THEORETICAL ANALYSIS OF STRENGTH RESISTANCE TO DISPLACEMENT OF IMPROVED DIGGING WORKING BODY OF POTATOE HARVESTING COMBINE
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ТЕОРЕТИЧНИЙ АНАЛІЗ СИЛ ОПОРУ ПЕРЕМІЩЕННЮ УДОСКОНАЛЕНОГО ПІДКОПУЮЧОГО РОБОЧОГО ОРГАНУ КАРТОПЛЕЗБИРАЛЬНОГО КОМБАЙНА

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ABSTRACT
The amount of energy required to perform technological processes in agriculture largely depends on the size of the resistance to the displacement of the working bodies of machines. The main factor of energy consumption performing the technological process of potato harvesting is the resistance to the displacement of the digging working body. In order to reduce the resistance to displacement an improved design of the digging body is proposed. An analytical study was conducted to determine the problem of moving the working body in the soil environment. The strength of the soil resistance is determined and the regularity of the influence on its change of parameters and the shape of the blade and separation parts of the digging working body is established. Calculations are made using the Mathematica application program. The graphic dependences and contours of the isocline of the traction flange of the working body ploughshare part are obtained. Analysis of the calculations allowed to set the parameters of the instrument panel surface, of which provide a minimum of traction resistance. The schedule and contours of isoclines of the change of the total resistance to the displacement of soil mass with the tubers on the working body separation surface depending on the distance between the bars and the size of their intersection are also obtained. Analysis of the dependence of soil resistance and tubers on the separation surface indicates that an increase in the size of the geometric size of rods intersection leads to a significant increase in the resistance of the medium. The material presented in the article can be used for analytical determination of the resistance of the digging working body of potato harvesting machines of arbitrary geometric shape in the soil medium with tubers.

РЕЗЮМЕ
Величина енергії, потрібна для виконання технологічних процесів у сільському господарстві, значним чином залежить від величин опорів переміщенню робочих органів машин. Основним чинником витрати енергії при виконанні технологічного процесу збирання картоплі є опір переміщенню викопуючого робочого органу. З метою зменшення опору переміщенню запропоновано удосконалену конструкцію викопуючого робочого органу. Виконано аналітичне дослідження, спрямоване на визначення опру переміщення робочого органу у ґрунтовому середовищі. Визначено силу опору грунту та встановлено закономірність впливу на її зміну параметрів і форми лемішної та сепарувальної частин викопуючого робочого органу. Розрахунки виконано з використанням прикладної програми Mathematica. Отримано графічні залежності та контури ізоліній зміни тягового опру лемішної частини робочого органу. Аналіз отриманих розрахунків дозволив встановити параметри поверхні лемішної частини, які забезпечують мінімум тягового опору. Отримано також графік та контури ізоліній зміни повного опору переміщенню маси грунту з бульбами по сепарувальній поверхні робочого органу у функції відстані між прутками та розміру їх перетину. Аналіз залежності опору грунту з бульбами, що знаходяться на сепарувальній поверхні свідчить про те, що збільшення величини геометричного розміру перетину прутків призводить до суттєвого зростання опору середовища. Матеріал, викладений у статті може бути використаний для аналітичного визначення опору переміщення викопувального робочого органу картоплезбиральних машин довільної геометричної форми у грунтовому середовищі з бульбами.

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INTRODUCTION

Potato is one of the most popular vegetable in the world with high yields *(Negar N. et al., 2015)*. Ukraine consumes 136 kg of potatoes per person each year, Russia, Poland - 131 kg, Rwanda - 125 kg, UK -102 kg. The producers of potatoes enrol about 130 countries. Among the most powerful potato producers are New Zealand (average yield of 502 pounds per hectare), the Netherlands (447 pounds/ha), Germany (423 pounds/ha), France (432 pounds/ha), England (405 pounds/ha) *(https://kartofan.org/skolko-sobirayut-kartoshki-v-rossii-i-mire.html)*.

Not only the volumes of produced products but also their high qualitative indices and the level of material and energy costs for growing and harvesting potatoes are important for successful competing in the world market. The formation of the above mentioned factors has a significant influence on the performance of machines for potato harvesting, in particular their traction-performance indicators, which are conditioned by the construction of working bodies, kinematic parameters.

This statement is proved by theoretical and experimental investigations of many scientists *(Amare D. et al, 2015; Popov A.A., 1984; Petrov D.G., 1989; Baio F.H.R. and al, 2004)*.

