UDC 631.5
DOI: 10.15587/1729-4061.2016.79912

DEVELOPING THE METHOD OF CONSTRUCTING MATHEMATICAL MODELS OF SOIL CONDITION UNDER THE ACTION OF A WEDGE

Описано математичну модель для визначення напружень, які виникають в грунті під впливом клина. Отримано залежності, за допомогою яких для різної глибини обробітку і показників міцності грунту в залежності від заданих параметрів якості проведення операцій можна визначити необхідний кут кришення. Отримані залежності дозволили визначити параметри динамічних систем, які сприяють зниженню їх енергоємності, підвищенню якісних показників роботи і створенню умов для підвищення продуктивності агрегатів

Ключові слова: *клин, грунт, метод варіаційного обчислення, пласт ґрунту, зрив, сколювання, зрушення, кришення, долото, чизельний робочий орган*

Описана математическая модель для определения напряжений, которые возникают в почве под воздействием клина. Получены зависимости, с помощью которых для разной глубины обработки и прочностных показателей почвы в зависимости от заданных параметров качества проведения операции можно определить необходимый угол крошения. Полученные зависимости позволили определить параметры динамических систем, которые способствуют снижению их энергоемкости, повышению качественных показателей работы и созданию условий для повышения производительности агрегатов

Ключевые слова: *клин, почва, метод вариационного исчисления, пласт почвы, срыв, скалывание, сдвиг, крошение, долото, чизельный рабочий орган*

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1. Introduction

In the course of mechanized treatment, working bodies of agricultural machines and tools act on soil thus contributing to changing its structural condition [1, 2]. For simplification of the study of physical essence of the process of action of working body on soil, [3] proposes to consider working body as a simple wedge or totality of the set of simple wedges. The history of development of the study on the work of a wedge was examined in the context of general theory of cutting materials.

Ref. [3] divided the process of forming a layer of soil, separated by wedge, into two phases: the first one is the crumpling and compaction of the undercut layer of soil; the second one is the shift of this layer. Analysis of results of the studies established that separation of the layer of soil from a monolith occurs by shift or separation depending on physical-mechanical properties of cultivated soils.

The described model of physical essence of the process of interaction between wedge and soil is widely used in practice for solving many problems on the substantiation of parameters of the soil-cultivating working bodies. However, the physical essence of the processes, which occur under the action of wedge in a separated layer of soil, has been examined insufficiently. By the summary of studies [3], this is caused by specific character of the process of interaction between soil and wedge, which is accompanied by deformation of the layer. The latter fact is the "basic obstacle for any kind of theoretical studies" [3].

A study of the technique of constructing a mathematical model, which will describe physical processes of crushing a layer of soil by a wedge, may be used for finding rational angles of crushing of the working bodies depending on mechanical properties of soil and depth of its cultivation, it will make it possible to increase the quality of work of agricultural machines, which is a relevant and promising task.

2. Literature review and problem statement

Based on the analysis [4–9] of results of numerous experiments, it was established that for the cohesive soils the separation of layer of soil by a wedge from its main mass occurs by its ripping. For describing physical essence of the phenomenon, we will use hypothesis about separation of the undercut layer of soil by a wedge by its bending. In this case, soil in the course of simulation will be considered as homogeneous medium with equal strength properties in its entire volume, exposed to the action of wedge, but with different mechanical characteristics at compression and under tension.

The values of maximum allowable stress are determined by original properties of the treated soil [10, 11]. For the loosely compacted or previously treated soils, the values of maximum allowable stress are insignificant and the process of separation of the layer of soil occurs with a smaller effort of bending. Normal and shearing stresses that occur in the layer of soil at bending depend on the ratio between length and thickness of the treated layer of soil. With the increase in this ratio, the values of shearing stresses are reduced and of those normal – grow. Therefore, it is possible to make a conclusion that the length of the formed layer of soil is relatively small for the loosely compacted soils and the soils with relatively low maximum allowable stress. In this case, predominant stresses in soil are the shearing stresses. As a consequence, the process of separation of the layer of soil occurs by the shift [9, 12]. In the cohesive soils with relatively large maximum permissible values of stress, destruction occurs at the larger values of bending, i. e., at a large length of the separated layer of soil. Predominant in that case are the normal stresses and separation of the layer of soil is performed due to its ripping from the bulk. The accepted hypothesis [11] of physical model of the destruction of soil under the action of wedge rather well agrees with the results of numerous studies. Furthermore, this hypothesis makes it possible to consider that the magnitude of normal and shearing stresses in the separated layer of soil is affected by the depth of soil treatment. That is why the process of formation a lump by its separation from the bulk by shift or by ripping is determined not only by the physical-mechanical properties of soil, parameters of a working body, but also by depth of its motion in the soil.

From energy point of view, there is a more perfect process, in the course of which soil cleaving is carried out by ripping. That is why we will further investigate such spatial orientation of wedge, at which this effect is observed. It is caused by predominance of normal stresses above the shearing ones. We will assume that the wedge that acts on the soil layer causes only bending moment in it, while transverse and normal forces are so low that it is possible not to consider them, i. e., there is a "pure" bend [13].

3. Aim and tasks of the study

The purpose of the work is theoretical studies of the process of action of wedge on soil, as a result of which, using the methods of the calculus of variations, it is necessary to construct rational profiles of the chisel of a chisel blade and the chisel of a chisel working body. Application of the method of the calculus of variations makes it possible to decrease energy intensity of the soil-cultivating working bodies by 20...30 %.

