Analysis of wellbore stability of gas underbalanced drilling technology

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Abstract—Gas underbalanced drilling technology has the advantages of high ROP and little damage to oil and gas reservoirs. In recent years, it has been widely used in the exploration and development of oil and gas fields in China. Under normal air drilling conditions, the pore pressure is basically zero, so it is necessary to establish the wellbore stability model under the condition of zero pore pressure to provide theoretical support for the wellbore stability analysis of air drilling. However, gas underbalanced drilling also has wellbore instability, more sand deposition at the bottom of the well, and even the malignant accident of sticking. Firstly, through the analysis of the traditional wellbore stability model, the influence of pore pressure is removed, and the wellbore stability model suitable for air drilling is obtained. At the same time, it is proposed that the sand deposition is mainly caused by the collapse material when the collapse ellipse is formed on the shaft wall, and the formation of the collapse ellipse is conducive to maintaining the stability of the shaft wall. For large and medium-sized gravel layers, the influence of cementation strength on wellbore stability should be considered.

1. PREFACE

Air drilling has great advantages in tight lithologic strata and difficult to drill strata. Gas drilling can greatly improve drilling speed and increase the footage of a single bit, which is of great significance for improving drilling speed in tight strata and difficult to drill strata. Since the 1960s, the world energy demand has entered an era dominated by oil and natural gas. With the development of economy and the growth of population, the demand for oil and natural gas is increasing rapidly [i]. The world oil industry is facing a very severe situation, under the new situation, the exploration and development of oil and gas fields have the following characteristics: The difficulty of exploration and development is getting bigger and bigger, the investment cost is getting higher and higher, and the risk is getting higher and higher. In order to meet the requirements of these new exploration and development situations, it is necessary to improve the exploration and development ideas and technologies, so as to reduce the exploration and development costs and risks and meet the needs of the current international energy demand [iii]. In the process of oil and gas field development, drilling investment often accounts for about two-thirds of the total cost. Therefore, improving drilling technology and reducing drilling costs have become an important means to reduce the whole exploration and development costs, and underbalanced drilling technology came into being under this background [ii].
Wellbore stability is an important problem in oil drilling engineering. Every year, the major oil companies in the world consume a lot of manpower, material resources and financial resources to solve various problems caused by wellbore instability. The safety and effectiveness of drilling operation can not be effectively guaranteed because of wellbore instability, resulting in huge economic losses\[iv\]. There are two main problems of wellbore stability, one is tensile fracture of wellbore surrounding rock due to the high liquid column pressure in wellbore which is greater than the fracture pressure of wellbore rock; the other is the shear failure caused by the low drilling fluid pressure which can not provide effective support to the wall rock. The former leads to lost circulation while the latter leads to the collapse of the wall and the enlargement of the well diameter\[v\]. The factors affecting wellbore stability can be summarized as man-made and natural. Natural factors include: stratum rock properties, geological structure types, in-situ stress, clay-bearing mineral types, soil mineral content, fracture development course, rock cementation, rock porosity, permeability and so on; human factors include the composition of drilling fluid, drilling fluid properties (fluid loss, viscosity, rheological property, density), bare time of wellbore, erosion of wellbore caused by annulus return velocity of drilling fluid, impact of drilling string vibration on wellbore, etc\[v\].

Gas underbalanced drilling technology has the advantages of high penetration rate and little damage to oil and gas reservoirs, and has been widely used in oil and gas field exploration and development in China in recent years. In the drilling process, there is no liquid column pressure in the well to support the wellbore and balance the formation pressure, and the formation fluid flows into the well under the action of negative pressure difference, thus changing the stress distribution around the well, so the wellbore stability problem is more prominent and becomes the biggest factor restricting the application of gas underbalanced drilling technology.

2. Materials and Methods

(1) The stress model of borehole lining under the condition of air drill

In the traditional wellbore stability model, when the cylindrical coordinate system is adopted for vertical wells, the effective stress around the wellbore can be expressed as:

\[
\sigma_{rr} = \frac{1}{2} (S_{Hmax} + S_{Hmin} - 2p_0) \left(1 - \frac{R^2}{r^2}\right) + \frac{1}{2} (S_{Hmax} + S_{Hmin}) \times \left(1 - \frac{4R^2}{r^2} + \frac{3R^4}{r^4}\right) \cos 2\theta + \frac{p_0 R^2}{r^2} \tag{1}
\]

\[
\sigma_{\theta \theta} = \frac{1}{2} (S_{Hmax} + S_{Hmin} - 2p_0) \left(1 + \frac{R^2}{r^2}\right) - \frac{1}{2} (S_{Hmax} - S_{Hmin}) \times \left(1 + \frac{3R^4}{r^4}\right) \cos 2\theta - \frac{p_0 R^2}{r^2} - \sigma^\Delta T \tag{2}
\]

\[
\tau_{r\theta} = \frac{1}{2} (S_{Hmax} - S_{Hmin}) \left(1 + \frac{2R^2}{r^2} - \frac{3R^4}{r^4}\right) \sin 2\theta \tag{3}
\]