In addition, the process of collecting potatoes and its parameters is influenced by the nature of the interaction of the working bodies of machines and soil, physical and mechanical properties of soil *(Kushnariov A.S., 1980; Kovbasa V.P., 2001; Frentisek V. et al., 2013)*. The design of the working bodies affects not only the conditions of operation of the machines but also the forces of soil treatment, thus, determining the energy costs for technological processes implementation *(Kosolapov, V.V. et al., 2019; Engin O. et al., 2017); Simdyankin A.A. et al., 2015)*. The solution to the problem of the working body interaction with the soil by establishing the relationship between the geometric parameters and modes of operation of the working body itself with the change of soil properties, as well as, the component of traction resistance is an urgent task that needs to be solved.

MATERIALS AND METHODS

In order to achieve the goal of reducing the energy intensity of the process of picking up potato tubers an improved digging working body for potato harvesting machines *(A. Shymko, O. Nalobina, 2018)* was developed and manufactured and is presented in Fig. 1.

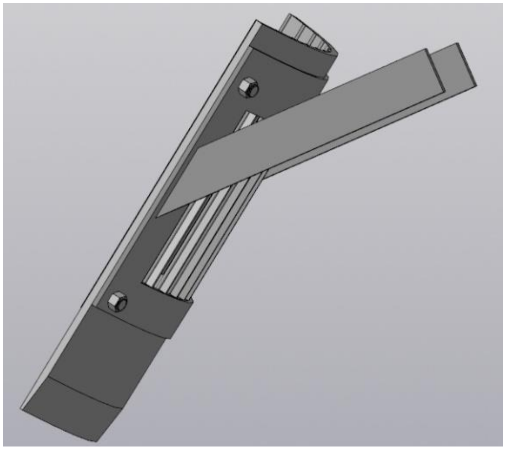


Fig. 1 - Undercutting working body

Schematically, the working body is presented in the form of a structure shown in Fig. 2. Studies on the interaction process of the working body provide a mathematical description of the surfaces of the working body constituent parts and the soil space of the field. With this in mind, two coordinate systems were introduced: xyz which corresponded to the soil space of the field and $\xi\eta\varsigma$, which is adopted to describe the surface equations of the working body constituent parts. Coordinate system $\xi\eta\varsigma$ idem xyz coincides with the coordinate system of the soil half-space. Axis direction x coincides with the direction of the velocity vector V_m of working body. Axis z is directed into the depths of the soil space, and the axis y is perpendicular to the movement direction of the working body and coincides with the surface $z = 0$. This system is adopted to describe the equations of the surfaces of the working body components.

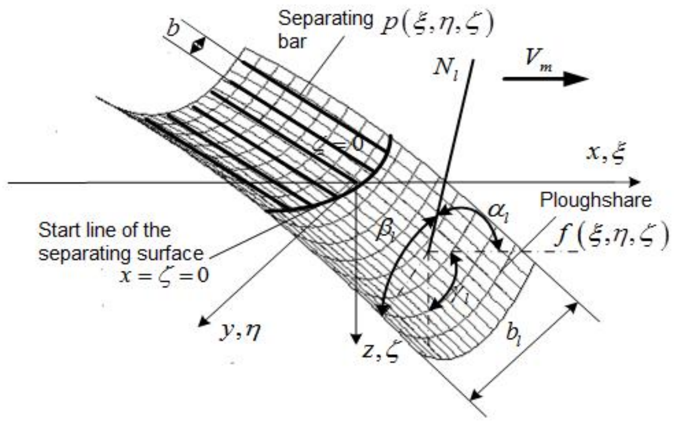


Fig. 2 - General scheme of digging-separating working body

Note*:* In the figure 2, the notations are: $f(\xi,\eta,\varsigma)$ - container surface equation, $p(\xi,\eta,\varsigma)$ - the equation of the surface of the separating rod, *b* - the step of placing the separating bars in the transverse direction, i.e. in the y-axis direction, N_1 - normal to the surface of the ploughshare, α_1 – the angle of inclination of the normal to the surface of the container to the axis ξ *idem* x, β_1 – the angle of inclination of the normal to the surface of the container to the axis η *idem* y, γ_1 the angle of inclination of the normal to the surface of the ploughshare to the axis ς *idem* z, V_m – the speed of movement of the working body in the direction of axis x.

