Analytical determination of the rational angle of lifting: the soil cooking organ

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Abstract. The aim of the study is to search for the analytical dependence of the force of resistance of the wedge on the lifting angle in the case of working with wet soil, which does not crumble into fragments, but slides along the wedge in the form of a continuous tape. Tillage tools can have front and rear sharpening angles. The front angle raises the soil layer, and this action is most common in tillage. The rear corner seals the bottom of the furrow, so it is undesirable in plows. To determine the rational angle of inclination of the entire working surface under working conditions with wet soil, an analytical equation has been obtained, which is applicable if the technological indicators of the soil are observed in a particular field, especially indicators of soil sticking to the working surfaces. In this equation, the traction resistance of the wedge depends on the density of the soil, friction coefficient, tensile strength and shear strength. In the calculations, the deformation of the soil layer was taken inherent in the wetted state with the presence of plant residues, that is, the soil retains the shape of a continuous ribbon in its movement along the working surface of the wedge. According to the results of field studies of the experimental and basic plows, it was determined that on loamy soil with a moisture content of 16 to 22%, an rational angle of elevation of the tillage tool can be taken as an angle of 18 °. An experimental plow with a plowshare angle of 18 ° compared to a basic plow with a lifting angle of 30 ° showed an increase in productivity by 19% and a reduction in specific fuel consumption by 17% due to a decrease in traction resistance and, as a result, by reducing the likelihood of sticking of the soil and rare stops for cleaning the working bodies.

1. Introduction

Soil-cultivating working bodies are established with various tilt angles in a vertical plane. These include chisels, tillers, plowshares, and other tools. They are intended for loosening the soil or for lifting layers and their turnover. The tilt angles of the tool affect the resistance of the soil, so the choice of blade sharpening angles and tilt angles of the entire working surface must be justified in terms of energy savings. The angles of sharpening are divided into front and rear, and the angles of inclination of the entire working surface are only front. The working body, which has both acute angles, has less resistance [1]. The front angle affects the main action of the working body. For most tools, it occurs in the vertical plane [2-4], so this angle is often called the angle of elevation. These authors argue that the drag of the working body increases if the front angle increases. In their opinion, there is a linear relationship between the lifting angle and the drag resistance, and this angle should not exceed 25 °. But there is an opinion that this angle should not remain constant, but increase as the soil moves along the working
body up to 40 ° [5, 6], and its effect on the resistance force is more intense than the linear dependence. Sometimes lateral movements of the soil are used, and then the front angle is measured in the horizontal plane. It is called the shear angle or angle of attack [7]. Such names of the corners were proposed by academician V.P. Goryachkin as applied to the working bodies of the plows [8]. He proposed a research method based on a simplified representation of the working body in the form of a wedge, which raises or shifts the soil layer. The soil layer behaves differently depending on humidity and the presence of residues of plant roots. It can either break up into separate fragments, or move around the working body with continuous tape. The aim of our study is to find the analytical dependence of the resistance force of the wedge on the lifting angle in the case of working with wet soil, which does not crumble into fragments, but slides along the wedge in the form of continuous tape.

2. Calculation method and materials

When sharpening the blade, the front face BC is formed (Figure 1) and the rear face AC, which are inclined to the direction of movement at angles $\alpha_1$ and $\alpha_2$. While the tool is running, the front face BC raises the soil layer, and the back face of the AC compacts the soil.

![Figure 1. Forces acting on the front and rear faces of the tillage tool.](image_url)

