OPERATIONAL CONTROL AND MANAGEMENT OF DRILLING PARAMETERS AS THE KEY TO EFFICIENT DIRECTIONAL AND EXTENDED REACH DRILLING

Vyacheslav Kadochnikov

Saint Petersburg Mining University, 199106 Saint Petersburg; kadochnikov93@gmail.com

ABSTRACT. Every year the volumes of drilling wells with complex trajectories increase, and vertical wells are successfully occupied by directional wells with large waste from the vertical ones (extended reach drilling). Several sections with changes in the zenith and azimuth angles have difficult trajectories. The drill string in the well is in a complex stress-deformed state, as a result, tool landing and tightening occur, as well as the risk of loss of its elements' strength. It should be noted that a change in the geometry of the drill string in the presence of critical trajectory angles determines the slurry (formation of a slurry pad) and the change in the equivalent circulating density (ECD). The paper substantiates the necessity of operational control and management of drilling parameters in order to prevent emergencies in the well, especially while drilling in a narrow range of absorption and fracturing pressures. The results of a multifactor computational experiment are presented: the dependence of the hydrodynamic pressure in the well on the consumption of the cleaning agent and on the rate of penetration. The principle of determining the actual axial load on the bit and the algorithm for the operational control and management of the drilling parameters are presented: axial load on the bit, rotational speed of the drilling tool, cleaning agent flow, rate of penetration.

Keywords: drilling parameters, operational control, equivalent circulation density (ECD), well flushing, axial load on bit, extended reach drilling (ERD)

ОПЕРАТИВЕН КОНТРОЛ И УПРАВЛЕНИЕ НА ПАРАМЕТРИТЕ НА СОНДИРАНЕ КАТО СРЕДСТВО ЗА ЕФЕКТИВНО НАСОЧЕНО И РАЗШИРЕНО ВЕРТИКАЛНО СОНДИРАНЕ

Вячеслав Кадочников

Санктпетербургски минен университет, 199106 Санкт Петербург

РЕЗЮМЕ. Всяка година обемите на сондажи със сложни траектории се увеличават, а вертикалните сондажи успешно се заменят от насочени сондажи с големи отпадъци от вертикалните сондажи (сондиране с разширен обхват). Трудните траектории съдържат няколко секции с промени в ъглите на зенита и азимута. Сондажният комплект е в сложно, деформирано от напрежението, състояние, в резултат на което инструментът се приземява и затяга, както и има риск от загубване на здравината на елементите му. Трябва да се отбележи, че промяна в геометрията на сондажния комплект, при наличието на критични ъгли на траекторията, определя сондажния разтвор (образуване на шламова подложка) и промяната в еквивалентната циркулираща плътност (ЕЦП). Докладът обосновава необходимостта от оперативен контрол и управление на параметрите на сондажа с цел предотвратяване на аварийни ситуации в него, особено при сондиране в малък диапазон на абсорбционно и разрушително налягане. Представени са резултатите от многофакторния изчислителен експеримент: зависимостта на хидродинамичното налягане в кладенеца от консумацията на промивката и от скоростта на проникване. Представени са принципът за определяне на действителното осово натоварване върху короната и алгоритъмът за оперативен контрол и управление на параметрите на сондиране: осово натоварване върху короната, скорост на въртене на сондажния инструмент, дебит на промивката, скорост на проникване.

Ключови думи: параметри на сондирането, оперативен контрол, еквивалентна циркулационна плътност (ЕЦП), промиване на сондажите, осево натоварване върху короната, разширено вертикално сондиране (РВС)

Introduction

The reliability and the highest productivity of the equipment in the well is achieved by monitoring and managing the basic drilling parameters, including the axial load on the bit, the tool's speed rotation and the mud flow rate. Analysis of directional wells drilling data showed that the drilling of complex trajectories (wells with a deviation from the vertical of more than 3000 m) is accompanied by a 25 to 30% likelihood of tool puffs and landings. These complications are caused by the uncontrollable nature of the drill string's stress-deformed state when an axial load is applied to the rock-breaking tool. This, taking into account the hydrodynamics of flushing of wells, leads to the twists-off and breaks of the drill string elements, differential sticking and kick.

