Analytical determination of speed coefficient in the formula of V.P. Goryachkin for plow resistance

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Abstract. For almost all tillage implements traction resistance is calculated by the rational formula of academician V. P. Goryachkin with possible refinements of incoming parameters in accordance with the design of working bodies or operating conditions. The rational formula includes three coefficients associated with the unstable properties of the soil and the variable form of the working bodies. For this reason, the coefficients may not be the same for all tool designs and soil types. Each coefficient contributes an element of uncertainty to its component of the formula. The third component of the formula with a speed coefficient determines the part of the tractive effort to push back and turn the soil layers. The article calculates the power required for both of these actions of the working body. This power is determined by the lateral force acting on the soil layer. Lateral force analytically is associated with the tractive effort of the tractor taking into account the angle of setting of the moldboard and the coefficient of friction of the soil. This data is sufficient to compile a method for analytically calculating the speed coefficient. It turned out that it does not depend on the speed of the plough or the depth of plowing. It is influenced only by the density of the soil, the angular dimensions of the moldboard and the angle of friction on the soil. The calculated dependency graphs are given. At the usual values of the friction angle of 28-30° and the angle of inclination of the moldboard 43°, the speed coefficient is 2400 kg / m³. If we apply vibration, the friction angle is reduced to 25-26°, and the speed coefficient becomes equal to 2000 kg/m³. High-speed moldboards, having their design features, have a speed coefficient of 1700-1800 kg / m³.

1. Introduction
Plowing requires a lot of energy. The study of the traction resistance of plows is carried out by modeling or field experiments. It is established that the minimum power consumption can be achieved by combining the working depth of 150 mm, speed of 1 m / s, low angle of rise (25 degrees) and cutting angle (from 30 degrees to 45 degrees). The results showed that the thrust force increases with a second-order polynomial function with depth, whereas the vertical and lateral forces have a linear relationship with depth. Moreover, these forces increased linearly with the speed of the unit [1, 2, 3]. In the simulation, the average pulling force was 1.4 and 2.7 times higher than the average vertical and lateral forces, respectively [4]. The lateral force, as well as the eccentric connection of the plow with...
the tractor, increases the traction resistance force. The efficiency of tractor power consumption on untreated stubble decreased by 5.72% if the eccentricity of the application of traction force increased to 0.16 m and by 12.33% if the eccentricity increased to 0.32 m [5, 6]. Academician V.P. Goryachkin believed that the lateral and vertical forces acting on the plough, ultimately act on the main force. The main force he thought the traction resistance of the plough. He proposed a rational formula for the calculation of traction resistance, which takes into account the forces of gravity, the resistance of the soil to crumple and the lateral force of the turnover of layers.

2. Calculation method and materials
The rational formula of academician V. P. Goryachkin for plough resistance [7] is a fundamental methodological basis for calculating the traction resistance of tillage implements. It is known that at deep plowing of the tractor work in the mode of heavy loading, and there the exact calculation of limit width of capture of a plow for each model of the arable tractor is required. The rational formula (1) consists of three components, and each of them has its own coefficient associated with the unstable properties of the soil and the variable shape of the working bodies. Therefore, the formula can not have these coefficients constant for all cases of plowing. Each specific calculation requires a reasonable choice of numerical values of the initial data.

\[ P = fG + kabn + \varepsilon abnv^2, \]  

where \( P \) is the drag force of the plough, N;  
\( f \) – coefficient of rolling of wheels;  
\( G \) – the force of gravity of the plough, N;  
\( k \) – the resistivity of the soil wrinkling, Pa;  
\( a \) – depth of ploughing, m;  
\( b \) – width of the working tool, m;  
\( n \) – number of working tools;  
\( \varepsilon \) – speed coefficient, kg / m³;  
\( v \) – speed of the unit, m/s.

