This study investigates the process of interaction between spherical disk working bodies and the soil environment. The task addressed is to establish a relationship between the generalized indicators and structural parameters of the disk working bodies (disk diameter, sphere radius, number of cutouts on the disk) at an angle of attack of the disk section of 20° and a speed of movement of 7–8 km/h.

The generalized parameters include the specific load on the disk, the stability of the movement of the working bodies according to the depth of cultivation, and the indicator of soil crumbling quality. The minimum specific traction resistance of the disks can be obtained with a disk diameter of 380 mm, a disk sphere radius of 682 mm, and a number of cutouts on the disk of 10 pcs.

Stabilization of the disk movement according to the depth of cultivation without an additional increase in the specific load on it leads to a significant improvement in both energy and quality indicators of the operation of the disk working bodies. The minimum root mean square deviation of the soil cultivation depth is achieved with a disk diameter of 380 mm, a disk sphere radius of 626 mm, and a number of cutouts on the disk of 10 pcs.

The indicator of soil loosening quality is determined by the stability of the disk movement along the cultivation depth. In this case, the disk is held at the technological cultivation depth, and most of its spherical surface, which is immersed in the soil environment, takes part in soil loosening. That is, stable disk movement along the set cultivation depth provides maximum soil loosening, which can be obtained with a disk diameter of 524 mm, a disk sphere radius of 710 mm, and a number of cutouts on the disk of 10 pcs.

The practical significance of the results is that they could be used to design disks for specific operating conditions. In this case, the ratio of the disk radius to its diameter (R/D) determines the disk's ability to work under specific soil conditions

Keywords: disk working elements, traction resistance, overcompacted soil, specific disk load

DETERMINING DESIGN PARAMETERS OF DISK WORKING BODIES FOR OVERCOMPACTED SOILS

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1. Introduction

Modern agricultural production is characterized by an increase in the share of over-compacted soils, which is a consequence of the intensification of agriculture, the widespread use of heavy agricultural machinery, and the reduction in the duration of agricultural breaks. Under such conditions, reducing the energy intensity of tillage operations, increasing

the efficiency of the functioning of tillage machines, and ensuring stable quality of tillage under different soil and climatic conditions becomes particularly relevant [1]. The costs of tillage in the structure of total resource costs for growing and harvesting crops account for approximately 26% of labor and 28% of energy costs, half of which are primary tillage. It is primary tillage that is the most energy-intensive, especially under conditions of increased soil density [2].

Disk working bodies occupy a leading place in the system of modern tillage tools and are widely used as part of tillage machines for both primary and secondary tillage. The most common are spherical disk working bodies, which are used to perform various technological operations, namely crumbling the soil layer, cutting and cultivating stubble, cultivating over-moistened and overcompacted soils [3].

Spherical disk working bodies are used both to equip specialized disk units and as components of combined machines [4]. During operation, such a working body simultaneously performs translational movement together with the unit and rotation around its own axis, which enables continuous interaction with the soil environment. This reduces the likelihood of clogging with plant residues, increases the passability of the unit and the efficiency of cultivating overcompacted soils. In addition, the rotating nature of the interaction with the soil leads to a decrease in the intensity of wear compared to non-rotating share working bodies, which is especially important in the presence of a significant amount of root residues in the upper compacted soil layer.

Spherical disk working bodies are used in almost all soil and climatic zones; the total area of cultivation reaches 14 million hectares [5, 6]. Such a high degree of their use determines the objective need for scientific research aimed at in-depth study of the interaction "spherical disk – soil environment". Such interaction is characterized by complex mechanical processes, which consider plastic and elastic deformations of the soil mass, friction forces and the distribution of reaction loads in space [7]. The design parameters of the disks (diameter, radius of the sphere, number of cuts, profile curvature, angle of attack), as well as their installation technique, have a significant impact on the nature of the deformation of the overcompacted soil, energy consumption, and the magnitude of the traction resistance of the soil tillage unit. However, despite the obvious advantages, the use of spherical disk bodies for work on overcompacted soils still remains insufficiently studied [8, 9].

In most published scientific works, the energy and agrotechnical performance indicators of disk working bodies are considered separately, without a comprehensive analysis of their interrelationship. In particular, the cumulative effect of the geometric parameters of the disk on the simultaneous provision of energy efficiency and quality of soil cultivation has not yet been fully investigated. At the same time, such design parameters as the number of cutouts in the spherical disk and their geometry were not taken into account in related studies at all. In addition, papers by predecessors did not consider the effect of the specific load on the disk. This leads to uncertainty regarding the conditions of stable disk movement in a compacted soil environment and the ratio of the influence of its design parameters and the weight characteristics of the unit.

Analysis of the current research reveals that the complex effect of the design parameters of spherical disk working bodies, the conditions of their operation on the energy and quality indicators of soil cultivation, especially under conditions of overcompacted soils, has not been studied in detail. The influence of the disk geometry, the number and shape

of the cutouts, as well as the specific load, was not taken into account, which necessitates further research into the process of interaction between the "disk working body and the soil environment". In this regard, studies aimed at defining the rational design parameters of disk working bodies for overcompacted soils are relevant and scientifically sound.

2. Literature review and problem statemen

Theoretical studies mainly differ in approaches to formalization of soil environment models. The vast majority of such papers consider the interaction of a spherical disk with the soil environment from the position of force interaction (traction resistance). The closest to the real process are theoretical studies reported in [10] that consider the cultivation of heavy tillage soils with disk working bodies. Based on the proposed model, the authors established the influence of the geometric parameters of the disk on the depth of soil cultivation, taking into account the friction forces necessary to ensure the clamping conditions of the processed material. Such material is considered to be plant residues in interaction with the soil environment. However, a number of issues remain unresolved. In particular, the soil environment model does not have a clear definition, despite the fact that the work focuses on "ensuring conditions for sliding cutting", which indicates a simplified idea of the process of interaction of the disk working body with the soil. The influence of variable physical and mechanical properties of the soil (moisture, density, structural state), which significantly determine the nature of the interaction of the disk with the soil, is not fully taken into account. The objective reason for this is the difficulty of formalizing the real behavior of the soil as a multifactorial and heterogeneous environment, which limits the universality and practical applicability of the results obtained. Therefore, the practical application of the presented methodology, taking into account significant assumptions, is possible only for a "smooth disk", while most disk working bodies have cutouts and do not form a solid blade.

