A method for predicting the build-up rate of single-bending positive displacement motor assembly in compound drilling

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Abstract: Accurately predicting the build-up rate of single-bending positive displacement motor (PDM) assembly in compound drilling is helpful to rational design the well trajectory, realize compound drilling in long well sections and improve the rate of penetration. Based on the calculation model of corrected build-up rate of single-bending PDM assembly in sliding drilling, the build-up rate calculation method of single-bending PDM assembly in compound drilling was established by combining the trajectory measurement data of the drilled sections, and the influence law of parameters such as bending angle, weight on bit, bit anisotropy index and formation inclination on the build-up rate of compound drilling was analyzed. And the following results are obtained. First, the build-up effect of the single-bending PDM assembly during compound drilling is mainly the result of the leverage effect and pendulum effect of the drill tool assembly, as well as the natural deviation of formation. Second, the composite drilling build-up rate is related to the drilling tool structure, bit performance, drilling parameters, formation inclination and other factors. In conclusion, the factors affecting the build-up rate of conventional drilling tool assembly also have impacts on the composite drilling build-up rate of single-bending PDM assembly. The method is important for the control of well trajectory during compound drilling.

1. Introduction

The single-bend screw drilling tool assembly can quickly build the deflection during sliding drilling, and at the same time, it can achieve the purpose of stabilizing, slightly increasing or slightly decreasing the deviation during compound drilling, has been widely used. Practice has shown that the friction problem is prominent during sliding drilling, and the ROP is also lower than that of compound drilling. In order to improve the drilling speed, reduce the drilling risk, and give full play to the technical advantages of the composite drilling method, it is necessary to increase the proportion of the composite drilling section as much as possible [1]. However, when the single-bend screw drilling tool assembly is used for compound drilling in long well sections, the actual drilling trajectory generally tends to increase or decrease slightly. Therefore, predicting the build-up rate of the single-bend screw drilling tool assembly during compound drilling is of great significance for the control and prediction of the wellbore trajectory.

Scholars at home and abroad have carried out a lot of research on the build-up rate during sliding drilling of single-bend screw drilling tool assemblies, mainly forming the geometric method [2-4], the mechanical method [5-8] and the trajectory method [9-10]. The ultimate curvature method [6] is a kind of mechanical method, which is similar to the equilibrium curvature method. It is considered that when the lateral force at the drill bit is zero or approaches zero, the corresponding borehole curvature is the limit build-up rate of the drilling tool, and then It can directly characterize the build-up rate of the drilling tool. However, this method is limited to two-dimensional models and also ignores the influence of the drilling process. The converted build-up rate method is a method developed based on the limit build-up rate. The converted build-up rate obtained by this method is generally smaller than the limit build-up rate, and there is an approximate proportional relationship between them. The proportional coefficient is closely related to the drilling process. The coefficient is determined by inversion of real drilling data [8].

At present, there are few studies at home and abroad on the deflection ability of single-bend screw drill assembly in compound drilling. Di Qinfeng et al. [11-13] once proposed that the deflection ability of the sliding-steering BHA composite drilling can be described by the average resultant steering force of the drill bit in one rotation of the turntable. Afterwards, domestic scholars have studied the inclination stability capability of single-bend and double stabilizers steering BHA in compound drilling based on this method [14].

According to the calculation method of the converted build-up rate of a push-the-bit rotary steerable drilling, the

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author proposes a calculation method of the single-bend screw drilling tool assembly compound drilling build-up rate, and analyzes the structure of the drilling tool, drilling parameters, bit anisotropy and formation. Influence of inclination angle on build-up rate of compound drilling with single-bend screw drilling tool assembly.

2. Calculation of sliding drilling corrected build-up rate

According to the interaction model between the bit and the formation, the three-dimensional ROP equation can be expressed as [15]:

$$\begin{bmatrix} V_a \\ V_1 \\ V_2 \end{bmatrix} = D_n \boldsymbol{M}_e^T \boldsymbol{I}_r \boldsymbol{M}_e \boldsymbol{M}_b^T \boldsymbol{I}_b \boldsymbol{M}_b \begin{bmatrix} W_b \\ F_{b,1} \\ F_{b,2} \end{bmatrix} \tag{1}$$