To formalize the surfaces of the working body parts, the equation of the surfaces of its constituent parts was recorded in the coordinate system $\xi\eta\zeta$. The equation of the surface of the ploughshare and the surface in which the separating rods are placed is presented in the form of a hyperbolic paraboloid in an implicit form:

$$f_l=\zeta-\left(d+c\left(\frac{((\phi\xi)+s)^2}{a}-\frac{(\kappa\eta)^2}{b}\right)\right) \tag{1}$$

where ϕ, s, a, κ, b - coefficients characterizing the shape of the location and the parameters of the curvature of the surface of the ploughshare part, which then turns into a bar separating part *(Shymko A., Nalobina O., 2018).* The change of these coefficients leads to a change in the configuration and geometric parameters of the working body *(Shymko A., Nalobina O., 2018).* They will be called form-forming parameters. In solving the problem of the working body interaction to separate the soil chunk from the tubers and further destroy its integrity, a soil model in the form of a viscoelastic medium was adopted, which can be formalized by the Kelvin-Voigt model. The mechanical model of such an environment is shown in Fig. 3. According to this model, due to the application of load, there is a viscoelastic deformation of the material, in which with the increasing speed of load application, the rate of deformation increases in proportion to the decrease in the modulus of viscosity.

For such a mechanical model, the physical equations of stress-strain relationship have the form:

$$\sigma_x=\frac{4}{9}\mathrm{e}^{\frac{Gt}{2\eta(1+\nu)}}\eta(1+\nu\dot{\varepsilon})(6_x-3(\dot{\varepsilon}_y+\dot{\varepsilon}_z)-\frac{\mathrm{e}^{\frac{Gt}{\eta(1+\nu)}}(1+\nu)\dot{\varepsilon}}{-1+2\nu})$$

$$\sigma_y=\frac{4}{9}\mathrm{e}^{\frac{Gt}{2\eta(1+\nu)}}\eta(1+\nu)(-3(\dot{\varepsilon}_x-2\dot{\varepsilon}_y+\dot{\varepsilon}_z)-\frac{\mathrm{e}^{\frac{Gt}{\eta(1+\nu)}}(1+\nu)\dot{\varepsilon}}{-1+2\nu})$$

$$\sigma_z=\frac{4}{9}\mathrm{e}^{\frac{Gt}{2\eta(1+\nu)}}\eta(1+\nu)(-3(\dot{\varepsilon}_x+\dot{\varepsilon}_y-2\dot{\varepsilon}_z)-\frac{\mathrm{e}^{\frac{Gt}{\eta(1+\nu)}}(1+\nu)\dot{\varepsilon}}{-1+2\nu})$$

$$\tau_{xy}=2\mathrm{e}^{\frac{Gt}{2\eta(1+\nu)}}\eta(1+\nu)\dot{\gamma}_{xy},\ \tau_{yz}=2\mathrm{e}^{\frac{Gt}{2\eta(1+\nu)}}\eta(1+\nu)\dot{\gamma}_{yz}, \tag{2}$$

$$\tau_{xz}=2\mathrm{e}^{\frac{Gt}{2\eta(1+\nu)}}\eta(1+\nu)\dot{\gamma}_{xz}$$

where:

$\sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{xz}, \tau_{yz}$ – components of normal deformations and shear deformations, Pa;

G– shear module, Pa; $G = E/\left(2(1+\nu)\right)$;

E – modulus of elasticity of linear deformations, Pa;

ν – Poisson's ratio;

$\dot{\varepsilon} = 1/3(\dot{\varepsilon}_x + \dot{\varepsilon}_y + \dot{\varepsilon}_z)$, where $\dot{\varepsilon}_x, \dot{\varepsilon}_y, \dot{\varepsilon}_z$ – components of linear deformations, s^{-1};

$\dot{\gamma}_{xy}, \dot{\gamma}_{xz}, \dot{\gamma}_{yz}$ – shear deformation components, s^{-1};

η - shear modulus of shear deformations, Pa·s;

t - deformation time, s

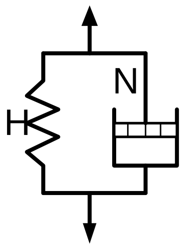


Fig. 3- Mechanical model of viscoelastic medium (soil).
***H* -- elastic element (Hooke's body), *I*-- viscous element (Newton's body)**

