STUDY OF SOIL STRATUM DEFORMATION BY DISC CULTIVATOR

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Abstract. The article presents the results of theoretical research of soil deformation by operating devices of disc cultivator depending on its constructive and technological parameters and taking into account specific soil conditions. The basis of a new soil-tilling implement contains separate sections, consisting of two discs, fixed on a curved axis with an option of free rotation. The disc rotation planes form an angle of α between themselves. The bending lines of axes of each section lie in one plane, inclined from the vertical line in the direction of forward movement of an implement at an angle of φ, which is provided by the minimum distance between the discs on the surface of the soil in their exit area. According to the research results, the analytical dependences for determining the relative deformation of soil at different values of the constructive and technological parameters of the disc cultivator were obtained. The character of soil destruction and the parameters of uncultivated hillock in the space between the operating devices of the disk were determined. According to the level of the factors influencing the relative soil deformation in depth we can rank the tillage as follows: a wider range of variation belongs to a disk inclination angle of γ, then follows the distance between the discs d and then the disk radius R. For various parameters of operating devices, the soil deformation will occur with different thickness of the destroyed layer, accordingly, with different height sizes of uncultivated hillock at the bottom of the furrow. Its profile will have a distinct arched shape. It is proved, that in conducting further laboratory and field experiments the following values: $\gamma = 9°$, $R = 0.25$ m, $d = 0.15$ m should be taken as a basic level of these factors.

Keywords: soil deformation, disc cultivator, character of soil destruction.

Introduction

The rotary implements with disc operating devices are widely used for surface tillage. They have a number of advantages that make them more preferable in comparison with other implements intended for performing the same operations: simplicity of construction, lower power consumption, higher operational reliability, relatively lower wearing process of operative parts etc. [1-4].

However, analysis of the research in this field demonstrates that all potentials of disc operating devices are not used yet. In Russia, as well as in many other leading countries of Europe, the USA and Canada active research work on development and updating of disc operating tillage devices is carried out [5-10]. Thus, in the process of functioning of concave disc operative parts, which has become a frequent practice for surface tillage, separating of the soil layer from soil monolith and its loosening to a greater extent happen due to deformations of compression and bending. At the same time, the resistance of compression deformation needs the biggest effort and tensile deformation needs the least effort. For example, if we take the tensile strength as 1, then resistance to compression, shear and bending deformations will be accordingly 13, 2 and 10. That is, depending on the type of soil and its moisture, the temporary resistance to compression is almost 13…20 times more, than the adhesive tension, and 2…3 times more than to resistance to shear [11; 12]. Consequently, the most rational way of tilling is using of tensile deformations and shear deformations.

It has been established, that according to the soil deformation and soil loosening theory the results can be achieved in a smaller diameter and flexure of the disc sphere. Flat discs and discs with a smaller diameter work the soil easier and at a less load demand [11].

Besides, while the disks are at work and installed at a disk approach angle in the direction of movement the soil layer shifts to the side. That restricts their use for such perspective technologies as "Strip-till" [8; 10; 13].

Taking the above into account, we have developed a cultivator, the operating parts of which consist of two flat discs inclined to each other in horizontal and vertical planes in a way that the distance between the upper front disc edges is bigger than between the lower back ones [14; 15]. When moving of the discs in the soil, the furrow slice binds between them, gets off the bottom of the furrow, slightly lifts up and settles back in the furrow in a loose state. During the work of the discs the topsoil is deformed and it lifts off the basic soil monolith due to tensile deformations. However, for accomplishment of the required quality of soil tillage, it is necessary to justify the rational value of the constructive and regulative parameters of the developed disc cultivator.

The aim of this paper is to identify the character of soil layer destruction in between the disk space and to justify the varying levels of the constructive and regulative parameters of the disc cultivator, affecting the relative soil deformation with the purpose of further enhancing of laboratory and field experiments.

Materials and methods

Operating devices of the disc cultivator contain separate sections (Fig.1), consisting of two discs, fixed on a curved axis with an option of free rotation. The disc rotation planes form an angle of α between themselves. The bending lines of the axes of each section lie in one plane, inclined from the vertical line in direction of forward movement of an implement V at an angle of φ, which is provided by the minimum distance between the discs at the surface of the soil in their exit area. The value of an angle φ, that satisfies this condition, was determined by the formula:

$$\varphi = \arccos\left(1 - \frac{a}{R}\right), \tag{1}$$

where a – the tillage depth, m;
R – the radius of the disks, m.

