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INVESTIGATION OF WEAR OF CUTTING PART OF POLYGONAL KNIFE CAR GRADERS IN DIFFERENT GROUND CONDITIONS

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Resume

The wear of cutting elements of auto graders allowed in practice causes an increase in the cutting force by 3 to 4 times, the energy intensity of the cutting process by 1.4 to 3 times, the cost of soil development by 8 to 15% with a decrease in productivity by 10 to 30%. This increases the stress state of the entire machine and reduces its operational reliability. Excessive wear of cutting elements leads to economic inexpediency or practical impossibility of further operation of machines.

The above-mentioned areas of research on the productive use of machines, the identification and creation of promising structures of working bodies have determined the task of further increasing the efficiency of auto graders based on improving the working elements taking into account their wear resistance.

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1 Introduction

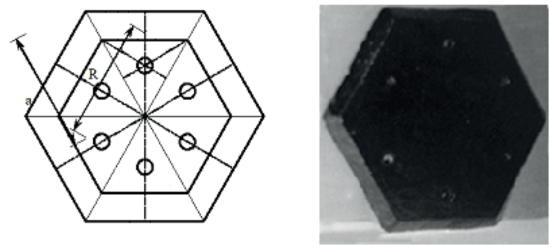
The main direction of improvement of the cutting part of the blade of the motor grader, as noted in the works [1-8], was the development of a reusable knife with a number of cutting faces more than four. Therefore, the object of theoretical research, first of all, were the parameters of the knife. The parameters of the dump were also investigated, which are influenced by an increase in the number of knives having smaller sizes compared to the standard ones. The results of the studies were supposed to provide initial data for choosing the optimal shape of the knife and the design of the blade cutting part.

The increase in the number of cutting faces necessitates that the knife be shaped like a polygon. In this case, the number of faces can be five, six, seven, eight. A further increase in the number of faces is obviously impractical due to an excessive decrease in the width of the face compared to the width of the knife.

In polygonal knives (Figure 1) [9-11], one of the cutting faces is the main working face, which forms the blade of the blade of the blade of the blade of the auto grader. At the same time, in order to ensure the continuity of the blade along its entire width, the knives are arranged in two rows. However, in addition to this face, two side faces, which are called the side working faces, also take part in cutting the soil or loosening it. They are located at an angle of more than 90° with respect to the main one. If the knife is the side knife of the dump [12-13], then one of its sides working faces will be the side face of the dump, and the second is, as it were, a leading step on the knife of the second row.

2 Materials and methods

During operation of dumps of motor graders equipped with polygonal knives, the main working faces of knives, forming the blade of the blade are subjected to the greatest wear [14-17]. The following geometric elements of the worn-out blade are installed by studies of the wear resistance of the cutting elements of the auto grader: a wear area located at a negative angle of inclination φ to the cutting plane and characterized by width a and the value of the φ' angle, rounding of the front edge of the knife, characterized by a radius r. Since different wear elements (r or a) can be determining in



a) b)

Figure 1 *Plate of autograder knife:*
a) - the diagram of the knife; b) - a general view

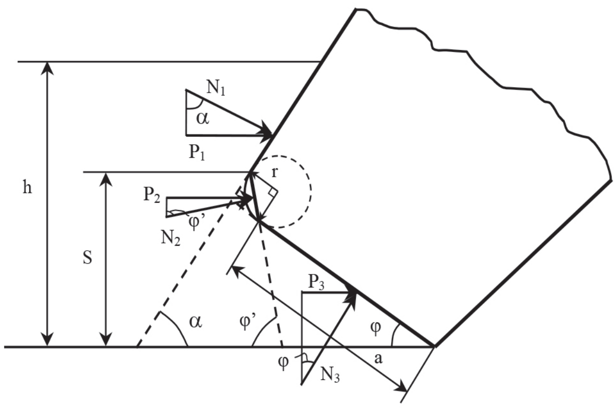


Figure 2 *Additional resistance forces generated at blade wear sites*

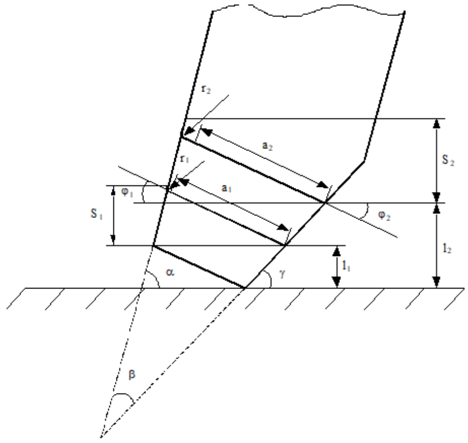


Figure 3 *Geometry wear of the blade of the dump of the auto grader*

different conditions, it is advisable to use the reduced wear size S proposed by Kabashev [18] to expand the field of application of the derived equations, which is a complex size that takes into account both the r value and the a value, as well as the φ value.