Where,

$$\boldsymbol{I}_r = \begin{bmatrix} 1 & & \\ & I_{r1} & \\ & & I_{r2} \end{bmatrix} \tag{2}$$

$$\boldsymbol{I}_b = \begin{bmatrix} 1 & & \\ & I_b & \\ & & I_b \end{bmatrix} \tag{3}$$

Where Va is the axial ROP of the bit; V_1 and V_2 are the components of the lateral ROP of the bit in the inclination and azimuth planes, respectively; D_n is the standard (normal) drilling efficiency; $\boldsymbol{M_e}$ is the conversion matrix for the bottom hole-formation reference coordinate system; $\boldsymbol{M_b}$ is the conversion matrix for the bottom hole-bit reference coordinate system; I_{r1} and I_{r2} are the anisotropy index of the formation; I_b is the anisotropy index of the bit; W_b is the WOB; $F_{b,1}$ and $F_{b,2}$ are the components of the lateral force of the bit in the inclination and azimuth planes, respectively.

The lateral force of the drill bit can be obtained from the force model of the single-bend screw drilling tool assembly, which is similar to the force model of the rotary steerable drilling tool, but the difference is the treatment of the bending point of the drill string. Due to the influence of the screw angle, the drilling tool assembly has a corner discontinuity at the screw bending point, and the corresponding sudden change value is related to the screw bending angle and the tool face angle. When the bending point is in contact with the borehole wall, the continuous conditions of displacement, rotation angle and bending moment at the bending point are defined as:

$$\begin{cases} u_{k,j}(L_{k,j}) = u_{k,j+1}(0) \\ u'_{1,j}(L_{k,j}) - u'_{1,j+1}(0) = \gamma \cos(\omega) \\ u'_{2,j}(L_{k,j}) - u'_{2,j+1}(0) = \gamma \sin(\omega) \\ EI_j u''_{k,j}(L_{k,j}) = EI_{j+1} u''_{k,j+1}(0) \end{cases} \tag{4}$$

where $k = 1$ is the inclination plane, and $k = 2$ is the azimuth plane; $u_{k,j}$ represents the lateral displacement of the j-th span of the pipe string on the borehole inclination plane and the azimuth plane; $u_{k,j+1}$ represents the lateral displacement of the j+1-th span of the pipe string on the borehole inclination plane and the azimuth plane; $L_{k,j}$ represents the length of the j-th span; γ is the screw bending angle; ω is the tool face angle; EI_j and EI_{j+1} represent the flexural rigidity of the j-th and the j+1-th span of the pipe string, respectively.

If the pipe string at the bend point is not in contact with the wellbore wall, the continuous conditions of displacement, rotation angle, bending moment and shear force are defined as:

$$\begin{cases} u_{k,j}(L_{k,j}) = u_{k,j+1}(0) \\ u'_{1,j}(L_{k,j}) - u'_{1,j+1}(0) = \gamma \cos(\omega) \\ u'_{2,j}(L_{k,j}) - u'_{2,j+1}(0) = \gamma \sin(\omega) \\ EI_j u''_{k,j}(L_{k,j}) = EI_{j+1} u''_{k,j+1}(0) \\ EI_j u'''_{k,j}(L_{k,j}) = EI_{j+1} u'''_{k,j+1}(0) \end{cases} \tag{5}$$

According to the definition of the corrected build-up rate [8], the calculation model of the corrected build-up rate for the sliding drilling of the single-bend screw drilling tool assembly is defined as:

$$\kappa_s = \lambda_s \sqrt{\kappa_1^2 + \kappa_2^2 \sin^2 \alpha} \tag{6}$$

where κ_s is the sliding drilling corrected build-up rate; λ_s Represents the correction coefficient, which is obtained from the inversion calculation of the wellbore trajectory measurement data;

α is borehole inclination angle; κ_1 and κ_2 represent the components of the limit build-up rate of sliding drilling of the single-bend screw drilling tool assembly, which can be obtained according to the definition of the limit build-up rate and combined with equations (1) to (5). The limit build-up rate takes into account the influence of drilling tool structural parameters, wellbore trajectory parameters, and drilling process parameters, and the correction coefficient

reflects the influence of other factors in the process of directional drilling in the drilled section, so the corrected build-up rate can more accurately predict the actual build-up capability of the drilling tool assembly.

