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Control and Management by Resource of Rolling Cutter Bits in Drilling Rock Massif

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Abstract: The paper considers a variety of structurally interrelated diverse systems for evaluation the boring rig effectiveness. The paper presents the technique of determining the tool life of a rolling cutter bit and drilling speed depending on the strength characteristics and structure of the array rock, and for calculating the unit cost of drilling. This technique allows analyzing the ratio between the boring rig performance and resource of the rolling cutter bits for drilling rocks, with different physical and mechanical properties and structure.

Key words: Efficiency of functioning · Drilling tool · Rock · Strength characteristics · Rock structure · Control by resource

INTRODUCTION

The problem of efficiency evaluation of system functioning “boring rig – rolling cutter bit – rock” in mining industry is connected with interaction of a large number of elements.

The efficiency of boring rigs functioning can be evaluated in terms of maximum reliability, maximum performance and optimal balance of these parameters [1-3]. For an objective evaluation of the reliability it is necessary to examine the operation conditions, to diagnose the technical condition and simulate failures boring rigs [1]. The performance evaluation can maximize the operating time of the boring rig. For this the effective regulation of the drilling modes is obligatory.

The feed force and rotation frequency of the working element, as well as structure and material properties of the drilling tool on the process are of special influence if we are speaking about a boring rig. As for the rock, strength characteristics are of the most importance which can be expressed by the indicator of the drillability [4, 5], as well as the structure of the rock. The rock massif can be characterized by properties such as fracture, lamination and other violations of the rock homogeneity. The penetration of the drilling tool borders or areas with varying physical and mechanical properties is invariably accompanied by attacks and strokes. The unpredictable impact loads, as a rule, does not lead to increase of drilling speed, but have a negative impact on the resource drilling tools and boring rig as a whole.

The remainder of the paper is organized as follows. Section 1 describes the problem of low resource rolling cutter bits and inadequate control of their operating modes. Section 2 shows the relationship tooth shape of the rolling cutter and the loading of the bit and defines the conditions of loading when drilling homogeneous layered and fractured rock. In subsection 3.1 discusses the equations for determining the resource of rolling cutter bits under different loading conditions. Subsection 3.2 presents the analysis of the productivity relationship and resource bits. Subsection 3.3 investigates the bit resource if you have multiple loading conditions. Subsection 3.4 determines the specific cost of rock drilling with a complex structure. Section 4 concludes the paper. Section 5 shows the educts on this paper.

Problem Formulation: While drilling rock the drilling tools and drilling rod experience some demanding loads. The most complex mechanical node of a drilling rod is a drilling tool. On the one hand, its details are experiencing the most complicated on the structure and value load, and on the other it has the resource based on the mechanical properties of materials. In 80 % of cases a drilling tool fails due to the collapse of bearing units [6, 7]. Rolling bearings are experiencing complex cyclic load.

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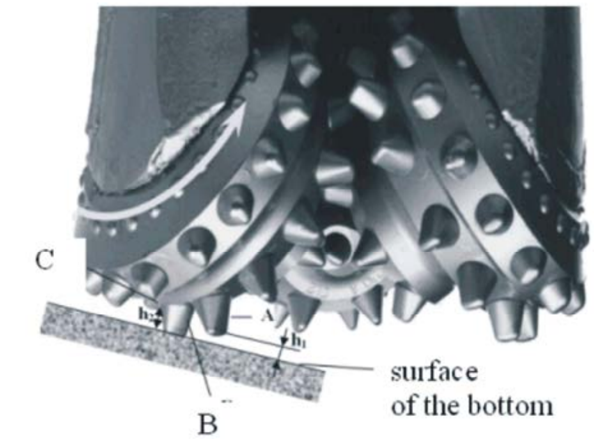

Fig. 1: The scheme of the course of the bearing cutter in the bottom

- A cyclic load on the element of the rolling bearing when rolling a bearing cutter on the bottom is described by the equations of the estimated life of the bearing [8].

For a rolling bearing cutter the evaluated resource should be measured by a number of load cycles.

According to [9] maximum strain in a rolling bearing is:

$$\sigma_r^{\max} = 600 \cdot \sqrt[3]{\frac{F_r}{z \cdot D_r \cdot L_r}} \qquad (1)$$

where F_r is radial force applied to the bearing, N; z - number of rolling elements in the bearing; D_r - roller diameter, mm; L_r - length of roller, mm.