To accomplish the goal, the following tasks were set:

– to substantiate the profile of chisel, which ensures reduction in its energy intensity;

– to perform calculation of rational parameters of chisel working bodies with the help of variational methods of calculation;

– to substantiate the profile of wing of a point;

– to experimentally investigate the process of interaction between wedge and soil.

4. Theoretical studies of parameters of action of wedge in the soil with their experimental identification

4. 1. Substantiation of parameters of the chisel working bodies

The substantiation of geometric parameters of the chisel of a chisel blade was carried out with the use of direct method of the calculus of variations [8, 14–16]. The rational profile of a chisel was determined after assigning the condition that its curve passes through the fixed points with the preset angle of inclination at the initial point. In this case, the variational problem is limited by the condition: among the set of the curves that pass through two fixed points and that emerge from the initial point at a preset angle, it is necessary to determine the curve, which corresponds to the profile line of the chisel of a chisel working body with a minimum traction resistance. In this formulation of the problem at $H_0=0$; $X_k=0{,}5$ m; $Z_k=0{,}3$ m; f=0,5; $Z'_0=0{,}57$; $X_0=0$; $Z_0=0$, the profile of the chisel was obtained.

The substantiation of the profile of a chisel was carried out with regard to its joint operation with a point at the fixed boundary conditions and the angle of inclination of the tangent at initial point equal to 30°. At the local loosening of soil, there is no need to use a point together with the chisel and thus increase the traction resistance of a chisel working body. In this case, it is expedient to search for the rational profile of a chisel with one floating boundary point.

The angle of inclination of the tangent at the initial point of the given curve was assigned based on the corresponding angle of inclination of the chisel of a standard working body of the chisel plow PCh-2.5, Geascon SS-7NR [17] and others. However, analysis of dependencies [8] of maximum tensile stresses in soil, which occur under the action of wedge, reveals that even at relatively high permissible stress $[\sigma]_p=8$ kN/m^2 at depths of motion of a wedge from 0,16 to 0,20 m, it is reached at the angle whose value is in the interval between 24 and 30°. Then the setting of the problem is formulated as follows. It is necessary, among the set of the curves that start from the given point at angle 27°, determined experimentally and passing through the second boundary point, which is displaced along the $Z=Z_k$ straight line, to find the curve that describes the profile of a chisel at the minimum traction resistance.

To solve the problem, we will use the method of direct calculus of variations. The desired profile is assigned in the form of equation that satisfies conditions of formulation of the problem [4, 14, 18]:

$$Z=-C_1\left\{\exp\left[C_2X^2\left(X_k-X\right)\right]-1\right\}+Z'_0X+\frac{X^2\left(Z_k-X_kZ'_0\right)}{X_k^2}, \quad (1)$$

where C_1; C_2 are the required coefficients.

The values of constant coefficients C_1, C_2 and boundary point X_k will be found from the solution of the following integral system of equations:

$$\frac{\partial R_x}{\partial C_i}=b\rho\vartheta^2\int_{x_0}^{x_k}\left\{\frac{(f+Z')\cdot Z'}{Z_k\left(f+(Z')^2\right)}\cdot\frac{\partial Z}{\partial Ci}+\left[1-\frac{Z-H_0}{Z_k}\right]\times\right.$$
$$\left.\times\left[\frac{\left(3+(Z')^2\right)(f+Z')}{\left(1+(Z')^2\right)^2}+\frac{Z'}{1+(Z')^2}\right]\frac{\partial Z'}{\partial Ci}\right\}(Z')^2\,dx+$$
$$+F\big|_{x=x_k}\frac{\partial X_k}{\partial C_i}=0;$$

$i=\overline{1;2}$;

$$X_k=\frac{F_1(f)}{2C_1C_2}+\left[\left(\frac{F_1(f)}{2C_1C_2}\right)^2+\frac{Z_k}{C_1C_2}\right];\qquad(2)$$

where $F_1(f)=C_1C_2X_k+Z_k/X_k$.

$$Z'=-2XC_1C_2\left(X_k-\frac{3}{2}X\right)\left\{\exp\left[C_2X^2(X_k-X)\right]-1\right\}+$$
$$+Z_0'+\frac{2X\left(Z_k-X_k'Z_0'\right)}{X_k^2};$$

$$\frac{\partial Z}{\partial C_1}=-\exp\left[C_2X^2(X_k-X)\ \right]+1;$$

$$\frac{\partial Z}{\partial C_2}=-C_1X^2(X_k-X)\exp\left[C_2X^2(X_k-X)\right];$$

$$\frac{\partial Z'}{\partial C_1}=-2XC_2\left(X_k-\frac{3}{2}X\right)\left\{\exp\left[C_2X^2(X_k-X)\right]-1\right\};$$

$$\frac{\partial Z'}{\partial C_2}=-2XC_1\left(X_k-\frac{3}{2}X\right)\times$$
$$\times\left\{\exp\left[C_2X^2(X_k-X)\right]\cdot\left[C_2X^2(X_k-X)+1\right]-1\right\}.$$

The system of equations was solved by numerical method, using the language Basic, at f=0,5 m; Z_0'=0,51; X_0=0; Z_0=0; Z_k=0,3 m; H_0=0.

As a result of solution of the system of equations (2), we obtained values of the coefficients C_1, C_2 and the final coordinate $X_к$, which are 1,425; 2,850 and 0,260 m, respectively.

Equation of the curve that describes the profile of a chisel of the minimum traction resistance will be written down:

$$Z=-1,425\left\{\exp\left[2,850X^2(0,26-X)\right]-1\right\}+$$
$$+0,51X+2,47X^2.\qquad(3)$$

The curved line, built by equation (3), reflects the profile of the chisel of a chisel working body (Fig. 1).

