The analytical dependence of the resistance force to digging with a bulldozer blade on the main influencing factors

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Abstract. The criteria for the similarity of the process of digging soil with a bulldozer blade are determined based on the use of the principles of the theory of similarity and modeling. When determining the similarity criteria, a rheological model of the process of interaction of the bulldozer blade with soil and the method of dimensional analysis were used. The processing of experimental data obtained with large-scale physical models in a criterion form made it possible to significantly reduce the time and material costs for conducting experiments. The criterion equation is valid for any change in the parameters included in the dependence that determines the force of digging the soil with a bulldozer blade. The main limitation is compliance with the equality of similarity criteria for the model and the original. Keywords: criterion, experiment, rheological model, bulldozer blade, resistance force, physical model, original.

1 Introduction

Bulldozers equipped with blade working bodies are used in almost all sectors of the national economy. One of the main indices of the efficiency of bulldozers and other earth-moving machines is productivity, but this index evaluates the machine only from one side, not taking into account energy costs.

However, the universal index for evaluating the efficiency of earth-moving machines, in particular, bulldozers, is the reduced unit costs. The use of the reduced unit costs often leads to difficulties due to the lack of data on operating costs, because this information is a trade secret.

In the absence or insufficient amount of information about the machines, it is advisable to use generalized indices for evaluating the effectiveness of the bulldozer, such as specific energy consumption and specific material consumption. The value of the resistance force that appears on the surface of the bulldozer blade determines the energy efficiency of the digging process.

A large number of analytical dependences were developed that relate the digging force of a bulldozer blade to the main design parameters of the blade and the properties of the dug soil [1-4].

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The values of almost all proposed models have discrepancies of the order of 20-75 percent between the resistance forces calculated from the analytical dependencies and experimental data. In our opinion, the reason for this discrepancy is that these analytical dependences do not take into account the non-homogeneity and isotropy of the medium, as well as the change in digging resistance forces over time, i.e. all these models are static in nature.

To establish the analytical dependence of the digging force of a bulldozer blade on its main design and technological parameters and soil properties, it is necessary to use physical modeling methods. Physical modeling can be used to find a solution to a problem when the phenomenon under study is so complicated that it is not possible to compile a satisfactory mathematical model for it, or the solution to the formulated problem fails to compile a satisfactory mathematical model for it, or the solution to the formulated problem encounters insurmountable mathematical difficulties. On the other hand, this method can significantly reduce the cost of experiments, including those aimed at testing analytical solutions [5-7].

References [8-10] are devoted to the issues of physical modeling of the process of digging the soil with a bulldozer blade.

2 Materials and methods of research

The simplest rheological models can be used to study the general patterns of the interaction processes of working bodies with the medium and to develop similarity criteria. In addition, they give a first approximation of the stress-strain relationship.

Figure 1 shows the rheological model of the interaction of the bulldozer blade with soil.

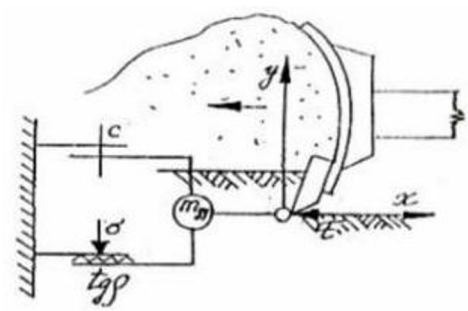

Fig.1. Rheological model of the bulldozer blade-soil system.

The material is presented in the form of a plastic medium, which has the properties of friction and cohesion between the particles that make up the medium. The movement of the tool is steady.

The stress state in the medium is described by the Mohr-Coulomb law. The rheological equivalent is shown in Fig. 1. The shear stress equation has the following form:

$$\tau = \sigma tg\rho + C, \tag{1}$$

$$\sigma = \frac{\gamma l^3}{l^2} \text{ or } \sigma = \gamma l. \tag{2}$$

If we substitute the value from formula (2) into (1), then the stress in the medium can be written as:

$$\tau = \gamma l tg\rho + C. \tag{3}$$

Based on (1), we obtain the equation of the integral analog:

$$\tau \sim \gamma l tg\rho \sim C. \tag{4}$$

Dimensionless function $tg\rho$ is obtained as a similarity criterion $\pi_2 = tg\rho$. The remaining terms $\tau \sim \gamma l \sim C$ are divided by each of them and two more similarity criteria are obtained:

$$\pi_1 = \frac{C}{\gamma l}, \qquad \pi_3 = \frac{C}{\tau}, \tag{5}$$

Criteria π_1 and π_2 are defining ones, as they include defining parameters of the process. Criterion π_3 is a defined criterion, as it contains in its structure a defined value of τ.

