The method of determining the parameters of the soil prism formed in front of the dump during digging

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Abstract. Problem. The studied dynamic process of digging, taking into account the variable total moving mass of wheeled ZTM equipped with a dump, is not sufficient for the development of recommendations for selecting rational parameters for the performance of such a technological operation. The issue of determining and analyzing the parameters of the variable mass and volume of the material prism moved by the dumper has not been sufficiently investigated. There is no engineering technique that allows you to determine the parameters of the material prism that is gradually forming before dumping. Methodology. The measures are aimed at determining the parameters of the soil prism before the dump in the digging process using analytical dependencies. Results. For the processes of development and analysis of dynamic models of machines with a shovel working body for the stages of digging and transportation of material, it is necessary to take into account its mass in the form of mass attached to the mass of the machine itself. Originality. The obtained dependencies allow to take into account the variable mass of the attached material when performing the analysis of the bulldozer movement in the process of digging the environment being developed. Practical value. The obtained results can be recommended when studying the disciplines of industrial mechanical engineering.

Keywords: bulldozer, prism, dump, dynamic process, technological operation

Introduction

Among machines for earthworks, experts single out earthmoving and transport machines (ZTM) in a separate group. These machines include bulldozers, scrapers, motor graders and grader-elevators. Some researchers also include single-bucket front loaders in ZTM. This division is due, first of all, to the peculiarities of technological operations. The driving force, which ensures the execution of a technological operation, is developed by the running equipment of such machines. This means that the operations of digging the soil, transporting it to the place of unloading and returning ZTM back to the slaughterhouse are provided due to the driving force that is formed in the contact zone of the running equipment (tracks, wheels) with the supporting surface. At the same time, a significant part of the external supports (general working supports) is perceived by the working body. The ZTM in the contact zone of the running equipment and the support surface is additionally affected by rolling resistance forces.

The operation of digging the developed environment with a dump working body is accompanied not only by the separation of shavings from the soil massif, but also by its successive accumulation in front of the dump in the form of a prism of material. Since the mass of the prism can be significant and comparable to the mass of the ZTM itself, the operation of digging the developed environment can be considered from the point of view of the dynamics of solid bodies as a stage of the undetermined movement of the ZTM. It should be especially taken into account that the volume, and therefore the mass, of the displaced material prism at this stage increases from zero to its limit value. This fact can affect the performance indicators of ZTM. For example, for a bulldozer in the situation of moving mined material over short distances, the duration of the digging stage can occupy a significant part of the entire working cycle of the machine. Since not
only the machine itself is moving, but also the 
variable mass of material attached to it, which is 
in the prism, it can be expected that the param- 
ters of this dynamic process will also change.

In particular, the duration of the stage of dig- 
ging the mined material may change. Failure to 
take into account this fact can lead to an incor- 
rect assessment of the productivity of the ZTM, 
and the lack of analytical dependencies that 
would take into account the variable mass of the 
material prism formed before the dump, will not 
allow to identify and analyze the dynamic char-
acteristics of the stage of digging the material 
and develop measures to increase the productiv-
ity of the ZTM.

Analysis of publications

In the works of K.O. Artemyeva, V.V. Nitschke, 
L.A. Clouds and other authors, when calculating the 
productivity of scrapers, it is recommended to take 
into account the variable mass of soil in the bucket 
of the machine during the digging operation [1-7]. 
The proposed analytical dependencies developed 
by the researchers take into account the decrease in 
the speed of the machine as the bucket is filled with 
mined material.

For machines equipped with a dump working 
body, calculations are usually performed only for 
situations of maximum load. The proposed ap-
proach is applied to tracked machines, since the 
slip coefficient of their running gear does not 
change significantly with the increase of external 
resistances and the increase of the total weight of 
the machine and the transported material. On the 
other hand, for wheeled ZTM with a dump work-
ning body (wheeled bulldozers, motor graders), 
the change of these parameters has a significant 
effect on the real speed of ZTM movement due to 
an increase in the slip coefficient, which is con-
firmed by the works of M.O. Ulyanova, P.I. 
Nikulin and their students. According to the con-
ducted studies, the slip coefficient of the wheel 
ZTM can be represented in the form of a polyno-
mial dependence of the fifth-sixth degree on the 
total resistances acting on the ZTM.

