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Development of math model of geokhod bladed working body interaction with geo-environment

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Abstract. The article describes basic mathematical dependencies for determining of power parameters of geokhods' bladed working bodies both conventional and toothed ones.

Introduction.
Some authors [1,2,3] consider mine working as rigid body motion in solid earth. This approach is the foundation of the geo-winch mining method, geokhods being its basic functional elements.

Geokhods are machines that move in the subsurface using geological environment for advancing. Geokhods are a new class of mining machinery and designed for mine workings of various purpose and spacing.

For geokhod underground workings at shallow depths in unstable rocks a bladed working body (WB) is proposed to use. Lack of design procedure for the bladed working bodies of different designs is a limiting factor of geokhod manufacturing.

Purpose of the work. The aim of the work is to develop a mathematical model of geokhod bladed WB interaction with rock mass.

Special mode of geokhod advancement causes formation of complex surfaces both of the face and of the WB [4]. The face surface has the form of several ledged helical surfaces [5,6,7]. Any point of the blade, located at a distance x (see Figure 1) from the geokhod rotation axis, advances to the face at an angle:

$$\beta_x = arctg\frac{h_B}{2\pi x} \tag{1}$$

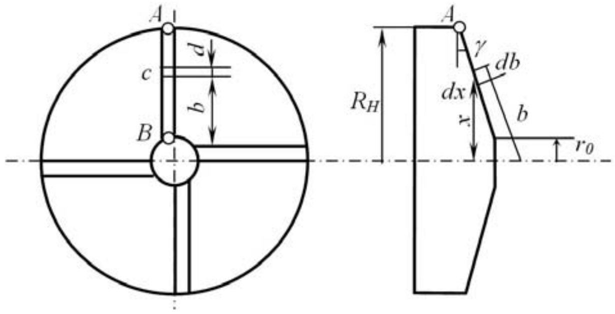

Figure 1. Scheme of the working body blade.

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The blade points being closer to the geokhod rotation axis advance to the face at a larger angle than the points being at the blade periphery (Figure 2a). In this way, at helical (screw-like) advancing of the blade to the face, radial blade points form a helicoid (screw-like) surface. Consequently, face surface in the sector between adjacent radial blades takes the form of a helical surface after their passage.

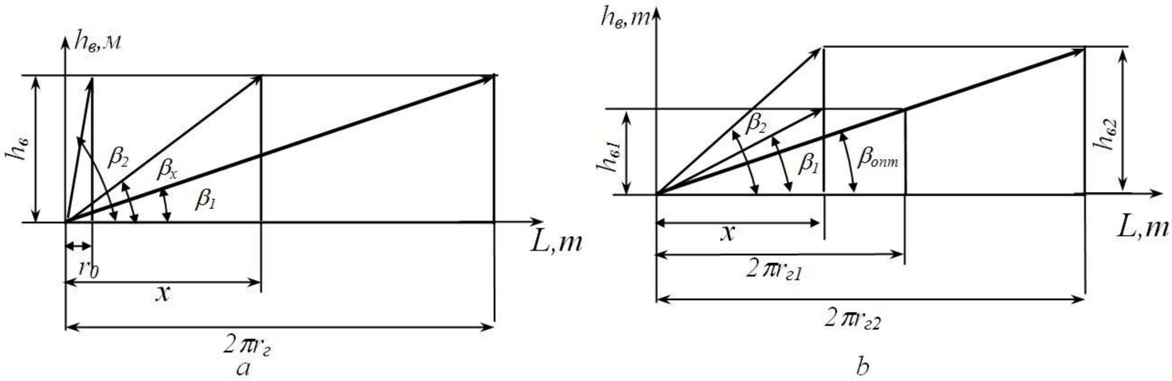

Figure 2 Direction of blade points movement, depending on:
a - location at a radial blade; b - geokhod standard size.