Fig. 2 presents an experimental device for laboratory and field research for justification of rational values of the following constructive and regulating parameters of the disc cultivator: the angle of incline of the discs γ, the distance between the discs d and the radius of the discs R.

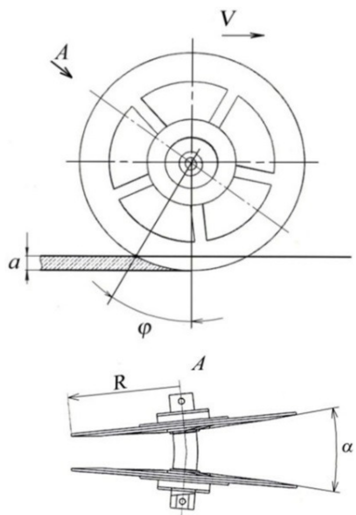

Fig. 1. **Section of a disc cultivator**

Fig. 2. **Experimental device for laboratory and field research**

Theoretical studies were performed using the methods of classical mechanics. It is necessary to obtain the formula of the disc edge rotation velocity for optimization of the constructive and regulating parameters of the operating device, taking into account specific soil conditions, characterized by major mechanical parameters of the soil, and depending on the tillage depth.

Coordinate axes, related to the aggregate frame, are marked as (x, y, z) (Fig. 3), the ones belonging to the disc are marked as (x_2, y_2, z_2) and intermediate axis as (x_1, y_1, z_1). Cylindrical coordinates were introduced for description (Fig. 4) of points on the disk in the system (x_2, y_2, z_2).

Herewith, the angle $\omega_2 t$ will be read from the lowest point of the disc in z-direction in the system (x, y, z). The beginning of disk input into the soil corresponds to the angle of$\omega_2 t = -\varphi_2$, and the exit from the soil corresponds to$\omega_2 t = \varphi_2$, where $\omega_2 = V/R$. Thus, the formula of a radius R circle in axes (x_2, y_2, z_2) will be:

$$\begin{cases} x_2 = b \\ y_2 = R\cos\left(\omega_2 t - \dfrac{\pi}{2} - \varphi_2\right), \\ z_2 = R\sin\left(\omega_2 t - \dfrac{\pi}{2} - \varphi_2\right) \end{cases} \tag{2}$$

where b – the shift of the disc center from the origin of coordinates, m.

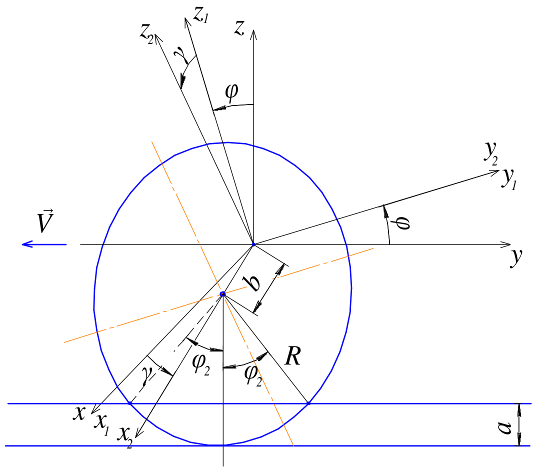

Fig. 3. **Transformation of disc coordinate points, in passing to the coordinate axis, related to the aggregate frame (x, y, z)**

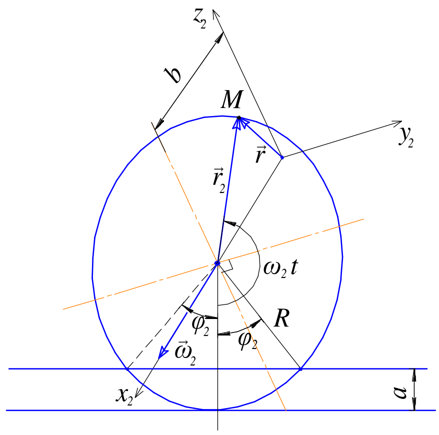

Fig. 4. **Diagram for determining the formula of the disc edge circumference in the system (x_2, y_2, z_2) in cylindrical coordinates**

For internal disc points, a current radius of which is $R_t \leq R$, the formula (2) will be valid for the replacement of R by R_t.

