Research Article

Effect of Pulsed Jet on Pore Pressure of Deep Formation Rock

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Pulsed jet significantly affects the pore pressure of deep formation and then affects the mechanical ROP. In this paper, the effect of jet pulsation on deep pore pressure in the formation is studied by the finite element method. Under the pulsed jet, the maximum relative negative pressure is along the wellbore axis, and the farther it is to the borehole axis, the smaller the relative negative pressure is. With the increase of pulse frequency, the relative negative pressure increases and the maximum point of relative negative pressure moves upward. The optimum pulse frequency is from 50 Hz to 500 Hz. There is a linear relationship between pulse amplitude and relative negative pressure.

1. Introduction

Pulsed jet drilling technology is proposed based on conventional jet drilling technology. The technology of raising rate of penetration (ROP) is applied in many aspects such as downhole pressurization and ultra-high-pressure jet [1]. Pulsed jet uses limited bottomhole hydraulic energy to produce local pulse negative pressure and impact force and to clean rock debris and change rock stress [2]. Wells and Bizanti experimentally and theoretically studied the effects of jet turbulence and fluctuation on carrying capacity of drilling fluid and concluded that the turbulence and fluctuation can improve carrying capacity of drilling fluid [3, 4]. By studying the pulsed jet nozzle, Xiong [5] theoretically analyzed the rock cleaning mechanism of pulsed jet and concluded that pulsed jet can reduce the chip hold-down effect.

Drilling technology assisted by pulsed jet has developed greatly [6–10]. But its research focuses on the field of impact crushing of rock [11–13] and numerical simulation of self-excited oscillation [14–18]. In conventional drilling, to balance the deep formation pressure, the fluid column pressure is higher than the pore pressure in the formation.

Fluid column pressure has a “chip hold-down effect” on the rock debris. This makes it difficult to leave the bottom of the well and results in repeated cutting of the rock debris by the bit. Pulsed jet can generate pressure pulsation in deep formation and cause local pore pressure variation. Therefore, the study of local pore pressure variation law of deep formation rock caused by pulsed jet at bottom of the well is helpful to reveal the accelerating mechanism of pulsed jet assisted rock breaking.

Most research studies on pore pressure focus on the stress distribution of borehole wall and analysis of factors affecting borehole stability [19–21]. Elastoplastic mechanics and pore elasticity mechanics are used to analyze the mechanical mechanism of borehole instability. In elastic-plastic mechanics, displacement and stress methods are used to solve the displacement and stress of rock [22], ignoring the pore fluid migration. It is considered that the system is in static equilibrium, the stress, strain, and displacement are functions of spatial coordinates, independent of time, and the calculated distribution of stress can be regarded as a stable solution after borehole excavation. There are relatively few studies on the distribution of stress at the bottom of the well. Warren and Smith [23] studied the influence of average

stress changes of rock at the bottom of the well on ROP. Ito et al. [24] studied the influence of stress concentration phenomenon at the bottom of the well on borehole collapse. Considering the fluid-structure coupling, the bottom of the well is divided into three-dimensional tension stress zone, three-dimensional compression stress zone, and tension and compression stress zone according to the stress in literature [25–28]. The dynamics of the bottom stress is ignored in the above research, and the time is also an important factor affecting stress distribution.

2. Numerical Model

The variation law of deep pore pressure in the formation under pulsed pressure is difficult to be measured by indoor test simulation, and the field test is more difficult. At present,

finite element software has made some progress in the application of seepage problems such as groundwater pumping, geothermal exploitation, nuclear waste treatment, and reservoir-induced earthquake. We can obtain the variation of pore pressure of any position with the method and comprehensively grasp the variation law of downhole seepage field. Therefore, the variation of pore pressure at the bottom of the well is analyzed by the finite element method. Simulations were conducted by using Abaqus.