Furthermore, if radius of the geokhod head section is increased at some optimal tilt angle (β_{opt}) of the external helical blade, then any point, being at a distance x from the geokhod center, passes a distance $h_{в2}$ differing $h_{в1}$ per revolution.

Therefore, helicoid geometric parameters, in the form of which a radial blade profile is manufactured, depend on parameters of the external mover ($r_г$ - radius of the geokhod head section, $h_в$ - helical blade step, β - tilt angle of the blade) and are specific for each standard size.

Ledge height h depends on a helical blade step and a number of radial blades mounted on a geokhod working body:

$$h = \frac{h_B}{n}, \tag{2}$$

where n is a number of blades.

Radial blades produce a corresponding amount of mutually conjugate helical areas at the face. A ledge that is formed between two mutually conjugate helical areas is continuously formed and destroyed by the blades as they advance on the face.

The complex helical face is determined only by the nature of geokhod advancing, so helical surface is formed by the work of any radial WB, regardless of its design and tools.

Using fragments of a structural portrait based on integrated approach geokhod bladed WBs are designed [8]. It is noted that the geometric parameters of blades are special for each geokhod radius.

As geokhod advances in the subsurface using geological environment its WB destroys (cuts) both loose and solid rocks. Then a rational number of WB blades must be chosen from the interval [9]:

$$n = \frac{tg\beta \cdot 2\pi r_г}{0{,}1 \div 0{,}2}. \tag{3}$$

Layout of the radial blades referred to the geokhod axis affects cutting forces.When cutting with one WB radial blade, a total blocking cutting force can be represented as a sum of three force components (Figure 3) [10]:

1 Force of earth resistance overcoming by the blade front edge $P_{cв}$, which is proportional to a cross-sectional area of the slot in front of the front blade edge and depends on a cutting angle and rock hardness;

2 Force of earth resistance overcoming in lateral slot widenings which (force) is proportional to these slot parts area and depends on rock hardness but does not depend on cutting angle and cut width;

3 Force of earth resistance overcoming by the blade lateral ribs at the slot bottom, proportional to the cut thickness, which (thickness) depends on rock hardness but does not depend on cutting angle and cut width.

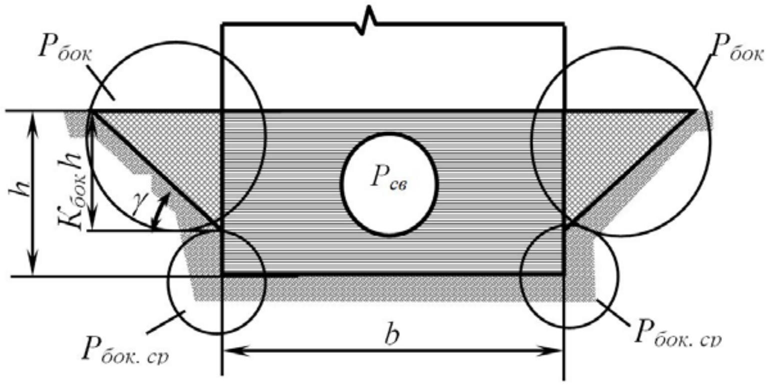

Figure 3. Diagram of the forces at block cut with a conventional blade.

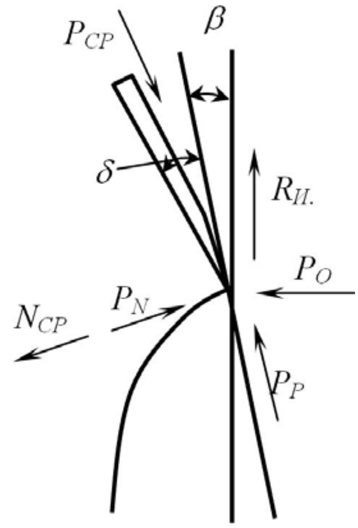

Figure 4. Design model for determination of total force of soil resistance to cutting by blade WB.