Taking into account the design of rolling contact bearing cutter, rolling contact bearings are experiencing the main load, and a bearing ball is a locking mechanism [10, 11]. Therefore taking into account axial loads, a special attention should be paid to the estimated resource of rolling bearings.

The mentioned equations consider only cyclic load on the element of a rolling contact bearing due to changes in the geometric location of the rolling elements. A rolling contact bearing cutter does not take into account strike loads when rolling teeth of the rolling cutter on the bottom and loadings arising when rolling in drilling on the rocks with higher drillability. Strikes recurring requires the evaluation of the fatigue strength [12]. The durability of machine parts is a factor fatigue strength n_r is sufficiently reliable characteristic of fatigue [13]. This value characterizes the number decrease of rolling contact bearings cycles depending on the additional cyclic load. Here the resource of bearing taking into account the additional cyclic load is:

$$L = 10^6 \cdot \left(\frac{\sigma_{u.s}}{\sigma_{\text{e.l}}}\right)^{10/3} \cdot \frac{\sigma_{-1}}{\sigma_a + \frac{\sigma_{-1}}{\sigma_{u.s}} \cdot \sigma_{\text{m.v}}}, \qquad (2)$$

where $\sigma_{e.l}$ - equivalent load; σ_{-1} - endurance limit of the material, MPa; $\sigma_{\grave{a}}$ - the amplitude of the variable stress cycle, MPa; $\sigma_{u.s}$ - ultimate strength, MPa; $\sigma_{m.v}$ - medium strain cycle, Mpa.

- A cyclic load when rolling bearing from a tooth to tooth is characterized by strike loads arising at strike of the next tooth on the surface of the bottom [14]. This process is characterized by the change of the kinetic energy and the transfer of the latest in energy mechanical strike. Changes in the kinetic energy of the working element are characterized by the change in velocity [15, 16]. The average speed of a drilling tool equals to the speed of drilling. But when rolling bearing cutter in to the bottom surface alternately hit teeth A, B and C and the bearing rotates according to the direction of the arrow (Fig. 1):

When rolling bearing from a tooth A to tooth B in the first half cycle, the height h_1 grows from 0 to $x/2$, and height h_2 decreases from x to $x/2$. In this half cycle a cutter bit and drilling rod relatively the surface of the bottom upwards, and the load on all the nodes is of a peak value. In the second half cycle the height h1 grows from $x/2$ to x, and the height h_2 descends from $x/2$ to 0. During the half cycle the load decreases, and the power of the feed drive is converted into kinetic energy. At the end of the second half cycle of the kinetic energy is converted into the energy of the strike, and the workload is of the peak value.

Strain of the rolling contact bearings with regard to strike loads under rolling picks of the bearing cutter in the bottom [13]:

$$\sigma_{\text{i.l.r}}^{\max} = 600 \cdot \sqrt[3]{\frac{F_r}{z \cdot D_p \cdot L_p}} \cdot \frac{2(v_d + v_s/2)}{2(v_d + v_s/2) - v_s/2}, \qquad (3)$$

where v_d - drilling speed with the existing properties of the rock by force feed and rotation speed of a drilling element, m/s [4]; v_s - lowering teeth speed of the bearing cutter in bottom, m/s.

- A cyclic load characterized by the change of physical and mechanical properties of rock has a similar mechanism. And the resulting strain is connected with the kinetic energy transfer of the drilling unit into the strike energy at the increase of rock drillability. The difference is in the source and the mechanism of strike formation.

The total strain in rolling contact bearings, resulting at the increase of the rock drillability also includes cyclic loads from the pick strikes on the tooth surface:

$$\sigma_{\text{i.l.r}}^{\Sigma} = 600 \cdot \sqrt[3]{\frac{F_r}{z \cdot D_p \cdot L_p}} \cdot \frac{2(v_d + v_s/2)}{2(v_d + v_s/2) - v_s/2} \cdot \frac{2I_d^1 + 2\Delta I_d}{2I_d^1 + \Delta I_d}, \quad (4)$$

where I_d - indicator of drillability [4]; ΔI_d - average difference of the drillability indicator and adjacent layers of the rock.

