Determination of the traction performance of the working body of the subsoiler in the soil environment depending on the working body configuration and the selected soil model

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Abstract. The cultivated soil environment changes its structure and is deformed; therefore, the considered model of the processes of interaction of the working body with soil remains understudied. The influence of soil criteria on the working body behavior can be taken into account through its density and tensile strength. To describe the movement of the soil near the leg during finite deformations, a plastic medium model proposed by academician Kh.A. Rakhmatulin and simplified equations obtained on the basis of the hypothesis of flat sections were used. It has been established that, depending on the coefficient of internal friction and soil adhesion, a zone of increased soil density can form near the working body of the cultivator, where a significant increase in resistance force is observed. The calculations were carried out based on the methods of mechanics of a deformable solid, soil mechanics, and were performed in the Maple-8 programming environment.

1. Introduction
The prevention of the subsurface horizons compaction ensures the soil quality and its ecological state, since compaction of the subsurface horizons is almost a constant phenomenon, which reduces yield and also increases the leaching of nutrients from the soil [1].

As is known, one of the effective methods of soil loosening and destroying the “plow pan” is mechanical loosening to a depth of 50 cm using subsoilers or chisel plows. Countries such as the USA, Germany, Canada, Romania and Hungary hold leading positions in the field of creation and production of special tools for loosening the soil (subsoilers, kilifiers, etc.).

According to foreign scientific research, it has been found out that long-term rotation and tillage has a negative effect on the surface soil and due to global climate change, water consumption in agriculture is becoming increasingly problematic. When loosening a dense subsurface soil layer to a depth of 60 cm, the infiltration of water and soil water capacity increases significantly due to water consumption, with the result that the lateral roots of plants develop better, and the crop is better [2].

On the basis of previous studies, this work has identified the main factors that affect the soil deformation and movement in the area where the working body of the subsoiler acts. Due to the selected soil model, thrust force during movement of the body (the working body of the subsoiler, presented in the form of a circular cone) is determined using constant speed.
2 Models of the process of interaction of the tillage machine working bodies with soil

During the movement of tillage machines in a soil environment, the soil is deformed and a time-dependent interaction force (resistance) arises on the contact surface of the processing elements and the moving part of the environment, the magnitude of which primarily depends on the dynamic structure of the soil, which undergoes constant changes due to a wide range of biotic and abiotic factors such as bioturbation and mechanical soil damage, considered in [3], and the design features of the tillage machine [4].

In [5], a working model of soil behaviour is described at the boundary of arable and subsurface horizons using the discrete element method. The research results showed that the range of soil damage in the upper (shallow) layer was the widest, followed by the range of soil damage in the middle layer and then the range of soil damage in the deep layer. The resistance force of soil particles in the deep layer was greatest, followed by the resistance force of soil particles in the middle layer and then in the shallow layer. Moreover, the speed of movement of soil particles in different places decreased with increasing distance between the arable and subsurface horizons. The percentage error between the simulated and experimental values of soil friability and soil damage coefficient was 14.45% and 12.06%, respectively. Thus, the results of this study can be used to study the interaction of soil with a cultivating leg and optimize the mechanisms of tillage machines.

In this case, the parameters of the power capability of the machines are ultimately determined by the nature of the interaction of the working bodies with the processed soil environment. Therefore, in theoretical terms, the choice of a model of the process of interaction of the soil environment with the working bodies of the processing machine is of particular importance. In [6], an exact solution was obtained for the one-dimensional Riemann problem of elasticity and plasticity, which is used to verify the reliability of a method for solving problems of a compressible fluid modelled with complex geometry in a solid area, which is used to study the reaction of various structural regions. When solving applied problems of the interaction of solids with soil, soil is most often modelled as a multicomponent continuous medium whose motion is characterized as an ideal fluid or an elastic (multicomponent) medium. Such a model can be used to describe the movement of water-saturated soils [7]. For soils of low or medium humidity, which consist of solid particles and air inclusions, the presence of large volume irreversible deformations and the presence of shear deformations are significant. Such soils are usually regarded as a compressible plastic medium.

