Development of model and analysis of one-dimensional movement of ploughshare of subsoiler

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Abstract. Soil medium changes its structure and deforms when the actuating tool of an agricultural machine interacts with the soil. The effect of soil on the performance of the actuating tool can be taken into account through soil density and tensile strength. The model of a plastic medium proposed by Academician Kh.A. Rakhmatulin and simplified equations obtained based on the hypothesis of plane sections were used to describe the movement of soil near the point under finite deformations. It was stated that, depending on the coefficient of internal friction and cohesion of soil, a zone of high soil density could form near the actuating tool of the subsoiler ploughshare, where a significant increase in the resistance force is observed.

1 Introduction

The formulation of research work based on modern scientific achievements and related to the study of increasing the productivity and reliability of machines at the operating stage is becoming increasingly important worldwide in agricultural production for developing complex mechanization of cotton growing [1, 2]. The development of energy-resource-saving agricultural (in particular, soil-cultivating and cotton harvesting) machines with high-quality work and efficiency is closely related to the problems of studying vibrations of parts and assembly units, which cause vibration and dynamic strength of machines as a whole [3, 4].

Special attention is paid to various physical and mathematical models for studying the behavior of soils under static and dynamic influences associated with the movement of tools in the soil medium, which is an objective necessity. Establishing the patterns of interaction between a rigid body and soil based on solving the problems of projectile entry (penetration) into the soil [5, 6], the landing of an aircraft, driving piles, and many others is related to determining the contact force (of resistance) on the surface of the body.

As is well known, soils differ in structure, shape, packing of solid particles, water, and air content. Consequently, this is a great variety of mechanical properties of soils under dynamic and static impacts. This explains the difficulties in practice associated with determining the pattern of motion of rigid bodies in soil, where an essential role belongs to soil's physical and mechanical properties.

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According to previous studies, it was established that long-term rotary tillage hurts the surface layer of soil, and due to global climate change, water supply in agriculture is becoming increasingly problematic. When loosening a dense subsoil layer to a depth of up to 60 cm due to water consumption, the soil's water permeability and moisture capacity increase significantly; this makes the lateral roots of plants develop better, and the crop is heavy [7-9].

It should be noted that the previously developed technological schemes for tillage and the corresponding designs of the actuating tool of the subsoiler ploughshare, operating under conditions of unlatched cutting of soil [10], experimental methods for studying the behavior of soils under static and dynamic impacts [11, 12], and the proposed soil models using the discrete element method [13] have made it possible to achieve certain success in solving problems of the dynamics of bodies moving in a soil medium.

As a rule, in solving applied problems, the soil is modeled as a multi-component continuous medium, the motion of which is characterized as an ideal fluid or an elastic (multi-component) medium. Such a model can describe the movement of water-saturated soils [14]. For soils of low or medium moisture content, consisting of solid particles and air inclusions, the presence of large volumetric irreversible deformations and the presence of shear deformations are significant. Such soils are considered as a plastic compressible medium. The theory of elastic and elastoplastic models covers a wide range of constitutive models for solids and liquids found in the scientific literature and used in many applied problems related to porous media saturated with liquid [15]. An improved method was developed using a hydro-mechanical finite element model to better understand soil structure behavior and make the substructure design process more practical. This model was substantiated by some case studies, one of which confirmed the ability to simulate soil movement and substructure deformation, the other - the ability to model by the method of discrete elements to determine the traction force during tillage depending on the speed, tillage depth, moisture content, and soil compaction [16, 17].

2 Methods

As a result of the movement of a rigid body (subsoiler ploughshare) in the soil medium, the soil is deformed, and a time-varying resistance force arises on the contact surface of the rigid body and the moving part of the medium. The value of this force primarily depends on the dynamic structure of the soil, which is subject to constant changes due to a wide range of biotic and abiotic factors such as biodegradation and mechanical disturbance of soil, considered in [18, 19] and the design features of the tillage machine [20]. The parameters of the power capabilities of machines are ultimately determined by the interaction pattern of their actuating tools with the tilled soil medium. Therefore, in theoretical terms, the choice of a model for the interaction process between the soil and the actuating tools of a tillage machine is of particular importance.

