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An new simple method of unsteady cuttings transport calculation during long inclined section drilling

Xiaole Guo[2,4], Boyi Xia[3], Chengwei Qi[2], Wenyin Li[2]

Abstract. The cuttings transport has an important influence on the calculation of hole cleaning and annular pressure loss during drilling or washing long highly-deviated well section. There are some theoretical models to simulate the dynamic process, but they are complex and hard to solve. Through analyzing the mechanism of cuttings transport and simplifying the dynamic three-layers cuttings transport model established early, a simple model used to calculate cuttings transport velocity was made and more importantly a new method using a mathematic function to describe the front edge of cuttings bed was proposed, combining these dynamic cuttings bed transport can be calculated simply, which makes real-time hole cleaning monitoring easier. The calculation results show that it takes a long time to spread the cuttings bed all over the annular or wash off all the cuttings bed in the annular, which makes a big error when a steady model is used to describe this process. Compared with the theoretical model, this method is convenient, fast and simple for fields application.

Key words. Extended reach drilling, cuttings deposit bed, dynamic transport velocity, unsteady cuttings transport, real time calculation.

1. Introduction

The extended-reach well (ERW) is essentially a directional well with longer horizontal displacement. Thus, the directional well research results are often used to design the drilling hydraulics of ERWs. When the highly deviated and horizontal

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[2]College of Oil and Gas Engineering, Chongqing University of Science and Technology, Chongqing, China

[3]Engineering Technology Research Institute, CNPC Greatwall Drilling Engineering Company Limited, Liaoning, China

[4]Corresponding Author, e-mail: gxl_cqusst@126.com

well section are not too long, the error is acceptable. But when it comes to the ERWs with high ratio of horizontal displacement to vertical displacement, a serious error will occur. The reasons are as follows, firstly, the highly deviated and horizontal well section of ERW is often 3000 to 5000 meters long, when drilling in this section, the leak pressure remains almost unchanged, while the downhole pressure increases gradually with the increase of annulus pressure lost. As a result, the safe mud density window becomes smaller and drilling accidents is easy to occur. To avoid these accidents, the annular pressure lost must be calculated and forecasted accurately and controlled precisely enough. Secondly, studies have shown that, in highly deviated and horizontal well section drilling cuttings are easy to deposit and form a cuttings bed, which has a great influence on annular pressure loss. Therefore, the cuttings bed height and distribution in annular must be calculated firstly to estimate the downhole pressure precisely.

The cuttings bed formation process is shown in Figure 1. Considering the influence of some drilling operations, the cuttings bed distribution changes in real time. Doron et al. [1], Nguyen et al. [2], Hyun et al. [3], Guo et al. [4] and Duan et al. [5] had established some steady-state models of cuttings transport, but all of them can only calculate the unchanging height of cuttings bed at the end of formation when the annular flow comes to stable at time of T_n, and can't calculate the cuttings bed distribution changes in the whole process. If cuttings bed distribution is unknown, the annulus pressure drop can't be calculated precisely also. In the same way, removing all the cuttings bed also needs a long time from the borehole. The steady models cannot describe this process apparently and meet the requirement of hole cleaning design and hydraulics calculation. Thus, Martins et al. [6] firstly proposed a dynamic cuttings transport model in 1999, and Shigemi et al. [7], Suzana et al. [8], Guo et al. [9] and Cayeux et al. [10] presented similar dynamic models in the past years. Most of them consist of a series of nonlinear equations, which is difficult and time-consuming to solve, thus it is not easy for real time calculation in fields application. Therefore, a new simply method to calculating cuttings dynamic transport is proposed by simplifying the three-layer cuttings transport unsteady model established by the author and analyzing the cuttings transport mechanism. This method will make drilling hydraulics design and real-time cuttings bed height calculation easier in the long and highly deviated sections drilling of ERWs.