Significance of equivalent circulation density's control

Today, in drilling complex intervals in directional drilling, rotary-steerable systems (RSS) are widespread. These systems allow to post the well profile closest to the design (smoother, with minimal waviness and helicity), and also significantly reduce the likelihood of tool sticking due to the high penetration rate with a constant rotation of the drill string (Dvoynikov et al., 2017). However, it is impossible to completely solve the problem of differential sticking using only the RSS. The main cause of this type of complications is the uncontrollability of the pressure in the annulus, which is determined by the equivalent circulating density (ECD) of the mud. Downhole pressure is determined by the hydrostatic and hydrodynamic pressure during circulation in the annulus, and/or the impulse pressures created by the movement of pipes in the well. The ECD consists of the equivalent static density (ESD) and the equivalent dynamic density (EDD) of the mud (1–4):

$$\rho_{ECD} = \rho_{ESD} + \rho_{EDD} \quad (1)$$

$$\rho_{ECD} = \frac{P_{bot}}{g \cdot H} + \frac{\Delta P_{bot}}{g \cdot H} \quad (2)$$

$$\Delta P_{bot} = \lambda \frac{\upsilon^2 \cdot \rho_{mud}}{D - d} L \quad (3)$$

$$Re = \frac{\upsilon \cdot D \cdot \rho_{mud}}{\mu} \quad (4)$$

where ρ_{ESD} and ρ_{EDD} – equivalent static and dynamic densities, respectively, kg/m^3; P_{bot} – bottom-hole pressure, MPa; ΔP_{bot} – pressure loss in the annular space, MPa; g – acceleration of gravity, m/s^2; H – vertical depth, m; λ – hydraulic resistance coefficient; υ – mud flow rate m/s; ρ_{mud} – mud density, kg/m^3; D – borehole diameter, m; d – bottom-hole assembly diameter, m; L – well length, m; Re - Reynolds criterion; μ - plastic viscosity, Pa·s (Makovey, 1986).

In fact, EDD, which depends on the hydraulic friction, is the mud density in the annular space and increases as the number of particles of drilled-cuttings in the annulus increases. This leads to a change in the density of the drilling fluid, and as a result, its rheological properties.

The problems of pressure regulation in the well are directly connected to the ECD, which is significantly higher in wells with large zenith angles and extended reach wells. The change in the ECD depending on the change in the wellbore length is considered (Fig. 1, Table 1).

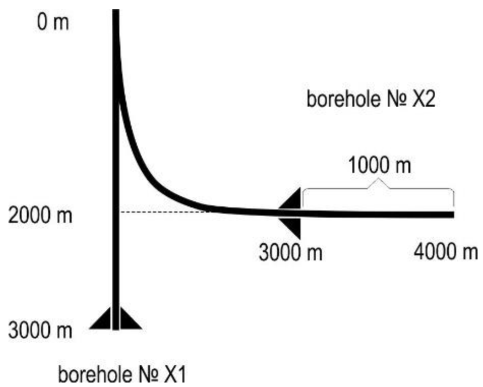

Fig. 1. ECD comparison in wells X1 and X2

Table 1. *Input data*

Parameter	Unit	Value
Mud density	kg/m^3	1200
Diameter of a bit	mm	220
Diameter of BHA	mm	120
Hydraulic resistance coefficient	-	0.02
Flow rate	m/s	1.2
Length of well X1	m	3000
Vertical depth of well X1	m	3000
Length of well X2	m	4000
Vertical depth of well X2	m	2000

The results showed that the ECD in well No. X1 is 1218 kg/m^3, and in well No. X2, 1235 kg/m^3. The ECD difference was 17 kg/m^3. It can be said that, the increasing of the well length along the trunk by 1000 m, while decreasing the vertical component by the same amount, leads to an increase in the ECD by 50% due to changes in the hydrodynamic environment. However, Figure 1 does not show changes in ECD associated with the complexity of interpreting processes at the bottom of a well like accumulation of drilled-cuttings, changes in pressure as a result of pipe movement (swab /surge).

