№ 1 (s) (3), 2020

УДК 681.5.015:622.24

B. Kaluzhnyi
Lviv Polytechnic National University,
Department of Electromechatronics and Computerized Electromechanical Systems,
bohdan.s.kaluzhnyi@lpnu.ua

A. Malyar
Lviv Polytechnic National University,
Department of Electromechatronics and Computerized Electromechanical Systems,
andrii.v.maliar@lpnu.ua

I. Holovach
Lviv Polytechnic National University,
Department of Electromechatronics and Computerized Electromechanical Systems,
ihor.r.holovach@lpnu.ua

DETERMINATION OF THE OPTIMAL DRILLING MODE BASED ON THE DURABILITY OF THE DRILL BIT

https://doi.org/10.23939/sepes2020.01s.001

The paper proposes one of the ways to set up an optimal mode of drilling oil and gas boreholes. The existing methods of control of the penetration rate and drill bit state were analysed. It was shown that due to incomplete and often distorted information it is difficult to perform control of the drilling process based on the mathematical model of the drill bit penetration, the solution of which is time dependencies of the penetration rate.

As while constructing the borehole, the net drilling time takes less than a half of the total time, and the rest of time is spent on auxiliary operations, the drilling speed per run was used for determining the optimal parameters of the drilling mode. Based on the analysis of the benefits and drawbacks of the methods of the drill bit state identification, it was decided to use the relative durability of the drill bit, which is invariant with respect to physico-mechanical properties of the rocks. The dependence of the drilling speed per run on the relative durability of the drill bit and other drilling parameters was derived. It was shown that such a transition makes it possible to unify the algorithm of assessing the optimal drilling speed per run, as it does not depend on the rock type and other factors. An example of calculating the maximum drilling speed per run ensuring the optimal durability of the drill bit for a selected drilling mode is presented.

Key words: borehole, drilling, well drill, durability of the drill bit, drilling speed per run.

Statement of the problem

One of the ways to ensure Ukraine’s energy security is drilling and construction of new oil and gas boreholes, using modern methods [1]. The construction of boreholes is characterized by a rapid change of situations and impact of numerous interrelated factors varying in time and space [2–5]. The modelling of this process will allow pinpointing the factors having influence on the main technical and economic indicators, establishing their relations and developing the algorithms of optimal control of borehole construction.

In a complex of technological stages of the construction of oil and gas boreholes, the most important, complicated and, at the same time, the least explored due to the lack of information is the process of the drill bit penetrating the rock (the drill bit crushing the rock), which has a significant impact on the quality of the borehole column and performance of the well rig.

The process of deepening boreholes, similarly to most technological processes, features non-stationarity and non-linearity, multidimensionality, incomplete a priori information on the correlation between the mode parameters and drilling conditions, which significantly complicates its mathematical description as an object of control. Therefore, an important task is to determine the optimal drilling speed per run, which has a direct effect on the durability of the drill bit and cost of a meter of penetration.

Analysis of the recent research

Control of borehole deepening is based on the two major models describing the interaction between the rock-crushing tool (drill bit) and the rock, namely rock crushing and drill bit wear [6,7]. They are used to form the target function and also to determine the control actions.

The mathematical models of the drill bit operation can be divided into two groups, which can be nominally named analytical and empirical [7–9].

Analytical models in most cases do not take into consideration the wear of the cutting structure and bearing of the drill bit. These models make it possible to set up the initial mode of rock crushing. To assess the weight on the bit, let us use the formula [6]

$$P = a_1 p_r F_k ,$$

where a_1 is a coefficient reflecting the effect of the bottom hole factors on the hardness of the rock; p_r is the hardness of the rock; F_k is the surface area of the contact between the drill bit and the bottom hole.

The presented mathematical model does not account for the wear of the cutting structure and bearing of the drill bit. Using this model, one can calculate the minimum weight at which the volumetric rock destruction occurs. However, this weight on the drill bit cannot be considered optimal.

In most cases, for setting up optimal drilling modes, empirical models are used [7, 8, 10], namely:

– integral models based on the integral indicators that determine the results of the run in whole;

$$H = F_1(P,\omega,Q,\theta),\ t_B = F_2(P,\omega,Q,\theta),\ t_0 = F_3(P,\omega,Q,\theta),$$

where H is the footage per run; P is the weight on the drill bit; t_0 is the bearing life; t_B is the cutting structure life; ω is the rotary speed of the bit; Q is the flow of drilling fluid; θ is the symbol denoting all the unaccounted factors (properties of the rock, properties of the drilling fluid, equipment of the drilling string, etc.)