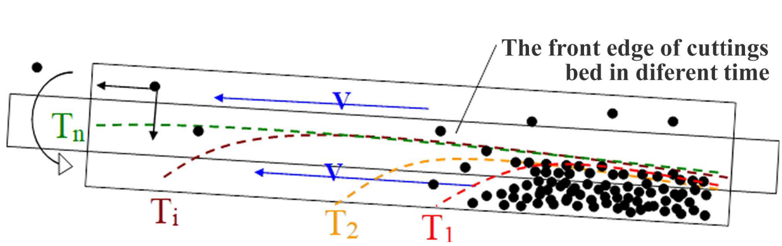

Fig. 1. Cuttings bed formation process in highly deviated well section

2. Model building

2.1. Cuttings bed height dynamic distribution change calculation

Assuming that the cuttings transport process is in accordance with which is shown in Figure 1. Based on cuttings transport rule, at some moment, the cuttings generated from bottom hole will formed a cuttings bed along the annular, which can be divided into two parts according to the bed height. The first part close to bottom, with a certain length, has a fixed height equal to the value calculated by steady model. The second part has a varied height from steady height to zero away from bottom. The process of well washing is the opposite. The length of first part lies on the transport velocity of cuttings bed. The front edge of cuttings bed in second part can be expressed by some simple mathematical function, like exponential function here.

Drilling:

$$H_{cx} = H_c \exp\left[1 - \frac{(MD - x)}{L_c}\right] . \tag{1}$$

Washing:

$$H_{cx} = H_c \left\{1 - \exp\left[1 - \frac{(MD - x)}{L_c}\right]\right\} , \tag{2}$$

$$L_c = tU_c , \tag{3}$$

where H_c is relative annular cuttings bed height to hole diameter, %; MD is the well measured depth, m; x is the distance from the well head, equal to MD at the bottom; H_{cx} is the relative cuttings bed height at position x; L_c is length of cuttings bed which has a steady or final height of H_c on the moment, m; t is drilling or washing time, s; U_c is the transport velocity of cuttings bed, m/s.

Thus, to calculate the gradually changing cuttings bed distribution, we need some other models, one is for steady height of calculation cuttings bed, one is for cuttings bed dynamic transport velocity calculation and the other is for calculation of annular pressure loss with cuttings bed if we want to know the downhole pressure in real-time, which are described respectively in the following.

2.2. Calculation model of steady cuttings bed height

Under certain conditions, the highest cuttings bed formed in annular space, is called the steady cuttings bed. The steady or final cuttings bed height is the basis of cuttings bed dynamic transport velocity calculation. Many researches have been made for the calculation of steady cuttings bed height, including two layers models, three layers models, theoretical models, regression models, etc. As known, the rotation of drill string has a great influence on cuttings bed height, but it will make the model more complicated to solve. As a result, most of theoretical models are lack of consideration of the effect of drill pipe rotation. Thus a regression model [11] is selected to use here.

$$
\begin{aligned}
H_c = {} & 4\rho_f^{-2.477}\rho_s^2(d_w - d_{po})^{(0.282-0.383e)}(d_w + d_{po})^{-0.276}\{1.45 \\
& - 50[E_v - 0.6U_a(d_w - d_{po})]\}^2 d_b^{0.582} ROP^{0.276}\cos(0.5\pi \\
& - 1.4286\theta U_a^{0.2}) d_s^{-0.174}(1 + 0.5e)(RPM + 1)^{-0.185}(1.056 \\
& - U_a^{2.262} + U_a^{-0.264}) ,
\end{aligned} \tag{4}
$$

where d_w is hole diameter, m; d_{po} is drill pipe diameter, m; U_a is annular return velocity, m/s; RPM is drill string rotation speed, rad/s; e is eccentricity, dimensionless; ρ_f is mud density, kg/m^3; ρ_s is cuttings density, kg/m^3; ROP is the rate of penetration, m/s; E_v is mud's effective viscosity, Pa $\cdot$ s.

2.3. Calculation of cuttings bed dynamic transport velocity

Assuming that the cuttings bed formation contains two processes, one is the settlement of the cuttings from upper layer and the other is the transfer from the neighboring cuttings bed. Thus, the cuttings bed transport velocity also should be divided to two parts, the velocity due to settlement of upper layer cuttings and the velocity due to transfer of neighboring cuttings bed. Cuttings bed erosion is similar. Through analysis of mechanism of cuttings transport and simplification of early established cutting dynamic transport model [9], a calculation model of cuttings bed dynamic transport velocity can be built [12].

$$
U_c = \frac{k_3 U_{cm} + (1 - k_3)U_{cd}}{2} , \tag{5}
$$

Where the velocity due to transfer of neighboring cuttings bed, U_{cm}, can be estimated by:

$$
U_{cm} = k_1 \frac{0.0625 f_{hd}\rho_f}{gC_d(\rho_f)(\tan\phi\sin\theta + \cos\theta)} \frac{(d_w - d_{po})}{(1 - A_C/A_a)^3 A_c} U_a^3 . \tag{6}
$$

When washing well (cuttings bed erosion), H_c means the height of existing cuttings bed before washing.