The theory for generalized compressible Newtonian fluids for elastic and elastic-plastic behaviour covers a wide range of constitutive models for solids and fluids [8] given in the scientific literature and can be applied for many engineering tasks associated with porous media filled with a fluid. Using the model of hydro-mechanical finite elements, an improved method has been developed for a deeper understanding of the behaviour of the soil structure and for a more practical process of designing substructures. This model was justified by some case studies, one of which confirmed the ability to simulate soil movements and deformation of the substructure, the other - the ability to simulate cracking of the substructure due to changes in the structure of the soil environment [9]. At very large compressive loads (pressures), where the average hydrostatic pressure is much higher than shear stresses, soils can be considered as a compressiblefluid with reversible or irreversible volumetric deformation.

In this paper, the model of “plastic gas” by academician Kh.A. Rakhmatulin [10] is used. According to this model, when loading, the soil changes its density according to a certain law, while unloading, it retains the density obtained during loading. In this work, the soil is modelled as a compressible plastic medium.

When generating the equation of motion for the soil, the “flat section hypothesis” proposed by Kh.A.Rakhmatulin and A. A. Ilyushin [11] is used to solve a number of aerodynamic problems. According to this hypothesis, soil particles make radial movements in a plane perpendicular to the axis of symmetry of a solid (cone). In this case, the problem of body motion is reduced to studying the motion of a compressible plastic (granular) medium with cylindrical symmetry [10]. Take the working body of the machine as a given circular cone. Let the cone begin to move according to the law $L(t)$
with a symmetrical profile relative to the axis $Oy$ and moving in the soil at a constant speed $V_0$ in the direction opposite to the axis $Ox$ (Figure 1). Consider an arbitrary section of the cone $L_4 = L(t_1)$ ($0 < L_4 < L_4$).

![Figure 1. Scheme of the movement of the subsoiler leg in the soil.](image)

As it is known, the three-dimensional theory of elasticity is used for structural modeling of a cylindrical shell [12]. Based on this, it is assumed that at the point of tangency of vertex of the cone of this section at the time $t = t_1$ a cylindrical compression wave occurs in the soil, and at the time $t > t_1$ the area boundary of soil disturbance will be limited by the radii of the cylindrical wave $r = L(t)$ and the radius $r = L(t) \cdot \tan \beta$, that is the line of intersection of the cone surface with the plane under consideration.

Assume that the density of the soil changes only at the front of the cylindrical wave and is determined by the intensity of this wave. Therefore, the density of the soil in the disturbance area is only a function of the coordinate $r$ and does not depend on time $t$. Take $r$ for the Lagrangian coordinate and derive the equation of motion and continuity in cylindrical coordinates in an arbitrary section $L = L_1$:

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

(1)

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

(2)

where $r$ - initial distance of particles from the axis of the cone, $u = u(r,t)$ - soil particle displacement at this distance, $t$ - time, $\rho_0$ and $\rho$ - initial and current soil density in the disturbed area $L_1 < r < L_2(t)$, $\sigma_r$ and $\sigma_\theta$ - radial and tangential stresses. Since the soil is modeled by a plastic (loose) medium, the stresses satisfy the Prandtl plasticity condition [10]:

$$
\sigma_r - \sigma_\theta = \tau_0 + \mu (\sigma_r + \sigma_\theta),
$$

(3)

where $\tau_0 = 2k \cdot \cos \theta$ and $\mu = \sin \theta$, $k$ - traction, $\theta$ - angle of internal friction.

Excluding voltage $\sigma_\theta$ from equation (1), bring it to the form:

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

(4)

This is $\nu = 2\mu/(1 + \mu)$. Multiply both sides of equation (4) by a function $(r+u)^{\nu-1}$ and integrate over the Lagrangian variable $r$:

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

(5)
where \( R = v_0 \beta \cdot t \) - the radius of the inner boundary of the perturbed area with the Lagrangian variable \( r = 0 \) at an arbitrary point of time.

We will denote the voltage at the front of the cylindrical wave \( r = n(t) \) by \( \sigma_r^* = \sigma_r(n(t), t) \), where the movement of particles is zero. Then equality (5) at the front \( r = n(t) \) is written in the form:

\[
\rho \frac{\partial}{\partial t} \sigma_r^* = \rho_0 \frac{R}{v} \int_0^{n(t)} (r + u)^{v-1} r \frac{\partial^2 u}{\partial t^2} dr + \frac{\tau_0 \rho}{1 + \mu} \frac{r - R^v}{v} + R^v \sigma_r^*(0, t).
\]

Subtracting (6) from (5), obtain:

\[
(r + u)^v \sigma_r(r, t) - r^v \sigma_r^* = -\rho_0 \int_0^{n(t)} (r + u)^{v-1} r \frac{\partial^2 u}{\partial t^2} dr + \frac{\tau_0 \rho}{1 + \mu} \frac{r - (r + u)^v}{v}.
\]