– differential models, which rely on additional current data on the technological processes at any moment of a run

$$\frac{dh}{dt} = f_1(P,\omega,Q,\theta,D_B)\ ;\ \frac{dD_B}{dt} = f_2(P,\omega,Q,\theta,D_B)\ ;\ \frac{dD_0}{dt} = f_3(P,\omega,Q,\theta,D_B)\ , \qquad (1)$$

where dh is the instant increment of the current footage, t is the current drilling time; D_B is the state of the bit cutting structure; D_0 is the state of the bit bearing.

The models (1) enable the determination of the current drilling speed when the mode is changed within the run.

Research objectives

It should be noted that to determine the coefficients of the differential model, which offers stronger benefits as compared with other empirical models, the information on the current wear of the bit in the drilling process is required. This task has no clear-cut solution for today. In most cases, to assess the bit wear rate, the indirect method based on the reduction of the drilling penetration rate is used.

This paper shows the possibility of selecting the indicator of the speed of the penetration rate reduction, which depends on the bit wear rate.

Presentation of the main material

The penetration rate is one of the main indicators characterizing the effectiveness of the borehole deepening. Using its current value and mode of its variation during the drilling, one can determine the wear rate of the bit cutting structure and physico-mechanical properties of the rock being drilled, and use it for optimization purposes in combination with other drilling indicators.

The bit penetration is described by a differential equation proposed in [11]

$$\frac{dV_t}{dt} = -k_c V_t^n ,$$

where t is the net time of drilling with a new drill bit (the time of the bit operation in the bottom hole for invariable mode parameters); V_t is the penetration rate [12]; n is the coefficient reflecting the drilling conditions; k_c is the coefficient of the rate of reduction of the penetration rate with time (durability), which features a complex correlation with the bit design, degree of the bottom hole cleaning, physico-mechanical properties of the rock, etc. Research showed that the value of k_c for rotary drilling vary within the range from zero to $0.005 \div 0.2$.

The solution of this equation for the initial conditions t=0, V_t=V_0 is the expression

$$V_t = V_0 \left(1 + k(n-1) V_0^{n-1} \cdot t\right)^{-\frac{1}{n-1}} .$$

If n is an integer, then this equation can be presented in the following way:

$$n = 0; \qquad V_t = V_0 - k \cdot t ; \qquad (2)$$

for n=1, taking into account the features of the exponential function, we will write

$$n = 1; \qquad V_t = V_0 \cdot e^{-k \cdot t} ; \qquad (3)$$

$$n = 2; \qquad V_t = V_0 \left(1 + V_0 k \cdot t\right)^{-1} ; \qquad (4)$$

$$n = 3; \qquad V_t = V_0 \Big/ \left(1 + 2 \cdot k \cdot V_0^2 \cdot t\right)^{1/2} . \qquad (5)$$

In practice, for different conditions of the cutting structure operation, it is necessary to select a function out of the set of all the presented functions V_t (0÷3) which would describe the averaged value of the bit wear and thereby would be the closest to all possible variants of solution (2)–(5). The most widely used in the mode calculations has been the model (3) [6, 13]. It also satisfy the quality picture of the bit dulling. In this model, we can assume that the coefficient k characterizes the bit wear rate

$$k = A \cdot P^{\alpha} \cdot \omega^{\beta} ,$$

where A is the abrasion factor; P is the weight on the drill bit; ω is the rotary speed of the bit; α and β are empirical coefficients the values of which can vary in a wide range depending on specific drilling conditions and cleaning of the bottom hole: $0 \le \alpha \le 3$; $0.2 \le \beta \le 1$.

