Mathematical model for determining the forces of interaction of geokhod systems with geo-environment and with each other

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Abstract. The article gives an example of constructing a generalized mathematical model of the interaction processes occurring in geokhod mining. An example of the solution of a particular problem is given, the determination of the values of the forces arising from the interaction of the blade of an external mover with geoenvironment.

1. Introduction
During geo-excitation of an underground mine, there are simultaneous processes of interaction of several geo-excavation systems with each other and with the geoenvironment [1-6]. Moreover, these processes are mutually influencing [7-10].

Modeling of the processes occurring during geo-excitation of an underground mine, in our opinion, pursues three main goals [9-15]:

Goal 1 Justification of the parameters of drives and forces arising from the interaction of geokhod systems with the geo-environment and with each other.

Goal 2 Ensure sufficient strength of the machine components.

Goal 3 Ensuring the bearing capacity of the adjacent (near-contour) rock mass.

Achievement of the first goal, in addition, allows the formation of initial data for solving problems pursuing the second and third goals. Therefore, we will consider a model for determining the forces of interaction of the geokhod systems with the geo-environment and with each other.

In [13-15], the use of the block-modular principle of constructing a mathematical model is substantiated, which will allow solving particular problems of modeling the operation of a separate system, using the results of modeling the operation of adjacent systems as input data.

Therefore, it is necessary to abstract from particular design features and simplify the task by replacing the power circuits of some systems with equivalent loads and the reduced total moments and forces.

2. Accepted assumptions and problem statement
To build a generalized model, the following assumptions were made and reduced loads were introduced:

1) All forces are centrally symmetric about the axis of the mine z.

2) From the side of the main face, the impact of the geomedium on the geokhod is transmitted through the executive module (IO GZ) and can be reduced to the total moment \( M_{IOGZ} \) and the total force \( F_{IOGZ} \) (Figure 1). The moment \( M_{IOGZ} \) is directed around the working axis \( z \), and the force \( F_{IOGZ} \) is directed along the axis \( z \).
3) The interaction of the executive bodies of the external mover (IO VD) is transmitted to the body of the head section and can be reduced to two forces: feed $F_{VD}^p$ directed along the direction of feed to the bottom of the channel and lying in a plane tangent to the shell; and cutting $F_{VD}^c$ directed perpendicular to the feed direction and lying in a plane tangent to the housing shell. The torques from the VD EUT counterbalance each other and may not be taken into account.

4) The interaction of the executive bodies of the counter-rotation elements (IO EP) is transmitted to the tail section body and can be reduced to two forces: feed $F_{EP}^p$ directed along the direction of feed to the bottom of the channel and lying in a plane tangent to the shell shell; and cutting $F_{EP}^c$ directed perpendicular to the feed direction and lying in a plane tangent to the housing shell. The torques from the EI EP counterbalance each other and may not be taken into account.

5) The interaction of the blades of the external propeller (VD) is transmitted to the body of the head section and can be brought to two forces: normal $F_{VD}^{N}$, directed along the normal to the supporting surface of the blade and applied to a point on the base of the blade; and friction applied $F_{VD}^{FR}$ to the base of the blade and directed along the base of the blade.

6) The interaction of the blades of the counter-rotation elements (EP) is transmitted to the tail section body and can be reduced to two forces: normal $F_{EP}^{N}$, directed along the normal to the support surface of the blade and applied to a point on the base of the blade; and friction applied $F_{EP}^{FR}$ to the base of the blade and directed along the base of the blade.

7) The interaction of the head section shell with the geomedium can be reduced to a friction force $F_{HS}^{FR}$ uniformly distributed over the shell and directed parallel to the VD helix.

8) The interaction of the tail section shell with the geo-environment can be reduced to a friction force $F_{TS}^{FR}$ uniformly distributed over the shell and directed parallel to the working axis.

9) The manifestation of overburden pressure can be brought to a normal load $p_{HS}$, evenly distributed over the shells of the hulls.

10) The interaction of the head and tail sections can be reduced to the total driving moment $M_{TD}$ and the total tractive force $F_{TF}$. The moment is directed around the working axis $z$, and the force is directed along the axis $z$.

3. Mathematical model

Figure 1 shows a diagram for the model of the force interaction of the main geokhod systems with the geo-environment and with each other.