Figure 2 shows the cross-sectional diagram of the blade of a worn knife with wear zones that provide additional resistance to soil cutting. To simplify the calculation, the rounding of the front face is replaced by a flat pad at an angle 45° to the pad a.

Since during the knife operation all the wear areas come into contact with the ground, resistance to soil cutting of the main straight working face of the knife will be:

$$P_n' = P_1' + P_2' + P_3', \tag{1}$$

where P'_1 - resistance to soil cutting in the unworn blade area (above wear zones); P'_2 - resistance to soil cutting on the site replacing the rounded wear zone r; P'_3- resistance to soil cutting at the wear site a.

The ultimate resistance to cutting will be:

$$P_{P\kappa} = P_n' + 2P_\kappa' = P_1' + P_2' + P_3' + 2P_\kappa', \tag{2}$$

here P'_1 corresponds to P'_n, but its range is limited by the width of the site $(h - S)/2$,
where h - is the depth of the soil cutting.

$$P_1' = B_n\cdot(h-S)\cdot\left(1+f\cdot\sqrt{\frac{1}{\sin^2\varphi'}-1}\right) = N_2\cdot\sin(\varphi+45^0)\cdot\left(1+f\cdot\sqrt{\frac{1}{\sin^2(\varphi+45^0)}-1}\right), \tag{3}$$

or one gets:

$$P_1' = N_1\cdot\sin\alpha\cdot\left(1+f\cdot\sqrt{\frac{1}{\sin^2\alpha}-1}\right), \tag{4}$$

$$P_2' = N_2\cdot\sin\varphi'\cdot\left(1+f\cdot\sqrt{\frac{1}{\sin^2\varphi'}-1}\right) = N_2\cdot\sin(\varphi+45^0)\cdot\left(1+f\cdot\sqrt{\frac{1}{\sin^2(\varphi+45^0)}-1}\right), \tag{5}$$

where φ' - is the inclination angle of the platform r to the cutting plane.

$$P_3' = N_3\cdot\sin\varphi\cdot\left(1+f\cdot\sqrt{\frac{1}{\sin^2\varphi}-1}\right). \tag{6}$$

In general, the $P_{P\kappa}$ value will be:

$$P_{P\kappa} = B_n\cdot\left[(h-S)\cdot\left(1+f\cdot\sqrt{\frac{1}{\sin^2\alpha}-1}\right)+ \frac{r}{\cos 45^0}\left(1+f\cdot\sqrt{\frac{1}{\sin^2(\phi+45^0)}-1}\right)\right]\times \frac{1-\sin\rho\cdot\cos 2\phi_H}{1+\sin\rho\cdot\cos 2\phi_H}\cdot\left\{3\cdot C_0\cdot\cos\rho+\gamma_n\times \left[\frac{h-S}{2}+\frac{r\cdot\sin(\phi+45^0)}{2\cdot\cos 45^0}+\frac{a\cdot\sin\phi}{2}\right]\right\}+ 2\cdot[K_S\cdot B_\kappa\cdot h\cdot\mu+\varepsilon\cdot B_\kappa\cdot h\cdot\mu\cdot\upsilon^2]. \tag{7}$$

Figure 4 *Investigation of the wear pattern of motor grader dumps blades in production conditions*

Table 1 *Change of geometrical parameters of motor graders knives during operation in various soils*

No.	Soil conditions and type of work	Classes of soil C	Average development volume soil V (thousand m^3)	Dull radius r (mm)	Wear and tear area a (mm)	Wear area inclination angle φ (degree)	Reduced size wear S (mm)
1	Development and movement of sandy soils	3-5	1.5	0	17	22	
		3-5	3.0	0	20	16	
		3-5	9.9	0	27	6	
2	Development and movement of sandy loam soils	10-15	1.5	3.0	14	20	9.0
		10-15	3.0	3.5	18	13	10.2
		10-15	7.2	4.5	21	9	13.3
3	Development and movement of loams	14-16	1.5	3.5	10	14	8.0
		14-16	3.0	4.0	12	17	9.5
		14-16	8.5	6.0	17	20	14.5
4	Development and movement of heavy loams and clays	18-20	1.5	3.0	9	10	8.0
		18-20	3.0	4.0	10	16	9.5
		18-20	14.4	8.0	16	18	20.0
5	Development of clays, loams with inclusions	20-30	1.5	6.0	9	19	
		20-30	3.0	8.0	12	22	
		20-30	3.8	10.0	11	30	

An expression was obtained that can be used to calculate the ground resistance forces to cutting and the corresponding cutting efficiency coefficients at different values of the dull sites.