Given the independence of density on time in the disturbed area, integrate the continuity equation (2):

\[
(r + u)^2 = 2\psi(r) + R^2(t),
\]

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

Knowing that \( u = 0 \) at the wave front \( r = n(t) \), from (8) it is derived:

\[
r^2 = 2\psi(n) + R^2(t),
\]

where

\[
\psi(n) = \int_0^n b(r) dr, \quad b = \rho_0 / \rho(r)
\]

With a constant speed of the cone, there is \( L = v_0 t \) \( (R = v_0 \beta \cdot t) \), then with the known law \( \rho = \rho(r) \), from the formula (9) the law of movement of the front of a cylindrical wave \( r = n(t) \) can be established.

Differentiating (8) with respect to time, the velocity and acceleration of soil particles in the disturbance area \( L_1 < r < n(t) \) are calculated:

\[
\frac{\partial u}{\partial t} = \frac{R \cdot \ddot{R}}{\sqrt{2\psi(r) + R^2(t)}},
\]

\[
\frac{\partial^2 u}{\partial t^2} = \frac{R^2 + R \cdot \dddot{R}}{\sqrt{2\psi(r) + R^2(t)}} - \frac{R^2 \cdot \dddot{R}}{[2\psi(r) + R^2(t)]^{3/2}},
\]

where \( R = v_0 \beta \cdot t, \quad \dot{R} = v_0 \beta, \quad \ddot{R} = 0 \).

The velocity of soil particles at the wave front is determined from the first formula (10), where it should be taken as \( r = n(t) \):

\[
\dot{u} = \frac{RR}{\sqrt{2\psi(n) + R^2(t)}} = \frac{\dot{R} R}{n},
\]

To determine the voltage at the wave front \( \sigma_r^* = \sigma_r^*(n, t) \) the law of conservation of mass and the momentum theorem are used [19]:

\[
\rho_0 D \dot{u} = \rho(D - \dot{u}^2),
\]

\[
\rho_0 Du = -\sigma_r^* - p_a.
\]
where $D$ - speed of cylindrical wave leading edge, $p_a$ - pressure ahead of the compression wave. From (12) and (13) wave velocity $D$ and voltage $\sigma_r^*$ are calculated:

$$D = \frac{\dot{u}_s}{1 - b(n)}, \quad \sigma_r^* = \frac{\rho_0 \dot{u}_s^2}{1 - b(n)} - p_a.$$ 

Substituting the particle acceleration and the formula $\sigma_r^*$ respectively from (12) and (13) in (7), the voltage in the disturbance area is calculated:

$$(r + u)^{\nu} \sigma_r = \rho_0(RR + R^2) \int_n^{r_n} \frac{rdr}{[2\psi(r) + R(t)]^{3/2}} - \rho_0(RR) \int_n^{r_n} \frac{rdr}{[2\psi(r) + R(t)]^{2-\nu/2}} + \frac{\rho_0}{1 - b(n)} \frac{(RR)^2}{n^{2-\nu}} + \frac{\tau_0}{1 + \mu} [\nu^2 - (r + u)^{\nu}] + p_a v^{\nu}.$$ (14)

Substituting the formula (8) in the formula (14), the spatiotemporal stress distribution in the disturbance area can be established, where it is necessary to consider the experimentally determined function to be known $\psi(r)$. If one considers the process of wave propagation in a short period of time, then it can be assumed that the density of the soil behind the wave front is constant and equal to $\rho = \rho_1 = const$. Taken $r = 0$, $u = R(t)$ obtain an explicit expression for the voltage $p = -\sigma_r$ on the cone surface:

$$p - p_a = Lt \rho_0 \frac{\varphi(v, b_1) \cdot \tan \beta}{b_1} + L^2 \rho_0 \frac{\varphi(v, b_1)(v - 2)}{b_1(v - 2)} \varphi(v, b_1) + b_1(v - 2) \cdot a^{\nu/2} - a^{\nu/2-1} + 1] + \frac{\tau_0}{1 + \mu} \nu \cdot p_a +$$

$$+ \frac{\varphi(v, b_1)}{v} \left[ v \cdot p_a + \frac{\tau_0}{1 + \mu} \right],$$ (15)

where $b_1 = \rho_0 / \rho_1$, $x = L - L_1$, $\varphi(v, b_1) = (a^{\nu/2} - 1) / v$, $a = 1/(1 - b_1)$.