3. Calculation of compound drilling build-up rate

According to the characteristics of compound drilling of single-bend screw drilling tool assembly, the process of compound drilling can be approximated as a process in which the directional tool face changes regularly. Therefore, the build-up rate during compound drilling cannot be described by the build-up rate during sliding drilling with a particular tool face. As shown in Figure 1, it is assumed that the blue arc in the figure represents the trajectory formed by the compound drilling for a period of time. At this time, the tangential footage of the trajectory is equal to 1m, and the lateral offset is H; the red arc in the figure represents the drilling tool assembly with a trajectory formed by sliding drilling with a certain directional tool face for a period of time, and the tangential footage of the trajectory is also equal to 1m, and the lateral offset is *Hi*. The lateral offset *H* can be considered as the average of all lateral offsets when the tangential footage is 1m with different directional tools during the drilling tool rotation process, and then the curvature radius of this trajectory can be calculated to obtain the single-bend screw drilling tool approximate value of build-up rate for compound drilling.

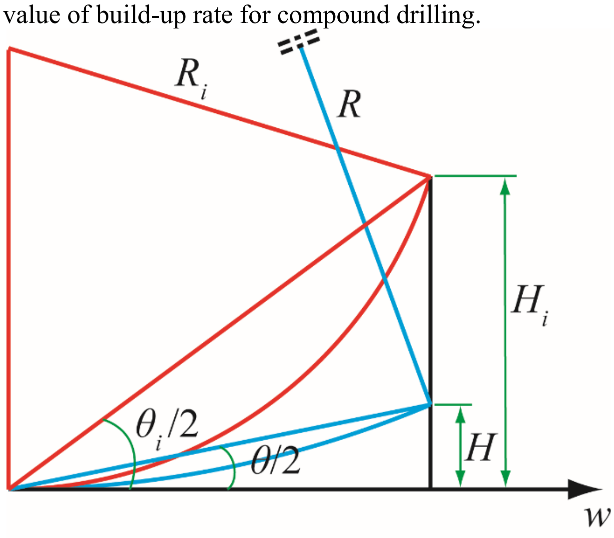

Figure 1. Calculation model of compound drilling build-up rate

Assuming that the directional tool face angle of the single-bend screw drilling tool assembly at a certain time is ω_i; the sliding drilling corrected build-up rate κ_{si} can be calculated at this time, and the curvature radius of the drilling trajectory can be expressed as:

$$R_i = \frac{30}{\kappa_{si}} \tag{7}$$

Where, R_i represents the curvature radius of the wellbore trajectory if sliding drilling is used at this moment; κ_{si} represents the corrected build-up rate if sliding drilling is used at this moment.

Assuming that when the drilling trajectory produces 1m footage along the axial direction, the rotation angle of the wellbore trajectory is θ_i, thus

$$2R_i \sin\left(\frac{\theta_i}{2}\right)\cos\left(\frac{\theta_i}{2}\right) = 1 \tag{8}$$

It can be obtained from the above formula:

$$\theta_i = \arcsin\left(\frac{1}{R_i}\right) \tag{9}$$

At this point, the lateral offset produced by the wellbore trajectory can be expressed as:

$$H_i = 2R_i \sin^2\left(\frac{\theta_i}{2}\right) \tag{10}$$

Therefore, the components H_{i1} and H_{i2} of the lateral offset on the inclination and azimuth planes can be expressed as:

$$H_{i1} = 2R_i \sin^2\left(\frac{\theta_i}{2}\right)\cos\omega_i \tag{11}$$

$$H_{i2} = 2R_i \sin^2\left(\frac{\theta_i}{2}\right)\sin\omega_i \tag{12}$$

When the single-bend BHA rotates once, the directional tool face angle ω_i changes continuously in the range of 0~2π rad. For the convenience of calculation, ω_i can be uniformly taken N values in the range of 0~2π rad with a certain step size. When the drilling tool assembly rotates one cycle and the drilling trajectory produces 1m footage along the axial direction, the components H_1 and H_2 of the lateral deviation of the trajectory on the inclination plane and azimuth plane can be expressed as:

$$H_1 = \frac{1}{N}\sum_{i=1}^{N}\left\{2R_i \sin^2\left(\frac{\theta_i}{2}\right)\cos\left[\frac{2\pi(i-1)}{N}\right]\right\} \tag{13}$$

$$H_2 = \frac{1}{N}\sum_{i=1}^{N}\left\{2R_i \sin^2\left(\frac{\theta_i}{2}\right)\sin\left[\frac{2\pi(i-1)}{N}\right]\right\} \tag{14}$$