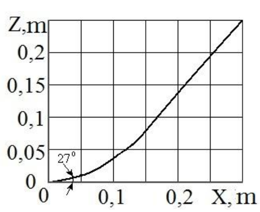

Fig. 1. Profile of the chisel of a chisel blade

The quality of soil treatment before sowing is determined by the depth of its treatment by chisel working bodies and by the distance between them. Moreover, these two parameters are connected together. An increase in the depth of soil treatment leads to increasing energy consumption and worsening soil crushing. A decrease in the depth of soil treatment necessitates a denser arrangement of chisel working bodies for the purpose of eliminating flaws between them. This also increases energy consumption for soil cultivation and for clogging the working bodies by the after-harvest remainders and weeds. Deformation of soil under the action of the points of chisel working bodies spreads at an angle. That is why the design substantiation of the system of arrangement of chisel working bodies is important for improving the working process. Analysis of the process of work of chisel blades demonstrates that their task is to ensure assigned depth of motion under conditions of increased density of soil, as well as to create conditions for better accumulation of moisture and air in soil. With regard to this, there is no need to overlap deformations in soil, which are distributed under the action of chisel blades.

The depth of motion of chisel working bodies and the distance between the treated strips under conditions of the local loosening of soil is determined by natural climatic conditions of a zone, by the condition of soil and by the requirements of growing crop. On one hand, an increase in this distance contributes to the reduction in energy consumption for soil cultivation; on the other hand, it is limited by the need to create conditions for maintaining fertility of soil. Therefore, selection of rational ratio between the depth of loosening and the distance between the loosened strips has important ecological-economic meaning, especially under conditions of minimal systems of soil treatment.

To substantiate parameters of a chisel blade, in particular geometric profile of the rack, we will apply the method of direct calculus of variations. The substantiation of the point of a chisel blade was carried out in two stages. During the first stage, we substantiated the profile of the chisel of the point taking into account the provision of necessary deepening into soil at minimum energy consumption, during the second stage – the profile of the point of minimal energy consumption by the results of the studies, connected with substantiation of the chisel.

To maintain reliability of chisel working bodies during their deepening into the soil, we will conduct the search for a rational profile, the curve of which runs through the fixed points with the preset angle of tangent inclination in the starting point. Then the variational problem is formulated as follows. Among the set of the curves that pass through the fixed points and that start from the initial one at a preset angle, we are to find such curve, which would correspond to the profile line of the chisel rack with the minimal traction resistance.

The energy functional, which determines traction resistance of a chisel blade, will be written down in the following form [18]:

$$R_x=b\cdot\rho\cdot\vartheta^2\int_{x_0}^{x_k}\left[1-\frac{Z-H_0}{Z_k}\right]\frac{Z^3(f+Z')}{1+Z'^2}dX.\qquad(4)$$

We will search for equations of the curve in the form of equation, which would satisfy assigned formulation of the problem, i. e., the curve must pass through coordinates of the boundary points with a preset angle of tangent in the starting point:

$$Z=-C_1\left\{\exp\left[C_2X^2\left(X_k-X\right)\right]-1\right\}+$$
$$+Z'_0X+\frac{X^2\left(Z_k-X_kZ'_0\right)}{X_k^2}, \quad (5)$$

where C_1, C_2 are the required coefficients.

Then

$$Z'=-2XC_1C_2\left(X_k-\frac{3}{2}X\right)\left\{\exp\left[C_2X^2\left(X_k-X\right)\right]-1\right\}+$$
$$+Z'_0+\frac{2X\left(Z_k-X'_kZ'_0\right)}{X_k^2}. \quad (6)$$

After introduction into equation (4) of expressions of formulas (5) and (6), the task is reduced to determining the coefficients C_1, C_2. For this purpose, it is necessary to take derivatives of the obtained equations by coefficients and to equate them to zero

$$\frac{\partial R_x}{\partial C_3}=\hat{a}\rho\vartheta^2\int_{x_0}^{x_k}\left\{\frac{\left(f+Z'\right)\cdot Z'}{Z_k\left(f+Z'^2\right)}\cdot\frac{\partial Z}{\partial Ci}+\left[1-\frac{Z-H_0}{Z_k}\right]\times\right.$$
$$\left.\times\left[\frac{\left(3+Z'^2\right)\left(f+Z'\right)}{\left(1+Z'^2\right)^2}+\frac{Z'}{1+Z'^2}\right]\frac{\partial Z'}{\partial Ci}\right\}Z'^2dx=0,$$

$$u=\overline{1;2}. \quad (7)$$

As a result of numerical solution of the system of equations (7) at $H_0=0$; $X_k=0{,}5$m; Z=0,3 m; f=0,5 m; $Z'_0=0{,}57$ m; $X_0=0$; $Z_0=0$, we will obtain value of coefficients C_1 and C_2, which are equal to 1,160 and 1,298, respectively.

Then the required profile of the chisel is described by equation:

$$Z=-1{,}16\left\{\exp\left[1{,}298X^2\left(0{,}5-X\right)\right]-1\right\}+$$
$$+0{,}57X+0{,}06X^2. \quad (8)$$

The curved line, built by equation (8), reflects the profile of the chisel of a chisel working body (Fig. 2).

