

Requirements for a digital twin of the bulldozer work tool

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Abstract. The paper presents a brief description of the bulldozer as a widely used machine for earthworks. The method for determining resistive forces to digging is analyzed based on the theory of layer-by-layer excavation works. The relationship for determining the area of the longitudinal section of the dragging prism is presented, and on its basis the productivity is further calculated. The characteristics of forces resistive to digging are constructed with the accepted parameters of the blade and soil for different angles of blade setting. The criterion for determining the efficiency of earthmoving operations is presented, which was developed on the basis of unit costs. It is stated that excavation works are performed effectively at a certain angle of blade setting. Requirements for a digital twin of the bulldozer work tool, which is designed to improve the efficiency of its operation, have been developed.

1. Introduction

Bulldozers are earth-moving equipment widely used in the construction industry. The simplicity of their design and operation accounts for their widespread use in earthwork construction. The bulldozer working tool can use pivoting or non-pivoting blades. Depending on the blade type, a universal blade frame or the one with push bars is used. The operation of bulldozers performing different construction works or conducting mining and stripping operations has led to the use of various types of blades [1]. The long-term use has led to the optimization of the parameters of their operating equipment and, in particular, blades. Today, the designs of bulldozer blades have reached a high degree of perfection and provide high productivity at the lowest possible costs in earthmoving operations and extraction of mineral resources.

Conditions for carrying out earthwork operations are very changeable and highly dependent on a number of factors, such as soil type, humidity, ambient air temperature, operator qualification, etc. The productivity of the machine, therefore, depends not only on the excellence of its work tool, but also on the conditions of its operation. The operation of the bulldozer work tool during carrying out earthworks is almost completely entrusted to the operator, who is guided only by his experience and perception of ongoing events. While performing earthworks, he does not have access to the information on the degree of the effect of blade position, penetration depth and travel speed on the efficiency and costs during each pass of the machine.

2. Methods and techniques

The theory of the bulldozer design offers a significant amount of scientific investigations [2] which allows choosing the optimal parameters for the blade and the working tool of the bulldozer depending on the soil type and its condition (Figure 1).



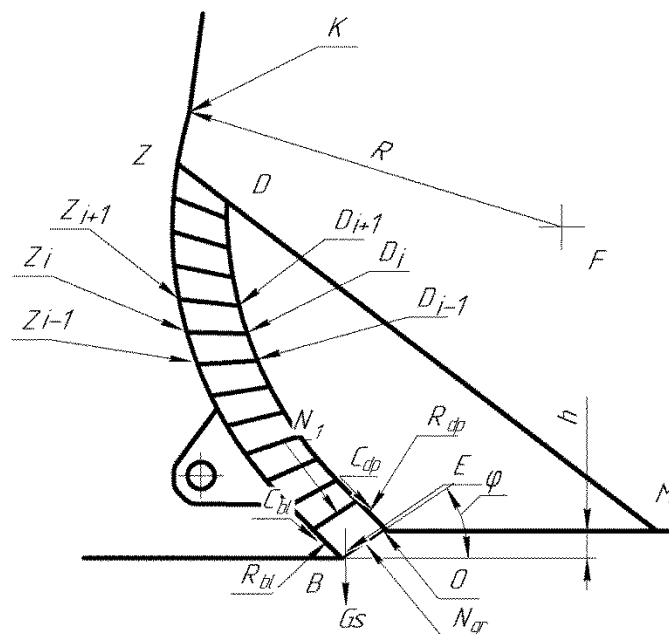


Figure 1. Diagram of blade-soil-dragging prism interaction.