\[
\delta = \frac{v_m - v_n}{v_m} = A \frac{T}{R} + B \left( \frac{T}{R} \right)^n
\]  

(1)

where \( \delta \) – slip coefficient; \( v_m \) – theoretical speed 
of movement of wheeled ZTM; \( v_n \) – actual speed 
of movement of the wheeled ZTM; \( T \) is the 
traction force on the driving moving wheels. This 
effort in transient processes is equal to

\[
T = \begin{cases} 
\Sigma W \ n_{pu} \Sigma W < T_0 \\
T_0 \ n_{pu} \Sigma W \geq T_0 
\end{cases}
\]  

(2)

where \( \Sigma W \) – total supports acting on the machine 
during the digging operation of the material being 
developed; \( T_0 \) – traction force under the 
conditions of traction of the running equipment 
with the support surface; \( R \) – support reaction on 
leading drivers; \( A, B, t \) are empirical coefficients.

Dependence (2) is valid for energy-saturated 
machines.

The analysis of scientific and technical infor-
mation dedicated to the study of the dynamics of 
the digging process, taking into account the vari-
able total moving mass of wheeled ZTM 
equipped with a dump, is not sufficient for the de-
velopment of recommendations for the selection 
of rational parameters for the performance of 
such a technological operation. In addition, the 
issue of determining and analyzing the param-
ters of the variable mass and volume of the mate-
rial prism moved by the dumper has not been suf-
ficiently investigated.

This fact can be explained by the lack of an 
engineering technique that allows you to deter-
mine the parameters of the material prism before 
the dump, which is gradually formed.

Purpose and Tasks

The purpose of the proposed article is to develop 
a method for calculating the parameters of the 
material prism, which is formed in front of the 
dump working body during the technological op-
eration of digging the developed environment.

Analysis of the parameters of the maximum 
mass of the material prism, which is formed 
before the dump of serial wheeled bulldozers.

Within the framework of the conducted research, 
it was decided to estimate the expected values of 
the mass of the soil, which is moved by a bull-
dozer during technological operations. Caterpil-
lar Inc.’s wheeled bulldozers were chosen as the 
research object. (see Fig. 1, 2) [8, 9]. During the 
analysis, the following aspects were taken into 
account:

– caterpillar Inc. supplies wheeled bulldozers 
with four different dump types: straight, spheri-
cal, hemispherical and coal (see Fig. 3) [8, 9];

– dumps are intended for various technologi-
cal operations. A straight dumper performs stand-
ard bulldozer operations such as digging soil, 
processing bulk materials and moving soil, min-

erals and construction materials. Spherical scrapers, thanks to their design features, make it possible to form larger prisms of the processed material compared to straight scrapers. The company generally recommends using them to move heavy materials over long distances in the mining industry. Hemispherical dumps occupy an intermediate position between straight and spherical dumps. To work with light materials, for example, to move coal, the company recommends using special coal dumps, which allow forming a prism of material much larger than spherical dumps. A rational choice of dump type, taking into account the performed technological operation, allows to significantly increase the productivity of the bulldozer [8, 9].

The calculations take into account the maximum volume of the material prism formed in front of each type of dump. This volume is regulated by the Caterpillar company in its prospectuses for the corresponding machines [8, 9].

![Fig. 1. Caterpillar Inc. wheeled bulldozer. 824k.](image1)

![Fig. 2. Caterpillar Inc. wheeled bulldozer. 854k](image2)

![Fig. 3. Types of scrapers installed on Caterpillar Inc. wheeled bulldozers: a – straight scraper; b – spherical dump; c – hemispherical dump; d - coal dump](image3)

The results of the calculations are given in Table 1.