It is known that the main factor in energy consumption is the resistance to movement of the working body during the process. Equilibrium equation on the contact surface of the working body with the soil, according to the solution of the elastic equilibrium problem of an anisotropic body *(Kovbasa V. P., Shvajko V. M., Gucol O.P., 2015*), has the form:

$$\left.\begin{aligned} \sigma_x l + \tau_{xy} m + \tau_{xz} n &= \overline{X}; \\ \sigma_y m + \tau_{yz} n + \tau_{xy} l &= \overline{Y}; \\ \sigma_z n + \tau_{xz} l + \tau_{yz} m &= \overline{Z}; \end{aligned}\right\} \tag{3}$$

where:

l, *m*, *n* – guide cosines of the external normal to the surface that limits the environment, i.e. the contact surface (the surface of the working body);

$\overline{X}, \overline{Y}, \overline{Z}$ -components of projections of forces distributed on the contact surface on the corresponding coordinate axes;

$\sigma_{x,}\ \sigma_{y,}\ \sigma_{z,}\ \tau_{x,}\ \tau_{y,}\ \tau_z$ - components of normal deformations and shear deformations, Pa.

To analyse the influence of parameters and modes of operation of the ploughshare part of the working body, it is necessary to determine the relationship of dynamic quantities, including stresses in the soil depending on their mechanical properties and geometric parameters and modes of operation of the ploughshare. Such dynamic quantities are the components of stresses in the soil environment. These components are determined by the dependences (2), which describe the relationship of the stress components with the components of the strain rates both normal and tangential. In equations (2) the following notations are accepted: for stress components $\sigma_{xl} \to \sigma_x, \sigma_{yl} \to \sigma_y, \sigma_{xl} \to \sigma_z, \tau_{xyl} \to \tau_{xy}, \tau_{xzl} \to \tau_{xz}, \tau_{yzl} \to \tau_{yz}$, and for the components of the relative strain rates - $\dot{\varepsilon}_{xl} \to \dot{\varepsilon}_x, \dot{\varepsilon}_{yl} \to \dot{\varepsilon}_y, \dot{\varepsilon}_{zl} \to \dot{\varepsilon}_z, \dot{\gamma}_{xyl} \to \dot{\gamma}_{xy}, \dot{\gamma}_{xzl} \to \dot{\gamma}_{xz}, \dot{\gamma}_{yzl} \to \dot{\gamma}_{yz}$. In this case, the values of the stress components in the soil will be determined by the dependencies:

$$\begin{cases} \sigma_x = \dfrac{2e^{\frac{GL}{\sqrt{2}\eta_1\sqrt{\frac{G-G\nu}{\rho-2\nu\rho}}}}\eta_1\left(\dot{\tau}_{xl}(5-7\upsilon)+2(\dot{\tau}_{yl}+\dot{\tau}_{zl})(-2+\upsilon)\right)}{9(-l+\nu)} \\ \sigma_y = \dfrac{2e^{\frac{GL}{\sqrt{2}\eta_1\sqrt{\frac{G-G\nu}{\rho-2\nu\rho}}}}\eta_1\left(\dot{\tau}_{yl}(5-7\upsilon)+2(\dot{\tau}_{xl}+\dot{\tau}_{zl})(-2+\upsilon)\right)}{9(-l+\nu)} \\ \sigma_z = \dfrac{2e^{\frac{GL}{\sqrt{2}\eta_1\sqrt{\frac{G-G\nu}{\rho-2\nu\rho}}}}\eta_1\left(\dot{\tau}_{zl}(5-7\upsilon)+2(\dot{\tau}_{xl}+\dot{\tau}_{yl})(-2+\upsilon)\right)}{9(-l+\nu)} \\ \tau_{xyl} = 2e^{\frac{GL}{\sqrt{2}\eta_1\sqrt{\frac{G-G\nu}{\rho-2\nu\rho}}}}\dot{\gamma}_{xyl}\eta_1 \\ \tau_{yzl} = 2e^{\frac{GL}{\sqrt{2}\eta_1\sqrt{\frac{G-G\nu}{\rho-2\nu\rho}}}}\dot{\gamma}_{yzl}\eta_1 \end{cases} \quad (4)$$

where:

l - distance distribution of waves in the soil

L - the distance of propagation of stress waves in the soil.

