Abstract: The purpose is to reduce the energy costs of soil tillage by developing more accurate methods for assessing the effectiveness of surface-plane and space-deep interaction of the needle with the soil. It is noted that the result of the interaction of the round needle of rotary harrow with the soil, there is a hole of regular shape with an ellipse at the base. The change in the semi-axis of the ellipse formed at the soil-air interface is analyzed. The developed method improves the accuracy of forecasting and evaluating the effectiveness of the rotary harrow needle interaction with the ground. The method creates the prerequisites for improving the quality and energy indicators of the technological processes of soil treatment with rotary harrows

KEYWORDS: NEEDLE OF A ROTARY HARROW, INTERACTION OF NEEDLE WITH SOIL, COEFFICIENT OF SURFACE-PLANE INTERACTION, SPATIAL-DEEP INTERACTION

1. Introduction

The natural and climatic conditions of the present are characterized by the formation of a dense soil crust on soils subject to wind erosion. This soil crust makes it difficult to germinate, damages the root system of plants, increases evaporation of moisture. For early-spring, pre-sowing and post-harvest small surface loosening of the stubble background, especially dense soil crust, effective tools with needle-like working bodies.

The reduction of terms and a significant improvement in the quality of execution of soil tillage technological processes are an important reserve for improving the efficiency of land resources and increasing the yield of agricultural crops [1]. Known implements with needle working units are intended for early-spring, pre-planting and shallow surface tillage of stubble in areas with soils that are prone to wind erosion. They have a low productivity, and an increase in the speed of their movement leads to a sharp decline in quality [2]. Rotary harrow tillage enhances soil organic C, total N and microbial C, N, and P stocks in comparison to moldboard plough management [3]. Soil processing is done without bringing moisture. For early-spring, pre-sowing and post-harvest small surface loosening of the stubble background, especially dense soil crust, effective tools with needle-like working bodies.

The analysis of the condition of soil treatment with needle harrows showed that there are grounds to conclude that the selected directions are legitimate, the relevance and feasibility of carrying out research and the perspective of the formulated goals and objectives of research, which are aimed at improving the qualitative and energy performance of soil tillage technological processes in needle harrows with variable angle of needle sharpening under conditions of their application for shallow surface fractures in the climatic zones that are prone to wind erosion.

The work [8] deals with the motion of a disk whose axis is connected to the axes of other disks and the direction of motion is directed horizontally. The authors analyzed both the insignificant depth of immersion of needles in the soil, and the case from the deepening into the soil of two needles simultaneously (Fig. 1).

![Fig. 1. A scheme for analyzing the motion of a disk of a needle harrow, whose axis is connected to the axes of other disks and the depth of needle immersion, is significant](image-url)

It is noted that the smaller \( h_K \), the smaller the angle \( \beta \). As \( h_K \) is reduced to 0, the angle \( \beta \) becomes also equal to zero, and the velocity \( v_K \) will be directed vertically downward, that is the puncturing of the soil will be carried out vertically. Under such puncturing conditions, the friction force of the needle with the soil will be less than for the angle \( \beta \) greater than zero.

Increasing the depth of processing does not lead to a change in the nature of the needle disk movement on the soil. However, the load on needles increases, which destroy a much larger number of soil particles than in cases of not significant depth of processing.

The velocity vector \( v_K \) of the point \( K \) (Figure 1) of the needle is directed at an angle \( \beta \) to the vertical. This angle \( \beta \) affects the conditions for puncturing the soil and is defined as:

\[
\beta = \arcsin \frac{h_k}{2 \cdot r_0 \cdot \sin \alpha},
\]

where: \( h_k \) – height of the point \( K \) above the line \( C_aC_aC_a \) (m); \( r_0 \) – radius of the harrow disk with the needles (m); \( \alpha \) – angle between the needles \( CK \) and \( CC_a \).

The result of the harrow depends on the degree of synchronization of the needles of different disks on the soil. So, if the lower needles of the discs simultaneously sink into the soil, there will be a simultaneous piercing of the soil surface with these needles, and the pressure is equal to the soil resistance to deepening
the needles. If the needles of different disks do not fall down into the soil at the same time, the needles of different disks will alternately sink into the soil, while the piercing pressure will also be equal to the soil resistance, but the puncturing of the soil will be random and depend on the position of the needle disks relative to each other before piercing.