To measure ECD and solve the difficulties associated with determining the pressure in the bottom-hole zone, an APWD (annular pressure while drilling) sensor is installed in the bottom-hole assembly (BHA), which provides the driller with real-time pressure information. However, it does not show reliable ECD values, as it is installed in the MWD measurement module (measurement while drilling), above the stabilizer located at least 10–20 m from the bit (Fig. 2). Its distance from the bit may underestimate the value of the ECD, while at the bottom of the hole the actual value may be significantly higher than that measured by the sensor.

The disadvantages of this measuring device include:

• The APDW sensor is not a reliable indicator of well cleaning during ERD;

• The APDW sensor detects ECD with a small amount of suspended drilled-cuttings;

• The APDW sensor does not detect a layer of drilled-cuttings deposited on the bottom wall of the well.

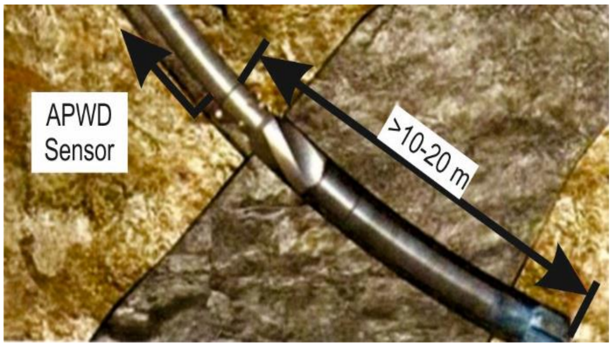

Fig. 2. APWD Sensor position in BHA

It is especially important for the driller to know the reliable value of the ECD and quickly regulate it at the bottom-hole not only during the drilling process, but also during tripping. The traditional method of drilling involves stopping the circulation, and the prolonged absence of circulation at the bottom-hole entails sticking of particles of drilled-cuttings onto the BHA elements and leads to sticking. Abrupt changes in ECD with a narrow range of mud density's acceptable values can lead to mud absorption or, conversely, to the manifestation of formation fluid, which would result in hydraulic fracturing or kick, respectively (Dolgopol'skiy, 2014; Cunningham et al., 2014).

It should be noted that the rate of penetration (ROP) is one of the main factors in determining and controlling ECD. This is because, the faster the rock destruction process, the bigger the amount of drilled-cuttings formed per unit time. Since the mechanical drilling speed is a function of tool rotational speed and axial load on the bit (5), determining the optimal drilling parameters is the primary task for an efficient and trouble-free well construction process.

$$ROP = f(G; n) \qquad (5)$$

where ROP – rate of penetration, m/h; G – axial load on the bit, t; n – tool frequency, rpm.

Control of equivalent circulation density

To determine the reliable value of EDS, a mathematical simulation of the flow of drilling in an inclined well was performed. To conduct a multifactor computational experiment, the drilling process of a J-shaped profile was modelled. The input data and the scheme are presented in Table 2 and in Figure 3.

Table 2. *Input data*

Parameter	Unit	Value
construction		
Measured depth (MD)	m	3000
Length of vertical section	m	1500
Radius of curvature	m	300
Length of slope part	m	1200
Angle of slope part	degree	45
tool		
Length of drill pipes	m	2920
Length of BHA	m	80
Diameter of drill pipes	mm	127
Diameter of BHA	mm	152
Diameter of bit	mm	216
mud		
Density	kg/m³	1050
Plastic Viscosity	mPa·s	30
other		
Rock density	kg/m³	2100
Diameter of particles	mm	3
ROP	m/h	50
Fracturing pressure (over static)	MPa	2

