

## FUNCTIONS DERIVATION OF STRESSES IN THE SOIL AND RESISTANCE FORCES TO THE MOTION OF A PLOUGH SHARE FOR CAVITY CREATION

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*Subsoil irrigation is an effective way to increase crop yields. The use of an anti-seepage screen improves the efficiency of water use during irrigation. The anti-seepage screen reduces the evaporation of introduced moisture and prevents its filtration into the lower soil layers. Laying a sprinkler with an impervious screen using a trenchless method is more efficient due to its cost reduction. Such laying is carried out by pulling the sprinkler together with a flat horizontal screen in the cavity formed by the share of plow. The share of plow must form a stable horizontal cavity in the soil. The geometrical parameters of the share of plow affect the stability of the cavity roof and energy costs. The article provides a dynamic analysis of the influence of the parameters and operating modes of the share of plow on the stresses on the contact surface of the share of plow - soil and determines the components of the resistance forces of its movement. During the dynamic analysis, the results of the main methods of continuum mechanics were used. The soil was modeled with an elastic-viscous medium. The tillage tool was modeled as an absolutely solid body. These values depend on the geometric parameters of the share of plow, the modes of its movement and the mechanical properties of the soil. Analytical dependences of stresses in the soil and forces of resistance to the movement of the share of plow are given. These analytical dependences were obtained using the previously performed kinematic analysis of the interaction of the share of plow with the soil. The results of the research can be used in the design of tillage tool for trenchless laying of subsurface irrigation systems.*

**Keywords:** Anti-seepage screen, ploughshare, geometric parameters of surface, continuum mechanics, elastic modulus, viscosity, resistance forces.

### 1. Introduction

There is a necessity of laying moisturizers together with an impervious screen for maintaining the moisture and best spread it in the horizontal direction under in-soil irrigation of agricultural plants [1].

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For this purpose, share of plow can be used. Substantiation of that tool's geometrical parameters and modes of operation is an actual scientific problem.

The solution of this problem requires the formalization of the soil, as a medium, which directed the action of the tool, as well as the formalization of the interaction of the tool with soil. Most commonly used models, more like the interaction with rigid body, or of the model used in the classical theory of soil mechanics, which are based on the mechanics of granular media [7]. In addition, when building models of interaction, typically use one-dimensional models, or at best flat solutions that do not always reflect the real process of changes of soil properties under the action of the tool [4, 5].

Analysis of recent researches and publications [2-9] shows that It should be noted that the density of the soil under the influence of the tool varies as a function of changes in all six components of strain or stresses that cannot be displayed in the planar statement of the problem, and especially one-dimensional. Furthermore, such formulation does not allow determining all three components of the resistance to movement of the tool in the soil medium.

Therefore, the problem of interaction of tool with soil in three-dimensional formulation with the establishment of the relationship of the geometric parameters and modes of operation of the tool and the change of soil properties and also the components of tractive resistance is urgent and requires solution.

In this regard, **the aim of the study** is the determination of stress components in the soil, its compaction and the components of the efforts on the surface of the share of plow as a result of the interaction with the soil, depending on its mechanical properties and also geometrical parameters and modes of operation ploughshare.

## 2. Methods

Numerical methods (FEM & DEM) have become widespread for solving the equations of the relationship between stresses and deformations of continuous media. These methods are used to simulate the interaction of tools with the soil. Such methods are more experimental in nature. To obtain a qualitative picture of the interaction, it is required to carry out a large number of simulations with different parameters of the tools and different properties of the soil [13-16].

The interaction of plowshare with soil can be attributed to the class of contact tasks. Assumptions and simplifications need to be made. The soil is a quasi-continuous elastic-viscous deformable medium. This assumption is based on the fact that the minimum size of the region in which stresses and strains are determined is an order of magnitude larger than the maximum size of a soil particle. This makes it possible to use the basic laws of continuum mechanics to solve the contact problem. The plow share is an absolutely rigid, non-deformable body.

In this case, the problem is reduced to the solving back task of contact, when the speeds of movement are set on the contact surface. From this formulation of the problem, it is necessary to determine the velocity components on the contact surface. The components of soil deformations on the contact surface are determined by differentiating the velocity components along the corresponding coordinates.

For find the strain rate components, biharmonic potential functions were used. These functions must satisfy the conditions at the contact surface, and at infinity. On the contact surface, the velocities are equal to the velocities of the projections of the share's translational velocity on the coordinate axes. at infinity these speeds are equal to zero. The potential of the double layer is such potential functions.

For the formation of the cavity in which the screen will be placed, using the method of broach can be used plowshare, scheme of movement of which is illustrated in Fig. 1.

The following notation is adopted in the Fig. 1: the coordinate system  $xyz$  represents the coordinates of the soil half-space and coincides with the share mole plow coordinate system  $\xi\eta\zeta$ ,  $H$  – the plowshare running depth relative to the field surface  $fs$ ,  $B_l$  – the working width of the plowshare,  $N_l$  – the normal to the plane of the plowshare.

