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IMPROVEMENT OF THE METHODOLOGY FOR CALCULATING THE EXPECTED DRILLING SPEED WITH PDC CHISELS

Purpose. Determination of the dependence of the depth of penetration of the PDC cutter into the bottom hole rock, taking into account its geometric parameters and spatial placement in relation to the destroyed array.

Methodology. The tasks were solved by a comprehensive research method, including analysis and generalization of literary and patent sources, conducting theoretical research, which consists in solving the theoretical problem of the impact of a superhard circular cutter on an elastically fragile mountain range, using computer and mathematical modeling methods.

Findings. A simplified expression has been obtained that allows taking into account the features of the PDC cutter with sufficient accuracy for engineering calculations when determining the depth of its penetration into the bottom hole rock. A method is proposed for calculating the depth of fracture in one revolution of a diamond carbide cutter PDC into the rock of the bottom of the well. The patterns of destruction by the proposed diamond-hard-alloy PDC chisel of a rock mass at the bottom of the well from the parameters of the drilling regime and the hardness of the drilled rocks have been established.

Originality. For the first time, the dependence has been obtained of the influence of the geometric parameters of the shape of a single diamond-carbide PDC cutter and its spatial placement in the body of the bit matrix on the magnitude of the technological parameters of drilling a well, and their effect on the nature of the destruction of the array PDC cutter.

Practical value. A technique for determining the depth of penetration of a single PDC cutter is proposed, the use of which will allow predicting the mechanical speed, depending on the geological and technical conditions of drilling wells. And taking into account the abrasive properties of rocks, it is possible to reduce the wear of the bits, and therefore the amount of necessary rock-crushing tools for the entire volume of drilling operations during the construction of the well.

Keywords: *chisel, cutter, PDC, downhole, borehole*

Introduction. Rock-breaking tools (drill bits) are designed to destroy rock during the drilling process. The destruction of rocks during rotational drilling occurs as a result of the action of two forces: the axial load on the bit, created by part of the weight of the drill pipe column, and the horizontal force created by the rotation of the drill pipe column.

Drill bits, according to the nature of rock destruction, are classified as follows [1, 2]:

- chisels of cutting and scalping action. The chisels are designed for the destruction of viscous, plastic, non-abrasive and slightly abrasive rocks;
- chisels of abrasive-scalating action. The chisels are designed for the destruction of non-abrasive and abrasive rocks of medium hardness;
- abrasive action chisels. Chisels are used for drilling non-abrasive and abrasive hard, strong and very strong rocks;
- chisels of cutting and erasing action. The chisels are designed for the destruction of non-abrasive, medium hardness and hard rocks. They are used for drilling of alternating hardness, abrasive and non-abrasive rocks.

According to the purpose, drill bits are combined into three groups:

- for drilling wells with a solid face, without core sampling;
- for drilling wells with core sampling;
- to perform special work in the well.

By design, drill bits are divided into: bladed; spherical; diamond and carbide ones [3, 4].

For drilling wells with a solid face, bladed, spherical, diamond and carbide bits are used [5, 6].

According to the principle of operation, polycrystalline diamond chisels belong to the chisels of cutting and scaling action. Their special feature is the presence of a thin layer of synthetic polycrystalline diamonds on the surface of the cutting elements, firmly connected to a hard alloy base [7, 8]. The cutting elements made in this way have high strength characteristics that are not inferior to natural diamonds.

The diameter of the plates with which the cutters are reinforced ranges from 12.7 to 50.8 mm. The thickness of the diamond layer is 0.5–0.7 mm. The plates are attached to the carbide base by welding. Thus, the elements of the chisel tooling are obtained in the form of a tooth or a cutter [9, 10].

Polycrystalline diamond bits provide high mechanical penetration speed. At the same time, when drilling wells, there is no need to create a large axial load. Due to this, less energy is spent on rock destruction, while increasing the mechanical drilling speed. And as a result, rock-crushing and drilling tools wear out less.

To date, polycrystalline diamond bits (PDC bits) in a wide range of types and sizes are produced by well-known foreign companies such as "Nughes Christensen", "Hycalos", "Reed Tool", "Diamond Boart", "J. K. Smith", "Security" [11, 12].

