Ultimate loads, arising on the blade during exploitation, according to existed design positions for calculations

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Abstract. In the paper a method for determining external loads on the working equipment of the bulldozer is presented. Using this method, it was revealed that the computations using the existing algorithm allow to obtain overestimated values of the loads, what leads to a significant increase in the metal intensity of the machine design. Also in the article is shown away for carrying out an experiment on the bulldozer stand, described the positions of bulldozer working equipment, according to which it will be tested and made the conclusions about the research.

1. Introduction
Currently, there are no clear recommendations on how to carry out design calculation and make a choice from different constructions of pushing arms. It is important because pushing calculation is used pushing arms are one of the most important elements of the bulldozer structure, they should have minimum mass of the design, at the same time provide the necessary strength during exploitation. Therefore, the urgent task is to develop optimal designs of pushing bars for any kinematic schemes of bulldozer working equipment and exploitation conditions of the machine. To reach this goal, it is necessary to elaborate a way of calculating the bulldozer design, which would allow to get loads on the operating equipment close to real. Because the existing design calculation has some inaccuracies in determining of the applied working loads, for example, the longitudinal force consists of the static and dynamic component, but according to existed calculation, the maximum values of these components are taken into consideration, regardless of what place this force is applied. Also, the method does not take into account the difference in the rates of increment and the nature of the dynamic and static efforts.

2. Goal
The purpose of the experimental research is to find the way how to get forces arising at the blade during the machine work and to test the strength of the elements of the bulldozer equipment at the existing design positions and according to the specified calculation. Moreover, to compare the results of the specified calculation with the results of the existing method.
3. Analytical model

To determine the real loads on the blade of the bulldozer, they will be considered according to the existing method:

\[ P = P_S + P_D, \]  

(1)

where:

- \( P_S \) – static load;
- \( P_D \) – dynamic load.

The maximum traction force occurs when the machine is at the moment of track skidding [1]:

\[ P_{ys} = G_B \cdot \varphi_{max}, \]  

(2)

where \( P_{ys} \) – static force on the blade of the bulldozer, directed along its longitudinal axis;
- \( G_B \) – bulldozer gravity;
- \( \varphi_{max} \) – maximum friction coefficient.

It is possible to accept the meaning of the \( \varphi_{max} \) coefficient while skidding will be 20% [1].

Thus, the actual speed of the bulldozer will be reduced by 20% compared with the theoretical:

\[ V_a = V_{th} \cdot (1 - \delta), \]  

(3)

where:

- \( V_a \) – actual speed of bulldozer;
- \( V_{th} \) – theoretical speed of bulldozer.

The value of \( \varphi_{max} \) depends on the distance from the point of force application on the blade to the longitudinal axis of the bulldozer.

The ratio of \( P_{ys} \) from the distance \( l \) of the point of the force application on the blade was revealed by V. S. Berezin [2].

It should be noted that in determining the maximum loads, it is necessary to take into account the friction ellipse (that is anisotropy of friction of a tracked machines on the ground) [3]. This reflects the fact that during the slipping of the bulldozer tracks (i.e. with the adhesion coefficient in the longitudinal direction \( \varphi = \varphi_{max} \)) when the position of the load on the blade is along the longitudinal axis of the bulldozer, we can disregard the lateral adhesion coefficient of the tracks \( (\varphi' = \varphi'_{max}) \varphi = 0 \).

To define the maximum possible static loads on the blade when the bulldozer run into a firm obstacle (look at the scheme on the Figure 1), we need to take into consideration friction ellipse (Figure 2). Maximum loads \( P_{ys} \) and \( P_{xs} \) become maximum together when their resultant is directed to the center of pressure (when the vertical force on the blade is absent— into the projection of the center of the bulldozer gravity to the bearing surface. In this case, the blade does not slip over the obstacle. Using the friction ellipse (Figure 2), we can get the following equation.

\[ \text{Figure 1. Scheme illustrated how bulldozed run into a firm obstacle.} \]
Figure 2. Ellipse of friction.

\[
\frac{\varphi^2}{\varphi_{max}^2} + \frac{\varphi'^2}{\varphi_{max}'^2} = 1
\]

or

\[
\varphi' = \varphi_{max}' \sqrt{\frac{\varphi_{max}^2 - \varphi^2}{\varphi_{max}'^2}}
\]

From the equation of the sum of the force moments in relation to the point O (Figure 1):

\[ G_B \varphi \cdot l = G_B \varphi' \cdot l_c \]

or after simplification of the equation we can get the following line:

\[ \varphi \cdot l = \varphi' \cdot l_c \]  

(5)

Put (4) into (5), we can get:

\[ \varphi = \frac{\varphi_{max} \cdot \varphi_{max}' \cdot l_c}{\sqrt{l^2 + \varphi_{max}^2 \cdot l_c^2}} \]

Static force on the blade in the horizontal direction:

\[ P_s = G_B \sqrt{\varphi^2 + \varphi'^2}; P_{ys} = G_B \varphi; P_{xs} = G_B \varphi'. \]  

(6)

Such forces on the blade occur when bulldozer works with a significant speed and when the engine power is sufficient to achieve the maximum of the traction force.