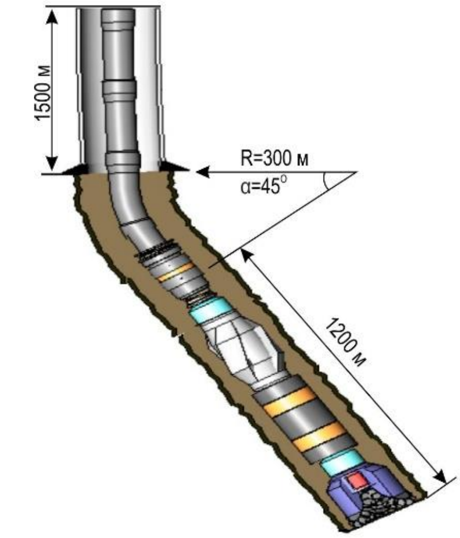

Fig. 3. Well profile and scheme of BHA

As a result of a multifactor computational experiment in the mathematical environment MathCad (Kudryavcev, 2005) the dependence (Fig. 4) of the change in the hydrodynamic pressure in the well on the mud flow was obtained at constant ROP – 50 m/h.

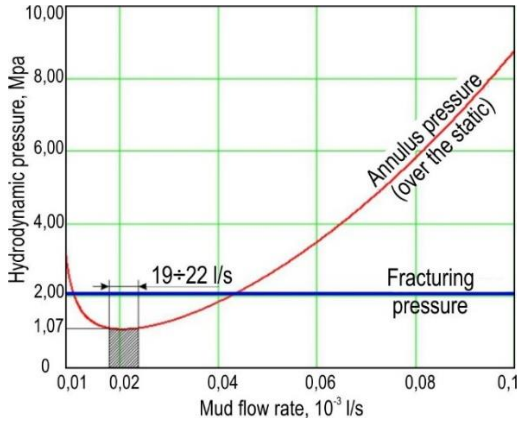

Fig. 4. The dependence of the hydrodynamic pressure (over the static) on the mud flow rate

This model takes into account the trajectory of the well, the sedimentation rate of the particles of the cuttings, the rheological properties of the cleaning agent, the ROP and the pressure due to hydraulic friction.

This dependence reflects the change in pressure with increasing flow rate of the cleaning agent from 9 l/s to 100 l/s and with the available upper limit of the hydraulic fracturing pressure at 2 MPa (over hydrostatics). The optimum flow rate at which the pressure drop is minimal, which is very important with a narrow window of absorption and fracturing pressures, ranges between 19–22 l/s.

When calculating the well pressure, pressure loss due to hydraulic friction and additional pressure caused by an increase in mud density due to drilled-cuttings accumulation were taken into account. To calculate the density of drilling mud with particles of drilled-cuttings at different intervals of the projected profile, the Moore correlation was adapted (Fig. 5). Preston Moore proposed a technique for calculating the sliding velocity of particles, taking into account the non-Newtonian behaviour of the drilling fluid, using the equation of the drag coefficient and the Reynolds number equation for spherical bodies during the deposition of particles through a non-Newtonian fluid (Sample, Bourgoyne, 1977).

```
CuttingsNACL :=          | for n ∈ 8..x
(Q, alpha, rop,          |   Vl ← 4Q / (π·(DLo[n,3])^2 − π·(DLo[n,1])^2)
rol, mul, Vmeh, x)       |   dp ← 10·10^−3
                         |   Up1 ← Uplam(rop, rol, dp, mul)
                         |   Up2 ← Uptrans(rop, rol, dp, mul)
                         |   Up3 ← Upturb(rop, rol, dp)
                         |   Up ← Up3
                         |   Up ← Up2  if  Rep(Up2, dp, mul) < 300
                         |   Up ← Up1  if  Rep(Up1, dp, mul) < 3
                         |   Up ← Up·cos((alpha/180)·π)
                         |   Vo ← Vmeh / 3600
                         |   Hp ← Vo / (Vl − Up + Vo)
                         |   ROM ← rop·Hp + rol·(1 − Hp)
                         |   Cut[n−1,0] ← Vl
                         |   Cut[n−1,1] ← Vl − Up
                         |   Cut[n−1,2] ← ROM
                         | Cut
```