The new wellbore stability model under the condition of air drilling is as follows, because the formation water must be avoided in the stage of horizon optimization under gravel drilling condition, and the new wellbore stability model under air drilling condition is as follows:

\[
\sigma_{rr} = \frac{1}{2} (S_{Hmax} + S_{Hmin}) \left(1 - \frac{R^2}{r^2}\right) + \frac{1}{2} (S_{Hmax} + S_{Hmin}) \times \left(1 - \frac{4R^2}{r^2} + \frac{3R^4}{r^4}\right) \cos 2\theta + \frac{R^2}{r^2} \tag{4}
\]

\[
\sigma_{\theta \theta} = \frac{1}{2} (S_{Hmax} + S_{Hmin}) \left(1 + \frac{R^2}{r^2}\right) - \frac{1}{2} (S_{Hmax} - S_{Hmin}) \times \left(1 + \frac{3R^4}{r^4}\right) \cos 2\theta - \frac{R^2}{r^2} - \sigma^\Delta T \tag{5}
\]

\[
\tau_{r\theta} = \frac{1}{2} (S_{Hmax} - S_{Hmin}) \left(1 + \frac{2R^2}{r^2} - \frac{3R^4}{r^4}\right) \sin 2\theta \tag{6}
\]

Where: \(\sigma_{rr}\)-radial stress around the wellbore, MPa; \(\sigma_{\theta \theta}\)-circumferential stress around the wellbore, MPa; \(\tau_{r\theta}\)-tangential stress around the wellbore, MPa; \(S_{Hmax}\)-the magnitude of the horizontal maximum principal stress, MPa; \(S_{Hmin}\)-the magnitude of the horizontal minimum principal stress, MPa; \(\theta\)-the angle between the azimuth of the horizontal maximum principal stress and the specified direction, °; \(p_0\)-formation pore pressure, MPa; \(\sigma^\Delta T\)-stress due to temperature, MPa; \(\Delta T\)-the difference between bottom hole temperature and formation temperature, °C; \(R\)-wellbore radius, m; \(R\)-the distance between a point in the formation and the center of the wellbore, m.
(2) The establishment of model and the process of wellbore instability

Because of the heterogeneity distribution of gravel formation, the whole failure process can not be effectively characterized by traditional software simulation. In order to solve this problem, the discrete element method is used to simulate the instability process of gravel wellbore lining. Based on the geology and engineering parameters of gravel stratum, the discrete element numerical model is established. The stratum depth is 2000m; gravel characteristics: medium and fine conglomerate; maximum radius of gravel: 50mm; minimum radius of gravel: 6mm; radius of filling matrix: 1 ~ 2mm; cementation degree: poor; formation porosity is 18%, and there is no fluid in the formation; maximum horizontal principal stress: 45MPa; minimum horizontal principal stress: 35MPa; borehole size: 431.8 mm.

Fig. 1 Stress loading and crack initiation

Fig. 1 shows the crack initiation process. In the left picture, the red line represents the stress loading, with the horizontal direction corresponding to the maximum horizontal principal stress and the vertical direction corresponding to the minimum horizontal principal stress. In the process of fracture propagation, the green dots near the borehole indicate tensile fractures, and the red dots indicate shear fractures. Fractures are first formed near the borehole wall, and the number of fractures in the figure is relatively small and not obvious. The number of fractures counted by program shows that tensile fractures are more than shear fractures. When there are large gravel particles around the borehole wall, tensile fractures are formed around the large gravel particles, and then a large number of shear fractures are gathered around the gravel particles, and the fractures are connected with each other, resulting in the shedding of gravel particles. In order to observe the fracture propagation form around the borehole wall, the integrity of the formation failure area is guaranteed by setting program commands, but in fact, the area where the fracture propagates has collapsed.

Fig. 2 Crack propagation process

After fractures are formed around large gravel particles around the well, they quickly penetrate with nearby fractures. Under the action of in-situ stress, a large number of accumulated fractures will propagate along the direction of minimum principal stress (see Figure 2). The minimum in-situ stress direction in the model of Figure 2 is along the longitudinal direction, so an elliptical wellbore with long axis in the longitudinal direction will be formed (red ellipse in Figure 3). Fig. 3 shows the failure mode of shaft lining, in which the thickness of black line represents the contact force between particles, and
the part without contact force indicates that falling and collapse have occurred. It is worth noting that a large number of falling blocks (blue circles) are also caused around gravel particles on the right side of the wellbore, while the left side of the wellbore is not damaged, because there are many large gravel particles distributed on the right side of the wellbore, which are poorly cemented with cements and have micro-fractures. Under the action of shear stress, the fractures expand and penetrate, reducing the rock strength of the wellbore, resulting in falling blocks on the wellbore.

![Fig. 3 Wellbore failure mode](image)

3. RESULTS

(1) Effect of particle size characteristics on wellbore instability

Based on the statistics of particle size distribution, the radii of gravel particles are $0.5 \sim 1.5$ mm, $1.5 \sim 3$ mm, $3 \sim 4$ mm and $4 \sim 5$ mm. The calculation time of the model is $2 \times 10$ s.