The unknown coefficients \( f \) and \( k \) depend on the state of the soil and can only be determined experimentally for each field. But as for the coefficient \( \varepsilon \), it can be calculated analytically. According to the definition of academician V. P. Goryachkin, the third member of his formula is spent on the coup and pushing the soil layer aside [7]. Its share in the total resistance of the plough is expressed by the third member of the rational formula and can reach up to 30% of the total resistance of the plough. The numerical value of the third member of the formula can be calculated by the expression

\[ P_3 = \varepsilon abnv, \]  

where \( P_3 \) – part of the traction force of the tractor, spent on the rotation and removal of soil layers, N. We will determine the necessary power for the turnover and removal of the soil layer on one working body of the plough. To do this, we draw a vertical and horizontal projection of the working body. On the horizontal projection, we draw the average generatrix AB at an angle \( \gamma \) to the direction of movement of the unit (figure 1). At right angle to it acts on the soil layer normal force \( Q \), which is always accompanied by a force \( F \) friction moldboard on the soil, and

\[ F = Q \cdot \tan \varphi, \]

where \( \varphi \) is the friction angle.
Figure 1. Diagram of the forces acting on the soil layer from the moldboard side

As a result, the formation is affected by the total force $C$, which can be decomposed into a longitudinal force $D$ and transverse $E$. Between them there is a ratio

$$D = E \cdot \tan(\gamma + \phi),$$

where $\gamma$ is the angle of inclination of the generatrix in the middle of the moldboard height.

The reaction from the transverse force $E$ is perceived by the field board, which adds its friction force against the furrow wall to the longitudinal force $D$ and thus completely complementing the third member of the rational formula:

$$P_3 = D + E \cdot \tan \phi = E \left[ \tan(\gamma + \phi) + \tan \phi \right].$$ (3)

The force $E$ moves the soil layer to the side and turn it around the longitudinal axis and it can be calculated through the power costs of both these actions. The power to move is determined through the force pulse:

$$N_1 = \frac{mv_1^2}{\Delta t},$$ (4)

where $N_1$ is the power to move layer, W;

$m$ – weight of the layer, kg;

$v_1$ – the speed of the moving layer in the direction lateral, m/s;

$\Delta t$ – time of the moving layer on the moldboard, s.

$$m = \rho abL, \quad v_1 = \frac{vs}{L} = \delta v, \quad \Delta t = \frac{L}{v},$$

where $\rho$ is the soil density in the initial state of the layer, $\rho = 1300-1500 \text{ kg/m}^3$;

$a, b, L$ – the size of the layer: the thickness, width and length, respectively, m;

$s$ – distance of the movement of the layer, m;

$\delta$ – the ratio of the distance of the movement of the layer to the length of the moldboard:

$$\delta = \frac{s}{L}. $$

Power for the turnover of the layer can be calculated according to the formula

$$N_2 = \frac{I(\omega)^2}{(\Delta t)^3},$$ (5)

where $N_2$ is the power for the rotation of the layer, W;
\[ I - \text{the moment of inertia of the layer, kg}\cdot m^2; \]
\[ \omega t - \text{the angle of rotation of the layer, rad.} \]
\[ I = \frac{1}{12} m(a^2 + b^2). \]

To determine the length of the formation, the distance of its movement and the angle of the turn should be measured on a vertical projection (figure 2) distance \( s \) between the centers of gravity of the layer in the original and inverted positions and the angle of rotation \( \omega t \).

\[ \text{Figure 2. Scheme of soil layer turnover by plough} \]

On the horizontal projection, the approximate length \( L \) of the layer be measured as the distance between the tip of the ploughshare and the rear point of the moldboard.

Adding the expressions (4) and (5), we obtain the total power to move and turnover \( N = N_1 + N_2 \).

The estimated force for move and turnover of a layer is equal to
\[ E = \frac{N}{v_1}, \quad (6) \]
where \( E \) is the total force to move and turnover the layer, \( N \);
\( N \) – total power, W;
\( v_1 \) – the speed of the moving layer in the direction lateral, m/s.

