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INVESTIGATION ON SOIL CUTTING BY NON-BUCKET BOTTOM ROTOR END CHISELS

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ABSTRACT: A new design of the bottom unload non-bucket rotor (BUNBR) for an open-pit excavator with additional end chisels is described. It makes it possible not only to increase the output due to additional end chisels on the shell, but also to reduce the slope stress due to soil cutting from top to bottom on the working face and creation of a wider berm in comparison with the existing constructions of rotary working bodies. The method of calculation of soil cutting with the end chisel in the form of a two-sided skewed wedge is presented. Based on the spatial scheme of the cutting force components acting in the soil cutting, the expressions in coordinate axes for soil resistance to cutting with the end chisel were determined. These results were used to derive expressions for the tangential and end (lateral) cutting force exerted by a two-sided skewed wedge mounted at the BUNBR end side and to determine the total soil cutting force simultaneously exerted by the corner and end chisels.

Keywords: Non-bucket rotor, Bottom unload, Corner and end chisels, Diagonal cutting, Output, Bucket digging force.

1. INTRODUCTION

The considered bottom unload non-bucket rotor with additional end chisels complies with the geotechnical requirements for safety of slopes in open-pits due to significant reduction of chipping extraction forces, pressure on the working face, presence of a broadened horizontal ramp between the ledges (berm) [4], compared with the existing gravity top rotors. Several methods of solving problems of soil cutting by other types of cutting elements were considered in [1, 2, 3, 10, 11,12].

2. METHOD

Based on the rotor working head under USSR Patent No. 1799413 dated 08.10.1993 [6], the author developed a new design of the rotor working head, for which the Invention Patent of the Republic of Kazakhstan No. 27061 dated July 15, 2015, Bulletin No. 7 [5] was obtained. Its novelty is the presence of additional end chisels shaped as two-sided diagonal wedges on both sides of the rotor shell, which, besides the main corner one-sided wedges additionally cut chippings from the end face of the working bench. This gives a significant increase in the amount of extracted soil and, consequently, significantly increases the output of the bottom unload non-bucket rotor(BUNBR) by simultaneous cutting with two chisels: the main corner and the additional end chisel. Cutting with a corner chisel was considered in [7, 8, 9].

Figure 1 shows the BUNBR scheme with additional end chisels shaped as two-sided diagonal wedges (shaded sections show the total cross-sectional area of the two chippings taken by the corner and additional end chisels). Shell 4 holds corner cutting chisels 1 and 2 shaped as one-sided diagonal wedges and transporting elements 3 in the form of plates installed behind the chisels 1 and 2 at an angle to each other and to the rotation plane (V_P). $\Delta\delta$, Δh and Δ_{tr}, are, respectively, lateral, height and trajectory displacements of the chisels. Both end faces of the shell 4 in the direction of rotor rotation hold the end cutting elements 8, 9 and 10 shaped as two-sided skewed wedges installed on the posts 7.