The rapid scientific and technological progress of drilling equipment and technologies has led to the creation of new rock-crushing tools. Recently, employees of Satbayev University, (the Republic of Kazakhstan), the Institute of Superhard Materials named after Bakul (Ukraine) and Dnipro University of Technology (Ukraine) proposed a number of designs of PDC chisels. Among the latter, PDC diamond carbide cutters occupy a special place. They are widely and effectively used for arming bits when drilling oil and gas and technological wells. A special feature of the design of the mentioned cutters is the round shape and the negative angle of inclination with respect to the face.

In recent decades, the staff of Satbayev University and Dnipro University of Technology have accumulated extensive experience in developing new types of chisels equipped with PDC cutters.

Literature review. Initially, let us consider the design of the EC PDC-161 bit (Fig. 1), designed for drilling technological wells with a diameter of 161 mm [13 The chisel contains a housing *1* with a thread *2* for connection to the drill string (not shown). Four blades *3* are welded to the body. The armament of the latter is made in the form of a pair: "cutter RDC *4* is a superhard cylindrical element *5*" (Fig. 1, *E*). A feature of the placement of each mentioned pair is that the cutting edge of the PDC cutter and the end of the carbide element are in the same plane. The peripheral (lateral) part of the blades contains superhard cylindrical inserts *6*. The body *1* of the bit from below (from the side of the well face) has a central, expanding hole with a thread to the top, with which the core *7* is mated, representing a pyramidal peak with a diamond-coated carbide cutter soldered in the truncated top. The core also has a central cavity mating with inclined channels. Above the internal thread of the housing *1*, inclined holes are made at an angle of 30° to its axis (Fig. 1, *E*) with an outlet thread, into which four hydraulic monitoring nozzles *9* are screwed (Figs. 1. *D, C*).

The drilling bit EC PDC – 220.7 (Fig. 2) designed for drilling oil and gas wells of constructive type is characterized by a large drilling diameter, the number of blades (six instead of four for EC PDC-161) and the absence of hydraulic monitoring nozzles [13, 14]. The location at the end of the pair "cutter PDC - the carbide cylindrical element" is "the same as in the EC PDC-161 bit" (Fig. 1, *E*).

The peculiarity of the destruction of the bottom of wells with EC PDC bits, regardless of diameter, is explained in Fig. 1, *E*.

After connecting the bit to the drill string, it is lowered to the bottom. At the same time, before reaching the bottom, a new bit is flushed and run-in in the bottom-hole part of the well. Then, in accordance with the geological and technical order (GTO), an axial load and a torque (rotational frequency) are applied to the drilling rig. The mentioned parameters and the consumption of drilling mud are adjusted to the required rational values. Each pair of downhole armament (PDC cutter and superhard cylindrical element) acts on the face as follows: superhard insert *5* forms a crack-weakened zone when exposed to the face. The power of the latter in hard rocks increases the depth of diamond grain penetration 8–10 times, which allows the blade of the PDC cutters to remove the rock of the mentioned zone without difficulty.

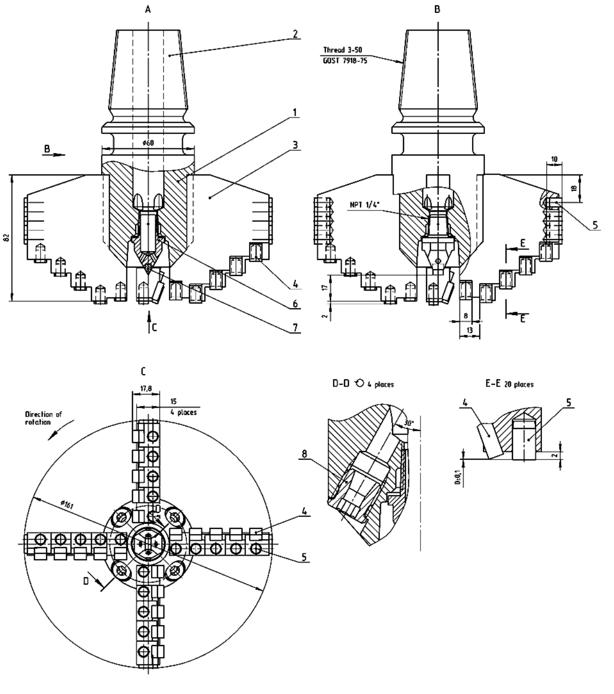


Fig. 1. Drilling bit EC PDC-161:

A – general view; B – left view; C – bottom view; D–D – an incision along the nozzle for the supply of flushing liquid; E–E – incision along the blade of a pair of PDC cutters; 4 – superhard cylindrical bead 5

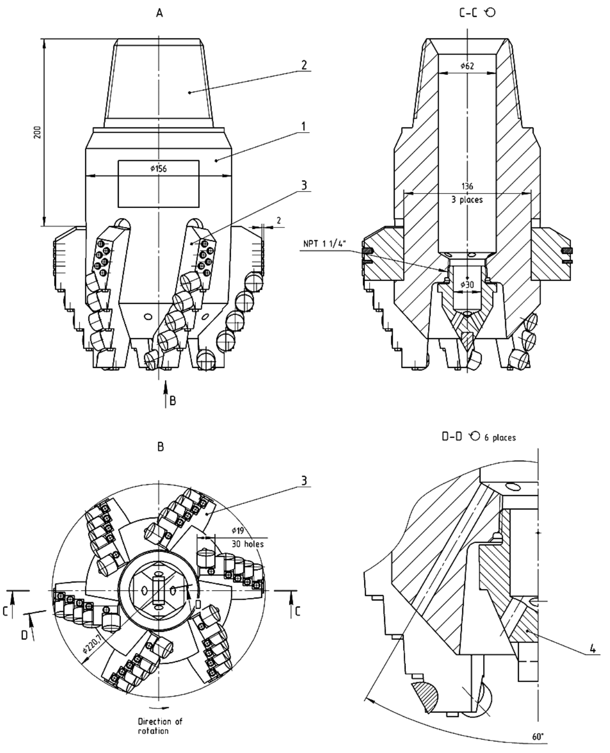


Fig. 2. EC PDC drill bit -220,7:

A – general view; B – bottom view (view of the end); C–C – incision; D–D – an incision along the opening for the supply of washing liquid

To realize the most effective destruction of the face, it is very important to determine the ratio of the distance between the plane in which the ends of superhard cylindrical inserts are placed and the PDC cutters. The following variants of spatial placement of the working elements of paired weapons relative to each other are possible (Fig. 3) [15, 16].

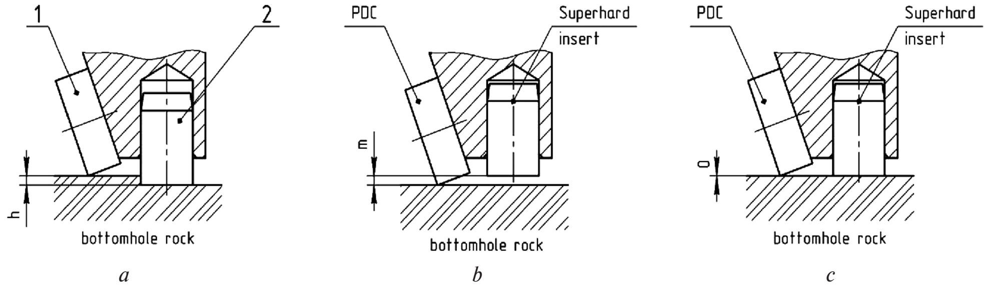
In the first variant (Fig. 3, *a*), the end of the superhard cylindrical insert is closer to the face than above the plane in which the edge of the PDC cutter is located. The disadvantage of this option is a slow, irrational decrease in the height of the insert to the plane in which the cutting edge of the PDC cutter is located, and the latter is inefficiently involved in the destruction of the bottom hole during this period [17, 18].

In the second variant, (Fig. 3, *b*) when the edge of the PDC cutter is closer to the face than the end of the insert, excessive load on the said cutter and its breakage will be observed.

The third option (Fig. 3, *b*) is the most rational, since it implements the combined effect of *2* weapons elements: the formation of cracks, weakening of the rock strength with a carbide insert and its subsequent removal with a PDC cutter blade.

It follows from the above that in the initial stage of drilling, when the zone of rock weakened by cracks has not yet been formed, it is necessary to reduce the axial load on the bit, which then gradually increases to a rational value in accordance with the GTO.