Loading Conditions of Rolling Cutter Bit: When bearing cutter works the tooth shape of bearing cutter also plays an important role [13, 17]. The tooth of the bearing cutter introduction helps to reduce the magnitude of the strike loads. The tooth shape affects its penetration into the rock.

The strain in the bodies of rolling bearings cutters taking into account the strike loads while teeth of bearing cutter rolling in the bottom, and with increasing rock drillability indicator with regard to the form of the indenter is in the following expression [13]:

$$\sigma_{\text{i.l.r}}^{\Sigma} = 600 \cdot \sqrt[3]{\frac{F_r}{z \cdot D_r \cdot L_r}} \cdot \frac{2(v_d + v_s/2)}{2(v_d + v_s/2) - v_s/2} \cdot \frac{2I_d^1 + 2\Delta I_d}{2I_d^1 + \Delta I_d} \cdot k_{ind}, \quad (5)$$

where $\sigma_{\text{i.l.r}}^{\Sigma}$ - strain in a roller of the rolling contact bearings; k_{ind} - shape coefficient of the indenter; k_{ind} = *0,79* for indenter with a shape of a rounded barrel; k_{ind} = 0,47 indenter with the form of the correct cone; k_{ind} = 0,7 for the indenter with a shape of the convex cone.

The presented expressions for stresses calculation in the rolling elements of rolling cutter bits using expression (2) allow determining a number of cycles to failure of the rolling elements under different loading conditions.

There are three types of loading conditions:

- Drilling homogeneous rock without integrity violations with approximately the same properties or variation in the drillability index within [delta]I_d<*1* [18, 19]. Drilling of such rock massif accompanied only by cyclic load with maximum strain in the rolling elements determined by the expression (3) taking into account the coefficient of the indenters shape of any kind of bearing cutters k_{ind}.
- Drilling layered rock is characterized by significant strike loads with the passage of the roller cutter bit boundaries between the layers of rocks with different physical and mechanical properties It is necessary to take into account a number of rock layers on the one running meter to find a number of loading cycles for crossing the boundaries between layers of rock with different physical and mechanical properties. The value of this index varies from 0 to 20 or more [20]. The maximum strains for data loading conditions can be determined from the expression (5).
- Drilling fissured rocks is characterized by significant strike loads with the passage of the roller cutter bit cracks or discontinuities in the array rock. A number of cracks per one meter of the wells is approximately in the range from 0 to 20 [20-22]. The maximum strains for data loading conditions are also can be determined from the expression (5), but unlike drilling layered rock, cheats crack is accompanied by a more significant strike. Conventionally, we can consider that currently drillability indicator is reduced to zero and increases to the previous value. While the passage of the boundaries between the layers is accompanied by a leap drillability indicator [delta] I_d<I_d.

For determining the stability of the rolling cutter bit working in drilling array rock characterized by the all three conditions of loading, it is necessary to define a fraction of the total number of loading cycles rolling bearing cutters, attributable to the drilling of homogeneous, layered and fissured rocks:

Drilling Tool Resource

Equation of the Resource: The total number of cycles before the failure of the rolling elements under different loading conditions we can find with the help of the expression:

$$L_{\Sigma} = L_h \cdot \eta_h + L_{fol} \cdot \eta_{fol} + L_{fis} \cdot \eta_{fis}, \quad (6)$$

where L_h - number of cycles before failure of the rolling elements when drilling homogeneous rock; L_{fol} - number of cycles before failure of the rolling elements under such conditions of drilling when each cycle of loading will be characterized by loads corresponding to overcome the boundaries between the layers of rocks with different physical and mechanical properties; L_{fis} - number of cycles before failure of rolling elements under conditions of drilling when each cycle of loading will be characterized by the loads corresponding to overcome cracks or discontinuities in the rock; η_h, η_{fol}, η_{fis} - fractions from the total number of loading cycles of elements of rolling bearing cutters, corresponding to the drilling of a homogeneous, foliated and fissured rocks correspondingly.