However, it is not yet known what values of the dull parameters should be taken as criteria and used in calculations. In order to determine these criteria, as well as to expand the field of use of the obtained formula, using it, in particular, for the reduced dull size, it is necessary to investigate the wear patterns of the blades of the dump of auto graders.

As noted above, an auto grader cutting element having a wedge-shaped cross-section may be characterized by the following wear geometries: a rounded wear area of the front face of the wedge or angular wear measured by the radius of rounding r, a flat dull area located at a negative angle φ to the cutting plane and a measured width of the area a. In addition, wear can be characterized by a loss of blade height or linear wear l, as well as a complex wear parameter - the reduced size S, combining the values r, a and φ (Figure 3).

The study of the wear nature of the blades of the dump of motor graders was carried out at the construction and repair facilities of the roads of JSC

Roads of Kazakhstan [2, 15] (Figure 4). Initially, all dimensions of the wear elements were recorded, with the exception of S. The data obtained are shown in Table 1.

However, it turned out that in different soil conditions, different wear elements play a decisive role. To take into account all these cases with a single formula, it is necessary to use the complex reduced wear size - S.

In order to link the reduced wear size S with the radius of rounding r, the wear pad a and the slope of the pad φ, consider the worn blade diagram in Figure 5.

As one can see from the diagram, the dimension S is made up of lines

$$S = bc + cd + de, \tag{8}$$

where $bc = nc\cos\alpha = r\cos\alpha$; $cd = ck\cos\varphi = r\cos\varphi$; $de = kp = km\sin\varphi = a\sin\varphi$.

Then

$$S = bc + cd + de = r\cos\alpha + r\cos\varphi + a\sin\varphi, \tag{9}$$

from where

$$S = r(\cos\alpha + \cos\varphi) + a\sin\varphi. \tag{10}$$

Equation (10) can be simplified by establishing the relationship of the change values r, a and φ. This can be done if the regularities of their change are known depending on the amount of work performed in different categories of soils. These patterns can also be used to predict the nature of the wear of knives during their operation and control this process. Therefore, based on the data of Table 1, graphs were plotted and equations of the above dependencies were derived.

Figures 6 and 7 show the graphs of the radius of rounding of the blade r and the wear site a dependences on the volume of excavated soil V, respectively. The obtained regression equations are summarized in Table 2.

The following conclusions can be drawn from the analysis of regression graphs and equations:

- clay-containing rocks (loams and clays) without inclusions have close relationships $r = f(V)$ and $a = f(V)$;
- loams and clays with inclusions are characterized by a more intensive increase in the radius of rounding of the blade r with an increase in the volume of mined soil V and a significant spread of data, which is due, apparently, to the chaotic

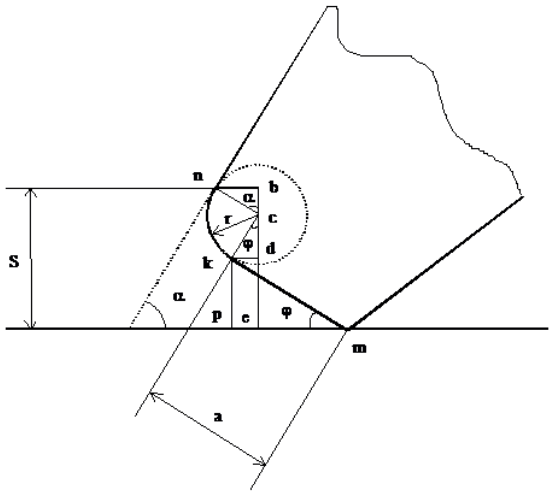


Figure 5 *Diagram for determination of the reduced wear size*

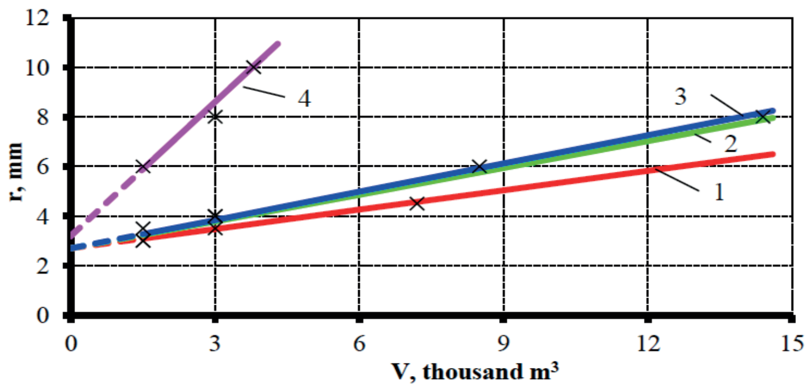


Figure 6 *Dependence of the rounding radius r on volume of the worked-out soil V for different soil types: 1 - sandy loam - r = 2.7 + 0.26V; 2 - loams - r = 2.7 + 0.36V ; 3 - heavy loams and clays - r = 2.7 + 0.38V; 4 - loam with inclusions - r = 3.2 + 1.80V*

