Development of scientific and methodical approaches to the optimization of drilling deep wells

V M Spasibov and V V Kozlov
Industrial University of Tyumen, 38 Volodarskogo st., Tyumen, 625000, Russia
E-mail: spasvm@tsogu.ru

Abstract: When optimizing the construction of oil wells, it is economically expedient to search for optimal control over the process of deepening. An important role for operational management is the creation of a mathematical model of the process. The task was to develop a model of the deepening process (MDP) based on the analysis of the amount of energy transferred to the bottom of the well and spent on the destruction of the rock, on the basis of which it is possible to obtain particular acceptable models for optimizing the process of managing the well deepening technology.

1. Introduction
There is a lot of research on improving the structure of the well deepening management system (WDMS) with an emphasis on the "system approach" [1,2,3], with the creation of a global management system that is formed out of independent private systems - subsystems.

The main types of work in the implementation of the method for deepening the wells are shown in Figure 1.

The implementation of each type of work, presented in Figure 1, is associated with a diverse complex of tasks that are often functionally unrelated, and which differ significantly in rotary and turbine drilling.

Obviously, the creation of a global management system leads to the need for creating complex, cumbersome, difficult-to-implement process control systems (PCS). At the same time, the diversity of processes, as well as their autonomy, make the creation of a single mathematical model for the construction of a well not only an extremely complex but also an inexpedient direction. Such a model cannot be used for operational control, so the decomposition of tasks and control systems is necessary.
Figure 1. Scheme of work for the implementation of the method of deepening wells.

In the construction of the well, the main costs are associated with the deepening, which include the costs of washing and about a third of the cost of equipment, materials, pipes, which is more than 40% of the total cost of construction and more than 50% of the time consumption. Therefore, in the system approach to solving the optimization problem, it is economically expedient to control the deepening process. Moreover, deepening only to the productive horizon when drilling with a circle-shaped bottom with a three-cone bit, with the wear-out of its supports earlier than of its cutting structure. The greatest difficulty in optimization is precisely the deepening of the well with a great influence of external both controlled and uncontrolled factors and the most complex mathematical description, and not the descent of the column with its cementing and other well construction processes.

2. Research
The first task that requires a solution is the development of a mathematical model for managing the deepening process - MMDP for turbine drilling. The MMDP should reflect the main patterns of rock destruction, preferably of a generalized nature, taking into account the interaction of the elements of the drilling tool, especially in dynamics, hence its structure should be created on the basis of the mathematical model of the well deepening process - MDP, to meet the drilling and drilling rig conditions, to have as short shape as possible, accessible and convenient for the operational management of the well deepening.
3. Results and discussion

3.1. Creating a model for the well construction
In order to develop a model of the deepening process, we outline the main links of the drilling process (Figure 2). At the mouth 5: 1 - drilling mode parameters controlled from the mouth; 2 - physical and mechanical properties of rocks; 3 - technical and technological parameters and mechanisms designed before drilling a well; 4 - destabilizing factors, the manifestation of which is possible during the deepening of the well; 6 - control device - controller; 7 - the operator.

At the cone base, the following things are reflected: $\delta_z$ - the magnitude of deformation of the rock with allowance for the number of bit teeth that are in simultaneous force contact with the bottom $K_z$; $\tau_K$ - contact time; $F_K^*$ - the area of contact between the tooth and the rock by the end of $\tau_K$; $K_P$ - number of hole coverages by drilling bit cutting structure per unit of time. These are the factors determining the speed of the deepening of the well $V$ ($V^*$ - the rate of penetration, fixed at the mouth), the work of the entire drilling tool and the effectiveness of the structure of the control system.

In the enlarged form, as follows from Figure 2, the system consists of two main parts: a ground - control device (6,7) and a drilling tool (drill string, BHM, bit) - a controlled object. The control device performs the functions of measuring, displaying information - the parameters of the drilling mode, including from the bottom of the well, developing, in accordance with certain algorithms, control commands and providing, in accordance with them, the drill string supply by means of an operator. Moreover, according to the corresponding program, the necessary parameters of the washing liquid are set: flow rate, pressure, viscosity, density ($Q_{ZH}, P_{ZH}, \eta_{ZH}, \rho_{ZH}$).