In the case of a compressible plastic medium, the "plastic gas" model of Kh.A. Rakhmatulin was used, according to which the soil under loading changes its density by a certain law; under unloading, it retains the density obtained under loading. To compile the equation of motion of soil, the "hypothesis of plane sections" proposed by A.A. Ilyushin was used, according to which soil particles perform radial motions in a plane perpendicular to the axis of symmetry of a rigid body (a cone). In this case, the body motion problem is reduced to studying the motion of a compressible plastic medium with cylindrical symmetry [21].

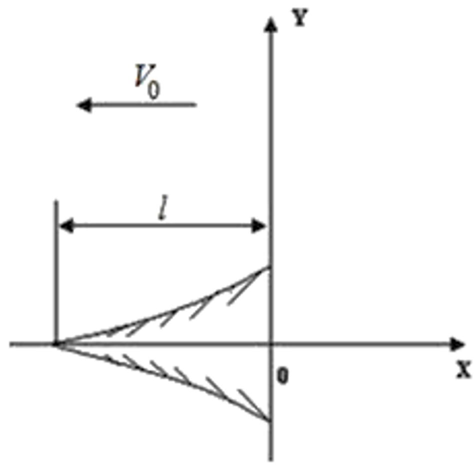


Fig. 1. Schematic presentation of a subsoiler ploughshare in a linear-elastic medium

It was determined that for each value of the density ratio behind the shock wave front, which is assumed to be constant, to the initial density, there is an initial velocity at which the rigid body begins to move. With an increase in this ratio, which corresponds to a more compacted initial state of the soil, the value of this velocity also increases.

The actuating tool of the machine – a subsoiler ploughshare – is taken as a thin, rigid body in the form of a curvilinear wedge of length l with a symmetrical profile relative to the *Ox–axis* and moving in soil at a constant velocity of V_0 in the direction opposite to the *Ox*–axis (Fig. 1).

The soil medium is modeled as an unbounded homogeneous linear elastic medium. The following expressions were obtained for the case of a thin wedge, for the stress tensor components σ_{22} and σ_{12} at an arbitrary point of an elastic medium [22].

$$\sigma_{22} = -\frac{i\cdot[-\left(1+\eta^2\right)^2 J_1\left(x_1, y_1, \alpha\right) + 4\eta\cdot\alpha J_1\left(x_1, y_1, \eta\right)]}{\left(1-\eta^2\right)^2\cdot\alpha} \tag{1}$$

$$\sigma_{12} = \frac{\left(1+\eta^2\right)[J_2\left(x_1, y_1, \eta\right) - J_2\left(x_1, y_1, \alpha\right)]}{\left(1-\eta^2\right)^2}, \tag{2}$$

where $J_1(x_1, y_1, k) = \frac{1}{\sqrt{2\pi}}\int_0^\infty [\bar{\gamma}_1(p)\exp(-ip\cdot x_1) - \bar{\gamma}_1(-p)\exp(ip\cdot x_1)]\exp(-pk\cdot y_1)dp$,

$$J_2(x_1, y_1, k) = \frac{1}{\sqrt{2\pi}}\int_0^\infty [\bar{\gamma}_1(p)\exp(-ip\cdot x_1) + \bar{\gamma}_1(-p)\exp(ip\cdot x_1)]\exp(-pk\cdot y_1)dp$$

k is replaced by α and η, $\bar{\gamma}_1(p)$ is a function describing the solid profile.