Let us introduce the expression for the drill bit durability, which is invariant with respect to the physico-mechanical properties of the rocks

$$R = \int_0^t P^{\alpha} \cdot \omega^{\beta} dt . \qquad (6)$$

In case of invariable P and ω the expression (4) will appear as

$$R = P^{\alpha} \cdot \omega^{\beta} \cdot t .$$

Then

$$k \cdot t = A \cdot R ,$$

and, respectively,

$$V_t = V_0 \cdot e^{-A \cdot R} . \tag{7}$$

The drill bit is considered worn out, i.e. its durability has been used up and $R = R_{max}$, if the rate of penetration into homogeneous rock drops to the value at which the power of the exponent in the equation (3) is $k \cdot t = 3$, which means the reduction of the rate down to $0.5V_0$. On this condition,

$$A \cdot R_{\max} = 3 , \; A = \frac{3}{R_{\max}} .$$

Then

$$V_t = V_0 \cdot e^{-\frac{3R}{R_{\max}}} = V_0 \cdot e^{-3\varepsilon} , \tag{8}$$

where $\varepsilon = R / R_{\max}$ is the relative durability of the drill bit from the start of spudding drilling.

The rate of penetration characterizes the effectiveness of the rock crushing or of the bottom hole deepening. However, because of the need to replace the worn-out bit, it cannot characterize the effectiveness of the borehole construction. The bit replacement implies running and pulling operations, which are time-, energy- and labour-consuming, including manual labour. In the general time schedule of a deep borehole construction, running and pulling operations take up to 60 %.

Therefore, the performance of the well drill should be described using the so-called drilling speed per run, the mean value of which can be expressed using the formula [9, 12]

$$V_{pc} = \frac{H_\partial}{t_\partial + T_{cn}} , \tag{9}$$

where H_∂ is the value of the borehole deepening with one drill bit for the whole time t_∂ of its operation in the bottom hole, defined as $H_\partial = \frac{\int_0^t V_t dt}{t_\partial + T_{cn}}$; T_{cn} is the duration of the running and pulling operations; $t_\partial + T_{cn}$ Is the duration of one run.

The drilling speed per run is defined by the bit durability and relative durability as

$$V_p = \frac{\int_0^t V_t \cdot dt}{t + T_{cn}} = \frac{\int_0^t V_0 \cdot e^{-3\varepsilon} dt}{t + T_{cn}} .$$

For the steady-state mode of drilling homogeneous rock,

$$V_p = \frac{\int_0^t V_0 \cdot e^{-\frac{3}{R_{\max}} P^\alpha \cdot \omega^\beta \cdot t} dt}{t + T_{cn}} = \frac{1}{t + T_{cn}} \cdot V_0 \cdot \frac{R_{\max}}{3 \cdot P^\alpha \cdot \omega^\beta} \left(1 - e^{-3\varepsilon}\right) .$$

As

$$R = \int_0^t P^\alpha \cdot \omega^\beta dt , \qquad \frac{dR}{dt} = P^\alpha \cdot \omega^\beta ,$$

then

$$V_p = \frac{1}{t + T_{cn}} \cdot V_0 \cdot \frac{R_{\max}}{3 \cdot dR/dt} \left(1 - e^{-3\varepsilon}\right) ,$$

where ***dR/dt*** is the rate of the drill bit durability change during the spudding drilling.

For the steady-state mode of drilling homogeneous rock,

$$\frac{dR}{dt}=\frac{R_{\max}}{T_L}=\frac{\Delta R}{\Delta t}=\frac{R}{t}=const\ ,$$

where R us the current durability; $T_д$ is the total spudding drilling time; t is the net drilling time.

Then

$$V_p=\frac{1}{t+T_{cn}}\cdot V_0\cdot\frac{R_{\max}}{3\cdot R/t}\left(1-e^{-3\varepsilon}\right)$$

or

$$V_p=\frac{1}{t+T_{cn}}\cdot V_0\cdot\frac{t}{3\cdot\varepsilon}\left(1-e^{-3\varepsilon}\right).$$

In the steady-state drilling mode, the time can be defined using the durability as

$$t=\frac{R}{P^{\alpha}\cdot\omega^{\beta}}\ ,$$

then

$$V_p=\frac{1}{\frac{R}{P^{\alpha}\cdot\omega^{\beta}}+T_{cn}}\cdot V_0\cdot\frac{\frac{R}{P^{\alpha}\cdot\omega^{\beta}}}{3\cdot\varepsilon}\left(1-e^{-3\varepsilon}\right)$$

or

$$V_p=\frac{P^{\alpha}\cdot\omega^{\beta}}{R+P^{\alpha}\cdot\omega^{\beta}\cdot T_{cn}}\cdot V_0\cdot\frac{R}{3\cdot P^{\alpha}\cdot\omega^{\beta}\cdot\varepsilon}\left(1-e^{-3\varepsilon}\right).$$

