Modeling of traction-coupling properties of wheel propulsor

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Abstract. In conditions of operation of aggregates on soils with low bearing capacity, the main performance indicators of their operation are determined by the properties of retaining the functional qualities of the propulsor. Therefore, the parameters of the anti-skid device can not be calculated by only one criterion. The equipment of propellers with anti-skid devices, which allow to reduce the compaction effect of the propulsion device on the soil, seems to be a rational solution to the problem of increasing traction and coupling properties of the driving wheels. The mathematical model is based on the study of the interaction of the driving wheel with anti-skid devices and a deformable bearing surface, which takes into account the wheel diameter, skid coefficient, the parameters of the anti-skid device, the physical and mechanical properties of the soil. As a basic mathematical model that determines the dependence of the coupling properties on the wheel parameters, the model obtained as a result of integration and reflecting the process of soil deformation from the shear stress is adopted. The total value of the resistance forces will determine the force of the hitch pressure on the horizontal soil layers, and the value of its deformation is the degree of wheel slippage. When the anti-skid devices interact with the soil, the traction capacity of the wheel is composed of shear forces, soil shear and soil deformation forces with detachable hooks. As a result of the interaction of the hook with the soil, the latter presses against the walls of the hook with the force equal to the sum of the hook load and the resistance to movement. During operation, the linear dimensions of the hook will decrease, which is not taken into account by the safety factor. Abrasive wear of the thickness of the hook is approximately proportional to the work of friction caused by the movement of the hook when inserted into the soil and slipping the wheel.

Keywords: anti-skid device, drag force, hook load, deformation, wheel diameter, tangential traction force

1. Introduction
When a wheel operates with removable devices, there are forces of resistance to movement from the wheel and removable hooks. We made a scheme for calculation the resistance to the movement of the wheel and the process of interaction with the soil. When the anti-skid devices interact with the soil, the traction capacity of the wheel is composed of shear forces, soil shear and soil deformation forces with detachable hooks. We took V.V. Guskov model as a basic model, which determines the dependence of traction-coupling properties on the wheel parameters.

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2. Research results and their discussion.

As skidding decreases, the drag force increases [1,2,3]. Let’s consider a driving wheel equipped with anti-skid devices. When the torque is applied, forces of resistance arise, due to the movement of the unit and the hook load. The total value of the resistance forces will determine the force of the hitch pressure on the horizontal soil layers, and the value of its deformation is the degree of wheel slippage.

We developed a removable device (Fig. 1) fixed to the rim disk. Fig. 2 demonstrates the scan of the bracket.

The device consists of a bracket (1), a stand (2) fixed to the bracket with bolts (3), a lug (4) connected to the bottom of the stand by a bolt connection (5). In order to increase the resistance of the bracket to the bending and torque, the stiffening rib is welded (6). The rubber gasket (7) serves to soften the impact of dynamic loads on the wheel disc. Bending the sweep of the bracket along the line AC, the triangle's legs are welded, and the cut out triangle of the CBD later serves as a stiffener [4, 5, 6, 7].

![Figure 1. A removable device fixed to the wheel rim](image1)

![Figure 2. Scan of the bracket](image2)

The principle of operation is as follows:

To fix the device to the rim of the wheel, it is enough to unscrew one of the nuts of the disc and, in combination with the hole "a", fix the bracket 1. Then, using the bolts 3 to the bracket 1, fasten the rack 2 with the lug 4.

When the wheel rolls on a soil with a low bearing capacity, the hook 4 is set to the maximum height of its interaction with the soil. With increasing soil density, the height, due to the bolts 3, is reduced. When the unit leaves the road, the anti-skid device, by turning the bracket 4 by 180 °, is moved to the transport position [8].

The advantage of this device lies in the simplicity of the design, which allows, due to one connection, fastening to the rim wheel rim, to mount and dismantle it on the propulsion device of the vehicle. The bracket at one end has a rubber gasket, and on the other the rack is fixed [9,10,11,12].
The bracket being mounted to the wheel rim with a single bolt connection, made in the form of a L-shaped form containing a stiffener.