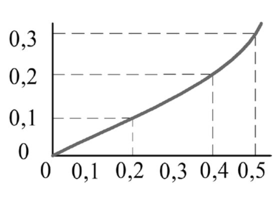

Fig. 2. Rational profile of the chisel of a chisel working body

On the surface of a wing of the point we separate elementary area (Fig. 2), which is exposed to action from specific pressure of soil q and specific frictional force dF. The latter is directed to the side of motion of the layer of soil on the surface of the point. However, the profile of the surface of the point is unknown to us and it is difficult to determine the pattern of motion of the layer of soil by it. Therefore, to simplify solution of the problem, we will consider that elementary frictional force is directed tangentially toward the desired surface and is located in the plane, parallel to the XOZ plane. The latter assumption is based on the fact that the wing of the point is located close to the plowshare of frontal cutting.

We formulate variational problem setting as follows. From a large number of surfaces Z=f(x, y) that pass through points O, C, B and A, we are to find the one, which would ensure an extremum to functional (9). The method of the calculus of variations of Ritz and a finite element method are utilized to solve the problem [19].

Energy functional for determining traction resistance of the point's wing takes the form [18, 19]:

$$R_x=\int_0^{X_a}\int_0^{Y_{ci}}\left(q_x+dF\right)dX\cdot dY, \quad (9)$$

$$q_x=\rho\vartheta^2\left[1-\frac{Z}{H}\right]\frac{Z_x'^4}{\left(1+Z_x'^2\right)\cdot\left(1+Z_x'^2+Z_y'^2\right)^{\frac{1}{2}}}, \quad (10)$$

$$dF=f\rho\vartheta^2\left[1-\frac{Z}{H}\right]\frac{Z_x'^3}{\left(1+Z_x'^2\right)^{\frac{3}{2}}}, \quad (11)$$

where H is the depth of motion of the point's wing.

Let us project the required surface onto the plane XOY (Fig. 3).

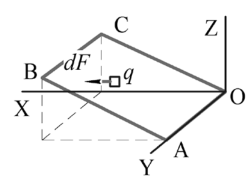

Fig. 3. Scheme to the substantiation of the point's wing profile

The equations of lines, which limit the projection of the wing's surface, will be written down [5, 17, 18]:

в=0; в=вce; x=xa; x=0. (12)

We present a piecewise linear approximation of the required surface in the form:

$$Z=\sum_{k=1}^{m}C_k\varphi_k, \quad (13)$$

where C_k are the required coefficients; φ_k are the basic functions.

Basic functions are linear, piecewise continuous and are equal to unity in the nodes and to zero beyond the area of determination. Basic functions are determined for all elements m, which have connections with the node k*:*

$$\varphi_k=\sum_{n=1}^{m}\varphi_k^{ej}, \quad (14)$$

where m=20.

We assign numbers to nodes и, j and k with strict retention of the order of motion of the sequence counterclockwise of indicated indices.

The system of functions of form takes the form [16, 17]:

$$\varphi_j^{eo}=\begin{cases}-\dfrac{1}{2S}\left[\left(X-X_j\right)\cdot\left(Y_k-Y_j\right)-\left(Y-Y_j\right)\cdot\left(X_k-X_j\right)\right] & \text{at } (X;Y)\in\ell^0,\\ 0 & \text{at } (X;Y)\notin\ell^0,\end{cases} \quad (15)$$

$$\varphi_j^{\ell^0}=\begin{cases}-\dfrac{1}{2S}\left[\left(X-X_k\right)\cdot\left(Y_i-Y_k\right)-\left(Y-Y_k\right)\cdot\left(X_i-X_k\right)\right] & \text{at } (X;Y)\in\ell^0,\\ 0 & \text{at } (X;Y)\notin\ell^0,\end{cases} \quad (16)$$

$$\varphi_k^{\ell^0}=\begin{cases}-\dfrac{1}{2S}\left[\left(X-X_i\right)\cdot\left(Y_j-Y_i\right)-\left(Y-Y_i\right)\cdot\left(X_j-X_i\right)\right] & \text{at } (X;Y)\in\ell^0,\\ 0 & \text{at } (X;Y)\notin\ell^0.\end{cases} \quad (17)$$

To find values of coefficients C_k, which would ensure minimum value to functional, we differentiate equation by C_k, equating them to zero

$$\frac{\partial RX}{\partial C_k}=\int_0^{X_A}\int_0^{Y_{ci}}\frac{\partial\left(q_x+dF\right)}{\partial C_k}dX\,dY=0,\ k=\overline{1,20}. \quad (18)$$

Numerical solution was carried out, using the language Basic [20], at X_a=0,33 m; Yc_i=0,14 m; f=0,5; dx=0,065; dy=0,035; Z_1=0,08; Z_4=0; Z_2=0,03; Z_3=0,05; Z_{17}=0,08 m; Z_{20}=0,08; H=0,16 m; Z_5=0; Z_{12}=0; Z_{13}=0.

Structural composition of soil after cultivation by standard and experimental points is given in Table 1. Energy indices were evaluated by the value of traction resistance.

Table 1

Structural composition of soil after cultivation by standard and experimental points

Point type	Fractions, mm					
	>30	30–20	20–10	10–0,25	<0,25	structure coefficient
Standard	13,30	11,85	11,90	62,55	0,35	1,64
Experimental	11,50	11,10	14,85	62,10	0,29	1,71

Data analysis of Table 1 revealed that the coefficient of structure of soil after its cultivation by chisel standard and experimental points has almost identical value.

Permissible tensile stresses, which appear in soil dependent on its type and properties, caused by humidity and temperature, are within the limits from 2 to 6 kN/m^2. At different strength values of the soil permissible tensile stresses (Fig. 4), its destruction under the action of wedge at the starting moment of motion occurs at the angles of crushing exceeding 18°, which is confirmed by experimental studies [16].