Fig. 5. Part of the software algorithm (Mathcad) for calculating the sedimentation rate of sludge particles

If we reconstruct the resulting graph of pressure change versus flow rate and obtain the dependence of the EDS change on the flow rate, then at a constant mechanical speed and a selected flow range of 19–22 l/s (when the pressure drop is minimal), the increase to the ECD value is 47 kg/m³. The obtained dependence is similar to the graph of the drilled-cuttings transportation model (Fig. 6) presented in the article "Using downhole annular pressure measurements to improve drilling performance" (Aldred, 1998).

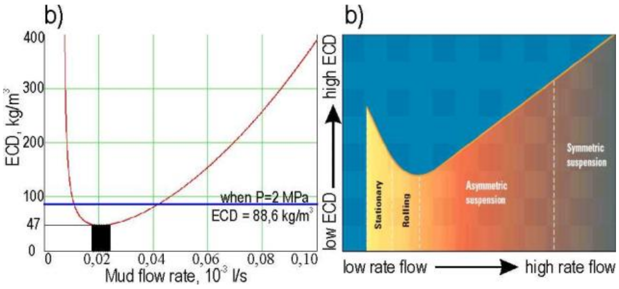

Fig. 6. The dependence of the ECD from the mud flow rate: a) received model; b) Schlumberger model

In Figure 6, it can be noticed that at low flow rates, drilled-cuttings can be deposited from the suspended state on the bottom wall of the wellbore, forming a slurry bed. The reduction of the annular space entails an increase in the ECD. With increasing mud flow, the particles of the drilled-cuttings begin to roll along the wellbore, destroying the cutting bed. Due to the partial destruction of the precipitated drilled-cuttings, the annular gap increases and the ECD begins to decrease. As the flow rate increases, most of the drilled-cuttings are transported along the bottom wall of the wellbore, with some particles being weighed in the fluid flow over the cutting bed (asymmetric suspension), which leads to an increase in ECD. At higher mud flow rates, pressure losses are significant due to viscous friction forces, and the drilled-cuttings are completely transferred to the fast-moving fluid (symmetrical suspension) (Walt, 1998).

Considering the drilling experience of Schlumberger, the similarity of the drilled-cuttings transportation model graphics and the dependence of pressure change with increasing cleaning agent consumption justifies the reliability of the model.

Figure 7 shows the graphs of pressure as a function of drilling fluid flow at various ROP. In accordance with the developed model, at a drilling rate of 15 m/h, the optimal mud flow rate (at which the pressure drop is minimal) is in the range of 13–18 l/s, at 30 m/h – 16–19 l/s and at 50 m/h – 19–22 l/s.

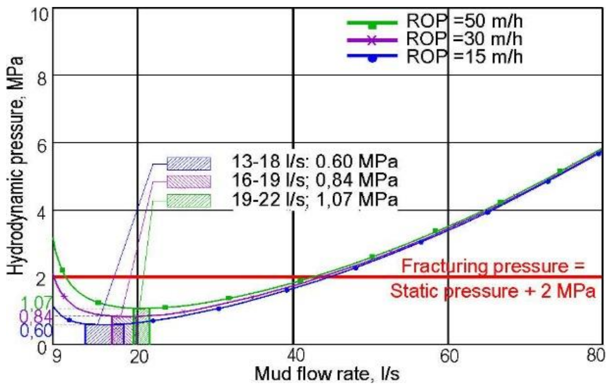

Fig. 7. Optimal mud flow rate (pressure drop is minimal) at various ROP

In the course of the simulation, the dependence of pressure on the ROP, with a constant value of the mud flow rate (Fig. 8), was determined. It can be seen from the graphs that only at low flow rates – 10 l/s, tg α ≈ 1 (α ≈ 45˚), which corresponds to a high intensity of pressure, increases with increasing the ROP.