2.1. Governing Equation. From the virtual work principle and the governing equation of pore fluid, the equilibrium equation and continuity equation in geotechnical medium can be obtained as follows [29]:

$$\int_V \sigma: \delta \varepsilon dV = \int_S t \cdot \delta v dS + \int_V f \cdot \delta v dV + \int_V (sn + n_t) \rho_w g \cdot \delta v dV, \quad (1)$$

$$\int \left[\delta u_w \left(\frac{\rho_w}{\rho_w^0} (sn + n_t) - \frac{1}{J} \left(\frac{\rho_w}{\rho_w^0} J (sn + n_t) \right) \right) + \Delta t \int_S \delta u_w \frac{\rho_w}{\rho_w^0} snn \cdot v_w, dS + \Delta t \frac{k_s}{\rho_w^0 g} \frac{\partial \delta u_w}{\partial x} \cdot k \cdot \left(\frac{\partial u_w}{\partial x} - \rho_w g \right) dV = 0,$$

where t is the surface force, f is the volume force except free water, $\delta \varepsilon$ is the virtual strain rate, δv is the virtual velocity, s is the saturation, n is the effective porosity, n_t is the trap porosity, ρ_w^0 is the initial pore fluid density, ρ_w is the pore fluid density, δu_w is the virtual displacement, k is the permeability coefficient of saturated rock, and k_s is the permeability coefficient.

Discretizing the above equation by the finite element method, the relevant equilibrium equation and continuity equation can be obtained as

$$K^{MN} \bar{c}_\delta^N - L^{MP} \bar{c}_u^P = P^M - I^M$$

$$\left(\hat{B}^{MQ} \right)^T \bar{v}^M + \hat{H}^{QP} \bar{u}^P = Q^Q \quad (2)$$

It is assumed that the pore fluid changes from t to $t + \Delta t$:

$$\bar{\delta}_{t+\Delta t}^N = \bar{\delta}_t^N + \Delta t \{ (1 - \varsigma) \bar{v}_t^N + \varsigma \bar{v}_{t+\Delta t}^N \} \quad (3)$$

Hypothesize $\varsigma = 1$, and the backward difference is

$$\bar{v}_{t+\Delta t}^N = \frac{1}{\Delta t} \left(\bar{\delta}_{t+\Delta t}^N - \bar{\delta}_t^N \right). \quad (4)$$

Thus, the pore fluid equation at time $t + \Delta t$ is

$$-\left(\hat{B}^{MQ} \right)^T \bar{c}_\delta^M + \Delta t \hat{H}^{QP} \bar{c}_u^P = \Delta t \left[-Q_{t+\Delta t}^Q + \left(\hat{B}^{MQ} \right)^T \bar{v}_{t+\Delta t}^M + \hat{H}^{QP} \bar{u}_{t+\Delta t}^P \right] \quad (5)$$

The equation can be solved with the equilibrium equation.

2.2. Physical Model. Analysis shows that the borehole is considered as a regular cylinder, and it is an axisymmetric structure. Based on the borehole axis, a cylindrical formation with a diameter of 2 m and a length of 2 m was selected as the research object. The borehole diameter is 215.9 mm, and its length is 1 m. In addition, to improve the accuracy of the analysis without increasing the scale of the model, a quarter of the model is simulated by the symmetry method.

The simulation process is described as follows. The initial pore pressure in the formation is first applied to face 1. After it becomes stable, the fluid column pressure is applied to face 2 and face 3. When pulsed jet drilling is used, the fluid column pressure with pressure fluctuation is applied to face 3. The model and boundary conditions are shown in Figure 1.

Analysis shows that the pore pressure near the borehole wall changes sharply. Therefore, the grid near the borehole wall is densified during grid division. The scale of the grid after division is 53120. The relevant grid division results are shown in Figure 2.

FIGURE 1: Physical model: 1, initial pore pressure application surface; 2, pressure surface of drilling fluid column; 3, impulsive pressure application surface; 4, restraint surface; and 5, symmetry plane.

Assuming that the underground rock mass is an elastomer, the material parameters are shown in Table 1.

2.3. Basic Assumptions

- (1) The rock is a porous medium, and the pores are evenly distributed in the rock mass.
- (2) Rock pores are saturated with fluid.
- (3) In the range of this model, the void ratio and permeability coefficient of rock are constants.
- (4) The pressure transmission between pore fluid and drilling fluid in the formation is smooth and in accordance with Darcy's law.
- (5) Borehole's irregularity and deviation are not considered.

3. Characteristic Analysis of Pore Pressure in Bottom Hole Rock

Figure 3 shows a cloud diagram of pore pressure distribution when the initial pore pressure is 40 MPa, the fluid column pressure is 46 MPa, and the permeability coefficient is 1×10^{-8} m/s. The figure shows that the pressure at the borehole wall and bottom of wellbore is the highest. The pore pressure gradually attenuates from and bottom to the formation. When it is 0.1 m away from the well bore, the pressure attenuation is more than 50%, when it is 0.5 m away from the well bore, the pressure attenuation is more than 90%, and when it is 0.8 m away from the well bore, the formation pressure is initial pore pressure. It shows that the effective influence scope of fluid column pressure on pore pressure in the formation is 0.5 m.

