Investigation of the mathematical model of the knife of geokhod executive body interaction with the bottomhole rock

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Abstract. The article presents the relevance of the research. The features of the work of the executive body of geokhod are given. A previously developed mathematical model for determining the power and energy parameters of the interaction of the knife executive body of the geokhod with the face rock is presented. On the basis of the model, a study was carried out of the influence of the pitch of the external mover on the power and energy parameters of the interaction of the knife executive body of the geokhod with the bottomhole rock. As a result of the study, it was found that the power parameters increase with increase in the step of the external mover, and the energy parameters decrease.

1. Introduction
Increase in population leads to continuous increase in road transport. The growth of which is the cause of the acute problems of modern society. In this regard, interest in the use of underground space is growing, thereby increasing the volume of construction of underground structures [1-5].

As a result of a number of studies aimed at increasing productivity, a new approach to the construction of underground structures has been formed – geo-excitation technology, the basic element of which is a new class of mining equipment – geokhod [6-9].

The development of prototypes of geokhod is constrained by the lack of scientific foundations for creating their systems. When carrying out underground structures in the technological cycle, one of the main ones is the process of separating rocks from the massif. This process is carried out by the executive body (EB) of the tunneling unit [10-12].

When developing and designing the executive body, the power and energy parameters affecting it are taken into account. As a result, the work aimed at reducing the power and energy parameters of the interaction of the EB geokhod with the bottomhole rock is relevant.

2. Features of the EB of Geokhod
• The operation of the EB geokhod has a number of features that distinguish them from the operating conditions of the executive bodies of other tunneling systems [13-15]:
• Has no analogues among the existing shaft-sinking and tunnelling systems.
• Placement of working mechanisms in a limited space on a rotating supporting structure.
• The need to receive energy carriers from a power plant located on a non-rotating stabilizing section.
• The need to destroy the bottomhole for the full section of the excavation being carried out and for a considerable distance in one revolution of the section.
• The complex nature of moving destructive tools to the bottom.
• The need for the formation and destruction of the ledge;
• The need to ensure compliance with the parameters of the external mover and rigid kinematic connection with it.
• Placement and simultaneous coordinated work of a large number of destructive tools (knives, screws, drums, bars, etc.). The operation of the EB geokhod has a number of features that distinguish them from the operating conditions of the executive bodies of other tunneling systems [13-15];
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3. Mathematical model of the knife EB geokhod interaction with the bottomhole rock
For the knife of EB geokhod, the total projection of the cutting resistance force on the axis of rotation of the geokhod \( P_a \) and the plane perpendicular to the axis of rotation \( R_{p,a} \), as well as the total moment of resistance to cutting \( M_{p,a} \), respectively, are equal [16-18]:

\[
P_a = n(P_{a,o} + P_s);
\]

\[
R_{p,a} = n(R_{p,a,o} + R_{p,a,s});
\]

\[
M_{p,a} = n(M_{p,a,o} + M_{p,a,s}).
\]

where \( n \) is the number of beams on the EB of the geokhod; \( P_{a,o} \) – projection of the component of the cutting resistance force, depending on the width of the cut, on the axis of rotation of the geokhod; \( P_s \) is the projection of the component of the cutting resistance force, independent of the cut width, onto the axis of rotation of the geokhod; \( R_{p,a,o} \) – the projection of the component of the cutting resistance force, depending on the width of the cut, on the plane perpendicular to the axis of rotation; \( R_{p,a} \) – the projection of the component of the soil resistance to cutting, independent of the width of the cut, on a plane perpendicular to the axis of rotation; \( M_{p,a,o} \) – the moment of resistance to cutting, depending on the width of the cut; \( M_{p,a,s} \) – the moment of resistance to cutting, independent of the width of the cut.

Projections of the component of the cutting resistance force, independent of the cut width, onto the axis of rotation of the geokhod and a plane perpendicular to the axis of rotation, as well as the moment of resistance to cutting from this component [16-18]:

\[
P_{a,s} = \frac{h_s}{n} \sum_{i=1}^{2} \left( m_s \frac{h_s}{n} \cos \beta_p + m_s \right) \left( \frac{\sin 2\beta_p}{2} - \frac{\cos (\delta + \phi_f) \cos^2 \beta_p}{2} \right);
\]

\[
R_{p,a,s} = \frac{h_s}{n} \sum_{i=2}^{2} \left( m_s \frac{h_s}{n} \cos \beta_i + m_s \right) \left( \cos^2 \beta_p + \frac{\cos (\delta + \phi_f) \sin 2\beta_p}{2} \right);
\]
\[ M_{p.a.s} = \frac{h_f}{n} \left( m_s \frac{h_e}{n} \cos \beta_1 + m_s k \right) \left( \cos^2 \beta_1 + \cot g(\delta + \phi_f) \frac{\sin 2\beta_1}{2} \right) + \]
\[ + \frac{h_f}{n} \left( m_s \frac{h_e}{n} \cos \beta_2 + m_s k \right) \left( \cos^2 \beta_2 + \cot g(\delta + \phi_f) \frac{\sin 2\beta_2}{2} \right). \]  