**Table 1. The value of the mass of the soil (processed material) formed into a prism before the dump of the bulldozer**

<table>
<thead>
<tr>
<th>Brand bulldozer</th>
<th>$N$, kW</th>
<th>$m_b$, t</th>
<th>Dump type</th>
<th>$V_{np}$, m$^3$</th>
<th>Material</th>
<th>$\delta_{\rho}$, t/m$^3$</th>
<th>$k_\rho$</th>
<th>$mg$, t</th>
<th>$m_s$, t</th>
<th>$m_s/m_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>824k</td>
<td>302</td>
<td>34</td>
<td>direct</td>
<td>5.0</td>
<td>difficult loam</td>
<td>1.95</td>
<td>1.26</td>
<td>7.74</td>
<td>0.228</td>
<td>(22.2%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>spherical</td>
<td>7.7</td>
<td>sand</td>
<td>1.7</td>
<td>1.15</td>
<td>11.38</td>
<td>0.335</td>
<td>(33.5%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>hemispherical</td>
<td>7.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>coal</td>
<td>16.2</td>
<td>coal</td>
<td>0.8</td>
<td></td>
<td>12.96</td>
<td>0.38</td>
<td>(36%)</td>
</tr>
<tr>
<td>834k</td>
<td>370</td>
<td>47.75</td>
<td>direct</td>
<td>7.9</td>
<td>difficult loam</td>
<td>1.95</td>
<td>1.26</td>
<td>12.23</td>
<td>0.256</td>
<td>(25.6%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>spherical</td>
<td>11.1</td>
<td>sand</td>
<td>1.7</td>
<td>1.15</td>
<td>16.4</td>
<td>0.344</td>
<td>(34.4%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>hemispherical</td>
<td>10.1</td>
<td></td>
<td></td>
<td></td>
<td>14.9</td>
<td>0.313</td>
<td>(31.3%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>coal</td>
<td>22.2</td>
<td>coal</td>
<td>0.8</td>
<td></td>
<td>17.76</td>
<td>0.372</td>
<td>(37.2%)</td>
</tr>
<tr>
<td>854k</td>
<td>607</td>
<td>101.72</td>
<td>hemispherical</td>
<td>25.4</td>
<td>sand</td>
<td>1.7</td>
<td>1.15</td>
<td>34.55</td>
<td>0.37</td>
<td>(37%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>coal</td>
<td>44.7</td>
<td>coal</td>
<td>0.8</td>
<td></td>
<td>35.76</td>
<td>0.352</td>
<td>(35.2%)</td>
</tr>
</tbody>
</table>
The following letter designations are used in the table: N – nominal power of the bulldozer engine, kW; \( m_0 \) – bulldozer mass, t; \( V_{np} \) – the maximum volume of the material prism (according to the company), \( m^3 \); \( \delta_{np} \) – density of the material in its natural state, \( t/m^3 \); \( k_p \) – coefficient of loosening of the material; \( m_g \) is the mass of the material in the prism, i.e.

The density of coal is indicated for the loosened state.

Analyzing the results of the performed calculations, it can be stated that the mass of material in a fully formed prism can be compared with the mass of the bulldozer itself and, depending on the type of dump and the characteristics of the environment being developed, can be from 23% to 38% of the mass of the machine itself. This fact can significantly affect the dynamic parameters of the bulldozer movement process.

**Justification of the method of determining the parameters of the soil prism before the dump in the process of digging using analytical dependencies**

As an object of research, we will choose a bulldozer with a non-rotating dump, which performs the operation of digging the soil. Since the volume of material in front of the bulldozer dump increases during the digging process, it is necessary to determine the dependence of the mass of the cut material in the form of a function of the movement of the machine in order to compile a dynamic model of the movement of the machine.

When deriving the dependence, we consider that the tilt angle of the dump in the vertical direction is equal to zero, and the capture angle corresponds to 90°. In general, the digging depth \( h \) can vary arbitrarily depending on the movement of the machine \( x \) (Fig. 4).

![Fig. 4. Longitudinal section of the face for the operation of digging the working environment with a bulldozer dump.](image)

The volume of cut material from the main array is determined by the integral dependence:

\[
V_{c} = \int_{0}^{x} B h(x) dx
\]

where \( B \) is the width of the chip of the cut material (the width of the knife system of the dump); \( h(x) \) is the chip thickness of the cut material (cutting depth); \( x \) is the longitudinal displacement of the bulldozer.

It should be taken into account that in the process of cutting the material, its destruction occurs. This leads to an increase in its volume. This fact can be taken into account using the coefficient of loosening of the material \( k_p \). The real volume of loosened material before the dump is determined by the formula

\[
V_{np} = k_p V_{c} = k_p B \int_{0}^{x} h(x) dx
\]

In the process of moving a prism of material with a bulldozer blade along the support surface, part of the prism will move into the side rollers. This loss of material from the prism can be accounted for using a material loss factor \( k_n \). Finally

\[
V_{np} = (1 - k_n) k_p B \int_{0}^{x} h(x) dx
\]

The coefficient of material loss is less than one and depends on the parameters of the support surface, material properties and the volume of the prism before the dump.

