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The Effects of Pore Pressure and Temperature Difference Variation on Borehole Stability

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Abstract

Considering that drilling fluid filtration and the temperature difference between borehole wall rock and drilling fluid can cause the stress variation of the borehole wall. The stress distribution model was derived under the effect of thermal-flow-solid coupling. The safe mud density window calculating model considering pore pressure and temperature difference variation was established according to Moore-Coulomb criterion and borehole wall rock tensile failure criterion. The result calculated by the model can be expressed as follow. (1) When the temperature difference between borehole rock and drilling fluid is constant, with the enhancement of fluid filtration, borehole rock pore pressure increasing, the collapse pressure increasing, breakdown pressure decreasing, the stability of the borehole becomes deteriorating. (2) When the borehole wall rock pore pressure is constant, if drilling fluid makes wall rock temperature decreasing, with the temperature difference increasing, both the collapse pressure and breakdown pressure decreasing, the stability of the borehole becoming deteriorating, it is not conducive to drilling safely. If drilling fluid make wall rock temperature increasing, with the temperature difference increasing, both the collapse pressure and breakdown pressure increasing, the borehole tending to stabilize, it is conducive to drilling safely.

Key words: Pore pressure; Temperature difference; Borehole stability; Safe mud density window

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INTRODUCTION

The study of borehole stability is a hotspot and difficult problem in drilling engineering[1-6]. In recent years, with the global economic growth, the use of oil and gas resources is increasing. Oil and gas exploration and development focus is gradually shifting to the complex geological conditions and unconventional reservoirs. The drilling environment is becoming more and more complex. However, in the process of drilling, under the effects of the drilling fluid in the borehole, the pore pressure and temperature can change, which causes stress redistribution of the borehole, and the stability of the borehole can be affected, it is easily causing well blowing, mud loss, borehole collapse and sticking accidents. Scholars at home and abroad have carried out a more comprehensive study on borehole stability. The borehole stability mechanism has been studied from fluid-solid coupling, thermal-flow-solid coupling and mechanics-chemical coupling. Xinglong Wang and Yuanfang Cheng[7] have established borehole wall temperature and pressure coupling mechanical model in shale formations, illustrating that temperature changes can cause the variation of pore pressure, changing the borehole wall stress distribution by numerical method. Baohua Wei[8] has analyzed the effect of temperature and pressure on borehole stability, establishing additional stress calculation model caused by pore pressure changes. Lewen Zhang[9] has established mechanics-chemical coupling mathematical model for calculating borehole wall stress, the wellbore wall pore pressure and stress

variation regulations have been analyzed under the effect of mechanics-chemical coupling. Although some scholars have discussed the effect of pore pressure and temperature difference variation on borehole stability, the theory of effects of pore pressure and temperature changes on porosity and wall stress is limited, and the borehole stability model considering simultaneous changes of pore pressure and temperature has not been reported. In this paper, the problem has been better explained in theory, which is a supplement and completeness for the existing borehole stability mechanism.

1. THE MECHANICAL MODEL OF BOREHOLE ROCK

In the process of drilling, the mechanical model of borehole rock is shown in Figure 1. Assuming that formation rock is isotropic elastic medium, the horizontal maximum principal stress σ_H and minimum principal stress σ_h are loaded on formation rock. p_i is the pressure caused by drilling fluid column in borehole, p_p is the initial formation pore pressure.

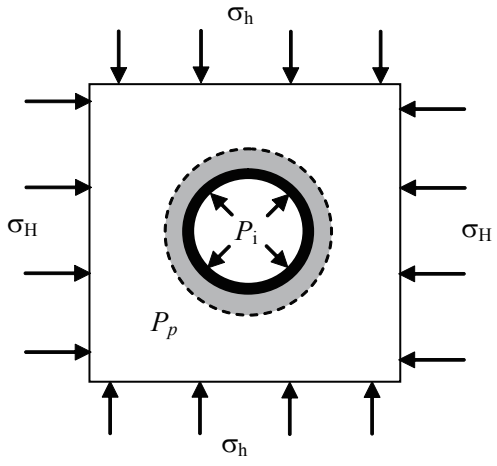

Figure 1
The Mechanical Model of Borehole Rock in the Process of Drilling

In the process of drilling, the key factor affects borehole stability is the variation of formation temperature and pressure. On the one hand, in order to prevent well blowing, mud loss, it is required that the drilling fluid column pressure is greater than the pore pressure, which can lead to drilling fluid filtrate seep into formation, and it can generate percolation zone around the borehole (gray area within the dotted line in Figure 1), and the solid phase particles in drilling fluid are left on the borehole wall in the forms of mud cake (the black ring region in Figure 1). On the other hand, the temperature difference between the deep formation and fluid can generate additional stress and strain on borehole wall rock on the basis of the original balance, which can change the original bearing force balance.

