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.
The value 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.

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 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.

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

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

\[ \tau = \sigma \tan \rho + C \]

\[ \sigma = \frac{\gamma l^3}{l^2} \]

\[ \sigma = \gamma l. \]

\[ \tau = \gamma l \cos \rho + C \]
Based on (1), we obtain the equation of the integral analog:

\[ \tau \sim \gamma l \tan \rho \sim C. \]

(4)

Dimensionless function \( \tan \rho \) is obtained as a similarity criterion \( \pi = \frac{\tau}{l} = \frac{\gamma}{\tan \rho} \).

The remaining terms \( \tau \sim \gamma l \sim C \) are divided by each of them and two more similarity criteria are obtained:

\[ \pi_1 = \frac{c}{\gamma l}, \quad \pi_3 = \frac{C}{\tau}. \]

(5)

Criteria \( \pi_1 \) and \( \pi_2 \) are defining ones, as they include defining parameters of the process.

Criterion \( \pi_3 \) is a defined criterion, as it contains in its structure a defined value of \( \tau \).

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 \( \alpha \).

The digging mode is determined by the depth of cutting \( h \), blade travel velocity \( \varphi \) and free fall acceleration \( g \).

The soil is considered the medium characterized by cohesion \( c \), angle of internal friction \( \rho \) and external friction \( \phi \), and volumetric weight \( \delta \).

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

\[ P = f(B, H, \alpha, c, \rho, \phi, h, \varphi, g). \]

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 \( \alpha, \delta, \rho \) 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 \( T \).

\[ [B] = [H] = [h] = L; [P] = PL^{-2}; [\delta] = PL^{-3}; [\varphi] = PL^{-1}. \]

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

\[ \begin{align*}
[B] &= L, \\
[H] &= L, \\
h &= L, \\
P &= PL^{-2}, \\
\delta &= PL^{-3}, \\
\varphi &= PL^{-1}.
\end{align*} \]

\[ \begin{align*}
\pi_1 &= \frac{\alpha}{\delta}, \\
\pi_3 &= \frac{\rho}{\varphi}.
\end{align*} \]

"To find an additional number of similarity criteria, one should choose basic values with independent dimensions: \( \alpha, B, g \) \((m = 3)\).

Then it remains to find 5 \((8 - 3 = 5)\) similarity criteria. To find criterion \( \pi_4 \), for example, the dimension of parameter \( P \) is written into the numerator, and the product of the dimensions of quantities \( \alpha, B, g \) and unknown exponents \( a_1, a_2, a_3 \) is written into the denominator:

\[ \pi_4 = \frac{(P)^{a_1}}{(PL^{-3})^{a_2}(L)^{a_3}}. \]

1, \( a_2 = 3, \ a_3 = 0 \)

\[ \pi_4 = \frac{(P)^1}{(PL^{-3})^3(L)^0}. \]

\[ \pi_4 = \frac{P}{\delta B^3}. \]
In the same way, we obtain the remaining similarity criteria. Let us write out all the similarity criteria:

\[
\begin{align*}
\pi_4 &= \frac{P}{\delta B^3} ; \\
\pi_5 &= \frac{\theta}{\sqrt{gB}} ; \\
\pi_6 &= \frac{h}{\delta B} ; \\
\pi_7 &= \frac{c}{\delta B} ; \\
\pi_8 &= \frac{B}{H} ; \\
\pi_9 &= \alpha ; \\
\pi_{10} &= \rho ; \\
\pi_{11} &= \varphi .
\end{align*}
\]

To make it easier to use, the \( \pi_2 \) criterion is squared. Then this criterion is represented as:

\[
\pi_5 = \frac{\theta^2}{gB}.
\]

According to the \( \pi \)-theorem \([14-16]\), we replace function (1) with a criterion equation. To do this, we write one of the criteria (in our case, \( P_\delta B_3 \)) as a function of the remaining similarity criteria and obtain the expression for function (1) in a criterion form:

\[
P_\delta B_3 = f(\epsilon B, \alpha, \rho, \varphi).
\]

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 \([17, 18]\).

\[
I_1 = K_m + 1 \cdot K_1 a_1 \cdot K_2 a_2 \ldots K_m a_m = 1; \\
I_{n-m} = \frac{K_m}{K_1 a_1 \cdot K_2 a_2 \ldots K_m a_m} = 1.
\]

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:

\[
k_p = \frac{k_\delta}{k_B} = 1.
\]

\[
k_p = \frac{k_c}{k_B} = \frac{k_h}{k_B} = \frac{k_\theta}{k_B} = \frac{k_\alpha}{k_\rho} = \frac{k_\varphi}{k_\varphi} = 1.
\]

\[
k_B = k_\delta = k_\theta = 1.
\]

\[
k_p = k_\delta^3 \cdot k_c = k_H = k_h = k_B \cdot k_\alpha = k_\rho = k_\varphi = 1.
\]

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 \( \delta \) 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:

\[
k_p = k_\delta = k_B = k_H = k_h = k_\theta = k_\alpha = k_\rho = k_\varphi = 1.
\]

\[
\Delta V \geq 200 d^3.
\]
where \( d \) is the average linear size of the particles that make up the medium;

\[ k_B = 4 \sqrt{\frac{P_0 \Delta_1 \cdot 100}{P_{max} \cdot k_i}} \]

\( P_0 \) is the maximum force of the original, \( kN \);
\( \Delta_1 \) 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, \( kN \); \( k_i \) is the accuracy class of the device (usually up to 2.5%).