When working at the high speeds, the traction force not always reach its maximum adhesion value.

The power balance equation for the earthmoving machine is [4]

\[ N_{np} = N_e - N_{pt} - N_s - N_f \]  

(7)

\[ N_{np} \] – netpower, spent for the creating force on the blade;
\[ N_e \] – the power of engine;
\[ N_{pt} \] – power, spent due to working of the powertrain;
\[ N_s \] – power, spent during skidding.

\[ N_e = (N_e - N_{pt}) \cdot \delta \]  

(8)

\[ N_f = V_{pt} \cdot G_B \cdot f, \]

where \( f \) – coefficient of rolling friction.

Power balance equation is:

\[ P'_{ys} \cdot V_{th} \cdot (1 - \delta) = (N_e - N_{pt}) \cdot (1 - \delta) + f \cdot G_B \cdot V_{th} \cdot (1 - \delta) \]  

(10)

then

\[ P'_{ys} = \frac{N_e - N_{pt}}{\omega_{sh} \cdot i_{gr} \cdot R_{sw}} - f \cdot G_B \]

\[ \omega_{sh} \] – angular velocity of the mover shaft;
\[ i_{gr} \] – power train gear-ratio;
\[ R_{sw} \] – radius drive sprocket wheel.
Since $N_e$ depend on $w_{sh}$, i.e. $N_e = f(w_{sh})$, then $P'_{ys}$ depend on the speed of the bulldozer motion. Moreover, the greater the angular velocity of the mover shaft of the bulldozer $\omega_{sh}$, the smaller $N_e$ and $P'_{ys}$ [4].

To determine the actual speed, we need to determine the skid at the moment when the ground still holds force without disintegration:

$$P_{ys} = G_B \ast \varphi \omega = \frac{P_{ys}}{G_B},$$

(12)

The value of $\varphi$ depending on the slip $\delta$ is described by different equations [1]. Knowing $\delta$, it is easy to find $\varphi$ by using any of these equations. For example, for the equation developed by A. P. Parfenov.

$$\varphi = \varphi_{max} - a \ast e^{-b\delta},$$

(13)

where $a$ and $b$ – coefficients, depended on the type of soil; $e$ – basement of natural logarithm.

Then $\delta = -\frac{1}{b} \ast \ln\left(\frac{\varphi_{max} - \varphi}{a}\right),$

where $V_e = V_{th} \ast (1 - \delta)$.

Maximum of the lateral constituent of force on the blade we can find according following equation:

$$P_{xs} = G_B \ast \varphi = G_B \ast \varphi_{max} \ast \sqrt{\varphi_{max}^2 - \left(\frac{P_{ys}}{G_B}\right)^2},$$

(14)

The dynamic force will be found from the condition that the difference in kinematic energies before and after the hit transforms into energy of design deformation.

The kinetic energy of a bulldozer in a straight-line motion before hit:

$$K_1 = \frac{m \ast v_{bf}^2}{2},$$

(15)

wherem – mass of bulldozer;

$V_{bf}$ – bulldozer speed before a hit.

Kinetic energy after hit:

$$K_2 = \frac{m \ast v_{af}^2}{2} + \frac{J \ast \omega^2}{2},$$

(16)

where $V_{af}$ – bulldozer speed after a hit;

$J$ – moment of inertia of the bulldozer around the axis of rotation;

$\omega$ – angular velocity of the axis of rotation of the earthmoving machine.

The rotation of the earthmoving machine after the impact occurs because the line of the dynamic force action does not pass through center of mass of the machine.

The force that appears on the blade when machine run into a rigid obstacle by its blade is determined from the thought that the change in kinetic energy during the impact is expended on elastic deformation.

$$P_d = \sqrt{2 \ast C \ast (K_1 - K_2)}$$

(17)

where $C$ – stiffness.

Scheme of the earthmoving machine hit is shown in the Figure 3.

To determine the maximum possible values, we assume that when machine hits by their edges of the blade, the rotation occurs in planes I-I and II-II, but when it hits by the center of the blade – in plane III-III. All three planes are parallel to the direction of the machine motion and they pass through the center – point A and the points of hit O, $O_1$, $O_2$.

If we consider the rotation of earthmoving machine only in one of the planes I-I, II-II or III-III, then the task will be transformed from space into a flat one, since bulldozer does not have a degree of freedom to move down due to the limitations of the base surface.