The transformation of coordinates (2) in a reference system, related to the aggregate frame, will be carried out by rotation of two axes.

The first rotation of the axes (x, y, z) towards the axes (x_1, y_1, z_1) will be performed at an angle of φ (1) around the axis of x. The second rotation of the axes (x_1, y_1, z_1) will be done to the angle γ around the axis y_1 (Fig. 2). Cylindrical radius $\bar{r}_2$ of an arbitrary point M on the circumference of the disc is connected with the disc center and rotates with an angular velocity of ω_2.

During analytical studies it is convenient to assume that the angular velocity is $\omega_2 = 1$, and consider it as the coefficient at a parameter of t for definition of a circle in cylindrical coordinates. Then the radius vector $\bar{r}$ relating to the origin of reading of $\bar{r}(x_2, y_2, z_2)$ is transformed as follows:

$$\begin{Bmatrix} x \\ y \\ z \end{Bmatrix} = [A_x(\varphi)][A_{y1}(\gamma)]\begin{Bmatrix} x_2 \\ y_2 \\ z_2 \end{Bmatrix}, \tag{3}$$

where $[A_x(\varphi)]$ – a matrix of rotation around the x-axis:

$$[A_x(\varphi)] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\varphi & -\sin\varphi \\ 0 & \sin\varphi & \cos\varphi \end{bmatrix}, \tag{4}$$

$$\left[A_{y1}(\gamma)\right]=\begin{bmatrix}\cos\gamma & 0 & \sin\gamma\\ 0 & 1 & 0\\ -\sin\gamma & 0 & \cos\gamma\end{bmatrix}. \qquad (5)$$

Angle γ corresponds to a disc inclination from the vertical plane. It equals to $\gamma = \alpha/2$, where α is a minimum angle between two discs. The value b is a shift of discs along the x_2-axis from the origin of reading and equals to:

$$b=\frac{d}{2}+R\sin\gamma,$$

where d – the minimum distance between the discs on a circle of the radius R, m.

According to formula (3) the results obtained are the following:

$$\begin{cases} x=b\cos\gamma+R\sin\left(\omega_2 t-\varphi_2-\frac{\pi}{2}\right)\sin\gamma \\ y=R\cos\left(\omega_2 t-\varphi_2-\frac{\pi}{2}\right)\cos\varphi+b\sin\gamma\sin\varphi-R\sin\left(\omega_2 t-\varphi_2-\frac{\pi}{2}\right)\cos\gamma\sin\varphi \\ z=R\cos\left(\omega_2 t-\varphi_2-\frac{\pi}{2}\right)\sin\varphi-b\sin\gamma\cos\varphi+R\sin\left(\omega_2 t-\varphi_2-\frac{\pi}{2}\right)\cos\gamma\cos\varphi \end{cases}. \qquad (6)$$

The relationship between the angles φ and φ_2 is presented by the following formula:

$$\tan\varphi_2=\tan\varphi\cos\gamma,$$

as φ is a projection of an angle φ_2 on the plane (z, y),subsequently:

$$\varphi_2=\arctan(\tan\varphi\cos\gamma).$$

At small angles of γ, the angle $\varphi_2 \approx \varphi$.

If $t = 0$, the radius of the disk r_2 is at the lowest point, then the soil deformation at the depth z depends on the difference of the x coordinates at $\omega_2 t = -\varphi_2$ and $\omega_2 t = \varphi_2$, and the relative deformation is written as:

$$\varepsilon(t)=\frac{x(-\omega_2 t)-x(\omega_2 t)}{x(-\omega_2 t)}. \qquad (7)$$

In the range of $-\varphi_2$ to φ_2 the values are changed by means of minor intervals, in that case $\omega_2 t = 0\ldots\varphi_2$ is true.

Using dependences $\varepsilon(t)$ from the depth of z-coordinate (Fig. 5-7), with the help of a well-known dependency diagram of soil resistivity to its crushing from its linear deformation [16, 17], we can determine the maximum working depth of the operating devices, in which the soil destruction occurs between the discs. The values of relative deformation, smaller than $\varepsilon_{lim.}$, correspond to the depth z (t), in which the soil between the disks will not be loosened.

According to the laboratory experiments the limit of relative deformation of light gray forest soil is $\varepsilon_{lim.} = 0.122$. Guaranteed soil destruction takes place at higher values of relative deformation.