In the case of a circular cone, the displacements $u_1(r_1,x_1)$ and $w_1(r_1,x_1)$ are determined by the following formulas

$$u_1(r_1, x_1) = \frac{1}{(1-\eta^2)\sqrt{2\pi}}\int_{-\infty}^{\infty}[(1+\eta^2)K_0(\alpha\cdot r_1|p|) - 2\eta^2 K_0(\eta\cdot r_1|p|)]\Gamma(p)\exp(-ipx_1)dp \tag{3}$$

$$w_1(r_1,x_1) = -\frac{i}{(1-\eta^2)\sqrt{2\pi}}\int_{-\infty}^{\infty}[\alpha(1+\eta^2)K_1(\alpha\cdot r_1|p|)-2\eta\, K_1(\eta\cdot r_1|p|)]\frac{p\Gamma(p)}{|p|}\exp(-ipx_1)dp \quad (4)$$

where $\alpha=\sqrt{1-\frac{V_0^2}{c_1^2}}$, $\eta=\sqrt{1-\frac{V_0^2}{c_2^2}}$, $c_1=\sqrt{\frac{\lambda_1+2\mu_1}{\rho}}$, $c_2=\sqrt{\frac{\mu_1}{\rho}}=c_1\sqrt{\frac{1-2\nu_0}{2(1-\nu_0)}}$ are the propagation velocities of longitudinal and transverse waves, respectively, (λ_1, μ_1 are the Lame constants, ρ is the density of the medium, ν_0 is the Poisson ratio), $K_0(z)$, $K_1(z)$ are the Bessel functions of the imaginary argument of zero and first orders. Function $\Gamma(p)$, included in formulas (3) and (4), is written as

$$\Gamma(p) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} f(x_1)\gamma(x_1)\exp(ipx_1)dx_1$$

where $f(x_1)$ is the function that satisfies the boundary conditions in the linear approximation at small angles between the tangent to the body profile, and the Ox–axis, $\gamma(x_1)$ is the function that describes the body profile.

Expressions for stresses σ_{22} and σ_{12} are determined according to Hooke's law. In the disturbed region, the values of the stress tensor and the contact force of interaction between the soil medium and the body (a subsoiler ploughshare) can be determined.

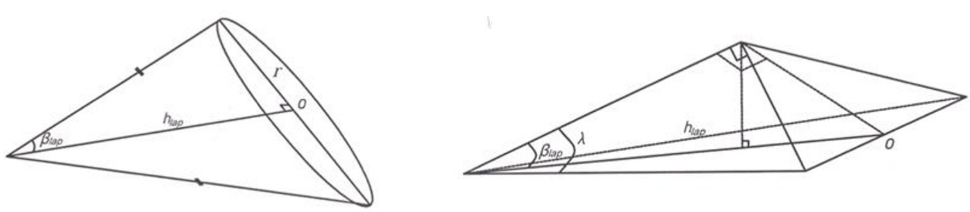
3 Results

Let the subsoiler ploughshare be represented as a sharp wedge with two identical triangular side faces with an acute apex angle λ (Fig. 2, a).

Then the surface area of the subsoiler ploughshare S_{wedge} in the form of a wedge-shaped body can be determined by the following formula

$$S_{wedge} = h_{pl}^2\frac{tg\lambda}{\cos^2\beta_{pl}} \quad (5)$$

where h_{pl} is the height of the subsoiler ploughshare, β_{pl} is the angle of the chisel point to the base, λ is the angle at the top of the wedge.



a) b)

Fig. 2. Schematic representation of a subsoiler ploughshare in the form of a thin wedge (a), and reduced circular cone (b)

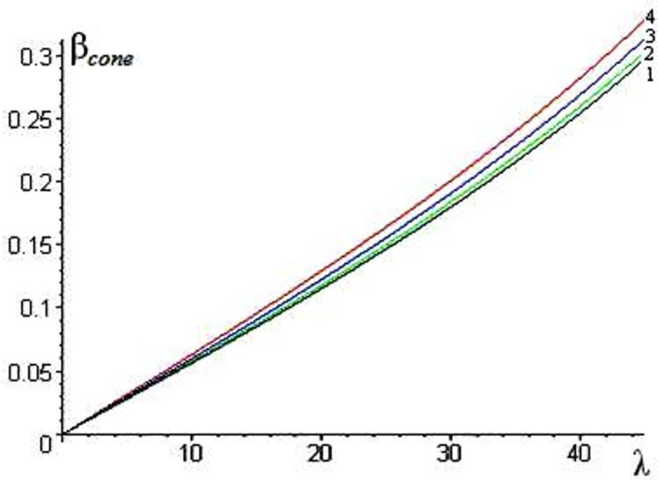
Let us replace the wedge-shaped subsoiler ploughshare with a reduced circular cone (Fig. 2, b). Denoting the height and angle at the vertex of the circular cone by h_{cone} and $2\beta_{pl}$, respectively, we obtain a formula for determining the surface area S_{cone} in the following form

$$S_{cone} = \frac{\pi \cdot h_{cone}^2 \cdot tg\beta_{cone}}{\cos\beta_{cone}} \tag{6}$$