When the drilling tool assembly rotates once and the drilling trajectory produces 1m footage along the axial direction, the rotation angle θ of the wellbore trajectory can be expressed as:

$$\theta = 2\arctan\left(\sqrt{H_1^2 + H_2^2}\right) \tag{15}$$

At this time, the curvature radius R of the wellbore trajectory can be expressed as:

$$R = \frac{\sqrt{H_1^2 + H_2^2}}{1-\cos\theta} \tag{16}$$

And because the build-up rate κ_c of compound drilling with single-bend screw drilling tool assembly can be expressed as:

$$\kappa_c = \frac{30}{R} \tag{17}$$

Therefore, by combining Eqs. (7), (9) and (13), (14), (15), (16), (17), we can obtain:

$$\kappa_c = 30\frac{1-\cos\left[2\arctan\left(\sqrt{H_1^2 + H_2^2}\right)\right]}{\sqrt{H_1^2 + H_2^2}} \tag{18}$$

Where,

$$H_1 = \frac{1}{N}\sum_{i=1}^{N}\left\{\frac{60}{\kappa_{si}}\sin^2\left[\frac{1}{2}\arcsin\left(\frac{\kappa_{si}}{30}\right)\right]\cos\left[\frac{2\pi(i-1)}{N}\right]\right\} \tag{19}$$

$$H_2 = \frac{1}{N}\sum_{i=1}^{N}\left\{\frac{60}{\kappa_{si}}\sin^2\left[\frac{1}{2}\arcsin\left(\frac{\kappa_{si}}{30}\right)\right]\sin\left[\frac{2\pi(i-1)}{N}\right]\right\} \tag{20}$$

4. Examples

The analysis is carried out with the single-bend unstable drilling tool combination used to drill into the reservoir in a well, as shown in Figure 2. It is designed with Φ149.2mm PDC bit + Φ120mm screw (1.5° angle) + one-flow valve + Φ120mm non-magnetic drill collar (including MWD instrument) + suspension short section + 311*DS380+Φ88.9mm drill pipe. The bit anisotropy index is 0.3, and the average WOB is 45kN.

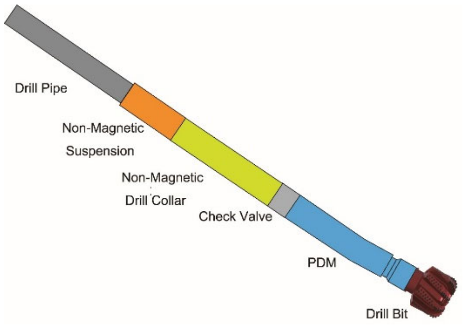

Figure 2. Schematic diagram of single-bending PDM assembly without stabilizer

The measured build-up rate is obtained according to the directional well section inclination data of the actual drilling trajectory in Figure 3. The calculated build-up rate is obtained from the sliding drilling build-up rate model when the correction coefficient is 0.83. The calculated results are the same as the measured results. Therefore, the calculated build-up rate shown in Fig. 3 can be used in combination with the compound drilling build-up rate model to predict the build-up rate of the BHA during compound drilling, and the calculated result is 1.53°/30m. After the directional section of the well was drilled, the drilling tool assembly continued to be used for compound drilling, and a slight increase in the wellbore trajectory was achieved. The actual build-up rate of the first 100m compound drilling section is shown in Figure 4. The average build-up rate of this well section is 1.49 °/30m, which is in line with the build-up rate of compound drilling predicted by the model in this paper, so the model in this paper is effective.