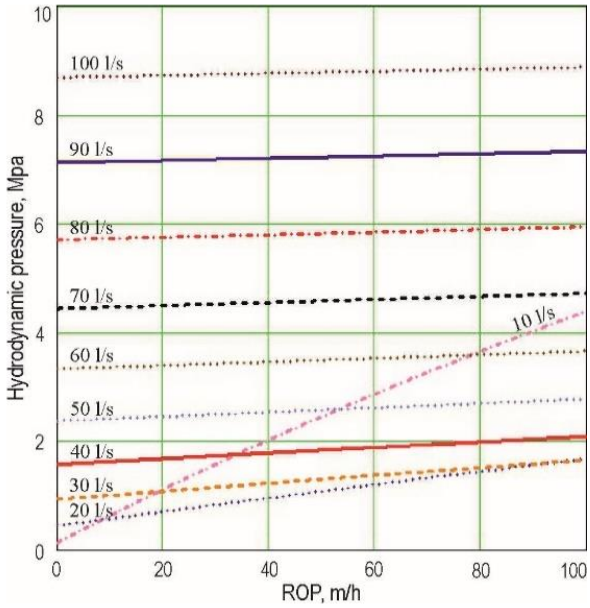

Fig. 8. The dependence of hydrodynamic pressure on ROP constant mud flow rate

An increase in the drilling mud consumption results in a decrease in *tan α* and the graph will take a flatter form. Hence, we can conclude that with increasing flow rate, the ROP has a far lesser effect on the pressure drop in the well. Further, the ROP completely loses its meaning, due to incompatibility with the drilling conditions, and the function takes the form (6):

$$P = f(ROP) \rightarrow const \qquad (6)$$

The resulting hydraulic model allows you to control the ECD in the bottom-hole zone by determining the optimal flow rate of the drilling fluid. However, for trouble-free well construction, in addition to effective flushing, it is also necessary to regulate the axial load on the bit and the rotational speed of the drill string.

Control of axial load on the bit

Analysis of practical data from drilling wells with a complex profile showed that the actual axial load on the bit differs significantly from the load measured at the geotechnical well testing (GWT) station. As a result, when drilling wells, the rate of penetration decreases, and the wellbore is formed with large cavities and grooves that impede the advancement of the BHA. Also, the intensity of the curvature and the radius of the build-up/drop off sections does not correspond to the permissible strength characteristics of the drill pipe. It is practically impossible to drill such areas using, for example, a hydraulic downhole drilling motor (DDM). This is primarily due to the large friction between the drill string and rocks. As a technological method of improving the efficiency of drilling with

DDM, while drilling oblique-rectilinear sections of the well, the drillers use the simultaneous periodic or constant rotation of the drill string with a rotor or with a top drive. Drillers call this method combined. Its use allows drilling wells of various depths with different types of profiles, a wide range of changes in the type and properties of drilling fluids, drilling mode parameters, as well as using different designs and sizes of rock-cutting tools (Dvoynikov et al., 2018).

The most effective technical solution of the problem aimed at improving the quality of the implementation of the project well trajectories and controlling the actual load on the bit is the use of displacement of the drill string relative to the axis of the well, the moment of resistance to friction of the drill string against the borehole wall, taking into account the loss of stability, as well as the tool rigidity when changing its stress-deformed state in the calculations of parameters.

The axial load on the GWT station is determined only by the change (loss) of the weight on the rig hook in terms of hydraulic weight indicator (7):

$$G_{GWT} = G_{hook} - G_{bit} \qquad (7)$$

where G_{hook} – drill string weight on hook, N; G_{bit} – load on the bit, N.