In particular, if the heights of the subsoiler ploughshare and the circular cone are taken as equal, that is, $h_{pl} = h_{cone} = h$, then by equating formulas (5) and (6), we obtain a relation for determining angle β_{cone} in the following form

$$\beta_{cone} = \arcsin\left(\sqrt{p^2+1} - p\right),\ \ p = \frac{\pi \cdot \cos^2\beta_{pl}}{2tg\lambda}. \tag{7}$$

Figure 3 shows graphs of curves that describe the dependence of angle β_{cone} on the angle λ for various values of β_{pl}.



1 - $\beta_{pl} = 5^0$; 2 - $\beta_{pl} = 10^0$; 3 - $\beta_{pl} = 15^0$; 4 - $\beta_{pl} = 20^0$

Fig. 3. Dependence of semi-vertex angle of cone β_{cone} (in radians) on λ, at different values of angle β_{pl} (in degrees)

Analyzing the curves in Fig. 3, we see that the change in the vertex angle β_{cone} of the cone for different values of angle β_{pl} is insignificant. In addition, a significant increase in angle β_{cone} of the opening of the cone is observed at large angles λ between the side faces of the chisel point.

Consider an arbitrary section of the cone at time t_1, $L_1 = L(t_1)$ (Fig. 1). Let at the point of contact of the vertex of the cone in the considered section at time $t=t_1$ a cylindrical compression wave is initiated in soil [21], and at time $t>t_1$ the boundary of the region of disturbed soil motion is bounded by the radii of the cylindrical wave $r = r_*(t)$ and radius $r = L(t)\cdot tg\beta$ ($\beta = \beta_{cone}$ is the angle at the vertex of the circular cone), which is the line of intersection of the surface of the cone with the plane under consideration.

Let us assume that the soil density changes only at the front of a cylindrical wave and is determined by the intensity of this wave. Therefore, the soil density in the disturbed region is only a function of the coordinate r and does not depend on time t. Let r be a variable Lagrange coordinate. Then the equation of motion and continuity in cylindrical coordinates in an arbitrary section $L = L_1$ has the following form

$$\rho_0 r \frac{\partial^2 u}{\partial t^2} = (r+u)\frac{\partial \sigma_r}{\partial r} + (\sigma_r - \sigma_\theta)\frac{\partial}{\partial r}(r+u) \tag{8}$$

$$\frac{1}{2}\frac{\partial}{\partial r}(r+u)^2 = \frac{\rho_0}{\rho} r \tag{9}$$

where r is the initial distance of the particles from the axis of the cone, $u = u\,(r,t)$ is the displacement of the soil particles at this distance, t is time, ρ_0 and ρ are the initial and current soil densities, respectively, in the disturbed area $L_1 < r < r_*(t)$, σ_r and σ_θ are the radial and tangential stresses, respectively. Since the soil is modeled by a plastic (irreversible) medium [5], the stresses satisfy the Mohr-Coulomb plasticity condition [20]

$$\sigma_r - \sigma_\theta = \tau_0 + \mu(\sigma_r + \sigma_\theta) \tag{10}$$

where $\tau_0 = 2k \cdot cos\theta$ and $\mu = sin\theta$, k is cohesion, θ is the angle of internal friction.