During tool operation, the front face lifts the soil layer and the back face seals the soil. The front angle $\alpha_1$ is sharp, but if it is increased more than 90 °, then it will act as the rear angle $\alpha_2$, compacting the soil at the bottom of the furrow. Normal force $N_1$ overcomes the resistance of the soil in tension and shear. When this occurs, the friction force $F_1$. The rear edge of the AC compresses the soil with a normal $N_2$ force, and friction force $F_2$ arises on this face. But the ultimate strength of the soil for these types of deformation is different. Loamy soil has a tensile strength of 5-6 kPa, a shift of 10-12, and 65-108 kPa for compression. One can imagine how much the forces of $N_2$ and $F_2$ are greater than the forces of $N_1$ and $F_1$. When studying the angles of setting the tool, it was noticed [9] that with an increase in the tool front angle of more than 90 °, the drag resistance becomes larger than at acute angles. Shields are also installed with an acute angle of attack to expand the furrow, which is necessary for a complete rotation of the soil layer [10]. From these considerations, the negative effect of the rear angle or the front angle greater than 90 ° on the energy consumption during tillage becomes apparent. Staging a tool with such angles can be justified only by the requirement of a tillage technology when compaction of the bottom of the furrow is required. As for the plows, their disadvantage is that they compact the bottom of the furrow when they are used annually in the same field. This compaction impedes the development of the root system. Therefore, for the plows, the presence of the back angle of the plowshare is undesirable.

The rational angle of elevation of the working surface of the wedge was determined by geometrical analysis of the strength of resistance of the soil, taking into account its technological properties such as
density, coefficient of friction, tensile strength and shear strength. In the calculations, the deformation of the soil layer was taken inherent in the wetted state with the presence of plant residues, that is, the soil retains the shape of a continuous ribbon in its movement along the working surface of the wedge. The reliability of the calculation results was estimated by the level of performance indicators of plows with different lifting angles of plowshares.

When a wedge is working, its working surface BC (Figure 2) raises the soil layer. Ahead of the wedge, the soil layer periodically forms advanced cracks, which close as the soil slides along the wedge. The soil resists bending, tearing, lifting and friction on the working surface.

![Figure 2. Forces acting on the wedge when lifting a continuous layer of soil.](image)

The active forces of the soil on the wedge are the force \( G \) of the soil gravity, the force \( N \) of normal pressure and the force of friction \( F \). These forces are balanced by the active force \( P \), which sets the wedge in motion. Acting forces depend on the angle of lift \( \alpha \), and it is required to determine this dependence to substantiate the rational angle of lift at which the force \( P \) applied by the pulling means will be minimal.

The height \( h \) of the lift must remain constant, equal to the depth of the tillage. As the wedge moves forward on the wheels, it is not affected by the force from the bottom of the furrow, that is, on the bottom surface AC. The calculation takes into account the entire length of the formation, which lies on the surface BC, and the forces \( N \) and \( G \) are applied to the middle of the formation.

\[
P = fN \cos \alpha + N \sin \alpha = \left( G + J \right) \cos \alpha + \frac{M \sin \alpha}{2h} (f \cos \alpha + \sin \alpha),
\]

where \( P \) is the thrust force required to move the wedge and is equal to its traction resistance, \( N \); \( f \) - the coefficient of external friction of the soil along the wedge; \( N \) - the force of normal pressure, N; \( G \) - the force of gravity of the layer lying on the wedge, N; \( J \) - the inertia force of the immobility of the soil layer, N; \( \alpha \) - the lifting angle; \( M \) - moment of resistance to bending of the soil layer, Nm; \( h \) - height of soil lifting, m.

The numerical values of the acting forces and their interrelations can be obtained from their dependencies on the parameters of the soil layer:

\[
G = m \cdot g = \frac{h \cdot a \cdot b \cdot \rho \cdot g}{\sin \alpha}; \quad J = mgv_1^2; \quad M = \sigma bh^2 / 6,
\]

where \( m \) is the mass of the soil layer lying on the working surface of the wedge, kg; \( g \) - gravitational acceleration, m/s\(^2\); \( a \) - the depth of tillage, m; \( b \) - formation width, m; \( \rho \) - the density of the soil, \( \rho = 1200 \text{ kg/m}^3 \) is assumed; \( g_1 \) - acceleration of the soil layer during lifting, m/s\(^2\); \( \sigma \) - the ultimate tensile strength of the cohesive soil, \( \sigma = 12 \text{ kPa} \) is assumed.