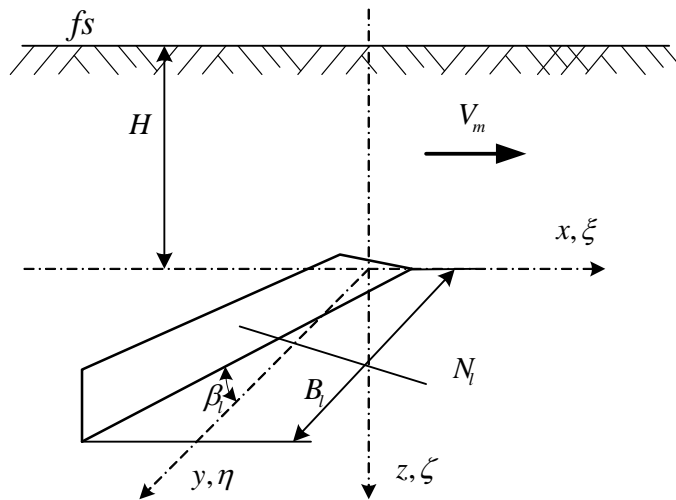


Fig. 1. Scheme of the share mole plow motion

The equation of the plowshare of the surface of the plowshare in the coordinate system idem has the form of equation of plane: [11]

$$f_l = \frac{\xi}{a} + \frac{r-\eta}{b} + \frac{(r/2)-\zeta}{c} = 0 \tag{1}$$

where  $a, b, c$  – the coefficients that determine the inclination of the plane to the

corresponding coordinate axes  $o\xi, o\eta, o\zeta$ ;  $r$  – the height of the share's vertical projection, which is due to the mounting height at the attachment point.

The kinematic research results of the interaction of share mole plow with the soil are presented in the paper [10]. As a result of the analysis, the strain rate components of the soil at the contact zone with share ploughshare were obtained.

### 3. Results and discussion

In accordance with the accepted model of the interaction of stresses with strain rates for the soil [9, 11], the components of the stresses are determined in soil on the contact surface of the share of plow with the soil. In this case the components of strain rates on the contact surface will be (defined in the article [10]):

$$\begin{aligned}\sigma_{xl} &= \frac{4}{9} e^{\frac{Gt}{2\eta(1+\nu)}} \eta(1+\nu) \left( 6\dot{\delta}_{xl} - 3(\dot{\delta}_{yl} + \dot{\delta}_{zl}) - \frac{e^{\frac{Gt}{\eta(1+\nu)}} (1+\nu)(\dot{\delta}_{xl} + \dot{\delta}_{yl} + \dot{\delta}_{zl})}{-1+2\nu} \right); \\ \sigma_{yl} &= \frac{4}{9} e^{\frac{Gt}{2\eta(1+\nu)}} \eta(1+\nu) \left( -3(\dot{\delta}_{xl} - 2\dot{\delta}_{yl} + \dot{\delta}_{zl}) - \frac{e^{\frac{Gt}{\eta(1+\nu)}} (1+\nu)(\dot{\delta}_{xl} + \dot{\delta}_{yl} + \dot{\delta}_{zl})}{-1+2\nu} \right); \\ \sigma_{zl} &= \frac{4}{9} e^{\frac{Gt}{2\eta(1+\nu)}} \eta(1+\nu) \left( -3(\dot{\delta}_{xl} + \dot{\delta}_{yl} - 2\dot{\delta}_{zl}) - \frac{e^{\frac{Gt}{\eta(1+\nu)}} (1+\nu)(\dot{\delta}_{xl} + \dot{\delta}_{yl} + \dot{\delta}_{zl})}{-1+2\nu} \right); \\ \tau_{xyl} &= 2e^{\frac{Gt}{2\eta(1+\nu)}} \eta(1+\nu) \dot{\gamma}_{xyl}, \tau_{yzl} = 2e^{\frac{Gt}{2\eta(1+\nu)}} \eta(1+\nu) \dot{\gamma}_{yzl}, \tau_{xzl} = 2e^{\frac{Gt}{2\eta(1+\nu)}} \eta(1+\nu) \dot{\gamma}_{xzl},\end{aligned}\quad (2)$$

where  $G = E/(2(1+\nu))$  – modulus of shear strains,  $\eta$  – the coefficient of viscosity for shear strains,  $E$  – the modulus of linear strains,  $G$  – the shear modulus,  $\nu$  – Poisson's ratio,  $\dot{\delta}_{xl}, \dot{\delta}_{yl}, \dot{\delta}_{zl}, \dot{\gamma}_{xyl}, \dot{\gamma}_{xzl}, \dot{\gamma}_{yzl}$  -- strain rate components, normal and shear (defined in the article [10]).

The obtained expressions are cumbersome, therefore of in this paper they are not given, and graphical interpretation of components of the stresses are shown in fig. 2 and fig. 3.