Moreover, the actual axial load on the bit, taking into account the stress-strain state of the drill string, is determined by the formula (8) (Dvoynikov et al., 2018):

$$G_{fact} = G_{GWT} - \left[\frac{(M_{rw} - M_{ri}) \cdot ROP}{\omega \cdot \pi \cdot D \cdot a}\right] \qquad (8)$$

where M_{rw} – moment on rotor in DDM operating mode, N·m; M_{ri} – moment on rotor in DDM idle mode, N·m; D – borehole diameter, m; ROP – rate of penetration (mechanical drilling speed), m/s; ω – the frequency of drill string rotation relative to the borehole wall, rad/s; a - displacement indicator (movement of drill string along the well axis), m.

$$a = \frac{\pi^4 \cdot f^2}{t} \qquad (9)$$

Where f – the gap between drill string and wall of the well, m; t – pipe helix pitch with respect to the well axis in 2π, m.

$$t = \sqrt{\frac{4\pi \cdot EI}{G_{GWT}}} \qquad (10)$$

where E – Young's modulus, Pa; I – drill string's polar moment of inertia, m.

The implementation was carried out using the example of drilling a section for stabilising the zenith angle using drill pipes with a diameter of 127 mm and a bit with a diameter of 215 mm. The ROP varied in the range from 20 to 28 m/h. Immediately before drilling, the following parameters were calculated: the rotational speed of the drill string; moments on the rotor in idle and operating modes of the DDM; displacement rate and the helix pitch of the drill string with respect to the well axis over 2π (Dvoynikov, 2018).

The difference of the moments on the rotor when the DDM operates in the idle mode and the operating mode is 5 kN·m, with measured Mrb= 5 kN·m, Mrw = 10 kN·m. The drill string's rotational speed relative to the borehole wall varies from 5.3 to 14.1 rad/s (with rotation from 30 to 80 rpm). The displacement of drill string with respect to the borehole axis a is $3.48 \cdot 10^{-3}$ m. The helix pitch of the drill string with respect to the well axis is 54.2 m. The axial load on the bit according to the GWT station is 10 kN.

Analysis of the results showed that the value of the actual load on the bit does not coincide with the value of the load on the bit at the GWT station (Fig. 9).

With a drill string's rotational speed of 5.1 rad/s (30 rpm) the load on the bit does not reach amounts to 7.8 kN. With increasing RPM to 14.1 rad/s (80 rpm) the load on the bit increases and is 9.2 kN (Dvoynikov et al., 2018).

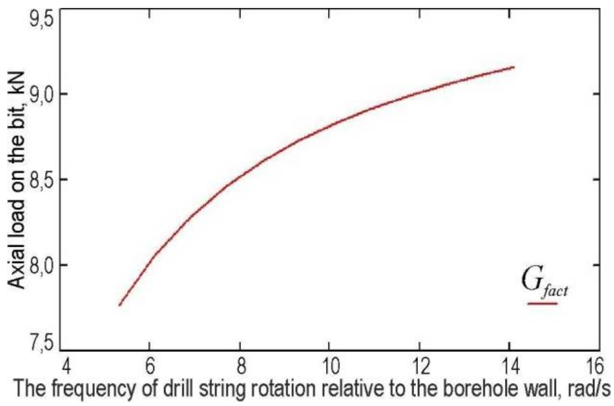

Fig. 9. Determination of the actual axial load on the bit

Algorithm of drilling parameters operational control

Knowing the axial load on the bit and the mechanical drilling rate, according to the data of the GWT station, the actual axial load reaching the bottom (with the available rotational speed of the drill string) is calculated using the formula (8).

The value of the mechanical speed, taking into account a certain actual load on the bit, is used when calculating the hydraulic programme, which allows controlling the ECD, maintaining the optimal mud flow rate. The algorithm of the programme is presented in Figure10.

In case of incompatibility of the drilling conditions, when there is likelihood of a hydraulic fracturing or kick, it is necessary to reduce (increase) the mechanical drilling speed, and the axial load reaching the bottomhole is achieved by adjusting the rotational speed of the drill string.