Since the obtained similarity criteria describe the process of digging the soil only in the first approximation, they must be supplemented using the dimensional analysis method.

At a given curvature, the blade can be determined by the following parameters: length *B*, height *H* and cutting angle *α*. The digging mode is determined by the depth of cutting *h*, blade travel velocity *ϑ* and free fall acceleration *g*.

The soil is considered the medium characterized by cohesion *c*, angle of internal friction *ρ* and external friction *φ*, and volumetric weight *δ*.

The dependence of the digging force *P* on the above parameters in implicit form has the following form:

$$P = f(B, H, \alpha, c, \rho, \varphi, \delta, h, \vartheta, g). \tag{6}$$

Let us define the similarity criteria for this process. In our case, there are 11 physical quantities characterizing the process ($n = 11$).

It follows from consideration of these quantities that 3 of them (α, δ, ρ) are the similarity criteria [11-13]. The dimensions of the remaining 8 (11-3=8) physical quantities can be expressed in terms of three basic units of measurement - force *P*, length *L*, and time *T*.

Let us write out the formulas for the dimensions of these quantities:

$$[B] = [H] = [h] = L; [P]; [c] = PL^{-2}; [\delta] = PL^{-3}; [\vartheta] = PL^{-1}$$

To find an additional number of similarity criteria, one should choose basic values with independent dimensions: α, B, g ($m = 3$). Then it remains to find 5 (8-3=5) similarity criteria. To find criterion π_1, for example, the dimension of parameter *P* is written into the numerator, and the product of the dimensions of quantities α, B, g and unknown exponents a_1, a_2, a_3 is written into the denominator:

$$\pi_4 = \frac{(P)^1}{(PL^{-3})^{a_1}(L)^{a_2}(LT^{-2})^{a_3}}.$$

The exponents are determined by equating the dimensions of the numerator and denominator to each other so that a dimensionless complex is obtained. Thus, for $a_1 = 1, a_2 = 3, a_3 = 0$, we have:

$$\pi_4 = \frac{(P)^1}{(PL^{-3})^1(L)^3}.$$

Instead of dimensions, we introduce symbols of physical quantities. Then, raising these quantities to the indicated powers, we finally obtain:

$$\pi_4 = \frac{P}{\delta B^3}.$$

In the same way, we obtain the remaining similarity criteria. Let us write out all the similarity criteria:

$$\pi_4 = \frac{P}{\delta B^3};\ \pi_5 = \frac{\vartheta}{\sqrt{gB}};\ \pi_6 = \frac{h}{B};\ \pi_7 = \frac{c}{\delta B};\pi_8 = \frac{B}{H};\pi_9 = \alpha;\pi_{10} = \rho;\pi_{11} = \varphi.$$

To make it easier to use, the π_2 criterion is squared. Then this criterion is represented as $\pi_5 = \frac{\vartheta^2}{gB}$. According to the π-theorem [14-16], we replace function (1) with a criterion equation. To do this, we write one of the criteria (in our case, $\frac{P}{\delta B^3}$) as a function of the remaining similarity criteria and obtain the expression for function (1) in a criterion form:

$$\frac{P}{\delta B^3} = f(\frac{c}{\delta B}, \frac{B}{H}, \frac{h}{B}, \frac{\vartheta^2}{gB}, \alpha, \rho, \varphi), \tag{7}$$

Now it is necessary to reveal the relationship between the scales of physical quantities. We will establish this relationship with formula (3) using similarity indices [17, 18].

$$I_1 = \frac{K_{m+1}}{K_1^{a_1} \cdot K_2^{a_2} \ldots, K_m^{a_m}} = 1; \ldots, I_{n-m} = \frac{K_n}{K_1^{a_1} \cdot K_2^{a_2} \ldots, K_m^{a_m}} = 1. \tag{8}$$