Results and discussion

From the preliminary analysis, it can be assumed that the tillage depth of the operating devices into the soil and the soil layer thickness, which undergoes destruction, are not the same, as the soil reaches the limit value of relative deformation at some distance from the bottom of the furrow, formed by the disc edges. With increasing the tillage depth, the undistorted layer thickness (a hillock) will decrease both in absolute terms and percentagewise to the treated layer thickness (the thickness of the tilled soil). For example, (Fig. 5) for the distance between disks $d = 0.20$ m and for a tillage depth of

0.06 m the height of the hillock will be 0.023 m or 38.3 % of the working depth, while tilling soil on the depth of 0.16 m it will be 0.015 m or 9.4 %.

According to the level of factors in the selected interval their changes depending on relative soil deformation in depth can be ranked as follows: a wider range of variation belongs to disk the inclination angle of γ, then follows the distance between the discs d and then the disk radius R. The significance of influence of factors on optimization criteria can be identified as a result of laboratory and field experiments.

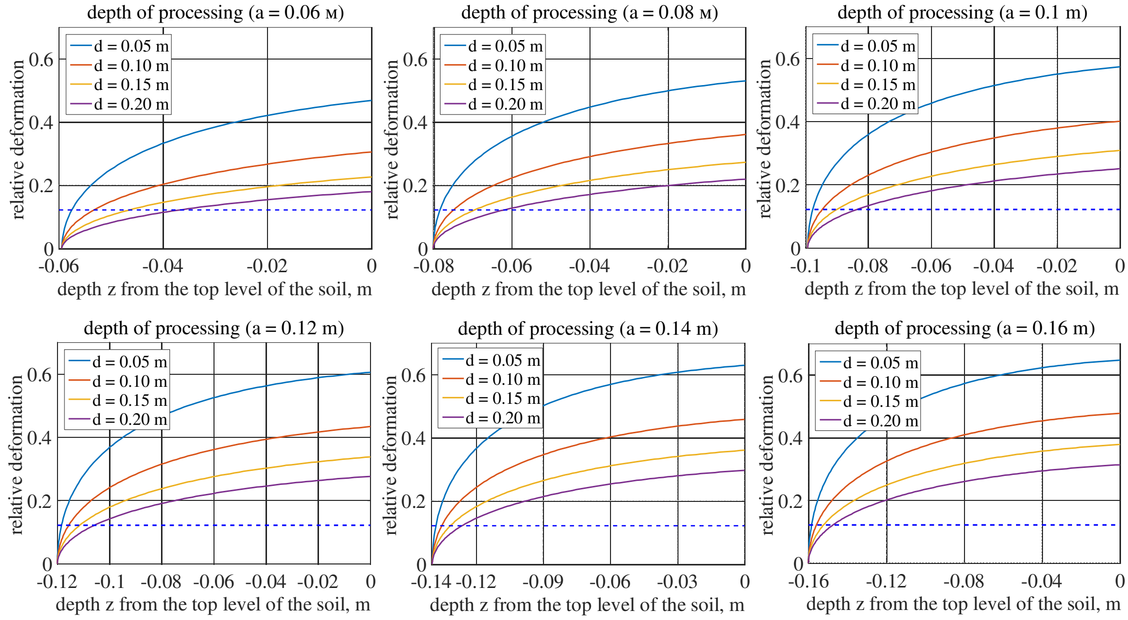

Fig. 5. **Dependence of relative soil deformation ε from z coordinate at different values of tillage depth and the distance between discs d (for fixed values of disc radius R = 0.25 m and the disc inclination angle of γ = 6°; ----- the limit value of relative soil deformation)**

