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ANALYTICAL STUDY OF SOIL STRAIN RATE WITH A PLOUGHSHARE FOR UNCOVERING SLIT

Olena Solona, Volodymyr Kovbasa, Ihor Kupchuk

Vinnytsia National Agrarian University, 3 Sonyachna St, UA 21008, Vinnytsia, Ukraine

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Vastutav autor: Corresponding author: Ihor Kupchuk
E-mail: kupchuk.igor@i.ua
Phone: +380 978 173 992

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ABSTRACT. The article is devoted to solving one of the most important tasks of substantiating rational design and technological parameters of the working body for the installation of elements of subsurface irrigation. To reduce the frictional resistance during pulling of intra-soil irrigation communications, it becomes necessary to form a cavity inside the soil. The energy efficiency of such a process is determined by the traction resistance and directly depends on the normal and shear stresses of the soil as a result of its relative deformation during interaction with a special working body – the share of a mole plough. The geometric shape and kinematic parameters of the share, together with the mechanical characteristics of the soil, have the greatest influence on the nature of the relative deformation. Therefore, the purpose of the article is to determine the functional dependences of the components of the soil deformation rates on the geometric and kinematic parameters of the working body surface. These equations are necessary to determine the stress components in the soil, which make it possible to determine the compaction of the soil on the walls of the formed cavity (molehill), as well as the components of the forces of resistance to the movement of the working body.

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 (Akutneva, 2014; Terpigorev *et al.*, 2017; Al-Khazaali, Kovbasa, 2016a).

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

The solution of this problem allows us to determine the functional dependences of the effect of the tool's geometric parameters and soil's mechanical properties on the distribution of its strain rates and stress components. This makes it possible, when share mole plough interacts with the soil, to predict the location of zones in which the ratio of the stress components corresponds to a transition to the plastic state up to the disruption of the continuity for a certain plasticity criterion.

Analysis of researches and publications (Bagirov, 1963; Vyalov, 1978; Johnson *et al.*, 1979; Kushnarev, 1980; Cullen *et al.*, 1986; Contreras *et al.*, 2013; Zhao *et al.*, 2016; Ahmadi, 2016) shows that the solution of this problem requires the formalization of the soil, as a medium, on which the tool's action is directed, and the formalization of the soil – tool interaction. There are used most often models that are more like as the interaction with a rigid body or are the models used in the classical theory of soil mechanics and are based on the mechanics of granular media (Sokolovsky, 1960). Besides, when modelling of interaction, typically use one-dimensional models, or at best two-dimensional that do not always adequately depict the actual process of changes of soil properties under the action of the tool (Contreras *et al.*, 2013; Lurie, 1955). Recent publications show that the soil often represented as a viscoplastic or plastic medium. For this, either experimental research methods or numerical simulation methods using finite element methods are used (Zhu *et al.*, 2017; Gürsoy *et al.*, 2017; Zhang *et al.*, 2018; Solona *et al.*, 2019).

However, the use of such methods does not provide a real display of the change in the stress-strain state in zones close to critical, namely within the tool point, where there are zones of both fracture and strain hardening.

Also, with such research methods, it is impossible to obtain functional dependences of the connection between the strain rate and stress components, depending on the geometric parameters of a tool, and therefore numerous physical or numerical experiments are necessary.

It should be noted that the soil density under the tool's effect varies as a function of changes in all six components of strain or stresses which cannot be obtained in the plane problem, and even more so in a one-dimensional one. 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 the soil – tool interaction in a three-dimensional formulation with the determination of the relation the geometric parameters and operating modes of the tool itself, as well as the properties of the soil, with components of the traction resistance is urgent and requires a solution.

In this regard, as one of the aims of the investigation was to determine if the strain rates in the contact zone of share mole plough with the soil, depending on its geometric and kinematic parameters. This will allow us to determine the values of the stress components and the soil density functions, depending on them. Besides, this will allow us to determine the soil force resistance to the movement of the share mole plough.