Eliminating σ_θ from equation (8), we reduce it to the following form

$$\nu\sigma_r \frac{\partial(r+u)}{\partial r} + (r+u)\frac{\partial \sigma_r}{\partial r} = \rho_0 r \frac{\partial^2 u}{\partial t^2} - \frac{\tau_0}{1+\mu}\frac{\partial}{\partial r}(r+u) \tag{11}$$

Here $\nu = 2\mu/(1+\mu)$. Multiplying both sides of equation (11) by function $(r+u)^{\nu-1}$ and integrating over the Lagrangian variable r, we obtain

$$(r+u)^\nu \sigma_r(r,t) = \rho_0 \int_0^r (r+u)^{\nu-1} r \frac{\partial^2 u}{\partial t^2} dr - \frac{\tau_0}{1+\mu}\frac{(r+u)^\nu - R^\nu}{\nu} + R^\nu \sigma_r(0,t) \tag{12}$$

where $R = V_0 t \cdot tg\beta$ is the radius of the inner boundary of the disturbed region at zero Lagrange value r at an arbitrary time point.

Let us denote the stress at the front of a cylindrical wave $r = r_*(t)$ by $\sigma_r^* = \sigma_r(r_*, t)$, where the displacement of particles is zero. Then equation (12) at the front $r = r_*(t)$ is written as

$$r_*^\nu \sigma_r^* = \rho_0 \int_0^{r_*} (r+u)^{\nu-1} r \frac{\partial^2 u}{\partial t^2} dr + \frac{\tau_0}{1+\mu}\frac{r_*^{\ \nu} - R^\nu}{\nu} + R^\nu \sigma_r(0,t)\,. \tag{13}$$

Subtracting (13) from (12), we obtain

$$(r+u)^\nu \sigma_r(r,t) - r_*^\nu \sigma_r^* = -\rho_0 \int_r^{r_*} (r+u)^{\nu-1} r \frac{\partial^2 u}{\partial t^2} dr + \frac{\tau_0}{1+\mu}\frac{r_*^{\ \nu} - (r+u)^\nu}{\nu}\,. \tag{14}$$

Considering the time independence of the density in the disturbed region, we integrate the continuity equation (9)

$$(r+u)^2 = 2\psi(r) + R^2(t)\,, \tag{15}$$

where $\psi(r) = \int_0^r \frac{\rho_0}{\rho(r)} r dr$.

Knowing that $u = 0$ at the wave front and $r = r_*(t)$, from (15) we have

$$r_*^2 = 2\psi(r_*) + R^2(t)\,, \tag{16}$$

where $\psi(r_*) = \int_0^{r_*} b(r) r dr$, $b = \rho_0 / \rho(r)$.

At a constant cone velocity, we have $L = V_0 t$ ($R = V_0 t \cdot tg\beta$). Then, from the known law $\rho = \rho(r)$, from formula (16), it is possible to determine the pattern of displacements of the cylindrical wave front $r = r_*(t)$.

Differentiating (15) concerning time, we find the velocity and acceleration of soil particles in the disturbed region $L_1 < r < r_*(t)$

$$\frac{\partial u}{\partial t} = \frac{R \cdot \dot{R}}{\sqrt{2\psi(r) + R^2(t)}} \tag{17}$$

$$\frac{\partial^2 u}{\partial t^2} = \frac{\dot{R}^2 + R \cdot \ddot{R}}{\sqrt{2\psi(r) + R^2(t)}} - \frac{R^2 \cdot \dot{R}^2}{[2\psi(r) + R^2(t)]^{3/2}} \tag{18}$$

where $R = V_0 t \cdot tg\beta$, $\dot{R} = V_0 \cdot tg\beta$.

The velocity of soil particles at the wave front is determined from expression (17), where it is assumed that $r = r_*(t)$

$$\dot{u}_* = \frac{R\dot{R}}{\sqrt{2\psi(r_*) + R^2(t)}} = \frac{R\dot{R}}{r_*} \tag{19}$$

To determine the stress at the wave front $\sigma_r = \sigma_r^*$, we use the mass conservation law and the momentum theorem [23]

$$\rho_0 D = \rho(D - \dot{u}_*) \tag{20}$$

$$\rho_0 D \dot{u}_* = -\sigma_r^* - p_a \tag{21}$$

where D is the velocity of the leading front of the cylindrical wave, p_a is the pressure ahead of the compression wave. From (20) and (21), we find the velocity of wave D and stress σ_r^*

$$D = \frac{\dot{u}_*}{1 - b(r_*)} \qquad \sigma_r^* = -\frac{\rho_0 \dot{u}_*^2}{1 - b(r_*)} - p_a \cdot$$