The Velocity due to upper layer cuttings settlement, U_{cd}, can be estimated by: When drilling

$$
U_{cd} = k_2 \frac{\sin\theta - 0.5}{C_d \sin\theta} \frac{Q_s}{Q_s + Q_f} \frac{A_a}{A_c} U_a . \tag{7}
$$

When washing

$$
U_{cd} = k_2 \frac{0.05}{C_d \sin\theta} (\frac{A_c}{A_a})^{0.5} U_a^2 , \tag{8}
$$

Where A_a is annulus area, m^2; A_c is cuttings bed area, can by calculated from H_c, m^2; f_{hd} is friction coefficient of suspended and mobile layer interface, seen in literature [6]; C_d is the cuttings concentration of moving bed layer; ϕ is internal friction angle of particle, $\tan\phi$ is equivalent of particle dynamic friction coefficient, related to cuttings concentration, the greater the concentration, the bigger the value, when $C_d = 0.3$–0.52, $\tan\phi = 0.7$–0.8; θ is hole deviation angle, °; Q_s is the inlet cuttings volume rate, m^3/s; Q_f is mud volume rate, m^3/s; k_1 and k_2 is the corrective coefficient, related to the annulus geometry, the error coming from simplification of model and so on, can be obtained according to the experiment or the fields data, assumed to be 1 here; k_3 is the weighting coefficient, affected by the cuttings suspended ability of mud, can be obtained according to the experiment or the fields data, assumed to be 0.5 here.

2.4. Calculation of annular pressure loss with cuttings bed

After cuttings bed distribution in annular is calculated, the annulus pressure loss with cuttings bed can be calculate immediately by the formula [13]:

$$\Delta P_c = \frac{0.0260686 H_c \Delta P_a}{f_b} \times \left[\frac{4Q_f^2 \rho_f}{g\pi^2 \left(d_w - d_{po}\right)^3 \left(d_w + d_{po}\right)^2 \left(\rho_s - \rho_f\right)}\right]^{-1.25} + \left(1 + 0.00581695 H_c\right) \Delta P_a \,, \tag{9}$$

Where ΔP_c is annulus pressure loss with cuttings bed, P_a; ΔP_a is annulus pressure loss without cuttings bed, P_a; f_b is Darcy-Weisbach coefficient, in laminar flow $f_b = \frac{64}{R_e}$, in turbulent flow $f_b = \frac{0.316}{R_e^{0.25}}$, R_e is flow reynolds number, details about this formular can be seen in the literature.

2.5. Calculation process

To calculate annular cuttings bed height distribution in some moment when drilling, the steps are:

(1) Use formula (4) to calculate the steady state of cuttings bed height;

(2) Use formula (5) to calculate the cuttings bed transport velocity;

(3) Use formula (3) to calculate cuttings bed transport distance L_c;

(4) If $x \geq MD - L_c$, then $H_{cx} = H_c$;

If $x < MD - L_c$, then H_{cx} should be calculated according to the formula (1).

To calculate annular cuttings bed height distribution in some moment when washing well, the first three steps are same as above, step 4 is as follows:

(4) If $x \geq MD - L_c$, so $H_{cx} = 0$

If $x < MD - L_c$, so H_{cx} calculate according to the formula (2).

(5) Use formula(9) to calculate annular pressure loss.

3. Calculation example

The well structure for example is shown in Figure 2, As it showns, 0–250 m is the vertical section, 250 m–1000 m is the angle bulit section from 0° to 90°, 1000 m–2000 m is the horizontal section, the whole well vertical depth is 800 m. Hole diameter is 311 mm, drill pipe diameter is 127 mm, the mud density is 1.1 g/cm^3, cuttings density is $2.5\,\mathrm{g/cm^3}$, cuttings particle size is 5 mm, the default mud flow rate is 60 L/s, the reheology model of mud is power law with the paremeters of $n = 0.5$, $K = 0.5\,\mathrm{Pa{\cdot}s^n}$, drill string rotation speed is 100 r/min, ROP is 50 m/h, the pipe eccentricity is 0.5, concentration of moving bed layer is $C_d = 0.52$, dynamic friction coefficient = 0.75. The calculation results are as follows.