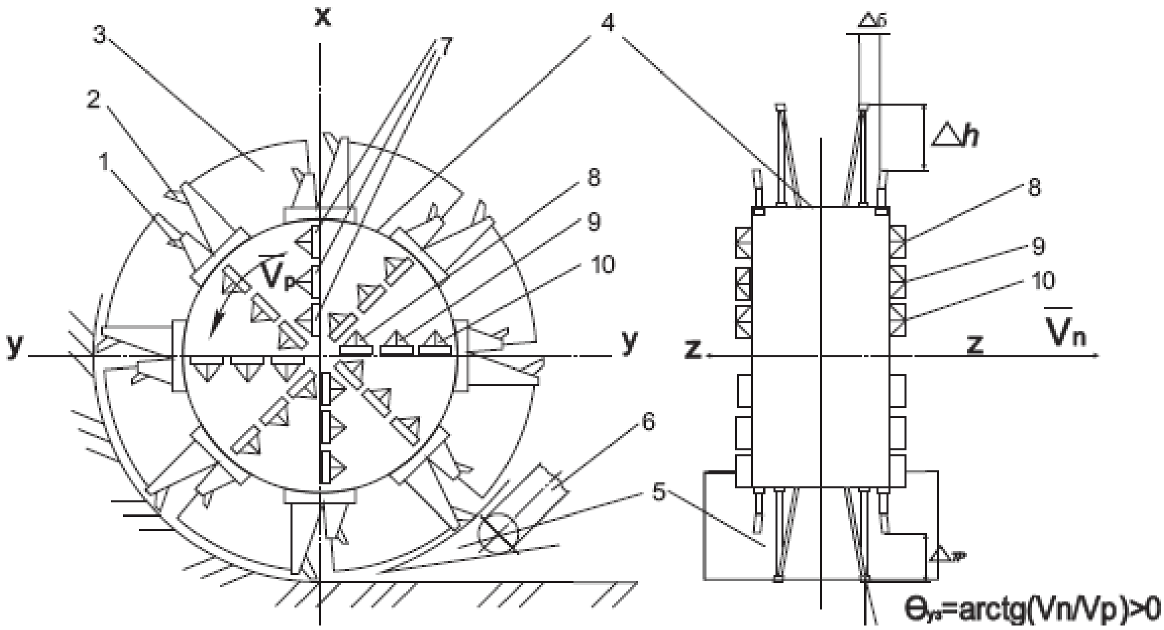
At the lateral rotor feed (v_n), the chisels cut additional lateral chippings under rotating from top to bottom against the working bench in a stepwise pattern, as well as chisels 1 and 2. The cut soil is ejected along the tray 5 onto the belt of the receiving conveyor 6. As a result of an increased cross-sectional area of the removed soil due to additional chippings 11, 12 and 13 (Fig. 1, b), the rotor output significantly increases.

Figure 2 shows the outline of the end cutting chisel shaped like a two-sided skewed wedge, where α_p is the cutting angle, $\gamma_{зх}$ is the gripping angle, $b_з$ and $h_з$ are the width and height of the chisel, A is the skewed cutting edges of the chisel, B and C are the lateral and bottom edges of the chisel.

To test the new design, the process of soil cutting with a two-sided skewed wedge was studied on the BUNBR, working out a working bench under transverse feed.

A two-sided skewed wedge is considered as a cutting element, its calculation schemes are given in Fig. 3, 4. The figures show a two-sided skewed wedge at the moment of its penetration into the soil, when chippings extraction begins.

The BUNBR cutting element (CE) has a shape of a two-sided sharp wedge with a lip angle α_z. The CE is mounted on the rotor shell under an angle α_{ust}. The process of transverse feeding and rotor rotation gives a kinematical angle $\alpha_{kin} = arctg\, V_n / V_f$. Hence, the CE cutting angle will be equal to $\alpha_p = \alpha_{ust} - \alpha_{kin}$. As a result, the CE will contact the working bench only by a small part of the rear edge.



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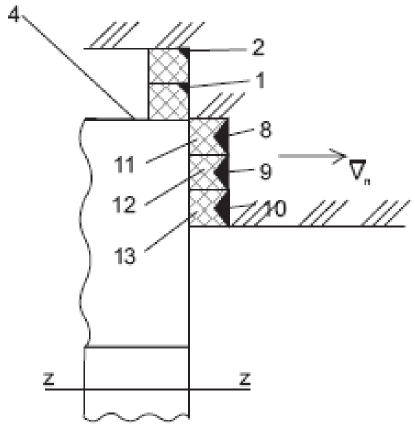

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a) rotor end view; b) front view
Fig.1 BUNBR layout with additional end chisels shaped as two-sided skewed wedges