The control object provides the required axial load on the bottom and carries out well deepening. The functions of the controlled organ are performed by a bit, and ultimately a bit tooth, which forms $\delta_z$, $\tau_K$, $K_n$, and hence $V^*$ by means of the axial load. The control system should work in accordance with the adequately reflecting conditions and the specifics of the method of drilling a well by a mathematical model of control over the process of borehole wiring and, first of all, by the model of the deepening process (MDP).

The output parameters considered in Figure 2 depend on the power that the turbo-drill can achieve at a given flow rate of the washing liquid $Q$ and the value of the axial load on the bottomhole - $P_3$ (or...
on the bit P). Parameters Q and P are independent control factors. However, the smooth regulation of the flow rate of the washing liquid presents significant difficulties (the need for frequency converters), therefore for turbine drilling P remains the main control action on the controlled body. The change in P is realized by feeding the upper part of the drill string (UP) to the bottom, while the speed of lowering the UP between the feeds is measured by V*. Naturally, the characters of changes of V* and V are different but with the elimination of errors in the measurement of V*, associated with the vibrations of UP, etc. V* = V.

The speed of drilling progress V, with the same rock for the same type of bit, is determined by δ1 – the deepening of the rock-breaking bit's tooth top into the rock, which depends on the area Fk, the number of hole coverages with the cutting structure of the bit - Kn and the contact time of the bit tooth with the rock Tk. At the same time, the value δ1 also depends on several basic parameters:

\[ \delta_1 = f(P; a_p; K_r), \]

where \( a_p \) - rigidity of the rock; \( K_r \) - the number of teeth of the bit being in simultaneous force contact with the bottom.

The value \( \delta_1 \) can be determined in accordance with the kinematics of the bit and the dynamics of the drill string [1,4,5]

\[ \delta_1 = r \cdot (\cos \omega_{\delta k} t - \cos \pi z) - U, \]

where \( r, \omega_{\delta k} \) – the radius of the bit cutter and the frequency of its rotation; \( z \) - number of teeth on peripheral crown of a cutter; \( U \) - displacement in a column during vibration process in it.

However, according to the results of many studies [5,6,7,8,9] it was not possible to obtain the calculated value of U, acceptable for its introduction into the MMDP. Moreover, it is difficult to determine the quantities entering the expressions in the process of deepening the well, so it is obvious that \( \delta_1 \) is not desirable to be left in the design expression of the MMDP.

3.2. Developing a model of the well deepening process

In the work, the task was solved of developing a model of MDP, on the basis of which it is possible to obtain particular acceptable models for optimizing the process of control of the technology of the well deepening.

The rate of well deepening depends on the amount of energy transferred to the bottom and spent on the destruction of the rock. In connection with this, MDP should be built on the basis of this universal physical parameter with the use of its derivative - power - \( N_i \). It is desirable that the basis of the MDP is the power consumed for the destruction of rocks \( (N_p) \), and during drilling it is possible to adjust the rate of well deepening using the components \( N_i \), which is important in the operational management of the well deepening process.

On the basis of the analysis of [1, 2, 5, 8], the type of MDP was chosen, which in general form is represented as

\[ N_p = \frac{p_p \delta_1 K_r}{\tau_{MD}}, \]

(3)

When drilling with the BHM, it is difficult to control only the \( N_p \), since the power of the turbodrill - \( N_T \) is also expended on other processes occurring at the bottom of the wells, i.e. all key components of \( N_p \) should be present in the MDP.

The power spent on the bit operation can be determined according to the recommendation of V.S. Fedorov [5]:

\[ N_i = \frac{1}{n_t} \left( N_{p1} + N_h + 1.8 N_T \right) + N_{B_T} + N_T, \]

(4)

where \( n_t \) - coefficient that takes into account the power costs in the bit support and for the grinding of the rock particles at the bottom of the well; \( N_{p1}, N_h, N_T \) - the powers spent on the rock destruction, the raising of a part of the drilling tool with the weight \( G \) "due to the tooth surface of the cutters" and the friction of the teeth of cutters on the bottom of the well; \( N_{B_T}, N_T \) - powers for friction of the bit on the borehole wall and in the drilling fluid.
However, not all components of $N_i$ are expended simultaneously, for example, the $N_p$ and $N_h$ powers are expended in different half-periods of the axial tooth vibrations of the bit.

Figure 3 shows the change in the amplitude of such bit vibrations in time $h_3 = f(t)$ and half-periods of such vibrations: $T_1 = \tau_{md} + \tau_m$ – when the tooth of the bit is pressed into the rock during the time $\tau_{md}$, and during the time $\tau_m$ – comes out of the indentation hole; $T_2 \cong T_H$, as it is assumed for an undeformable bottom.