2. THE BOREHOLE WALL STRESS DISTRIBUTION CONSIDERING PORE PRESSURE AND TEMPERATURE DIFFERENCE VARIATION

Pore pressure and temperature difference variation will cause the wall stress distribution variation. Considering in situ stress, drilling fluid column pressure, fluid seepage and thermal stress effects separately that can cause borehole wall stress variation, borehole wall stress is analyzed.

2.1 Borehole Wall Stress Distribution Caused by in Situ Stress

When the borehole is opened, the stress concentration can generate around the borehole wall under in situ stress field, wall rock stress state can be expressed as follow[10].

$$\begin{cases} \sigma_r = \dfrac{\sigma_H+\sigma_h}{2}\left(1-\dfrac{r^2}{R^2}\right)+\dfrac{\sigma_H-\sigma_h}{2}\left(1-4\dfrac{r^2}{R^2}+3\dfrac{r^4}{R^4}\right)\cos 2\theta \\ \sigma_\theta = \dfrac{\sigma_H+\sigma_h}{2}\left(1+\dfrac{r^2}{R^2}\right)-\dfrac{\sigma_H-\sigma_h}{2}\left(1+3\dfrac{r^4}{R^4}\right)\cos 2\theta \\ \sigma_z = \sigma_v - 2\mu\left(\sigma_H-\sigma_h\right)\dfrac{r^2}{R^2}\cos 2\theta \end{cases} \tag{1}$$

Where: σ_r is radial stress of the wall rock, MPa; σ_θ is circumferential stress of the wall rock, MPa; σ_z is the vertical stress of the wall rock, MPa; σ_H is the horizontal maximum principal stress, MPa; σ_h is the horizontal minimum principal stress, MPa; σ_v is overburden stress, MPa; r is the distance between any point on the borehole wall rock and the center of the borehole, m; R is the radius of the borehole, m; θ is the included angle between any point on the borehole wall rock and the horizontal maximum principal stress, (°); μ is the poisson ratio of the rock.

2.2 Borehole Wall Stress Caused by Drilling Fluid Column Pressure and Seepage Effects

Under the effects of drilling fluid column pressure and the additional stress caused by fluid seepage, the stress distribution caused by wall surrounding area can be expressed as follow[10].

$$\begin{cases} \sigma_r = \dfrac{r^2}{R^2}P_i+\left[\dfrac{\alpha(1-2\mu)}{2(1-\mu)}\left(1-\dfrac{r^2}{R^2}\right)-\phi\right]\left(P_i-P_p\right) \\ \sigma_\theta = -\dfrac{r^2}{R^2}P_i+\left[\dfrac{\alpha(1-2\mu)}{2(1-\mu)}\left(1+\dfrac{r^2}{R^2}\right)-\phi\right]\left(P_i-P_p\right) \\ \sigma_z = \left(\dfrac{\alpha(1-2\mu)}{2(1-\mu)}-\phi\right)\left(P_i-P_p\right) \end{cases} \tag{2}$$

Where: P_i is drilling fluid column pressure in borehole, MPa; P_p is formation initial pore pressure, MPa; α is effective stress factor; ϕ is the porosity of the wall rock.

2.3 The Thermal Stress Analysis of the Borehole Wall

The borehole wall stress variation caused by the temperature difference between drilling fluid and borehole rock can be expressed as follow.

$$\begin{cases} \sigma_r = -\dfrac{E\alpha}{2(1-\mu)}(T-T_0)(1-\dfrac{R^2}{r^2}) \\ \sigma_\theta = \dfrac{E\alpha}{2(1-\mu)}(T-T_0)(1+\dfrac{R^2}{r^2}) \\ \sigma_z = \dfrac{E\alpha}{1-\mu}(T-T_0) \end{cases} \tag{3}$$

Where: E is Young's modulus of borehole rock, MPa; T is the temperature of borehole rock that has change, (℃); T_0 is the initial temperature of borehole rock, (℃).