If we take into account that $R=\varepsilon R_{\max}$, the resulting equation will appear as

$$V_p=\frac{R_{\max}}{3\left(\varepsilon\cdot R_{\max}+P^{\alpha}\cdot\omega^{\beta}\cdot T_{cn}\right)}\cdot V_0\left(1-e^{-3\varepsilon}\right)\ . \qquad (10)$$

To find $R_{\max}$, we take the logarithm of both sides of the expression (7). As a result,

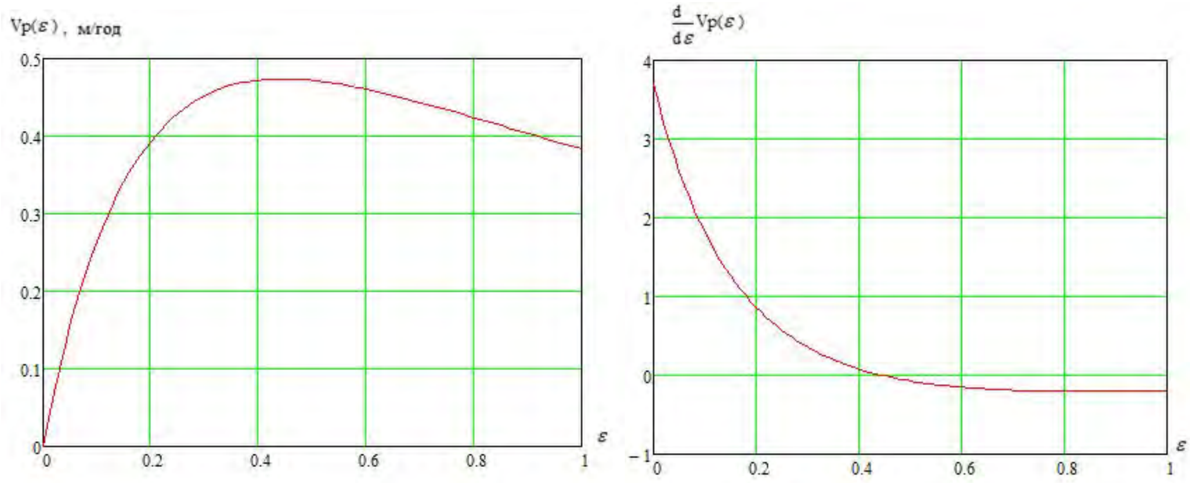
$$\ln(V)=\ln(V_0)-\frac{3R}{R_{\max}};\qquad R_{\max}=\frac{3R}{\ln(V_0/V_t)}.$$

Using one experimental point, $R_{\max}$ can be easily assessed in case of the exponential relationship between V_t and R by measuring the current durability and current rate of penetration. The value 3 in the power was taken arbitrarily. The durability of the drill bit at the moment when the penetration rate drops e^3-fold is taken as the maximum allowable one.

As the maximum allowable value of $R_{\max}$ we can take a durability at which the speed decreases e^a folds. The value a can be determined statistically during further drilling with measuring the parameters of the pulled bit as

$$R_{\max}=\frac{a\cdot R}{\ln\frac{V_0}{V_t}}.$$

Taking $dV_P/d\varepsilon=0$, we determine the optimal value of the relative durability ε_{opt}, based on which $Vp_{\max}$ for a selected drilling mode can be found. For example, Fig. 1 presents the dependencies of the drilling speed per run and its derivative for P = 15 kN, V_0 =1.8 m/hour, ω = 5.23 rad/s, α = 1, β = 0.2, $R_{\max}$= 18.5·10^5. The aim of determining the maximum drilling speed per run $Vp_{\max}$ is to find the reasonable drill bit durability at the selected values of P and ω and for the given drilling conditions. In the case under consideration it is seen that the optimal drilling speed per run is $Vp_{\max}$ = 0.474 m/hour, and the relative durability is ε_{opt} = 0.445.



a *b*

Fig. 1. Drilling speed per run (a) and its derivative (b) vs. ε

Conclusions

The time of operation of the drill bit in the bottom hole or the moment of its pulling is determined by the wear of its cutting structure, which can be assessed based on the value of the current penetration rate during the deepening of the borehole in homogeneous rock and drill bit durability from the start of drilling. The proposed model $V_м = f(\varepsilon)$ is invariant with respect to physico-mechanical properties of the rocks and can be effectively used for the operative control of the borehole deepening process.