![Fig. 4 Wellbore instability characteristics of different gravel particle size distributions](image)

Fig. 4 shows the failure characteristics of four different gravel particle sizes in phase wellbore model, the red dots represent cracks, the red arrow represents the crack propagation direction, the aggregation of red dots represents the formation of fracture zone and the spalling of surrounding rock blocks. The large gravel particles around the well reduce the compressive strength of surrounding rock. Under the action of borehole shear stress, the confining pressure of gravel layer produces blocks, forming an irregular caving ellipse with the direction of minimum horizontal principal stress as its long axis. At the
same time, the fracture propagation direction of wellbore models with different gravel particle size
distribution is slightly different. The larger the gravel particle size, the greater the influence of gravel
location distribution on fracture propagation, and the failure area around the well extends to the direction
of large gravel particle size. When the radius of gravel particles is 0.5 ~ 1.5 mm, the collapse area of
borehole wall is near the borehole, the shedding of gravel particles and the fracture of cement almost
occur at the same time, the distribution of gravel around the borehole has little influence on the fracture
propagation direction, and the fracture propagates almost along the minimum principal stress direction,
that is, the Y-axis direction, but the distance of the failure area in the Y-axis direction is short; when the
radius of gravel particles is 1.5 ~ 3mm, the failure area around the well covers the area where large
gravel particles are located in the X-axis direction, and the cementation surface around the large gravel
particles has low strength, which leads to preferential failure and forms a fracture aggregation area. At
the same time, multiple fracture aggregation areas penetrate each other, which accelerates the fracture
propagation process, and the failure area has a long distance in the Y-axis direction; when the radius of
gravel particles is 3 ~ 4mm, the micro-cracks propagate along the direction of maximum principal stress,
and gradually connect with the fracture aggregation area of large-size gravel particles nearby, and the
propagation process is faster, and the failure area is farther away in the Y-axis direction; when the radius
of gravel particles is 4 ~ 5mm, the gravel particles peel off from the cement and form irregular wellbore,
and the wellbore instability is more prominent in the area where large gravel particles gather around the
wellbore. For the gravel layer with the same borehole size, under the action of non-uniform tectonic
stress, the particle size distribution of gravel particles affects the fracture propagation process around
the well. The larger the particle size (larger than 3mm), the multiple fracture aggregation areas penetrate
each other, and the fracture propagation is farther, and the wellbore failure area extends to the depth
around the well.

The results of discrete element simulation show that the strength between cement and gravel and the
size of gravel particle play a decisive role in wellbore stability. When the gravel layer is unstable and
destroyed, only cement is destroyed, and then gravel particles peel off from the borehole wall. When air
drilling is used, it is necessary to ensure that gravel particles can be carried out of the wellbore; when
gravel particles cannot be taken out, it is easy to cause sand settling at the bottom of the hole and even
sticking.

(2) Field application

1) Analysis of strength and particle size of cement in gravel layer

When the gravel content is the same, the larger the gravel particle size, the lower the rock strength;
the greater the strength of cement, the greater the strength of rock. Through statistical analysis, it is
found that the larger the gravel particle size is, the easier it is to form collapse and block falling. When
the gravel particle size is larger (generally larger than 5mm), it is difficult for cuttings to be taken away
from the bottom of the well, resulting in excessive sand settling, resistance in tripping and sticking.

2) Law of sand settling

The law of sand settling in a 333.375 mm borehole is 8m/100m (i.e. 7m sand settling per 100m
formation), and that in a 333.375 mm borehole is 17.5 m/100m. The main factors affecting the thickness
of grit settling are cement strength and gravel particle size (Figure 5).
3) Cause analysis of sand settling

According to the simulation of air drilling, when the wellbore diameter is 333.375 mm and the well depth is 4500m, the simulation results are shown in Figure 6. The 400m/min gas injection rate can only carry 5mm grain size sand when the wellbore is enlarged by 20%, and only 3mm grain size sand when the wellbore is enlarged by 40%.

After the drill bit opens the formation, a collapse ellipse is formed, and a large number of grit is formed, which is gravel. Therefore, the rock carrying capacity of the air injected into the wellbore will have a great influence on the grit speed and depth.

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4. CONCLUSION

1) When drilling in gravel layer, the collapse ellipse is beneficial to reduce the stress concentration around the borehole wall, and the main source of bottom hole sand settling is the rock forming the collapse ellipse.

2) The content and strength of cement and the size of gravel have great influence on wellbore stability. Air drilling is suitable for small conglomerate formation with uniform gravel distribution (the size of gravel is less than 5mm). For large and medium gravel layers, the influence of cementation strength on wellbore stability should be considered.

3) At present, the influence of irregular well diameter is not considered in the calculation of rock carrying capacity under air drilling conditions, so further research is needed. Strengthen and improve the data collection of upper gravel electrical measurement, further strengthen and refine the research on gravel content, particle size and distribution law, and provide basic data for air drilling well location optimization.
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