2.4 The Porosity Variation of Borehole Rock

In the process of drilling, the porosity of rock will change under the effect of pore pressure and thermal stress. By changing the porosity that has changed can be expressed as follow.

$$\phi = \frac{\phi_0 - \dfrac{\phi_0}{E}\Delta p - 2\alpha(T-T_0)}{1-\dfrac{\phi_0}{E}\Delta p - 2\alpha(T-T_0)} \tag{4}$$

Where: ϕ is the porosity of the rock that has changed; ϕ_0 is the initial porosity of the rock; Δp is the pore pressure variation difference caused by drilling fluid filtration, MPa.

2.5 The Stress Distribution of Borehole Wall

The rock stress distribution can be obtained by the superposition of the various parts of the stress according to linear superposition theory in elastic mechanics theory.

$$\begin{cases} \sigma_r = \dfrac{r^2}{R^2}P_i + \dfrac{\sigma_H+\sigma_h}{2}\left(1-\dfrac{r^2}{R^2}\right) + \dfrac{\sigma_H-\sigma_h}{2}\left(1-4\dfrac{r^2}{R^2}+3\dfrac{r^4}{R^4}\right)\cos 2\theta \\ \quad + \left[\dfrac{\alpha(1-2\mu)}{2(1-\mu)}\left(1-\dfrac{r^2}{R^2}\right)-\phi\right](P_i-P_p) - \dfrac{E\alpha}{2(1-\mu)}(T-T_0)\left(1-\dfrac{R^2}{r^2}\right) \\ \sigma_\theta = -\dfrac{r^2}{R^2}P_i + \dfrac{\sigma_H+\sigma_h}{2}\left(1+\dfrac{r^2}{R^2}\right) - \dfrac{\sigma_H-\sigma_h}{2}\left(1+3\dfrac{r^4}{R^4}\right)\cos 2\theta \\ \quad + \left[\dfrac{\alpha(1-2\mu)}{2(1-\mu)}\left(1+\dfrac{r^2}{R^2}\right)-\phi\right](P_i-P_p) + \dfrac{E\alpha}{2(1-\mu)}(T-T_0)\left(1+\dfrac{R^2}{r^2}\right) \\ \sigma_z = \sigma_v - 2\mu(\sigma_H-\sigma_h)\dfrac{r^2}{R^2}\cos 2\theta + \left[\dfrac{\alpha(1-2\mu)}{2(1-\mu)}-\phi\right](P_i-P_p) + \dfrac{E\alpha}{1-\mu}(T-T_0) \end{cases} \tag{5}$$

The effects of pore pressure and temperature difference of the rock on borehole rock stress can be obtained by analyzing the above equation, then study their effects on safety mud density window by analyzing stress variation of the borehole wall.

3. THE DETERMINATION OF SAFE MUD DENSITY WINDOW

The different stress states can be obtained by borehole wall stress distribution model. The caving pressure can be obtained by deriving Moore-Coulomb criterion. The breakdown pressure of the borehole wall can be gotten according to the tensile failure criterion. The safety mud density window calculating model is established considering fluid seepage and temperature variation on the condition that the overburden stress is the intermediate principal stress.

By deriving the drilling fluid density that is equivalent to the caving pressure can be expressed as follow.

$$\rho_{\mathrm{m}} = \frac{3\sigma_H - \sigma_h - \left(\dfrac{\alpha(1-2\mu)}{(1-\mu)} - \phi - K^2\phi\right)P_p - 2KC_0 + \dfrac{E\alpha}{1-\mu}\Delta T}{K^2(1-\phi-\alpha)+1-\dfrac{\alpha(1-2\mu)}{2(1-\mu)}+\phi+\alpha} \times \frac{100}{H} \tag{6}$$

Where: ρ_{m} is the drilling fluid density that is equivalent to the caving pressure, g/cm^3; $K = \cot(45^\circ - \beta/2)$, β is the angle of internal friction of the rock, (°); H is the well depth, m; C_0 is cohesive force of the rock, MPa.