Methods

The use of the method of differential components of bi-harmonic potential functions in the contact zone of soil with share mole plough.

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

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

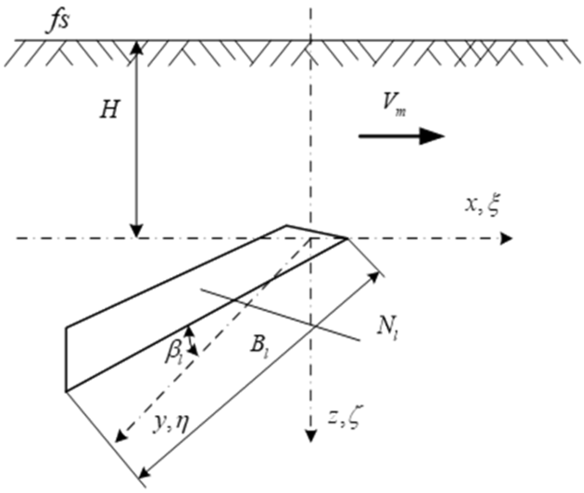

Figure 1. Scheme of the share mole plough motion

The equation of the working part of the surface of the ploughshare in the coordinate system idem has the form of the equation of plane:

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

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 introduction of this height to equation defines the displacement of the centre of the plane to the origin in the direction of the axis $o\zeta$.

The cosines of the inclination angles of the surface normal to the coordinate axes expressed by the dependencies:

$$l_l = \frac{\partial f_l/\partial\xi}{\sqrt{(\partial f_l/\partial\xi)^2 + (\partial f_l/\partial\eta)^2 + (\partial f_l/\partial\zeta)^2}} = 1\Bigg/\left(a\sqrt{\frac{1}{a^2}+\frac{1}{b^2}+\frac{1}{c^2}}\right);$$

$$m_l = \frac{\partial f_l/\partial\eta}{\sqrt{(\partial f_l/\partial\xi)^2 + (\partial f_l/\partial\eta)^2 + (\partial f_l/\partial\zeta)^2}} = -1\Bigg/\left(b\sqrt{\frac{1}{a^2}+\frac{1}{b^2}+\frac{1}{c^2}}\right);$$

$$n_l = \frac{\partial f_l/\partial\zeta}{\sqrt{(\partial f_l/\partial\xi)^2 + (\partial f_l/\partial\eta)^2 + (\partial f_l/\partial\zeta)^2}} = -1\Bigg/\left(\sqrt{\frac{1}{a^2}+\frac{1}{b^2}+\frac{1}{c^2}}\,c\right).$$

The displacements velocities of the soil on the ploughshare surface are determined based on the fact that the projection of the velocity on the normal to the ploughshare surface has the form: $V_{Nl} = V_m / l_l$:

$$v_{l0} = V_{nl}\, m_l = -a V_m / b\ ;\ w_{l0} = V_{nl}\, n_l = -a V_m / c\ ;\ u_{l0} = V_{nl} l_l = V_m\ .$$

Analytical solutions of contact problems are possible only in the elastic or elastic-viscous formulation. Moreover, these solutions are allowed only for the case when successive substitutions of geometric equations in the physical equations of stress-strain relations and further substitution of the resulting stress components into the equations of statics (dynamics) of the continuous medium will lead to equations of elliptic type. In this case, the solution can be found when using the bi-harmonic potential functions that satisfy the

conditions on the body surface (coordinate system ξ, η, ζ) and medium with which it interacts (coordinate system x, y, z). In this case, when $x - \xi = 0,\ y - \eta = 0,\ z - \zeta = 0$, the components of the velocities (displacements) are equal to their initial values.
For our case this means that the components of velocity for the ploughshare take the form:

$$u_l\big|_{x-\xi=0, y-\eta=0, z-\zeta=0} = u_{l0}\ ;$$
$$v_l\big|_{x-\xi=0, y-\eta=0, z-\zeta=0} = v_{l0}\ ;$$
$$w_l\big|_{x-\xi=0, y-\eta=0, z-\zeta=0} = w_{l0}\ .$$

