INFLUENCE OF THE CUTTING ANGLE ON THE RESISTANCE OF BULLDOZER WORKING EQUIPMENT BLADE BURIAL WHEN THE MACHINE IS MOVING

Nursat Baikenzhe[1], Shynbolat Tynybekov[1], Bakytzhan Kyrgyzbay[2], Kazyna Ashim[3], Nurbol Kamzanov[1], Rustem Kozbagarov[2,*]

[1]Satbayev University, Almaty, Republic of Kazakhstan
[2]Mukhametzhan Tynyshbayev ALT University, Almaty, Republic of Kazakhstan
[3]Nazarbayev Intellectual Schools of Chemistry and Biology, Almaty, Republic of Kazakhstan

*E-mail of corresponding author: ryctem_1968@mail.ru

Nursat Baikenzhe 0009-0000-0290-9056, Shynbolat Tynybekov 0009-0002-6146-2076,
Bakytzhan Kyrgyzbay 0009-0004-0317-7917, Kazyna Ashim 0009-0002-1496-1278,
Nurbol Kamzanov 0000-0002-2420-8362, Rustem Kozbagarov 0000-0002-7258-0775

Resume

The influence of the cutting angle on the resistance to the bulldozer blade burial during its movement, taking into account the one-sided stressed state of the soil, was studied in the research results of which are presented in this paper. It is established that the resistance to deepening is significantly reduced when the machine is moving, which allows using smaller cutting angles without increasing the energy consumption. Constructive features and kinematics of the working equipment are considered, including a promising parallelogram scheme, which provides automatic reduction of the cutting angle during deepening. Calculations of the resistance of the blade penetration into the ground, and experimental data confirming the cutting force reduction up to 7%, for each degree of angle reduction, are given. It is determined that the optimum cutting angle is 30-40°. The obtained results can be used to increase the productivity of bulldozers and optimize the design of their working equipment.

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1 Introduction

The study and systematization of the results of conducted research on bulldozer equipment allows to identify trends in their development and establish directions for further research. The generalizing work [1-6] indicates that a promising direction of research in the field of universal earthmoving machines, including bulldozers, is the creation of working bodies with the properties of wide adaptation to external conditions and types of work performed.

In the case of bulldozers, this trend is manifested in the creation of designs of working equipment that allow for transverse skewing of the blade and changing the cutting angle, as well as equipping the moldboards with a jaw grip, protruding middle blade. Improving the efficiency of bulldozer is largely associated with improving the design of working equipment, its kinematic and force parameters. At the same time, the working equipment schemes used in practice are usually structurally similar regardless of the layout of the basic machine. However, the efficiency of the bulldozer is influenced not only by the parameters of the working equipment and the base machine taken separately, but by the consistency of their mutual work, as well. Thus, there is a question of choosing a rational scheme of working equipment.

To determine the ways of solving this issue, authors considered the impact on the efficiency of the working process of the bulldozer, as a result of research on the features of the working equipment and its links with the base machine. It is known that in the process of bulldozer operation most of its power is spent on cutting the soil and moving it along the working body - blade. Since the process of soil cutting is carried out as a result of force interaction with it as a result of both the working equipment and the running system of the base tractor, it

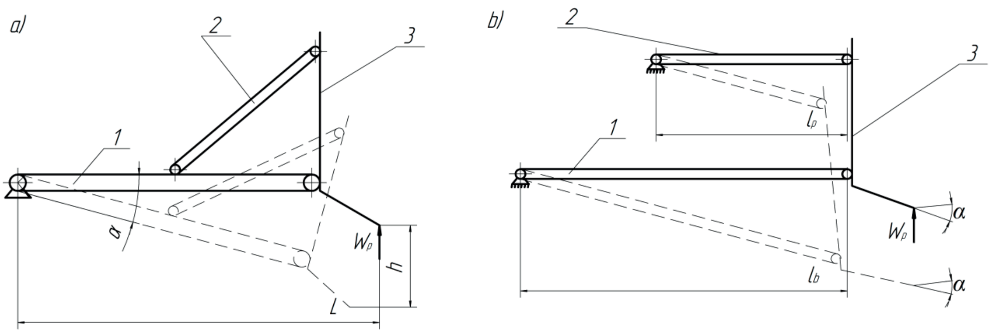

Figure 1 *Scheme of burial into the ground of the blade of the working equipment of the bulldozer: a) scheme "traditional"; b) scheme "parallelogram"; 1- strut, 2 - push bar, 3 - moldboard*