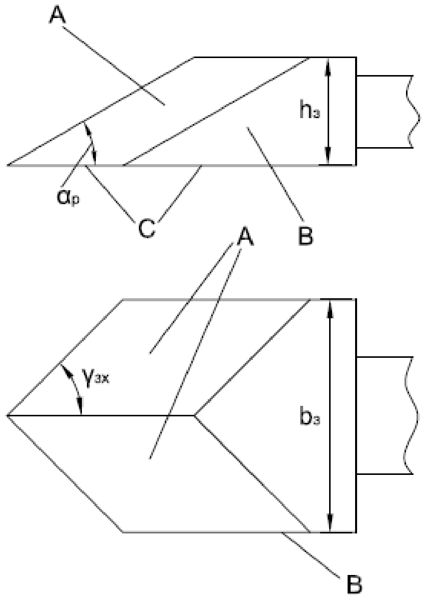
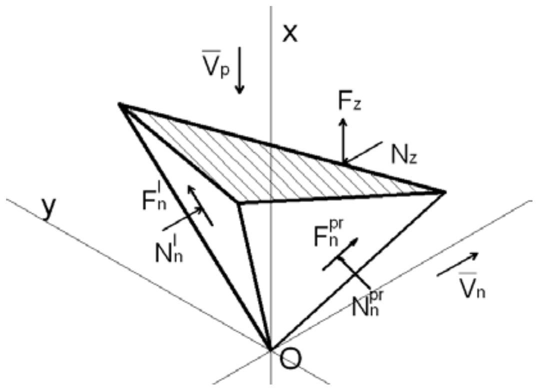


Fig.2 Additional chisel shaped as a two-sided skewed wedge



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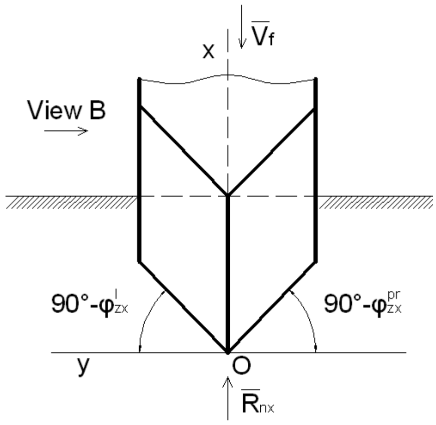
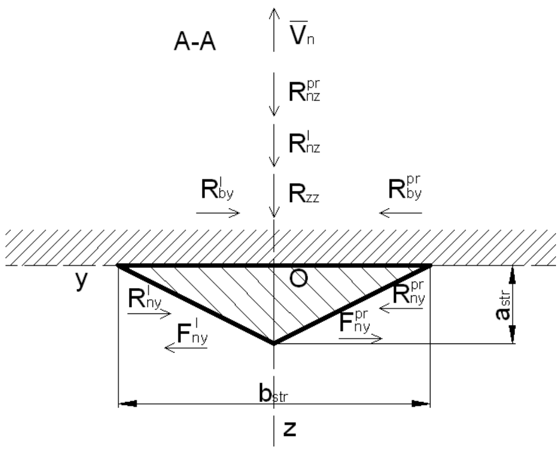


b)

a – Axonometric projection; b – XOY longitudinal section

Fig.3 Calculation scheme of the forces on the end two-sided wedge of BUNBR undercutting



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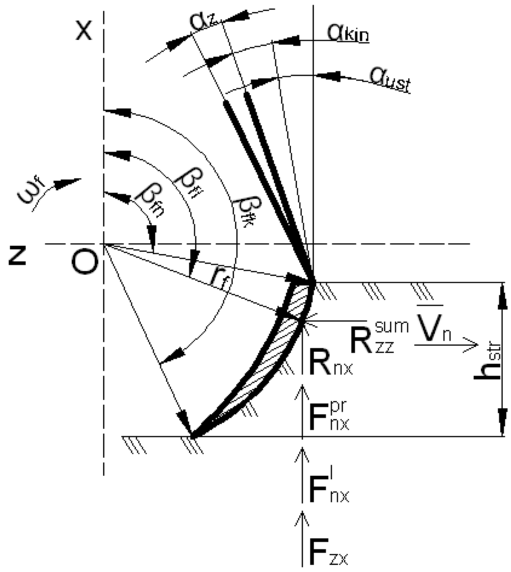

b)

a –YOZ horizontal section; b – XOZ plane projection

Fig.4 Calculation scheme for the forces acting on the two-sided end wedge of BUNBR undercutting