Substituting the particle acceleration and expression σ_r^* from (19) and (21), respectively, into (14), the stress in the disturbed region is determined as

$$\begin{aligned}(r+u)^\nu \sigma_r &= \rho_0\left(R\ddot{R} + \dot{R}^2\right)\int_r^{r_*} \frac{rdr}{\left[2\psi(r) + R(t)\right]^{1-\nu/2}} - \rho_0 (R\dot{R})^2 \int_r^{r_*} \frac{rdr}{\left[2\psi(r) + R(t)\right]^{2-\nu/2}} \\ &+ \frac{\rho_0}{1 - b(r_*)} \cdot \frac{(R\dot{R})^2}{r_*^{2-\nu}} + \frac{\tau_0}{1+\mu}\left[r_*^\nu - (r+u)^\nu\right] + p_a \cdot r_*^\nu\end{aligned} \tag{22}$$

By substituting expression (15) into formula (22), it is possible to determine the spatiotemporal distribution of stresses in the disturbed region, where it is necessary to assume that the experimentally determined function $\psi(r)$ is known. If we consider the wave propagation process over a short period, then we can assume that the soil density behind the wave front is constant and equal to $\rho = \rho_1 = const$. Assuming that $r = 0$, $u = R(t)$, we obtain an explicit expression for stress $p_1 = -\sigma$ on the surface of the cone

$$\begin{aligned}p_1 - p_a &= \ddot{L}\frac{\rho_0 \cdot \varphi(\nu, b_1) \cdot xtg^2\beta}{b_1} + \dot{L}^2 \frac{\rho_0 \cdot tg^2\beta}{b_1(\nu-2)}\left[(\nu-2)\cdot\varphi(\nu,b_1) + b_1(\nu-2)\cdot a^{\nu/2} - a^{\nu/2-1} + 1\right] + \\ &+ \varphi(\nu, b_1)\cdot\left[\nu \cdot p_a + \frac{\tau_0}{(1+\mu)}\right],\end{aligned} \tag{23}$$

where $b_1 = \rho / \rho_1$, $x = L - L_1$, $\varphi(\nu,b_1) = (a^{\nu/2} - 1) / \nu$, $a = 1 / (1 - b_1)$.

Based on the known values of stresses σ_{yy} and σ_{xy}, determined according to Hooke's law, and the pressure p_1 on the body surface according to formula (23) and integrating them, the contact force of interaction between the soil environment and the body can be determined.

As noted above, the value of the contact force of interaction (resistance force) depends on the chosen model of soil medium and the configuration of the body. The total resistance force acting on the surface of the subsoiler ploughshare (a circular cone) is calculated using the following integral [20]:

$$F = 2\pi(\sin\beta + \mu_0 \cos\beta)\cdot \int_0^h (p - p_0) x \cdot tg\beta\sqrt{1 + tg^2\beta}\,dx \tag{24}$$

where μ_0 is the coefficient of friction between the soil medium and the cone's surface, h is the height of the cone. Equation (24) is integrated numerically under zero initial conditions: $L = 0$ and $\dot{L} = 0$, at $t = 0$. Integrating equation (1), with $R = L\cdot tg\beta$, we obtain:

$$F = \pi(1 + \mu_0 ctg\beta)\cdot\left(A + B\rho_0\dot{L}^2 + \rho_0 Ch\ddot{L}\right)\cdot h^2 \tag{25}$$

where

$$A = \pi \cdot tg^2\beta \cdot \left[p_a + \frac{\tau_0}{\nu(1+\mu)} \right] \cdot \left(a^{\nu/2} - 1 \right),$$

$$B = \frac{\pi \cdot tg^4\beta}{b_1(\nu-2)} \left[\frac{\nu-2}{\nu} \cdot \left(a^{\nu/2} - 1 \right) + b_1(\nu-2) a^{\nu/2} - \left(a^{\nu/2-1} - 1 \right) \right] \qquad (26)$$