More thorough results are reported in studies involving the discrete element method (DEM) [3, 4, 11, 12].

In particular, in [11] it is emphasized that the use of the DEM method allowed the authors to build a model that reproduces the interaction of soil and implement with maximum accuracy. However, the soil environment is complex and heterogeneous, it contains both microflora and microfauna, which calls into question the possibility of obtaining "high-precision models" based on this approach alone. Especially if such an approach is used as a forecasting tool in designing the shape of the implement [11]. In addition, the concepts of "working body" and "implement" should be clearly distinguished since they are not identical.

In [4], using the DEM method, a study of the traction force of disk working bodies in high-speed cultivation modes (over 12 km/h) was performed. The model was calibrated on sandy-loamy soil at a cultivation speed of 6 km/h. To ensure a relative error of the model of about 1%, verification was additionally performed on other types of soils. The model built makes it possible to estimate the dependence of the traction force on the angle of installation of the disk group, the diameter and angle of inclination of the disk, as well as the speed and depth of soil cultivation. It is shown that the traction force increases with an increase in the angle of installation of the disk group, the depth of cultivation and the speed of movement, decreases with an increase in the angle of inclination

of the disk and remains practically unchanged in the case of a change in the disk diameter. A regression equation is derived to determine the change in the traction force of the disk working body during high-speed cultivation (16 km/h). Despite the value of the results for optimizing the design of disk working bodies and assessing the influence of their operating parameters under similar soil and technological conditions, the universality of the conclusions is limited. In particular, this is the calibration of the model only at low speed, conducting research on a limited number of soil types with a slight variation in physical and mechanical properties. The authors also did not investigate the change in traction force depending on the degree of disk penetration into the soil, which is an important factor in assessing energy costs and choosing rational operating modes of disk implements.

Such studies are partially reported in [3]. Modeling of the process of interaction of the disk working body with the soil was performed using a technique that combines DEM and MBD (Multi Body Dynamics) methods. The use of this approach allowed the authors to estimate the angular velocity of the disk plow and soil movement with high accuracy. At the same time, the relative error of the angular velocity prediction was 6.9%, and the correlation between the simulated and actual soil movement data reached $R^2 = 0.68$. It was established that the unevenness of the disk working body's penetration into the soil depends on its angular velocity – at different speeds, the disks are immersed unevenly, which leads to incomplete integration of the soil into deeper layers. This unevenness of penetration, in turn, leads to an uneven increase in traction force at different depths of immersion of the disk working bodies. This indicates the complex nonlinear nature of the interaction of the soil-working body system and the significant influence of kinematic parameters on the energy indicators of the cultivation process. The results are of high value for optimizing the design of disk working bodies and their subsequent numerical modeling, however, their versatility and practical applicability are limited by the narrow formulation of the problem and simplifications of the model.

The influence of the disk design on the force and kinematic indicators of interaction with the soil, as well as on the processes of cutting and redistribution of plant residues in the soil environment is considered in work [12]. The authors designed a disk with a cutting blade with a profile of the involute to replace conventional disks. Six disk working bodies were studied using a method that combines theoretical analysis of the stubble cutting process with numerical modeling based on DEM. Two of them were standard, and four were of a new design, differing in the number of teeth and had 7, 8, 9, and 10 teeth, respectively. Simulations were carried out in two directions of rotation (forward and reverse) and at operating speeds of 10 and 12 km/h. The best results, compared to the conventional disk, were demonstrated by the designed disk with 9 teeth, providing high productivity, optimal degree of stubble cultivation, and rational combination of soil resistance forces with minimal crushing of its structure. The disk with the reverse direction of rotation contributed to the reduction of soil resistance and provided a more uniform redistribution of stubble in the soil environment compared to the disk with the forward direction of rotation. Field studies on the sowing unit equipped with a disk working body with nine teeth and a knife for stubble cleaning demonstrated an increase in the efficiency of stubble cleaning. In addition, a decrease in the coefficients of variation of the spatial arrangement of plants and their lateral deviation during high-speed

sowing was observed. The results have high practical value for optimizing the design of disk working bodies and increasing the efficiency of plant residue management during high-speed sowing. The limitation of the work is the use of DEM and experimental tests for a limited list of disk designs and soil conditions, which makes it impossible to generalize the results for the purpose of reliable prediction of traction forces.

In turn, study [13] proposes a three-dimensional model of soil destruction for a narrow blade, which makes it possible to predict both traction forces and the volume of disturbed soil. The model is based on the description of rectilinear destruction zones and minimizing the theoretical traction force relative to the angle of inclination of the soil destruction zone. In this case, the force coefficients depend on the ratio of the width, height, angle of inclination of the blade, and the angle of soil friction. The advantage of the model is the ability to optimize the design of tools and assess their effectiveness without conducting complex field tests. However, in the work, the model of the soil environment is also represented in a simplified form; the system-wide qualitative indicators of the operation of the disk working bodies are not determined.

The analytical research model reported in [14] describes the physical and mechanical processes of the interaction of the disk body with the soil and is aimed at determining the optimal conditions for achieving high agronomic indicators. The work considers in a simplified form models that take into account various factors, such as soil density, cultivation speed, and design features of disk tools. The results of the study allow for adjustments to be made to the settings during the operation of the tool depending on the operating conditions but do not substantiate rational design parameters of the disks.

It is obvious that the results of any theoretical studies serve as the initial basis for characterizing the process of interaction of the working bodies with the soil environment. Any theory, whatever it may be, provides the definition of the main quantities that control the process, while further field tests provide practical guidance on the directions of improvement and correction of this theory. At the same time, field studies are usually carried out for the designs of existing disk working bodies and the parameters of spherical disks in order to assess their qualitative and energy characteristics.