The second condition, which must satisfy the biharmonic potential functions to determine the composition of the velocity has the form:

$$u_l\big|_{x-\xi=\infty, y-\eta=\infty, z-\zeta=\infty} \to 0\ ;$$
$$v_l\big|_{x-\xi=\infty, y-\eta=\infty, z-\zeta=\infty} \to 0\ ;$$
$$w_l\big|_{x-\xi=\infty, y-\eta=\infty, z-\zeta=\infty} \to 0\ .$$

Such bi-harmonic potential functions, according to (Lurie, 1955; Kovbasa *et al.*, 2015; Al-Khazaali, Kovbasa, 2016b) are of the form:

$$u_l = \int_r^B \int_{-r}^r \frac{a_0\, u_{l0}(x-\xi_l+\delta)}{((x-\xi_l+\delta)^2+(y-\eta_l+\delta)^2+(z-\zeta_l+\delta)^2)^{3/2}} \mathrm{d}\zeta_l \mathrm{d}\eta_l\ ;$$
$$v_k = \int_{-r}^r \int_0^{L_k} \frac{a_0\, v_{l0}(y-\eta_k+\delta)}{((x-\xi_l+\delta)^2+(y-\eta_l+\delta)^2+(z-\zeta_l+\delta)^2)^{3/2}} \mathrm{d}\xi_l \mathrm{d}\zeta_l; \qquad (1)$$
$$w_l = \int_r^B \int_0^{L_l} \frac{a_0\, w_{l0}(z-\zeta_l+\delta)}{((x-\xi_l+\delta)^2+(y-\eta_l+\delta)^2+(z-\zeta_l+\delta)^2)^{3/2}} \mathrm{d}\xi_l \mathrm{d}\eta_l,$$

where $L_l = -B\,Cos(1/a)$ – the projection length of the ploughshare in the direction of the axis $o\xi$; B – the projection length of the ploughshare in the direction of the axis $o\eta$.

$a_0 = \frac{1}{\pi}\frac{4}{Log[-\delta+\sqrt{3}\sqrt{\delta^2}]-Log[\delta+\sqrt{3}\sqrt{\delta^2}]}$ – factor that enforces initial conditions with the introduction of a small magnitude δ. This magnitude eliminates the singularity of the expressions (1). Bi-harmonic potential functions should satisfy the equation $\Delta^2 f = 0$, where Δ – Laplacian, $f = \{u_l, v_l, w_l\}$.

Due to the complexity of integration of the equations (1), which represent the components of the displacement velocities of soil in space in front of the share mole plough, in the general form, it is possible to solve the problem of finding the distribution of displacement velocities, strain rates and the stress components in a differential form, as it was proposed in (Vyalov, 1978; Zhao, 2016).

The essence of the method consists in the fact that to find the components of strain rates it is necessary to the differentiation of equations (1).

For this, equations (1) can be transformed in such a way that as a result, the components of the differential components of the soil displacement velocities in front of the share mole plough will be obtained. In this case, due to the cumbersome of the equations at the last stage, it is possible to apply numerical methods of integration:

$$du_l = \frac{d^2}{d\eta_l d\zeta_l}\int_0^B \int_{-r}^r \frac{a_0\, u_{l0}(x-\xi_l+\delta)}{((x-\xi_l+\delta)^2+(y-\eta_l+\delta)^2+(z-\zeta_l+\delta)^2)^{3/2}} \mathrm{d}\zeta_l \mathrm{d}\eta_l =$$
$$= \frac{15\, a_0 V_m (z+\delta-\zeta_l)(y+\delta-\eta_l)(x+\delta-\xi_l)}{((z+\delta-\zeta_l)^2+(y+\delta-\eta_l)^2+(x+\delta-\xi_l)^2)^{7/2}};$$
$$dv_l = \frac{d^2}{d\zeta_l d\xi_l}\int_{-r}^r \int_0^{L_l} \frac{a_0\, v_{l0}(y-\eta_k+\delta)}{((x-\xi_l+\delta)^2+(y-\eta_l+\delta)^2+(z-\zeta_l+\delta)^2)^{3/2}} \mathrm{d}\xi_l \mathrm{d}\zeta_l = \qquad (2)$$
$$= -\frac{15 a\, a_0 V_m (z+\delta-\zeta_l)(y+\delta-\eta_l)(x+\delta-\xi_l)}{b((z+\delta-\zeta_l)^2+(y+\delta-\eta_l)^2+(x+\delta-\xi_l)^2)^{7/2}};$$
$$dw_1 = \frac{d^2}{d\eta_l d\zeta_l}\int_r^B \int_0^{L_l} \frac{a_0 w_{l0}(z-\xi_l+\delta)}{((x-\xi_l+\delta)^2+(y-\eta_l+\delta)^2+(z-\zeta_l+\delta)^2)^{3/2}} d\xi_l d\eta_l =$$
$$= -\frac{15 a a_0 V_m (z+\delta-\zeta_l)(y+\delta-\eta_l)(x+\delta-\xi_l)}{c((z+\delta-\zeta_l)^2+(y+\delta-\eta_l)^2+(x+\delta-\xi_l)^2)^{7/2}}.$$

From equations (2) the differential components of the strain rates of the soil using geometric equations (cauchy equations) can be obtained:

$$d\dot{\epsilon}_{xl} = \frac{d}{dx}du_l = \frac{15a_0V_m(z+\delta-\zeta_l)(y+\delta-\eta_l)((z+\delta-\zeta_l)^2+(y+\delta-\eta_l)^2-6(x+\delta-\xi_l)^2)}{((z+\delta-\zeta_l)^2+(y+\delta-\eta_l)^2+(x+\delta-\xi_l)^2)^{9/2}};$$

$$d\dot{\epsilon}_{yl} = \frac{d}{dy}dv_k = \frac{105a\,a_0V_m(z+\delta-\zeta_l)^2(y+\delta-\eta_l)(x+\delta-\xi_l)}{c((z+\delta-\zeta_l)^2+(y+\delta-\eta_l)^2+(x+\delta-\xi_l)^2)^{9/2}} - \frac{15a\,a_0V_m(y+\delta-\eta_l)(x+\delta-\xi_l)}{c((z+\delta-\zeta_l)^2+(y+\delta-\eta_l)^2+(x+\delta-\xi_l)^2)^{7/2}};$$

$$d\dot{\epsilon}_{zl} = \frac{d}{dz}dw_l = 15a_0V_m(\delta-\zeta_l+z)\times$$
$$\times\frac{\left(\frac{7a(\delta-\xi_l+x)^2(\delta-\eta_l+y)}{b} - \frac{a(\delta-\eta+y)((\delta-\xi_l+x)^2+(\delta-\eta_l+y)^2+(\delta-\zeta_l+z)^2)}{b} - 7(\delta-\xi_l+x)(\delta-\eta_l+y)^2+(\delta-\xi_l+x)((\delta-\xi_l+x)^2+(\delta-\eta_l+y)^2+(\delta-\zeta_l+z)^2)\right)}{((\delta-\xi_l+x)^2+(\delta-\eta_l+y)^2+(\delta-\zeta_l+z)^2)^{9/2}};$$