It should be noted that in the case of using a harrow with synchronous operation of the disks in the section and small values of gravity force of the disks with needles, turning the disks by 30° will result in several simultaneous punctures of the soil, and the rest of the time there will be no puncture of the soil. With such harrow work and rigid connection between the disk axes, the force acting on the needles during their immersion into the soil is equal to the gravity of the harrow section. And a force acting on each disk (and thus on the needle which plunges into the soil) is equal to the section gravity force divided by the number of disks in it.

The angle of rotation of the disk for piercing the needle and leaving the needle is called the piercing angle. In existing harrows, this angle is theoretically equal to 30° of which half is used to dip the needle into the soil, and the other half is used to exit it. In general, this angle can be 36° or 45°. However, at a piercing angle of soil 30°, the piercing frequency is higher than in other cases (angles of 36° or 45°). That is, the piercing angle 30° is the most rational.

In studies [6] the interaction of the needle harrow with the soil in the case when the needle pierces it and carries out the motion strictly vertically is considered in detail. This is a somewhat simplified view of the movement of the points of the needle as a result of its interaction with the soil. However, under certain conditions and at the phase of needle entry into the soil and at the phase of its exit, there may be processes that will differ from those taken. That is why research of the processes of interaction between the needles of a needle harrow and the soil under conditions when the phases of entry and exit from the soil are considered in a plane that differs from the general accepted idea (vertical movement of the needle at all phases of its movement in the soil) is quite important and urgent task.

According to the results of research [9], it was established that the main factors that influence the determination of the required force for deepening the needles of the needle harrow in the soil are: the depth of the needle immersion, the angle of friction of the needle along the ground, and the angle characterizing the taper of the needle. In addition, the force needed to deepen the needle into the soil depends on the hardness of the soil, that is, on its mechanical composition and moisture content. However, the existing technologies of mechanical tillage do not provide for the use of needles for high moisture soil values.

It is established that the work W is the larger, the more the number of disks, the number of needles on the disk, the pressure of the needles on the soil and the penetration depth of the needle into the soil [8].

2. Purpose of the study

The aim of the study is to reduce the energy costs of soil tillage by developing more accurate methods for assessing the effectiveness of surface-plane and space-deep interaction of the needle with the soil.

Based on the analysis carried out and in accordance with the purpose of this work, the following research tasks are formulated:

- determine the features of the interaction of the needle with the ground in phases, both the indentations and its exit from the soil;
- analyze the surface-plane and space-deep interaction of the needle with the soil, and develop a mechanism for evaluating such interaction.

3. Material and methods

The object of study is the technological processes of treatment, the soil and the working bodies of the rotary harrow, methods for evaluating the effectiveness of the interaction of the needle with the ground. The subject of the research is the interaction of the working bodies of the rotary harrow with the soil, the effect of its parameters on the indicators of the efficiency of the technological process of tillage.

Theoretical research are based on the basic principles of theoretical mechanics, the theory of mechanisms and machines, differential calculus and mathematical modeling of needle movement of any shape and design at various phases of its interaction with the soil (entry and exit from it)

The analysis of the operation of a needle harrow is carried out under such assumptions:

- the harrow with discs and needles is considered as a body moving along the traction unit (tractor) to the left horizontally, with the disk axes perpendicular to the plane of motion, and the disks with needles rotate counter-clockwise around their axes;
- the lower right needle that emerges from the soil does not affect it, and the force of attraction is transferred, mainly, to the needle that contacts the soil.

4. Results and Discussion

Consider the interaction with the ground points of the lateral surface of the needle, subject to moving its lower point along the vertical axis of symmetry formed by the needle hole.