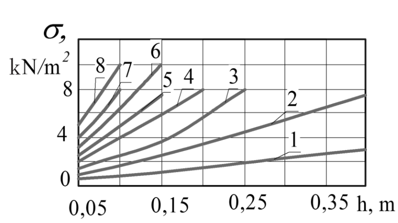

Fig. 4. Dependency of the maximum tensile stresses in soil, which appear under the action of wedge, on the depth of its motion at different angles of crushing: 1 – α=6°; 2 – α=12°; 3 – α=18°; 4 – α=24°; 5 – α=30°; 6 – α=36°; 7 – α=42°; 8 – α=48°

At the angles of crushing 6°, the process of destruction of the integral layer occurs at the depths of motion of wedge exceeding 0,25 m, at 12° – exceeding 0,12 m and at 18° – exceeding 0,07 m. If the soil permissible tensile stresses have maximum value, then at the starting moment of motion of the wedge at the angles of crushing 6° and 12°, and to the depth of its motion equal to 0,3 m, the destruction of the undercut layer of soil does not occur. At the angles of crushing 18°, 24°, 30°, 36°, 42° and 48°, the destruction of layer occurs at the depths of motion of the wedge exceeding 0,20; 0,15; 0,12; 0,09; 0,07 and 0,06 m, respectively [14, 16].

The soil permissible shear stresses vary within the limits of 6...15 kN/m^2. Fig. 5 demonstrates that at the initial moment of motion of the wedge, the shear stresses compared to the tensile stresses have the magnitude, closer to the maximum.

The calculated values of length of the cleaved layer of soil at different depths of cultivation and angles of crushing by a wedge depending on the maximum permissible values of the soil tensile stresses are shown in Fig. 6–8.

The graphs show that with an increase in the depth of motion of wedge and a decrease in the angle of crushing, the size of the formed lumps grows; moreover, it is more intensive with an increase in the strength tensile properties of soil.

For the purpose of reducing the size of lumps in the course of soil cultivation, and at the increase in its depth, it is expedient to increase the angle of crushing the soil by a wedge [16, 19].

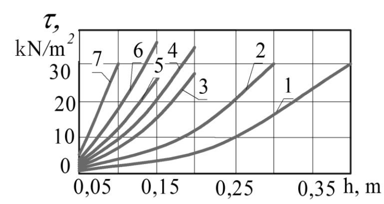

Fig. 5. Dependency of maximum shearing stresses in soil, occurring under the action of wedge at changing the depth of its motion and at different angles of crushing: 1 – α=6°; 2 – α=12°; 3 – α=18°; 4 – α=24°; 5 – α=30°; 6 – α=36°; 7 – α=42°

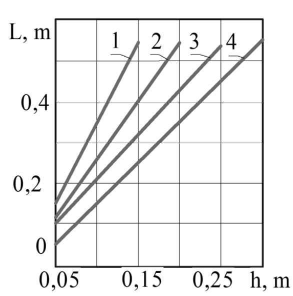

Fig. 6. Dependency of length of the cleaved layer of soil on the depth of motion of wedge for different angles of crushing at permissible tensile stress of 5 kPa: 1 – α=18°; 2 – α=24°; 3 – α=30°; 4 – α=36°

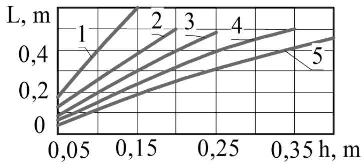

Fig. 7. Dependency of length of the removed layer of soil on the depth of motion of wedge for different angles of crushing at permissible tensile stress of 3,5 kPa: 1 – α=12°; 2 – α=18°; 3 – α=24°; 4 – α=30°; 5 – α=36°

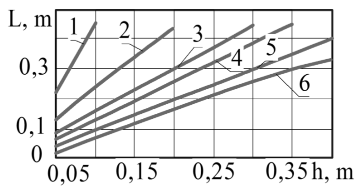

Fig. 8. Dependency of length of the removed layer of soil on the depth of motion of wedge for different angles of crushing at permissible tensile stress of 2 kPa : 1 – α=6°; 2 – α=12°; 3 – α=18°; 4 – α=24°; 5 – α=30°; 6 – α=36°

On the soils with high strength tensile properties, the wedges with angle of crushing less than 18° are expedient to use for treating the soil by depth of up to 0,1 m, with the medium ones – to 0,15 m and with the low ones – to 0,24 m.

Fig. 9, 10 display dependencies of length of the cleaved layer of soil on the depth of soil treatment at different angles of crushing and different permissible values of the soil shearing strength. The character of influence of the depth of motion of wedge and the angle of its crushing on the length of the cleaved layer of soil is the same as when destroying the latter by ripping [16].

Thus, with an increase in the depth of motion of wedge, normal and shearing stresses in soil under its action are growing. If the permissible normal stresses in soil exceed 2 kN/m^2, then the wedges with angles of crushing up to 12° with the depth of motion less than 0,13 m do not ensure creation in the soil of their maximum magnitudes and cleaving of the layer of soil [18].

For treating the soil with the permissible tensile stress of 6 kN/m^2 at the depth of cultivation 0,15 m, the angle of crushing must exceed 24°, and at the depth of 0,22 m – 18°.

For the loosely cohesive soils with maximum permissible shearing stress about 5 kN/m^2, the process of cleaving the layer of soil with wedge with low angles of crushing 6° and 12° starts at the depths of motion exceeding 0,18 and 0,13 m, respectively. With soils treatment by 0,15 m at maximum permissible value of 15 kN/m^2, its boundary values are reached by a wedge with angle of crushing exceeding 18°, while at depth of 0,22 m – exceeding 12°.