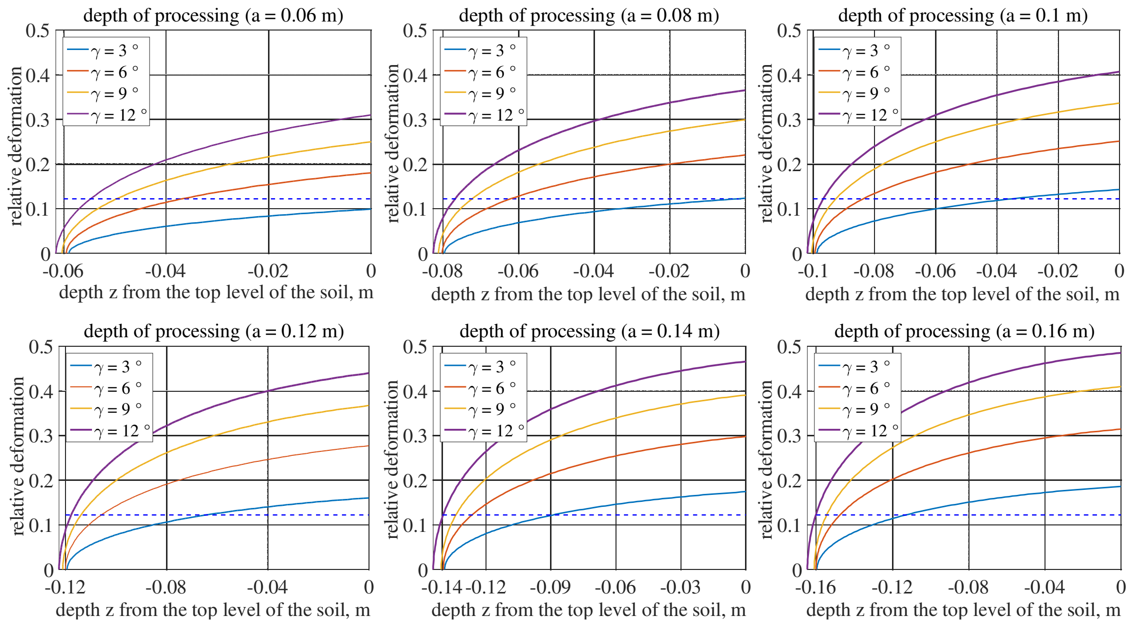

Fig. 6. **Dependence of relative soil deformation ε from z coordinate at different values of tillage depth and the disc inclination angle of γ (for fixed values of disc radius R = 0.25 m and the distance between discs d = 0.2 m; ------ the limit value of relative soil deformation)**

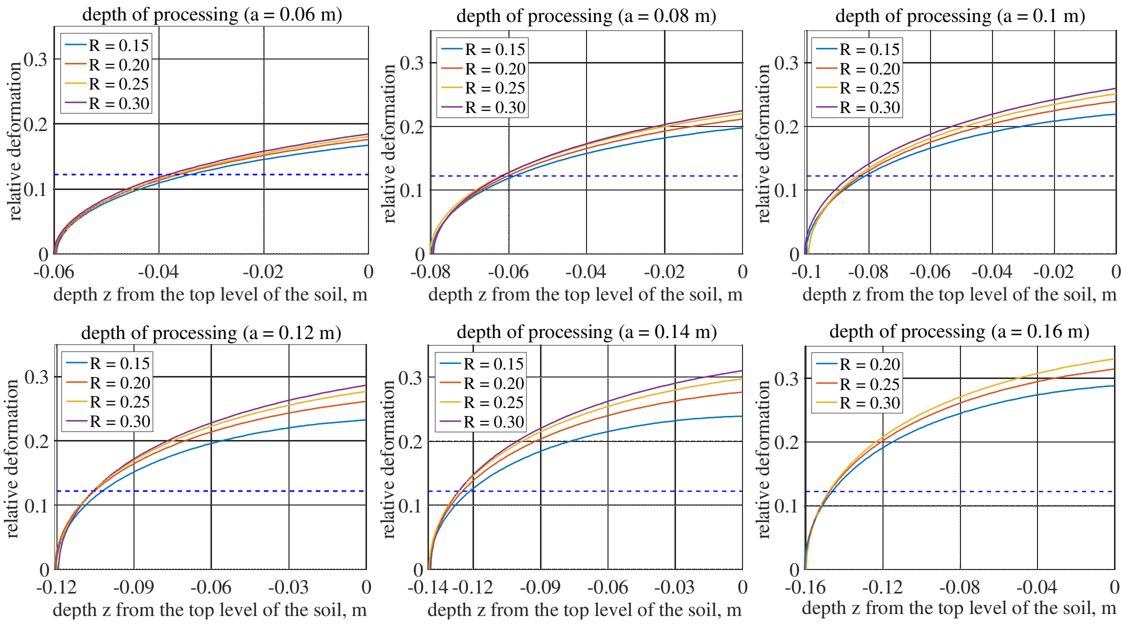

Fig. 7. **Dependence of relative soil deformation ε from z coordinate at different values of tillage depth and distance between discs d (for fixed values of disc radius R = 0.25 m and the disc inclination angle of γ = 6º; ------- the limit value of relative soil deformation)**