The scheme uses the following notations: N_n^l, N_n^{pr} are normal reaction forces of the front left and right edges of the two-sided skewed wedge, N; F_n^l, F_n^{pr} are corresponding friction forces of the front left and right edges, N; N_z, F_z are the normal force and the friction force acting on the rear edge, N; V_f, V_p are the cutting (rotation) speed and the transverse rotor feeding, m/s; ω_f is the rotation frequency, s^{-1}; R_{nx}^l, R_{nx}^{pr}, R_{ny}^l, R_{ny}^{pr}, R_{nz}^l, R_{nz}^{pr} are projections of normal forces N_n^l and N_n^{pr} on the X, Y, Z axes;

F_{nx}^{l}, F_{nx}^{pr}, F_{ny}^{l}, F_{ny}^{pr}, F_{nz}^{l}, F_{nz}^{pr} are the corresponding projections of friction forces on the X, Y, Z axes; R_{zz}, R_{nz}^{l}, R_{nz}^{pr} are projections of reaction forces from transverse feed and from the forces N_n^l and N_n^{pr} on the left and right edges on the Z axis, friction forces on the rear edge on the Z axis; F_{zx}, F_{nx}^{l}, F_{nx}^{pr} are projections of friction forces from transverse feed and friction forces on the front left and right edges F_n^l and F_n^{pr} on the X axis; α_{ust}, α_{kin}, α_{rez}, α_z are installation, kinematic, cutting and pointing angles, respectively, degrees; φ_{zx}^{l}, φ_{zx}^{pr} are gripping angles on the left and right cutting edges of the wedge, degrees; r_f is the rotor radius along the cutting edges, m; $\beta_н$, β_i, β_k are initial, current and final values of the angle of the cutting elements on the cutting arc, degrees; a_{cmp}, b_{cmp}, h_{cmp} are thickness, width and height of the chippings, m.

The following forces act on both faces of a skewed wedge:

1) soil crushing resistance forces N_n^l N_n^{pr}, which act on the front left and right edges and are directed perpendicularly to them. Due to the relatively small size of it, the front edge of the chisel will be considered to be attached to the sharpened part of the cutting edge;

2) friction forces on the front edges F_n^l, F_n^{pr}, acting in the direction of chippings extraction along the front edges, determined by angular parameters of a skewed wedge and the normal force N_n;

3) working bench soil reaction forces from a transverse feed acting on the rear ramp of the CE R_z and additional forces from the normal forces N_{nz}^l and N_{nz}^{pr}, directed normally towards the rear ramp of the chisel;

4) friction forces F_{zx} F_{nx}^l F_{nx}^{pr} acting towards the rear edge plane opposite to the CE movement with respect to the working bench, which depends on the forces R_z, N_{nz}^l and N_{nz}^{pr} acting on the edges.

In accordance with Prof. S. Nurakov's methodology [3, 4, 5] the effect of all applied forces is considered in three dimensions: tangential (along the X-axis), lateral (along the Y-axis) and normal (along the Z axis) with respect the rotation direction of the cutting element of the two-sided skewed wedge.

Normal soil crushing strength forces to the left and right edges N_n^l and N_n^{pr} are decomposed into the X, Y, Z axes. If in accordance with the skewed wedge theory, it is assumed that the tangential components $R_{nx}^{l,pr}$ are equal to the cutting force and, hence, are known as normal $R_{nz}^{l,pr}$ and lateral $R_{ny}^{l,pr}$ components on the left and right edges, equal to each other due to identical conditions, as follows:

$$R_{nz}^{l,pr} = R_{nx}^{l,pr} \frac{\cos\alpha_p - \mu_м \sin\alpha_p \cos\omega_{kl}}{\cos\varphi_1 + \mu_м \sin\psi_1} \quad (1)$$

and

$$R_{ny}^{l,pr} = R_{nx}^{l,pr} ctg\left[arctg\left(\frac{\sin\alpha_p}{\mu_м \sin\omega} + \cos^2\alpha_p tg\varphi_{zx} \right) + \varphi_{zx} \right], \quad (2)$$