To determine the similarity index, the similarity criterion for the original is divided by the similarity criterion for the model. For example, the relationship of scale k_p with other scales is:

$$\frac{k_p}{k_\delta k_B^3} = 1.$$

In the same way, we determine the relationship for the remaining scales. Then we obtain the following series of equations for the relationship between the scales of the parameters that determine the process:

$$\frac{k_p}{k_\delta k_B^3} = 1;\ \frac{k_c}{k_\delta k_B^3} = 1;\ \frac{k_B}{k_H} = 1;\ \frac{k_h}{k_B} = 1; \frac{k_\vartheta}{k_g k_B} = 1; k_\alpha = k_\rho = k_\varphi = 1.$$

Now it is necessary to choose independent scales. They can be any of the available scales, however, based on the convenience of modeling, it is better to choose independent scales $k_\delta = k_g = 1$ since modeling the physical quantities δ and g is very difficult [19, 20]. Then the experiments are performed under conditions of approximate physical modeling, and the scales of physical quantities are determined by the linear scale of the model:

$$k_p = k_B^3; k_c = k_H = k_h = k_B; k_\alpha = k_\rho = k_\varphi = 1.$$

When determining the scale k_ϑ, it should be borne in mind that the velocity for traditional full-scale machines is small (0.56÷0.89) and therefore does not have a significant effect on the digging force. In these cases, according to [21, 22], criterion π_2 may not be observed, as a result of which it is possible to set up experiments under conditions of approximate physical modeling.

At increased velocities, criterion π_2 must be observed and, accordingly, the scale of digging velocity must be maintained.

The limit value of the model scale is determined by:

a) the allowable volume of the medium interacting with the model of the working body

$$\Delta V \geq 200 d^3, \tag{9}$$

where d is the average linear size of the particles that make up the medium;
b) accuracy of measuring instruments

$$k_B = \sqrt[4]{\frac{P_0 \Delta_1 \cdot 100}{P_{max} \cdot k_{i.a}}}, \tag{10}$$

where P_0 is the maximum force of the original, kN: Δ_1 is the relative measurement error when testing the original (usually up to 10%); P_{max} is the maximum force for which the scale of the device is calculated, kN (the limit of measurement by the device according to the tensometric method); $k_{i.a}$ is the accuracy class of the device (usually up to 2.5%).

So, assuming that $P_0 = 300\ kN$, $P_{max} = 100\ \ kN$, $\Delta_1 = 10$, $k_{i.a} = 2{,}5$, we obtain:

$$k_B = \sqrt[4]{\frac{300 \cdot 10 \cdot 100}{100 \cdot 2{,}5}} \approx 6.$$

Using dependence (4), we determine the linear scale of the model by the limiting volume of the medium interacting with the model.

The volume of the medium in front of the bulldozer blade is determined depending on the length of the full-scale blade B and its height H according to the following formula:

$$V = \frac{BH^2}{2tg\rho},$$

where ρ is the angle of repose of the soil prism in front of the blade. Then, substituting the indicated quantities into expression (3), in terms of the model, we obtain:

$$\frac{1}{2} \cdot \frac{B}{k_B} \cdot \frac{H^2}{k_B^2} \geq 200d^3.$$

Hence, it follows that

$$k_B \leq \frac{1}{d} \sqrt[3]{\frac{BH^2}{400tg\rho}}.$$

Assuming that $B = 4030$ mm; $H = 1720$ mm; $\rho = 45^0$; $d = 45$ mm, we obtain:

$$k_B \leq \frac{1}{45} \sqrt[3]{\frac{4030 \cdot (1720)^2}{400 \cdot 1}} \leq 6{,}9.$$

From the two scales obtained (6 and 6.9), we choose the smaller value, that is, 6. The practice of studying the working processes of earth-moving machines shows that generally $k_B \leq 7 \div 10$.

Using the chosen scale, a physical model of the bulldozer blade was built and a series of experiments were conducted.

When preparing the soil medium, it is very laborious to control the cohesion of particles on a shear device. A number of researchers have established correlations between soil cohesion and the number of impacts of the striker designed in the DORNII. On this basis, under conditions of approximate physical modeling, the cohesion value can be controlled by this index, changing it in proportion to the scale of the model [23-26].