Let's consider a driving wheel equipped with anti-skid devices (Figure 3). When the torque is applied, forces of resistance arise, due to the movement of the unit and the hook load. The total value of the resistance forces will determine the force of the hitch applied, forces of resistance arise, due to the movement of the unit and the hook load. The total value of the resistance forces will determine the force of the hitch applied, forces of resistance arise, due to the movement of the unit and the hook load. The total value of the resistance forces will determine the force of the hitch applied, forces of resistance arise, due to the movement of the unit and the hook load.

![Figure 3. Scheme for calculating wheel slippage](image)

The amount of crushing of the soil is determined by the product of the area ABCF by the length of the hook, then:

\[
S_{ABCF} = S_{AOF} - S_{OBC} - S_{AOF} - (S_{OBD} - S_{OCD})
\]

\[
S_{AOF} = \frac{\pi (R_k + h_c)^2 (\beta_1 - \beta_2)}{360} = 0.0087 \left( (R_k + h_c)^2 (\beta_1 - \beta_2) \right)
\]

\[
S_{OBD} = \frac{|OD| \times |DB|}{2} = \left( ((R_k - h_c - h_c)^2/2) \right) \cdot \tan \beta_3,
\]

\[
S_{OCD} = \frac{|OD| \times |CD|}{2} = \left( ((R_k - h_c - h_c)^2/2) \right) \cdot \tan \beta_2,
\]

\[
|OD| = R_k - h_c - h_c; |DB| = (R_k - h_k - h_c) \cdot \tan \beta_3,
\]

\[
|CD| = (R_k - h_c - h_c) \cdot \tan \beta_3.
\]

Therefore,

\[
S_{ABCF} = 0.0087 \left( (R_k + h_c)^2 (\beta_1 - \beta_2) - ((R_k - h_k - h_c)^2/2) \right) \cdot (\tan \beta_1 - \tan \beta_2)
\]

where \( R_k \) – the radius of the wheel, m; \( \delta_{cw} \) – coefficient of wheel skidding at the moment of interaction of removable and tire hooks; \( h_c \) – height of anti-skid devices, m; \( h_k, h_c \) – tire deflection and gauge depth, m; \( \alpha \) – the angle of interaction of the hook with the soil, deg.

Expressing the difference of angles \( \beta_1 \) and \( \beta_2 \) from formula (1), substituting in expression (2), we obtain the model of the slip process. Bearing in mind that the tangential force of the thrust \( P_C \), realized by a detachable hook, is the product of the volume of the crushing of the soil by the coefficient of the volume crushing \( K_I \), we obtain:

\[
\cos \alpha = 2 \cdot (R_k - h_c - h_c) \div (R_k + h_c); \quad \beta_1 = (\delta_{cw} \cdot \alpha) + \beta_2;
\]

\[
\beta_1 = \delta_{cw} \cdot (2 \cdot \arccos (R_k - h_c - h_c) / (R_k + h_c)) + \beta_2.
\]

Taking into account that \( P_C = l_c \cdot K_I \cdot S_{ABCF} \), we obtain:

\[
P_C = l_c \cdot K_I \cdot 0.0087 \left( (R_k + h_c)^2 \cdot \delta_{cw} \cdot \arccos (R_k / (R_k + h_c)) - (R_k - h_k - h_c)^2/2 \right) \cdot (\delta_{cw} \cdot (2 \cdot \arccos (R_k - h_k - h_c) / (R_k + h_c)) + \beta_2) - \tan \beta_2
\]

Analysis of the obtained model in the range of variable factors (Table 1) shows that with an increase in the height of anti-skid devices, regardless of their length the \( P_C \) rises along a curve with negative acceleration at a central level of factor variation (Fig. 3). For \( l_c = 0.1 \) m, in the interval \( h_c \) from 0.1 to 0.2 m, the \( P_C \) increases by 198%, at \( l_c = 0.2 \) m - by 177%, at \( l_c = 0.3 \) m - by 192% . With
an increase in $h_c$ from 0.2 to 0.3 m, the $P_C$ rises, depending on its length by 66; 58 and 14% respectively.