Prospects of further research

Further research in this area can be focused on the synthesis of a model for search of the extremum in order to study the effect of random factors on the drilling speed per run.

References

1. *Vyrvinskyi P. P., Kuzin Yu. L., Khomenko V. L. Drilling technology. D.: NHU, 2014. 280 p. (Ukr)*
2. *Ma, T., Chen, P. & Zhao, J. Overview on vertical and directional drilling technologies for the exploration and exploitation of deep petroleum resources // Geomech. Geophys. Geo-energ. Geo-resour. 2016. No. 2. pp. 365–395.*
3. *Denys B. D., Boychuk B. H., Kaluzhnyi B. S. Electrical equipment and automation of oil production: Textbook. Lviv: Lviv Polytechnic National University, 2007. 171 p. (Ukr)*
4. *Gandzhumyan R. A., Kalinin A. G., Serdyuk N. I. Drilling calculations. Textbook / Under. ed. A. G. Kalinin. M.: RGGU, 2007. 668 p. (Rus)*
5. *Maistrenko, A. L., Bondarenko, M. O., Gargin, V. G. et al. Methods of improving efficiency of drilling operations for increasing oil and gas production in Ukraine // Jornal of Superhard Materials. 2007. No. 29. pp. 307–315.*
6. *Vityaz O. Yu., Hrabovskyi R. S., Tyrlych V. V. Influence of service life on the results of assessment of conditions of destruction of drill string pipes during tripping processes // Naftohazova enerhetyka. 2017, No. 1. pp. 7–14. (Ukr)*
7. *Horbiychuk M. I., Kropyvnytska V. B. Modeling and identification of the borehole deepening // Burinnya naftovykh ta hazovykh sverdlovyn. 2004. No. 1(3). pp. 9–12. (Ukr)*
8. *Sementsov H. N., Hutak O. V. Modeling and identification of the drilling process for control tasks optimization: monograph. Odesa: Kupriyenko SV, 2014. 295 p. (Ukr)*

9. Decision-making in choosing drill bits and drilling operational parameters based on initial data / G. M. Efendiev et al. // Geoinformatika. 2016, No. 3 (59). pp. 30–39. (Rus)

10. Makarova I. G., Sitnikov N. B. Borehole penetration rate // Izvestiya UHHU. 2005. No. 20. URL: https://cyberleninka.ru/article/n/mehanicheskaya-skorost-bureniya-skvazhin.(Rus)

11. Badalov R. A. Rate of penetration curve and its analytical expression // Neft I gaz. 1958, No. 1. pp. 51–55. (Rus)

12. AL-Mahasneh M. Optimization drilling parameters performance during drilling in gas wells // International Journal of Oil, Gas and Coal Engineering. 2017. No. 5(2). pp. 19–26.

13. Invention certificate No. 872736 USSR.E21 B 47/00. Device for determining bit wear during drilling / B. D. Denys, R. V. Dzyadyk, E. A. Ivanitskyi, B. S. Kaluzhnyi, A. D. Martynchuk, S. F. Molchanova, applicants Lvovvskyi ordena Lenina politekhnicheskiy institut and Borislavskoye upravleniye burovykh rabot, petition. 18.12.1979, publ. 15.10.1981. Bulletin No. 38.

Список використаних джерел

1. Вирвінський П. П., Кузін Ю. Л., Хоменко В. Л. Технологія буріння. Д.: НГУ, 2014. 280 с.

2. Ma, T., Chen, P. & Zhao, J. Overview on vertical and directional drilling technologies for the exploration and exploitation of deep petroleum resources // Geomech. Geophys. Geo-energ. Geo-resour. 2016. No. 2. pp. 365–395.

3. Денис Б. Д., Бойчук Б. Г., Калужний Б. С. Електрообладнання і автоматизація видобування нафти: навч. посіб. Львів: Нац. ун-ту "Львівська політехніка", 2007. 171 с.

4. Ганджумян Р. А., Калинин А. Г., Сердюк Н. И. Расчеты в бурении. Справочное пособие / под ред. А. Г. Калинина. М.: РГГУ, 2007. 668 с.