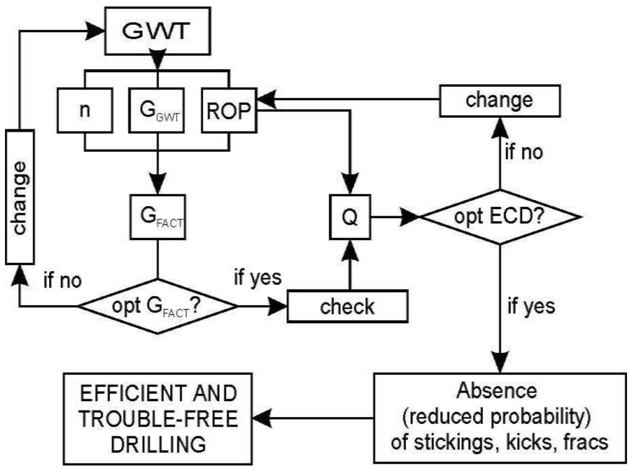

Fig. 10. Algorithm of operational control and management of drilling parameters

Conclusion

The resulting EDS control model takes into account well trajectory, sedimentation rate of particles of drilled-cuttings, mud rheological properties, ROP, pressure loss due to hydraulic friction and additional pressure caused by an increase in mud density due to cuttings accumulation. The similarity of the hydraulic model with the Schlumberger drilled-cuttings transport model justifies the correctness of the model.

However, for trouble-free drilling, it's necessary to regulate the axial load on the bit and the rotation frequency of drill string, in addition to effective flushing. This is achieved through the implementation of the method of controlling the axial load on the bit. The distinctive feature of the method involves the use of parameters like displacement indicator, moment of friction resistance and tool rigidity in the calculations.

The algorithm presented in the paper is a scheme for operational selection of optimal drilling parameters. This scheme is simplified and requires input of more factors.

The implementation of operational control and monitoring of the actual load on the bit, taking into account the rotational speed of the drill string, with insufficient speed and quality of signal transmission through the hydraulic communication channel from the telemetry system, allows us to predict ROP, to regulate the ECD, and also it preserves the reservoir properties and prevents problems in the well.

Acknowledgements. The author gratefully acknowledges the mentoring of the scientific supervisor Mikhail Dvoynikov, the recommendations of Dmitry Vodorezov in computer modelling, and the support of Daniel Edem Tsikplornu.

References

Aldred, W. 1998. Using downhole annular pressure measurements to improving drilling performance. – *Oilfield Review,* 40–55.

Cunningham, J., R. K. Bansal, G. George, E. De Leos. 2014. A New Continuous Flow System (CFS) for Managed Pressure Drilling. – *IADC/SPE Drilling conference and exhibition*, 7 p.

Dolgopol'skiy, A. L. 2014. Sistema neprerivnoy cirkulyacii dlya bureniya s kontrolem davleniya. – *Inzhenernaya Praktika*, *9*, 32–34 (in Russian).

Dvoynikov, M. V., P. A. Blinov, V. G. Kadochnikov. 2018. Sposob kontrolya osevoy nagruzki na doloto pri burenii naklonno napravlennih skvazhin vintovim zaboynim dvigatelem. – *The patent of Russia № 2646651 RU, E 21B 44/02, Byul. 7* (in Russian with English abstract).

Dvoynikov, M. V., V. G. Kadochnikov, A. A. Kunshin. 2017. Programmno-informitsionnoe soprovozhdenie stroitel'stva skvazhin arkticheskogo shelfa. – *Inzhener-neftyanik*, *1*, 23–28 (in Russian with English abstract).

Kudryavcev, E. M. 2005. MathCad 11. *Polnoe rukovodstvo po russkoy versii*. DMK Press, Moscow, 592 p. (in Russian)

Makovey, N. 1986. *Gidravlika bureniya*. Nedra, Moscow, 536 p. (translation from Romanian to Russian)

Sample, K. J., A. T. Bourgoyne. 1977. An experimental evaluation of correlations used for predicting cutting slip velocity. – *SPE Annual fall technical conference and exhibition*, 15 p.