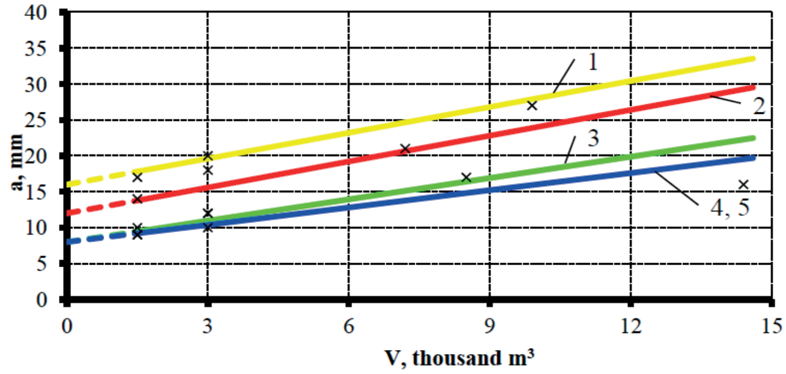


Figure 7 *Dependence of the wear site a on volume of mined soil V for various soil types:*
1 - sandy soil - a = 16 + 1.20V; 2 - sandy loam soil - a = 12 + 1.20V; 3 - loams - a = 8 + 0.99V;
4 - heavy loams and clays - heavy loams and clays a = 8 + 0.80V;
5 - loam with inclusions - a = 8 + 0.85V

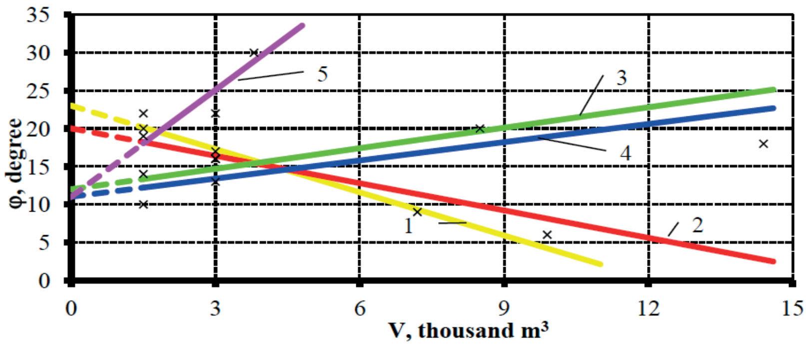


Figure 8 *Dependence of the slope angle a of the wear site on the volume of mined soil V for various soil types:*
1 - sandy soil - $\phi = 23 - 1.90V$; 2 - sandy loam - $\phi = 20 - 1.20V$; 3 - loams - $\phi = 12 + 0.90V$;
4 - heavy loams and clays - $\phi = 11 + 0.80V$; 5 - loam with inclusions - $\phi = 11 + 4.70V$

Table 2 *Regression equations for determining the geometric parameters of wear of motor graders knives*

No.	Soil conditions	Radius blurring r	Platform wear a	Wear area inclination angle φ
1	Sand	$r = 0$	$a = 16 + 1.20V$	$\varphi = 23 - 1.90V$
2	Sandy loam	$r = 2.7 + 0.26V$	$a = 12 + 1.20V$	$\varphi = 20 + 1.20V$
3	Loams	$r = 2.7 + 0.36V$	$a = 8 + 0.99V$	$\varphi = 12 + 0.90V$
4	Heavy loams and clays	$r = 2.7 + 0.38V$	$a = 8 + 0.80V$	$\varphi = 11 + 0.80V$
5	Loam and clay with inclusions	$r = 2.7 + 1.80V$	$a = 8 + 0.85V$	$\varphi = 11 + 4.70V$

nature of inclusions, which reduces the reliability of the calculation results according to the obtained formulas;

- wear along the radius of rounding r of the knife blades during operation in sandy soils does not appear, and in sandy loams it appears with less intensity than in the clay-containing soils. The change in the wear site in sands and sandy loams also differs in intensity from clay-containing soils.

Figure 8 shows graphs of the dependence of the inclination angle of the wear site to the cutting plane (angle of φ) on the volume of the developed soil. The regression equations obtained are shown in Table 2.

The given graphs and equations confirm the earlier conclusions that the change in wear elements in the clay-containing soils can be expressed by generalized formulas. In addition, it can be seen that in sandy and sandy loam soils the φ value decreases with increasing V, and in clay-containing soils it increases.