Where α_p is the cutting angle in degrees;

φ_{zx}^{l}, φ_{zx}^{pr} are gripping angles, the angles of installation of the left and right cutting edges with respect to the cutting directions, in degrees;

$\mu_м$ is the coefficient of the soil friction against metal;

ω_{kl} is the angle between the friction force direction along the front edge of the skewed wedge F_n and the normal N_n to the cutting edge, degrees;

ψ_1 is the angle between the force N_n and the axis X on the skewed wedge, in degrees.

Despite the complexity of the formulae (1) and (2), determination of R_{nz} and R_{ny} for a definite condition does not imply significant difficulties as the values of the angles ω_{kl} and ψ_1 may be easily calculated, if introduced the most optimal widely-used values of the angles α_p = 30-35°, φ_{zx} = 45° and the CE dimensions.

Consider the following notations:

$$K_z = \frac{\cos\alpha_p - \mu_м \sin\alpha_p \cos\omega}{\cos\varphi_1 - \mu_м \sin\psi_1}, \quad (3)$$

$$K_y = ctg\left[arctg\left(\frac{\sin\alpha_p}{\mu_м \sin\omega} + \cos^2\alpha_p tg\varphi_{zx} \right) + \varphi_{zx} \right], \quad (4)$$

Where K_y, K_z are the coefficients calculated using the known optimal values of the skewed wedge parameters replacing the coefficients in formulae (1) and (2).

Then the expressions (1) and (2) can be rewritten as:

$$R_{nz}^{l(pr)} = K_z \cdot R_{nx}^{l(pr)}, \quad (5)$$

$$R_{ny}^{l(pr)} = K_y \cdot R_{nx}^{l(pr)}. \quad (6)$$

The formulae (5) and (6) are convenient for engineering calculations.

Let us determine the current projections of the corresponding summarized forces on the X, Y, Z axes – R_{xi}^c, R_{zi}^c, R_{yi}^c, acting on the two-sided skewed wedge during chipping.

Tangential resistance to cutting is determined by the formula:

$$R_{nx_i} = K_F a_{oc} в_c \sin\beta_i, \quad (7)$$

where K_F is the specific resistance to cutting by a single cutting element, MPa; a_{0c} is the chipping thickness at the rotor axis, m; $в_c$ is the chipping width, m; β_I is the current value of the chisel rotation angle at the cutting arc, degrees.

The X-axis projection of the cutting tangential resistance $R_{nx_i}^c$ on the CE is a sum of the corresponding values of its components on the left and right edges, as they are assumed to be equal due to the identity of the sizes and angles of both edges:

$$R_{nx}^c = 2\left(R_{nx_i}^{l(pr)} + F_{x_i}^c\right), \quad (8)$$

where $\boldsymbol{F_{x_i}^c}$ is the X-axis projection of the soil friction at the front, back and lateral edges of the chisel which will be determined below.

The Y-axis projection of the summarized lateral resistance $R_{y_i}^c$, which, as it is seen from the scheme, due to the identity of $R_{ny}^l = R_{ny}^{pr}$ and $F_{ny}^l = F_{ny}^{pr}$, is equal to zero. Thus:

$$R_{y_i}^c = 0. \quad (9)$$

The Z-axis projection of the summarized normal resistance $\boldsymbol{R_{z_i}^c}$ is determined by the expression:

$$R_{z_i}^c = R_{zzi} + R_{nz}^l + R_{nz}^{pr}, \quad (10)$$

where R_{zzi} is the force of the soil reaction to the back edge of the CE from the line feed of the working face, which is determined by the resistance to the indentation of the CE back edge into the working face and is equal to:

$$R_z = \sigma_v \cdot S_z \cdot l_z, \quad (11)$$

Where σ_v is the specific resistance to indentation of the CE back edge into the soil, MPa;

S_z is the width of the CE back edge, contacting with the soil, m;

l_z is the length of the horizontal ramp of the CE back edge, m;

R_{nz}^l and R_{nz}^{pr} are projections of the soil reaction against the CE back edge by the forces N_n^l and N_n^{pr}, which are equal to each other - $R_{nz}^l = R_{nz}^{pr}$, N.