Based on the equilibrium equations on the surface, the constituents of the resistance that arise in the contact interaction look like this (in accordance with equation (2)):

$$\left.\begin{aligned} \sigma_{xl}l_l + \tau_{xyl}m_l + \tau_{xzl}n_l = dF_x; \\ \sigma_{yl}m_l + \tau_{yzl}n_l + \tau_{xyl}l_l = dF_y; \\ \sigma_{zl}n_l + \tau_{xzl}l_l + \tau_{yzl}m_l = dF_z; \end{aligned}\right\} \quad (5)$$

where:

dF_x, dF_y, dF_z are components of projections of forces, which are assigned to the unit of contact area.

Thus, in order to obtain the components of the soil resistance to the movement of the ploughshare part of the working body, the components dF_x, dF_y, dF_z are necessary to integrate in corresponding planes that are perpendicular to the distributed forces for dependencies:

$$\left.\begin{aligned} F_{xli} = \int_0^h \int_{-b_l}^{b_l} (\sigma_{xl}l_l + \tau_{xyl}m_l + \tau_{xzl}n_l) d\eta d\varsigma, \\ F_{yli} = \int_0^h \int_{L_l}^{0} (\tau_{xyl}l_l + \sigma_{yl}m_l + \tau_{yzl}n_l) d\xi d\varsigma, \\ F_{zli} = \int_0^h \int_{L_l}^{0} (\tau_{xyl}l_l + \tau_{yzl}m_l + \sigma_{yl}n_l) d\xi d\varsigma, \end{aligned}\right\} \quad (6)$$

where:

h – the depth of the ploughshare of the working body into the ground;

L - the distance of propagation of stress waves in the soil;

b_1 - the half-width of the working body.

The components of the resistance forces act on the surface of the working body in three mutually perpendicular directions. To determine the total resistance force acting in the direction of motion, it is necessary to take into account the component of the resistance force in the direction of motion and take into account the external friction on the surface of the working body:

$$F_{xl} = F_{xli} + (\sqrt{F_{xli}^2 + F_{yli}^2 + F_{zli}^2}) \cdot tg[\psi], \quad (7)$$

where:

tg[ψ] is the coefficient of external friction of the soil on the material of the working body.

The resistance forces that occur on the separation surface are determined in a similar way. At the same time there is one difference, which consists in the fact that the forces of resistance consist of the sum of the bars. Expressions for the determination of forces have the form:

$$\left.\begin{aligned} F_{xli} &= 2\sum_{n_p=1}^{n_p}\int_{-\chi/2}^{\chi/2}\int_{\varsigma_0}^{\varsigma_k}(\sigma_{xp}l_p+\tau_{xyp}m_p+\tau_{xzp}n_p)d\varsigma d\chi,\\ F_{ypi} &= 2\sum_{n_p=1}^{n_p}\int_{\varsigma_0}^{\varsigma_k}\int_{\xi_0}^{\xi_k}(\tau_{xyp}l_p+\sigma_{yp}m_p+\tau_{yzp}n_p)d\xi d\varsigma,\\ F_{zpi} &= 2\sum_{n_p=1}^{n_p}\int_{-\chi/2}^{\chi/2}\int_{\xi_0}^{\xi_k}(\tau_{xzp}l_p+\tau_{yzp}m_p+\sigma_{zp}n_p)d\xi d\chi, \end{aligned}\right\} \tag{8}$$

where:

χ is geometric dimension of the bar of the working surface of the working body (the size of their diameter),

n_p- is the number of bars.

Limits of integration in equations (8) are defined as follows: the lower limit of integration on the height of the separating surface for each specific rod ζ_0 due to the need to locate the rod in the middle of the surface at $\eta=0$ that it should not be below the surface of the field, therefore $\zeta_0\big|_{(\varkappa-b_p n_{pp})\to 0,\ n_{pp}=\{-1,1\}}=0$. The upper limit of integration ζ_k due to the need to raise the middle part of the surface to ensure the movement of soil with tubers and ensure a minimum clearance h_p, so $\zeta_k\big|_{(\varkappa-b_p n_{pp})\to 0,\ n_{pp}=\{-1,1\}}=h_p$. Since the separation surface is a continuation of the ductile surface, the parameters characterizing its geometric shape remain unchanged. Therefore, the only variable values of the separating surface remain the geometric size of the bar (diameter) χ and the distance between the bars on the surface b_p *(Shymko A., Nalobina O., 2018)*.