However, in general, the limits of variation of the φ value for all the soils, with the exception of soils with inclusions, are small. If one takes all the obtained values as a sample of random variables, then the average sample is $\varphi = 15.08°$. With corrected mean quadratic deviation $S_{isp} = 0.8°$, determine with reliability $\gamma = 0.95$ limits of confidence interval of true value of φ inclination angle. At $\gamma = 0.95$ and $n = 12$ according to the reference book [6] one finds the value t expressed in fractions of the mean quadratic error σ, t = 2.13. The accuracy of estimate of δ, given that at $n \leq 30$ $\sigma \approx S_{isp}$ is found.

$$\delta = \frac{t \cdot \sigma}{\sqrt{n-1}} = \frac{t \cdot S_{isp}}{\sqrt{n-1}} = \frac{12.3 \cdot 0.8}{\sqrt{12-1}} = 0.51^{\circ}.$$

The confidence interval is defined as: (φ - 0.51; φ + 0.51) and its limits are:

$$\varphi - 0.51 = 15.08 - 0.51 = 14.57 \approx 14.6^{\circ};$$
$$\varphi + 0.51 = 15.08 + 0.51 = 15.59 \approx 15.6^{\circ}.$$

So, with a reliability of γ = 0.95, that is, in 95 cases out of 100, the true value of the inclination angle φ is in the confidence interval $14.6^{\circ} \leq \varphi_{^{\circ}ist} \leq 15.6^{\circ}$. Therefore, it is permissible to accept for all the soils, with the exception of soils with inclusions, the average value of the angle φ = 15°.

Substituting the average value of the angle φ in Equations (5) and (6) one obtains:

$$P_2' = B_n \cdot 1.43r \cdot (1 + 0.574f) \times \frac{1 - \sin \cdot \rho \cdot \cos 2\varphi_H}{1 + \sin \cdot \rho \cdot \cos 2\varphi_H} \cdot (C_O \cdot \cos\rho + \gamma_n \cdot 0.62r). \quad (11)$$

$$P_3' = B_n \cdot a \cdot (1 + 3.73f) \cdot \frac{1 - \sin \cdot \rho \cdot \cos 2\varphi_H}{1 + \sin \cdot \rho \cdot \cos 2\varphi_H} \times (C_O \cdot \cos\rho + \gamma_n \cdot 0.13r). \quad (12)$$

In general, the $P_{P\kappa}$ value will be:

$$P_{P\kappa} = B_n \cdot \Big[(h - s) \cdot \Big(1 + f \cdot \sqrt{\frac{1}{\sin^2\alpha} - 1}\Big) + 1.43r \cdot (1 + 0.574f) + a(1 + 3.73f)\Big] \times \frac{1 - \sin \cdot \rho \cdot \cos 2\varphi_H}{1 + \sin \cdot \rho \cdot \cos 2\varphi_H} \cdot \Big[3 \cdot C_0 \cdot \cos\rho + \gamma_n \times \Big(\frac{h - S}{2} + 0.62r + 0.13a\Big)\Big] + 2 \cdot (K_S \cdot B_\kappa \cdot h \cdot \mu \times \varepsilon \cdot B_\kappa \cdot h \cdot \mu \cdot \upsilon^2). \quad (13)$$

Equation (10) can be represented as:

$$S = r(\cos\alpha + \cos 15^{\circ}) + a \sin 15^{\circ}, \quad (14)$$

from here

$$S = r(0.966 + \cos\alpha) + 0.26a \quad (15)$$

The equations found $r = f(V)$ and $a = f(V)$ are substituted in Equation (15).

For sandy loam soils, we get:

$$S = 2.7(2.13 + \cos\alpha) + 0.26V(2.16 + \cos\alpha). \quad (16)$$

Consider that 2.16 ≈ 2.13. Then

$$S = (2.7 + 0.26V)(2.13 + \cos\alpha). \quad (17)$$

Similarly, for the clay-containing soils after transformations, one obtains:

$$S = (2.7 + 0.38V)(1.70 + \cos\alpha). \quad (18)$$

Verification of the obtained equations became possible when the data on the wear of knives were obtained at the objects of the trust Construction mechanization LLP (Figure 9), given in Table 3. Here, not only the parameters r and a were recorded, but the complex size S, as well, when working in the clay-containing soils. The results of measurements were compared with the calculated data obtained from equations given in Table 2 and Equations (17) and (18). As one can see, the average error of the measured and calculated values is about 5%, and the maximum - does not exceed 11%, which is permissible in such unorganized processes as wear of the cutting elements of the auto grader.