The geokhod WB advances to the face in accordance with steps of the helical blade mounted on the outer surface of the head section. Each point of the blade moves along a spiral trajectory. The blade points being closer to the geokhod rotation axis advance to the face at a larger angle than the points being at the blade periphery. So, at helical advancing of bladed WB to the face, radial blade points form a helicoid surface. Consequently, the face takes a helical form.

The blades produce a corresponding amount of mutually conjugate helical areas at the face. A ledge that is formed between two mutually conjugate helical areas is continuously destroyed by the WB blades as they advance to the face.

Total force of blocking cutting by a conventional blade (Figure 4)[11]:

$$P_{ср} = \varphi m_{св} bh + 2m_{бок}h^2 + 2m_{бок.ср}h \, , \tag{4}$$

where $\varphi\ m_{св}bh$ is cutting force component for front resistance overcoming ($P_{св}$ in fig. 3), H;

$2m_{бок}h^2$ - total rock destruction force in lateral slot widenings ($P_{бок}$ in fig. 3), H;

$2m_{бок.ср}h$ - lateral cut forces ($P_{бок.ср}$ in fig. 3), H;

φ - coefficient of cutting angle impact;

$m_{св}$ - specific cutting force for earth resistance overcoming by a front edge at cutting angle 45^0, Pa;

b - blade width, m;

h - cut depth, m;

$m_{бок}$ - coefficient of destruction force in slot lateral parts, Pa;

$m_{бок.ср}$ - coefficient of specific force of cut by a lateral edge, H/m.

Dependencies for determination of cutting forces of bladed WB are developed in [9]. General dependencies are as follows:

$$P_{о.св} = \frac{\varphi m_{св} h_в^2 + h_в n P_{изн}}{2\pi n \cos\gamma} \cdot \left(\ln \frac{tg\left|\frac{\beta_2}{2}\right|}{tg\left|\frac{\beta_1}{2}\right|} \right) - \quad ; \tag{5}$$

$$-\frac{h_в}{2\pi}\left(\varphi m_{св} \frac{h_в}{n} \frac{ctg(\delta+\varphi_{TP})}{\cos\gamma} - \frac{ctg(\delta_1+\varphi_{TP})}{\cos\gamma} P_{изн}\right) \frac{\sin\beta_2 - \sin\beta_1}{\sin\beta_1 \sin\beta_2}$$

$$R_{и.о.св} = \frac{\varphi m_{св} h_в^2 + h_в n P_{изн}}{2\pi n \cos\gamma} \cdot \frac{\sin\beta_2 - \sin\beta_1}{\sin\beta_1 \sin\beta_2} +$$

$$+\frac{h_в}{2\pi}\left(\varphi m_{св} \frac{h_в}{n} \frac{ctg(\delta+\varphi_{TP})}{\cos\gamma} - \frac{ctg(\delta_1+\varphi_{TP})}{\cos\gamma} P_{изн}\right) \cdot \left(\ln \frac{tg\left|\frac{\beta_2}{2}\right|}{tg\left|\frac{\beta_1}{2}\right|} \right); \tag{6}$$

$$M_{и.о.св} = \frac{\varphi m_{св} h_в^3 + h_в^2 n P_{изн}}{8\pi^2 n \cos\gamma} \left(\ln\left| \frac{tg\frac{\beta_1}{2}}{tg\frac{\beta_2}{2}} \right| + \frac{\cos\beta_2 \sin^2\beta_1 - \cos\beta_1 \sin^2\beta_2}{\sin^2\beta_1 \sin^2\beta_2} \right) + . \tag{7}$$

$$+\frac{h_в^2}{4\pi^2}\left(\varphi m_{св} \frac{h_в}{n} \frac{ctg(\delta+\varphi_{TP})}{\cos\gamma} - \frac{ctg(\delta_1+\varphi_{TP})}{\cos\gamma} P_{изн}\right) \cdot \frac{\sin\beta_2 - \sin\beta_1}{\sin\beta_1 \sin\beta_2}$$