The blade parameters are determined based on the criterion for minimizing resistive forces to digging. At the initial stage of digging, the blade penetrates the soil by the value h . While the blade moves forward, a compacted zone is formed in the soil under the action of compressive forces, and normal and tangential stresses originate [3]. These stresses are increasing, and a force arises that acts on the blade and resists its movement. When the stresses reach their limit values, the soil is shifted along the area BO (Figure 1). At this time the force acting on the blade reaches its maximum value, as this corresponds to the moment of shear area formation. The magnitude of forces acting on the blade at this stage depends on the cohesion forces of the soil and the slope angle of the shear area. Upon further movement of the blade, a dragging prism is formed from the soil separated from the massif. The soil moves up the blade and forms the dragging prism from the segments Z_{i-1} , Z , D , D_{i-1} . To perform calculations, it was assumed that the dragging prism consists of a conditionally stationary part OMZ and a conditionally mobile part BODZ, the dimensions of its elements being dependent on the size of the shear area and the radius of the blade curvature R . The elements of the mobile part are acted upon by the gravity forces, the normal reaction N from the lower and upper soil segments, the normal forces from the blade R_{bl} and the stationary dragging prism R_{dp} , the friction forces between the blade C_{bl} and the stationary dragging prism C_{dp} . The interaction of these forces forms the resultant resistive force to digging that is applied to the bulldozer blade. In the process of digging, the dragging prism is growing. Its gravity force affects the magnitude of ultimate stresses in the soil, which is in the undisturbed condition and additionally loaded by the dragging prism. Due to the presence of the additional load from the force of gravity of the soil and the increase in the ultimate stresses, the inclination angle of the shear area BO changes and the resistive forces to digging increase.

During the design process, the designers choose the blade parameters that provide the optimal magnitude of digging resistive forces. But when the work is performed on a specific work site, the resistive forces to digging can be far from minimal, because during the digging process, the operator measures their magnitude by the engine loading, i.e. by indirect indicators not having any numerical expression [5]. In addition, the size of the dragging prism and the productivity depend on the angle of blade setting, the value of which can vary in modern bulldozer.

The volume of the dragging prism depends on the blade width and the triangle, which is limited by the segments DM and MO and the curve OD. The dimensions l_{DM} and l_{MO} depend on the height of the dragging prism H and the angle of repose γ . (Figure 2)

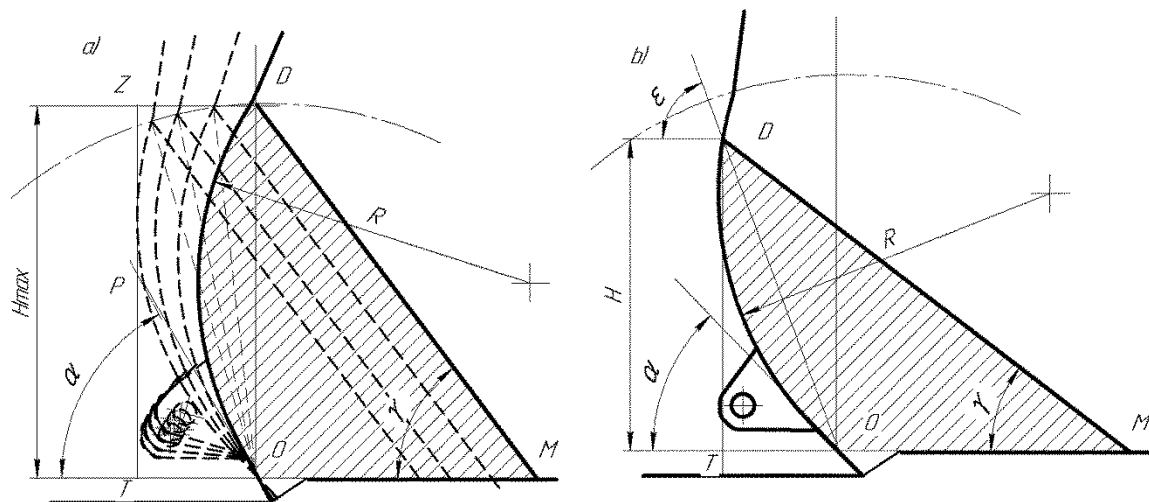


Figure 2. Parameters of the dragging prism.

As a rule, when digging the ground, the blade is mounted at some angle ε , other than 90° (Figure 2b). This angle is optimal for soils of different types which have different properties. But, when working on a specific work site and under specific ambient conditions, there can be found such a blade setting angle ε , at which the productivity will be maximum, and the resistive forces are minimum.

The determining factor for calculating productivity is the volume of the dragging prism, which depends on the area of the shaded region in Figure 2 and can take different values depending on the blade angle (Figure 2a).

The area of the dragging prism as a function of ε can be found by the formula:

$$S = \left[H_{\max} (1 - \tan(\varepsilon)) \right]^2 \cdot \tan(\gamma) + R^2 \left[\arcsin \left[\frac{1}{\cos(\varepsilon) \cdot R} \right] - \frac{1}{\cos(\varepsilon) \cdot R} \right] \quad (1)$$

where H_{\max} is the maximum blade height corresponding to the case when $\varepsilon = \pi/2$ (Figure 2b), γ is the angle of repose, R is the radius of the blade curvature.