The general resistance to the displacement of soil mass with the tubers on the separation surface has the form:

$$F_{xp}=F_{xpi}+\left(\sqrt{F_{xpi}^2+F_{ypi}^2+F_{zpi}^2}\right)\cdot tg[\psi]. \tag{9}$$

The results of theoretical research have been proven in experiments. For this purpose, three variants of the working body with the following shaping parameters are proposed: the first: $c=0.95$; $b=1.5$; $\phi=0.25$; second: $c=1.05$; $b=1.5$; $\phi=0.25$; third: $c=0.95$; $b=1.5$; $\phi=0.15$. Rational values of shaping parameters have been established by the authors in previous studies (*Shymko A., Nalobina O., 2018*) on the condition of the greatest loosening of the soil.

According to these shaping parameters, 3D models are built, which are the basis for the manufacture of physical models of the working body. A laboratory soil channel was used for research (Fig.4). The working body was fixed on the frame of the tensometric trolley, which was moved along the channel with the soil and the value of traction resistance was fixed.

Fig. 4 - A laboratory soil channel was used for research

RESULTS

On the received dependencies the calculation has been made. The value of the parameters of the working body was obtained by the authors in the course of the previous theoretical studies and is partly presented in the authors' work *(Shymko A., Nalobina O., 2018)*. Calculations are made using the Mathematica application.

In fig. 4 is shown a graphical solution of function (4), depending on changes in the parameters of the separating part of the working body.

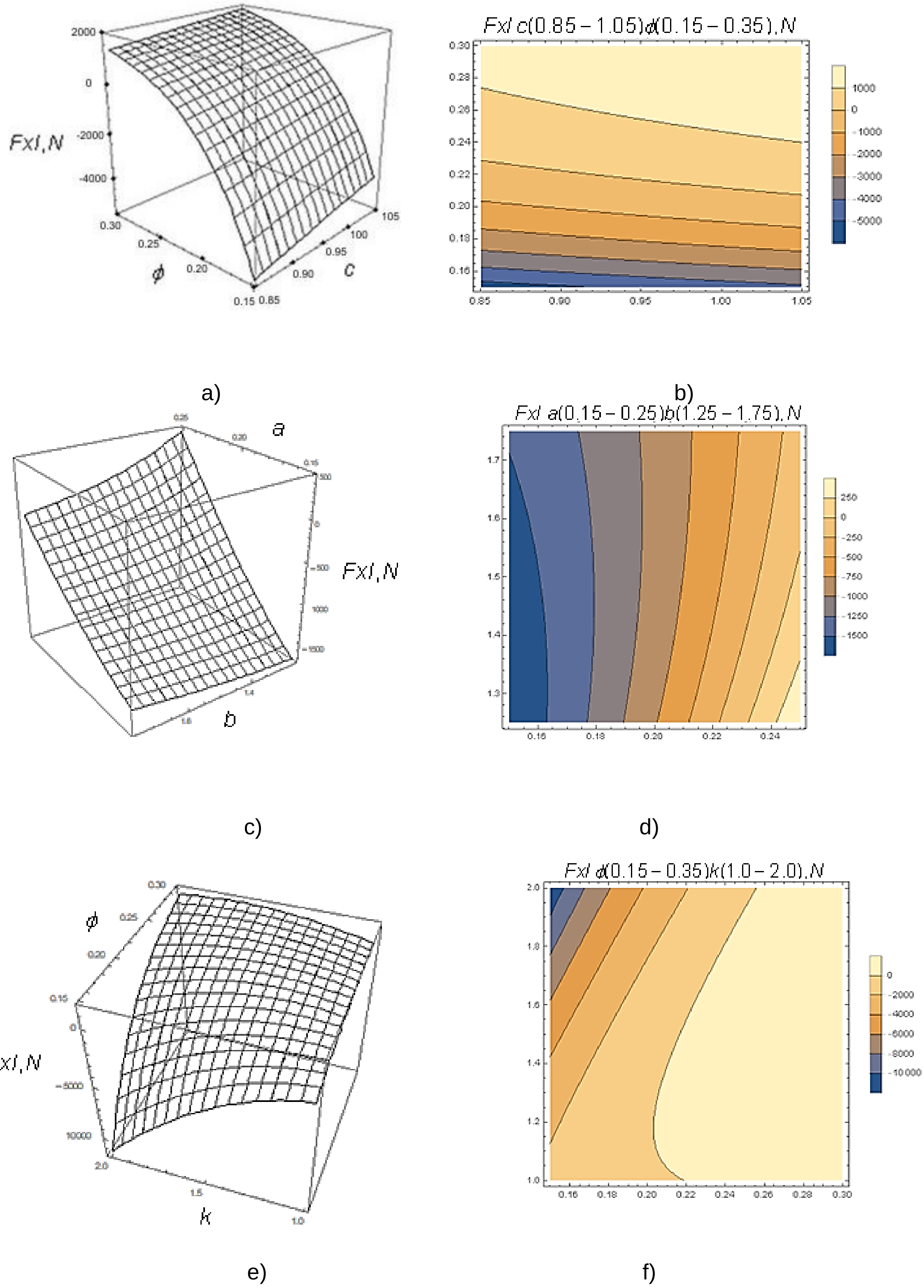
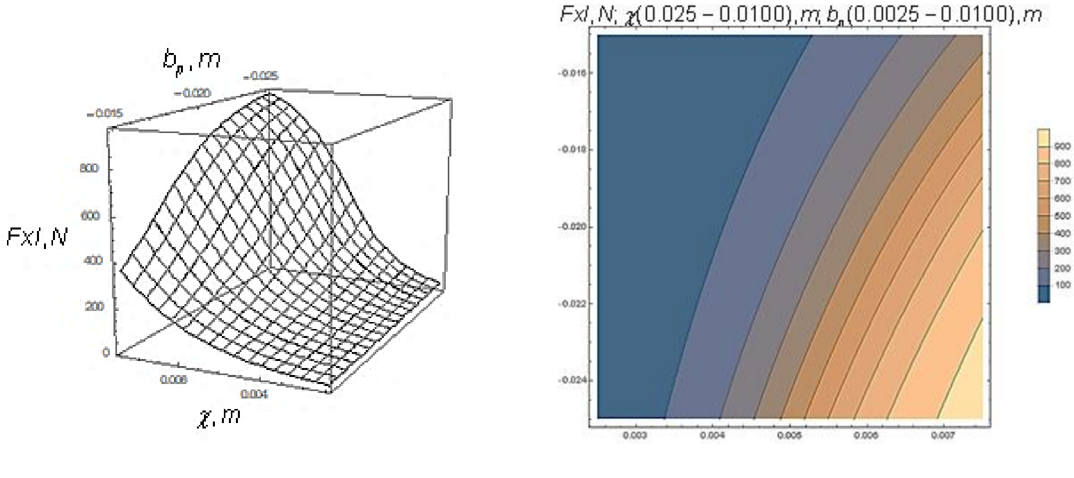