After checking the formulas, Table 1 was supplemented with the calculated values of S and

Table 3 *Change of geometric parameters of wear of motor grader dumps blades at the objects of Construction mechanization LLP trust*

No.	Soil conditions	Soil development volume V (thousand m^3)	Magnitude of wear geometric parameters (mm)					
			r		*a*		S	
			by measurement	settlement	by measurement	settlement	by measurement	settlement
1	Loams	10	6	6.3	20	18.0	15	16.0
		15	8	8.1	22	22.8	20	20.6
		20	10	9.9	30	27.8	25	25.3
		25	12	11.7	34	32.7	30	30.0
2	Heavy loams and clays	10	7	6.5	18	16.8	17	16.0
		15	9	8.4	20	20.2	22	20.6
		20	10	10.3	25	24.0	26	25.3
		25	13	12.2	30	28.1	32	30.0

Figure 9 *Wear of motor graders knives at the facilities of the trust Construction mechanization LLP*

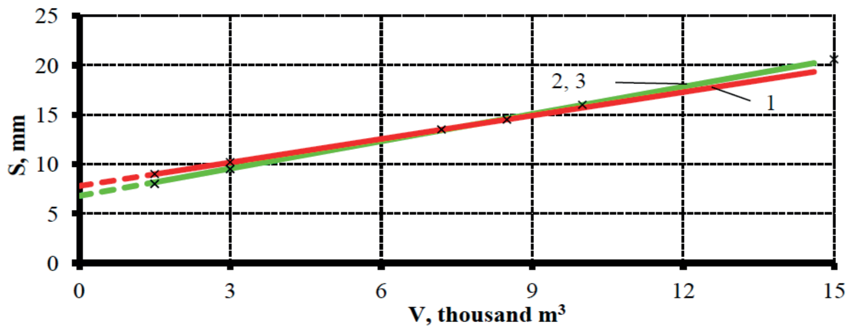


Figure 10 *Dependence of the reduced dull size S on the volume of mined soil V for various soil types: 1 - sandy loam; 2 - loams; 3 - heavy loams and clays*

Table 4 *Pair correlation equations for calculations of wear parameters depending on the reduced wear size for different soil types*

Soil type	$r = f(S)$	$a = f(S)$
Sandy	$r = 0.35S$	$a = 0.6 + 1.63S$
Clay-containing	$r = 0.42S$	$a = 1.8 + 0.84S$

graphs of the change S in clay-containing and sandy loam soils, shown in Figure 10, were drawn on them.

It can be seen that with an increase in the volume of developed soil V, wear S in sandy loam soils first exceeds wear in clay-containing soils, but its growth intensity is smaller and after mining 6.0 - 6.5 thousand m^3 of soil, the wear value in clay-containing soils becomes larger.

Equations (17) and (18) can be used in workflow planning and control in production conditions.

3 Results and discussions

Thus, theoretically, Equation (10) is derived, expressing the relationship of the reduced size S with the wear parameters r, a and φ. The relationship of these parameters in the production process was experimentally investigated, which made it possible to clarify Equation (10) and obtain the Equation (15). The values of S, corresponding to the initial data r and a in production experiments (Table 3) and Equations (17) and (18), expressing the dependence of S on V, made it possible to plan and control the process of working the blade elements are obtained.

Now it is possible to establish a pair of correlation relationship between r and S, a and S, which is necessary to transform the Equation (18) in order to universalize it.

The data obtained correspond to equations given in Table 4.

Substituting the obtained expressions into Equations (11) and (12), one gets:

- for sandy loam soils:

$$P_2' = 0.5 \cdot B_n \cdot S \cdot (1 + 0.574f) \times \times \frac{1 - \sin\beta \cdot \cos 2\varphi'_H}{1 + \sin\beta \cdot \cos 2\varphi'_H} \cdot (C_O \cdot \cos\rho + 0.22 \cdot \gamma_n \cdot S), \quad (19)$$

$$\begin{aligned}P_3' = {} & B_n\cdot(0.6+1.63S)\cdot(1+3.73f)\times\\ & \times\frac{1-\sin\beta\cdot\cos2\varphi_H''}{1+\sin\beta\cdot\cos2\varphi_H''}\cdot(C_O\cdot\cos\rho+0.22\cdot\gamma_n\cdot S),\end{aligned} \tag{20}$$

$$\begin{aligned}P_{Pк} = {} & P_1'+P_2'+P_3' = B\Big\{(h-s)\times\\ & \times\left(1+f\cdot\sqrt{\frac{1}{\sin^2\alpha}-1}\right)\cdot\frac{1-\sin\beta\cdot\cos2\varphi_H''}{1+\sin\beta\cdot\cos2\varphi_H''}\times\\ & \times\left[C_0\cdot\cos\rho+0.5\cdot\gamma_n\cdot(h-S)\right]+(C_0\cdot\cos\rho+\\ & +0.22\cdot\gamma_n\cdot S)\cdot\Big[0.5S\cdot(1+0.574f)\times\\ & \times\frac{1-\sin\beta\cdot\cos2\varphi_H''}{1+\sin\beta\cdot\cos2\varphi_H''}\Big]\Big\}+2(K_\varsigma\cdot B_к\cdot h\cdot\mu+\\ & +\varepsilon\cdot B_к\cdot h\cdot\mu\cdot\upsilon^2),\end{aligned} \tag{21}$$