### Table 1. Levels and intervals of factor variation

| Levels of variation | Interval | $l_c$, m | $h_c$, m | $D_k$, m | $\delta_{cm}$ | $\beta_{z,^o}$ | $W_a$, % | $K_{ll}$ | $h_z$, m |
|---------------------|----------|----------|----------|----------|---------------|----------------|---------|----------|----------|
| Lower               | - 1      | 0,1      | 0,1      | 0,5      | 0,15          | 20             | 17      | 1,0      | 0,02     |
| Central             | 0        | 0,2      | 0,2      | 1,0      | 0,20          | 30             | 20      | 1,5      | 0,04     |
| Upper               | + 1      | 0,3      | 0,3      | 1,5      | 0,25          | 40             | 23      | 2,0      | 0,06     |
| Variation interval  | $\Delta X$ | 0,1    | 0,1     | 0,5      | 0,05          | 10             | 3       | 0,5      | 0,02     |

With increasing wheel diameter, regardless of the height of anti-skid devices, at a central level of factor variation $P_C$ rises along a curve with negative acceleration (Figure 4). For $D_k = 0.5$ m, in the interval $h_c$ from 0.1 to 0.2 m, the $P_C$ increases by 175%, at $D_k = 1.0$ m - by 91%, at $D_k = 1.5$ m - by 68%. With an increase in $h_c$ from 0.2 to 0.3 m, the $P_C$ rises, depending on the diameter of the wheel by 90, 86 and 46%, respectively.

![Figure 4](image)

**Figure 4.** Dependence of the traction force on the height of the hook and its length:

1 – $l_c = 0,1$ m; 2 – $l_c = 0,2$ m; 3 – $l_c = 0,3$ m

With the increase in the coefficient of wheel slippage, at the moment of interaction of the removable and tire hooks, regardless of the height of the anti-skid devices, at the central level of factor variation, $P_C$ rises along the curve with positive acceleration (Fig. 5). For $\delta_{cm} = 0.15$, in the interval $h_c$ from 0.1 to 0.2 m, the $P_C$ increases by 80%, at $\delta_{cm} = 0.20$ - by 95%, at $\delta_{cm} = 0.25$ - by 112%. With an increase in $h_c$ from 0.2 to 0.3 m, the $P_C$ rises, depending on the skidding ratio of 67; 59 and 50% respectively.

![Figure 5](image)
With an increase in the angle \( \beta_2 \), regardless of the height of the anti-skid devices, at the central level of factor variation, \( P_c \) decreases along the curve with negative acceleration (Fig. 4). For \( \beta_2 = 200 \), in the interval \( h_c \) from 0.1 to 0.2 m, \( P_c \) decreases by 34%, with \( \beta_2 = 300, 400 \) - by 54% and 71%, respectively. With an increase in \( h_c \) from 0.2 to 0.3 m, the \( P_c \) decreases, depending on the angle \( \beta_2 \) by 35; 34 and 33% respectively.

![Figure 5. Dependence of traction force on wheel diameter and hitch height](image)

With an increase in the amount of air in the soil, regardless of the height of the anti-skid devices, at a central level of factor variation, \( P_c \) decreases along the curve with negative acceleration (Figure 6). For \( K_\Pi = 1.0 \), in the interval \( h_c \) from 0.1 to 0.2 m, the \( P_c \) decreases by 19%, at \( K_\Pi = 1.5 \), by 25%, at \( K_\Pi = 2.0 \), by 29%. With an increase in \( h_c \) from 0.2 to 0.3 m, the \( P_c \) decreases, depending on the amount of air in the soil at 28; 30 and 33% respectively.

![Figure 6. Dependence of the traction force on the wheel slip and hitch height](image)

Graphically, analysis of the model (3) shows that in practice it is difficult to apply it because of the need to determine the angles of the hooks in the period of their interaction with the soil [13]. The
height of interaction of the hooks with the soil, depending on the angle of rotation of the wheel, changes, so in order to eliminate these drawbacks, we will determine the reduced height of the anti-skid devices $h_p$, m:

$$h_p = \frac{\sum_{i=1}^{in} (R_k + h_c) \cdot (\cos (0.0175 \cdot \alpha )) - R_k}{\arccos (R_k / (R_k + h_c))},$$

$$0 < \alpha < \arccos (R_k / (R_k + h_c));$$

The reduced altitude of anti-skid devices can also be determined by the ratio of the area of the segment formed as a result of the interaction of the hook to the area of the rectangle (Fig. 7). Then, the area of ANBK $S_{cseg}$ segment is defined:

$$S_{cseg} = \frac{\pi R_k^2 \cdot \arccos ((R_k - h_z) / (R_k + h_c))}{180} - (R_k - h_z) \cdot \arccos (R_k / (R_k + h_c));$$