The disk with needles of the needle harrow moves uniformly and rectilinearly with speed \( V_d \). In Fig. 1 shows the scheme for piercing the soil with a needle. The moment of the beginning of the interaction corresponds to the instantaneous position OA. When the center of the disk \( B \) is moved to the position \( O_2 \), the needle is immersed to a depth \( y_i \). This corresponds to \( OA_1 \) (Fig. 2). If the center of the disk occupies the position \( O_2 \), the needle will be deepened to the maximum depth \( y_{max} \) (\( O_2A_2 \)). The vertical position of the needle ends the phase of its entry into the soil and it begins to move in the opposite direction. We note that the stage of penetration of the needle into the soil is characterized by a gradual increase in the resistance to movement of the needle. In position \( A_1 \), at depth \( y_{max} \), these forces reach a maximum value. The exit of the needle from the soil (movement on the section \( A_2 \)) rightly does not take into account the influence of the resistance forces to the movement of the needle. Note that the section \( OO_2 \) - the distance that the needle passed in time \( t \) is equal to the distance \( AA_2 = y_{max} = O_2O \).

Fig. 2. Trajectory needle OA given its interaction with the soil

The peculiarities of the interaction of the needle with the soil on the phases, both the indentations and its emergence from the soil, include the presence of flattening (dents), which are formed on the soil surface in the direction opposite to the needle movement. In the case of the movement of the needle during the phase of entry into the soil, the observed flattening occurs from the side of the acute angle of contact with the soil. In the conditions of the needle exit from the soil, the flattening will appear on the other side of the funnel formed by the needle. In conditions of penetration of the needle into the soil in the form of a rod, a funnel (hole) formed by the results of such interaction can be represented as a cylinder. In case of penetration into the soil of a cone-shaped needle, the figure formed as a result of such interaction with the soil will represent a cone with a circle at the base. With increasing depth of penetration of such a needle, the area of the base of the cone will grow. According to the results of observations under conditions of real operation, the interaction of the needle of any shape and design with
The penetration of the needle into the soil takes place in such a way that characterizes the point of contact between the needle and the soil. This point, from the triangle $\Delta_A$, the depth of its immersion in the soil. In the vertical position of the needle, its end (the extreme point of the needle) will be determined by the radius of the circle of the cone-shaped part of the needle in intermediate position, whose small semi axis is equal to the radius of the conical part of the needle that penetrated into the soil.

As known, the ellipse is a closed figure in the plane, which can be obtained as the intersection of a plane and a circular cylinder, or as an orthogonal projection of a circle onto a plane. The circle is a special case of an ellipse [10].

In the case of the vertical position of the needle (O$_2$A$_2$) in Fig. 1, the area of its contact with the ground is a circle whose radius is equal to the radius of the part of the needle immersed in the soil.

The area of the ellipse (the hole formed by the penetration of the needle into the ground) will be determined by the dependence.

The process of interaction between the needle and the soil occurs in three directions. A flat figure (circle, ellipse) is formed on the soil surface, the volume of the figure can be estimated from the area of the near-flatness (the figure of an ellipse (circle) on the surface of the soil).

According to the results of the interaction of the needle, which has a circular cross-section with the soil, a hole of regular shape is formed, at the base (on the surface of the soil) which will not be a circle, but an ellipse.

Let us consider the case of the interaction of a cone-shaped needle with the soil (a cone-shaped needle consists of a cone and a cylindrical part). Only the cone-shaped part of the needle penetrates the soil (Fig. 1). As noted above, the disc of a harrow with needles carries out a complex movement. Due to the realization of such a needle movement, its end (the extreme point of the needle) will constantly move along the vertical axis. The phase of the needle entering the soil (in Fig. 2) corresponds to the left part: the position of the needle $O_A$, the beginning of the contact, $O_A A$ – maximum immersion of the needle in the soil. The penetration of the needle into the soil changes the point of contact between the needle and the soil. The penetration of the needle into the soil takes place in such a way that the movement of the extreme point of the needle $A_1$ is carried out along the vertical (y-axis), from the beginning of the contact of point $A_1$ (Fig. 2) to the position $A_1$, the coincidence of the axis of symmetry of the needle and the vertical axis $y$. During the movement of the harrows section its needles carry out by a compound motion: translational with velocity $v_0$ (center $O_1$) and rotational with angular velocity around center $O_1$. The plane of the contact of the needle with the soil occurs at the moment when the point of the needle $A$ meets the soil - position $A_1$ (Figure 2).