The purpose of the study. Determination of the dependence of the depth of penetration of the PDC cutter into the bottom hole rock, taking into account its geometric parameters and spatial distribution in relation to the destroyed array.



a *b* *c*

Fig. 3. Options for spatial placement of paired work items relative to each other:

a — the end of the insert is located closer to the bottom than the PDC cutter; b — the PDC cutter is located closer to the bottom than the end of the insert; c — the PDC cutter and the end of the insert are in the face plane

Setting the task. The chisel works at the bottom of the well until the armament is completely worn out, unless there are other requirements for the drilling process. Since the chisel is experimental, the mechanical drilling speed is fixed during the downhole deepening, and when lifting the tool from the well, the travel speed, the length of the drilled interval and the durability of the bit are fixed. The drill bit is a tool that directly destroys and deepens the bottom of the well, and works in very difficult conditions. Therefore, it is very important to comply with the drilling technology specified in the geological and technical order. Excessive load on the face can cause the bit to burn, and the lack of drilling fluid consumption can lead to the jamming of wells and the abandonment of drilling tools at the bottom. During descent operations and assembly of the projectile, attention should be paid to diamond-containing weapons, avoid sharp impacts, it is necessary to screw the chisel with a cap wrench, clamping it by the body of the chisel, and not by its armament.

At the same time, there is currently no theoretical research that would take into account the features of the geometric parameters of the PDC cutters (circular shape) and the placement of the latter in space (negative angle of the cutter when meeting the bottom of the well). In the proposed work, an attempt is made to take into account the mentioned features when the incisors come into contact with the bottom hole rock.

It was previously established [18] that during rotational drilling, the initial velocity V of the downhole deepening is determined by the following formula

$$V = h \cdot m \cdot n, \tag{1}$$

where h is the deepening of the face in one revolution of the tool by cutters located at the same radius of rotation; m is the number of cutters deepening the annular face of the well; n is the rotation speed of the tool, rpm.

Certain problems arise when determining the depth h of the incisor insertion. For a long time, its value h has been determined when a prismatic sharpened cutter is embedded in the rock, in which the configuration of the embedded part of the cutter, both the front and rear faces, represents rectangles. Currently, as a result of a rapid technical process, drilling tools armed with diamond-carbide PDC cutters have been created and are being used with great effect [19, 20]. However, in order to preserve the strength of the diamond layer of the cutter, the latter is installed with a negative angle of the front face, and the latter is pressed into the rock and has the shape of a segment, unlike prismatic cutters. The above features undoubtedly influenced the determination of the height h depending on (1). The authors [21, 22] solved the problem for these features of the shape of the PDC incisor (a circle, and the pressed part of the circle into the rock is a segment), and its placement in space is the negative front angle of the incisor face (Fig. 4).

Research results and their analysis. When considering the equilibrium of forces acting on the embedded diamond carbide cutter PDC, the following equation is obtained

$$P_0\frac{(\cos\beta-\sin\beta)}{\sin(2\beta)(1+f^2)}=H_k\sin\beta f_{segm}= \\ =H_k\sin\beta\cdot 0.5\left[rl-c(r-h_{\max})\right], \tag{2}$$

where P_0 is the axial load on the PDC cutter; β is the angle of inclination of the upper face of the PDC cutter relative to the vertical; f is the coefficient of friction between the PDC cutter and the rock; H_k is the contact strength of the rock. $H_k = 0.62P_h$ [23, 24] (P_h is the hardness of the rock according to A. A. Schreiner); C is the chord length of the segment of the PDC cutter