FIGURE 2: Mesh.

Figure 4 shows the vertical pressure attenuation of four different locations on the bottom of the well. The curve in the figure shows that the pressure attenuates rapidly in the beginning and gradually slows down later. The pressure attenuation law of these points is similar, but the initial attenuation along the axis of the wellbore is the slowest, and the attenuation at the edge of the bottom wellbore is the fastest. Over 0.1 m from bottom hole, the attenuation below the wellbore axis is relatively fast, and the attenuation at the edge of the bottom wellbore is relatively slow. When it is 0.4 m from the bottom of the well, the pore pressure is almost the same at this position, and the pressure is about 40.5 MPa. The curve in the figure shows that the pore pressure attenuation along the axis of wellbore is relatively slow, the "chip hold-down effect" caused by the drilling fluid column is relatively low, and the rock debris is relatively easy to leave the bottom of the well. The rock debris on the wellbore wall is more difficult to leave the wall than that at the axis of wellbore due to the rapid pore pressure attenuation, and rock debris is more likely to be crushed repeatedly here.

Figure 5 shows the attenuation along the wellbore axis in two cases: (1) initial pore pressure is 5 MPa, fluid column pressure is 11 MPa, and permeability coefficient is 1×10^{-8} m/s and (2) initial pore pressure is 40 MPa, fluid column pressure is 46 MPa, and permeability coefficient is 1×10^{-8} m/s. It is found that when the initial pore pressure is different, the attenuation law of pore pressure in the formation is the same. It is concluded that initial pore pressure does not affect pore pressure attenuation.

TABLE 1: Material parameters.

Elastic modulus (Pa)	Poisson's ratio	Void ratio	Permeability coefficient ($\text{m}^* \text{s}^{-1}$)	Density (g/cm^3)	Pore fluid density (g/cm^3)
73×10^9	0.25	0.25	1×10^{-8}	5	1

FIGURE 3: The distribution of pore pressure.

FIGURE 4: Attenuation law of pore pressure.

Figure 6 shows the effect of formation permeability coefficient on pore pressure in the formation when the initial pore pressure is 40 MPa and the fluid column pressure is 46 MPa. The curve in the figure shows that when permeability coefficients are different, the attenuation law and attenuation amplitude of pore pressure in the formation along the borehole axis are also similar. It indicates that the

FIGURE 5: The effect of initial pore pressure on pore pressure attenuation.

FIGURE 6: The effect of permeability coefficient on pore pressure.

initial pore pressure and permeability coefficient have little effect on the attenuation of bottom hole pore pressure with the stable liquid column pressure.

4. Analysis of Pore Pressure in Deep Rock with Pulsed Jet

When bottom hole pressure fluctuates, the main factors affecting the local pore pressure of bottom hole formation are pulse frequency, pulse amplitude, initial pore pressure, and permeability coefficient.

4.1. Pulse Frequency. To study the effect of pulse frequency on the attenuation law, it is assumed that (1) the permeability coefficient is 1×10^{-8} m/s; (2) the loading curve is sinusoidal; (3) the amplitude is 1 MPa; (4) the initial pore pressure in the formation is 40 MPa; and (5) the fluid column pressure is 46 MPa. The attenuation law of deep pore pressure in the formation with pulsed jet at different frequencies is analyzed in Figure 7.

Figure 7 shows that the pore pressure in the formation increases first and then decreases along the axis of the wellbore, and the influence depth of frequency on the pore pressure in the formation is 20 mm. When the frequency is 5 Hz, the maximum pore pressure is at 10 mm from the bottom of the well, which is 45.45 MPa; when the frequency is 50 Hz, the maximum pore pressure is at 5.18 mm, which is 45.86 MPa; when the frequency is 500 Hz, the maximum pore pressure is at 5.18 mm, which is 46.07 MPa; when the frequency is 5000 Hz, the maximum pore pressure is at 5.18 mm, which is 46.11 MPa. It shows that with the increase of frequency, the maximum pore pressure difference gradually increases, but the increase of amplitude gradually slows down, and the difference between 500 Hz and 5000 Hz is relatively small. When the pulse frequency is higher, it will generate larger relative negative pressure at the bottom of the well.