Projection of cutting resistance force, independent of cut width, to rotation axis and a plane perpendicular to the rotation axis; and cutting resistance moment of this component:

$$P_{о.бок} = (\sin\beta_1 + \sin\beta_2)\frac{P_{бок}}{2} - (\cos\beta_1 + \cos\beta_2)\frac{N_{бок}}{2}; \tag{8}$$

$$R_{.и.о.бок} = (\cos\beta_1 + \cos\beta_2)\frac{P_{бок}}{2} + (\sin\beta_1 + \sin\beta_2)\frac{N_{бок}}{2} \tag{9}$$

$$M_{.и.о.бок} = (r_г \cos\beta_1 + r_о \cos\beta_2)\frac{P_{бок}}{2} + (r_г \sin\beta_1 + r_о \sin\beta_2)\frac{N_{бок}}{2}. \tag{10}$$

Insert (5), (6) and (7) in the formulas obtained and after some rearrangements we obtain

$$P_{о.бок} = \frac{h_B}{n}\left(m_{бок}\frac{h_B}{n} + m_{бок.ср}\right)\left[-\frac{\cos(\delta+\varphi_{тр}+\beta_1) + \cos(\delta+\varphi_{тр}+\beta_2)}{\sin(\delta+\varphi_{тр})}\right]; \tag{11}$$

$$R_{и.о.бок} = \frac{h_B}{n}\left(m_{бок}\frac{h_B}{n} + m_{бок.ср}\right)\left[\frac{\sin(\delta+\varphi_{тр}+\beta_1) + \sin(\delta+\varphi_{тр}+\beta_2)}{\sin(\delta+\varphi_{тр})}\right]; \tag{12}$$

$$M_{и.о.бок} = \frac{h_B}{n}\left(m_{бок}\frac{h_B}{n} + m_{бок.ср}\right)\left[\frac{r_г \sin(\delta+\varphi_{тр}+\beta_1) + r_о \sin(\delta+\varphi_{тр}+\beta_2)}{\sin(\delta+\varphi_{тр})}\right] \tag{13}$$

For the bladed WB a total projection of earth cutting resistance force to rotation axis and a plane perpendicular to the rotation axis; and a total cutting resistance moment are equal to:

$$P_o = n\left(P_{o.св} + P_{бок}\right); \tag{14}$$

$$R_{и.о} = n\left(R_{и.о.св} + R_{и.о.бок}\right); \tag{15}$$

$$M_{и.о} = n\left(M_{и.о.св} + M_{и.о.бок}\right). \tag{16}$$

Toothed cutting part of the bladed WB has a complex shape: the teeth are mounted on a radial bar. Therefore, to determine cutting forces, toothed bladed WB will be considered as a complex blade consisting of interacting conventional blades.

Calculation of the complex blade operation is based on conventional blades interaction and values of superposition of rock rapture zones produced by each blade separately.

Mount of the teeth on radial blade reduces rock cutting resistance. As the teeth destroy rock in front of the main cutting edge, that reduces or eliminates cutting by side edges of the main blade of the WB [6].

The value of b (Figure 5) is the width of the tooth, which should be 0,06-0,08m. Wider teeth increase crowd force. Smaller width does not provide sufficient strength to the teeth.

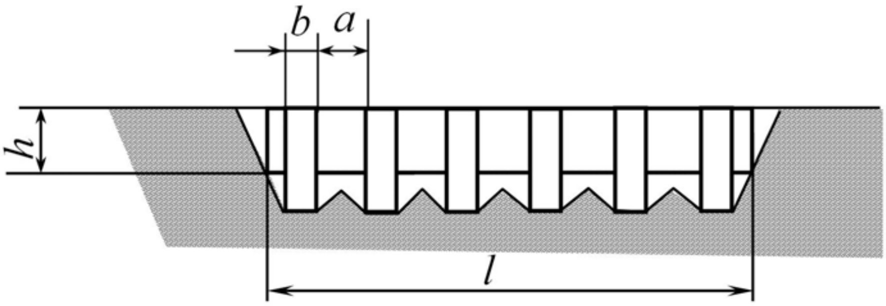

Figure 5. Scheme of teeth arrangement along the blade length.