Works that report experimental studies are typically divided into separate groups. In some, fuel consumption is investigated depending on the technological settings. In others, the productivity and efficiency of processing plant residues depends on the design parameters of the disk working elements.

For example, the authors of study [15] established qualitative indicators of the operation of the disk implement and fuel consumption depending on the setting of the technological parameters of the disk harrow in the aggregate with the CASE 135 tractor. The results showed that the optimal parameters (disk angle 10°, speed 3.5 m/s, depth 8 cm for loam and 5 cm for clay-loam soil) provide minimal fuel consumption and effective stubble wrapping. The study comprehensively takes into account the influence of the angle of inclination of the disks, the depth of cultivation, and the speed of movement on the quality of cultivation and energy efficiency. At the same time, the authors investigated only two types of soils, one tractor, and certain disk designs, which limits the generalization of the results.

Papers [16, 17] address the productivity of disk working bodies for vertical tillage. In [16], a comparison of milled rollers and grooved disks was considered in terms of the volume of displaced soil, the content of plant residues in the soil and cutting forces. However, the work did not consider the influence of

variable soil moisture and density, as well as the behavior of disk tools under different operating conditions, since the study was limited to a depth of 100 mm and a speed of 16 km/h. A partial solution to this issue is proposed in [17]. The authors evaluated similar indicators in the rice-wheat crop rotation system, including the width of displaced soil and the efficiency of cutting residues, and also took into account the influence of disk geometry and working depth (70–100 mm) on productivity. In contrast to [16], [17] covers a wider range of parameters on which productivity depends. However, questions remain unresolved regarding the applicability of the findings to other soil types, in particular sandy-loamy, and the lack of a mechanistic model of the soil-tool-remains interaction.

A supplement to [16, 17] is work [18], in which the productivity of disk working bodies (driven concave disk and flat disk without drive) on sandy-loamy soil was investigated under laboratory conditions. The depth of cultivation (10 mm) and the speed of movement of the working body (0.5–1 m/s) were maintained stable. During the experiment, traction, vertical, and lateral forces, as well as the volume of displaced soil, were measured. The results showed that the drive disk increased the volume of displaced soil by 15–20%, while the vertical and traction forces increased by 12–14 kN/m^2. Analysis of soil deformation profiles revealed that the drive disk forms deeper and wider soil disturbance zones with a greater slope of the shear surface, which ensures increased efficiency of incorporating soil and plant residues into the cultivation process. Therefore, the study has practical value for comparing driven and free disks under standardized laboratory conditions and for assessing their power characteristics. It also confirms the prospects of studying the influence of non-standard designs of working bodies on the technological parameters of soil cultivation. A common limitation of papers [16–18] is a detailed study of the productivity of disk working bodies with insufficient attention to the qualitative indicators of cultivation, in particular the efficiency of cutting and wrapping of stubble.

Studies aimed at increasing the efficiency of cutting and wrapping of plant residues into the soil are reported in [19–21]. These papers show that the design parameters of the working bodies (type of disk, diameter, blade shape) and operating modes (depth of cultivation, speed of movement) significantly determine the force interaction of the working body with the soil and stubble. In [19] it is stated that increasing the diameter of the double disk coulter from 330 to 450 and 600 mm leads to an increase in the average traction forces from 648.9 to 737.2 and 784.6 N, respectively. At the same time, the efficiency of cutting stubble reaches a maximum value of 88.6% at a disk diameter of 450 mm and a cultivation depth of 90 mm, which indicates the existence of an optimal ratio between the power and technological parameters of the process. However, the study was carried out on one type of soil under conditions of increased humidity, which limits the possibility of extrapolating the results to other technological and soil-climatic conditions.

Study [20] builds on the results reported in [19]. In [20], a comparative assessment of different types of disk coulters was carried out, as a result of which it was clearly shown that it is the design parameters of the disk that are the determining factor in the efficiency of cutting plant residues. It was found that the cutting efficiency for smooth and notched disks was low and amounted to only 11.4–12.4%, for a toothed disk it increased to 46.2%, while a double disk provided an average efficiency of 78.5% (with a maximum value of up to 88.6%). The disadvantage is that such efficiency was achieved mainly by increasing the traction force.

Work [21] expands [19, 20] as it focuses on the influence of the blade shape and the depth of cultivation on the process of cutting soil and plant residues in a vertical tillage system. It is shown that increasing the depth from 63.5 to 127 mm increases the soil cutting forces by 53.4%, soil movement by 34.9% and residue mixing by 5.1%. At the same time, the grooved disk has the highest intensity of impact on the soil and requires maximum traction and vertical forces. However, similar to [19, 20], the study was carried out for one type of soil and without a full mechanistic description of the processes.

Thus, papers [19–21] have significant practical value since they provide a quantitative assessment of traction and vertical forces, stubble cutting efficiency, and the influence of the design parameters of the disks and working depth on the productivity of the disk working elements. At the same time, the issues of predicting the operation of the disk working elements using mechanistic models remain unresolved, which is necessary for scientifically substantiated selection and optimization of their design parameters.

Analysis of other studies tackling the design of disk working bodies from the point of view of their interaction with the soil environment reveals that the physical understanding of this process has not changed significantly since 1967 [22]. During this time, the basic geometric parameters of the disk (diameter, radius of the sphere, number and shape of the notches), as well as the specific load on the disk, were not systematically considered in the context of their influence on the qualitative and energy performance of disk tools. In addition, technological parameters, such as the angle of attack, the angle of installation of the disk axis in the vertical plane, the speed of movement, and the depth of cultivation, were also not analyzed in relation to the efficiency of work.