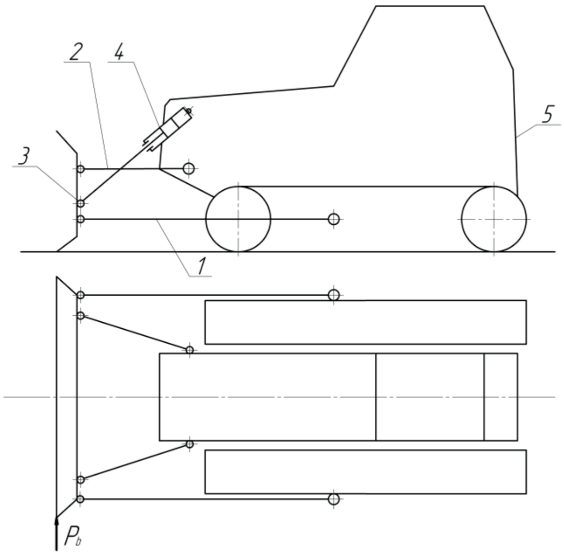

Figure 2 *Kinematic diagram of bulldozer working equipment: 1 - push bar; 2 – strut; 3- moldboard; 4 - hydraulic cylinder; 5 - tractor base*

is necessary to identify the influence of their parameters on its efficiency.

There are known designs of working equipment having a traditional scheme, in which both skews are made in the form of hydraulic cylinders, serving both for realization of blade skew and for controlled change of cutting angle in the process of cutting W_p [5-7]. However, they have not become widespread due to the increased cost of construction. Therefore, a promising way to improve this function should be recognized as the creation of a scheme of working equipment that reduces the blade cutting angle as it is embedded in the ground due to its own kinematics. The changes in the cutting angle α depending on the digging depth h in the traditional bulldozer scheme were considered, [8-10]. In accordance with the notations in Figure 1, and taking into account that h << L, one obtains the relationship between the changes in cutting angle α and h

$$\alpha = 57.7\frac{h}{L}. \qquad (1)$$

As can be seen from Equation (1), the cutting angle at h << L is linearly related to the digging depth h. From the point of view of kinematics, this dependence is determined by the impossibility to rotate the moldboard 3 relative to the push bars 1, which is prevented by the presence of links between the struts 2 and the bars. Therefore, in this case, the pushing bars and struts cannot be connected to each other, for example, in a "parallelogram" pattern (Figure 1, b).

If the condition $l_p << l_b$ is provided in this mechanism, the cutting angle decreases as the blade penetrates the ground. Such technical solution is known (Figure 1, b), however, it has not been practically realized on industrial bulldozers, which is explained by peculiarities of basic tractors design. In particular, in tractors with semi-rigid suspension, the frame is not rigid enough in the horizontal plane and is not designed to absorb lateral forces. In the scheme of the bulldozer shown in Figure 2, when it is loaded with force P_b applied to the moldboard 3, its lateral stability is provided by struts 2, which leads to loading of the tractor frame 5 by a bending moment in the horizontal plane.

Related to this, it seems reasonable, using the advantages of the "parallelogram" scheme, to ensure loading of the tractor frame by forces lying only in its vertical-longitudinal plane, due to redistribution of forces acting on the tractor between the crawler tracks designed to absorb complex loading (forces lying in three planes can act on them simultaneously). Another advantage of this scheme of blade connection with bars and struts is the fact that bending moments in the vertical plane do not act on the pushing bars. This makes it possible to significantly reduce the metal consumption of the structure, it is possible to manufacture pushing bars from pipes and thereby reduce the cost and labor intensity of their manufacture.