5. Maistrenko, A. L., Bondarenko, M. O., Gargin, V. G. et al. Methods of improving efficiency of drilling operations for increasing oil and gas production in Ukraine // Jornal of Superhard Materials. 2007. No. 29. pp. 307–315.

6. Витязь О. Ю., Грабовський Р. С., Тирлич В. В. Вплив тривалості експлуатації на результати оцінювання умов руйнування труб бурильних колон під час спуско-підіймальних операцій // Нафтогазова енергетика. 2017, № 1. С. 7–14.

7. Горбійчук М. І., Кропивницька В. Б. Моделювання та ідентифікація процесу заглиблення свердловин // Буріння нафтових та газових свердловин. 2004. № 1(3). С. 9–12.

8. Семенцов Г. Н., Гутак О. В. Моделювання та ідентифікація процесу буріння для задач оптимізації управління: монографія. Одеса: КУПРІЄНКО СВ, 2014. 295 с

9. Принятие решений при выборе долот и режимных параметров бурения в зависимости от характера исходной информации / Г. М. Эфендиев и др. // Геоінформатика. 2016, № 3 (59). С. 30–39.

10. Макарова И. Г., Ситников Н. Б. Механическая скорость бурения скважин // Известия УГГУ. 2005. № 20. URL: https://cyberleninka.ru/article/n/mehanicheskaya-skorost-bureniya-skvazhin.

11. Бадалов Р. А. Кривая изменения механической скорости проходки и ее аналитическое виражение // Нефть и газ. 1958, № 1. С. 51–55.

12. AL-Mahasneh M. Optimization drilling parameters performance during drilling in gas wells // International Journal of Oil, Gas and Coal Engineering. 2017. No. 5(2). pp. 19–26.

13. А. с. 872736 СССР.Е21 В 47/00. Устройство для определения износа долота в процессе бурения / Б. Д. Денис, Р. В. Дзядик, Е. А. Иваницкий, Б. С. Калужний, А. Д. Мартинчук, С. Ф. Молчанова, заявители Львовский ордена Ленина политехнический институт и Бориславское управление бурових работ, заявл. 18.12.1979, опубл. 15.10. 1981. Бюл. № 38.

УДК: 681.5.015:622.24

Б. С. Калужний
Національний університет "Львівська політехніка",
кафедра електромехатроніки і комп'ютеризованих електромеханічних систем,
bohdan.s.kaluzhnyi@lpnu.ua,

А. В. Маляр
Національний університет "Львівська політехніка",
кафедра електромехатроніки і комп'ютеризованих електромеханічних систем,
andrii.v.maliar@lpnu.ua

І. Р. Головач
Національний університет "Львівська політехніка",
кафедра електромехатроніки і комп'ютеризованих електромеханічних систем,
ihor.r.holovach@lpnu.ua

ВИЗНАЧЕННЯ ОПТИМАЛЬНОГО РЕЖИМУ БУРІННЯ НА ОСНОВІ РЕСУРСУ ВІДПРАЦЮВАННЯ ДОЛОТА

Пропонується один з способів встановлення оптимального режиму буріння нафтових та газових свердловин. Проаналізовано існуючі способи контролю за темпом буріння та станом долота. Показано, що в силу неповної та часто спотвореної інформації, важко здійснювати контроль та керування процесом буріння на основі математичної моделі заглиблення долота, розв'язком якої є часові залежності механічної швидкості буріння.

Оскільки під час будівництва свердловини чистий час буріння займає менше половини всього затраченого часу, а решту часу йде на допоміжні операції, для визначення оптимальних параметрів режиму буріння використано рейсову швидкість. У результаті аналізу переваг та недоліків методів ідентифікації стану бурового інструменту прийнято рішення використовувати такий параметр, як відносний ресурс відпрацювання долота, який інваріантний відносно фізико-механічних властивостей гірських порід. Виведено залежність рейсової швидкості від відносного значення ресурсу відпрацювання долота та інших параметрів процесу буріння. Показано, що такий перехід дає змогу уніфікувати алгоритм знаходження оптимальної рейсової швидкості, оскільки він не залежить від типу породи та інших чинників. Наведено приклад розрахунку максимального значення рейсової швидкості, за якої забезпечується оптимальне значення ресурсу спрацювання долота для вибраного режиму буріння.

Ключові слова: свердловина, буріння, бурова установка, ресурс долота, рейсова швидкість.