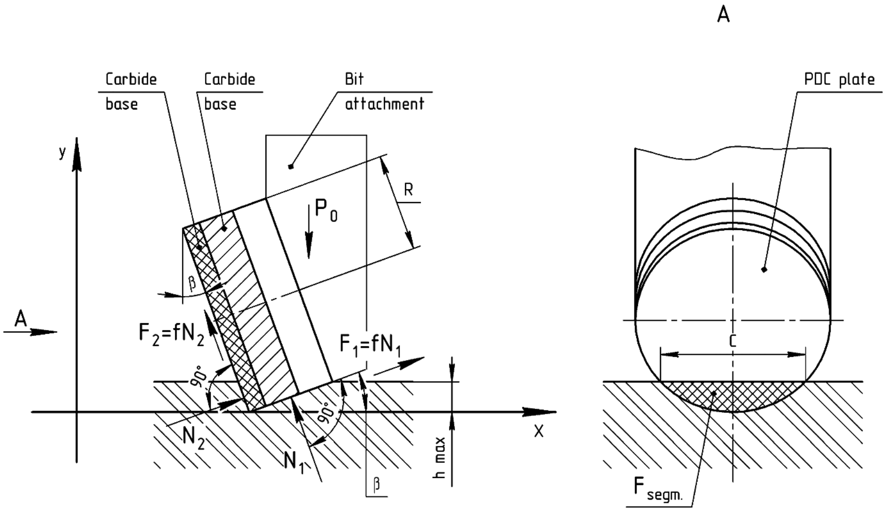


Fig. 4. The scheme of embedding the PDC cutter into the bottom hole rock

embedded in the rock (Fig. 5); f_{segm} is the area of the segment formed when the PDC cutter is pressed into the bottom of the well; r is the radius of the diamond-holding plate of the PDC cutter (Fig. 1); l is the arc length of the AEDKB segment (Fig. 1).

However, it is difficult to use the obtained formula (3) [25, 26], since the result obtained (the value of $h_{\max}$ is the height of the segment) will be negatively affected by its other parameters (r, l, c) of the second layer associated with the value of $h_{\max}$. Taking into account these difficulties, we establish dependence (3) with some approximation that allows its use in calculations.

Having resolved (2) with respect to $h_{\max}$ and performed the necessary transformations, we obtain

$$h_{\max} = P_o \frac{(\cos\beta - \sin\beta)}{c \cdot \sin 2\beta (1+f^2) H_{\hat{E}} \sin\beta} - \left(\frac{rl}{c} - r\right). \qquad (3)$$

To this end, we replace the AEDKB segment of the PDC cutter embedded in the rock to a depth of h with an isosceles triangle ADB embedded in the rock to the same depth h. It was found that at shallow depths h, the area of the ADB triangle decreases relative to the area of the AEDKB segment by about 30 %, i.e. if the area of the segment and the isosceles triangle are designated S_1 and S_2, respectively, then their ratio is $S_1 : S_2 = 1.3$ [27, 28].

Therefore, approximately replacing the area of the segment with the area of the mentioned triangle ADB, we get

$$\frac{P_o(\cos\beta - \sin\beta)}{\cos(2\beta 1 + f^2)} = 0.62 P_h \sin\beta \frac{Ch_{\max}}{2}. \qquad (4)$$

From the approximate dependence (4), we find the depth of the $h_{\max}$ insertion of the PDC cutter

$$h_{\max} = \frac{2P_o(\cos\beta - \sin\beta)}{C \cdot 0.62 P_h \sin\beta \cos(2\beta)(1+f^2)}. \qquad (5)$$

Substituting the $h_{\max}$ value into formula (2), we obtain the initial drilling speed with a chisel. The analysis of the dependence (5) shows that not all difficulties in using the mentioned formula (5) have been overcome, since in the real segment the values h and C are related to each other. Therefore, when calculating, it is necessary to assign the exact value of the C chord of the segment, which would actually correspond to the last one when calculating the depth h of the PDC incisor (Fig. 6). In other words, the first calculation according to formula (4) is approximate, it shows in which direction the value h needs to be changed (sideways increases in the C chord, or in the opposite direction with a decrease in magnitude). If the radius of the diamond-hard-alloy plate cutter and the hardness of the drilled rocks are known, it is possible to try to approximate the amount of the recess in one turn of the bit using the real drilling speed and the applied modes [29, 30], and assign the value C according to its value according to Table 1 and calculate the recess of h wells more accurately using formula (5). If there are no mentioned data, the value of C is determined approximately, substituted into formula (5), h_{max} is calculated, which is compared with the theoretical h corresponding to the initially selected value of C. Then the calculation according to formula (5) is repeated using the new value C. Corresponding to this new value C, the value h is again compared with the h_{max} obtained by calculation. The calculation is repeated until there is a slight discrepancy between the calculated max and h corresponding to the tabular value C (Table).