2 Materials and methods

From the above considerations follows the requirement for the design of the working equipment: to reduce the energy intensity of digging, reduce the metal intensity of the working equipment and its production costs, the scheme of blade connection with struts and push bars should be made according to the scheme "parallelogram" with the absence of links between the push bars and struts, ensuring that the tractor frame can absorb the forces lying in its longitudinal plane of symmetry.

Deepening of the working tool into the ground [8, 11] is the initial and important stage of digging, which has a significant impact on the working process of the earthmoving machine. To create the conditions for optimal kinematic mode of the blade penetration into the ground, it is necessary to know the magnitude of forces acting on the blade during the process of burrowing when calculating the control mechanism of the working tool. When the knife penetrates into the ground, a stress state of the second type is created in front of it, the so-called limit stress state.

The scheme of the bulldozer working equipment suspension is represented as a flat mechanism consisting of links connected by joints. In this case, the suspension is an articulated four-link *EFGH* (Figure 3, a) in the form of a closed four-link chain with one degree of freedom, which has a leading link *EF* (strut), connecting rod *FG* distance between the attachment points of the strut and push bar on the moldboard) and a fixed link *EH* (distance between the attachment points of the strut and push bar on the base machine). In single degree of freedom mechanisms, one generalized coordinate completely determines the position of all links in the mechanism. By changing the angle φ of inclination of the driving link *HG*, one can determine the angle ψ of inclination of the driven link EF, and vice versa, knowing the position of the driving link *HG* and driven link *EF*, one can determine the angle λ of rotation of the connecting rod link *FG*. For this purpose, in the scheme of the four-link mechanism, conditionally is distinguished the parallelogram $EFF^{/}H$. From $FGF^{/}$ and $HGF^{/}$, one determines the length *GF* by the cosine theorem:

$$|GF| = R^2 + r^2 - 2Rr\cos(\varphi - \psi), \tag{2}$$

where *L*- length of the fixed link *EH*; l- length of connecting rod *FG*; λ - angle of rotation of the connecting rod link *FG* to the fixed link *EH*; *R* - drive link length *HG*; *r* - slave length *EF*; φ - angle of inclination of drive link *HG* to the vertical axis; ψ - inclination angle of the driven link *EF* to the vertical axis.

Equating the values of $/FG/$ and transforming the resulting expression one finds the value of angle λ:

$$\lambda = arccos\Big(\frac{L^2 + l^2}{2Ll} - \frac{R^2 + r^2}{2Li} + \frac{Rr}{Ll}\cos(\varphi - \psi)\Big). \tag{3}$$

The angle of rotation of the connecting rod link *FG*, in the articulated four-link diagram, corresponds to the