Formula 1 and Figure 2 show that the dragging prism has the maximum area in the blade position, in which $\varepsilon = \pi/2$. Thus, in the bulldozer operation this is the position of blade that needs to be maintained in order to achieve maximum productivity.

In addition to productivity, an important component of the operation process is the cost of the work performed. The costs directly depend on the forces resistive to digging because the operation speed of the bulldozer is 1 ... 1.4 m/s, and the resistive forces to digging can vary within wide limits.

With the help of the software developed on the basis of the investigations [4] forces of resistance to digging by the bulldozer blade were calculated for the soil parameters presented in table 1 and the blade.

Table 1. Soil parameters

Parameter name	Measurement unit	Magnitude
Internal friction angle	deg	28
Soil-metal friction angle	deg	26
Slope angle of the segment DM to the horizon	deg	35
Specific cohesion of soil (undisturbed)	kPa	25
Specific resistance to cutting	Pa	70
Soil density in the dragging prism	t/m ³	1.8

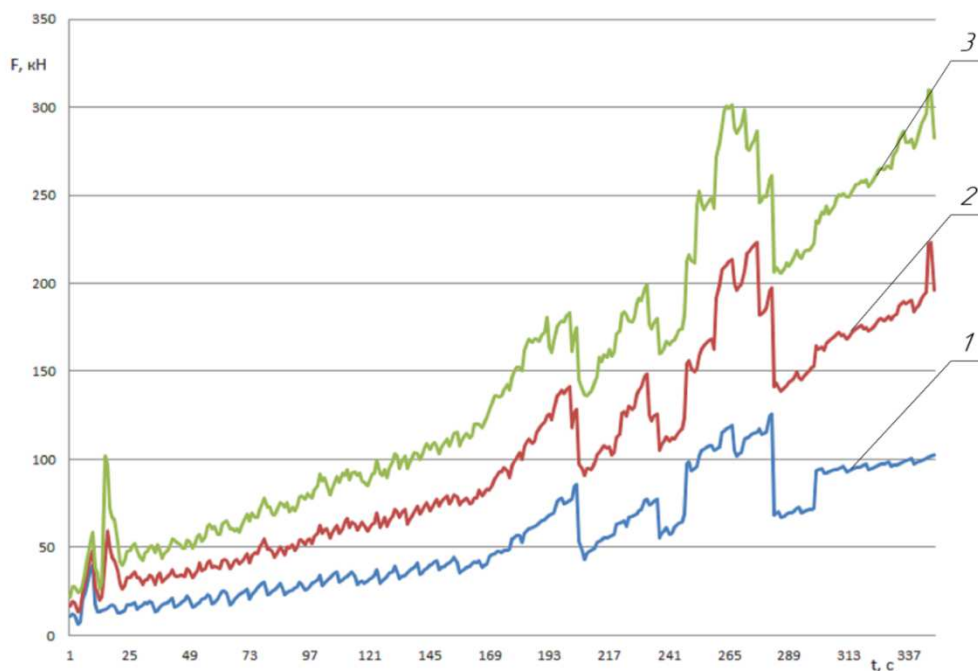
Table 2. Blade parameters

Parameter name	Measurement unit	Magnitude
Blade height	m	1.2
Height of blade's top spill plate	m	0.2
Length of blade knife	m	0.2
Width of blade	m	3
Blade curvature radius	m	1.2
Blade setting angle (ϵ)	deg	85, 75, 65
Cutting angle (α)	deg	changes based on the blade position

Based on the calculations, plots of the resistive forces to digging were obtained for the blade moving through the soil and the dragging prism being formed (Figure 3). The diagrams show that the blade setting angle can have a significant effect on the magnitudes of the resistive forces to digging, which, in turn, will affect the value of the unit costs.

The analysis of Figure 3 shows that the resistive forces to digging mostly depend on the height of the dragging prism. The effect of the blade angle is also significant. By increasing the blade angle by 20 degrees, a significant reduction in resistive forces to digging can be achieved.