The drilling fluid density that is equivalent to the breakdown pressure can be expressed as follow.

$$P_f = \frac{3\sigma_h - \sigma_H + \frac{E\alpha}{1-\mu}\Delta T - \left(\frac{\alpha(1-2\mu)}{(1-\mu)} - \phi\right)P_p + S_t}{1+\phi+\alpha-\frac{\alpha(1-2\mu)}{(1-\mu)}} \times \frac{100}{H} \quad (7)$$

Where: P_f is the drilling fluid density that is equivalent to the breakdown pressure, g/cm^3; S_t is the tensile strength of the rock, MPa.

4. THE EFFECTS OF PORE PRESSURE AND TEMPERATURE DIFFERENCE VARIATION ON BOREHOLE STABILITY

In order to analyze the effects of pore pressure and temperature difference variation on borehole stability, the rock mechanics parameters are obtained from the rock at the depth of 2400 m. The horizontal maximum principal stress is 48 MPa. The horizontal minimum principal stress is 38 MPa. Poisson's ratio is 0.26. The Young's modulus is 13700 MPa. The porosity is 0.2. The tensile strength of rock is 3.55 MPa. The cohesive force is 6.33 MPa. The angle of internal friction is 33.11°. The effective stress coefficient is 0.7. The thermal expansion coefficient is 0.00005. The initial formation pore pressure is 23.86 MPa.

The effects of borehole rock pore pressure and temperature difference variation on safe mud density window can be shown in Figure 2 and Figure 3. The result can be shown as follow: (1) When the temperature difference is constant, with the enhancement of fluid filtration, borehole rock pore pressure increasing, causing the collapse pressure increasing, breakdown pressure decreasing, the safe drilling fluid density window becoming smaller, and it is not conducive to drilling safely. Thus, for a narrow safe density window drilling, the building capacity of the fluid should be strengthened, reducing effects of fluid filtration on wellbore stability. (2) When the borehole wall rock pore pressure is constant, if the wall rock temperature increases, with the temperature difference increasing, both the collapse pressure and breakdown pressure increasing, safe drilling fluid density window becoming larger, it is conducive to drilling safely. If wall rock temperature is lowered, with the temperature difference increasing, both the collapse pressure and breakdown pressure decreasing, the safety drilling fluid density window becoming smaller, it is not conducive to drilling safely. It can be shown that the cooling effect of drilling fluid to the formation is not conducive to borehole stability.

