Mathematical model for determining characteristic points on the radial knife of the geokhod executive body

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Abstract. The article presents a mathematical model for determining the values of the characteristic points of the knife executive body (EB) of the geokhod. For this, the boundary conditions for determining the characteristic points on the radial knife of the geokhod executive body are indicated. The result of the work are the obtained expressions for determining: $P_{ac}$ is the projection of the component of the soil cutting force, depending on the cutting width, onto the main axis of rotation of the geokhod, $R_{ac}$ is the projection of the component of the soil cutting force on the plane, which is located perpendicular to the main axis of rotation of the geokhod. Based on the work carried out, tasks for further research were identified.

1. Introduction

Modern technologies for the construction of underground structures, as well as the extraction of minerals by the underground method, are rapidly developing. However, in technologies for the formation of a cavity in the underground space, devices capable of performing operations of the technological cycle in a combined mode [1–3] are practically not used.

In connection with this urgent problem, the tasks of developing new approaches to technologies for the construction of underground structures arise, in the field of creating new machines and mechanisms capable of automatic modes, at the level of robotization, to perform all processes for the formation of a cavity in the underground space [4–6].

One of the new approaches to the formation of a cavity in an underground space is a geo-propellant technology. In this approach, the geokhod is taken as the basic element capable of performing the basic operations of the technological cycle for the construction of underground structures.

At present, a team of authors is developing elements of geohome technology, in which there is an urgent need to develop constructive and rational technical solutions for the destruction organs of the face, the use of which makes it possible to form cavities in the massif of soft rocks with a strength coefficient of up to 1 on the scale of M.M. Protodyakonov [7–10].

Therefore, works aimed at substantiating the parameters of the executive bodies of a geokhod for the destruction of soft rocks are relevant.
2. Research methodology

When determining the power parameters of the knife executive body of the geokhod [11–13], the cutting force of the soil is represented by two components:

- \( P_{a.c} \) is the projection of the cutting force, depending on the cutting width of the soil, on the axis of rotation of the geokhod;
- \( R_{e.a.c} \) is the projection of the cutting force onto a plane perpendicular to the axis of rotation of the geokhod.

Earlier in works [14–21] expressions were obtained for determining the components of the soil force for cutting \( P_{a.c} \) and \( R_{e.a.c} \):

\[
P_{a.c} = \frac{\phi m_c h_e + n P_i}{n \cos \gamma} \int \sin a \cot \frac{h_e}{2 \pi x} dx - \left( \frac{\phi m_c h_e \cot (\delta + \varphi_f)}{n \cos \gamma} - \frac{ctg (\delta_1 + \varphi_f)}{n \cos \gamma} P_i \right) \int \sin a \cot \frac{h_e}{2 \pi x} dx.
\]

\[
R_{e.a.c} = \frac{\phi m_c h_e + n P_i}{n \cos \gamma} \int \cos a \cot \frac{h_e}{2 \pi x} dx + \left( \frac{\phi m_c h_e \cot (\delta + \varphi_f)}{n \cos \gamma} - \frac{ctg (\delta_1 + \varphi_f)}{n \cos \gamma} P_i \right) \int \sin a \cot \frac{h_e}{2 \pi x} dx.
\]

In addition, in [22–27], the boundary conditions of integration were justified, which are necessary to determine the characteristic points on the knife of the executive body of the geokhod.

![Knife actuator picture.](image)

Figure 1. Knife actuator picture.

To obtain expressions that allow us to determine the positions of the characteristic points, we formulated three problems:

1) Obtain an expression for determining the radial position of the characteristic point, at which the component of the cutting force \( P_{a.c} \) in the varying limits of integration from 0 (center of rotation of the geokhod) to \( x \) (coordinate of the knife point (Figure 1)), will be equal to the component of the cutting force \( R_{e.a.c} \) within varying limits of integration from \( x \) to \( R_g \) (geokhod radius), i.e.