For drilling conditions of homogeneous rock the expression (2) for the life of rolling contact bearings will be as follows:

$$L_h = 10^6 \cdot \left(\frac{\sigma_{u.s}}{\sigma_{\text{i.l.r}}^{\max}}\right)^{10/3} \cdot \frac{\sigma_{-1}}{\frac{\sigma_{\text{i.}l\text{.r}}^{\max} - \sigma_r^{\max}}{2} + \frac{\sigma_{-1}}{\sigma_{u.s}} \cdot \frac{\sigma_{\text{i.}l\text{.r}}^{\max} + \sigma_r^{\max}}{2}}. \quad (7)$$

For drilling conditions of the foliated rock the expression (2) becomes as follows:

$$L_{fol} = 10^6 \cdot \left(\frac{\sigma_{u.s}}{\sigma_{\text{i.}l\text{.r}}^{\Sigma}}\right)^{10/3} \cdot \frac{\sigma_{-1}}{\frac{\sigma_{\text{i.}l\text{.r}}^{\Sigma} - \sigma_r^{\max}}{2} + \frac{\sigma_{-1}}{\sigma_{u.s}} \cdot \frac{\sigma_{\text{i.}l\text{.r}}^{\Sigma} + \sigma_r^{\max}}{2}}. \quad (8)$$

For drilling conditions of fissured rocks, the expression (2) will be as follows because the minimum strain cycle $\sigma_{min} = 0$:

$$L_{fis} = 10^6 \cdot \left(\frac{\sigma_{u.s}}{\sigma_{\text{i.l.r}}^{\Sigma}}\right)^{10/3} \cdot \frac{\sigma_{-1}}{\frac{\sigma_{\text{i.}l\text{.r}}^{\Sigma}}{2} + \frac{\sigma_{-1}}{\sigma_{u.s}} \cdot \frac{\sigma_{\text{i.}l\text{.r}}^{\Sigma}}{2}}. \quad (9)$$

Based on the equations of defining the life of rolling contact bearings, it is possible to determine an estimated tool life (in meters) of rolling cutter bits with a rolling cones:

$$T = \frac{L_{\Sigma}}{2 \cdot n_{rot} \cdot \frac{D_1}{D_{b.c}^{\max}}} \cdot v_d, \quad (10)$$

where n_{rot} - frequency of the roller bit rotation turn/min; D_1 - diameter of the roller bit m; $D_{b.c}^{\max}$ - maximum diameter of the bearing cutter; v_d - drilling speed at existing properties of the rock by a forced feed and rotation speed of a drilling unit, m/min.

Ratio of the Performance and Resource: The given technology allows analyzing the ratio between the performance of the boring rig of the rolling cutter drilling and resource of the drilling bit for drilling rocks with different drillability indicators, number and size of cracks and rock layers with different physical and mechanical properties.

Using the developed technology some dependencies for rocks with the average drillability I_d - 10, 15, 20, greatly differing fracture and lamination are built (Fig. 2). The vertical lines demarcate areas of curves corresponding to the effort of drilling rod filing in the range recommended by the manufacturer for rolling cutter bits with rollers bearing.

Here $n_{r.l}$ – the number of rock layers; n_{cr} - the number of rock cracks.

The figure shows that in assessment of drilling, the speed range is significantly different on different rates drillability I_d. While analyzing the curves when the number of cracks and rock layers the tool life of the bits changes considerably. From the economic aspect, the use of the ratio is more feasible for finding of specific expenses for drilling.

Resource and Specific Expenses for Drilling Based on Loading Conditions: The drilling tool resource can be found taking into account physical and mechanical properties of the rock and specific operating parameters.

If we consider that $\sigma_{-1} = 0{,}5 \cdot \sigma$, then after the substitution of expressions, showing the strain at different loading conditions, tool life is in the following expression:

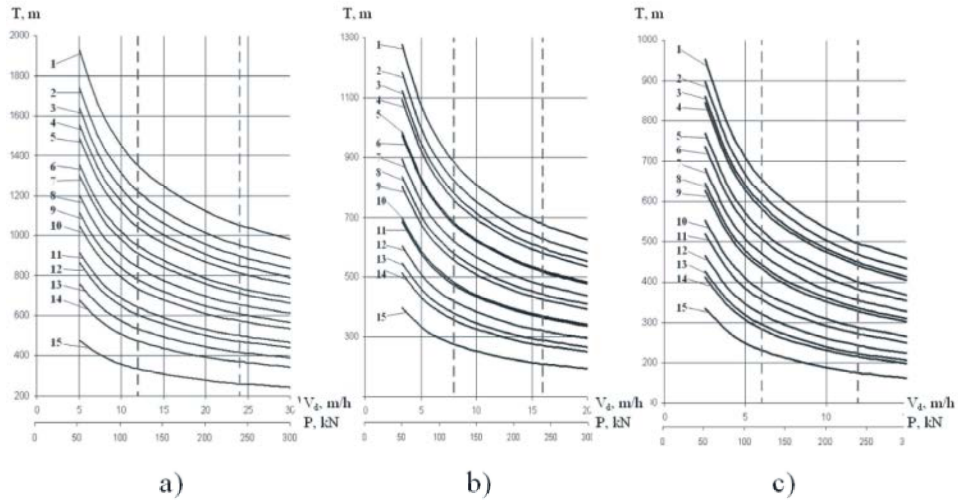

Fig. 2: The dependence of rolling cutter bits durability, drilling speed and efforts of the drilling rod supply: a) I_d = 10, b) I_d = 20, c) I_d = 10. On the charts, a, b, c rock characteristics of the curve: 1) $n_{r.l}$ = 0, n_{cr} = 0; 2) $n_{r.l}$ = 10, [delta]I_d = 2, n_{cr} = 0; 3) $n_{r.l}$ = 10, [delta]I_d = 4, n_{cr} = 0; 4) $n_{r.l}$ = 20, [delta]I_d = 2, n_{cr} = 0; 5) $n_{r.l}$ = 0, n_{cr} = 10; 6) $n_{r.l}$ = 20, [delta]I_d = 4, n_{cr} = 0; 7) $n_{r.l}$ = 10, [delta]I_d = 2, n_{cr} = 10; 8) $n_{r.l}$ = 10, [delta]I_d = 4, n_{cr} = 10; 9) $n_{r.l}$ = 20, [delta]I_d = 2, n_{cr} = 10; 10) $n_{r.l}$ = 0, n_{cr} = 20; 11) $n_{r.l}$ = 20, [delta]I_d = 4, n_{cr} = 10; 12) $n_{r.l}$ = 10, [delta]I_d = 2, n_{cr} = 20; 13) $n_{r.l}$ = 20, [delta]I_d = 4, n_{cr} = 10; 14) $n_{r.l}$ = 20, [delta]I_d = 2, n_{cr} = 20; 15) $n_{r.l}$ = 20, [delta]I_d = 4, n_{cr} = 20.

$$T = 10^6 \cdot \left(\frac{\sigma_{u.s}}{600 \cdot \sqrt[3]{\frac{v_d \cdot I_d^1 \cdot D_1^2}{360 \cdot n_{\text{rot}} \cdot z \cdot D_r \cdot L_r} \cdot \frac{2(v_d + v_s/2)}{2(v_d + v_s/2) - v_s/2}} \cdot k_{ind}} \right)^{10/3} \cdot \frac{0,5 \cdot \sigma_{u.s} \cdot}{1,7 \cdot 600 \cdot \sqrt[3]{\frac{v_d \cdot I_d^1 \cdot D_1^2}{360 \cdot n_{\text{rot}} \cdot z \cdot D_r \cdot L_r}} \cdot k_{ind}} \times$$
$$\left(\frac{1 - \delta_{r.l} - \delta_{cr}}{1,5 \cdot \frac{2(v_d + v_s/2)}{2(v_d + v_s/2) - v_s/2} - 0,5} + \frac{\delta_{r.l}}{1,5 \cdot \frac{2(v_d + v_s/2)}{2(v_d + v_s/2) - v_s/2} \cdot \frac{2I_d^1 + 2\Delta I_d}{2I_d^1 + \Delta I_d} - 0,5} + \frac{\delta_{cr}}{2 \cdot \frac{2(v_d + v_s/2)}{2(v_d + v_s/2) - v_s/2} \cdot I_d^1} \right) \quad (11)$$

where $\delta_{r.l}$ - the thickness of the boundary layer or its size along the axis of a drilling rod, m; δ_{cr} - thickness cracks or its size along the axis of drilling rod, m.