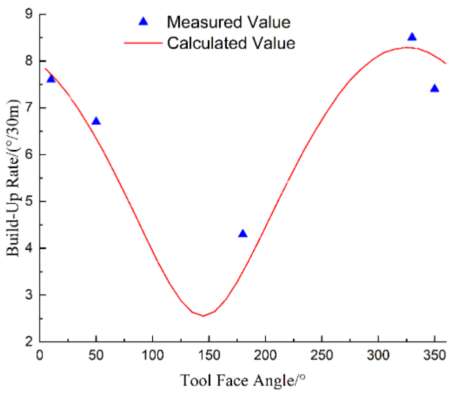

Figure 3. Sliding drilling build-up rate

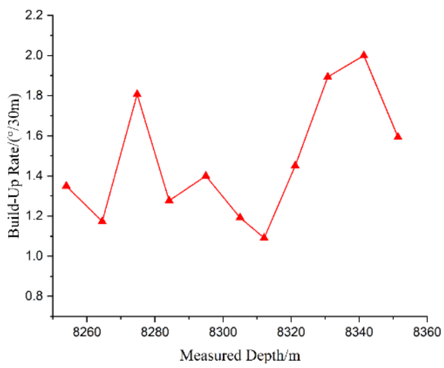

Figure 4. Compound drilling build-up rate

The compound drilling slope of the single-bend screw drilling tool assembly with different bending angles under different WOBs at the borehole inclination of 83.53° are in Table 1. The results show that when the bending angle is constant, as the WOB increase, the leverage effect increases, resulting in a slight increase in the compound drilling build-up rate; when the WOB remains unchanged, as bending angle increase, the compound drilling build-up rate increases.

The compound drilling slope of the single-bend screw drilling tool assembly with different bending angles under different bit anisotropy index at the borehole inclination of 83.53° are in Table 2. The results show that when the bending angle is small, as the bit anisotropy index increase, the compound drilling build-up rate decreases slightly; when the bending angle is large, as the bit anisotropy index increase, the compound drilling build-up rate showed a trend of first decreasing and then increasing. As the bit anisotropy index increase, the cutting capacity of the bit increase, resulting in the simultaneous the pendulum effect and the leverage effect increase. When the bending angle is small, as the bit anisotropy index increase, the pendulum effect increases faster than the lever effect, resulting in a decreasing trend of the compound drilling build-up rate; when the bending angle is large, as the bit anisotropy index increase, the pendulum effect rate increase is first greater than that of the lever effect and then smaller than that of the leverage effect, resulting in a trend of first decreasing and then increasing the build-up slope of compound drilling.

The compound drilling slope of the single-bend screw drilling tool assembly with different bending angles under different formation dips at the borehole inclination of 83.53° are in Table 3. The results show that with the formation dip increase, the natural build-up capacity of the formation increases, resulting in an increase in the compound drilling build-up rate.

Table 1. Predicted results of compound drilling build-up rate for different bending angles and WOB

WOB /(kN)	compound drilling Build-up rate under different bending angles /(°/30m)			
	0.75°	1°	1.25°	1.5°
30	0.84	1.07	1.29	1.51
40	0.85	1.08	1.30	1.52
50	0.86	1.09	1.31	1.53
60	0.87	1.09	1.32	1.54
70	0.87	1.10	1.32	1.55

Table 2. Predicted results of compound drilling build-up rate for different bending angles and bit anisotropy index

bit anisotropy index	compound drilling Build-up rate under different bending angles /(°/30m)			
	0.75°	1°	1.25°	1.5°
0.2	0.86	1.09	1.31	1.54
0.3	0.86	1.08	1.31	1.53
0.4	0.85	1.07	1.30	1.64
0.5	0.84	1.07	1.46	1.68

Table 3. Predicted results of compound drilling build-up rate for different bending angles and formation inclination

the formation dip /(°)	compound drilling Build-up rate under different bending angles /(°/30m)			
	0.75°	1°	1.25°	1.5°
5	0.79	1.01	1.23	1.42
10	0.86	1.08	1.31	1.53
15	0.91	1.14	1.37	1.59
20	0.96	1.19	1.42	1.64

5. conclusions

(1) The sliding drilling build-up rate of the single-bend screw drilling tool assembly is related to the directional tool face. The compound drilling build-up rate of the single-bend screw drilling tool assembly can be obtained from the sliding drilling build-up rate of one rotation of the drilling tool. The factors of the sliding drilling build rate of the curved screw drilling tool assembly also have an impact on the compound drilling build-up rate.

(2) The compound drilling build-up effect of the single-bend screw drilling tool assembly is mainly the result of the leverage effect and the pendulum effect of the drill tool assembly, as well as the formation natural build-up ability. Therefore, the compound drilling build-up rate is related to factors such as drilling tool structure, bit performance, drilling parameters, and formation dip.

(3) In order to increase the ROP and accurately control the wellbore trajectory, it is necessary to accurately evaluate the formation natural build-up ability, reasonably design the wellbore trajectory, optimize the drilling tool assembly and bit, reasonably control the drilling parameters, and accurately predict the build-up rate.

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