\[
\int_0^x P_{a.c} dx = \int_x^{R_g} R_{e.a.c} dx.
\]
2) Obtain an expression for determining the radial position of the characteristic point, at which the component of the cutting force \( P_{a,c} \) in the varying limits of integration from 0 to \( x \), will be equal to the component of the cutting force \( P_{a,c} \) in the varying limits of integration from \( x \) to \( R_{e} \), i.e.

\[
\int_{0}^{x} P_{a,c} \, dx = \int_{x}^{R_{e}} P_{a,c} \, dx ;
\]

(4)

3) Obtain an expression for determining the radial position of a point, at which the component of the cutting force \( R_{e,a,c} \) in the varying range of integration from 0 to \( x \), will be equal to the component of the cutting force \( R_{e,a,c} \) in the varying range of integration from \( x \) to \( R_{e} \), i.e.

\[
\int_{0}^{x} R_{e,a,c} \, dx = \int_{x}^{R_{e}} R_{e,a,c} \, dx.
\]

(5)

After integration, expressions (1) and (2) take the form

\[
P_{a,c} = \frac{q m_{c} h_{e}^{2} + h_{e} n P_{i}}{2 \pi n \cos \gamma} \cdot \left( \ln \frac{\tan \frac{\beta_{2}}{2}}{\tan \frac{\beta_{1}}{2}} \right) - \frac{h_{e}}{2 \pi} \left( \frac{q m_{c}}{n} \frac{\cos \gamma}{\cos \gamma} - \frac{\alpha_{2}}{\tan \frac{\beta_{2}}{2}} \right) P_{i} \cdot \frac{\sin \beta_{2} - \sin \beta_{1}}{\sin \beta_{1} \sin \beta_{2}} + \frac{h_{e}}{2 \pi} \left( \frac{q m_{c}}{n} \frac{\cos \gamma}{\cos \gamma} - \frac{\alpha_{2}}{\tan \frac{\beta_{2}}{2}} \right) P_{i} \cdot \left( \ln \frac{\tan \frac{\beta_{2}}{2}}{\tan \frac{\beta_{1}}{2}} \right).
\]

(6)

\[
R_{e,a,c} = \frac{q m_{c} h_{e}^{2} + h_{e} n P_{i}}{2 \pi n \cos \gamma} \cdot \frac{\sin \beta_{2} - \sin \beta_{1}}{\sin \beta_{1} \sin \beta_{2}} + \frac{h_{e}}{2 \pi} \left( \frac{q m_{c}}{n} \frac{\cos \gamma}{\cos \gamma} - \frac{\alpha_{2}}{\tan \frac{\beta_{2}}{2}} \right) P_{i} \cdot \left( \ln \frac{\tan \frac{\beta_{2}}{2}}{\tan \frac{\beta_{1}}{2}} \right).
\]

(7)

The obtained expressions (6) and (7) are difficult for determining the values of the characteristic points of the knife executive body of the geokhod. To transform expressions (6) and (7), it is proposed to use trigonometric identities:

\[
\cos \alpha = \frac{1}{\sqrt{\tan^{2} \alpha + 1}}.
\]

(8)

\[
\sin \alpha = \frac{\tan \alpha}{\sqrt{\tan^{2} \alpha + 1}}.
\]

(9)

When determining the components of the cutting forces \( P_{a,c} \) and \( R_{e,a,c} \), the angle alpha is taken equal to [28-30]:

\[
\alpha = \arctg \frac{h_{e}}{2 \pi x}.
\]

(10)

Then, after substitution, expressions (8) and (9) take the form

\[
\cos \left( \arctg \frac{h_{e}}{2 \pi x} \right) = \frac{1}{\sqrt{\tan^{2} \left( \arctg \frac{h_{e}}{2 \pi x} \right) + 1}} = \frac{1}{\sqrt{\left( \frac{h_{e}}{2 \pi x} \right)^{2} + 1}}.
\]

(11)

\[
\sin \left( \arctg \frac{h_{e}}{2 \pi x} \right) = \frac{\tan \left( \arctg \frac{h_{e}}{2 \pi x} \right)}{\sqrt{\tan^{2} \left( \arctg \frac{h_{e}}{2 \pi x} \right) + 1}} = \frac{h_{e}}{2 \pi x \sqrt{\left( \frac{h_{e}}{2 \pi x} \right)^{2} + 1}}.
\]