For the bladed WB a blade length $l = r_г - r_o$ where $r_г$ is a radius of geokhod head section; r_o is the distance from the geokhod rotation axis to the nearest point of the blade. The number of teeth on one blade is:

$$n' = \frac{l}{3{,}5b''}. \tag{17}$$

Cutting force of a sharp complex blade by Y.A. Vetrov is equal [6]

$$P = \sum_{i=1}^{n'} p_{св_i} F_{св_i} + p_{бок} \sum_{i=1}^{n'} F_{бок_i} + p_{бок.ср} \sum_{i=1}^{n'} L_{бок.ср_i}. \tag{18}$$

If teeth are blunted or have a wear pad then the expression (18) takes the form

$$P = \sum_{i=1}^{n'} p_{св_i} F_{св_i} + p_{бок} \sum_{i=1}^{n'} F_{бок_i} + p_{бок.ср} \sum_{i=1}^{n'} L_{бок.ср_i} + \sum_{i=1}^{n'} p_{пл.изн\,i} L_{пл.изн_i}, \tag{19}$$

where $F_{св_i}, F_{бок_i}$ are sub-areas, m^2; $L_{бок.ср_i}, L_{пл.изн_i}$ - cut line lengths, m; $p_{св_i}, p_{бок}, p_{бок.ср}, p_{пл.изн\,i}$ - specified cutting sub-forces.

Normal cutting force of a sharp complex blade by Y.A. Vetrov is equal [6]

$$N = \sum_{i=1}^{n'} p_{св_i} F_{св_i} ctg(\delta_i + \mu) + p_{бок} \sum_{i=1}^{n'} F_{бок_i} ctg(\delta_i + \mu) + p_{бок.ср} \sum_{i=1}^{n'} L_{бок.ср_i} ctg(\delta_i + \mu) \tag{20}$$

Considering the force arising from operation with blunt or having a wear pad teeth, expression (20) takes the form

$$N = \sum_{i=1}^{n'} p_{св_i} F_{св_i} ctg(\delta_i + \mu) + p_{бок} \sum_{i=1}^{n'} F_{бок_i} ctg(\delta_i + \mu) + \\ + p_{бок.ср} \sum_{i=1}^{n'} L_{бок.ср_i} ctg(\delta_i + \mu) + \sum_{i=1}^{n'} p_{пл.изн\,i} L_{пл.изн_i} ctg(\delta_i + \mu). \quad (21)$$

When calculating force dependencies one should consider technical features and specifications of the teethed bladed working body, as well as the calculation scheme of rock cutting resistance total force.

Projection of cutting resistance force to rotation axis and a plane perpendicular to the rotation axis; and cutting resistance moment of this component [12]:

$$P_o^з = \sin\beta_i P - \cos\beta_i N; \quad (22)$$

$$R_{и.о}^з = \cos\beta_i P + \sin\beta_i N; \quad (23)$$

$$M_{и.о}^з = x_i R_{и.о}^з, \quad (24)$$

where x – is a distance from rotation axis to every n' tooth, m.

The final expressions of determining forces for sharp teeth

$$P_o^з = \sum_{i=1}^{n'} p_{св_i} F_{св_i} A_i + p_{бок} \sum_{i=1}^{n'} F_{бок_i} A_i + p_{бок.ср} \sum_{i=1}^{n'} L_{бок.ср_i} A_i; \quad (25)$$

$$R_{и.о}^з = \sum_{i=1}^{n'} p_{св_i} F_{св_i} B_i + p_{бок} \sum_{i=1}^{n'} F_{бок_i} B_i + p_{бок.ср} \sum_{i=1}^{n'} L_{бок.ср_i} B_i; \quad (26)$$

$$M_{и.о}^з = \sum_{i=1}^{n'} p_{св_i} F_{св_i} x_i B_i + p_{бок} \sum_{i=1}^{n'} F_{бок_i} x_i B_i + p_{бок.ср} \sum_{i=1}^{n'} L_{бок.ср_i} x_i B_i, \quad (27)$$

where $A_i = (\sin\beta_i - ctg(\delta_i + \mu)\cos\beta_i)$ and $B_i = (\cos\beta_i + ctg(\delta_i + \mu)\sin\beta_i)$;