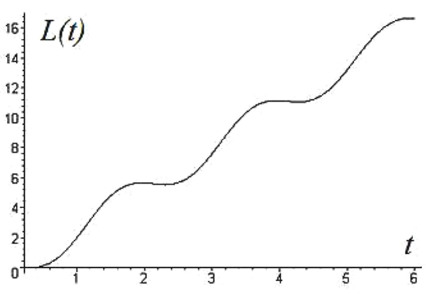
$$C = \frac{\pi \cdot tg^4\beta}{3 b_1 \nu} \left(a^{\nu/2} - 1 \right) \; a = 1/(1-b_1).$$

Let us assume that a subsoiler ploughshare, represented as a circular cone, performs a one-dimensional movement in the soil medium along the cone's axis. Let the movement of the chisel point be realized through an elastic element rigidly coupled to the strut of the subsoiler ploughshare moving at constant velocity V_0. In this case, the equation of motion of the subsoiler ploughshare in the form of a circular cone, considering expression (24), is described by the following formula

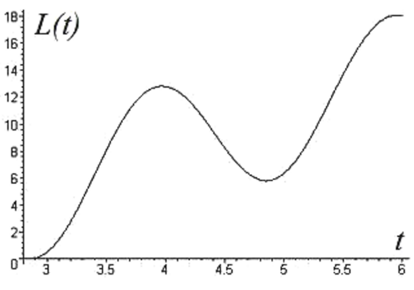
$$\left[m + m_{np}(h) \right] \cdot \dot{L} = -\pi\left(1 + \mu_0 ctg\beta\right)\left(A + B\rho_0 \dot{L}^2\right) \cdot h^2 + k_0\left(L - V_0 t\right) \qquad (27)$$

where k_0 is the stiffness coefficient of the elastic element.

Figures 4–5 show the subsoiler ploughshare displacement L(m) dependences on time t *(sec)* for various values of the stiffness coefficient k_0 and the ratio $b_1 = \rho_0 / \rho_1$ for the initial stages of movement.

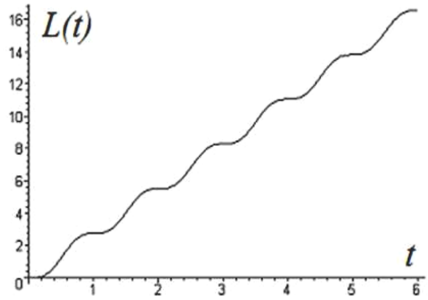


$b_1 = 0.2$

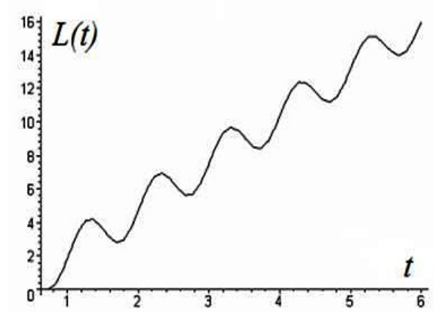


$b_1 = 0.8$

Fig. 4. Change in displacements of the subsoiler ploughshare *L(t) (m)* on time *t (sec),* for $k_0 = 50$ *H/m* for different values of $b_1 = \rho_0 / \rho_1$



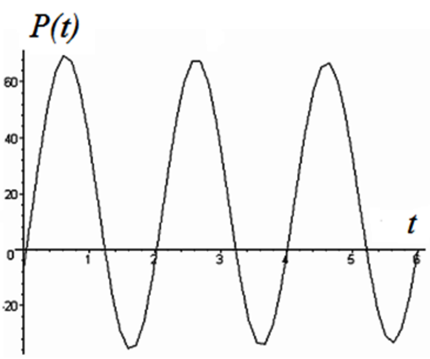
$b_1 = 0.2$



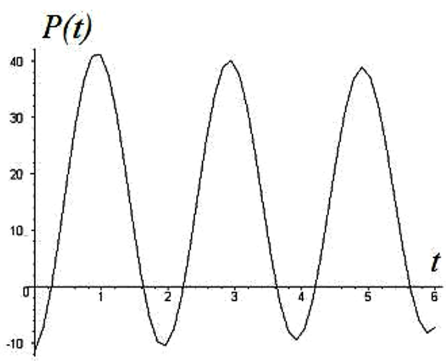
$b_1 = 0.8$

Fig. 5. Change in displacements of the subsoiler ploughshare *L(t) (m)* on time *t (sec)*, for $k_0 = 200$ *H/m* for different values of $b_1 = \rho_0 / \rho_1$