$$d\dot{\gamma}_{xyl} = \frac{d}{dy}du_l + \frac{d}{dx}dv_l = 15a_0V_m(\delta-\zeta_l+z)\times$$
$$\times\frac{\left(\frac{7a(\delta-\xi_l+x)^2(\delta-\eta_l+y)}{b} - \frac{a(\delta-\eta_l+y)((\delta-\xi_l+x)^2+(\delta-\eta_l+y)^2+(\delta-\zeta_l+z)^2)}{b} - 7(\delta-\xi_l+x)(\delta-\eta_l+y)^2+(\delta-\xi+x)((\delta-\xi+x)^2+(\delta-\eta_l+y)^2+(\delta-\zeta_l+z)^2)\right)}{((\delta-\xi_l+x)^2+(\delta-\eta_l+y)^2+(\delta-\zeta_l+z)^2)^{9/2}}; \quad (3)$$

$$d\dot{\gamma}_{xzl} = \frac{d}{dz}du_l + \frac{d}{dx}dw_l = 15a_0V_m(\delta-\eta_l+y)\times$$
$$\times\frac{\left(-\frac{a(\delta-\zeta_l+z)((\delta-\xi_l+x)^2+(\delta-\eta_l+y)^2+(\delta-\zeta_l+z)^2)}{c} + \frac{7a(\delta-\xi_l+x)^2(\delta-\zeta_l+z)}{c} + (\delta-\xi_l+x)((\delta-\xi_l+x)^2+(\delta-\eta_l+y)^2+(\delta-\zeta_l+z)^2) - 7(\delta-\xi_l+x)(\delta-\zeta_l+z)^2\right)}{((\delta-\xi_l+x)^2+(\delta-\eta_l+y)^2+(\delta-\zeta_l+z)^2)^{9/2}};$$

$$d\dot{\gamma}_{yzl} = \frac{d}{dy}dw_l + \frac{d}{dz}dv_l = 15a_0V_m(\delta-\eta_l+y)\times$$
$$\times\frac{\left(-\frac{a(\delta-\zeta_l+z)((\delta-\xi_l+x)^2+(\delta-\eta_l+y)^2+(\delta-\zeta_l+z)^2)}{c} + \frac{7a(\delta-\xi_l+x)^2(\delta-\zeta_l+z)}{c} + (\delta-\xi_l+x)((\delta-\xi_l+x)^2+(\delta-\eta_l+y)^2+(\delta-\zeta_l+z)^2) - 7(\delta-\xi_l+x)(\delta-\zeta_l+z)^2\right)}{((\delta-\xi_l+x)^2+(\delta-\eta_l+y)^2+(\delta-\zeta_l+z)^2)^{9/2}};$$

where $d\dot{\epsilon}_{xl}$, $d\dot{\epsilon}_{yl}$, $d\dot{\epsilon}_{zl}$, $d\dot{\gamma}_{xyl}$, $d\dot{\gamma}_{xzl}$, $d\dot{\gamma}_{yzl}$ – differential components of the velocities of relative normal and shear strains of soil in front of the ploughshare.

To understand how the share mole plough, namely its geometric shapes and sizes affects the changes of the strain components in the area of direct contact with the soil, the expressions can be integrated (3), according to expressions (1).

But the same time it should be taken into account that the zone of direct contact will be analyzed, namely the conditions: $\{\zeta_l - z = 0,\ \eta_l - y = 0,\ \xi_l - x = 0\}$. This greatly simplifies the expression (3):