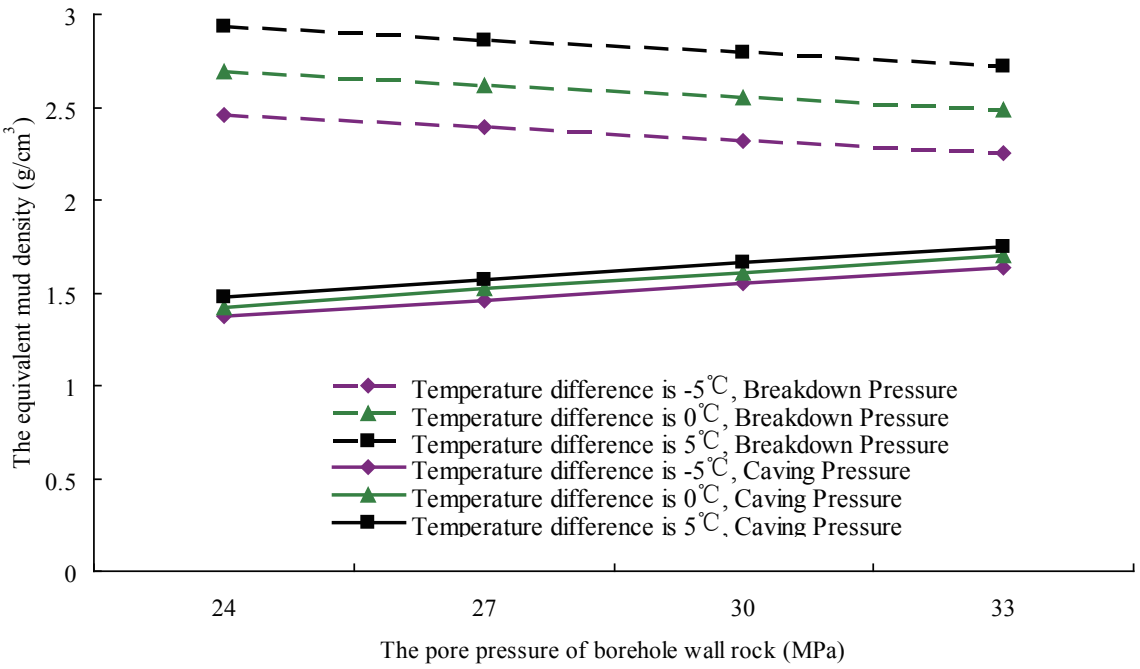

Figure 2
The Effect of Borehole Rock Pore Pressure Variation on Safety Mud Density Window Under Different Temperature Difference

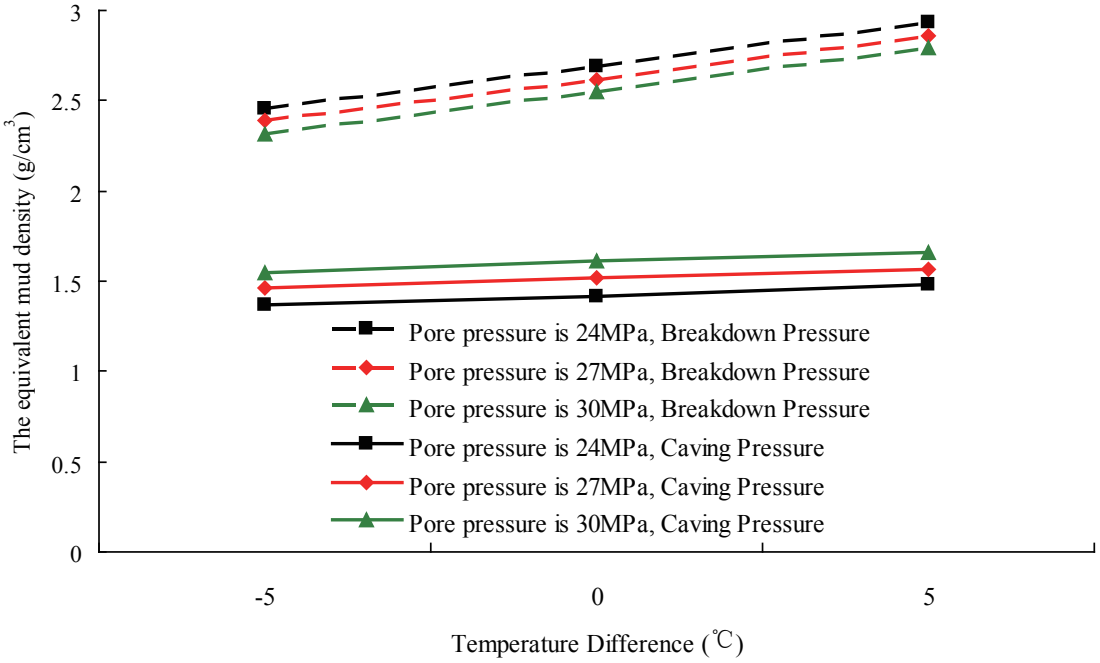

Figure 3
The Effect of Temperature Variation on Safety Mud Density Window Under Different Borehole Rock Pore Pressure

CONCLUSION

When the temperature difference between borehole rock and drilling fluid is constant, with the enhancement of fluid filtration, borehole rock pore pressure increasing, causing the collapse pressure increasing, breakdown pressure decreasing, the safe drilling fluid density window becoming smaller, borehole stability becoming deterioration, it is not conducive to drilling safely. When the borehole wall rock pore pressure is constant, if drilling fluid makes wall rock temperature decreasing, with the temperature difference increasing, both the collapse pressure and breakdown pressure decreasing, the safety drilling fluid density window becoming smaller, borehole stability becoming deterioration, it is not conducive to drilling safely. If drilling fluid make wall rock temperature increasing, with the temperature difference increasing, both the collapse pressure and breakdown pressure increasing, safe drilling fluid density window becoming larger, the borehole wall tending to stabilize, it is conducive to drilling safely.

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