The first attempts to systematize the study of the relationship between the geometric parameters of disk working bodies and their productivity are given in [23]. It is concluded that the criterion for optimizing disk working bodies can be the stability of disk movement along the depth at a minimum specific traction resistance. The stability of the disk movement along the depth of soil cultivation has a decisive effect on the qualitative and energy performance of the spherical disk. This criterion assumes the maximization of the projection of the normal soil reaction onto the vertical axis and the minimization of its projection onto the direction of movement, i.e., the minimization of traction resistance. Theoretical studies [23] have shown that the angle of attack and the diameter of the disk should be considered in direct correlation with the radius of the sphere at a given specific load on the disk. Each value of the angle of attack corresponds to a certain optimal ratio of the radius of the sphere to the diameter of the disk. Therefore, adjusting the angle of attack of disk working bodies without taking this ratio into account could lead to a loss of compliance of the design parameters with the operating conditions.

From the above it follows that a comprehensive study on the influence of the design parameters of disk working bodies on the traction resistance of the disks, the stability of the movement of the working bodies over the depth of cultivation, and the quality of soil crumbling should be carried out taking into account the properties of the soils. That is, at present, no systematic dependence has been established between the design parameters (disk diameter, sphere radius, number of notches on the cutting edge) and indicators of energy efficiency and quality of soil cultivation under conditions of overcompacted soils. Therefore, a study aimed at

substantiating the rational design parameters of disk working bodies to ensure effective work under conditions of overcompacted soils is advisable.

3. The aim and objectives of the study

The purpose of our study is to improve the quality of soil loosening and reduce the traction resistance of disk spherical working bodies for surface tillage by determining rational values of the diameter of the disks, their sphere radii, and the number of cutouts on the disk. This will provide the opportunity, depending on the operating conditions, to select disk working bodies by geometric parameters in order to ensure their qualitative and energy performance.

To achieve the goal, the following tasks were set:

– to determine the influence of the diameter, radius of the sphere, and the number of cutouts on the traction resistance of the disks;

– to determine the influence of the diameter, radius of the sphere, and the number of cutouts on the stability of the movement of the working bodies in terms of the depth of tillage;

– to determine the influence of the diameter, radius of the sphere, and the number of cutouts on the quality of soil crumbling.

4. Materials and methods

4. 1. The object and hypothesis of the study

The object of our study is the process of interaction of spherical disk working bodies with the soil environment.

The principal hypothesis assumes that by determining the quality of soil loosening and specific traction resistance, it is possible to determine rational values of the radius of the disk sphere, the diameter of the disk, and the number of notches on the cutting edge of the disk. Results will serve as a basis for further improvement of disk working bodies.

The simplification was that the experiment was planned for the three most significant factors that characterize the process of interaction of the spherical disk working body with the soil environment. In addition, the shape of the notch on the spherical disk was performed in the form of a radius of a circle, which depends on the diameter of the disk. Depending on the diameter of the disk, the distance between the disks on the battery was also selected. The initial layer-by-layer moisture and soil density before conducting experimental studies were assumed to be constant.

4. 2. Methodology for determining rational values of design parameters for disk spherical working bodies

The methodology for conducting laboratory and field studies is based on DSTU 7435:2013 "Agricultural machinery. Methods for determining test conditions" and SOU 74.3-37-155:2004 "Testing agricultural machinery. Machines and implements for soil cultivation. Test methods", as well as generally accepted methodology. For express analysis of soil density and moisture, the RPP-2 radioisotope device was used.

The defining design parameters of the disk were as follows: radius of the sphere – R (mm), disk diameter – D (mm), and n – the number of cuts or the number of teeth on the cut disk. The cut radius was set as a constant value at 80 mm for a diameter of 720 mm (based on a priori information). Changing the diameter of the disk led to a change in the radius of the

cutout (Fig. 1). The distance between the disks on the battery was selected depending on the diameter of the disk.
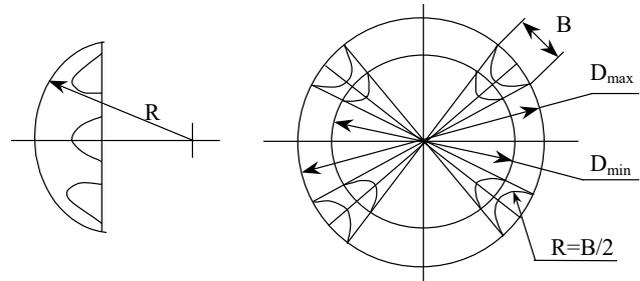

Fig. 1. Schematic representation of a disk for research purposes

Given that the contact of the soil with the surface of the disk occurs below the axis of rotation, the optimization condition is as follows [23]

$$-N\left(\frac{z}{R} - \frac{\sqrt{x^2 + y^2}}{R}\cos\left(\operatorname{arctg}\frac{x}{y} - \beta\right)\right) \to \max, \qquad (1)$$

where N is the normal reaction force; R is the radius of the disk sphere; β is the angle of attack.

To fulfill the condition of stability of movement along the depth of cultivation at the minimum specific traction resistance, the angle of attack and the diameter of the disk were considered in direct correlation with the radius of the disk sphere and, vice versa (at a given specific load on the disk). Each angle of attack (β) corresponded to a certain optimal value of the ratio of the radius of the sphere to the diameter of the disk (R / D).

During the research, the unit moved uniformly at a speed of 6.8 km/h (1.9 m/s), and the depth of soil cultivation was set at 14 cm. The field background was homogeneous with a cover of 70% of stubble and 30% of weeds. The angle of attack was set at 20°, as is typical for most similar designs. The average value of the specific load on the spherical disk was set at 90 kg, which ensured the same operating conditions for the disks.

The study of the interaction process of the spherical disk working body with the soil environment was carried out using a multifactorial experiment according to the D-optimal Box-Benkin plan for the three studied factors [24, 25].

The adequacy of the derived regression equations was assessed using the Fisher criterion. Statistical assessment of the level of dispersion of the results was carried out using the Cochrane criterion. The significance of the regression equation coefficients was assessed using the Student criterion. All criteria were determined at a 95% confidence level. The value intervals and levels of variation of the variable factors that were used in the research are given in Table 1.