After that, the axis of needle rotation will move to position $O_2$, and its lower point will occupy the intermediate position $A_2$. Under such conditions, the lateral surface of the cone-shaped part of the needle, deforming the soil, will occupy a position corresponding to the point $B_2$. We note that the trajectory of contact point between the needle and the soil at the air-ground interface will be characterized by the following features: first the distance from the point of the primary contact ($A_1$) to the left part of the needle will increase with penetrates into the soil (point $B_2$), then, reaching a maximum, this distance will decrease, and in the vertical position of the needle it will be determined by the radius of the circle of the cone-shaped part of the needle that penetrated into the soil. The contact of the needle with soil takes place in a circle with a radius equal to $A_2 B_2=r_{cc}$ in the vertical position of the needle. The taper angle of the needle is $\alpha_A$.

From the triangle $A_2 B_2 A_1$, we determine the depth of penetration of the needle into the soil:

$$A_1 y = r_{cc} \cdot \tan \alpha_A,$$

where: $\alpha_A$ – the angle between the altitude and slant height of cone of needle; $r_{cc}$ – radius in the vertical position of the needle.

When the needle penetrates the soil, its $O_A A_1$ axis is inclined to the surface at an angle $\beta_1$, and the lateral surface is $\varphi_1$. That is $\beta_1=\varphi_1+\alpha_1$. In the intermediate position of the needle $O_A A_2$, the $O_A A_2$ axis is inclined to the soil surface at an angle $\beta_2$, and the lateral surface is $\varphi_2$, respectively (Fig. 3). And $\beta_2=\varphi_2+\alpha_2$. In the vertical position, the angle of the needle $O_A A_1$ coincides with the vertical, the angle $\beta_3=90^\circ - \varphi_3 + \alpha_3$, where $\varphi_3$ is the angle between the lateral side of the conical part of the needle and the soil in the position of maximum needle location in it. Thus, the angle $\beta$ varies in the interval:

$$\beta_1 \leq \beta \leq \beta_3, \quad or \quad \varphi_1 + \alpha_1 \leq \beta \leq 90^\circ - \varphi_3 + \alpha_3,$$

where: $\varphi_1$ – the angle of inclination of the needle to the soil; $\alpha_1$ – the angle between the altitude and slant height of cone of needle; $\beta$ – angle of the needle axis to the soil surface at the time of penetrates; $\varphi_3$ – angle between the lateral side of the conical part of the needle and the soil in the position of maximum needle location. 

Using the known equation of the ellipse, and taking $b=r_{cc}$ is the radius of the needle part, plunged into the soil, $a$ is the maximum distance from the point, plunged into the soil in a position where this point begins to enter the soil, that is the semi major axis of the ellipse, we get:

$$B_2 A_1 \cdot \tan (90^\circ - \varphi_3) = C_A A_1 \cdot \tan (90^\circ - \beta_3),$$

where: $\beta_3$ – angle of the needle axis to the soil surface at the intermediate position; $\varphi_3$ – angle between the lateral side of the conical part of the needle and the soil in intermediate position.

Using the notation that is inherent in an ellipse, we get:

$$a^2 = b^2 + c^2,$$

Then, in accordance with the well-known dependence of the ellipse $a^2+b^2+c^2$, we get:

$$a^2 = (B_2 A_1)^2 + b^2 + c^2 = r_{cc}^2 + c^2.$$
In accordance with accepted assumptions, the value of $B/A_1$ determines the size of the semi major axis of the ellipse formed by the results of the interaction of the needle with the soil. This ellipse, as noted above, is formed at the soil-air interface. Parameter $r_{nc}$ varies from zero in the beginning position of the contact and to some value that characterizes the depth of penetration of the needle into the ground. The angle $\beta_2$ varies according to (4). Determine the area of the ellipse as the area of the figure, which formed the needle by the results of penetration into the soil as

$$S_d = \pi \cdot a \cdot b = \pi \frac{r_{nc}^2 \cdot tg\beta}{\sqrt{\beta_2} \cdot -tg \phi},$$

where: $S_d$ – area of the ellipse (m$^2$); $a$ – semi-major axis of the ellipse (m); $b$ – semi-minor axis of the ellipse (m).