$$\dot{\epsilon}_{xl} == \int_r^B\int_{-r}^r d\dot{\epsilon}_{xl}\,d\zeta_l\,d\eta_l = \int_r^B\int_{-r}^r \frac{\partial u}{\partial x}d\zeta_l\,d\eta_l\,;\ \dot{\epsilon}_{xl} = \int_{-r}^r\int_0^{L_k} d\dot{\epsilon}_{yl}\,d\xi_l\,d\zeta_l = \int_{-r}^r\int_0^{L_k}\frac{\partial v}{\partial y}d\xi_l\,d\zeta_l\,;$$
$$\dot{\epsilon}_{zl} = \int_r^B\int_0^{L_l} d\dot{\epsilon}_{zl}\,d\xi_l\,d\eta_l = \int_r^B\int_0^{L_l}\frac{\partial w}{\partial z}d\xi_l\,d\eta_l\,;$$
$$\dot{\gamma}_{xyl} = \int_{-r}^r\int_0^{L_k}\frac{\partial u_l}{\partial y}d\xi_l\,d\zeta_l + \int_r^B\int_{-r}^r\frac{\partial v_l}{\partial x}d\zeta_l\,d\eta_l\,;\ \dot{\gamma}_{xzl} = \int_r^B\int_0^{L_l}\frac{\partial u_l}{\partial z}d\xi_l\,d\eta_l + \int_r^B\int_{-r}^r\frac{\partial w_l}{\partial x}d\zeta_l\,d\eta_l\,; \quad (4)$$
$$\dot{\gamma}_{yzl} = \int_r^B\int_0^{L_l}\frac{\partial v_l}{\partial z}d\xi_l\,d\eta_l + \int_{-r}^r\int_0^{L_k}\frac{\partial w_l}{\partial y}d\xi_l\,d\zeta_l\,.$$

Results and discussion

Unfortunately, the final expression of strain rates components in its complete form $\dot{\epsilon}_{xl}$, $\dot{\epsilon}_{yl}$, $\dot{\epsilon}_{zl}$, $\dot{\gamma}_{xyl}$, $\dot{\gamma}_{xzl}$, $\dot{\gamma}_{yzl}$ is not possible lead within the paper, because of their cumbersomeness. Graphical interpretation of these expressions is shown in Figs. 2 and 3.

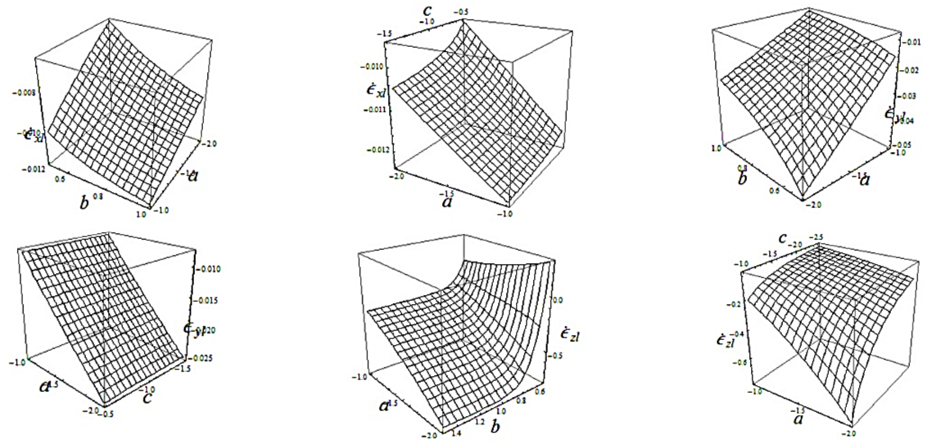

Figure 2. Graphs of the normal strain rate components of the soil $\dot{\epsilon}_{xl}, \dot{\epsilon}_{yl}, \dot{\epsilon}_{zl}$, depending on the coefficients *a, b, c* of the equation of the plane