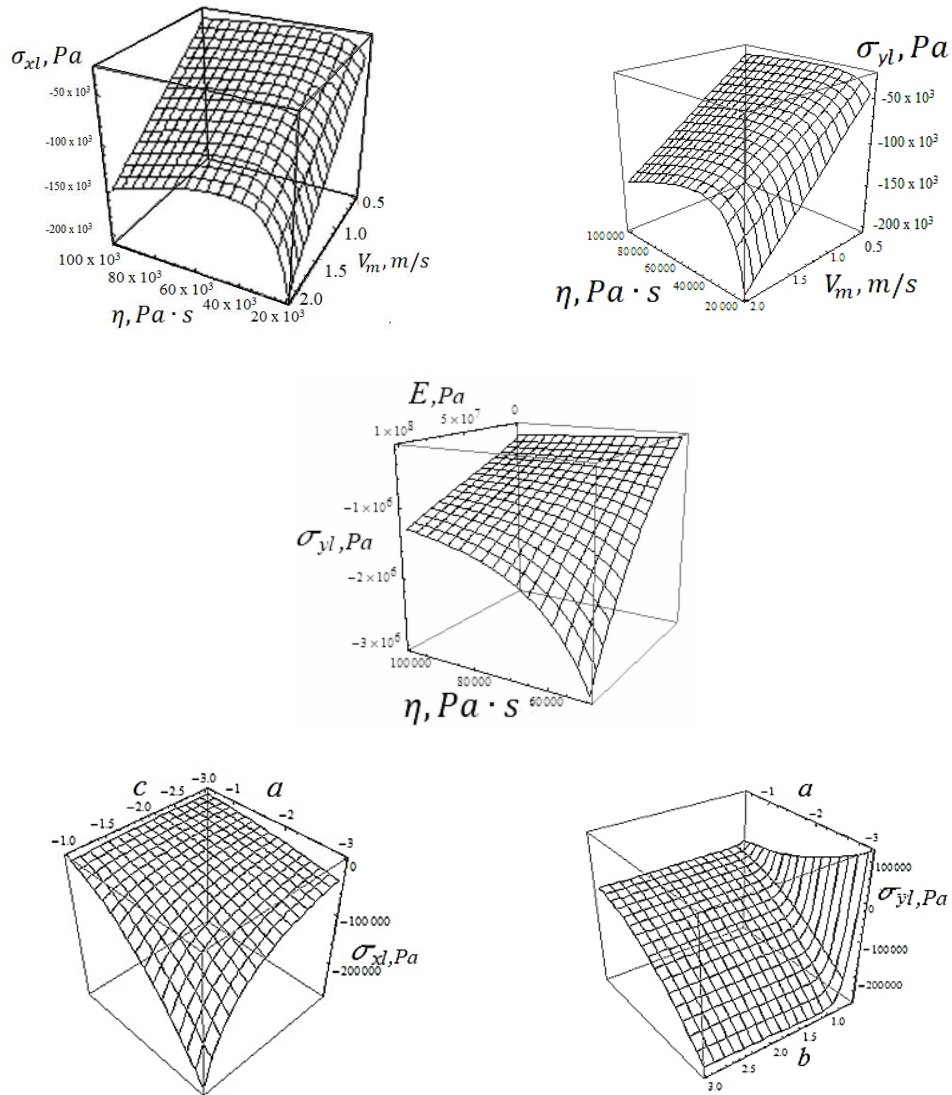


Fig. 2. Graphs of the components of normal stresses  $\sigma_{xl}, \sigma_{yl}$  depending on the soil properties  $E, \eta$ , the speed  $V_m$  of the share plow and the coefficients  $a, b, c$  of the equation its plane

The analysis of these functions changes of the components stresses showed that the increase of the elastic modulus  $E$  and viscosity  $\eta$  leads to increase of all stress components.