Figures 6 – 7 show the dependences of elastic force $P(t) = k_0(V_0 t - L)$ on time for two values of the stiffness coefficient k_0 for different values of $b_1 = \rho_0 / \rho_1$.

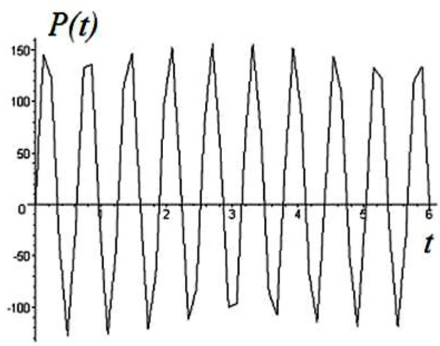


$b_1 = 0.2$

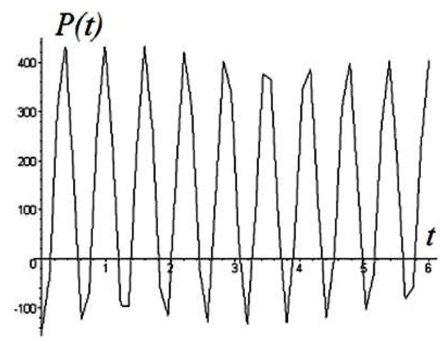


$b_1 = 0.8$

Fig. 6. Change in elastic force *P(t)* on time *t (sec),* at $k_0 = 50$ *N/m* for different values of $b_1 = \rho_0 / \rho_1$



$b_1 = 0.2$



$b_1 = 0.8$

Fig. 7. Change in elastic force *P(t)* on time *t (sec),* for $k_0 = 500$ *N/m* for different values of $b_1 = \rho_0 / \rho_1$

4 Discussions

It is seen (Figs. 4, 5) that with an increase in the stiffness coefficient k_0, the subsoiler ploughshare performs high-frequency oscillations with increasing amplitude. With an increase in the compaction parameter $b_1 = \rho_0 / \rho_1$, the oscillation period also increases, while the amplitude for small values of k_0 first decreases (for $b_1 = 0.2$) and then increases with an increase in this parameter. At large values of the stiffness coefficient k_0, the oscillation amplitudes for all values of the soil compaction parameter $b_1 = \rho_0 / \rho_1$ are almost the same; their increase is observed for $b_1 = 1$.

From the analysis of the curves given in Figs. 6, 7, it follows that the elastic element in the process of movement of the subsoiler ploughshare is, to a greater extent, in a state of compression, the value of which also increases with an increase in the value of $b_1 = \rho_0 / \rho_1$. However, the stiffness coefficient practically does not affect the oscillation amplitude.

5 Conclusions

The results obtained and their analysis allow us to formulate the following main conclusions:

1. To describe the dynamics of cultivated soil, a model of a compressible plastic medium was chosen under the Coulomb-Mohr plasticity condition. Based on the calculations performed using this model, it was found that the value of the contact force of interaction depends on the chosen model of the soil medium and the configuration of the body.
2. Based on the model of a compressible plastic medium and the "plane section hypothesis", an analytical and numerical method was presented for solving the equation of motion of a subsoiler ploughshare in the form of a circular cone, which is rigidly connected to the subsoiler strut through an elastic element and moves in the soil medium at a constant velocity.
3. Analysis of the results obtained shows that with an increase in the stiffness coefficient, the subsoiler ploughshare performs high-frequency oscillations at increasing amplitude; that is, the elastic element during the movement of the point is in a state of compression, the value of which also increases with the growth of the soil compaction parameter. However, the stiffness coefficient practically does not affect the oscillation amplitude.

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