Fig. 11 displays dependencies of length of the cleaved layer of soil at different angles of crushing for maximum permissible values equal to 13,5 kPa. The character of effect of angle of crushing and depth of motion of wedge on the length of the cleaved layer is the same as under the action of normal tensile stresses and tangential shearing stresses [19].

The quality of crushing the soil, which is determined by the size of lumps and chunks, formed under the action of the soil-cultivating working bodies, depends on the distance they pass to reaching limiting stresses in soil. An increase in the passage of working bodies to the beginning of the process of cleaving the layer of soil contributes to the formation of lumps and chunks of larger size. Studies revealed that a wedge, depending on the angle of crushing, strength indices of soil and depth of cultivation, can create in it the stresses necessary for cleaving at the initial moment of motion after covering a distance equal to 10 mm and longer. Stresses in soil grow with an increase in the angle of crushing and the depth of cultivation.

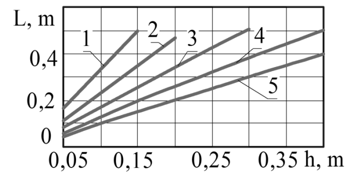

Fig. 9. Dependency of length of the cleaved layer of soil on depth of soil treatment at different angles of crushing for permissible tangential stress of 10,5 kPa: 1 – α=12°; 2 – α=18°; 3 – α=24°; 4 – α=30°; 5 – α=36°

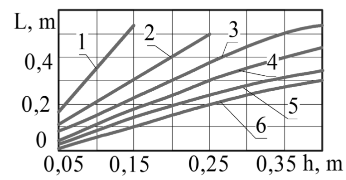

Fig. 10. Dependency of length of the cleaved layer of soil on depth of soil treatment at different angles of crushing for permissible tangential stress of 6 kPa: 1 – α=6°; 2 – α=12°; 3 – α=18°; 4 – α=24°; 5 – α=30°; 6 – α=36°

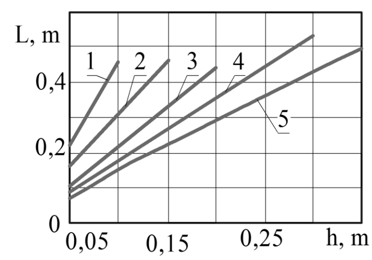

Fig. 11. Dependency of length of the cleaved layer of soil on depth of the motion of wedge at different angles of its crushing for the maximum permissible values: 1 – α=12°; 2 – α=18°; 3 – α=24°; 4 – α=30°; 5 – α=36°

On the soils with high strength properties, the flat cutting blades with angle of crushing less 18° are expedient to be used for treating the soil to depth of up to 0,10 m. Whereas, on the soils with medium strength properties, recommended depth is up to 0,15 m, and with the low ones – up to 0,24 m. At the initial moment of motion of the wedge, the shear stresses relative to the tensile stresses have the magnitude closer to maximum.

Therefore, on the loose soils and at small depths of soil cultivation, the predominant form of deformation is the shift.

The process of crushing soil by wedge by its ripping or shift is determined by physical-mechanical properties of soil, by angle of crushing and by depth of soil treatment [12, 16, 18].

4. 2. Experimental studies of technological processes and working bodies of machines for soil treatment

The soil was crushed and sifted on the sieve with circular openings of diameter 10 mm before putting into a laboratory container. Then the soil was stirred and moistened to humidity of 25...27 %. After moistening, the soil was placed into the container by layers 0,02 m thick. Before filling the soil and after each layer, a chalky layer was laid. The soil in the container was dried to humidity of 24 % and the experiment was carried out in accordance with matrix, given in Table 2.

Before conducting the experiment, in the container with the aid of a shovel, a vertical cross-section of soil was made, a wedge was put under it and the preset angles of crushing and depth of motion were established (Fig. 12).

Table 2

Matrix of experiment on studying the process of interaction between wedge and soil

No. пп	Depth of wedge motion, m	Angle of wedge crushing, degree
1	0,04	15
2	0,06	15
3	0,08	15
4	0,10	15
5	0,04	25
6	0,06	25
7	0,08	25
8	0,10	25
9	0,04	35
10	0,06	35
11	0,08	35
12	0,10	35

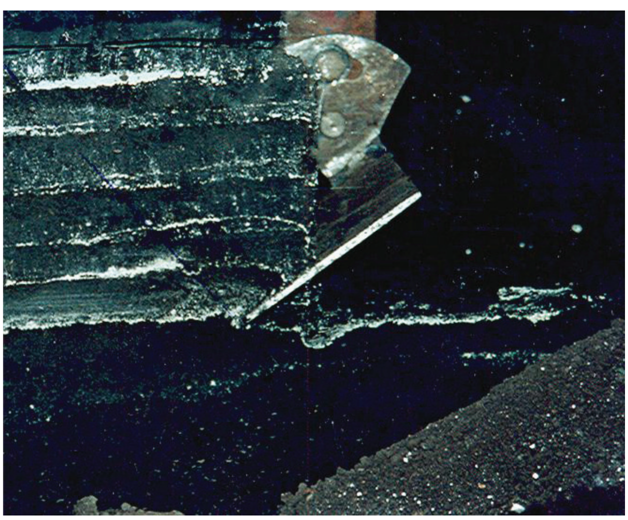

Fig. 12. Scheme of position of the wedge before conducting the experiment

In the process of conducting the experiment, we determined angle of cleaving the soil, the distance covered by wedge prior to the beginning of the process of cleaving and predominant type of the deformation of soil, which leads to cleaving of soil by shift or ripping.