- for clay soils:

$$\begin{aligned}P_2' = {} & 0.6\cdot B_n\cdot S\cdot(1+0.574f)\times\\ & \times\frac{1-\sin\beta\cdot\cos2\varphi_H'}{1+\sin\beta\cdot\cos2\varphi_H'}\cdot(C_O\cdot\cos\rho+0.26\cdot\gamma_n\cdot S),\end{aligned} \tag{22}$$

$$\begin{aligned}P_2' = {} & B_n\cdot(1.8+0.84S)\cdot(1+3.73f)\times\\ & \times\frac{1-\sin\beta\cdot\cos2\varphi_H''}{1+\sin\beta\cdot\cos2\varphi_H''}\times\\ & \left[C_O\cdot\cos\rho+\gamma_n\cdot(0.23+0.11S)\right],\end{aligned} \tag{23}$$

$$\begin{aligned}P_{Pк} = {} & P_1'+P_2'+P_3' = B_n\cdot\Big\{(h-S)\times\\ & \times\left(1+f\cdot\sqrt{\frac{1}{\sin^2\alpha}-1}\right)\cdot\frac{1-\sin\beta\cdot\cos2\varphi_H''}{1+\sin\beta\cdot\cos2\varphi_H''}\times\\ & \times\left[C_o\cdot\cos\rho+0.5\cdot\gamma_n\cdot(h-S)\right]+0.6S\times\\ & \times(1+0.574f)\cdot\frac{1-\sin\beta\cdot\cos2\varphi_H'}{1+\sin\beta\cdot\cos2\varphi_H'}\times\\ & \times(C_o\cdot\cos\rho+0.26\cdot\gamma_n\cdot S)+(1.8+0.84S)\times\\ & \times(1+3.73f)\cdot\frac{1-\sin\beta\cdot\cos2\varphi_H''}{1+\sin\beta\cdot\cos2\varphi_H''}\times\\ & \times\left[C_O\cdot\cos\rho+\gamma_n\cdot(0.23+0.11S)\right]\Big\}+\\ & 2(K_\varsigma\cdot B_к\cdot h\cdot\mu+\varepsilon\cdot B_к\cdot h\cdot\mu\cdot\upsilon^2)\end{aligned} \tag{24}$$

According to Equation (5), the coefficients K_c of the unaffected blade of the knife as compared to the blunted blade will be:

$$K_c=\frac{P_{Pк}'/A}{P_{Pк}/A}=\frac{P_{Pк}'}{P_{Pк}}, \tag{25}$$

where $P_{Pк}'$ - is resistance to cutting with an unaffected knife; $P_{Pк}$ - resistance to cutting by blunted knife with reduced wear size S; A - projection of the contact area of working faces of knife with soil in a vertical plane.

Then:

- for sandy loam soils:

$$K_c=\frac{\begin{aligned}& B_n\times\\ & \times\left\{\begin{aligned}& (h-S)\cdot\left(1+f\cdot\sqrt{\frac{1}{\sin^2\alpha}-1}\right)\times\\ & \times\frac{1-\sin\beta\cdot\cos2\varphi_H}{1+\sin\beta\cdot\cos2\varphi_H}\cdot\left[\begin{aligned}& C_0\cdot\cos\rho+\\ & +0.5\cdot\gamma_n\times\\ & \times(h-S)\end{aligned}\right]+\\ & +\left[\begin{aligned}& 0.5S\cdot(1+0.574f)\times\\ & \times\frac{1-\sin\beta\cdot\cos2\varphi_H'}{1+\sin\beta\cdot\cos2\varphi_H'}+\\ & +(0.6+1.63S)\times\\ & \times\frac{1-\sin\beta\cdot\cos2\varphi_H''}{1+\sin\beta\cdot\cos2\varphi_H''}\end{aligned}\right]+\\ & +(C_0\cdot\cos\rho+0.22\cdot\gamma_n\cdot S)\end{aligned}\right\}+\\ & +2(K_\varsigma\cdot B_к\cdot h\cdot\mu+\varepsilon\cdot B_к\cdot h\cdot\mu\cdot\upsilon^2)\end{aligned}}{\begin{aligned}& B_n\cdot h\cdot\left(1+f\cdot\sqrt{\frac{1}{\sin^2\alpha}-1}\right)\cdot\frac{1-\sin\beta\cdot\cos2\varphi_H}{1+\sin\beta\cdot\cos2\varphi_H}\times\\ & \times(C_0\cdot\cos\rho+0.5\cdot\gamma_n\cdot h)+2\cdot\left(\begin{aligned}& K_\varsigma\cdot B_к\cdot\mu+\\ & +\varepsilon\cdot B_к\cdot\mu\cdot\upsilon^2\end{aligned}\right)\end{aligned}} \tag{26}$$