From the theorem of impulses for plane motion:

$$m \ast (V_{bf} - V_{af}) = S$$

$$m \ast r_i^2 \ast \omega = S \ast l_i; l_i = A \ast O_l$$

(18)

where $S$ – force impulse;
\[ r_i - \text{radius of inertia} \]

where \( \varepsilon \) – recovery coefficient;
\( V_{af} \) – speed after a hit;
\( V_{bf} \) – speed before a hit.

Then

\[ \omega = \frac{l_i V_{bf}}{l_i + r_i} (1 + \varepsilon); \quad V_{af} = \frac{l_i^2 - \varepsilon r_i^2}{l_i^2 - r_i^2} \cdot V_{bf} \]  

(20)

Since \( r_i^2 = \frac{a_i^2 + b_i^2}{12} \)

![Diagram](image)

**Figure 3.** Scheme for the determination of a dynamic force on a blade.

From previous equations we have:

\[ V_{af} = \frac{12a_i^2 - \varepsilon r_i^2}{12 + a_i^2 + b_i^2} \cdot V_{bf} \]  

(21)

\[ \omega = \frac{12l_i^2 + 4(1 + \varepsilon)}{12l_i^2 + a_i^2 + b_i^2} \]  

(22)

In the plane I-II \( l_1 = OA \), in the plane II-III \( l_2 = O_1A \), in the plane III-III \( l_3 = O_2A \).

The energy of deformation is maximum at \( \varepsilon = 0 \).

In the equation for determination of the dynamic force, should be found the stiffness in the Y direction, since we will consider the dynamic force only in the Y direction because the force impulse is parallel to this axis. The stiffness of the bulldozer design was sufficiently considered in the papers of A. M. Kholodov and N. F. Fedotov [5, 6]. In the horizontal plane, the stiffness of the earthmoving machine will influence on the stiffness of the pushing arms \( C_{p.a} \) (Figure 4) in case when the mechanisms for compensating the tilt of the blade connect them to each other. In case when the compensation mechanism is made in the form of a diagonal rod, connecting the blade with the base tractor, the stiffness of the bulldozer design in all directions can be determined by the formula [7]:

\[ C_1 = \alpha \times \frac{G_{bt}}{m} \]  

(23)
where $G$ – gravity of the base tractor;
$\alpha = (0.9 \ldots 1.0)$ – coefficient of stiffness of the operating equipment per 1 kilogram of tractor mass.

Stiffness:

$$C = \frac{C_1 \cdot C_2}{C_1 + C_2}$$  \hspace{1cm} (24)$$

where $C_2$ – stiffness of the obstacle.

![Figure 4](image-url)

**Figure 4.** Scheme where is shown how to take into account stiffness of the pushing arms.

The equations that were found on the blade allow to get real values of the forces and let us to estimate the actual stress strain state of the metal elements of the working equipment earthmoving machineduring exploitation. The values of the loads when they are determined by the existing method [7] are overestimated. The static load on the edge of the blade is less by following value:

$$\Delta P_{ys} = G_B \cdot \varphi_{max} - G_B \cdot \frac{\varphi_{max} \cdot \varphi_{max} \cdot l_c}{\sqrt{1 + \varphi_{max}^2 + l_c^2}}$$  \hspace{1cm} (25)$$

The difference of the found equation for the dynamic force in comparison with that found by the existing method is also significant when a tractor power sufficient to drive at the same speed on 1st gear

$$\Delta P = V_{th} \cdot \sqrt{2 \cdot C \cdot m - \sqrt{2 \cdot C \cdot (K_1 - K_2)}}$$  \hspace{1cm} (26)$$

4. Experiments and results

The program and procedure of the bulldozer stand testing was developed together with Research and Production Association «VNIIStroydormash» and Moscow Automobile and Road construction State Technical University. A full-scale sample of the bulldozer equipment was made on the basis of a DET-250 tractor (bulldozer stand). The scheme of the bulldozer equipment corresponds to the scheme DZ-
132 [8]. The mass of the pushing arms of the bulldozer stand is less than the mass of the pushing arms of the DZ-132 bulldozer by 10%.

The purpose of the experimental research on the bulldozer stand is:

- Verification of the forces, arising on the blade at the existing design positions, for strength testing of the elements of the earthmoving machine equipment.
- Determination of the stress-strain state of the push arms at additional design positions.

Foil stress gauges with a base of 15 mm were used to measure the voltages at the test points.