So, assuming that \( P_0 = 300 \ kN \), \( P_{max} = 100 \ kN \), \( \Delta_1 = 10 \), \( k_i = 2.5 \), we obtain:

\[ k_B = 4 \sqrt{\frac{300 \cdot 10 \cdot 100}{100 \cdot 2.5}} \approx 6 \]

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:

\[ V = \frac{B H^2}{2 \tan \rho} \]

\( \rho \) 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:

\[ \frac{1}{2} \cdot \frac{B}{k_B} \cdot \frac{H^2}{k_B} \geq 200 d^3 \]

\[ k_B \leq \frac{1}{3} \frac{B H^2}{d \cdot 400 \tan \rho} \]

\( B = 4030 \ mm; \ H = 1720 \ mm; \ \rho = 45^0; \ d = 45 \ mm \)

\[ k_B \leq \frac{1}{45} \frac{4030 \cdot (1720)^2}{400 \cdot 1} \leq 6.9 \]

\( k_B \leq 7 \div 10 \)
\[
\left(\frac{h}{B}\right)_{org} = \left(\frac{h}{B}\right)_{m} \cdot \frac{h_{org}}{h_{m}k_B} = \frac{h_{m}}{h_{m}k_B} \cdot h_{org} = h_{m}k_B \]

Hence,
\[
\left(\frac{h}{B}\right)_{org} = \left(\frac{h}{B}\right)_{m} \cdot \frac{h_{org}}{h_{m}k_B} = \frac{h_{m}}{h_{m}k_B} \cdot h_{org} = h_{m}k_B.
\]

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

\[
P_{org} = P_{m}k_B^{3};
\]

\[
H_{org} = H_{m}k_B;
\]

\[
h_{org} = h_{m}k_B;
\]

\[
B_{org} = B_{m}k_B;
\]

\[
\rho_{org} = \rho_{m};
\]

\[
\varphi_{org} = \varphi_{m};
\]

\[
c_{org} = c_{m}k_B;
\]

\[
\alpha_{org} = \alpha_{m};
\]

\[
\beta_{org} = \beta_{m}, \quad \beta_{org} = \beta_{m}\sqrt{k_B}.
\]

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

<table>
<thead>
<tr>
<th>№</th>
<th>Parameter</th>
<th>Measurements units</th>
<th>Numeric value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Blade model length, $B_m$</td>
<td></td>
<td>0.785</td>
</tr>
<tr>
<td>2</td>
<td>Blade model height, $H_m$</td>
<td></td>
<td>0.29</td>
</tr>
<tr>
<td>3</td>
<td>Maximum depth of cut, $h_m$</td>
<td></td>
<td>0.12</td>
</tr>
<tr>
<td>4</td>
<td>Cutting angle by the blade, $\alpha$</td>
<td>degree</td>
<td>50 - 55</td>
</tr>
</tbody>
</table>

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.

It is known from literary sources that the most typical soils in the Republic of Uzbekistan are sand soils, 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

<table>
<thead>
<tr>
<th>№</th>
<th>Parameter</th>
<th>Sands</th>
<th>Sandy loamy soil</th>
<th>Loamy soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cohesion, ( c_\omega, \text{MPa} )</td>
<td>0.0001</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>2</td>
<td>Number of strokes, ( C_{\text{уд}} )</td>
<td>1</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>Angle of internal friction, ( \rho ), deg</td>
<td>29</td>
<td>27</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>Angle of external friction, ( \phi ), deg</td>
<td>18</td>
<td>25</td>
<td>21</td>
</tr>
<tr>
<td>5</td>
<td>Volume weight: in a dense body, ( \delta ), t/m(^3)</td>
<td>1.8</td>
<td>1.7</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>in a loose body, ( \delta ), t/m(^3)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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:

\[
P \frac{\delta}{B^3} = k_p F(\pi_6)
\]

(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:

\[
P = k_p \delta B^3 \cdot \frac{h}{B} = k_p \delta B^2 h
\]

(12)

The series of experiments conducted made it possible to determine the value of coefficient \( k_p = 1.34 \).

Finally, we obtain:

\[
P = 1.34 \delta B^2 h
\]

(13)

3 Conclusions

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.

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 cut is adequately reflected in the experimental data.

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