- for clay soils:

$$K_c=\frac{\begin{aligned}& B_n\times\\ & \times\left\{\begin{aligned}& (h-S)\cdot\left(1+f\cdot\sqrt{\frac{1}{\sin^2\alpha}-1}\right)\times\\ & \times\frac{1-\sin\beta\cdot\cos2\varphi_H}{1+\sin\beta\cdot\cos2\varphi_H}\cdot[C_0\cdot\cos\rho+\\ & +0.5\cdot\gamma_n\cdot(h-S)]+0.6S\times\\ & \times(1+0.574f)\frac{1-\sin\beta\cdot\cos2\varphi_H'}{1+\sin\beta\cdot\cos2\varphi_H'}\times\\ & +(C_0\cdot\cos\rho+0.26\gamma_nS)+\\ & +(1.8+8.84S)\cdot(1+3.73f)\times\\ & \times\frac{1-\sin\beta\cdot\cos2\varphi_H''}{1+\sin\beta\cdot\cos2\varphi_H''}\cdot[C_0\cdot\cos\rho+\\ & +\gamma_n(0.23+0.11S)]\end{aligned}\right\}\times\\ & \times2(K_\varsigma\cdot B_к\cdot h\cdot\mu+\varepsilon\cdot B_к\cdot h\cdot\mu\cdot\upsilon^2)\end{aligned}}{\begin{aligned}& B_n\cdot h\cdot\left(1+f\cdot\sqrt{\frac{1}{\sin^2\alpha}-1}\right)\cdot\frac{1-\sin\beta\cdot\cos2\varphi_H}{1+\sin\beta\cdot\cos2\varphi_H}\times\\ & \times(C_0\cdot\cos\rho+0.5\cdot\gamma_n\cdot h)+2\cdot\left(\begin{aligned}& K_\varsigma\cdot B_к\cdot\mu+\\ & +\varepsilon\cdot B_к\cdot\mu\cdot\upsilon^2\end{aligned}\right)\end{aligned}} \tag{27}$$

***Table 5** Coefficients K_c, characterizing the increase in soil resistance to cutting as a result of blunting of the blade of the knife, measured by the reduced size S*

Dull value S (mm)	*Soil*	
	sandy loam	*loams*
5	*0.60*	*0.72*
10	*1.18*	*1.35*
15	*1.90*	*2.08*
20	*2.36*	*2.76*
25	*3.04*	*3.54*
30	*3.62*	*4.28*

Results of K_c coefficient calculation at α = 40°, f = 0.7 and h = 80 mm are given in Table 5.

As one can see, when the reduced wear size S increases to 30 mm, the soil resistance increases in 3 to 4 times, which reduces productivity and increases the costs of work of the auto grader.

4 Conclusions

1. Production experiments were carried out, as a result of which regularities of changes in geometric parameters of wear of dump of auto graders in various soils were established: the radius of rounding of the blade r from the volume of mined soil V; wear sites a from the volume of excavated soil V; the angle of inclination of the wear area to the cutting plane φ of the volume of excavated soil V; reduced wear size S of volume of excavated soil V; wear elements r and a of the reduced wear size S. The corresponding equations are obtained.
2. It has been established, that in clay-containing soils - loams and clays without inclusions, close relationships $r = f(V)$, $a = f(V)$ and $\varphi = f(V)$, are obtained, which makes it possible to use generalized regression equations for these soils.
3. In loams and clays with inclusions, the obtained experimental data are characterized by significant variation and the dependencies obtained from them differ from the corresponding dependencies for other clay-containing soils. Therefore, the proposed formulas for clay-containing soils cannot be used for clay-containing soils with inclusions and the obtained dependencies for these soils cannot be recommended for wide use due to the weak correlation of design and experimental data due to the large dispersion of the latter.
4. In sandy soils, wear of the blade along the radius r does not occur. The regression equations of the above dependencies in sands and sandy loams have a different character than in clay-containing soils. So, the wear r in sandy loam is manifested with less intensity, and the wear site a in sands and sandy loam increases more intensively; the angle of φ decreases with increasing V, while in clay-containing soils it increases. For sands and sandy loams there are proposed formulas different from those proposed for the clay-containing soils.
5. It has been found that the angle of the wear site φ varies within insignificant limits and its average value can be taken 15°. With a reliability of $\gamma = 0.95$ this value is contained in the confidence interval $14.6° < \varphi < 15.6°$.
6. A formula is proposed for determining the reduced wear size S through r, a, φ and α, cutting angle, specified using the obtained results of experimental studies.
7. A formula is proposed for determining the reduced wear size S depending on V, which makes it possible to plan and control the process of working blade cutting elements.

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