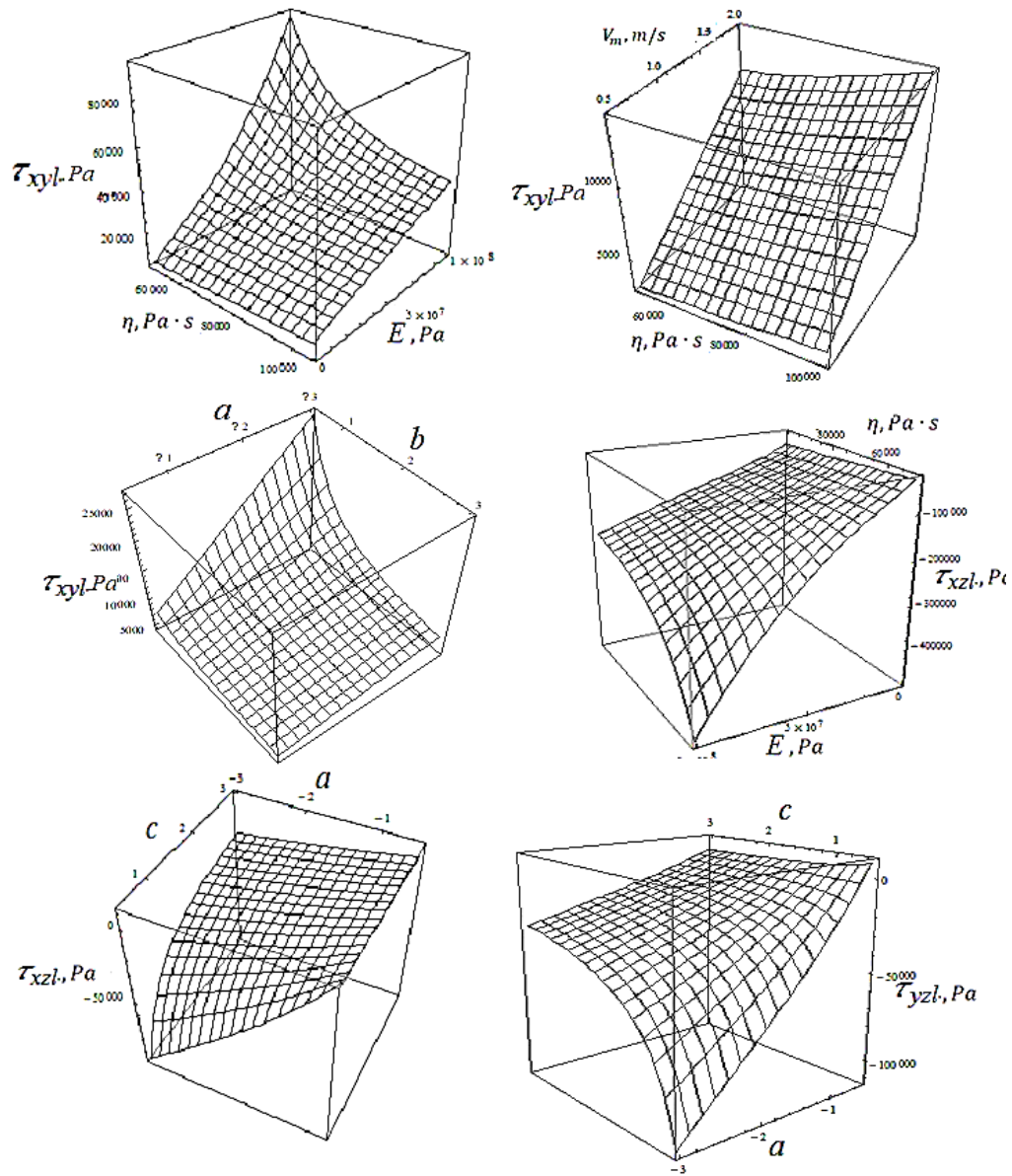


Fig. 3. Graphs of the components of shearing stresses  $\tau_{xyl}, \tau_{xzl}, \tau_{yzl}$  from the soil properties  $E, \eta$ , the speed  $V_m$  of the ploughshare and the coefficients  $a, b, c$  of the equation its plane

The increase in the translational velocity  $v_m$  of the share of plow leads to a linear increase of the component stresses, which is manifested more significantly with the increase of the modulus of viscosity of the soil. The influence of the slope angles of the surface normal of the share of plow is the same that is shown for the components of the strain rates.

Under the influence of the stress-strain state of soil at the interface with the tool, the density of the soil is changed. The most well-known regression that link the density change of the soil with changes in stress are expressions [6, 7]:

$$BVW = m \ln \left[ \sqrt{\sigma_{ml}^2 + \tau_{ml}^2} \right] + n \left( \frac{\tau_{ml}}{\sigma_{ml}} \right) + b; \rho_l = \rho_0 + b \ln[\sigma_{ml}(1 + \tau_{ml})], \quad (3)$$

where  $BVW$  – the volume change of the soil, referred to the weight [ $m^3/\kappa g$ ],  $\rho_l$  – the final density of the soil [ $\kappa g/m^3$ ],  $\rho_0$  – the initial density of the soil,  $\sigma_{ml}$  – the mean or hydrostatic stress in the considered volume,  $\tau_{ml}$  – the maximum shear stress in the considered volume,  $m, n, b$  – empirical coefficients that are specific to a certain type of soil at different humidities and are subject to experimental determination.

The magnitude of the hydrostatic stress is defined as  $\sigma_{mk} = (\sigma_{xl} + \sigma_{zl} + \sigma_{yl})/3$ , and the maximum shear stress for the applied solutions, according to the research Novozhilov [6], can be represented by the RMS value of the components of the tangential stresses in the form:  $\tau_{ml} = \sqrt{(\tau_{xyl}^2 + \tau_{xzl}^2 + \tau_{yzl}^2)}/3$ .

The functions of the hydrostatic stresses and maximum shear stresses from the soil properties and parameters of the share of plow are shown in fig. 4.

Using the second of the expressions (3) and considering that for a specific soil at a certain its state value  $b = const$ , we can construct density variation equations of the soil from its mechanical properties, geometric parameters of the tool and its speed. These functions in the final form cannot be given within the publication, and their graphic interpretation is presented in fig. 5.