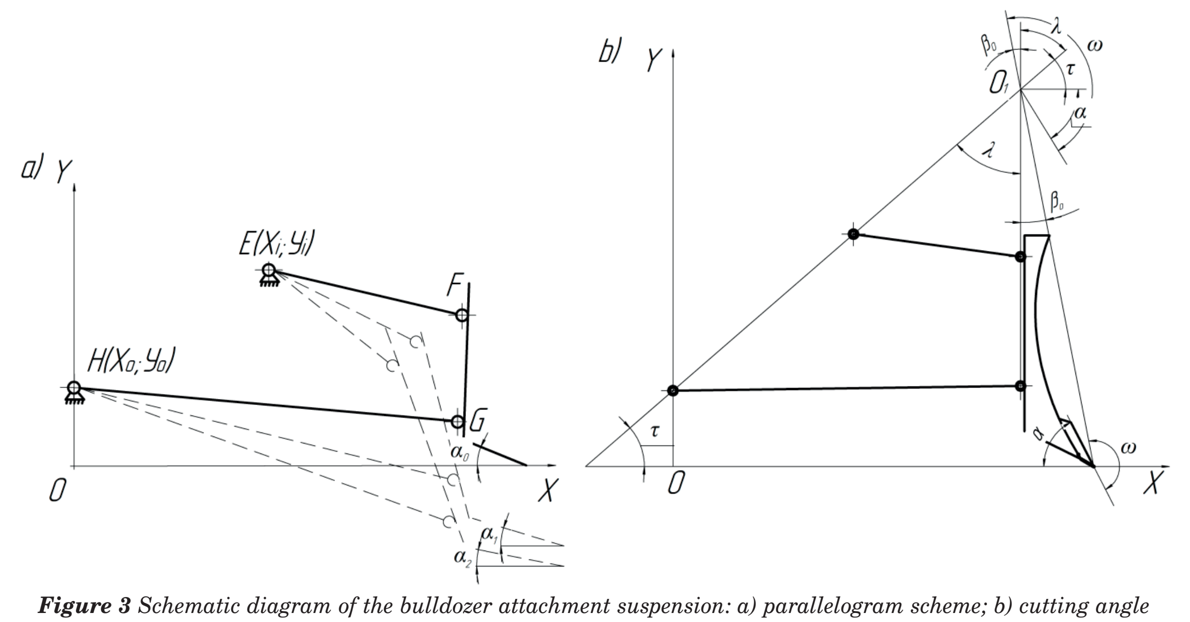

Figure 3 *Schematic diagram of the bulldozer attachment suspension: a) parallelogram scheme; b) cutting angle determination scheme*

angle of rotation of the dozer blade in real conditions when its position is changed.

The main angles $\lambda, \omega, \tau, \beta_0$, characterizing the suspension of attachments and the blade design will be transferred to the point O_1 of intersection of the line connecting the fixing points of the pusher bar and strut on the base machine with the line of fixing the same elements on the blade (Figure 3, b). The cutting angle will be equal to:

$$\alpha = \omega - \beta_0 - \tau - \lambda\,, \tag{4}$$

where ω - angle between the line connecting the upper edge of the moldboard surface with the cutting edge of the moldboard blade and the moldboard cutting element, $\omega = 160^\circ$; τ - angle between the line connecting the fixing points of the strut and push bar on the tractor base and the horizontal axis:

$$\tau = arctg\Big(\frac{Y_i - Y_0}{X_i - X_0}\Big), \tag{5}$$

where X_i, Y_i - coordinates of point E; X_0, Y_0 - coordinates of point H; β_0 - the angle between the line connecting the strut and push bar attachment points on the moldboard and the line connecting the upper edge of the moldboard surface with the cutting edge of the moldboard middle blade, $\beta_0 = 19 - 21^\circ$.

The values of angles $\lambda, \omega, \tau, \beta_0$ are entered into Equation (3) and one obtains:

$$\alpha = 141^\circ - arctg\Big(\frac{Y_i - Y_0}{X_i - X_0}\Big) - \\ - arccos\Big(\frac{L^2 + l^2}{2Ll} - \frac{R^2 + r^2}{2Ll} + \frac{Rr}{Ll}\cos(\varphi - \psi)\Big). \tag{6}$$

The value of the cutting angle α according to the Equation (6) is determined by the points of fixing the strut on the tractor base and on the moldboard, i.e., the length of the strut, as well as the moldboard depth (values φ and ψ). Thus, the obtained expression allows determining the cutting angle of the bulldozer working equipment for all the intermediate values (thickness of the cut chips).The rigorous solution of the problems on the ground limit state is given in analytical form in [12-13] and graphically in [8-9]. The interaction of the working body with the soil is considered from the point of view of those provisions of the theory of limit equilibrium, which are related to the definition of passive soil pressure on retaining walls.