Naturally, this form of vibration (or the pattern of interaction between the tooth and the bit) during the destruction of the bottom varies somewhat depending on the properties of the rock and other factors, but in the first approximation such a scheme can be adopted.

As a result of the research it was found out that the hydraulic power of the turbodrill (except for the costs in the engine itself) is consumed in various ways in each half-cycle of the axial tooth vibrations of the bit (Figure 4).

One of the differences is due to the fact that during $T_1$, the main part of the power – $N_p$ under the influence of the axial load on the bit $P$, consisting of the static part $P_C$ and the dynamic part $P_D$, is expended on the direct destruction of the rock, whereas during $T_2$, $N_{DP}$ power supplied to the bottom face, is realized mainly on the friction of the working surface of the bit on the rock under the force $P_C$. The other differences can be seen in Figure 4.

In accordance with the above-mentioned characteristics of $N_{TG}$, the components of this power are calculated in the course of turbine drilling of wells.

![Figure 3. Scheme of amplitude variation of axial tooth vibrations of the bit and power costs $N_{rH}$ during $T_1$ and $T_2$.](image-url)
Figure 4. The scheme of the power consumption of the drilling pumps during the period $T$ of axial tooth vibrations of the bit: $N_{gh}$ – drilling pump power; $N_{mg}$ – hydraulic power of the downhole motor expended in the half-periods $T_1$ and $T_2$ in time $t = T$; $N_p, N_{up}, N_{tp}$ – the power consumed for direct rock destruction, elastic interaction of the bit and the drill string with the bottom, and the friction of the bit on the borehole wall, in the axial and radial engine supports, during the operation of calibrators connected to the motor shaft, etc. $N_{dp}$ – power supplied from the engine to the bottom of the well (not taking into account $a N_{f1}$); $N_{f1}$ – power used to restore the moment of inertia of the rotor of the BHM; $N_{g}$ – part of $N_{ghi}$, spent on the destruction of the rock at the bottom of the well and its purification $N_{do}$, on energy dissipation in the flow of the fluid under vibrations $N_{gm}$, on the hydro-resistances $N_{rc}$.

The accepted scheme of expenses $N_i$ allows obtaining MDP of various completeness with an output to the resulting parameters: a deepening (elastic deformation) for one tooth-bottom interaction – $\delta_1$, penetration per one bit rotation, mechanical penetration rate $V$, or penetration per one spudding drilling.

Below we propose a procedure for obtaining MDP, on the basis of which it is not difficult to create a MMDP without an abundance of hard-to-determine coefficients.

In accordance with the adopted cost scheme $N_i$, we give the main expressions and calculate the necessary components $N_{tg}$:

- $N_{up}$ – the total power that returns to the drilling tool when the axial load is removed from the bottom, and is spent on the dispersion in the rock ($N_{pc}$) and the drilling tool (in the drill string – $N_K$)

$$N_{up} \equiv N_{pc} + N_K.$$ (5)

Power $N_{up}$ is determined by the elastic properties of the bottom and tools; $N_{tp}$ – half the power spent on friction of the bit on the borehole wall and the washing liquid, in the elements and mechanisms of the turbodrill (in the axial and radial supports, etc.),

$$N_{tp} = 2 \cdot N_{tp}.$$ (6)

$N_{dp}$ – The power put to the well bottom at the time $T_1$ and expended on the interaction between a bit's cutting structure and a bottom without its intensive destruction is defined as
\[
N_{DP} = 2\pi \cdot M_U \cdot P_C = N_{DP} + N_{J1}, \tag{7}
\]

\[
N_{DO} = N_{OCH} + N_{DP}, \tag{8}
\]

where \(M_U\) — the specific moment at work of a bit at the bottom, connected with the coefficient of friction (resistance) of its cutting structure with rock — \(\mu_{GP}\); \(N_{OCH}\), \(N_{DP}\) — the cost of power for cleaning the bottom of the well and for its destruction by a jet of fluid leaving the bit nozzles; \(N_{GC}\), \(N_{GM}\) — (hydraulic) power consumed by the hydraulic resistors in the entire hydraulic tract of the drill string and borehole, as well as the formation of hydro-impulse pressure in the flow of the washing fluid under the influence of the vibrating shaft of the BHM on the flow [4,10].