Taking into account the above relations, the expression (2.10) can be rewritten as:

$$\begin{aligned} R_{zzi}^c &= \sigma_v S_z \cdot l_z + K_z R_{nz}^l + \\ &+ K_z R_{nz}^{pr} = \sigma_v S_z \cdot l_z + 2K_z R_{nz} \end{aligned}. \quad (12)$$

The projections of the total friction forces of the skewed wedge against the working face may be determined by projecting the friction forces on the front – F_n, back – F_z and lateral – F_b CE edges on the corresponding axes.

The projection of the total friction force on the X axis is equal to the sum of projections the friction forces on the front left, and right, lateral and back edges of the chisel:

$$F_{x_i}^c = 2F_{nx}^{l(pr)} + F_{zx} + F_{bx} \quad (13)$$

or

$$F_{x_i}^c = 2F_n^{l(pr)} \cos(90-\psi_1) + F_{zx} + F_{bx} \quad (14)$$

where 90-ψ_1 is the angle between the X axis and chipping direction along the rotor chisel front edges, *in degrees*.

The components of the total friction force are determined at the front left and right edges.

The projection of the friction forces on the front left and right edges on the X axis is:

$$\begin{aligned} F_{nx_i}^l &= F_n \cos(90-\psi_1) = \mu_м N_n \sin\psi_1 = \mu\sqrt{R_{nx_i}^2 + R_{ny_i}^2 + R_{nz_i}^2} \cdot \sin\psi_1, \\ F_{nx_i}^{pr} &= F_n \cos(90-\psi_1) = \mu_м N_n \sin\psi_1 = \mu\sqrt{R_{nx_i}^2 + R_{ny_i}^2 + R_{nz_i}^2} \cdot \sin\psi_1 \end{aligned} \quad (15)$$

or

$$F_{nx_i}^{l} = \mu_м R_{nz_i}\sqrt{1+K_y^2+K_z^2}\cdot\sin\psi_1,$$
$$F_{nx_i}^{pr} = \mu_м R_{nz_i}\sqrt{1+K_y^2+K_z^2}\cdot\sin\psi_1, \quad (16)$$

where the normal destruction forces N_n^l and N_n^{pr} are equal to:

$$N_n^l = \sqrt{R_{nx}^2+R_{ny}^2+R_{nz}^2},$$
$$N_n^{pr} = \sqrt{R_{nx}^2+R_{ny}^2+R_{nz}^2} \quad (17)$$

or

$$N_n^l = R_{nx}\sqrt{1+K_y^2+K_z^2},$$
$$N_n^{pr} = R_{nx}\sqrt{1+K_y^2+K_z^2}. \quad (18)$$

As $R_{y_i}^c = 0$ (9), projections of the friction forces at the lateral edges on the X axis will also be equal to zero:

$$F_{bx_i}^{l,pr} = \mu_м R_y^c = 0. \quad (19)$$

The projection of the friction force at the back edge on the X axis will be equal to:

$$F_{zi} = \mu_м \cdot R_z^c = \mu_м (R_з^c + 2K_z \cdot R_{nz}) \quad (20)$$

or

$$F_{z_i} = \mu_м (\delta_b \cdot S_z \cdot l_z + 2K_z \cdot R_{nz}). \quad (21)$$