The process of deepening is considered as periodically repeated chipping of the elements of the cut chip, caused by the introduction of a knife with a broken front edge into the slope of the massif formed during the previous chipping by a value of h_3. The calculation consists of two stages:

I - determination of sliding surfaces in the soil massif using characteristic circles in works [8-11];

II - analytical determination of pressures perceived by the knife faces. When calculating the passive

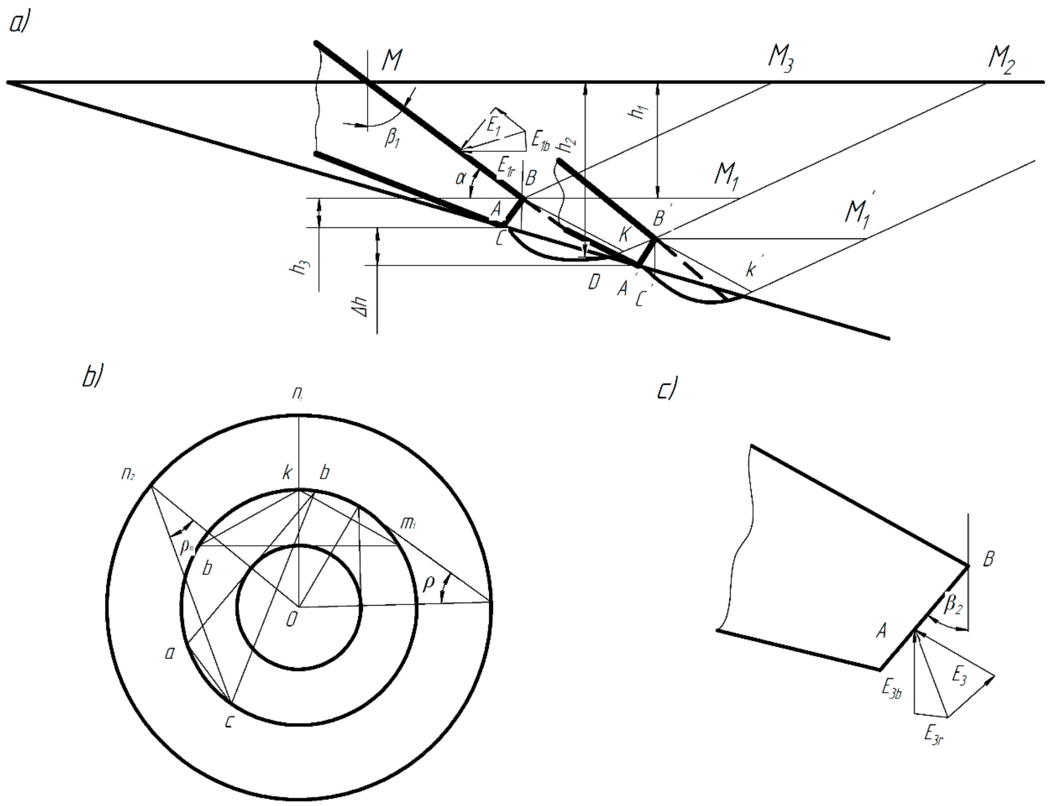

Figure 4 *Scheme for determining the resistances acting on the knife during burial:*
a - design scheme, b - system of characteristic circles, c - scheme of forces acting on edge AB

ground pressure acting on the knife faces, one uses the method proposed in [5].

When the knife is buried in the ground, there is actually a resistance of the ground to cutting, since the amount of ground on the working body is insignificant and other resistances to digging are relatively small. To determine the total resistance of the knife penetration into the ground, it is necessary to determine the cutting resistance of each edge of the knife. The cutting resistance is first determined for a knife of a width of 1 m, without taking into account the resistance to chipping on the side edges [14-15].

The soil pressure on the *MB* face (Figure 4, a) is defined as the pressure of a loose body on the retaining wall, since the MM_3B soil prism was punched out earlier and now only its displacement is carried out.

The horizontal component of pressure on the *MB* face will be determined by the formula:

$$E_{1r} = M_1 K_1 \frac{\gamma h_1^2}{2}, \quad (7)$$

where M_1, K_1 – coefficient depending on the angle β_1 of *BM* face inclination to the vertical; γ - volumetric weight of soil; h_1 - digging depth at 1 position.

The vertical component is found by the formula:

$$E_{1B} = M_2 K_1 \frac{\gamma h_1^2}{2}, \quad (8)$$

where M_2 - coefficient depending on the angle β_1.