Figure 2 shows a diagram of the reduction of the cutting forces and feed on the IO GB to the total moment and the total force (Figure 1).

The reduced moment acting from the side of the face was determined by formula (1):

$$M_{10GZ} = 2F_{10GZ}^p \frac{R_B}{z},$$  

(1)

Where $R_B$, $m$, is the working radius.

The reduced total force acting from the side of the face is determined by the formula:

$$F_{10GZ} = 2F_{10GZ}^c \cos \alpha,$$

(2)

The reduced friction force acting on the head section and the outer (rotating) body of the interface module was determined by the formula:

$$F_{HS}^{FR} = p_{HS} f_{FR} 2\pi R_C L_{HS},$$

(3)

where $f_{FR}$ – is the coefficient of friction of the metal of the rock.
Figure 1. Scheme to the model of interaction of the geokhod with the geoenvironment: $\alpha_1$ is the angle of tilt of the EP support surface; $\alpha_2$ is the angle of tilt of the VD support surface.

Figure 2. Forces acting on the IO GZ from the side of the geomedium; $\alpha$ is the drum tilt angle.

The reduced friction force acting on the tail section was determined by the Formula:

$$F_{TS}^{FR} = p_{HS}f_{TP}2\pi R CL_{TS},$$

(4)

The speed of movement of the geokhod is rather low and the forces of inertia can be neglected, therefore, let us make the assumption that the geokhod moves uniformly and rectilinearly, this made it possible to compose a system of equations of equilibrium.
Equation of projections of forces on the z-axis:

\[ \sum F_z = F_{TS}^{FR} + F_{HS}^{FR} \sin \beta - F_{10GZ} + 2F_{IOVD}^{P} \sin \beta - 2F_{IOVD}^{C} \cos \beta + 4F_{IOEP}^{P} - 2F_{VD}^{N} \cos \beta \cos \alpha_1 + 2F_{VD}^{FR} \sin \beta + 4F_{EP}^{FR} = 0 \]  \hspace{1cm} (5)

The equation of the moments of forces about the z-axis:

\[ \sum M_z = F_{TS}^{FR} R_C \cos \beta + M_{10GZ} + 2F_{IOVD}^{P} R_C \cos \beta + 2F_{IOVD}^{C} R_C \sin \beta - 4F_{IOEP}^{C} R_C + 2F_{VD}^{N} R_C \sin \beta \cos \alpha_1 + 2F_{VD}^{FR} R_C \cos \beta - 4F_{EP}^{N} R_C \cos \alpha_2 = 0 \]  \hspace{1cm} (6)

Considering that the frictional forces are proportional to the normal forces:

\[ F_{VD}^{FR} = f_{FR} \cdot F_{VD}^{N} \]
\[ F_{EP}^{FR} = f_{FR} \cdot F_{EP}^{N}, \]  \hspace{1cm} (7)

the equilibrium equations can be reduced to the system:

\[
\begin{align*}
F_{TS}^{FR} + F_{HS}^{FR} \sin \beta - F_{10GZ} + 2F_{IOVD}^{P} \sin \beta - 2F_{IOVD}^{C} \cos \beta + 4F_{IOEP}^{P} - 2F_{VD}^{N} \cos \beta \cos \alpha_1 & - f_{FR} \sin \beta) - 4f_{FR} F_{EP}^{N} = 0 \\
F_{TS}^{FR} \cos \beta - \frac{M_{10GZ}}{R_C} + 2F_{IOVD}^{P} \cos \beta + 2F_{IOVD}^{C} \sin \beta + 4F_{IOEP}^{C} \sin \beta \cos \alpha_1 & + f_{FR} \cos \beta) - 4F_{EP}^{N} \cos \alpha_2 = 0
\end{align*}
\]  \hspace{1cm} (8)

The forces arising on the executive bodies can be preliminarily determined based on the types of executive bodies and the given machine productivity and section of production [16, 17]. The same can be said about the overall dimensions of the geokhod and its sections, as well as the strength of the rock pressure manifestation. The value of the angle of inclination of the VD blades is limited by the parameters of the IO GZ [2, 3]. That is, the definition of these parameters is a particular task of individual blocks that form a general block-modular model. The values of the cutting forces and feeds do not directly depend on the varied geometric parameters (and), and they can be considered as constants or independent variables.