The change in the area that was formed on the surface of the soil will be estimated by the index of the difference in the areas of the ellipse and the circle with the radius $r_{nc}$

$$\Delta S_g = S_g - S_d = \pi \frac{r_{nc}^2 \cdot tg\beta}{\sqrt{\beta_2} \cdot -tg \phi} - \pi \frac{r_{nc}^2}{\sqrt{\beta_2} \cdot -tg \phi} = \pi \frac{r_{nc}^2 (tg\beta - 1)}{\sqrt{\beta_2} \cdot -tg \phi},$$

where: $S_g$ – area of the circle with the radius $r_{nc}$(m$^2$). Adopt

$$k_g = \frac{r_{nc}^2 \cdot tg\beta}{\sqrt{\beta_2} \cdot -tg \phi} - 1$$

where: $k_g$ – coefficient of surface-plane interaction of the needle with the soil. Expression (10) takes the form

$$\Delta S_g = \pi \cdot r_{nc}^2 \cdot k_g = S_g \cdot k_g$$

The space-depth interaction of the needle with the soil is estimated by the change in the volume of figures that were formed from the penetration of the needle into the soil.

$$\Delta V_{sd} = V_{ke} - V_{ec} = \frac{2}{3} \pi \cdot r_{nc}^2 \cdot y_{max} \cdot k_g = V_{ec} \cdot k_g$$

where: $\Delta V_{sd}$ – $V_{sd}$ – $V_{ke}$, $V_{ec}$ – volume change, the volume of the cone with the base ellipse and the volume of the cone with the circle at the base, respectively (m$^3$).

It should be noted that the main factors that influence the determination of the required force for deepening the needles of the needle harrow in the soil are: the depth of the needle’s immersion, the angle of friction of the needle along the ground, and the angle characterizing the taper of the needle. In addition, the force required to deepen the needle into the soil depends on the hardness of the soil, that is, its mechanical composition and moisture content.

It is established that the interaction of the needle of any shape and design with the soil leads to the appearance on its surface of figure close in shape to the ellipse. Moreover, in the phase of the needle entering the soil in the direction opposite to the motion, a semi-ellipse is formed, whose small semi axis is equal to the radius of the conical (cylindrical) part of the needle that penetrated the soil.

The semi major axis of the semi-ellipse depends on the parameters of the needle, their number on the disk, the depth of penetration of the needle into the ground. Leaving from the soil, the needle on its surface leaves the flattening in the form of the second ellipse (m$^2$).

The developed method improves the accuracy of predicting and evaluating the efficiency of interaction rotary-harrow needle with soil. The method creates the prerequisite $s$ for reducing the energy costs of soil cultivation.

The use of research results in the practice of agricultural enterprises makes it possible to solve the key task - to increase production efficiency through the management of technological processes, using machines and implements adapted for specific production conditions, as well as methods for their evaluation. The developed theoretical background complements the existing experimental methods for determining the indicators of soil quality, thereby increasing the accuracy of assessment and experimental determination of the indicators of the quality of the implementation of the technological process of tillage.

4. Conclusions

1. It is noted that the result of the interaction of the round needle of rotary harrow with the soil, is a regular-shaped hole with an ellipse at the base.

2. Theoretically justified and noted that in the phase of needle entry into the soil in the direction opposite to the movement, a semi-ellipse is formed, the small semi-axis of which is equal to the radius of the conical (cylindrical) part of the needle, which penetrates the soil. The semi-major axis of the semi-ellipse depends on the parameters of the needle, their number on the disk, the depth of penetration into the soil. In the phase of emergence from the soil, the needle on its surface also forms a semi-ellipse.

3. The method has been developed and the coefficients for estimating of surface-plane and space-deep interaction of the needle with the soil are theoretically justified, which makes it possible to improve the accuracy of forecasting and evaluating the effectiveness of the interaction of the needle of rotary harrow with the soil. Space-deep interaction is estimated in terms of the change in the volume of a figure, which is formed from the results of needle penetration into the soil. The method creates the prerequisites for improving the quality and energy indicators of the technological processes of soil treatment with rotary harrows, especially under conditions of their application for the shallow surface soil fracturing in the climatic zones that are prone to wind erosion.

5. References