According to Table, a graphical dependence of the height of the h segment (which in this case means the depth of a single PDC cutter during drilling) on the length of the C segment

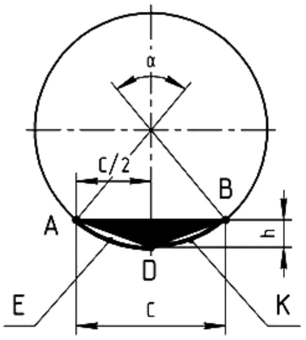


Fig. 5. The actual (AEDKB arc) and proposed approximate shape (isosceles triangle ADB) of the profile of the depressed PDC incisor)

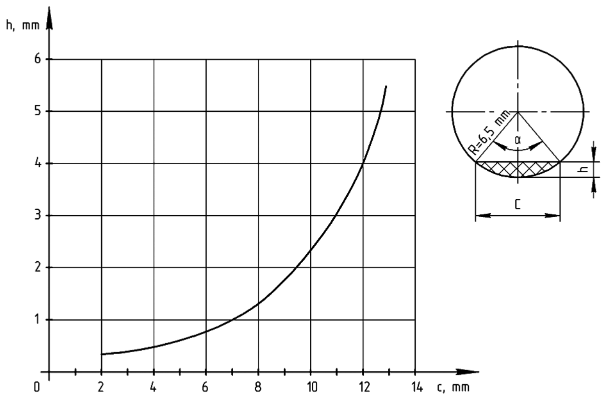


Fig. 6. Dependence of the height of the segment h on the length of the chord C

Table

Segment parameters (arc length l, chord length C, height h, area S) for different angles of the segment α

The radius of the PDC cutter is $R = 6.5$ mm	Formulas for calculating segment parameters: $L = \alpha R$; $c = 2R \cdot \sin\alpha/2$; $h = R(1 - \cos\alpha/2)$; $S = 1/2 \cdot R^2(\alpha - \sin\alpha)$					
	$\sin\alpha/2$	$\cos\alpha/2$	c, mm	h, mm	$\alpha - \sin\alpha$	S, mm^2
$\alpha = 30° = 0.523$ rad	0.259	0.966	3.370	0.442	0.523 – 0.500 = 0.023	0.486
$\alpha = 60° = 1.047$ rad	0.500	0.866	6.500	0.871	1.047 – 0.860 = 0.181	3.820
$\alpha = 90° = 1.57$ rad	0.707	0.707	9.191	1.904	1.570 – 1.000 = 0.570	12.040
$\alpha = 105° = 1.832$ rad	0.793	0.609	10.310	2.541	1.832 – 0.966 = 0.866	18.290
$\alpha = 120° = 2.093$ rad	0.866	0.500	11.260	3.250	2.093 – 0.866 = 1.227	25.920
$\alpha = 135° = 2.355$ rad	0.924	0.383	12.010	4.010	2.355 – 0.707 = 1.648	34.810
$\alpha = 150° = 2.617$ rad	0.966	0.259	12.560	4.820	2.617 – 0.500 = 2.117	44.720
$\alpha = 165° = 2.878$ rad	0.991	0.130	12.880	5.650	2.878 – 0.665 = 2.213	55.520
$\alpha = 180° = 3.14$ rad	1.000	0.000	13.000	6.500	3.140 – 0.000 = 3.140	66.330

is constructed. With the existing drilling technology, calculations most often use part of the $h \cdot H(c)$ graph in the range from $C = 2$ to $C = 8.5$ mm. The corresponding h values are in the range $0.3 < h < 1.7$ mm (Fig. 6). Taking into account the mentioned ranges, the expected initial drilling speed will be from 2 m/h (very hard rocks) to 3.5 m/h (very soft rocks).

An example of determining the depth of insertion of a PDC cutter in one revolution.

Initial data: axial load on the chisel $P_g = 80$ kH, the number of incisors at the end of the chisel $m_o = 30$, and at one rotation radius $m = 4$; rotation speed $n = 1.5$ rpm; anterior angle of inclination of the front face $\beta = 15°$; rock hardness according to A. A. Schreiner $P_h = 3$ kH/mm; $f = 0.3$.