Table 1

Intervals of magnitude and variations in the levels of the studied factors

Factor ID	Designation	Levels of factor variation			Variation intervals
		−1	0	+1	
Disk diameter, mm	D	380	550	720	170
Sphere radius, mm	R	480	630	780	150
Number of cutouts, pcs.	n	0	5	10	5

To implement the experimental plan, a set of standard sizes of disk working bodies-analyzers was manufactured (Fig. 2). Experimental disks were manufactured by the surfacing method, for which "mushrooms" were manufactured for surfacing with three radii of the sphere and a diameter calculated for surfacing disks of the largest diameter. Cutting of disks and forming of cutouts was performed using a plasma torch, at an angle of 250° to the disk plane, which allowed us to obtain a strengthened cutting edge.

Fig. 2. General view of research disks

The design of the experimental laboratory-field installation (Fig. 3) provided for the installation of the necessary disks on a trailer equipped with a strain gauge attachment and wheels for transport position. The trailer also contains a device for installing ballast loads to maintain a given value of the specific load on the disk.

Fig. 3. General view of the experimental setup for conducting research

Many years of technogenic load on the soil environment of southern Ukraine led to the over-compaction of the arable horizon of southern Ukrainian black earths and dark chestnut soils under conditions of insufficient moisture. Thus, during the period of surface tillage, according to our studies, its density in the 0–10 cm layer at a moisture content of 10...14% is 1.26–1.29 g/cm^3, and in some years it reaches 1.30–1.32 g/cm^3. With such a soil density, the spherical disk is very difficult to immerse in the soil environment and does not maintain the given depth of tillage – it is constantly dug out. In most cases, only by significantly loading the disk tool, the disk can be held at a given depth, which leads to additional compaction of individual soil aggregates.

A study on the laboratory-field installation to examine the parameters of disk working bodies was carried out on southern Ukrainian black soil (Novomykolayivka village, Tokmak region, Zaporizhia oblast, November 2021). The repetition of the studies was 6-fold. The soil moisture in the layers was:

– 0–5 cm – 8–12%;
– 5–10 cm – 10–14%;
– 10–15 cm – 12–15%.

In these layers, the soil density was, respectively: 0.98–1.10 g/cm^3; 1.22–1.25 g/cm^3; and 1.29–1.31 g/cm^3.

To record the traction resistance, a tension clamp with a ring-type tension link, a KAD-WA-4 analog-to-digital converter, a personal computer, and a rechargeable battery were installed on the tractor. Signal processing and accumulation of measurement results were performed using the GAUS 8 package.

The parameters under study:

– T – specific traction resistance, N/cm^2;
– σ – root mean square deviation of soil cultivation depth, mm;
– γ – indicator of soil crumbling quality.

The parameter γ was taken as the ratio of the weight of the soil fraction with a size of 10–20 mm in the 0–10 cm layer to the weight of the total sample.

5. Results of determining the rational values of the design parameters of disk spherical working bodies

5. 1. Determining the influence of the diameter, radius of the sphere, and the number of cuts on the traction resistance of disks

The regression equation, which describes the traction resistance of disks taking into account significant regression coefficients, takes the following form

$$T = 21.3554 + 0.0019D - 0.0391R - 2.6117n +$$
$$+ 0.001Dn - 0.0007Rn - 0.0096n^2. \qquad (2)$$

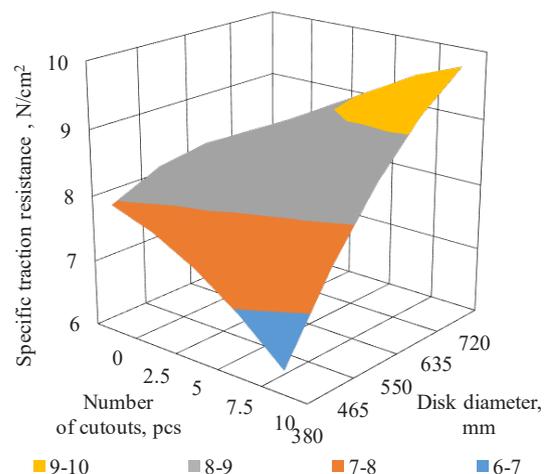In graphical form, regression equation (2) is shown in Fig. 4–6.

Fig. 4. Dependence of specific traction resistance on the number of cutouts on the disk and the disk diameter at a disk sphere radius of 630 mm
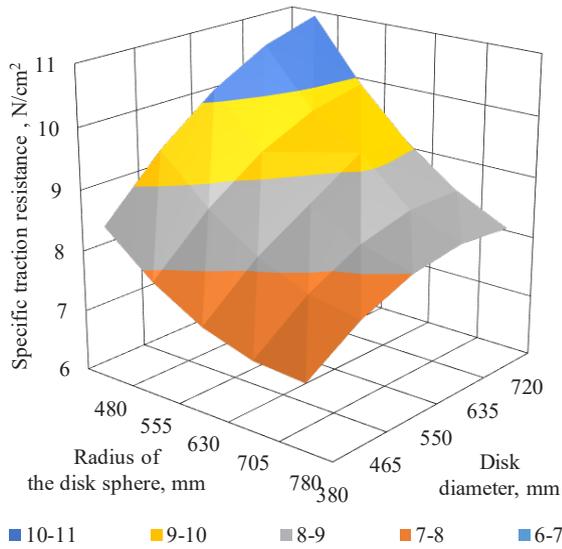
Fig. 5. Dependence of specific traction resistance on the radius of the disk sphere and the disk diameter with the number of cutouts on the disk of 5 pcs

Fig. 6. Dependence of specific traction resistance on the radius of the disk sphere and the number of cutouts on the disk with a disk diameter of 550 mm

Thus, it can be stated that the results of determining the specific traction resistance take into account the given range of the disk diameter, the radius of the disk sphere, and the number of cutouts on the disk. It was established that the maximum specific traction resistance of the disks is 13.04 N/cm^2 with a disk diameter of 720 mm, a disk sphere radius of 480 mm, and a number of cutouts on the disk of 10 pcs. The minimum specific traction resistance of the disks of 6.31 N/cm^2 can be obtained with a disk diameter of 380 mm, a disk sphere radius of 682 mm, and a number of cutouts on the disk of 10 pcs.