Components distribution of the stresses soil on the surface of share of plow can be determined from the equilibrium conditions on the surface:

$$\begin{aligned} dF_{xl} &= \sigma_{xl}l_l + \tau_{xyl}m_l + \tau_{xzl}n_l; dF_{yl} = \tau_{xyl}l_l + \sigma_{yl}m_l + \tau_{yzl}n_l; \\ dF_{zl} &= \tau_{xzl}l_l + \tau_{yzl}m_l + \sigma_{zl}n_l, \end{aligned} \quad (4)$$

where  $dF_{xl}, dF_{yl}, dF_{zl}$  – the projections on the corresponding coordinate axis of components of the stresses soil on the tool surface,  $l_l, m_l, n_l$  – the directional cosines of the normal to the tool surface.

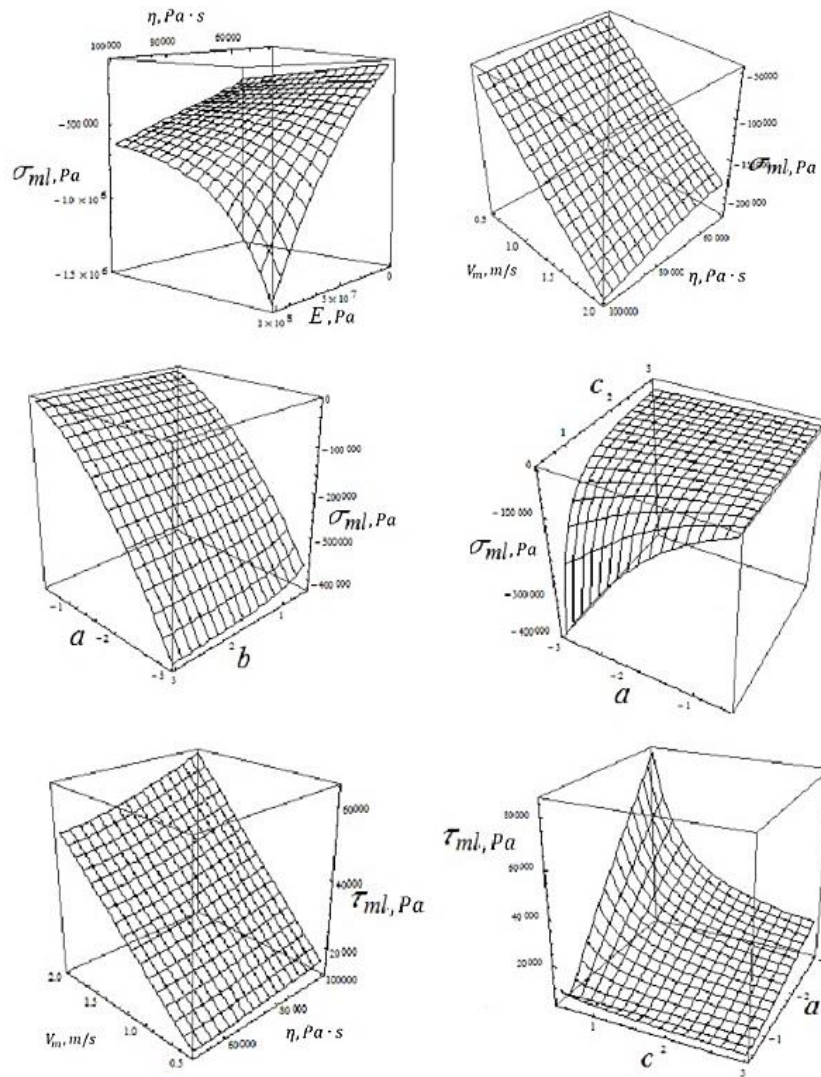


Fig. 4. Graphs of the hydrostatic stresses and maximum shear stresses  $\sigma_{ml}, \tau_{ml}$  in soil depending from its properties  $E, \eta$ , the speed  $V_m$  of the share plow and the coefficients  $a, b, c$  of the equation of its plane

The integration of expressions (4) on projections, which are perpendicular to the indexes of components of pressure, gives us the magnitude of the forces of resistance to movement of tool in the soil:

$$F_{xl} = \int_{-r}^r \int_0^B dF_{xl} d\eta_l d\zeta_l; F_{yl} = \int_{-r}^r \int_0^{L_2} dF_{yl} d\xi_l d\zeta_l; dF_{zl} = \int_0^B \int_0^{L_2} dF_{zl} d\xi_l d\eta_l. \quad (5)$$



where  $-r, r; B; L_l$  – projections of the geometric dimensions of the ploughshare on the axis  $oz, oy, ox$ , respectively.