Figure 8 shows the cyclic variation of the difference between the bottom hole pressure and the maximum pore pressure along the axis. By observing the curve in the figure, it is found that the pressure difference increases in the first $1/4T$, decreases in $1/4$ to $3/4T$, and increases in $3/4T$ to T . the whole curve is similar to the loading curve, which is a sinusoidal variation; when the pulse amplitude is constant, the time length of reducing the original “chip hold-down effect” is gradually shortened with the increase of frequency, and the relative negative pressure is gradually enhanced. The greater the negative pressure difference between bottom hole pressure and pore pressure in the formation is, the easier it is to overturn the rock debris at bottom hole and the fewer the repeated cutting of rock debris is. In drilling, the length of negative pressure time is also an important factor to evaluate the pulsation effect. The longer the relative negative pressure time is, the more it is conducive to improve the rock breaking efficiency. Through comprehensive analysis of these two factors, it can be concluded that 50–500 Hz frequency is more suitable for drilling.

4.2. Pulse Amplitude. The permeability coefficient is assumed to be 1×10^{-8} m/s, the loading curve is sinusoidal, the frequency is 50 Hz, the initial pore pressure in the formation is 40 MPa, and the fluid column pressure is 46 MPa. The attenuation law of pore pressure of bottom hole formation under different amplitudes is analyzed, as shown in Figure 9. It is found that the pulse amplitude mainly affects the bottom hole pressure and has little effect on the maximum pore pressure in the formation; when the amplitude is 0.5 MPa and 1 MPa, the maximum pore pressure of the formation appears at 5.18 mm below the bottom of the well, and when

FIGURE 7: The effect of pulse frequency on pore pressure.

FIGURE 8: The effect of pulse frequency on pore pressure.

the amplitude is 1.5 MPa and 2 MPa, the maximum pore pressure of the formation appears at 10.9 mm. Thus, it mainly affects the pressure difference at the surface of the well.

Figure 10 shows the variation of pore pressure difference with pulse amplitude. When the pulse amplitude is 0.5 MPa, 1 MPa, 1.5 MPa, and 2 MPa, the difference between bottom hole pressure and pore pressure in the formation is -0.28 MPa, -0.74 MPa, -1.23 MPa, and -1.71 MPa, respectively. The results show that with the increase of pulse amplitude, the relative negative pressure produced underground gradually increases and changes approximately linearly. It can be concluded that the large downhole pressure pulsation is beneficial to ROP.

FIGURE 9: The effect of pulse amplitude on pore pressure.

FIGURE 10: The pressure difference under different pulse amplitudes.

4.3. Initial Pore Pressure. The pore pressure in the formation is assumed to have a permeability coefficient of 1×10^{-8} m/s, the loading curve is sinusoidal, the frequency is 50 Hz, and the difference between fluid column pressure and formation initial pore pressure is 6 MPa. The attenuation law of pore pressure in the formation at the bottom of the well with different initial pore pressure is analyzed, as shown in Figure 11.

The curve shows that the initial pore pressure of the formation only changes the initial value of the pore pressure, and the relative negative pressure difference between the bottom hole and the formation is the same. It shows that when pulsation

FIGURE 11: The effect of initial pore pressure on pore pressure attenuation.

frequency and amplitude are the same, only the initial pore pressure of the well is different, and the relative negative pressure at the bottom of the well is the same. It can be considered that the initial pore pressure of the formation has no effect on the attenuation of the pore pressure.

4.4. Permeability Coefficient. Assuming that a sinusoidal pressure pulsation with a frequency of 50 Hz and an amplitude of 1 MPa is applied to the bottom of the well, the fluid column pressure is 46 MPa, and the initial pore pressure difference of the formation is 40 MPa. Figure 12 shows the effect of permeability coefficient on pore pressure in the formation attenuation when other conditions remain unchanged. The curve in the figure shows that the influence scope of permeability coefficient on the pore pressure is 20 mm. When the permeability coefficient is 1×10^{-8} , the maximum pore pressure appears at 5.18 mm, which is 45.86 MPa; when the permeability coefficient is 2×10^{-8} , the maximum pore pressure appears at 10.09 mm, which is 45.68 MPa; when the permeability coefficient is 5×10^{-8} , the maximum pore pressure appears at 11 mm, which is 45.57 MPa; when the permeability coefficient is 1×10^{-7} , the maximum pore pressure appears at 13.45 mm, which is 45.39 MPa. It is indicated that the relative negative pressure of bottom hole and formation pores gradually slows down with the increase of permeability coefficient. The position of the maximum pore pressure gradually moves down with the increase of permeability coefficient, and the influence scope gradually increases.

