Wellbore characteristics of air drilling with hammer in thick conglomerate and its influence on hole deviation

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Abstract. Air drilling with hammer is generally recognized as an effective drilling method, but the hole obtained in thick conglomerate formation is very irregular, and the control of hole deviation is very difficult. Although many studies have been carried out, the mechanism of this phenomenon has not been found out yet. In this paper, based on the numerical simulation of rock breaking process of air hammer, the influence of the heterogeneity of conglomerate on the wellbore regularity and hole deviation is analyzed. The results show that the direction of the bit will be changed due to the heterogeneous distribution of gravel particles, which make the wellbore with a severely irregular shape. On this basis, the finite element models of BHA in regular and irregular wellbores are established respectively, and the influence of wellbore irregularity on the stress of BHA is analyzed. It can be found the irregular wellbore is easy to form additional fulcrum, shorten the effective swing distance of pendulum bottom hole assembly. The additional fulcrum greatly changes the mechanical characteristics of the BHA, reducing the angle dropping force on bit, or even produce the angle building force.

1. Introduction

Compared with the mud drilling, air drilling has many advantages, e.g. increasing the ROP, reducing the lost circulation, decreasing the damage of mud to formation and extending the bit life[1-3]. However, there are two bottlenecks in air drilling. One is that the vertical well is easy to deviate, the other is that it is difficult to run casing[4-6]. The reasons for the difficulty of deviation control include the heterogeneity of formation, the strong vibration of BHA and the complex downhole conditions (such as formation water outflow, wellbore collapse, sand settling, etc.)[7-11]. At present, air drilling with hammer is generally recognized as an effective drilling method, which mainly breaks rock through high-frequency impact and assisted by low speed rotary of drillstring. It not only has a high ROP, but also has an acceptable deviation control effect in sandstone, shale and carbonate formation.

However, it is difficult to control hole deviation when drilling with air hammer in the thick conglomerate of Tarim oilfield in China. Moreover, the wellbore is irregular and it is difficult to run the casing. The thickness of conglomerate in piedmont area of Tarim oilfield is more than 5,000 meters and there is a very low mud drilling speed. In order to improve the ROP, a well in the piedmont
area was drilled with air hammer between 2505m and 2926m. The diameter of air hammer bit is 431.8mm. The measurement results of wellbore diameter show that the cross-section of the wellbore presents obvious elliptical characteristics (the length of long axis is about 508.0mm, the length of short axis is about 431.8mm) and the wellbore section varies greatly along the axis of the wellbore, as shown in Figure 1(a)[12]. The hole deviation measurement results show that hole deviation angle increases rapidly from 0.59°to 4.48°, as shown in Figure 1(b)[13]. This kind of situation is very common in air drilling of thick conglomerate in this area, and its mechanism is not yet clear. The traditional mechanical analysis of drillstring assumes that the borehole wall is smooth and regular and so it cannot reveal the mechanism of deflection under the condition of irregular wellbore. To solve this problem, the formation mechanism of irregular wellbore was studied by rock breaking simulation. On this basis, the influence of wellbore irregularity on bit lateral force is analyzed. It has important reference value to understand the cause of borehole deviation in gas drilling in heavy gravel bed.

2. Finite element model of air hammer rock breaking in air drilling of thick conglomerate

2.1 The characteristics of thick conglomerate and air hammer
In the piedmont area of Tarim Basin, the conglomerate layer is more than 5,000 meters thick and contains a large amount of quartz gravel with high hardness and poor drillability but the accompanying cementation is of low strength, as shown in Figure 2(a)[14]. That is, the gravel formation is highly heterogeneous. Figure 2(b) is a typical air hammer tool[15]. It produces high-frequency impact under the action of continuous high-pressure gas. When the air hammer bit hits the rock at the bottom of the well at high frequency, it is easy to form an uneven force distribution on the end face of the bit. Obviously, the strong heterogeneity of the gravel layer will further aggravate this kinds of heterogeneous stress distribution. That means an uneven stress area exists on the rock of hole bottom and may cause hole deviation and wellbore irregularity.
2.2 Mesh Model

The finite element method is used to simulate the rock breaking process of air hammer in thick conglomerate. Figure 3 (a) shows a BHA for air drilling with an air hammer without any stabilizer. The interaction model between air hammer and rock is established as shown in Figure 3 (b) and Figure 3 (c). The length of BHA is 4m in this model, in which the diameter of the air hammer bit is 431.8mm and the diameter of the drill collar is 228.6mm. A formation model with a diameter of 3m was established in which only three unequal diameter gravel particles were contained and the rest were homogeneous cementing material. Tetrahedral mesh and C3D4 element type are adopted. The number of elements in the whole model is 1,374,388, and the number of nodes is 543,713.