Since \(N_j\) — total power to maintain the main moment of inertia of the rotating shaft of the turbodrill, equal to \(2N_{J1}\), is mainly spent on overcoming the dynamic component \(N_P(N_D)\), then \(N_j = 2 \cdot N_D\).

Since \(n\) decreases over time \(T_1\), and increases \((n_2 > n_1)\) during \(T_2\), then due to the difference \(n_1 - n_2 = \Delta n\), the turbodrill power is restored to its average value, which is constantly provided by the turbodrill.

In accordance with Figure 4, we represent the costs of the hydraulic power of the drilling pumps consumed during the time \(T_1\) and \(T_2\)

\[
\begin{align*}
N_{G1} & \equiv N_{G2}, \\
N_{G1} & = N_P + N_{UP} + N_Z, \\
N_{G2} & = N_{DP} + N_D + N_Z, \\
N_Z & = N_{TP} + N_{OCH} + N_{DP} + N_{GC} + N_{GM}. \\
\end{align*} \tag{9, 10, 11, 12}
\]

Here \(N_P\) and \(N_{PC}\) should be calculated with the total value \(P_Z\).

Applying equations (8) - (12), the model of the well deepening process can be represented in different variants and at different levels of detailing of the MP.

From expressions (9) - (12), we find

\[
\begin{align*}
N_P & = (N_{DP} + N_D) - N_{PC}, \\
N_{P, P} & = N_P + N_{UP} = N_{DP} + N_D, \\
N_{P, P} & = 2\pi \cdot M_U \cdot P_C \cdot n \quad \text{and} \quad N_D \equiv 2\pi \cdot M_U \cdot P_D \cdot n, \\
N_{PP} & = 2\pi \cdot M_U. \\
\end{align*} \tag{13, 14, 15}
\]

According to the recommendation [4,5] and our improvements, to create MDP we take expression (3) and then

\[
\begin{align*}
N_{UP} & \equiv \frac{P_C \cdot \delta_1 \cdot K_Z}{1,8 \cdot \tau_{MD}}, \\
N_{PP} & = \frac{1,5P_C \cdot \delta_1 \cdot K_Z}{\tau_{eb}}. \\
\end{align*} \tag{16, 17}
\]

In accordance with the foregoing, we obtain the expanded form of the MDP

\[
\frac{P_C \cdot K_D \cdot \delta_1 \cdot K_Z}{\tau_{MD}} = 2\pi \cdot P_C \cdot n \cdot M_U - \frac{P_C \cdot \delta_1 \cdot K_Z}{1,8 \cdot \tau_{M}}, \tag{18}
\]

where \(\delta_1\) — the value of a bit tooth indentation into the rock (usually \(\delta_1\) is equal to the value of the elastic deformation of the rock); \(K_Z\) — the number of bit teeth participating in simultaneous force contact with the bottom, as recommended in [4] \(K_Z = 3\); \(K_D\) — coefficient of dynamic effect of \(P\) on the bottom; \(\tau_{MD}, \tau_{M}\) — the time of the bit tooth indentation into the rock and exiting it from the indentation hole, and besides

\[
\tau_{MD} + \tau_{M} = T_1. \tag{19}
\]

In general, \(K_D = 1,0 - 1,5\), but on average \(K_D \leq 1,25\).

In the formula (18), the load \(P_C\) is not reduced for the convenience of the corresponding transformations and the derivation of the mathematical MMDP.

MDP by formula (18) can be converted in the required form and volume, including with acceptable accuracy for the creation of MMDP.

Let’s bring the expression (18) to a simpler form, taking \(\tau_{MD} \equiv 1,1\tau_{M}\), \(K_Z = 3\), the instantaneous radius of the bit rotation at the contact of the cutter with the bottom \(R_M = (0,55 - 0,9) R\) and using the known calculation method \(M_U\).
\[ M_U = R_M \cdot \mu_{GP} \]  

Then, on average  
\[ \delta_1 = \frac{0.97 \cdot R \cdot n \cdot \mu_{GP}}{K_D} \]  

where \( \mu_{GP} = 0.4 - 0.05 \) - coefficient of friction (resistance) of a bit cutting structure with a bottom at the upper limit of \( \mu_{GP} \) for very soft rocks, and 0.05 for rocks of type T,TK; \( R \) - bit radius.  