5. 2. Determining the influence of the diameter, radius of the sphere, and the number of cuts on the deviation of the depth of cultivation

The regression equation that describes the root mean square deviation of the depth of cultivation of the soil, taking into account the significant regression coefficients, takes the following form

$$\sigma = -12.1172 + 0.3568D - 0.1902R -$$
$$- 4.7419n - 0.0002DR + 0.0009Dn -$$
$$- 0.0016Rn - 0.0002D^2 + 0.0002R^2 - 0.014n^2. \quad (3)$$

In graphical form, regression equation (3) is shown in Fig. 7–9.
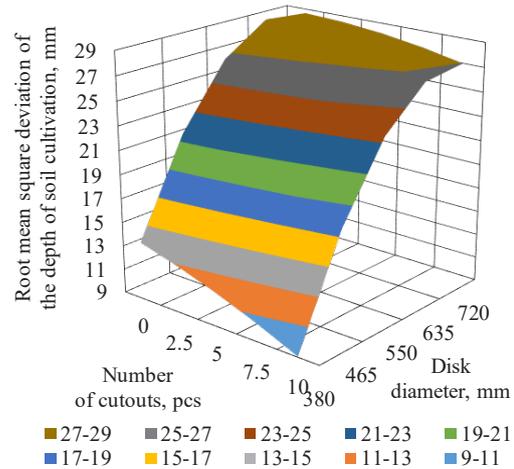
Fig. 7. Dependence of the root mean square deviation of the depth of soil cultivation on the number of cutouts on the disk and the disk diameter at a disk sphere radius of 630 mm

Fig. 8. Dependence of the root mean square deviation of the depth of soil cultivation on the radius of the disk sphere and the disk diameter with the number of cutouts on the disk of 5 pcs

Fig. 9. Dependence of the root mean square deviation of the depth of soil cultivation on the radius of the disk sphere and the number of cutouts on the disk with a disk diameter of 550 mm

Thus, we have the results of determining the root mean square deviation of the depth of soil cultivation depending on the

given range of the disk diameter, the radius of the disk sphere, and the number of cutouts on the disk. It was established that the maximum value of the root mean square deviation of the depth of soil cultivation is 47.3 mm with a disk diameter of 720 mm, a disk sphere radius of 480 mm, and the number of cutouts on the disk of 10 pcs. The minimum value of the root mean square deviation of the depth of soil cultivation is approximately 9 mm with a disk diameter of 380 mm, a disk sphere radius of 626 mm, and the number of cutouts on the disk of 10 pcs.

5. 3. Determining the influence of the diameter, radius of the sphere, and the number of cuts on the soil crumbling quality indicator

The regression equation that describes the soil crumbling indicator, taking into account significant regression coefficients, takes the following form

$$\gamma = -5.279 + 0.0087D + 0.0091R + 0.343n - 0.0000054DR -$$
$$- 0.0005Dn - 0.000324Rn + 0.00000053DRn -$$
$$- 0.0000041D^2 - 0.0000043R^2 - 0.00508n^2. \quad (4)$$

In graphical form, regression equation (4) is shown in Fig. 10–12.

Fig. 10. Dependence of the soil crumbling quality indicator on the number of cutouts on the disk and the disk diameter at a disk sphere radius of 630 mm

Fig. 11. Dependence of the soil crushing quality indicator on the radius of the disk sphere and the disk diameter with the number of cutouts on the disk of 5 pcs
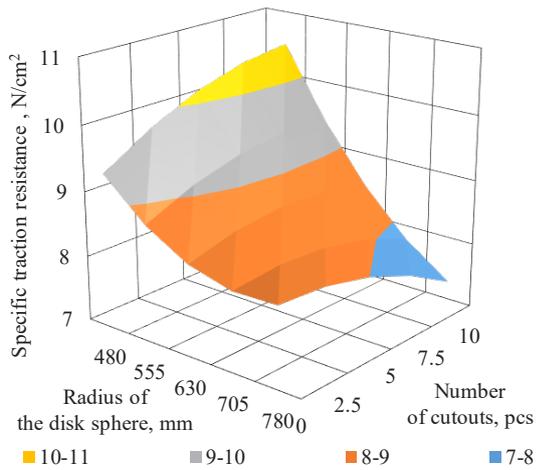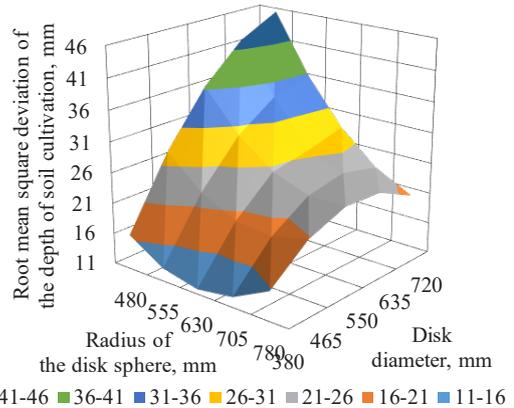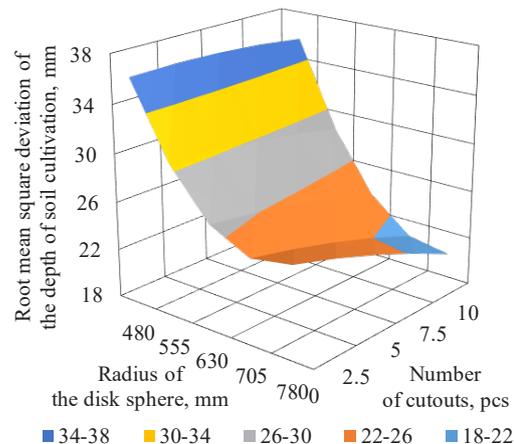

Fig. 12. Dependence of the soil crumbling quality indicator on the radius of the disk sphere and the number of cutouts on the disk with a disk diameter of 550 mm

Our results, shown in Fig. 10–12, give an idea of the influence of the given range of disk diameter, disk sphere radius, and number of cutouts on the disk on the soil crushing quality index. It was established that the minimum value of the soil crushing quality index is practically zero with a disk diameter of 380 mm, a disk sphere radius of 480 mm, and the absence of 10 cutouts on the disk. The maximum value of the soil crushing quality index is approximately 0.567 rel. units with a disk diameter of 524 mm, a disk sphere radius of 710 mm, and the number of cutouts on the disk of 5 pcs.