It is assumed that the air hammer bit is a rigid body in the calculation, that is, the bit does not deform and wear in the process of rock breaking. The elastic modulus of BHA is 210GPa and Poisson's ratio is 0.29. The material parameters of gravel particles and cement are shown in Table 1.

![Figure 3. The model of air hammer and conglomerate rock](image)

### Tab.1 The material parameters of cement and gravel particles

|                | density (kg/m³) | elastic modulus (GPa) | poisson's ratio | angle of friction(°) | flowstress ratio | dilation angle(°) |
|----------------|-----------------|-----------------------|----------------|----------------------|-----------------|------------------|
| cement         | 2000            | 13.55                 | 0.26           | 24.47                | 0.918           | 20.3             |
| gravel particles | 2000            | 53.28                 | 0.42           | 29.47                | 0.918           | 23.3             |

2.3 Interaction model between air hammer and conglomerate rock

The interaction between air hammer and conglomerate rock is a complex nonlinear contact problem. Static friction coefficient $F_s$, dynamic friction coefficient $F_d$ and exponential attenuation coefficient $D_c$ constitute the friction coefficient of contact and the friction coefficient $\mu_c$ is related to the relative velocity $V_{vel}$ of contact surface[16-18].

$$
\mu_c = F_d + (F_s - F_d)e^{-D_vV_{vel}}
$$

(1)

To limit the maximum friction $F_{max}$, set the viscosity coefficient $V_c$:

$$
V_c = \frac{F_{max}}{A}
$$

(2)

Where, $A$ is the contact area.

The shear yield stress can be expressed as, $V_c = \sigma_0 / \sqrt{3}$, where $\sigma_0$ is the yield stress of the material.

In order to avoid unnecessary oscillation during contact, contact damping perpendicular to the contact surface must be used. The contact damping coefficient is:
\[ \xi = \xi_c \omega V_c D_c = 2mw V_c D_c \]  \hspace{1cm} (3)

Where, \( \xi \) is the critical damping coefficient, \( m \) is the mass, \( \omega \) is the natural frequency, and there is \( \xi_c = 2mw \).

In this paper, the extended linear Drucker-Prager model is used, and the element will peel off from the rock when the plastic strain of rock reaches 0.05. The model considers the influence of confining pressure on the yield property and can reflect the rock dilatancy caused by shear.

2.4 Boundary condition
The contact between bit and rock is a non-linear and time-varying random process, which is a typical dynamic process. In this paper, ABAQUS/Explicit is used.

A reference point is established in the center of the bit, and the bit can rotate around the axis passing through it (rotating speed is 30 r/min) while applying a 20 kN static WOB on it. At the same time, an impact load with a shock frequency of 1200 times per minute and a peak impact force of 50kN is also applied at the reference point. In the calculation, the surrounding rock is constrained to ensure that the bit can effectively breaks the rock.

3. The wellbore characteristics of air drilling with hammer in thick conglomerate
Air drilling with hammer is actually a process in which the compressed air pushes the air hammer piston to produce high-frequency impact load on the bit and then the bit hits the rock at the bottom of the hole, breaks the rock and forms the wellbore. During this process, the BHA rotates at a very small speed, which is beneficial to the correction of the wellbore and the improvement of the cuttings cleaning efficiency. It is easy to see that this process is very difficult and time-consuming to simulate. Therefore, this paper can only give the simulation results in a relatively short time, as shown in Figure 4, which is the stress of gravel particles during the rock-breaking process at the five moments of 40s, 60s, 100s, 160s and 200s as well as the formed wellbore characteristics.