To determine the acceleration \( g_1 \), the assumption was made that the lift rate \( v \) is proportional to the plow motion speed \( v_1 \) and the aspect ratio of the wedge:

\[v = hv_1 l^1,\]

where \( v \) is the lifting rate, m/s; \( v_1 \) - plow speed, m/s; \( l \) - the length of the soil layer, m.

The rise time corresponds to the residence time of the soil layer on the wedge:

\[t = lv_1 l^1,\]
then \( g_1 = h v_1^2 t^2 \).

3. Results

During field tests of our plows, it was observed that when the soil moisture is greater than 18%, soil sticking to the working bodies begins. The likelihood of soil sticking increases with increasing humidity to a certain limit, as well as increasing the angle of inclination of the working surface of the tool. Adhesion of the soil significantly worsens the working conditions. Instead of the angle of friction of the soil on steel \((28-30^\circ)\), the angle of friction of the soil on the soil \((50-65^\circ)\) acts, the configuration of the working surface is sharply disturbed. With full sticking of the wedge at lifting angles of 25-30° instead of lifting the soil layer, the soil begins to collapse with a specific resistance of about 35 kPa. If we make all these corrections into equation (1), then we get one of the possible variants of the graphical dependence of the resistance force of the wedge on its lifting angle when working with wet soil (Figure 3). The tendency of the curve shows that with an increase in the angle of elevation to 17–18°, the resistance force decreases as the length of the wedge decreases and the amount of soil sliding along its surface decreases. But with the increasing likelihood of sticking of the working surface, the sliding of the soil becomes difficult and gradually turns into crushing of the entire soil layer. With regard to plowshares, a rational angle of inclination can be considered 18-20°.

![Figure 3. Influence of the wedge lifting angle on traction resistance in wet soil.](image)

A comparative assessment of the work of two plows was carried out on the black-earth soil of loamy composition with humidity at the depth of the arable layer from 16 to 22%. The experimental tool was a mounted four-body PPN-4-45 plow with a working width of 1.8 m and a plowing depth of 0.26 m. Its distinguishing feature was the lifting angle of plowshares, which was 18°. In addition, vertical knives were placed on the working bodies, and the stands of the working bodies had the opportunity to vibrate in the lateral direction from the variable resistance of the soil. The basic tool was another similar four-body plow, but with a ploughshare angle of 30°. This plow did not have a vertical knife, and its working bodies did not vibrate (figure 4).

![Figure 4. Plow working bodies tested in field conditions: 1 – serial plow body; 2 – experimental working body.](image)
Both plows worked with 110 kW T-150K tractors with the same plowing depth. Time observation of the operation of both units in the field showed the advantage of the experimental plow, which was manifested in the performance of the unit and specific fuel consumption (table 1).

Table 1. Performance indicators of two arable units.

| Values of indicators                     | Base plow | Experimental plow |
|------------------------------------------|-----------|-------------------|
| Plowed area, ha                         | 8.8       | 11.6              |
| Plow width, m                           | 1.8       | 1.8               |
| Average plowing depth, cm               | 26        | 26                |
| Average working speed, km / h           | 9.1       | 10.8              |
| Productivity per hour of net time, ha / h| 1.63      | 1.94              |
| Stops for cleaning the working bodies, min. | 64        | 12                |
| Specific fuel consumption, kg / ha       | 22.04     | 18.1              |

4. Conclusion

Analytical determination of the rational angle of elevation of the soil-cultivating body shows a reliable result only if the technological indicators of the soil are observed in a particular field, especially indicators of sticking of working surfaces. On loamy soil with a moisture content of 16 to 22%, an angle of 18 ° can be adopted by the rational lifting angle of a tillage tool. An experimental plow with a plowshare angle of 18 ° compared to a basic plow with a lifting angle of 30 ° showed an increase in productivity by 19% and a reduction in specific fuel consumption by 17% due to a decrease in traction resistance and, as a result, by reducing the likelihood of sticking of the soil and rare stops for cleaning the working bodies.

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