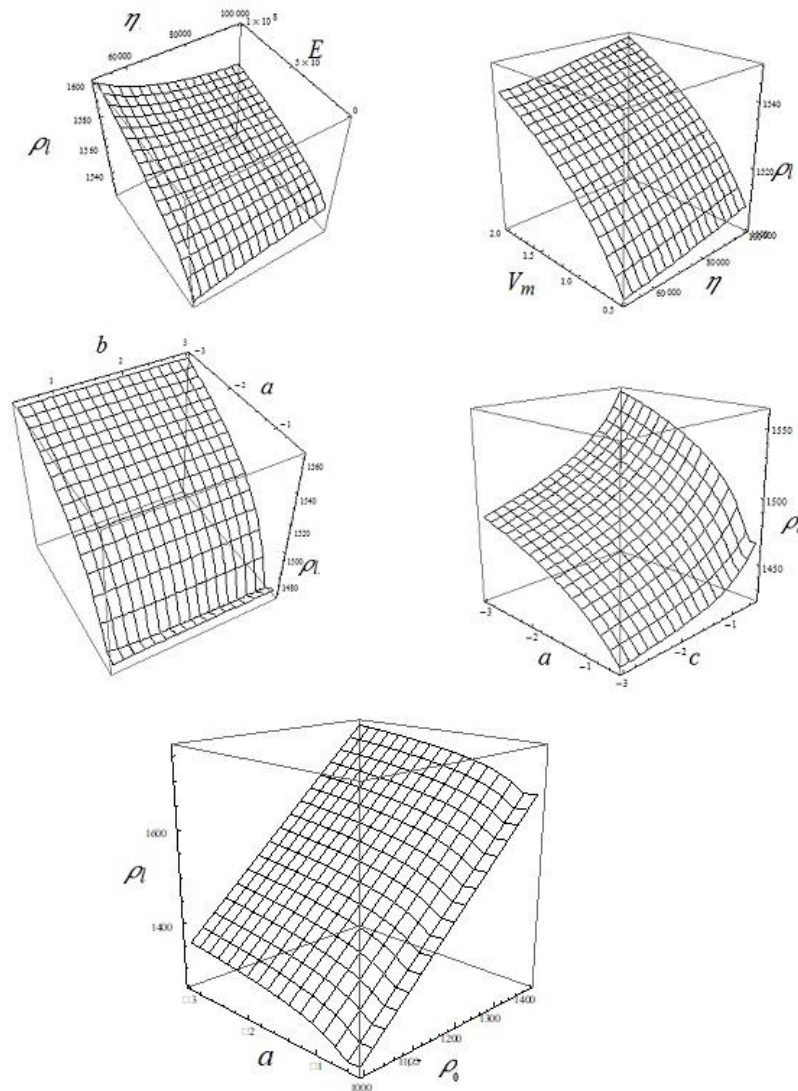


Fig. 5. Graphs of the density of the soil  $\rho_l$  in the zone of contact with the share plow depending from soil properties  $E, \eta$ , the speed  $V_m$  of the share of plow and the coefficients  $a, b, c$  of the equation of its plane

The expressions (5) in the final form cannot be given within the publication (due to their bulkiness), and their graphical interpretation are shown in figures 6, 7, 8.

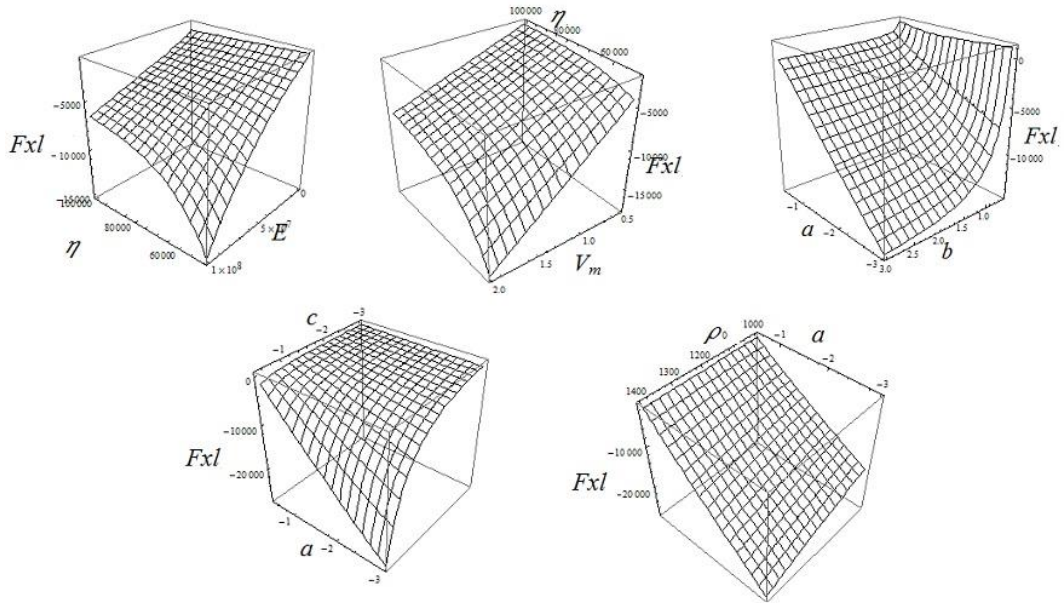


Fig. 6. Graphs of the resistance to the movement of the ploughshare  $F_{xl}$  in the direction of translational movement of the tool depending from the soil properties  $E, \eta$ , the speed  $V_m$  of the ploughshare and the coefficients  $a, b, c$  of the equation of its plane