Considering an impact of inclination of the disc angle of γ on relative soil deformation (Fig. 6), we see that when γ = 3° at a tilling depths of 0.06 m and 0.08 m light gray forest soil does not reach the limiting value of relative deformation. Considering the influence of disk inclination angles on stability of the deformed soil layer at varying depths of the operating devices, we come to a conclusion that it will be the highest with this factor. If an angle value is γ = 9° and the discs are installed on the depth of 0.06 m, the soil layer thickness, exposed to the guaranteed destruction, will be 83.3 % of the given and if the installation discs are on the depth of 0.16 m, it will be 94.4 % of the given. Therefore, in future studies we will use the value of this angle as the major factor of this level.

The greatest variation of the thickness of soil being destroyed from the depth of tillage was detected for the disc radius R (Fig. 7). It will be 60 %, when installing the disc with the radius of 0.25 m at the tilling depth of 0.06 m and it will be 93.7 % at the tilling depth of 0.16 m. It should be noted, that there has not been revealed a significant change in the soil layer thickness with the guaranteed destruction depending on the radius of the disc. That is why, from the point of view of technical and technological considerations we will use the value of R = 0.25 m as the main level of this factor.

The factor d has a slightly lower varying value of the deformable soil layer depending on the tillage depth of the disc operating devices than the R has. Thus, it will be 61.6 % of the initial one, when installing discs at a distance of 0.20 m and at a depth of tillage of 0.06 m, and it will be 91 % at a depth of 0.16 m. The resulting graphical dependences allow us to conclude, that the greatest relative soil deformations are developed at short distances between the discs. At the same time, increasing the distance between them to values in the range from 0.15 to 0.20 m, does not lead to a significant reduction of soil deformation. Therefore, we will use the value of the distance between the discs d = 0,15 m as the basic level of this factor.

Figures 5, 6, 7 present dependences of relative soil deformation ε from the constructive and regulating parameters of the operating device due to the impact of only one disk. For a visual representation of the character of soil destruction and hillock parameters in between the disk space, the diagrams of soil deformation depending on exposure of two discs are shown in Figures 8 and 9.

According to the figures, the guaranteed destruction of the soil will occur when the limit value of soil deformation is $\varepsilon_{lim.}$ = 0.122 and more. On the charts, it is between the vertical lines, marked $\varepsilon_{lim.}$ and are, respectively, on the right for the left disc and on the left for the right disc. In the figures the discs are fixed at a distance corresponding to ε = 1, that is when they can be completely overlapped. Its numerical value is slightly less, than the radius of the disk, which is equal to 0.25 m.