A cart of the soil channel with the wedge was moved with a low speed (υ<0,05 m/s) to the moment of the start of the process of cleaving the layer of soil by the wedge, which was determined visually. After stopping the cart, the path passed by the wedge was photographed and measured with the help of a ruler. The angles of cleaving the layer of soil were determined with the help of a protractor in the photograph. The predominant form of the deformation of soil was judged by the character of change in the positions of chalky layers of the container.

Fig. 13, 14 demonstrate the processes of destruction by ripping and shift, respectively. At the shift of the layer of soil, the character of change in the form of chalky layer in the direction of the surface of cleaving is identical in all layers, located by the depth of treatment. At ripping, the process of destroying the chalky layer begins near the blade of wedge.

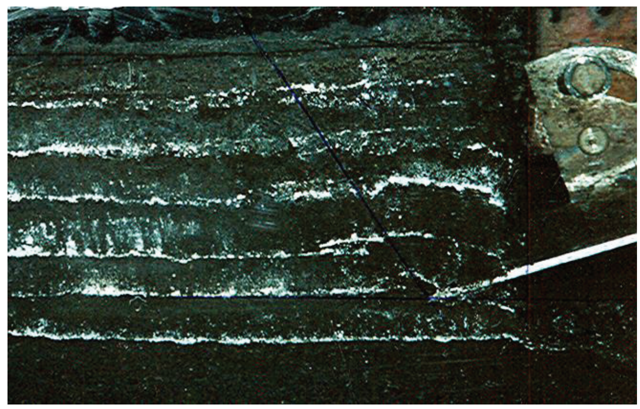

Fig. 13. Scheme of the process of cleaving the layer of soil by ripping

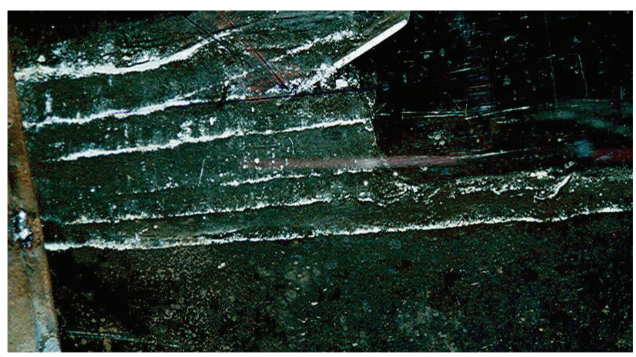

Fig. 14. Scheme of the process of cleaving the layer of soil by shift

For the purpose of reducing influence on the process of cleaving the layer of the soil by random factors, the procedure of experiments was randomized. Experiment on the study of the process of interaction between wedge and soil was carried out at the soil humidity of 24 % in in double repetition.

We studied the influence of parameters of operation of wedge, in particular, angle of crushing and depth of motion in the soil, on the angle of cleaving the layer, the magnitude of the covered distance until the start of the process of cleaving and its character. Results of the conducted studies are given in Table 3.

Table 3

Results of experiment on studying the process of interaction between wedge and soil

No.	Depth of wedge motion, m	Angle of crushing, degree	Covered distance until the start of the process of cleaving, m·10^{-3}			Angle of cleaving, degree			Type of cleaving process
			Repetition			Repetition			
			1	2	Average	1	2	Average	
1	0,04	15	30	32	31,0	40	41	40,5	Shift
2	0,06	15	40	41	40,5	42	43	42,5	Ripping
3	0,08	15	55	53	54,0	49	48	48,5	Ripping
4	0,10	15	62	59	60,5	52	51	51,5	Ripping
5	0,04	25	26	24	25,0	37	38	37,5	Shift
6	0,06	25	33	31	32,0	43	42	42,5	Ripping
7	0,08	25	43	44	43,5	48	45	46,5	Ripping
8	0,10	25	51	49	50,0	52	48	50,0	Ripping
9	0,04	35	22	23	22,5	35	36	35,5	Shift
10	0,06	35	28	26	27,0	43	39	41,0	Ripping
11	0,08	35	35	37	36,0	48	46	47,0	Ripping
12	0,10	35	42	44	43,0	51	52	51,5	Ripping

5. Discussion of results of the studies

Statistical processing of experimental data demonstrates [13, 16] that the factor of influence of the depth of motion of wedge on the magnitude of the covered path until the start of the process of cleaving the layer of soil is 72,67 %, of angle of crushing – 17,45 %, of their pairwise interaction – 2,38 %. Statistical processing of the results was conducted with using two-factor variance analysis [20].

Traction resistance of the chisel working bodies with chisels and points is given in Table 4.

Table 4

Traction resistance of the chisel working bodies, H

Type of chisel	Repetition			Average
	1	2	3	
Standard	1180	1290	1150	1207
Experimental	880	910	990	927
Experimental for local loosening of soil	830	900	880	870

Data analysis of Table 4 demonstrates that the chisel working body with experimental chisel, compared to the standard one, has a lower resistance by approximately 24 %, and with experimental chisel for local loosening of soil – by 28 %.

Statistical processing of the results was conducted using single-factor variance analysis [20]. Variance analysis of the obtained data revealed that they are reliable with probability of 95 %. Comparison of traction resistances of the standard and experimental chisels testifies to the reduction in energy consumption of the latter. Thus, compared with a standard chisel, the experimental chisel has resistance that is lower by 23 %, and the chisel for local loosening – by 28 %.

The variance data analysis of influence of the wide points' profiles on their traction resistance shows that the share of influence of the factor equals 97,04 %; obtained data are reliable with probability of 95 %.

Thus, experimental studies confirm reliability of results of theoretical studies on substantiation of the profile of the chisel of a chisel working body from the point of view of reduction of their energy consumption while keeping the quality of crushing the soil.