From the forces indicated in the diagram of the interaction of the geokhod with the geomedium (Figure 1), only the forces acting on the blades of the external propeller (and) and counter-rotation elements (and) directly depend on the varied geometric parameters (and).

Determination of the values of the forces arising from the interaction of the VD with the geoenvironment is a particular task that pursues "goal 1" and allows obtaining initial data for the tasks pursuing "goal 2" and "goal 3".

Therefore, we will consider a particular problem - determining the influence of the angle of inclination of the VD support surface on the forces of interaction of the geokhod with the boundary massif. To do this, we will consider that the angle \( \alpha \) of inclination of the supporting surface of the EP is a certain given constant.

Let's introduce constants that do not depend on the angle \( \alpha_1 \):

\[ C_1 = F_{TS}^{FR} + F_{HS}^{FR} \sin \beta - F_{10GZ} + 2F_{IOVD}^{P} \sin \beta - 2F_{IOVD}^{C} \cos \beta + 4F_{IOEP}^{P}; \]
\[ C_2 = -2 \cos \beta; \]
\[ C_3 = 2f_{FR} \sin \beta; \]
\[ C_4 = -4f_{FR}; \]
\[ C_5 = F_{TS}^{FR} \cos \beta - \frac{M_{10GZ}}{R_C} + 2F_{IOVD}^{P} \cos \beta + 2F_{IOVD}^{C} \sin \beta + 4F_{IOEP}^{C}; \]
\[ C_6 = 2 \sin \beta; \]
\[ C_7 = 2f_{FR} \cos \beta; \]
\[ C_8 = -4 \cos \alpha_2. \]
Then the system of equations (8) takes the form:

\[
\begin{align*}
C_1 + F_{\text{vd}}^N(C_1 \cos \alpha_1 + C_1) + C_1 F_{\text{p}}^N &= 0 \\
C_2 + F_{\text{vd}}^N(C_2 \cos \alpha_2 + C_2) + C_2 F_{\text{p}}^N &= 0
\end{align*}
\] (9)

Then the system of equations (8) takes the form:

\[
F_{\text{vd}}^N = \frac{C_2 C_4 - C_2 C_8}{(C_2 C_5 + C_2 C_6 \cos \alpha_2 + C_5 C_7 - C_7 C_4)}
\] (10)

Let’s introduce constants:

\[A_1 = C_4 C_5 - C_1 C_8 \quad A_2 = C_2 C_8 - C_4 C_6 A_3 = C_4 C_7 - C_3 C_8\]

Let’s introduce constants:

\[
F_{\text{vd}}^N = \frac{A_1}{A_2 \cos \alpha_1 - A_3}
\] (11)

The range of possible angles of inclination of the support surface of the HP blade is determined by the condition:

\[A_2 \cdot \cos \alpha_1 - A_3 > 0\] (12)

Obviously, the minimum load on the blade will be at the radial location of the generatrix of the support surface of the HP blade, i.e. at

Critical value of the angle of inclination of the bearing surface:

\[\alpha_{1\text{cr}} = \arccos \left( \frac{A_1}{A_2} \right)\] (13)

With the above given initial data, the critical value of the angle of inclination of the support surface of the HP blade was: \(\alpha_{1\text{cr}} = 54^\circ 28'\).

Let us introduce a dimensionless parameter \(f_{\text{vd}}^N\) the coefficient of the influence of the angle \(\alpha_1\) on the load on the HP blade:

\[
f_{\text{vd}}^N = \frac{F_{\text{vd}}^N}{F_{\text{vd}}^N} = \frac{A_2 - A_3}{A_2 \cos \alpha_1 - A_3}
\] (14)

where \(F_{\text{vd}}^N = A_1/(A_2 - A_3)\) –is the value of the normal force on the HP blade at \(\alpha_1 = 0\).

4. Conclusion

It can be seen from the (14) that the significant influence of the angle \(\alpha_1\) is manifested at \(\alpha_1 > 30^\circ\), and at values of the angle \(\alpha_1\) up to \(15^\circ\), the increase in the load does not exceed 10%.

The presented model allows obtaining initial data for modeling the stress-strain state of the boundary and geokhod elements interacting with the rock of the boundary massif.

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