6. Discussion of results of determining rational design parameters for disk working bodies

For a comprehensive assessment of disk working bodies, it is necessary to take into account both the qualitative and energetic indicators of their work. Unlike studies [3, 6, 10, 12], in which the diameter and radius of the disk sphere were not analyzed in relation to the energetic and qualitative indicators, our work reports their systematic analysis. The number of notches on the cutting edge of the disk in previous studies was not taken into account at all as an influence parameter. In addition, in previous studies, the specific load on the disk was not taken into account and therefore there was uncertainty about whether the disk moves in the soil environment due to its own characteristics or is "pressed" into the soil by the weight of the tool. For this purpose, the stability of the disk stroke was determined by the depth of cultivation, taking into account the specific load on the disk. Thus, a comprehensive assessment of the influence of the disk diameter, its radius of the sphere, and the number of notches on the cutting edge of the disk on the energetic and qualitative indicators of the operation of disk working bodies was obtained. This was achieved through the use of mathematical planning of experiments with a wide range of studied factors and by using working bodies-analyzers.

The graphical interpretation of the research results is shown in Fig. 4, 6. Based on Fig. 4, it can be concluded that at a depth of cultivation $h = 12 \pm 2$ mm, an angle of attack $\beta = 20°$, and a maximum number of notches on the disk, the minimum specific traction resistance is achieved at a disk diameter $D = 380$ mm and a sphere radius $R = 682$ mm. In this

case, the ratio of the radius of the disk sphere to its diameter determines the magnitude of the convexity. The smaller the value of the value R/D, the more convex the disk is and the smaller the angle formed by the tangent to the disk sphere in the cutting edge zone and the plane of the bottom of the furrow. In the above case, $R/D = 1.80$.

If there are no notches on the disk, then it is possible to obtain the minimum possible value of T at $R = 720$ mm, the ratio $R/D = 1.90$. That is, in the absence of notches, the disk parameters approach a flat one. Changing the number of notches on the disk from minimum to maximum leads to a change in the radius of the disk sphere. Based on Fig. 5, the presence or absence of notches determines the pattern of the influence of the diameter and radius of the disk sphere on its specific traction resistance.

Naturally, the more stress concentrators – the number of teeth (the result of the number of notches), the less traction resistance, but with an increase in the number of notches, the width of the tooth and its strength decrease, which leads to its destruction. In addition, with a decrease in the interdental space, the process of its "sticking with soil" begins and the effect of stress concentrators is leveled. At the same time, the work of the tooth in the soil is directly related to the radius of the disk sphere, which determines the angle of inclination of the tooth in the horizontal plane at the moment of maximum deepening. It was determined (Fig. 6) that with an increase in the disk diameter, to achieve the minimum value of T, it is necessary that the convexity of the disk surface increases. Whereas for $D = 380$ mm and $n = 10$ the ratio $R/D = 1.80$, then for $D = 720$ mm and $n = 10$ $R/D = 1.08$. This is explained by the fact that with an increase in the disk diameter, the contact area of the disk with the soil increases and, consequently, the volume of soil that is compacted. To ensure minimal traction resistance, it is necessary to have a minimum angle of soil entry onto the disk, which is ensured by a decrease in the ratio R/D and the absence of a solid blade, i.e., the blade must be "notched".

Thus, the ratio R/D characterizes the specific traction resistance, and the efficiency of the disk teeth in relation to the traction resistance is determined by the radius of the disk sphere.

The influence of the studied design parameters of the disk (D) on its stability of movement in depth is shown in Fig. 7–9. From Fig. 7 it follows that changing the number of cutouts on the disk to achieve the minimum value of σ will not lead to a change in the diameter value ($D = 380$ mm) but will lead to a decrease in the radius of the sphere $R = 626$ mm. Thus, R/D will decrease from 1.80 to 1.65. However, the absence of cutouts on the disk leads to a significant deterioration in the stability of the disk movement in depth – by approximately 40%. At the same time, changing the disk diameter (Fig. 9) significantly affects the change in the dependence of the specified dependence. To achieve the minimum σ value, it is necessary to reduce the value of R/D (increase the convexity of the disk). That is, there is a need to reduce the angle of entry of the disk into the soil to maximize the projection of the normal soil reaction on the disk surface. The smaller the value of the R/D value, the more convex the disk and the smaller the angle formed by the tangent to the disk sphere in the cutting edge zone and the plane of the furrow bottom.

Reducing the traction resistance and increasing the stability of the disk movement in terms of depth of cultivation are interrelated concepts. By reducing the traction resistance due to the disk parameters, it is possible to improve the stability of the disk movement. If the stability of the movement is solved by increasing the specific load on the disk due to the weight of the tool, and not due to the geometry of the disk, this will lead to an increase in its traction resistance. Therefore, it is impractical to produce heavy disk tools in order to stabilize the movement of the disks in terms of depth.