For blunt or having a wear pad teeth expressions (25), (26), (27) take the form

$$P_o^з = \sum_{i=1}^{n'} p_{св_i} F_{св_i} A_i + p_{бок} \sum_{i=1}^{n'} F_{бок_i} A_i + p_{бок.ср} \sum_{i=1}^{n'} L_{бок.ср_i} A_i + \sum_{i=1}^{n'} p_{пл.изн\,i} L_{пл.изн_i} A_i; \quad (28)$$

$$R_{и.о}^з = \sum_{i=1}^{n'} p_{св_i} F_{св_i} B_i + p_{бок} \sum_{i=1}^{n'} F_{бок_i} B_i + p_{бок.ср} \sum_{i=1}^{n'} L_{бок.ср_i} B_i + \sum_{i=1}^{n'} p_{пл.изн\,i} L_{пл.изн_i} B_i; \quad (29)$$

$$M_{и.о}^з = \sum_{i=1}^{n'} p_{св_i} F_{св_i} x_i B_i + p_{бок} \sum_{i=1}^{n'} F_{бок_i} x_i B_i + p_{бок.ср} \sum_{i=1}^{n'} L_{бок.ср_i} x_i B_i + \sum_{i=1}^{n'} p_{пл.изн\,i} L_{пл.изн_i} x_i B_i. \quad (30)$$

Determination of force parameters of the blades cutting a peripheral edge helical channel is presented in [9].

For the radial bladed WB with one blade for cutting the helical channel [12,13,14], component cutting forces and resistance moment will be equal:

For conventional WB	*For teethed WB*
$P_{и.о.общ} = nP_o + \kappa P_o^в$	$P_{и.о.общ} = nP_o^з + \kappa P_o^в$
$R_{.и.о.общ} = nR_{и.о.} + \kappa R_{и.о}^в$	$R_{.и.о.общ} = nR_{и.о}^з + \kappa R_{и.о}^в$
$M_{и.о.общ} = nM_{и.о} + \kappa M_{и.о}^в$	$M_{и.о.общ} = nM_{и.о}^з + \kappa M_{и.о}^в$

Values of friction force and friction resistance moment are determined depending on rock pressure value [9,10,11,13]:

$$T_{HO} = \frac{\pi f_{TP} \lambda \gamma_{nop}}{f} \left(1 + 2tg\left(45^0 - \frac{\rho}{2} \right) \right) r_г^3; \quad (31)$$

$$M_{T.HO} = \frac{2\pi f_{TP} \lambda \gamma_{nop}}{3f} \left(1 + 2tg\left(45^0 - \frac{\rho}{2} \right) \right) r_г^4, \quad (32)$$

where λ - lateral pressure coefficient; γ_{nop} – rock specific weight, Нм^3; f - hardness coefficient on the M.Protodjakonov scale; ρ - rock internal friction angle, degrees.

Conclusions

A mathematical model of geokhod bladed WB interaction with geo-environment is obtained on the basis of the developed force parameters calculation method.

This method allows determining:

- Cutting forces on one radial blade both of the conventional and the teethed geokhod working body;
- Cutting forces on the geokhod bladed WB of various designs.
- Helicoid geometric parameters (l - radial blade length, β_i – angle of each i-th point of the blade), in the form of which a radial blade profile is manufactured, depend on parameters of the external mover ($r_г$ - radius of the geokhod head section, $h_в$ - helical blade step, β - tilt angle of the blade) and are specific for each standard size.

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