The values of the coefficients M_1, M_2, K_1 are determined depending on the angle β_1 of inclination of the *BM* face to the vertical [13].

To determine the pressure on the knife edge *AB*, the directions of the sliding surfaces are found by the characteristic circles (Figure 4, b), taking the horizontal plane drawn through point *B* as the ground surface.

The value of the final radius of the logarithmic spiral is determined by the formula:

$$\overline{BK} = \overline{BC} e^{\theta tg\rho}, \quad (9)$$

where θ - angle of *CBK*; *e* - base of natural logarithms.

The sliding plane KM_1 is extended up to the ground surface (point M_2). Three zones appear in the ground in front of the sloping face *AB*: BKM_1, *BKC*, *ABC*. The pressure on the face *AB* is determined in the following way. Due to the smallness of the protrusion prism KBM_1, without much damage to accuracy, the pressure on the face *BK* can be assumed to be approximately equal to the pressure on the plane *BD*, which is a continuation of the knife *BM*. The horizontal and vertical components of the pressure on the plane *BD* are defined as the difference of pressures on the faces *MD* and *MB*:

$$\begin{aligned} E_{2r}' &= M_1 \Big\{ K_1 \Big[\frac{\gamma}{2}(h_2^2 - h_1^2) + ch_2 ctg\rho \Big] - ch_2 ctg\rho \Big\}, \\ E_{2B}' &= M_2 \Big\{ K_1 \Big[\frac{\gamma}{2}(h_2^2 - h_1^2) + ch_2 ctg\rho \Big] - ch_2 ctg\rho \Big\}, \end{aligned} \quad (10)$$

where ρ - angle of internal ground friction; *c* - soil coefficient.

To obtain the required solution in closed form, the actions of the horizontal and vertical components E_{2r}' and E_{2B}' are transferred to the plane BM_1 and for that some corrections to the obtained values of the components had to be done. We subtract from the obtained values the mass of the prism BM_1D of the coupling force along the plane M_1D.

The horizontal component of the coupling force C_r is equal to:

$$C_r = \overline{DM}_1 c \cos\Big(\frac{\pi}{4} - \frac{\rho}{2}\Big). \quad (11)$$

The vertical component of the coupling force C_B is equal to

$$C_B = \overline{DM}_1 c \sin\Big(\frac{\pi}{4} - \frac{\rho}{2}\Big). \quad (12)$$

The mass of the prism BM_1D is equal to:

$$G_B = \frac{\overline{BM}_1 \gamma h_4}{2}, \quad (13)$$

where

$$\overline{BM_1} = h_4\Big[ctg\alpha + ctg\Big(\frac{\pi}{4} - \frac{\rho}{2}\Big)\Big]; \ \overline{DM_1} = \frac{h_4}{\sin\Big(\frac{\pi}{4} - \frac{\rho}{2}\Big)};$$

$$h_4 = \frac{\overline{AB} \sin\alpha' \sin\alpha}{\cos\beta_1} e^{\theta_1 tg\rho};$$

$$\alpha_1' = \frac{1}{2}\Big[\frac{\pi}{2} + \rho + \rho_0 + \arcsin\frac{\sin\rho_0}{\sin\rho}\Big];$$

$$\theta_1 = \frac{\pi}{2} - \frac{1}{2}\Big[\frac{\pi}{2} + \rho - \rho_0 - ar\sin\frac{\sin\rho_0}{\sin\rho}\Big],$$

where ρ_0 - angle of friction of the ground against the blade; α_1' = *BAC* angle; θ = *CBD* angle.

The value of *AB* can be determined directly on the machine or set.