Next we have: $S_{cseg} = (\pi R_k^2 \cdot \arccos ((R_k - h_z) / (R_k + h_c)) / 180) - (R_k - h_z) \cdot \arccos (R_k / (R_k + h_c));$

$$\sqrt{(R_k + h_c)^2 - (R_k - h_z)^2};$$

**Figure 7.** Influence of the angle $\beta_2$ on the thrust force on the height of the hooks:

1 – $h_c = 0.1$ m; 2 – $h_c = 0.2$ m; 3 – $h_c = 0.3$ m

The area of the rectangle ABCD will be determined as:

$$S_{spr} = 2a \cdot h_c = 2a \cdot \sqrt{(R_k + h_c)^2 - (R_k - h_z)^2};$$

Then $h_p = \frac{S_{cseg} \cdot h_c}{S_{spr}}.$

Analysis of the obtained model, in the range of variable factors, shows that with increasing height of anti-skid devices, regardless of the diameter of the wheel, at the central level of factor variation, $h_p$ increases linearly (Fig. 8). In the interval $h_c$ from 0.1 to 0.2 m, $h_p$ increases by 102%, and with increasing $h_c$ from 0.2 to 0.3 m, $h_p$ increases by 51%.
Figure 8. Change in traction force from soil moisture and height of anti-skin devices:
\[1 - h_c = 0.1 \text{ m}; 2 - h_c = 0.2 \text{ m}; 3 - h_c = 0.3 \text{ m}\]

With the increase in the diameter of the wheel, regardless of the depth of the track, at a central level of factor variation, the reduced altitude is reduced along a curve with negative acceleration. For \( h_k = 0.05 \text{ m}, 0.10 \text{ m}, 0.15 \text{ m} \) in \( D_k \) interval from 0.5 to 1.0 m, \( h_p \) decreases by 3.4%, 3.7%, 5.3%, respectively. With an increase in \( D_k \) from 1.0 to 1.5 m, \( h_p \) decreases, depending on the depth of the track, by 1.4, 2.6 and 2.9%, respectively.

In general, in analyzing these formulas, it should be noted that the values of the reduced height of the hooks [14] according to model (4), depending on \( \alpha_{\text{max}} \), are obtained 2-4% lower than in the model (5).

Thus, applying the parameter of the reduced height of the anti-skin devices, the tangential force of the thrust of the \( P_C \), realized by a detachable hook, is determined:

\[ P_C = l_c \cdot h_p \cdot K_f \cdot \delta_{\text{cut}} \cdot S_{T_1}, \]

where \( S_{T_1} \) – The theoretical path of wheel movement, respectively, in the joint interaction of tire and anti-skin devices with soil, m:

\[ S_{T_1} = 0.035 \cdot R_k \cdot \arccos(R_k / (R_k + h_c)). \]

Analysis of the model for calculating the tangential force of traction, which appears from anti-skin devices (6), shows the identical influence of the studied factors on the response of the function; however, with respect to the model (3), the values for traction forces are obtained lower by 4-5% due to the average value of the hook height.

3. Conclusion

When the anti-skin devices interact with the soil, the traction capacity of the wheel is composed of the forces of shear and shear of soil "bricks" sandwiched between the tire hooks and the deformation forces of the soil by removable hooks.

With the increase in the coefficient of wheel slippage, at the moment of interaction of the removable and tire hooks, regardless of the height of the anti-skin devices, at the central level of factor variation, \( P_C \) rises along the curve with positive acceleration (Fig. 5). For \( \delta_{\text{cut}} = 0.15 \), in the interval \( h_c \) from 0.1 to 0.2 m, the \( P_C \) increases by 80%, at \( \delta_{\text{cut}} = 0.20 \) - by 95%, at \( \delta_{\text{cut}} = 0.25 \) - by 112%. With an
increase in $h_c$ from 0.2 to 0.3 m, the $P_C$ rises, depending on the skidding ratio of 67; 59 and 50% respectively.

With a decrease in skidding, the drag force increases. Consequently, the process is extreme. To find the conditional extremum, the optimization of the process was carried out by jointly solving the regression equations to determine the slipping and the resistance to movement from the device. For this purpose, the problem of process optimization was considered and solved taking into account the quantitative and qualitative parameters.

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