In the process of deriving the formula for determining the mass of the material before the bulldozer dump, it is necessary to take into account that the size of this prism is limited. The maximum possible volume of the prism depends on the geometric dimensions of the dump and the characteristics of the material. Experts recommend using the following dependency [1]:

\[
V_{np}^{max} = \frac{BH^2}{2 \tan \rho} k_\phi = \frac{BH^2}{2 \tan \rho} \left(1 - \frac{H}{B \tan \rho}\right); \quad (6)
\]

where \( H \) is the height of the dump; \( \rho \) – the angle of the natural slope of the material; \( k_\phi \) – prism shape factor.

Thus, the calculated volume of the material prism before the bulldozer dump is determined by the following conditions:
The mass of the material in the prism can be calculated as follows

\[ m_v = V_{np} \frac{\delta_p}{k_p} \]  

where \( \delta_p \) - the density of the material in the natural massif.

When analyzing the dynamic characteristics of a bulldozer during technological operations, researchers often consider the machine as a dynamic single-mass system (Fig. 5) [10]. In the above diagram, the letter \( c \) indicates the elasticity coefficient of the working equipment and other systems of the bulldozer. Theoretically, in the process of moving the bulldozer, oscillating processes can occur inside the system itself, which will lead to the periodic disconnection and attachment of the mass of the material to the total mass of the machine.

Fig. 5. Dynamic scheme of the bulldozer

If we take into account that during digging, the resistance forces on the dump increase and during forward movement of the machine, its acceleration is less than zero, and during oscillatory backward displacement - more than zero, then the total mass of the moving system can be determined from the condition:

\[ \Sigma m = \begin{cases} m_m + m_z & npu \ddot{x} \leq 0 \\ m_m & npu \ddot{x} > 0 \end{cases} \]  

where \( m_m \) – bulldozer mass; \( \ddot{x} \) – acceleration of the center of mass of the bulldozer.

Conclusions

On the basis of the conducted research, the following conclusions can be drawn:

1. The mass of the soil (the material being developed), which is cut and moved by the bulldozer during the digging operation, can be compared with the mass of the machine itself and can reach 35% ... 38% of its mass.
2. The mass of the material in the prism in front of the bulldozer dump is variable and changes from 0 at the beginning of cutting to the maximum value that corresponds to the maximum permissible volume of the material prism.
3. In the process of developing and analyzing dynamic models of machines with a shovel working body for the stages of digging and transporting material, it is necessary to take into account its mass in the form of mass attached to the mass of the machine itself.
4. The proposed dependencies (7), (8) and (9) allow you to take into account the variable mass of the attached material when performing an analytical analysis of the bulldozer movement in the process of digging the environment being developed.

Conflict of interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Метод визначення параметрів призми ґрунту, яка формується перед відвалом під час копання

Анотація. Проблема. Досліджуваний динамічний процес копання в урахування змінної сумарної інерційної маси, обладнаної відвалом, не є достатнім для розробки рекомендацій щодо вибору раціональних параметрів виконання такої технологічної операції. Недостатньо досліджено питання визначення та аналізу параметрів змінної за масою та обсягом переміщуваної відвалом призми матеріалу. Відсутність інженерної методики, яка дозволяє визначити параметри поступово формуючої перед відвалом призми матеріалу. Мета. Розробка методу розрахунку параметрів призми матеріалу, яка формується перед відвалом робочим органом під час виконання технологічної операції копання розроблюваного середовища. Методологія. Заходи спрямовані на визначення параметрів призми грунту перед відвалом у процесі копання за допомогою аналітичних залежностей. Результати. Для процесів розробки та аналізу динамічних моделей машин з відвалом робочим органом для етапів копання та транспортування матеріалу необхідно враховувати її масу у вигляді маси, приєднаної до маси самої машини. Оригіналість. Отримані залежності, що дозволяють врахувати змінну масу матеріалу, що приєднується, при проведенні аналітичного аналізу руху бульдозера в процесі копання середовища, що розробляється. Практична цінність. Отримані результати можна рекомендувати при вивченні дисциплін галузевого машинобудування.

Ключові слова: бульдозер, призма, грунт, динамічний процес, технологічна операція

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