From expressions (3) and (6) can be obtained
\[ P_3 = D + E \cdot tg \varphi = \frac{N}{v_1} [tg(\gamma + \varphi) + tg \varphi]. \]

Given equality (2), we have
\[ \varepsilon = \frac{N [tg(\gamma + \varphi) + tg \varphi]}{v_1 abv^2}. \quad (7) \]

By algebraic transformations equality (7) can be given the form
\[ \varepsilon = \rho \left[ \delta + \frac{(a^2 + b^2) \cdot (\omega^2)}{12 \delta L^2} \right] [tg(\gamma + \varphi) + tg \varphi]. \quad (8) \]

3. Results and discussion

The equation (8) shows that the speed coefficient depends only on the angular dimensions of the moldboard, the density of the soil and the angle of friction. As for the linear dimensions of the soil layer, they practically do not affect the velocity coefficient, since in our equation they mutually compensate each other. The speed of the unit also does not affect the speed coefficient. Three sizes of the formation \( a, b, L \), as well as the range of its lateral movement \( s \), associated with the parameter \( \delta \), have their geometric relationships. Taking into account these relations, a graph of the dependence of the speed coefficient \( \varepsilon \) on the friction angle \( \varphi \) (figure 3) is constructed.
Figure 3. Effect of soil friction angle on steel on the speed coefficient $\varepsilon$

The graph obtained for the following parameters: plowing depth $a=0.25$ m, width of layer $b=0.45$ m, length of layer $L=3.2\cdot b=1.44$ m, the range of lateral movement of the soil layers $s=0.60$ m, soil density $\rho=1180$ kg/m$^3$, the angle of inclination of the generatrix $\gamma=43^\circ$, the ratio range of lateral movement of the soil to the length of the layer $\delta=0.41$. During plowing typically the ploughshare and the moldboard is polished to a Shine. According to our research, in such conditions, the friction angle $\phi=28-30^\circ$. If the vibration of the working body is used, the friction angle is reduced to $\phi=25-26^\circ$. Therefore, in the calculation of the traction resistance of the plough can be taken $\varepsilon=2400$ kg/m$^3$, if vibration is not used, and $\varepsilon=2000$ kg/m$^3$ using vibration. The angle $\gamma$ of inclination of the generatrix has a similar effect on the speed coefficient (figure 4). The graph is constructed for the same initial data at an angle of friction $\phi=28^\circ$. The analogy with the previous graph is obvious, and it confirms the conclusion of V. P. Goryachkin's that the action of the friction angle during the wedge operation is similar to the increment of the wedge angle [7]. An increase in the angle of the wedge in the horizontal or vertical planes leads to an increase in its resistance [8].

Figure 4. Dependence of the $\varepsilon$ coefficient from the average angle of inclination of the generatrix
In modern ploughs, the angle $\gamma$ of inclination of the generatrix in the middle part of the moldboard is usually 44-45°. The exception is high-speed moldboard, in which the angle of inclination of the generatrix is reduced to 38-39°. In addition, the length $L$ of the moldboard is reduced, and this reduced the mass $m$ of the wrapped soil layer. The obtained analytical expression (8) allows calculating the high-speed coefficient $\varepsilon$ for these ploughs. It turns out to be equal to 1700-1800 kg $/ m^3$. The analysis of forces acting on the plough body in the horizontal plane shows that all lateral forces cause friction force increasing traction resistance. Moreover, friction forces occur not only on the working surface of the ploughshare and moldboard, but also on the field board. To eliminate the friction force of the field on boards, we developed a symmetrical plough [9]. There are no field boards on this plough at all. As for the additional working bodies on the plough, they can reduce the lateral forces on the entire unit [10], and in each case an individual calculation is required.

4. Conclusion
As a result of the analysis of the lateral forces acting on the working body of the plough in the horizontal plane, and their connection with the traction resistance, a calculated equation for determining the speed coefficient in the formula of academician V. P. Goryachkin is obtained. It turned out that the speed coefficient depends only on the angular dimensions of the moldboard, soil density and friction angle. The linear dimensions of the soil layer and the speed of movement of the unit do not affect this coefficient. The angle of inclination of the moldboard generatrix and the angle of friction of the moldboard on the soil layer increase the speed coefficient of the analytical curve of the second order. When the angle of friction of 28-30° and the angle of inclination of the generatrix is 43° speed coefficient takes a value of 2400 kg$m^{-3}$. With the use of vibration of the working body, the friction angle is reduced to 25-26°, and the speed coefficient is up to 2000 kg$m^{-3}$. High-speed moldboard with reduced inclination angles of the generatrix, their length and the angle of active influence on the turnover of the soil layers have a reduced speed coefficient, which is 1700-1800 kg$m^{-3}$.

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