An important task is to choose such an angle of blade setting, at which the productivity will be maximum, and the costs involved in performing earthworks will be minimal.



1. Blade setting angle $\epsilon = 65^\circ$; 2. blade setting angle $\epsilon = 75^\circ$; 3. blade setting angle $\epsilon = 85^\circ$.

Figure 3. Magnitudes of forces resistive to digging depending on the blade setting angle.

Calculating the productivity by the formula:

$$P = \frac{3600V_{dp}}{t_w + t_{rm}} \quad (2)$$

where V_{dp} is the volume of the dragging prism, t_w is the time of the operation pass, t_{rm} is the time of the reverse travel, and considering that the bulldozer operates at the rated power corresponding to

some constant value, it is possible to establish the criterion for the optimal ratio of productivity and power as the relationship:

$$K = N / P \quad (3)$$

where N is the accepted constant power value.

Let us assume that the length of the work area is 130 m, the reverse travel speed is 2.5 m/s, then the speed of the operation pass is calculated as:

$$v_{rm} = N / F_i$$

where F_i is the average magnitude of the resistive forces to digging at a fixed angle of the blade. After determining the productivity under the accepted conditions, the value of the criterion K can be defined. The calculation results for the accepted values are presented in Figure 4.

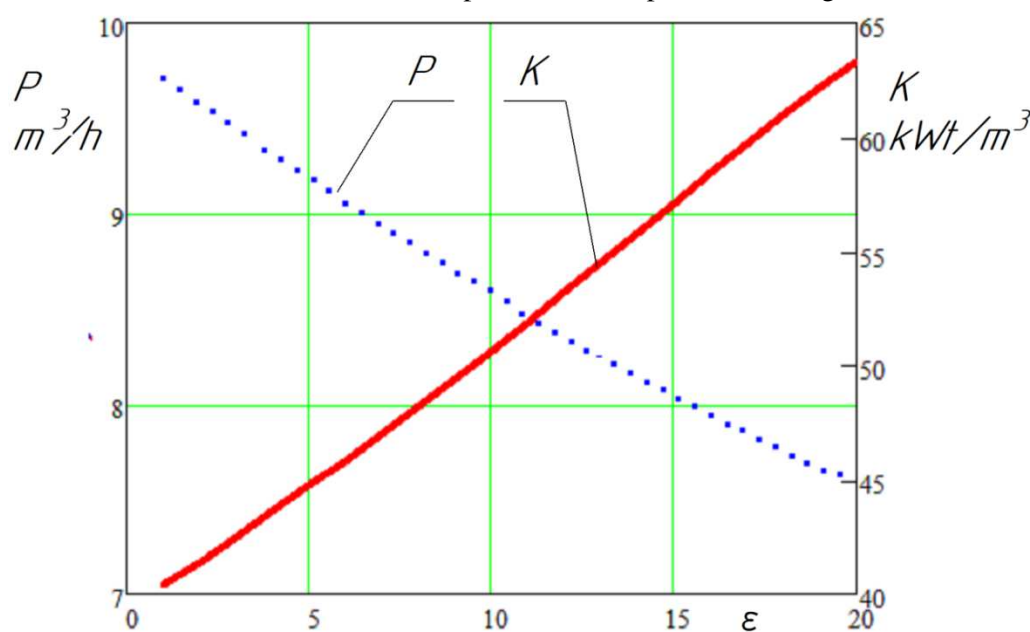


Figure 4. Relationships between productivity and the efficiency criterion of the bulldozer, and the angle of blade setting.

The analysis of Figure 4 shows that the blade angle of 11 ... 13 degrees is the most effective under the accepted conditions and the maximum dragging prism. The calculations show that the efficiency of earthmoving works is affected not only by the angle of blade installation, but also by the size of the work area, bulldozer speed, gear selected, maximum engine power, soil parameters and weather conditions prevailing at the time of the work.

3. Conclusion

Thus, the digital twin of the bulldozer work tool should receive, as initial data, the height of the dragging prism or its volume, the magnitude of resistive forces to digging, and the bulldozer speed. The software package of the digital twin must calculate bulldozer performance during one pass and throughout a number of passes; determine the energy required for digging the soil and the specific fuel consumption per 1 m^3 . The information storage unit should contain information on several passes, and, based on the statistical data processing, either set automatically the optimal position of the blade or provide the operator with the information about it.

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