The transition from the parameters of the model to the parameters of the original is performed according to the formulas following from the equality of the similarity criteria of the model and original.

For example, the transition formula by the following criterion is derived as:

$$(\frac{h}{B})_{org} = (\frac{h}{B})_m, \text{ then } \frac{h_{org}}{B_m k_B} = \frac{h_m}{B_m}. \text{ Hence, } h_{org} = h_m k_B.$$

Formulas for the transition from the model parameters to the original parameters are obtained likewise:

$$P_{org} = P_m k_B^3;\ H_{org} = H_m k_B;\ h_{org} = h_m k_B;\ B_{org} = B_m k_B;\ \rho_{org} = \rho_m;$$

$$\varphi_{org} = \varphi_m;\ c_{org} = c_m k_B;\ \alpha_{org} = \alpha_m;\ \vartheta_{org} = \vartheta_m \text{ or } \vartheta_{org} = \vartheta_m \sqrt{k_B}$$

The parameters of the scaled physical model are presented in Table 1.

Table 1. Parameters of the scaled physical model

№	Parameter	Measurements units	Numeric value
1	Blade model length, *B*	m	0.785
2	Blade model height, *H*	m	0.29
3	Maximum depth of cutting, *h*	m	0.12
4	Cutting angle by the blade, α	degree	50-55

A fragment of the experiment to determine the soil digging force on the physical modeling stand is shown in Fig. 2.

Fig. 2. A fragment of the experiment of digging the soil with a bulldozer blade at the physical modeling stand.

The stand of physical modeling was developed in the Department "Engineering of Technological Machines" of the Tashkent State Transport University.

Strain gauges were glued to the horizontal and vertical rods of the mounting bracket. The signals from the horizontal and vertical voltage sensors were amplified and recorded using a 24-BITLI voltage sensor device and an HX-711V recorder.

It is known from literary sources that the most typical soils in the Republic of Uzbekistan are sands, sandy loamy and loamy soils [23].

The average values of the physical and mechanical properties of the main types of soils and some rational design and technological parameters of the bulldozer are shown in Table 2.

Table 2. The average values of the physical and mechanical properties of the main soil types and some rational design and technological parameters of the bulldozer

№	Parameter	Soil type		
		Sands	Sandy loamy soil	Loamy soil
1	Cohesion, c_{ω}, MPa	0.0001	0.01	0.03
2	Number of strokes, $C_{уд}$	1	6	12
3	Angle of internal friction ρ, deg	29	27	25
4	Angle of external friction φ, deg	18	25	21
5	Volume weight: in a dense body δ, t/m³ in a loose body δ, t/m³	 1.8 1.7	 2.0 1.8	 2.1 1.8
Some rational design and technological parameters of the bulldozer				
6	Soil cutting angle α, deg	50-55	50-55	50-55
7	Bulldozer digging velocity, m/s	0.89	0.72	0.56
8	Blade height to blade length ratio $\frac{H}{B}$	0.43	0.43	0.43

Under fixed values of the angles of internal and external friction, the angle of soil cutting, as well as for a specific brand of bulldozer with constant values of the ratio of the blade height to its length, the force of digging the soil with the bulldozer blade depends on the depth of soil cutting.

If, as a first approximation, we assume that the dependence of the digging force on the depth of cutting has a linear dependence, then the following dependence will be obtained:

$$\frac{P}{\delta B^3} = k_p F(\pi_6), \tag{11}$$

where k_p is the proportionality factor, found experimentally.

Based on formula (5), the dependence of the force of digging the soil with a bulldozer blade will have the following form:

$$P = k_p \delta B^3 \cdot \frac{h}{B} = k_p \delta B^2 h. \tag{12}$$

The series of experiments conducted made it possible to determine the value of coefficient k_p =1,34.

Finally, we obtain:

$$P = 1{,}34 \delta B^2 h, \tag{13}$$

3 Conclusions

1. The use of similarity theory and modeling methods in determining the analytical dependence of the digging force on the main design and technological parameters made it possible to establish this dependence with the least material and time costs.

2. The rheological equivalent of the process of digging the soil with a bulldozer blade in the first approximation describes the relationship between stresses and strains that occur in front of the working body.

2. The assumption of a linear dependence of the force of digging the soil with a bulldozer blade on the depth of cutting is adequately reflected in the experimental data.

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