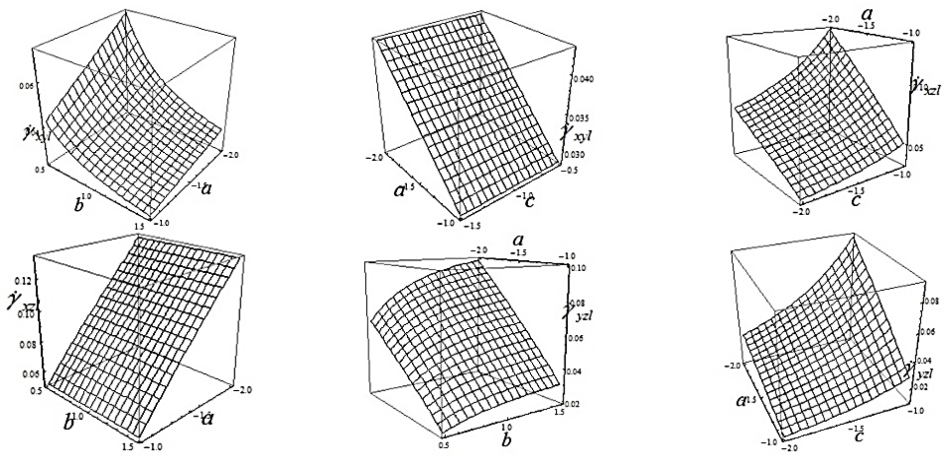

Figure 3. Graphs of the shear-strain rate components of the soil $\dot{\gamma}_{xyl}, \dot{\gamma}_{xzl}, \dot{\gamma}_{yzl}$, depending on the coefficients *a, b, c* of the equation of the plane

The analysis showed that the effect of the plane equations coefficients a, b, c on the change in the components (Fig. 2) of normal strain rates by such functions is characterized:

1) the decrease in the slope of the normal of the plane to the axis ox that is longitudinal to the direction of motion (magnitude $1/a$), leads to an increase in the normal strain rate components $\dot{\epsilon}_{xl}, \dot{\epsilon}_{zl}$ (compression) and a decrease in the component $\dot{\epsilon}_{yl}$ that is transverse to the direction of motion;

2) the increase in the slope of the normal of the plane to the axis oy that is transverse to the direction of motion (magnitude $1/b$), leads to a decrease in the normal strain rate components $\dot{\epsilon}_{xl}, \dot{\epsilon}_{yl}, \dot{\epsilon}_{zl}$;

3) the increase in the slope of the normal of the plane to the axis oz that is vertical to the direction of motion (magnitude $1/c$), leads to a decrease in the normal strain rate components $\dot{\epsilon}_{xl}, \dot{\epsilon}_{zl}$, and the component $\dot{\epsilon}_{yl}$ remains unchanged.

It should be noted that:

1) the decrease in the slope of the normal of the plane to the axis ox (magnitude $1/a$), leads to an increase in all three shear-strain rate components $\dot{\gamma}_{xyl}, \dot{\gamma}_{xzl}, \dot{\gamma}_{yzl}$;

2) the decrease in the slope of the normal of the plane to the axis oy (magnitude $_{1/b}$), leads to an increase in components $\dot{\gamma}_{xyl}$, $\dot{\gamma}_{yzl}$ and does not affect the change $\dot{\gamma}_{xzl}$;

3) the increase in the slope of the normal of the plane to the axis oz (magnitude $1/c$), leads to an increase in the $\dot{\gamma}_{yzl}$, $\dot{\gamma}_{xzl}$, while component $\dot{\gamma}_{xyl}$ remains unchanged (Fig. 3).

Conclusions

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

These expressions are the starting point for the further determination of the stresses components in the soil that determine the soil compaction on the walls of the formed of the cavity for impervious screen and components of resistance forces to the movement of share mole plough. In the future, this will make it possible to determine the geometric parameters of the tool, under various mechanical properties of the soil, to ensure the stability of the cavity walls with minimum energy costs.

The solution is common for a certain class of problems of the kinematics of the contact interaction of a rigid body with a deformable medium.

The proposed solution makes it possible to determine the changes in the components of the soil's strain rates as a function of the slope of the ploughshare plane.

In the future, this allows us to determine the dynamic components of the contact interaction of the ploughshare with the soil.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Author contributions

OS, VK – study conception;
VK, IK – analysis and interpretation of data;
OS, IK– drafting of the manuscript;
IK – editing the manuscript;
VK – critical revision and approval of the final manuscript.

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