Structural composition of soil after treatment by a chisel working body with experimental chisel is given in Table 5.

Table 5

Structural composition of soil after treatment by a chisel working body with experimental chisel

Repetition No.	Fractions, mm					
	>30	30–20	20–10	10–0,25	<0,25	structure coefficient
1	17,32	13,58	17,21	51,18	0,7	1,04
2	17,96	21,56	14,37	52,69	0,59	1,10
Average	17,64	17,57	15,79	52,28	0,64	1,07

Based on results of studies [21], continuous loosening of soil by cultivators may be replaced by local chiselling. In this case, the points of chisel working bodies are to be replaced with chisels. The latter contributes to reduction in the resistance of working bodies by 1,8 times.

It should be noted that under conditions of the wooded plain of Ukraine, the technologies of soil cultivation today are based mainly on fulfilling of a relatively large number of operations, which contributes to the increase in energy consumption and to the reduction in the fertility of soil. Furthermore, when soil is treated by traditional tools, the creation of favorable conditions for the germination of seeds and development of plants is not provided for. That is why the examined task of increasing ecological-economic efficiency of the cultivation of agricultural crops by the development of theory of the process of interaction between soil and wedge may be considered promising. Rational value of angle of crushing soil, dependent on its properties, periods and depth of treatment can be substantiated with the help of the obtained mathematical model, compiled on the basis of hypothesis about separation of a layer of cohesive soil by a wedge through its bending.

6. Conclusions

1. Based on hypothesis about separation of a layer of cohesive soil by a wedge through its bending, we obtained a mathematical model for determining normal and shearing stresses in soil under the action of a wedge. It is demonstrated that the process of crushing of soil with wedge by ripping or shift is determined not only by physical-mechanical properties of soil and by angle of crushing, but also by the depth of treatment. To reduce the size of lumps in the course of soil cultivation while increasing the depth of its execution, it is expedient to increase the angle of crushing. For treating the soil with high strength properties (chernozems of medium and heavy mechanical composition with humidity less than 22 %), the flat cutting blades with angle of crushing less than 18° are expedient to use for treatment by depth of up to 0,10 m, the soils with medium strength properties – to 0,15 m, the soils with low strength properties – to 0,24 m. The obtained mathematical model, which describes physical essence of the process of crushing of the layer of soil by a wedge, can be used for finding rational angles of crushing of working bodies, dependent on the properties of soil and depth of its cultivation.

2. The profile of a chisel from the point of view of reducing its energy consumption is substantiated. It is experimentally established that the value of angle of cleaving the soil practically does not depend on angle of crushing of the layer of soil and it is determined mainly by depth of motion of a wedge. An increase in depth of soil treatment contributes to the growth of the angle of cleaving. In this case, the intensity of increase in the angle of cleaving is reduced with an increase in depth of motion of the wedge. At small depths of soil cultivation up to 0,05 m, the predominant form of deformation is the shift, and with an increase in depth of motion of the wedge – ripping.

3. Experimental studies revealed that the improvement of profile of the chisel of a chisel working body from the point of view of reduction in traction resistance, does not render essential influence to the quality of crushing the soil. In this case, it is found that the angle of propagation of deformations to the side under the action of chisel depends mainly on the depth of its motion in soil and practically does not depend on the angle of crushing, which confirms reliability of results of the studies on examining the process of interaction between soil and wedge. The angle of propagation of deformations in soil is within the limits of 45...75°.

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UDC 621.791:621.926
DOI: 10.15587/1729-4061.2016.81207

DEFINITION OF THE AMOUNT OF HEAT RELEASED DURING METAL CUTTING BY ABRASIVE GRAIN AND THE CONTACT TEMPERATURE OF THE GROUND SURFACE

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Предметом дослідження є процес теплоутворення при шліфуванні металів і сплавів, а об'єктом дослідження – визначення кількості теплоти, що виділяється при різанні металу окремими абразивними зернами, підсумовування теплових потоків від окремих зерен і формування потужності теплового джерела в зоні контакту шліфувального круга зі шліфованої деталлю. Знання теплонапруженості процесу шліфування дає можливість не допускати шліфувальних прижогів і тріщин. Це різко знижує міцність, надійність і довговічність деталі

Ключові слова: шліфування металів, кількість теплоти, теплові потоки, кількість теплоти, теплонапруженість процесу

Предметом исследования является процесс теплообразования при шлифовании металлов и сплавов, а объектом исследования – определение количества теплоты, выделяющееся при резании металла отдельными абразивными зернами, суммирование тепловых потоков от отдельных зерен и формирование мощности теплового источника в зоне контакта шлифовального круга со шлифуемой деталью. Знание теплонапряженности процесса шлифования дает возможность не допускать шлифовочных прижогов и трещин. Это резко снижает прочность, надежность и долговечность детали

Ключевые слова: шлифование металлов, количество теплоты, тепловые потоки, теплонапряженность процесса

1. Introduction

To improve the service life of components operating in harsh conditions, it is necessary that the working surfaces of these parts have the required complex of properties. Increasing requirements for precision of machine parts, the use of new hard manufactured materials, sharply raised the question of an effective fine treatment of blanks, giving them the ultimate accuracy and the necessary range of physical-mechanical characteristics. One type of such treatment and often only one possible is grinding.

Formation of the physical properties of the surface layer of the ground parts largely depends on the temperature range in the contact zone of a wheel with the workpiece that provides a certain phase – structural composition and the texture of the layer, its state of stress. All this has a great influence on the performance of the parts – reliability and durability.