(12)

In expressions (1) and (2), two types of integrals can be distinguished

\[
\int \sin \left( \arctg \frac{h_{e}}{2 \pi x} \right) \, dx,
\]

(13)

\[
\int \cos \left( \arctg \frac{h_{e}}{2 \pi x} \right) \, dx.
\]

(14)

Substitute expressions (11) and (12) into integrals (13) and (14) and integrate.
\[
\int \sin \left( \arctan \frac{\frac{x}{2}}{\frac{\sqrt{h_e}}{2\pi x}} \right) dx = \int \frac{\frac{x}{2\pi}}{\sqrt{\left(\frac{x}{2\pi}\right)^2 + 1}} dx = \frac{\frac{x}{2\pi}}{\sqrt{\left(\frac{x}{2\pi}\right)^2 + 1}}.
\]

Taking into account the limits of integration [0, x], from conditions (3), (4) and (5), expressions (15) and (16) take the form

\[
\int_0^x \sin \left( \arctan \frac{\frac{x}{2}}{\frac{\sqrt{h_e}}{2\pi x}} \right) dx = \left. \frac{\frac{x}{2\pi}}{\sqrt{\left(\frac{x}{2\pi}\right)^2 + 1}} \right|_0^x = \frac{\frac{x}{2\pi}}{\sqrt{\left(\frac{x}{2\pi}\right)^2 + 1}} - \frac{\frac{0}{2\pi}}{\sqrt{\left(\frac{0}{2\pi}\right)^2 + 1}} = \frac{\frac{x}{2\pi}}{\sqrt{\left(\frac{x}{2\pi}\right)^2 + 1}} - \frac{0}{\sqrt{\left(\frac{0}{2\pi}\right)^2 + 1}} = \frac{\frac{x}{2\pi}}{\sqrt{\left(\frac{x}{2\pi}\right)^2 + 1}}.
\]

3. Results

Taking into account the limits of integration [x, R_g], from conditions (3), (4) and (5), expressions (15) and (16) take the form:

\[
\int_x^{R_g} \sin \left( \arctan \frac{\frac{x}{2}}{\frac{\sqrt{h_e}}{2\pi x}} \right) dx = \left. \frac{\frac{x}{2\pi}}{\sqrt{\left(\frac{x}{2\pi}\right)^2 + 1}} \right|_x^{R_g} = \frac{\frac{R_g}{2\pi}}{\sqrt{\left(\frac{R_g}{2\pi}\right)^2 + 1}} - \frac{\frac{x}{2\pi}}{\sqrt{\left(\frac{x}{2\pi}\right)^2 + 1}} = \frac{\frac{R_g}{2\pi}}{\sqrt{\left(\frac{R_g}{2\pi}\right)^2 + 1}} - \frac{\frac{x}{2\pi}}{\sqrt{\left(\frac{x}{2\pi}\right)^2 + 1}} = \frac{\frac{R_g}{2\pi}}{\sqrt{\left(\frac{R_g}{2\pi}\right)^2 + 1}} - \frac{\frac{x}{2\pi}}{\sqrt{\left(\frac{x}{2\pi}\right)^2 + 1}} = \frac{\frac{R_g}{2\pi}}{\sqrt{\left(\frac{R_g}{2\pi}\right)^2 + 1}} - \frac{\frac{x}{2\pi}}{\sqrt{\left(\frac{x}{2\pi}\right)^2 + 1}} = \frac{\frac{R_g}{2\pi}}{\sqrt{\left(\frac{R_g}{2\pi}\right)^2 + 1}} - \frac{\frac{x}{2\pi}}{\sqrt{\left(\frac{x}{2\pi}\right)^2 + 1}} = \frac{R_g}{2\pi} - \frac{x}{2\pi}.
\]