Figure 13 shows the variation of pore pressure difference with permeability coefficient. The curve of relative negative pressure on bottom hole is like the pulse amplitude curve, but with the increase of permeability coefficient, the relative negative pressure decreases gradually.

FIGURE 12: The effect of permeability coefficient on pore pressure attenuation.

FIGURE 13: The effect of permeability coefficient on pressure difference.

5. Mechanism of Pulsed Jet Raising ROP

Whether the rock debris can be removed in time has a significant impact on the ROP. If rock debris is not separated from the rock matrix, the fluid column pressure is P_b , the pore pressure in the formation is P_p , and the pressure of the jet acting on the bottom of the well is ΔP_j . Currently, the normal pressure on the rock debris is $P_b + \Delta P_j + w$, where w is the weight of the rock debris. Since the debris is not yet separated from the rock matrix, the pressure in the crack between the debris and its matrix can be approximately taken as P_p . When $P_b + \Delta P_j + w > P_p$, the rock debris will be

FIGURE 14: Pore pressure difference in different positions.

held at the bottom of the well. To separate the rock debris from the bottom of the well, a horizontal load T must be applied to the rock debris, and its minimum value can be calculated by the friction law:

$$T = (P_b + \Delta P_j + w - P_p)\mu, \quad (6)$$

where μ is the dimensionless coefficient between matrix and rock debris.

When there is a pressure drop ΔP_n at the bottom of the well, equation (6) becomes

$$T = (P_b + \Delta P_j + w - P_p - \Delta P_n)\mu. \quad (7)$$

Equation (7) shows that when P_p increases, the horizontal load T decreases, which is more conducive to reducing the “chip hold-down effect” and improving rate of penetration. When the pulsation P_p is large enough, $P_b + \Delta P_j + w - P_p - \Delta P_n < 0$. At this time, there is no “chip hold-down effect” on the rock debris at bottom hole, and the rock debris will start to move automatically.

It is assumed that the initial pore pressure of bottom hole formation is 40 MPa, the fluid column pressure is 46 MPa, and the formation permeability coefficient is 1×10^{-8} m/s. Apply sinusoidal pressure pulsation with frequency of 50 Hz and amplitude of 1 MPa to the bottom hole and analyze the bottom hole relative negative pressure effect and mechanism of enhancing ROP under this pressure fluctuation.

Figure 14 shows the comparison of relative negative pressure generate at different positions on the bottom of the well. The figure shows that the relative negative pressure along the wellbore axis is the largest, the farther it is to the axis, the smaller the relative negative pressure is, and even there is only positive pressure at the edge of the bottom well. However, the shapes of the four curves in Figure 14 are similar, and any curve can be formed through the translation of other curve. This phenomenon is related to the attenuation rate of pore pressure at different positions on the bottom of the well.

FIGURE 15: The maximum negative pressure in different positions.

Figure 15 shows that the maximum relative negative pressure gradually decreases with the increase of distance from the wellbore axis, and the initial decrease is slow. When it is near the wellbore wall, the relative negative pressure value decreases rapidly.

6. Conclusion

The effect of pulse frequency, pulse amplitude, formation initial pore pressure, and permeability coefficient on rock pore pressure is studied.

- (1) With the increase of pulse frequency, the maximum value of bottom hole rock pore pressure gradually increases, but the growth rate is declining. The growth rate is very small in the range of 500 Hz to 5000 Hz.
- (2) The pulse amplitude mainly affects the bottom hole pressure and has little effect on the maximum pore pressure, but it affects the relative negative pressure.
- (3) The initial pore pressure in the formation has little effect on the attenuation of bottom hole rock pore pressure and the relative negative pressure at bottom hole. It only changes the initial value of bottom hole pressure, which can be ignored in practical analysis.
- (4) The permeability coefficient mainly affects the value of the relative negative pressure and the position of the maximum pore pressure. With the increase of permeability coefficient, the relative negative pressure decreases, and the position of negative pressure deepens gradually.
- (5) The value of the relative negative pressure along the axis of the well is the largest, and the closer it gets to the wall, the less relative the negative pressure is.

Data Availability

The raw data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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