It can be seen from the figure that at 40s, the bit has not encountered gravel particles, and the BHA keeps vertical drilling. At 60s, the bit has encountered the first gravel particle. The heterogeneity of the formation aggravates the nonuniformity of the stress on the bit. The bit deviates to a certain extent, and the formed wellbore has a certain deviation characteristics. At 100s, the bit encounters the second gravel particle. Because the inclination angle of the gravel is different from that of the first gravel particle, the drilling direction is forced to take another deflection. The second gravel particle corrects the hole deviation to a certain extent but at the same time, it also makes the wellbore appear a certain degree of dogleg. At 160s, the bit encountered the third gravel particle, and the drilling direction of bit deviated again. Because the inclination angle of the third gravel particle is very small. The bit breaks the rock along the vertical direction almostly. Since then (160s ~ 200s), there are no gravel particles in the drilling path of the bit. So the bit almost breaks a straight borehole.

![Figure 4. The rock breaking process of air hammer in thick conglomerate](image-url)
4. The influence of wellbore irregularity on hole deviation

At present, all three-dimensional mechanical analysis of BHA is based on regular and smooth wellbore assumption. However, the above analysis shows that the air hammer is easy to form irregular wellbore when drilling in gravel layer.

Figure 5 shows the characteristics of the irregular wellbore and its effect on the BHA forces. Under the action of gravity, BHA tends to contact with the low side of wellbore. In a regular wellbore, the BHA lies on the bottom wall. This characteristic will change in irregular wellbore. The bulge on the lower side of the wellbore in an irregular wellbore will form additional fulcrum, as shown in Figure 5.

In order to analyze the influence of the irregular wellbore on the bit's lateral force, the finite element models of the BHA in regular wellbore (case 1), medium irregular wellbore (case 2) and severely irregular wellbore (case 3) are established respectively. For case 1, the wellbore is regular and not curved. For case 2, the wellbore has a certain degree of bending characteristics. The drill collar contacts the wellbore at a specific position (just forming an additional fulcrum) but the drill collar does not deform. For case 3, the wellbore has a large degree of bending characteristics. The drill collar contacts the wellbore at a specific position, and the additional fulcrum makes the drill collar bend.

The BHA is a pendulum one with single stabilizer. The diameter of bit and wellbore is both 431.8mm, the outer diameter and inner diameter of drill collar is 228.6mm and 71.4mm respectively. The outer diameter of stabilizer is 428mm. The distance between stabilizer and bit is 27m. The hole deviation angle is 5°. The friction coefficient between BHA and wellbore is assumed to be 0.2.

The influence of different regular degree of wellbore on bit lateral force is calculated under the action of BHA weight and 50kN WOB. The force acting on the bit under three cases is shown in Figure 6, where the negative value means to angle dropping force and the positive force mens to the angle building force. It can be seen that the angle dropping force of the bit is -1708.5N in case 1 and the BHA has a good effect of reducing well deviation. In case 2, the irregularity of wellbore makes an additional fulcrum at BHA which reduces the swing distance of pendulum and then reduces the angle dropping force of the bit to -998.3N. In case 3, the serious irregular wellbore makes the drill string deform greatly and then produce 7435.7N of angle building force. The results show that the more irregular the wellbore is, the weaker the angle dropping ability of the pendulum BHA is. Particularly, a serious irregular wellbore may even make the pendulum BHA become an angle building assembly.

5. Conclusion

By analyzing the wellbore features of air drilling and the interaction between BHA and irregular wellbore, the following conclusions can be obtained:

1) The numerical simulation of rock breaking in heterogeneous formation is realized, which can reveal the mechanism of irregular wellbore formed by air drilling with hammer in thick gravel conglomerate.

2) The gravel particles aggravate the heterogeneity of the rock, which makes the force on the bit very uneven, and the direction of drilling is easy to deflect, which results in irregular wellbore.
3) It is easy to form additional fulcrum on BHA in irregular wellbore and short the effective swing distance of pendulum BHA, which will greatly reduce the angle dropping force of the bit and even make it become an angle building force.

4) When drilling thick conglomerate with air hammer, irregular wellbore will increase the difficulty of deviation control. It is necessary to ensure that the wellbore has good regularity as far as possible.

5) In this paper, the force of the drill string in the irregular wellbore is obtained based on the statics calculation. In the follow-up study, the dynamic lateral force of the bit in the rock-breaking process can be calculated in real time to better reflect the influence of the irregular wellbore on the lateral force of the bit.

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