The stresses were measured at the following points of the push arms:

1. On the left arm along the axis at a distance of 1170 mm from the axis of the vertical pin of the hinge which attaches the arm to the blade, in front of the loop of the pitch rod (numbers of sensors 15 and 16).
2. On the left arm from the top, along the axis, at a distance of 480 mm from the axis of the loops of the pitch rods at the rear (numbers of sensors 17 and 18).
3. On the right arm, at the rear of the pitch rod loop at the distance of 480 mm of the axis of this loop (numbers of sensors 19 and 20).
4. On the right arm from the top front of the loop at a distance of 1170 mm from the axis of the vertical pin of the hinge which attaches the arm to the blade (numbers of sensors 21 and 22, Figure 5).
5. On the right arm on the side from the inside at a distance of 1170 mm from the axis of the vertical pin of the hinge which attaches the arm to the blade (numbers of sensors 23 and 24).

The sensors were glued perpendicular to the axis of the bulldozer (odd sensors) and parallel (even sensors). The sensor 23 is glued parallel to the axis of the bulldozer, the sensor 24 is vertically.

The test points, where the stresses were determined, were chosen in order to determine the maximum stresses from the forces and stresses on the blade according to additional design positions. The sensors were connected by a bridge circuit.

![Image](image_url)

**Figure 5.** The fourth point on the design where stresses were measured.

Tesometric equipment was installed in the laboratory. The force on the blade was measured with the help of a tare strainer up to 30 tons.

In Figure 12 shows one of the test moments when the bulldozer ready for testing, the load on the blade was transferred by a special hook.

Experimental studies included the following tests:

1. Hanging the bulldozer in the middle of the blade, on the left and right edge of the blade. The force is created by hydraulic cylinders for raising and lowering the blade. The blade rests on the hook, which is connected with the use of a strain-measuring load gage to the hook of an overhead crane (load capacity 15 tonnes). Strain-measuring load gage measures the vertical force on the blade, which is sufficient to overturn the bulldozer relative to the drive sprockets of the base tractor.
2. Test of the bulldozer traction: the force from the rigid load (8.2 tonnes × 5) on the strain-measuring load gage and hook was attached to the center of the blade, to the right side and the left side of the blade, parallel to the longitudinal axis of the bulldozer.

3. Determination of dynamic forces when bulldozer lowering their blade. Then the blade at the maximum lowering speed hit by its center, left and right edge of the blade (Figure 7) into a metal obstacle mounted on a hard concrete floor.

Figure 7. Example of the ninth test.

Thanks to the tests number 1 and 2, that were carried out, the maximum static horizontal, parallel to the longitudinal axis of the bulldozer and the vertical forces on the blade at the existing design positions were determined; test number 3 helped to reveal dynamic forces are when the blade hits a rigid obstacle while lowering the blade at maximum working speed; Preliminary tests showed that for the level of confidence probability γ = 0.95 the required number of experiments is r = 5. The calculation was carried out according to the well-known method \[9-11\].

Let us calculate the difference of the static force, according to the formula (25) of the existed and presented in this paper method. We will find how much the values that were gotten according to the existing method were overestimated.

\[
\Delta P_{ys} = G_B \cdot \varphi_{max} - G_B \cdot \frac{\varphi_{max} \cdot \varphi_{max}' \cdot l_c}{\sqrt{l_c^2 + \varphi_{max}^2 \cdot l_c^2}} = 335000 \cdot \left(0.71 - \frac{0.71+0.75+4468}{\sqrt{2135^2+0.75^2+4468^2}}\right) = 2,141 \times 10^5 N
\]

5. Conclusions

1. Analysis of the correlations, received for the determination of the changing of the static force on the blade, depending on the coordinates of its application to the blade, shows that the maximum longitudinal static force generated by the bulldozer at the bottom corner of the blade is less than the longitudinal static force generated in the center of the blade cutting edge in 1.5 times.

2. The longitudinal static force at the lower corner of the blade, determined by the existing method, is in 1.5 times overestimated.
3. It was revealed experimentally that for the most common heavy bulldozers, for example the DZ-132 bulldozer, the longitudinal static force in the center of the cutting edge of the blade is in 1.5 times high the longitudinal static force in the lower corner of the blade.

4. The existing design positions, suggesting that the maximum longitudinal and transverse forces on the blade can act together, do not confirm by the real scheme of bulldozer loads. The adhesive coefficients of the tracks with the ground in the longitudinal and transverse directions are interconnected in such a way that the maximum value of one of them corresponds to the minimum value of the other.

5. It has been established experimentally that the stiffness of the metal structure of the bulldozer equipment in the longitudinal direction with the application of hit force to the lower corner of the blade and to the center of its cutting edge can be considered in the computations the same.

6. It has been established experimentally that for heavy bulldozers, for example bulldozer DZ-132, when it pushes by a pushing arm into an rigid obstacle during its turning, the stresses in the pushing arms become maximum.

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