Specific Cost of Drilling: As criteria for evaluating the work effectiveness of the rolling cutter bit and the whole technological process of drilling (including operational parameters) operational drilling costs of *1* m hole expressed by the following formula are accepted:

$$S(v_d, T) = \frac{A \cdot t_{m.o}}{t_s \cdot \eta} + \frac{A}{t_s \cdot \eta \cdot v_d} + \frac{C_{r.b}}{T} = \gamma \cdot t_{m.o} + \frac{\gamma}{v_d} + \frac{C_{r.b}}{T}, \quad (12)$$

where *S* - specific drilling costs, rubles/m; *A* - price of a machine-shift work of a boring rig without the of drilling tools costs, ruble/cm; $t_{m.o}$ - specific costs of time spent on auxiliary machining operations, min/m; t_s – shift time, min; η - coefficient of effective use of the rig during the shift (usually η = 0,75 - 0,85); γ - cost machine-hours of production work of boring rig expressed by the ratio γ = *A/(T•η)*; $C_{r.b}$ - roller bit cost, rubles.

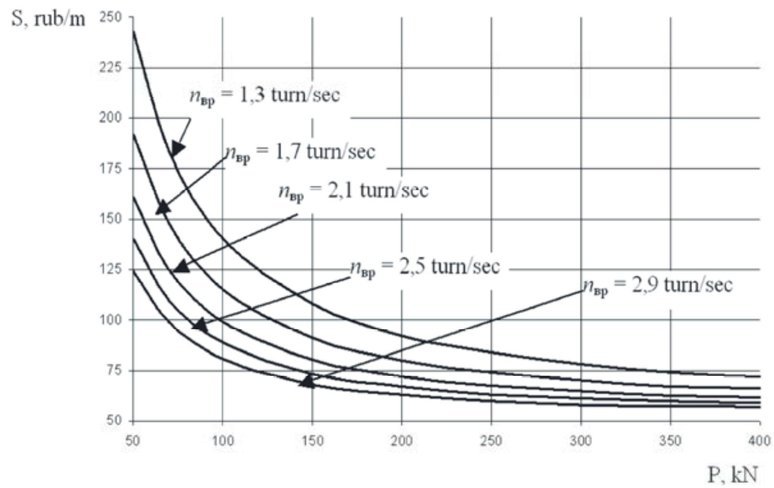

Fig. 3: The calculated dependences of the specific cost for drilling of rock boring rigs

In the conditions of Mazulsk limestone mine JSC Rusal-Achinsk: the cost of the machine-shift work of a drilling unit without the costs of drilling tools A = 6000 rubles/cm; the specific cost of time spent on auxiliary machining operations $t_{m.o}$ = 0,013 h/m; shift time t_s = 8 hours; the effective use of the machine during a shift η = 0,8; the cost of rolling cutter bits III 244,5-TK of home manufacturers in average $C_{r.b}$ = 26000 - 34000 rubles. For the approximate calculation we consider $C_{r.b}$ = 26000 rubles.

Taking into account the expression (11) formula (12) allows to define the specific costs of drilling at various rock characteristics and operating conditions of boring equipment.

The specific costs for drilling can be shown as the calculated dependences (Fig. 3):

The graph shows that with increasing efforts, the irrespective of the loading conditions and frequency of rotation of a drilling tool, drilling cost is reduced. However, one should pay attention that the destruction efficiency of rock by indenters of a rolling cutter decreases with the speed increasing and the time of contact with the rock reducing.

CONCLUSIONS

Having summarized, we can pay attention that the technology for determination the recommended ratio of the rolling cutter bit tool life and drilling speed corresponding to the optimal efficiency of technical systems «boring rig – rolling cutter bit - rock» functioning is necessary to be applied. In its turn, the tool life of the bit persistence and drilling speed should be monitored continuously taking into account changing properties of the rock.

The application of the given technology, control, resource management, and the following these recommendations will improve the effectiveness of the system «boring rig – rolling cutter bit - rock» functioning and reduce operating costs at optimum productivity in the conditions of unpredictable changing and strike loads.

Educts:

- With increasing efforts, the irrespective of the loading conditions and frequency of rotation of a drilling tool, drilling cost is reduced.
- The destruction efficiency of rock by indenters of a rolling cutter decreases with the speed increasing and the time of contact with the rock reducing.
- As criteria for evaluating the work effectiveness of the rolling cutter bit and the whole technological process of drilling operational drilling costs take of 1 m hole.

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