where \( h_f \) is the pitch of the external mover, \( m_s \) is the coefficient characterizing the force of soil destruction in the lateral parts of the slot, \( \beta_1 \) is the angle of movement of the point of the knife of the geokhod EB located at a distance of \( r_s \), \( m_k \) is the coefficient characterizing the specific shear force of one of the side edges of the knife \( \delta \) is the cutting angle, \( \phi_f \) is the angle of friction of the soil against the knife, \( \beta_2 \) is the angle of movement of the point of the knife of the EB of the geokhod located at a distance of \( r_o \), \( r_s \) is the radius of the head section of the geokhod, \( r_o \) is the radius of the generatrix.

The projections of the component of the cutting resistance force, depending on the width of the cut, on the axis of rotation of the geokhod and the plane perpendicular to the axis of rotation, as well as the moment of resistance to cutting from this component [16-18]:

\[ P_{a.c} = \phi m_o \frac{h_e}{n} \left( \frac{h_e}{2\pi n} \ln \left( \frac{\sin \beta_2}{\sin \beta_1} \right) - \cot g(\delta + \phi_f) \left( r_g - r_o + \frac{h_e}{2\pi} (\beta_1 - \beta_2) \right) \right); \]  

\[ R_{p.a.c} = \phi m_o \frac{h_e}{n} \left( \left( r_g - r_o + \frac{h_e}{2\pi} (\beta_1 - \beta_2) \right) + \cot g(\delta + \phi_f) \frac{h_e}{2\pi} \ln \left( \frac{\sin \beta_2}{\sin \beta_1} \right) \right); \]  

\[ M_{p.a.o} = \phi m_o \frac{h_e^2}{2\pi n} \left( \frac{h_e}{2\pi n} \left( \frac{\sin^2 \beta_2 - \sin^2 \beta_1}{2 \sin^2 \beta_1 \sin^2 \beta_2} \right) + \ln \left( \frac{\sin \beta_1}{\sin \beta_2} \right) \right) + \]
\[ + \cot g(\delta + \phi_f) \left( \left( r_g - r_o \right) + \frac{h_e}{2\pi} (\beta_1 - \beta_2) \right). \]

where \( \phi \) is a coefficient that takes into account the effect of the cutting angle, \( m_o \) is the specific cutting force to overcome the resistance of the soil with the front face at a cutting angle of \( 45^0 \).

Energy intensity of the destruction of the bottomhole rock with the knife EB of the geokhod [16-18]:

\[ H_o = \frac{R_{p.a.o} + R_{p.a.s}}{k_e} \left( \frac{h_e^2}{2\pi n} \left( \frac{\sin \beta_2 - \sin \beta_1}{\sin \beta_1 \sin \beta_2} \right) + \kappa^2 \cot g(\cos^2 \beta_1 + \cos^2 \beta_2) \right). \]

where \( k_e \) is the coefficient of the depth of the expanding part of the slot (drill slot); \( \gamma \) is the angle of inclination of the widening part of the slot to the horizon.

4. Description

Knife EB is characterized by cutting soft rocks with a strength coefficient of up to \( f = 1 \) on the scale of professor M.M. Protodyakonov. To study the dependences of the force parameters of the interaction of the knife EB geokhod with the bottom rock on the geometric parameters of the design decisions, a rock with a strength coefficient \( f = 1 \) was adopted – weak sandstone.

For weak sandstone V.Yu. Vetrov determined the values of the specific cutting force and the coefficients of the working conditions with sharp knives [19]. The values of these parameters are presented in Table 1.

The geometric parameters of the design solutions of the geokhod EB include the radius of the geokhod \( r_s \), the radius of the generating line \( r_0 \), the step of the external mover \( h_e \), the number of rays on the EB of the geokhod \( n \) [20].

According to expressions (1) – (10), the dependences of the projection of the total force of the rock resistance to cutting on the axis of rotation of the geokhod \( (R_o) \), as well as the projection onto the plane perpendicular to the axis of rotation of the geokhod \( (R_{EB}) \), the moment of resistance to cutting \( (M_{EB}) \) and the energy intensity of destruction of the bottom rock are determined knife EB from the step of the external mover.
Table 1. The values of the specific cutting force and its coefficients for working conditions with sharp knives.