Solution: since there are no other clarifying data, we assume the length of the chord of the segment in contact with the rock when the incisor is inserted $C = 8$ mm, which corresponds to the length $h = 1.27$ mm (Table and Fig. 6). The load on one PDC cutter will be $P_o = P_g/m_o = 80$ kH/30 = 2.67 kH.

We calculate the depth $h_{\max}$ of the incisor insertion into the rock, mm

$$h_{\max} = \frac{2 \cdot 2.67(\cos 15° - \sin 15°)}{8 \cdot 0.62 \cdot 3 \sin 15° \cos 38° (1 + 0.3^2)} = \frac{8.296}{8} = 1.03.$$

At $C = 8$ mm, $h_{tabl} = 1.27$ mm. If we had set $C = 7$, then when calculating $h_{\max}$ according to formula (5), the value $h_{\max} = 8.296/7 = 1.185$ mm was obtained, which is closer to the real value of $C = 7$ mm, which should be applied when calculating according to formula (5).

The speed calculation according to (1) showed $V = 1.185 \times$ $\times\, 4 \cdot 1.5 = 25.586 = 25.5$ m/h.

Conclusions.

1. The formula we derived earlier to determine the depth of penetration of the PDC cutter into the bottom hole rock in one turn of the bit requires some simplification and approximate estimation, since the depth of penetration due to the round shape of the cutting part of the cutter is the height of the segment and depends on its other parameters: chord length, segment angle and segment arc length, into the formula. In order to make it possible to use the formula with some approximation, the area of the segment forming the PDC incisor embedded in the rock was replaced by the area of an isosceles triangle, the base of which is the chord, and its height coincides with the height of the segment. At the same time, due to the decrease in the area of the triangle relative to the area of the segment, the error is on average 30 %.

2. A technique has been developed for using a simplified formula to determine the depth of insertion of a PDC cutter in one revolution. Its essence lies in correctly assigning the value of the chord of the segment, which would correspond to the depth of the embedding and its tabular value (i.e., the height of the segment with the selected chord length). This requires several calculations that approximate the values of the calculated value and the tabular values of the embedding depth and segment height to each other.

3. The obtained simplified dependences of the depth of penetration of a single PDC cutter make it possible, with known parameters of the PDC bit drilling mode and the hardness of rough rocks, to predict with satisfactory accuracy the expected mechanical drilling speed at a particular geological object, and in the future, taking into account the abrasive properties of rocks, to reduce the number of rock-crushing tools for the entire volume of drilling operations.

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Удосконалення методики розрахунку очікуваної швидкості буріння долотами PDC

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Мета. Встановлення залежності глибини проникнення різця PDC у породу вибою свердловини з урахуванням його геометричних параметрів і просторового розміщення по відношенню до масиву, що руйнується.

Методика. Поставлені завдання вирішувалися комплексним методом дослідження, що включає аналіз й узагальнення літературних і патентних джерел, проведення теоретичних досліджень, що полягають у вирішенні теоретичного завдання впливу надтвердого різця круглої форми на пружно крихкий гірський масив, з використанням методів комп'ютерного й математичного моделювання.

Результати. Отримано спрощений вираз, що дозволяє з достатньою для інженерних розрахунків точністю врахувати особливості різця PDC щодо глибини його проникнення в породу вибою свердловини. Запропонована методика розрахунку глибини руйнування за один оборот алмазотвердосплавного різця PDC у гірській породі вибою свердловини. Встановлені закономірності руйнування запропонованим алмазотвердосплавним PDC долотом масиву гірських порід на вибої свердловини від параметрів режиму буріння та твердості буримих порід.

Наукова новизна. Уперше отримана залежність впливу геометричних параметрів форми одиничного алмазотвердосплавного різця PDC і просторового його розміщення в тілі матриці долота від величини технологічних параметрів буріння свердловини, та їх впливу на характер руйнування масиву різцями PDC.

Практична значимість. Запропонована методика визначення глибини проникнення одиничного різця PDC, використання якої дозволить залежно від геолого-технічних умов буріння свердловин прогнозувати механічну швидкість. А з урахуванням абразивних властивостей порід знизити зношування долот, а отже кількість необхідного породоруйнівного інструменту на весь обсяг бурових робіт при будівництві свердловини.

Ключові слова: *долото, різець, PDC, вибій, свердловина*

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