Finally, for the forces acting on the plane BM_1

$$E_{2r} = E_{2r}' - C_r; \qquad E_{2B} = E_{2B}' - C_B - G. \quad (14)$$

Then, the vertical uniformly distributed load acting on the plane BM_1 is equal to:

$$q = \frac{E_{2B}}{BM_1}. \quad (15)$$

The pressure on the face *AB*, under conditions where the boundary of the bulk solid is a horizontal surface with a confinement of intensity q, can be defined in a closed form:

$$\begin{aligned} E_{3r} &= M_3 \Big\{ K_2 \Big[\frac{\gamma h_3^2}{2} + qh_3 + Ch_3 ctg\rho \Big] - Ch_3 ctg\rho \Big\}; \\ E_{3B} &= M_4 \Big\{ K_2 \Big[\frac{\gamma h_3^2}{2} + qh_3 + Ch_3 ctg\rho \Big] - Ch_3 ctg\rho \Big\}. \end{aligned} \quad (16)$$

The coefficients M_3, M_4, M_2 are determined depending on the angle β_2 of inclination of the face *AB* to the vertical (Figure 4, c).

The distance between the two consecutive spalls h is defined as

$$h = \frac{\overline{BM_1} \sin\delta \sin\left(\frac{\pi}{4} - \frac{\rho}{2}\right)}{\sin\left(\delta + \frac{\pi}{4} - \frac{\rho}{2}\right)}, \tag{17}$$

where $\delta = arctg\frac{\nu_2}{\nu_1}$ - ν_2 - implemented lowering speed; ν_1 - forward speed of the machine.

The total cutting resistance by *MBA* edge at cutting width b:

$$W_p = (W_p' + W_p'') \cdot b, \tag{18}$$

where $W_p' = E_{1r}$ - cutting resistance by *BM* edge; $W_p'' = E_{3r} + E_{2r}$ - resistance to cutting with edge *AB*.

The additional vertical pressure on the blade required for stable penetration of the blade into the ground will be equal to:

$$\sum E_B = (E_{3B} - E_{1B}) \cdot b. \tag{19}$$

When the bulldozer blade is embedded into the ground, while the machine is moving in front of the cutting blade, the ground is stressed only on one side, located in front of the blade in the direction of travel. Therefore, the resistance to the blade sinking when the machine is moving is smaller than when it is embedded in the ground when the machine is stationary. This allows the blade to be driven into the ground at lower cutting angles.

3 Results and discussions

The cutting angle determines the ratio of machine operating speeds and rational trajectories, but the study of the effect of the cutting angle cannot yet be considered complete. The authors measured the force separating the chip from the furrow wall with a sharp knife with a vertical cutting edge (such cutting is close to semi-free cutting) [8, 16-17].

Measurements were made in a soil channel (Figure 5) on medium loam with moisture content from 9.4 to 10.8% and density by statistical density meter from 13.1 to 13.2 N/cm. The width of the cut was equal from 165 to 178 mm, thickness - 100 and 50 mm. It was found that as the cutting angle changed from 20 to 38°, the cutting force increased by an average of 1.7% for each degree of increase in the cutting angle. When changing the cutting angle from 40 to 90°, the average increase in cutting force is 6% per degree.

The change of cutting force is not the same at different cutting angles. It decreases intensively with decreasing of cutting angle up to 35÷40°, but at cutting angle less than 35÷40° the intensity of its decrease slows down. According to some data, the dependence has a minimum in the area of small values of the cutting angle. The study of the considered dependence was carried out by means of dynamometric stands. The results of the experiments confirmed the general character of the dependence established by the previous studies. Decrease of cutting angle up to 35÷40° is accompanied by intensive decrease of cutting force for the majority of soils. With further reduction of the cutting angle the decrease of cutting force slows down, and for some soils (loam, weak sandstone when cutting along the layers, sulfur earth merilic clay) in the area of small values of the cutting angle the cutting force increased again.