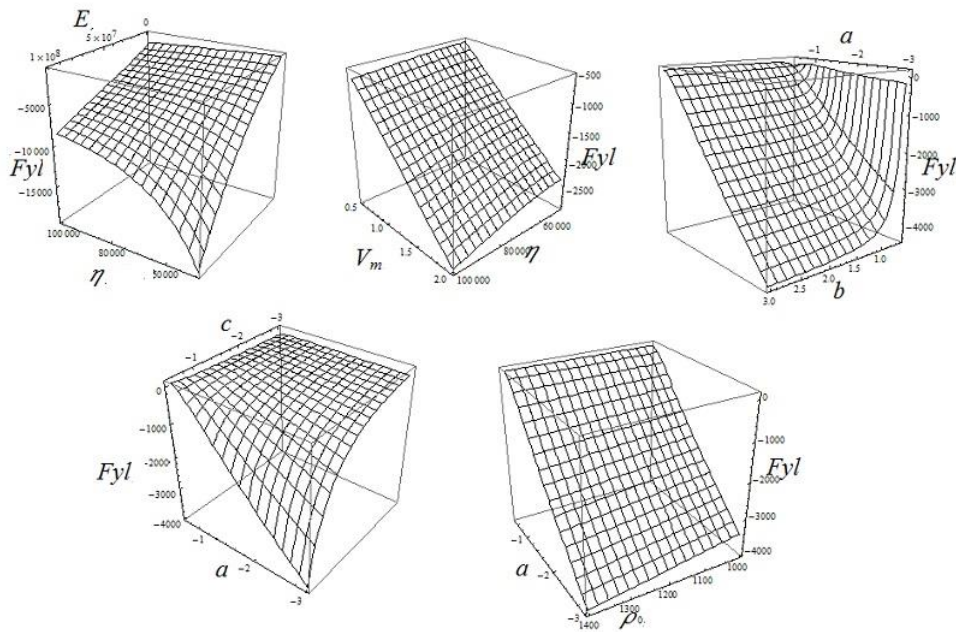


Fig. 7. Graphs of the resistance to the movement of the share of plow  $F_{yl}$  in horizontal transverse direction depending from the soil properties  $E, \eta$ , the speed  $V_m$  of movement ploughshare and the coefficients  $a, b, c$  of the equation of its plane

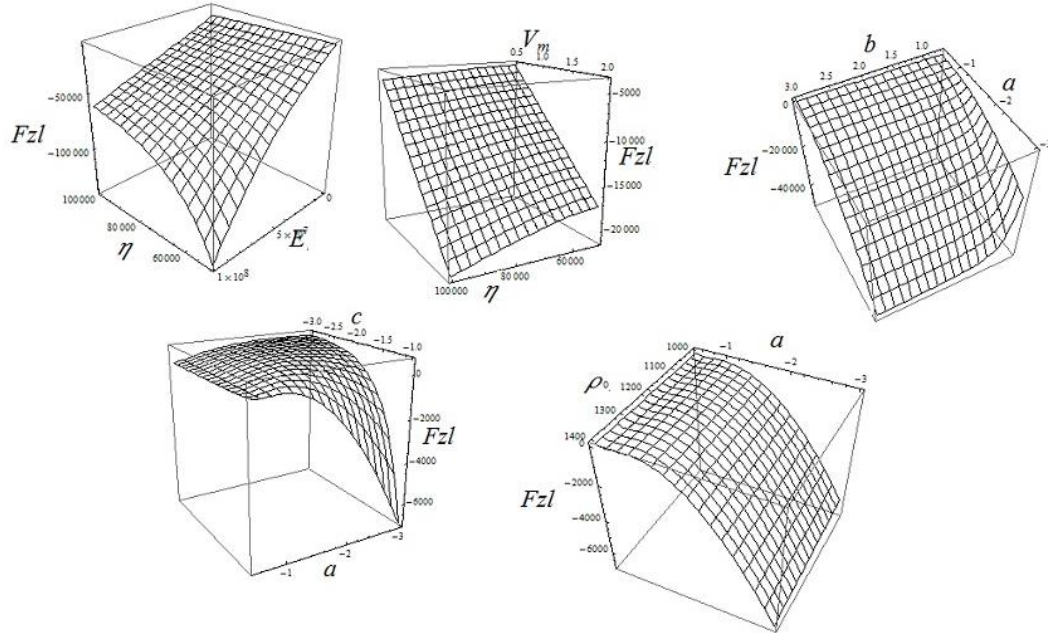


Fig. 8. Graphs of the resistance to the movement of the share of plow  $F_{zl}$  in the vertical direction depending from the soil properties  $E, \eta$ , the speed  $V_m$  of the ploughshare and from the coefficients  $a, b, c$  of the equation of its plane

The total resistance to the movement of share of plow in the soil consists of a component of soil resistance  $F_{xl}$  and friction forces on the tool surface, projected on the direction of movement. Then the total resistance force is expressed as follows:

$$F_{xt} = F_{xl} + \left( \sqrt{(F_{yl} ml)^2 + (F_{zl} nl)^2} \right) \operatorname{tg} \psi, \quad (6)$$

where  $\psi$  – the angle of external friction of soil to the surface of the ploughshare.