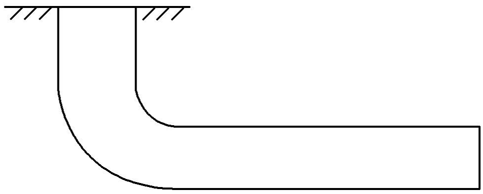

Fig. 2. Example well structure diagram

3.1. Cuttings bed dynamic transport process calculation

According to the above model, the calculation results of cuttings bed formation process in 311 mm well section when drilling, and cuttings bed erosion process when washing, are shown in Figure 3. The changes of annular pressure loss during cuttings bed formation and erosion are shown in Figure 4. It can be seen, when drilling or washing in a long well section, it takes a long time for cuttings bed to cover the entire annulus or be removed completely, as shown in Figure 1. Using steady model will cause a big error to estimate the cuttings bed distribution or annular pressure loss. The well section in this example is just 1000 m, for extended-reach well's, it will be longer, and the error will be larger correspondingly.

Comparing the cuttings bed formation or erosion process with the simulation results of theoretical models in literature of dynamic models, we can see that the changes pattern is almost same. But this method makes calculation process more easily and speed more quickly.

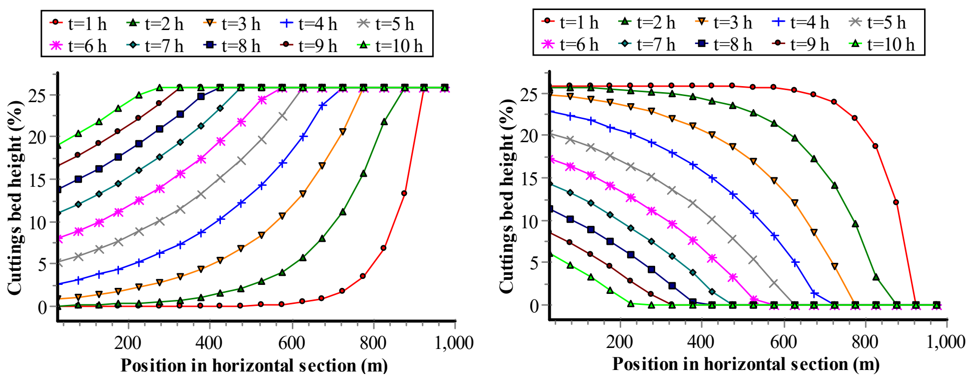

Fig. 3. Cuttings bed formation (left) and erosion (right) process diagram

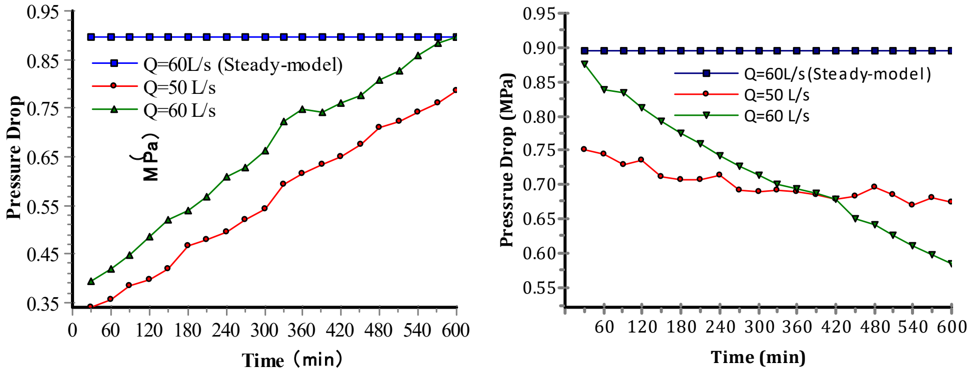

Fig. 4. Annular pressure loss change during cuttings bed formation (left) and erosion (right) process

3.2. Model verification

Because the experiment data of cuttings bed dynamic transport, especially the cuttings bed formation is lack, the model in this paper is compared with the established data of the cuttings removing time in the literature [14] All input parameters are same to the data in the literature, and the calculation ends when the residual of cuttings bed height is 1%. The results are shown in Table 1. As can seen that the cuttings bed removing time of calculation using this model is much bigger than the data of literature, but in general the error is still within the acceptable scope of fields.