Finally, the expression for determining the projection of the cutting force, which depends on the cutting width of the soil, onto the axis of rotation of the geokhod \( P_{a,c} \), taking into account the segment of integration [0, x] defined above, will have the form

\[
\int_0^x P_{a,c} = \frac{\varphi m_e h_e + n P_i}{\cos \gamma} \cdot \frac{\frac{x}{2\pi}}{\sqrt{\left(\frac{x}{2\pi}\right)^2 + 1}} - \left( \varphi m_e \frac{h_e \tan(\delta + \varphi_f)}{\cos \gamma} - \frac{\varphi(\delta_1 + \varphi_f)}{\cos \gamma} P_i \right) \left( \sqrt{\left(\frac{h_e}{2\pi}\right)^2 + 1} + x^2 - \frac{x}{2\pi} \right).
\]
Finally, the expression for determining $R_{e.a.c}$, taking into account the above-defined interval of integration $[0, x]$, will have the form

$$\int_0^x R_{e.a.c} = \frac{\phi m_e h_e + n P_i}{n \cos \gamma} \left( \sqrt{\frac{h_e^2}{2\pi}} + x^2 - \frac{h_e}{2\pi} \right) + \left( \frac{h_e}{n \cos \gamma} - \frac{ctg(\delta + \varphi_f)}{\cos \gamma} \right) P_i \ln \left( \frac{x + \sqrt{x^2 + \left( \frac{h_e}{2\pi} \right)^2}}{\frac{h_e}{2\pi}} \right). \quad (22)$$

Finally, the expression for determining the projection of the cutting force, depending on the cutting width of the soil, onto the axis of rotation of the geokhod $P_{a.c}$, taking into account the segment of integration $[x, R_g]$ defined above, will have the form

$$\int_x^{R_g} P_{a.c} = \frac{\phi m_e h_e + n P_i}{n \cos \gamma} \frac{h_e}{2\pi} \ln \left( \frac{R_g + \sqrt{R_g^2 + \left( \frac{h_e}{2\pi} \right)^2}}{x + \sqrt{x^2 + \left( \frac{h_e}{2\pi} \right)^2}} \right) - \left( \frac{h_e}{n \cos \gamma} - \frac{ctg(\delta + \varphi_f)}{\cos \gamma} \right) P_i \left( \sqrt{\frac{h_e^2}{2\pi}} + R_g^2 - \frac{h_e^2}{2\pi} + x^2 \right). \quad (23)$$

Finally, the expression for determining the projection of the cutting force on a plane located perpendicular to the axis of rotation of the geokhod $R_{e.a.c}$, taking into account the segment of integration $[x, R_e]$ defined above, will have the form

$$\int_x^{R_e} R_{e.a.c} = \frac{\phi m_e h_e + n P_i}{n \cos \gamma} \left( \sqrt{\frac{h_e^2}{2\pi}} + R_g^2 - \frac{h_e^2}{2\pi} + x^2 \right) + \left( \frac{h_e}{n \cos \gamma} - \frac{ctg(\delta + \varphi_f)}{\cos \gamma} \right) P_i \frac{h_e}{2\pi} \ln \left( \frac{R_g + \sqrt{R_g^2 + \left( \frac{h_e}{2\pi} \right)^2}}{x + \sqrt{x^2 + \left( \frac{h_e}{2\pi} \right)^2}} \right). \quad (24)$$

4. Conclusion

Expressions are obtained for determining the components of the cutting force of the soil: $P_{a.c}$ is the projection of the cutting force, depending on the width of the soil cutting, on the axis of rotation of the geokhod and $R_{e.a.c}$ is the projection of the cutting force on the plane located perpendicular to the axis of rotation of the geokhod.

Based on the selected limits of integration (boundary conditions), a mathematical model has been developed for determining the radial position of the characteristic points of the knife of the executive body: for problem 1, equations (21), (22), for problem 2, equations (21), (23), for problem 3, equations (22), (24).

For further research it is necessary:

- to obtain the values of the characteristic points of the knife executive body of the geokhod;
- to determine the influence of the properties of the geomedium on the location of the characteristic points;
- to determine the influence of the geokhod parameters on the location of the characteristic points.

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