Graphically the functions of total resistance to the movement and the change in the soil density for the closest to the rational values of plane coefficients are presented in figure 9.

The main result achieved under the work of share of plow, must be soil compaction. This is to save space for pull-through of the screen. With here, the density of the soil should increase. Since on the mechanical properties of the soil influence to render impossible, to achieve maximum compaction, you can change slope angles of the normal to the surface of the share of plow relative to the coordinate axes of the soil space and the change of the velocity of translational motion of the tool.

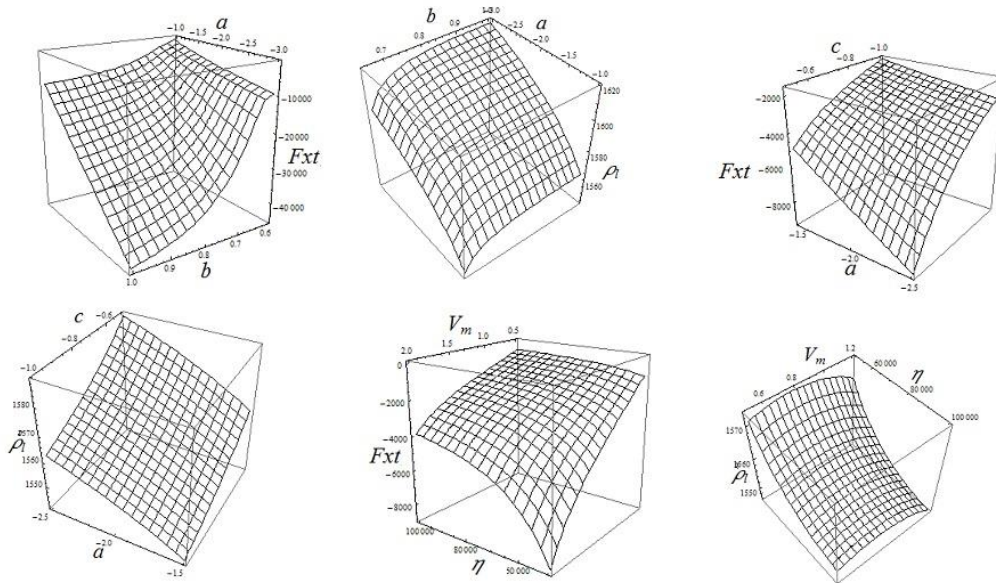


Fig. 9. Graphs of the resistance to movement of the ploughshare  $F_{xt}$  in the direction of tool movement and the changes of soil density  $\rho_1$  depending from the modulus of soil viscosity  $\eta$ , the speed  $V_m$  of the share of plow and from the coefficients  $a, b, c$  of the equation of its plane

Analysis of the influence of the coefficients of plane equations  $a, b, c$  for the change of the soil density (Fig. 5) showed that the slope coefficient  $b$  has no effect on the change of the soil density  $\rho_1$ , but the increase of the coefficient  $a$  leads to an increase of the soil density in the contact zone.

Similarly, the reduction of ratio  $c$  leads to an increase in the soil density. And the increase of the velocity of the translational movement  $v_m$  of the tool also leads to the increase of density. However, account must be taken of the change of the components of the resistance forces to movement of the tool (Fig. 6, 7, 8).

Thus, increasing velocity  $v_m$ , reducing the ratio  $c$  and increasing the ratio  $a$  leads to increase the resistance forces to movement of the tool. That is, to obtain the necessary compaction of the walls crack, which will ensure smooth pulling of the screen, need to spend a lot of effort.

## 6. Conclusions

Theoretical studies with minimal assumptions and simplifications are less costly in terms of the amount of labor and material resources invested. At the same time, they are of a more fundamental nature and can reduce the cost of experimental research.

Thus, studies have shown that to ensure unhindered pulling of the screen (minimum friction of the screen against the walls of the slot), the share can be made in the form of a plane with the minimum possible coefficients  $b < 1$  and  $c < -1$ , at the same time, the coefficient  $a \rightarrow -2$ , taking into account the geometric dimensions of such a plane. The speed of movement of the ploughshare must be within  $V_m \approx 1 m/c$ .

With such parameters, the share plane will provide the maximum possible compaction of the soil with the least possible resistance to movement of the ploughshare.

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