It should be noted that the parameters D, R, and n should be considered in relation to each other. Fig. 10, 12 show graphical interpretations of the influence of D, R, and n on the quality of soil loosening. Increasing the number of cuts on the disk does not lead to a significant increase in the loosening index. However, the absence of cuts leads to an increase in the diameter and convexity of the disk ($R/D = 0.85$) since, in this case, it is possible to qualitatively loosen the soil layer only by increasing the curvature of the disk surface. This significantly increases its metal content and specific traction resistance. The maximum loosening index can be obtained with a disk diameter of $D = 524$ mm, $R = 710$ mm, $n = 5$ ($R/D = 1.355$). However, for a given diameter, the number of cuts on the disk, which is greater than 6, leads to a decrease in the quality of soil loosening. It should be noted that the stability of the disk movement in depth determines the quality of soil loosening, i.e., the disk is constantly immersed in the soil and the process of its interaction with the soil environment is continuous, which improves crumbling over the entire depth of cultivation.

On heavy, over-compacted soils, it is desirable to increase the productivity of disk tools not by increasing the speed but by increasing their width of soil cultivation. Due to the geometric parameters of the spherical disk, it is possible to keep it at the cultivation depth with a certain specific load and without over-compaction of soil aggregates only up to a speed not exceeding 10 km/h. Based on the need to reduce the intensity of the impact on the soil environment, the operating mode of the disk working elements at a speed of up to 8 km/h is the most economical. Excessive increase in speed leads to additional load on the soil environment, which is redirected to its plastic deformation, which intensifies the processes of dehumification.

Thus, the following conclusion can be drawn – stabilization of the disk movement along the depth of cultivation without an additional increase in the specific load on it leads to a significant improvement in both the energy and qualitative indicators of the work of disk working bodies.

The uniqueness of our studies on the process of interaction of disk working bodies with the soil environment is determined by the fact that these studies were conducted in a wide range of basic parameters of the working bodies. At the same time, regression equations were derived regarding the qualitative and energy indicators of the disk tool's operation. This makes it possible to ensure the superiority of our studies compared to similar ones [14, 21], in which the systemic influence of parameters on the performance indicators was not considered.

The practical significance of the research results is that they could be used to design and improve disk tools of various types (double-track disk harrows, disk cultivators, disk sections as part of combined tools).

Our results enable the improvement of the energy and qualitative indicators of the cultivation of the soil environment by determining the rational design parameters for disk working bodies. But the research results are limited by the conditions of the experiment in terms of humidity, initial layered soil density, and background weediness. At the same time, the range of variation of the studied factors was determined exclusively by the design capabilities of existing disk tools and the generally accepted form for the design of spherical cut disks.

The disadvantages of our studies include the fact that they were conducted under certain soil and climatic conditions; they are zonal in nature. In addition, the studies were performed within certain limits regarding the speed of the unit ≈ 2 m/s with a battery attack angle $\beta = 20°$, specific load on the disk – 90 kg, and a soil cultivation depth of 12 ± 2 cm. Such conditions were accepted as a basic assumption, which narrowed the range of use of the research results.

In the future, the methodological foundations and results of our studies could serve as the basis for conducting field studies under other soil and climatic conditions when using the designed working bodies-analyzers for other technological modes and tasks. One of the areas of research might be an increase in the speed of the unit to 3.3 m/s and the depth of cultivation to 16 cm while varying the specific load on the disk from 60 to 110 kg.

7. Conclusions

1. It has been established that to ensure the minimum traction resistance of the disk, it is necessary to have a minimum angle of soil entry onto the disk, which is ensured by the ratio of the radius of the disk sphere to its diameter and the "cut-out" blade. The ratio of the disk radius to its diameter determines the ability of the disk to work in specific soil conditions. The minimum specific traction resistance of the disks can be obtained at $D = 380$ mm, $R = 682$ mm, $n = 10$, at $\beta = 20°$, and $V = 7–8$ km/h.

2. We have established that stabilization of the disk movement along the depth of cultivation without an additional increase in the specific load on it leads to a significant improvement in both energy and quality indicators of the disk working elements. The minimum root mean square deviation of the depth of soil cultivation is achieved at $D = 380$ mm, $R = 626$ mm, $n = 10$, at $\beta = 20°$, and $V = 7–8$ km/h. The stability of the course along the depth of cultivation significantly determines the performance of spherical disks. With stable operation of the disks along the depth, the uniformity of the quality of soil loosening is achieved, the field surface is leveled, and the completeness of weed cutting and wrapping of their seeds is ensured. At the same time, the dynamic load on the working bodies and their fastening nodes to the tool frame is reduced.

3. It has been established that the quality of soil loosening is determined by the stability of the disk movement along the depth of cultivation. If the disk is held at the technological depth of cultivation during operation, then most of its spherical surface, which is immersed in the soil medium, takes part in soil loosening. That is, stable movement of the disk at the set cultivation depth provides maximum soil loosening, which can be obtained at $D = 524$ mm, $R = 710$ mm, $n = 5$, at $\beta = 20°$, and $V = 7–8$ km/h.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they used artificial intelligence technologies to translate, proofread, and edit the text in the sections "Introduction" and "Analysis of Literary Data and Problem Statement":

– ChatGPT, GPT-5.2 language model from OpenAI;

– sections "Introduction" and "Analysis of Literary Data and Problem Statement";

– translation of some sentences from English to Ukrainian, division of long sentences (over 30 words) into shorter ones, and checking the text for spelling and grammar;

– the results provided by AI tools were checked using a spelling dictionary and using the textbook program: Oliynyk O. Grammar of the Ukrainian language: teaching manual. Condor, 2019. 544 p.;

– the result provided by the AI tool did not affect the conclusions of the study in any way.

Authors' contributions

Igor Shevchenko: Conceptualization; Formal analysis; Resources; **Gennadii Golub**: Methodology; Formal analysis; Data curation; **Nataliya Tsyvenkova**: Validation; Writing – review & editing; Funding acquisition; **Andriy Martynyuk**: Supervision; Project administration; **Ivan Rogovskii**: Formal analysis; Investigation; **Oleksandr Medvedskyi**: Writing – original draft; Visualization; **Volodymyr Kulykivskyi**: Software; Data Curation; **Maksym Zayets**: Investigation; Resources; **Victor Biletskii**: Formal analysis; Writing – original draft; Visualization.

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