The assumption of independence of cutting force from the cutting angle of the part of the cutting force that is spent on overcoming the resistance of the ground on the sides of the knife, allowed along with the conclusion and practical proportionality, to directly compare the measurement data on different soils and to obtain a general experimental picture of the effect of the cutting angle on the cutting force. Comparison of the experimental values of the blocked cutting force excluded a part of it, which is used to overcome the resistance of the soil on the sides of the knife at a given thickness of the cut, thus determining the part of the cutting force that depends on the cutting angle. This part of the cutting force at a cutting angle of 45° was taken as one, and its value at all other values of

Figure 5 *Stand for physical modeling of bulldozer working processes*

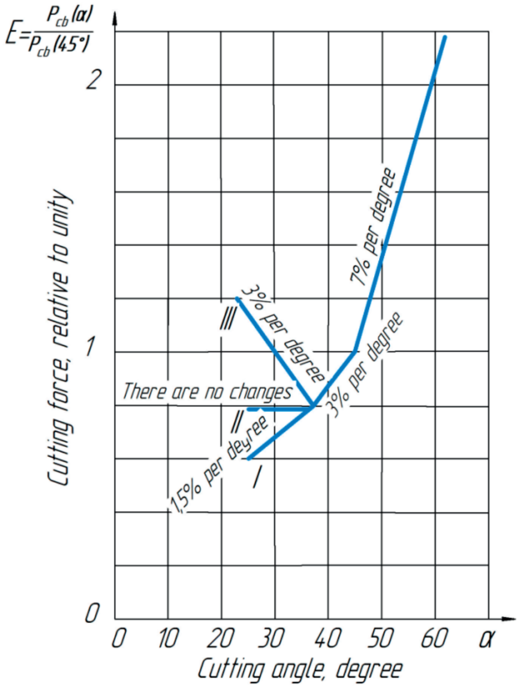

Figure 6 *Graph proposed for characterization of the frontal resistance force to the knife dependence on the cutting angle of soils: I - plastic clay soils; II - layered, cutting along layers; III - other sandy-clay soils*

cutting angle was determined in relation to this value. As a result of such an analysis, a graph (Figure 6) was obtained, proposed to characterize the changes in the part of the cutting force that goes to overcome the frontal resistance of the knife.

Based on the obtained data, it can be noted that at the cutting angle value over 45° there is an intensive change in the part of the cutting force, which goes to overcome the frontal resistance to the knife (on average 7% per degree of cutting angle, but in relation to the value at a cutting angle of 45°). In the cutting angle range 37÷30° the reduction of the mentioned part of the cutting force slows down. At further reduction of the cutting angle for some soils there is sometimes an increase in the soil resistance. Thus, when changing the cutting angle of the soil with the bulldozer attachment, it is necessary to provide the possibility of its reduction to 20÷30°.

Comparison of the results of mathematical modelling to the data of physical experiments confirmed the adequacy of the developed model to describe the process of burial of the bulldozer's working body into the soil. It was found that the model accurately reflects the nature of the dependence of the cutting force on the cutting angle, including the presence of the minimum force value at an angle of 35-40°, which coincides with the results of the bench tests. The obtained analytical expressions allow us to quantitatively evaluate the influence of kinematic and design parameters of the suspension of the working equipment on the change of the cutting angle and the corresponding force of interaction with the ground. Thus, the developed model can be used in engineering practice to optimize the design of working equipment and to select a rational blade trajectory minimizing the energy intensity of the cutting process.

4 Conclusions

In the course of the research, it has been established that the process of burrowing the bulldozer's working body into the ground is characterized by a one-sided stress state arising in front of the cutting blade along the machine's movement. This allows the blade to penetrate into the ground at lower values of the cutting angle, which contributes to reduction of the cutting resistance. The optimal trajectory of the blade movement from the energy point of view is recognized as such a trajectory of the blade movement, at which the cutting angle at the moment of penetration into the ground is maximum, with its subsequent reduction. The developed mathematical model adequately describes this process, confirming both qualitative and quantitative dependencies established in the course of physical experiments. In particular, the presence of minimum cutting resistance at cutting angle of 35-40° is confirmed, and the sensitivity of cutting force to changes in structural and kinematic parameters of the moldboard suspension is revealed. The model can be recommended for practical application in the design and optimization of bulldozer working equipment to improve its efficiency and reduce the energy consumption of earthmoving operations.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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