| Name                                                      | Designation | Unit of measurement | Value  |
|-----------------------------------------------------------|-------------|---------------------|--------|
| Factor taking into account the effect of the cutting angle| $\varphi$   |                     | 0.59   |
| Specific cutting force in the frontal part of the slot at a cutting angle of 45° | $m_o$       | N/m$^2$             | 97000  |
| Breaking force in the lateral parts of the slot           | $m_s$       | N/m$^2$             | 36000  |
| Specific shearing force of one of the side edges of the knife | $m_{s,k}$  | N/m                 | 8490   |
| Cutting angle                                            | $\delta$    | grad                | 25     |
| Friction angle                                           | $\varphi_f$ | grad                | 31.4   |
| Depth ratio of the expanding part of the slot            | $k_s$       |                     | 0.9    |
| The angle of inclination of the expanding part of the slot to the horizon | $\gamma$    | grad                | 30     |

5. Results

Figure 1 shows the dependence of the projection of the total cutting force on the axis of rotation of the geokhod ($R_{O}$) for sharp knives when changing the step of the external mover of the geokhod. The projection values are obtained at constant $r_s = 0.3$ m; $r_o = 0.05$ m; $n = 2$ pcs. The energy intensity of the geokhod movement makes it expedient to use the propeller helix angle of elevation $3^\circ < \beta < 16^\circ$ [21]. Consequently, the appropriate value of the step of the external mover for the accepted conditions will be in the range from 0.1 m to 0.55 m. The ordinate shows the values of the projection of the total cutting force on the axis of rotation of the geokhod (N), and the abscissa shows the step of the external mover (m).

![Figure 1](image)

External mover step, m

Figure 1. Dependence of the projection of the cutting resistance force on the axis of rotation of the geokhod on the step value of the external mover.

It can be seen from the graph (Figure 1) that the projection of the cutting resistance force on the axis of rotation of the geokhod ($R_{O}$) changes nonlinearly.

In the range from 0.1 m to 0.32 m, the force will decrease by 61%, with values $0.32 \text{ m} < h < 0.55 \text{ m}$, the projection of the cutting resistance force on the axis of rotation of the geokhod will increase by 23%.
In Figure 2, a graph of the change in the projection of the cutting force on the plane perpendicular to the axis of rotation of the geokhod \((R_{EB})\) for sharp knives from the step of the external mover is built. The projection values are obtained at constant \(r_g = 0.3\) m; \(r_o = 0.05\) m; \(n = 2\) pcs.

The ordinate shows the values of the projection of the cutting force on the plane perpendicular to the axis of rotation of the geokhod (N), and the abscissa shows the step of the external mover (m).

The dependence of the projection of the cutting resistance force on the plane perpendicular to the axis of rotation on the pitch of the external mover (Figure 2) is linear. With an increase in the step of the external mover, the projection of the cutting resistance force on the plane perpendicular to the axis of rotation increases. In the interval \(0.1\) m < \(h_e\) < 0.55 m, they increase by an average of 18 kN.

![Figure 2. Dependence of the projection of the cutting resistance force on the plane perpendicular to the axis of rotation on the step of the external mover.](image)

The dependence of the moment of resistance to cutting \((M_{RO})\) for sharp knives on the pitch of the external mover is shown in Figure 3. The values of the moment are obtained at constant \(r_g = 0.3\) m; \(r_o = 0.05\) m; \(n = 2\) pcs.

The ordinate shows the values of the cutting resistance moment (Nm), and the abscissa shows the step of the external mover (m).

As a result of the analysis of the dependence, it was found that with an increase in the step of the external mover, the following occurs:

- non-linear increase in the moment of resistance to cutting;
- the value of the moment of resistance to cutting will increase by 4.3 kN in the interval \(0.1\) m < \(h_e\) < 0.55 m.

![Figure 3. Dependence of the moment of resistance to cutting on the step of the external mover.](image)
In Figure 4, a graph of the change in the energy intensity of the destruction of the bottomhole rock by the knife EB of the geokhod from the step of the external propeller is built. The values were obtained at constant \( r_g = 0.3 \) m; \( r_o = 0.05 \) m; \( n = 2 \) pcs.

The ordinate shows the values of the energy parameter \((J/m^3)\), the abscissa shows the step of the external mover (m).

During the analysis of the relationship presented in Figure 4 it follows that:

- the value of the energy intensity of the destruction of the bottomhole rock with the knife IO of the geokhod changes nonlinearly;
- with an increase in the step value of the external propeller from 0.1 m to 0.55 m, the energy parameter will decrease by 18%.

![Figure 4. Dependence of the energy intensity of the destruction of the bottomhole rock by the knife EB of the geokhod on the step of the external mover.](image)

6. Conclusion

With an increase in the step of the external mover, the projections of the total cutting resistance force on the axis of rotation of the geokhod and onto a plane perpendicular to the axis of rotation of the geokhod, as well as the moment of resistance to cutting for sharp knives, increase, in turn, an increase in the step of the external mover leads to a decrease in the energy consumption of destruction of the bottomhole rock with the knife EB of geokhod.

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