Using the known values of stresses, $\sigma_{xy}$, $\sigma_{yx}$ (12) and pressure $p$ from the (15) on the body surface, integrating them, the contact force of the interaction between the soil medium and the body can be found.

3 Determination of traction when moving the body at a constant speed

The value of the contact force of interaction (resistance force), as noted above, depends on the chosen model of the soil environment and body configuration. The formula of this force in the case of body motion in the form of a circular cone in a compressible plastic medium is found. Then the total resistance force acting on the surface of the cone is calculated using the integral ($\mu_0$ - the coefficient of friction between the soil and the cone surface):

$$F = 2\pi \sin \beta \mu_0 \cos \beta \int_0^H (p - p_a) \tan \beta \sqrt{1 + \tan^2 \beta} dx.$$ 

Substituting the pressure expression from (15) and making the integration, тогда с учетом taking into account, it is obtained:

$$F = \pi (1 + \mu_0 \tan \beta) (A + B p_0 L^2 + \rho_0 C \cdot H \cdot \dot{H}) \cdot H^2 \tan^2 \beta,$$ (16)

where

$$A = [p_a + \frac{\tau_0}{\nu (1 + \mu)} (a^{\nu/2} - 1) \cos^4 \beta],$$

$$B = \frac{1}{4 b_1 (v - 2)} \left[ \frac{\nu - 2}{\nu} (a^{\nu/2} - 1) + b_1 (v - 2)a^{\nu/2} - (a^{\nu/2-1} - 1) \right] \cos^2 \beta \sin^2 2 \beta,$$

$$C = \frac{1}{6 b_1 \nu} (a^{\nu/2} - 1) \cos^2 \beta \sin^2 2 \beta, \quad a = 1/(1 - b_1).$$
In the case of a cone moving at a constant speed, there is $L = v_0 t, L = v_0, L = 0$. Then the formula (16) takes the form:

$$F = (1 + \mu \cot \beta)(A + B \cdot \rho_0 v_0^2) h^2. \quad (17)$$

Figure 1 and Figure 2 (for curves 1, 2, 3, 4 with values $\mu = 0, \mu = 0.5, \mu = 0.7, \mu = 0.9$) show graphs of changes in resistance force depending on $b_1 (b_1 = \rho_0 / \rho_0)$ for two values of the angle $\lambda$ and for different values of the soil parameter $\mu = \sin \theta$. The accepted values are: $\beta_{\text{tan}} = 20^0$, $k = 50000 H / m^2$, $\rho_0 = 2000 kg / m^3$, $v_0 = 2.777 m / s \cdot 10 km / h$, $\mu_0 = 0.2, h_{\text{tan}} = h_{\text{con}} = 0.2 m$.

As can be seen from the graphs, with an increase in the ratio $b_1 = \rho_0 / \rho_1$, which corresponds to a more compacted state of the soil behind the front of a cylindrical wave, the resistance force $F$ significantly increases. On the other hand, an increase in the angle of internal friction $\theta$ leads to a certain decrease in the drag force.

**Figure 2.** The graph of the dependence of the soil resistance force $F(L)$ depending on $b_1$ for various parameter values $\mu = \sin \theta$ at $\lambda = 10^0$.

**Figure 3.** The graph of the dependence of the soil resistance force $F(L)$ depending on $b_1$ for various parameter values $\mu = \sin \theta$ at $\lambda = 20^0$.

**4. Conclusion**

To describe the dynamics of the cultivated soil, models of linearly elastic and compressible plastic medium are used. When using the model of linearly elastic and compressible plastic medium, the resistance forces of the soil medium are determined when the legs of the subsoiler, presented in the form of a circular cone, move. It has been established that the magnitude of this force substantially depends on the type of contact conditions between the body and the soil, and its greatest value is achieved in the case of continuous motion.

The dependence of the resistance force on time is obtained. According to the results of graphoanalytical studies, it is obvious that at the initial stage, while the contact area of the circular cone with the soil is variable, the resistance force depending on time changes according to a parabolic law, and then it remains constant. In the case of the movement of the subsoiler leg at a constant speed, it was found that, depending on the coefficient of internal friction and soil traction, a zone of increased soil density can form near the working body of the cultivator, where there is a significant increase in resistance force. With an increase in the angle of internal friction, a slight decrease in the resistance force is observed.

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