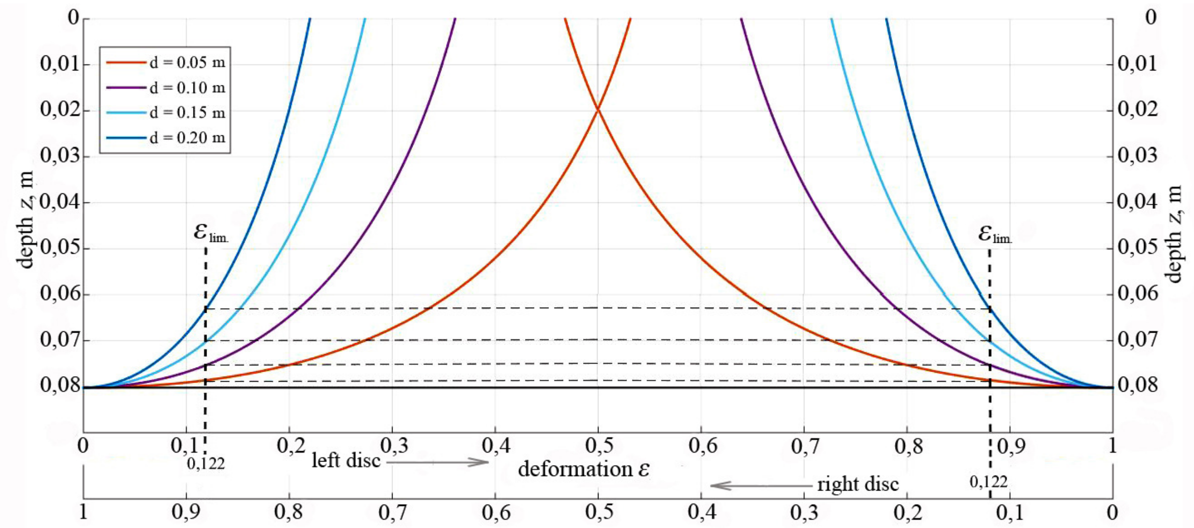

Fig. 8. **Diagrams of soil deformation at tilling depth of *a* = 0.08 m and at different values of distance between disks *d* (for fixed values of disc radius *R* = 0.25 m and inclination angles of *γ* = 6º)**

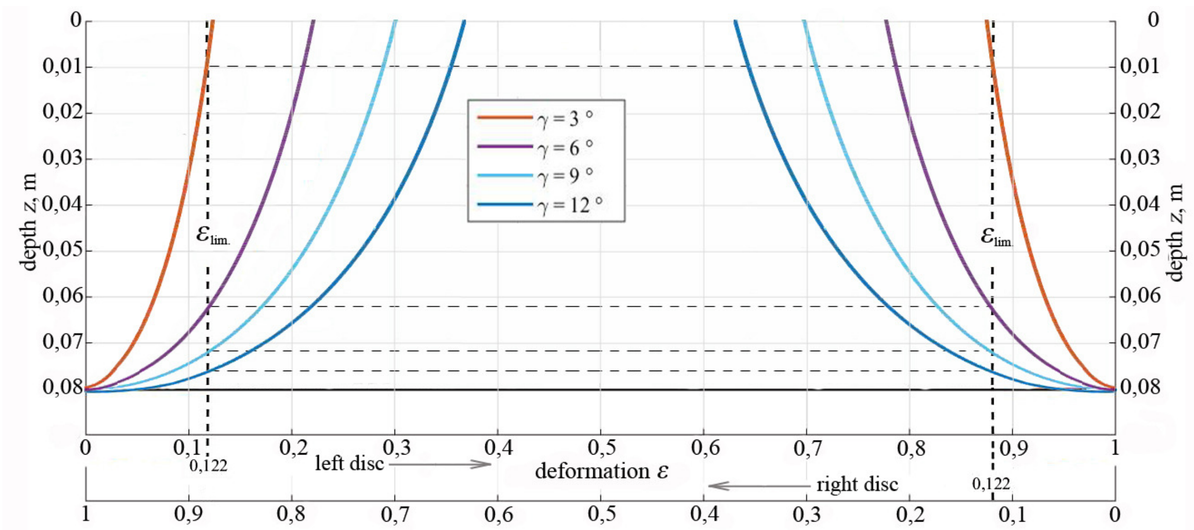

Fig. 9.**Diagrams of soil deformation at tilling depth of *a* = 0.08 m and different values of disc inclination angle of *γ* (for fixed values of disc radius *R* = 0.25 m and distance between discs *d* = 0.2 m)**

In real conditions, the distance between the discs will be less on the aggregate. As it has been suggested earlier, for various parameters soil deformation will occur with varying thickness of the destroyed layer and, respectively, with different sizes in the height of the soil hillock at the bottom of the furrow. Its profile is indicated by dashed lines in the figures. Nevertheless, we believe, that there will not be weeding, which is parallel to the soil surface, because the stress in the soil will die out as the distance from the discs increases, and the profile of uncultivated hillock will have a distinct arched shape. That is why it is necessary to carry out pilot studies to confirm the theoretical assumptions.

Conclusions

Thus, the level of factors influencing relative soil deformation according to its tillage depth can be ranked as follows: a wider range of variation belongs to the disk inclination angle of *γ*, then follows the distance between the discs *d* and then the disk radius *R*.

Inconductingfurtherlaboratoryandfieldexperimentsforgrayforestsoilsthe following values should be taken into consideration as the basic level of these factors: *γ* = 9º, *R* = 0.25 m, *d* = 0.15 m. For other types of soils having different physical properties, the rational values of the given factors will be different. They will be defined by the value of $\varepsilon_{пред}$, for the relevant soil conditions.

For various parameters of the operating devices soil deformation will occur with different thickness of the destroyed layer and, accordingly, with different height sizes of uncultivated hillock at the bottom of the furrow. Its profile will have a distinct arched shape.

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