3 \), \( \sigma_v = 2.46 \text{g/cm}^3 \), \( \sigma_h = 1.99 \text{g/cm}^3 \), and the mechanical properties of the rock are shown in Table 1 [14]. In addition, comparative study is carried out using the analysis model based on the permitted breakout angle and Mohr-Coulomb criteria.

**Table 1.** Mechanical parameters of the rock at different depth [14]

| Depth (m) | c (MPa) | \( \phi \) (°) | \( \nu \) |
|----------|---------|---------------|-----|
| 2000     | 26.0    | 28.8          | 0.25 |
| 2500     | 27.0    | 29.0          | 0.25 |

Figure 4-6 show the magnitude of the principal stresses around borehole in the range of two times borehole diameter (2×311.2mm) at the depth of 2000m. The stress concentration around the borehole
occurs in the direction of the minimum horizontal stress and is illustrated by the maximum principal stress and the intermediate principal stress. The magnitude of the minimum principal stress on the well wall is almost negligible. There is a great difference between the minimum principal stress and the intermediate principal stress. In traditional stability analysis, the place where the stress concentration occurs is usually considered to be potentially unstable, but it is accompanied by the strengthening of the intermediate principal stress on the rock strength. Therefore, it is necessary to use the Mogi-Coulomb criterion to predict the wellbore stability. A similar situation exists at depth of 2500m.

![Figure 4. The maximum principal stress around borehole.](image1)

![Figure 5. The intermediate principal stress around borehole.](image2)

![Figure 6. The minimum principal stress around borehole.](image3)

Figure 7 shows the borehole breakout of gas drilling at depth of 2000m calculated by the analysis models. The evaluation of the model based on Mohr-Coulomb criterion reveals that there is a breakout angle of 81.05° in the direction of the horizontal minimum principal stress. According to the permitted borehole breakout, it is believed that some rock blocks fall off the well wall at depth of 2000m, but the breakout cannot cause the downhole accidents. On the other hand, the analysis based on the Mogi-Coulomb criterion suggest that there is no breakout around borehole. Therefore, the well diameter does not change significantly, which is consistent with the reality [14].

The results of the borehole stability analysis at depth of 2500m are shown in Figure 8. The breakout angle of 111.99° is obtained by the analysis model based on Mohr-Coulomb criterion. So, it is concluded that the formation at depth of 2500m is not suitable for gas drilling. However, due to the intermediate principal stress effect, the breakout angle calculated by the new model is 46.97°, which meets the condition of the permitted borehole breakout. Therefore, there is an application potential of gas drilling in the formation at depth of 2500m.
Figure 7. The analysis results of borehole stability at depth of 2000m. (a) M-C: the breakout calculated by Mohr-Coulomb criterion; (b) MG-C: the breakout calculated by Mogi-Coulomb criterion.

Figure 8. The analysis results of borehole stability at depth of 2500m. (a) M-C: the breakout calculated by Mohr-Coulomb criterion; (b) MG-C: the breakout calculated by Mogi-Coulomb criterion.

6. Conclusion
A new analysis model of borehole stability in gas drilling is established by considering the triaxial stress state of the rock around well and the possibility of the borehole breakout. Practice has proved that the appropriate borehole breakout does not cause underground accidents, and the permitted angle of borehole is therefore introduced to the borehole stability model. For gas drilling in dry formation, the stress state around borehole is analysed by linear elastic theory without considering the pore pressure. The stress concentration of the intermediate principal stress around the well is similar to that of the maximum principal stress. And there is a significant difference between the stresses $\sigma_2$ and $\sigma_3$ around borehole. Therefore, the Mogi-Coulomb criterion considering the intermediate principal stress effect is used to control the rock failure in the new model. The case study shows that compared with the borehole stability model based on the permitted breakout and Mohr-Coulomb criterion, the new model can provide more reasonable results and find more formations suitable for gas drilling.

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