Time \( \tau_{MD} \) can be found in accordance with the known expression for calculating the period of axial tooth vibration of the bit with an undeformable bottom  
\[ \tau_{MD} \equiv \frac{t_Z}{2 \pi R n} \]  

where \( t_Z \) - bit cutter teeth spacing on the peripheral crown.  

From the formulas (21) and (22) we obtain  
\[ \delta_1 \equiv \frac{(7.6 \cdot 10^{-2} \cdot t_Z \cdot \mu_{GP})}{K_D} \]  

For the implementation of the presented MDP, it is necessary to have almost one order lower coefficients difficult to determine. Note that for \( Q = const \), there is no special need to operatively control the power values \( N_{TP}, N_{OCH}, N_{DP}, N_{GO}, N_{GM} \), it is enough to check them periodically.  

The MDP given include all physically understandable parameters and are simpler than those proposed, for example, in [1].

3.3. Mathematical models for managing the process of deepening wells

Expression (21) can be used as a MMDP, but it is not convenient for operational control purposes. Firstly, because of the small value of \( \delta_1 \). Secondly, because of the need to introduce \( \delta_1 \) by calculation. Thirdly, the record  
\[ \delta_1 \equiv \frac{0.97 \cdot R \cdot n \cdot \tau_{MD} \cdot \mu_{GP} \cdot P_c}{P_r + P_l} \]  

is unusual, although the meaning is clear from the diagrams and figures 3 and 4.  

Fourthly, the time \( \tau_{MD} \) is not directly controlled and is not regulated from the wellhead and this model does not reflect the number of hole coverages by the bit cutting structure \( K_p \).

At the mouth of the well, information about \( V \), and not about \( \delta_1 \) is received, then it is natural that the MDP should be presented in such a way that \( V \) in the MMDP is explicitly related to the controlled parameters. Managed parameters should be definable, and the models themselves should reflect the physical essence of the well deepening. Moreover, it is necessary to reflect the influence of the static part of the axial load on the bit in the MDP and MMDP.  

In this regard, we considered another option for obtaining MMDP. For that, we will write the equality of the specific volumetric works of rock destruction under the tooth of the bit \( A_{V_1} = A_{V_2} \) in the form  
\[ \frac{N_p}{V_c \cdot F_Z} = \frac{T_U}{V_L} \]  

Or as  
\[ \frac{P_Z \delta_1}{V_c \cdot F_Z \cdot \tau_{MD}} = \frac{P_Z \delta_1}{K_L \cdot \delta_V \cdot F_c \cdot K_p} \]  

where \( T_U, V_L \) – the energy of the tooth impact on the rock and the volume of the indent hole; \( V_c \) – average value of \( V \); \( K_L \) – coefficient, taking into account the change in the volume of the hole \( V_L \) of the destroyed rock in comparison with \( \delta_1 \cdot F_K^* \).

In studies based on processing of the commercial material of the stations of the AMDP, the validity of the value of \( K_L \) was confirmed in the range of 0.35 - 0.50 - the lower limit for hard rocks, the upper one for the type MC, M. Next, we obtain \( V_c \) with the dimension m/h, (i.e., multiplying by 3600 sec), taking into account \( K_p = K_{PO} \cdot n \),  
\[ V_c = \frac{3.6 \cdot 10^3 \cdot n \cdot \delta_1 \cdot K_{PU} \cdot F_c^* \cdot K_L}{F_3 \cdot \tau_{MD}} \]
where $K_{PO}$ - number of hole coverages by the bit teeth per one revolution.

The formula (27) must be transformed so that it clearly contains the control parameter $P_3$ and there are no parameters that need to be continuously calculated while managing the drilling.

The value of $\delta_i$ can be determined by several methods, but in any case $\delta_i \leq h_3$, which is due to the construction of the cone bits and follows from [4,5] – here $h_3$ is the amplitude of the axial tooth vibrations of the bit. We find $\delta_i$ as

\[
\delta_i = \frac{N_p T_{MD}}{P K Z},
\]

(28)

\[
N_p = (N_T - N_1),
\]

(29)

\[
\delta_i = \frac{P_3}{a_p}
\]

(30)

where $N_T$ - the power of the turbodrill, at which it is required to find $\delta_i$ ($\delta_i$ is maximum at $N_{TMAX}$); $a_p$ - rock stiffness,

\[
N_1 = N_p + N_0 + N_K + N_I + N_M + N_{UP},
\]

(31)

where $N_p, N_0, N_K$ - the frictional power in the axial support of the downhole motor, the friction of the bit on the borehole wall and the washing liquid, and also on the operation of the calibrators; $N_{UP}$ - the power consumed by the elastic interaction of the bit and the drill string with a bottom; $N_I, N_M$ - additional power costs when working of the bottom of the drilling tool on a curved well section and on the rotation of the flywheel.