Table 1. Comparison result with Martins' experimental data

Mud flow rate (L/s)	**22.1**	**28.4**	**34.7**
Rotating speed (r/min)	90	120	50
Literature results (s)	1177.6	656.4	925.5
Model in this paper (s)	1284	702	986
Relative error (%)	9.04	6.95	6.54

4. Conclusion

A new method to calculate the real-time cuttings bed height dynamic distribution and annular pressure loss when drilling or washing is established, which offers help for hydraulics design and hole cleaning monitoring of extended-reach wells. The calculation results show that, when long well section drilling or washing, it takes a long time for cuttings bed to cover the whole annular or be removed completely, and thus using steady state model to calculate cutting bed height or annular pressure will bring a big error. Compared with theoretical model, the method is convenient, fast and easy for fields application.

References

[1] P. Doron, D. Grranica, D. Barner: *Slurry flow in horizontal pipes—experimental and modeling.* Int. J. Multiphase Flow *13* (1987), No. 4, 535–547.

[2] D. Nguyen, S. S. Rahman: *A three-layer hydraulic program for effective cuttings transport and hole cleaning in highly deviated and horizontal wells.* Proc. SPE/IADC Drilling Conference and Exhibition, 9–11 September 1996, Kuala Lumpur, Malaysia. SPE 36383.

[3] H. Cho, S. N. Shah, S. O. Osisanya: *A three-segment hydraulic model for cuttings transport in horizontal and deviated wells.* Proc. SPE/CIM International Conference on Horizontal Well Technology, 6–8 November 2000, Calgary, Alberta, Canada. SPE 65488.

[4] X. L. Guo, Z. M. Wang: *Study on cuttings transport in ERW.* Proc. of the 20th National Conference on Hydrodynamics, 23–25 August 2007, Tai Yuan, Shan Xi, China.

[5] M. Q. Duan, S. Z. Miska, M. J. Yu: *Transport of small cuttings in extended reach drilling.* Proc. International Oil & Gas Conference and Exhibition, 5–7 December 2006, Beijing, China. SPE 104192.

[6] A. L. Martins, M. L. Santana, W. Campos: *Evaluating the transport of solids generated by shale instabilities in ERW drilling.* SPE Drill & Completion, *14* (1999), No. 4, 254–259.

[7] S. Naganawa, T. Nomura: *Simulating transient behavior of cuttings transport over whole trajectory of extended-reach well.* Proc. IADC/SPE Asia Pacific Drilling Technology Conference, 13–15 November 2006, Bangkok, Thailand. SPE 103923.

[8] S. C. Suzana, S. Sidney, A. B. Sergio: *Simulation of transient cuttings transportation and ECD in wellbore drilling.* Proc. SPE Europec/EAGE Annual Conference and Exhibition, 9–12 June 2008, Rome, Italy. SPE 113893.

[9] X. L. Guo, Z. M. Wang, Z. H. Long: *Study on three-layer unsteady model of cuttings transport for extended-reach well.* Journal of Petroleum Science and Engineering. *73* (2010), 171–180.

[10] E. Cayeux, T. Mesagan, S. Tanripada: *Real-time evaluation of hole cleaning conditions using a transient cuttings transport model.* Proc. SPE/IADC Drilling Conference and Exhibition, 5–7 March 2013, Amsterdam, The Netherlands. SPE 163492.

[11] Z. M. Wang, X. N. Hao, X. L. Guo: *A study on the thickness of a cutting bed monitor and control in an extended reach well.* Petroleum Science and Technology. *29* (2011), No. 13, 1397–1406.

[12] X. L. Guo, Z. H. Long, C. W. Qi, J. L. Liu: *An engineering model for calculation of cuttings bed formation or erosion velocity during long inclined well section drilling.* Electronic Journal of Geotechnical Engineering. *20* (2015), No. 27, 13275–13284.

[13] H. G. Wang, X. S. Liu, G. Ding: *Development of model for pressure drop in annular space of horizontal well.* Journal of China University of Petroleum. *20* (1996), No. 2, 30–35.

[14] A. L. Martins, W. Campos, F. S. Liporace: *On the erosion velocity of a cuttings bed during the circulation of horizontal and highly inclined wells.* Proc. SPE/IADC Drilling Conference and Exhibition, 29–30 August 1997, Rio de Janeiro, Brazil. SPE 39021.

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