Fig. 5 - Graphical dependencies of traction resistance changes F_{xl} at various parameters of the shape of the working body surface *c, a, b, ϕ, k*

By analysing the dependence of the resistance on the displacement of the working platform of the excavator in the soil (Fig. 5), one can conclude that the minimum traction resistance can be achieved with the use of a working body with surface parameters: $c \to 0.95, \phi \to 0.25, b \to 0.20, k \to 1.50$.

Graphically, the dependence of full resistance F_{xp} displacement of soil mass with tubers by separation surface depending on the distance between bars b_p and the size of their intersection χ on a one-sided number of bars 13 is shown in Fig. 6



a) b)

Fig. 6 - Chart and contours of isocline change of full resistanceF_{xp} displacement of soil mass with tubers by separation surface depending on the distance between barsb_p and the size of their intersection χ on a one-sided amount of the number of bars 13 by one-sided amount of bars $n_p = 13, V_m = 1.0\frac{m}{s}$

CONCLUSIONS

The minimum traction resistance is provided by means of a working body with the parameters of the ploughshare surface: $c \to 0.95, \phi \to 0.25, b \to 0.20, k \to 1.50$. These values of the parameters coincide with the values of these parameters, which provide soil loosening. This is explained by the fact that under such parameters there is a destruction of the soil in the maximum possible area before the working body, therefore the resistance of the soil to the displacement of the working body is reduced. This has been proven by experimental studies. The use of a working body with the following shaping parameters provided: minimum traction resistance.

Analysis of the dependence of soil resistance and tubers on the separation surface indicates that an increase in the size of the geometric size of the intersection of bars χ leads to a significant increase in environmental resistance. At the same time increasing the distance between the axes of bars b_p has insignificant influence on the change of resistance movement at small valuesχ but this resistance increases significantly at higher values χ.

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