By formula (31), the value $\delta_i$ can be calculated more easily, but it is more difficult to determine $a_p$ experimentally.

The error level in the calculation of $V$, as can be seen in expression (27), may depend on the values of the parameters $\tau_{MD}$ and $K_{PO}$. Therefore, consider the possibility of reducing such an error by refining the formula for calculating $K_{PO}$.

In accordance with the well-known recommendation, $K_{PO}$ is usually defined as

\[
K_{PO} = e_{SH} \cdot Z_0 \cdot R/r_{SH},
\]

(32)

where $e_{SH}, Z_0$ - the number of cutter bits and the total number of teeth on the cutter; $R, r_{SH}$ - radius of bit and crown cutter P.

The data given in [1,4,5], as well as calculations, have shown that the energy spent on the destruction of the central part of the bottom with $R_i < R_{MG}$ is almost by an order less than those spent on the destruction of the peripheral part $F_3$. Usually the average value of the instantaneous well radius $R_{MG}$ is calculated [4] within the range (0.72 - 0.55) $R$.

As a result of studies of the energy expended on the peripheral and central parts of the well bottom during turbine drilling, we obtained an expression for calculating $K_{PO}$

\[
K_{PO} \approx \frac{11,4R}{\delta_z}
\]

(33)

From formula (18) we find $R_{MD} = 0,63R$

\[
\delta_z = 2,04 \cdot \frac{n_{TMD}R_{MG}}{K Z}
\]

(34)

make a replacement

\[
F'_K = \frac{P Z}{K Z P_{SH}}, \quad F_Z = \pi \cdot R^2, K_Z = 3, K_L = 0,425.
\]

(35)

Substituting the results in (27), we obtain

\[
V_C = \frac{1,25 \cdot 10^3 P Z n^2 \mu_{GP}}{P_{SH}^2 Z}
\]

(36)

The stiffness of mining works on the $P_{SH}$ stamp can be determined in the conditions of drilling organizations according to the data of the study [5,10].

This expression can be adopted as a mathematical model for controlling the process of deepening wells.

4. Conclusion

The paper presents a method for developing a model for deepening a well MDP, in the form of a scheme for the total power of a turbodrill, in the form of an asymptotically compressed mathematical
model with the possibility of calculating the turbodrill power components consumed for a period T. The MDP reflects the parameters of the bit, drillable rocks and modal parameter \( P_Z = P_C \cdot K_D \).

The developed MDP allowed obtaining particular acceptable models for optimization of the process of control over the technology of well deepening.

References

[1] Balaba V I 2010 Ensuring the effectiveness and efficiency of drilling oil and gas wells on the basis of the system approach Thesis for a degree of Doctor of Engineering (Moscow) 318 p
[2] Aldred W et al 2012 Drilling automation Oilfield Review 2 24 pp 18-27
[3] Zamora M and Geehan T 2013 Developing Drilling Automation 14 p
[4] Lyons W, Kaoyo T and Lapeyrrouse N J 2013 Formulas and Calculations for Drilling, Production and Workover of Wells (Moscow: Premium Engineering) 344 p
[5] Fedorov V S 1991 Scientific Bases of Drilling Modes (Moscow: Gostoptekhizdat) 248 p
[6] Spasibov V and Kulyabin G A 2001 Construction of models for wells deepening management in turbine drilling Higher Educational Institutions News. Oil and Gas 6 pp 6-11
[7] Lind Yu B, Mulyakov R A and Zayrullina E I 2012 Software complex for automation of oil and gas well design Oil Industry (Moscow: Oil Industry Publishing House) 4 pp 35-8
[8] Tsuprikov A A 2015 Analysis of mathematical models of the mechanical speed of penetration to optimize the process of oil and gas wells drilling Scientific Journal of KubSAU 107 (03) pp 903-15
[9] Cheryi S G 2015 The problems of automation technological process of drilling oil and gas wells Software @ Systems 2 (110) pp 113-18
[10] Lukyanov E B and Strelchenko V V 1997 Geological and Technological Research in the Process of Drilling (Moscow: Oil and gas) 679 p