The projection of the total friction force on the Y-axis will be equal to zero, as the summarized projections of the friction forces at the front left and back edges F_{ny}^l, F_{ny}^{pr} and $F_{mp}^{l,pr}$ will be equal to each other and oppositely directed. Hence:

$$F_y^c = 0. \quad (22)$$

Let us project all friction forces acting on the two-sided skewed wedge on the X, Y, Z axes and find the resulting values:

$$R_{x_i}^p = 2R_{nx}^c + 2F_{nx_i} + F_{zx_i}, \quad (23)$$

$$R_{by_i}^p = 0, \quad (24)$$

$$R_z^c = \sigma_{bд} S_z l_z + 2R_{nz}. \quad (25)$$

To determine the tangential and normal cutting forces of the two-sided skewed wedge, it is necessary to project the resulting reaction forces on the X ', Y', Z 'axes: X' is parallel to the plane of the chisel trajectory, Y 'coincides with the axis of the rotor rotation, Z' is directed along the radius of the rotor in the process of complex motion (rotation and line feed):

$$P_{k_i}^{'} = 2R_{x_i}^p \cos\alpha_{kin}, \quad (26)$$

$$P_{н_i}^{'} = \left(2K_z R_{nx}^p + \sigma_b S_z l_z\right)\cos\alpha_{kin}, \quad (27)$$

where $\cos\alpha_{kin} = arctg\, {}^{V_n}\!/_{V_f}$.

In expanded form, these formulae will be rewritten as:

$$P_{k_i}^{'} = (2R_{nx_i}^c + 2F_{nx_i} + F_{zx_i})\cos\alpha_{kin},$$
$$P_{н_i}^{'} = \left(2R_{nz} + \sigma_b S_z l_z\right)\cos\alpha_{kin} \quad (28)$$

or

$$P_{k_i}^{'} = [2(R_{nx} + \mu_м R_{nx}\sqrt{1+K_z^2+K_z^2}\sin\psi_1) + \mu_м(\sigma_в S_з l_з - 2K_z R_{nx})]\cos\alpha_{kin}, \quad (29)$$

$$P_{н_i}^{'} = (\sigma_b S_z l_z + 2K_z R_{nx})\cos\alpha_{kin}.$$

3. RESULTS

The equations describing variations in the tangential and end (lateral) components of the cutting force exerted along the cutting arc by a single cutting element shaped as a two-sided skewed wedge were obtained.

These equations enable us to obtain expressions for the average values of the tangential and end (lateral) components of the cutting force exerted by a single cutting element along the cutting arc, taking into account that $a_i = a_0 \sin\beta_i$:

a) tangential force on the rotor:

$$P'_{\kappa(cp)} = \left[\frac{K_F a_0 b\left(1+\cos\beta_{н} + \sigma_b S_z l_z\right) + K_E a_0 b\left(1+\cos\beta_{н} + \sigma_b S_z l_z\right)\mu_l \sqrt{1+K_y^2+K_F^2}\,\sin\varphi}{2\pi} + \right. \\ \left. + \mu_{м}\left(\sigma_b S_z l_z - K_z \frac{K_F a_0 b\left(1+\cos\beta_{н} + \sigma_b S_z l_z\right)}{2\pi}\right)\right]\cos\alpha_{kin}, \quad (30)$$

where $\beta_{н}$ is the initial cutting angle, *degrees*; $\mu_{т}$ is the coefficient of the soil friction against the metal.

b) end (lateral) force on the rotor:

$$P'_{н(cp)} = \left[\sigma_b S_z l_z K_F \frac{K_F a_0 b\left(1+\cos\beta_{н} + \sigma_b S_z l_z\right)}{2\pi}\right]\cos\alpha_{kin} \quad (31)$$

4. DISCUSSION

A spatial diagram of the forces acting on the BUNBR end cutting element shaped as a two-sided skewed wedge was first obtained, and it was used to derive expressions for calculation of the tangential and normal components of the cutting force at the end chisel of BUNBR, taking into account constructive and kinematic features of the end feed of the working head.

5. CONCLUSIONS

Summarizing expressions (30) and (31) and the previously derived formulae for the corner BUNBR chisels [3], it is possible to obtain a formula for calculation of the total cutting force simultaneously for two types of BUNBR chisels (corner and end). This enables us to tackle calculation of the average load for the full BUNBR turnover with two types of chisels. The correctness of the obtained theoretical dependences must be further confirmed by experimental data.

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