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

Davronbek Kuldoshev* Nargiza Djuraeva and Aziz Urinov
Institute of Mechanics and Seismic Stability of Structures of the Academy of Sciences of the Republic of Uzbekistan, Tashkent, Uzbekistan

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

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 impact. 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.
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 [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].
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 \( \sigma_{22} \) and \( \sigma_{12} \) at an arbitrary point of an elastic medium [22].

\[
\sigma_{22} = -i \cdot \left( \eta + \eta^2 \right) J \left( x, y, \alpha \right) + \eta \cdot \alpha J \left( x, y, \eta \right) \cdot \alpha \quad \quad \quad \quad (1)
\]

\[
\sigma_{12} = \frac{\left( \eta + \eta^2 \right) J \left( x, y, \eta \right) - J \left( x, y, \alpha \right)}{-\eta} \quad \quad \quad \quad (2)
\]

\[
J \left( x, y, \eta, \alpha \right) = \frac{\Gamma}{\sqrt{\pi}} \int_0^\infty \left( \eta \cdot p \cdot i x \cdot \eta - \eta \cdot p \cdot i \cdot p \cdot x \cdot \eta - p \cdot k \cdot \eta \right) dp \quad \quad \quad \quad (3)
\]
\[
\begin{align*}
\Psi(x, \alpha) &= -\frac{i}{\eta \sqrt{\pi}} \int_{-\infty}^{\infty} \left(\alpha^2 + \eta^2 K_0 \alpha r \right) |p| - \eta K_1 r |p| \frac{p^\Gamma(p)}{p} \exp(-ipx) dp
\end{align*}
\]

where

\[
\gamma(x) = \sqrt{\frac{V_0}{c_p}}
\]

\[
\beta = \sqrt{\frac{\lambda + \mu}{\rho}}
\]

\[
\sigma = \sqrt{\frac{\mu}{\rho}}
\]

\[
\Omega_0 = \frac{1}{2} \left(-r - v \right)
\]

\[
\Gamma(p) = \left\{ \begin{array}{ll}
\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x) \gamma(x) \exp(-ipx) dx
\end{array} \right\}
\]

3 Results

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

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

\[
S_{\text{wedge}} = h_{pl} \sin \lambda \beta_{pl}
\]

where \( h_{pl} \) is the height of the subsoiler ploughshare, \( \beta_{pl} \) is the angle of the chisel point to the base, \( \lambda \) is the angle at the top of the wedge.

Fig. 2. Schematic representation of a subsoiler ploughshare in the form of a thin wedge (a), and reduced circular cone (b).
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 $\beta_{cone}$ in the following form.

$$\cos \left( \frac{\beta_{cone}}{2} \right) = \frac{h_{pl}}{h}$$

$$\beta_{cone} = 2 \arcsin \left( \sqrt{\frac{h_{pl}}{h}} \right)$$

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

Analyzing the curves in Fig. 3, we see that the change in the vertex angle $\beta_{cone}$ of the cone for different values of angle $\beta_{pl}$ is insignificant. In addition, a significant increase in angle $\beta_{cone}$ of the opening of the cone is observed at large angles $\lambda$ between the side faces of the chisel point.
\[ \rho \frac{d}{dt} \frac{\partial}{\partial t} \mathbf{u} = \mathbf{r} + \mathbf{u} \frac{\partial}{\partial \mathbf{r}} \sigma \mathbf{r} + (\sigma_{\mathbf{r}} - \sigma_{\theta}) \frac{\partial}{\partial \mathbf{r}} (\mathbf{r} + \mathbf{u}) \]

\[ \frac{\partial}{\partial \mathbf{r}} (\mathbf{r} + \mathbf{u}) = \frac{\rho}{\rho} \mathbf{r} \]

\[ \sigma_{\mathbf{r}} - \sigma_{\theta} = \tau + \mu (\sigma_{\mathbf{r}} + \sigma_{\theta}) \]

\[ \nu \sigma_{\mathbf{r}} \frac{\partial}{\partial \mathbf{r}} (\mathbf{r} + \mathbf{u}) + (\mathbf{r} + \mathbf{u}) \frac{\partial}{\partial \mathbf{r}} \sigma_{\mathbf{r}} = \rho \frac{\partial}{\partial t} \mathbf{u} - \frac{\tau}{\rho} \frac{\partial}{\partial \mathbf{r}} (\mathbf{r} + \mathbf{u}) \]

\[ \mathbf{r} + \mathbf{u} \frac{\partial}{\partial \mathbf{r}} \sigma_{\mathbf{r}} = \rho \int_{r}^{r} \mathbf{r} + \mathbf{u} \frac{\partial}{\partial t} \mathbf{u} \mathbf{dr} - \frac{\tau}{\rho} \frac{\mathbf{r} + \mathbf{u} - R}{\nu} + R \sigma_{\mathbf{r}} \]

\[ \mathbf{r} \frac{\partial}{\partial \mathbf{r}} \sigma_{\mathbf{r}} = \rho \int_{r}^{r} \mathbf{r} + \mathbf{u} \frac{\partial}{\partial t} \mathbf{u} \mathbf{dr} + \frac{\tau}{\rho} \frac{\mathbf{r} - R}{\nu} + R \sigma_{\mathbf{r}} \]

\[ \mathbf{r} + \mathbf{u} \frac{\partial}{\partial \mathbf{r}} \sigma_{\mathbf{r}} = -\rho \int_{r}^{r} \mathbf{r} + \mathbf{u} \frac{\partial}{\partial t} \mathbf{u} \mathbf{dr} + \frac{\tau}{\rho} \frac{\mathbf{r} - \mathbf{r} + \mathbf{u}}{\nu} \]
\[ \mathbf{r} + u = \mathbf{r} + R \mathbf{t} \]

\[ \mathbf{r} = \int_0^r \frac{\rho \mathbf{r}}{\rho \mathbf{r}} - \mathbf{r} \mathbf{dr} \]

\[ \mathbf{r} = \int_0^r b \mathbf{r} \mathbf{dr} - b = \rho \mathbf{r} \mathbf{r} \]

\[ \frac{\partial u}{\partial t} = \frac{R \cdot \dot{R}}{\sqrt{\psi \mathbf{r} + R \mathbf{t}}} \]

\[ \frac{\partial \mathbf{u}}{\partial t} = \frac{\dot{R}^2 + R \cdot \dot{R}}{\sqrt{\psi \mathbf{r} + R \mathbf{t}}} - \frac{R \cdot \dot{R}}{\sqrt{\psi \mathbf{r} + R \mathbf{t}}} \]

\[ \dot{u} = \frac{R \dot{R}}{\sqrt{\psi \mathbf{r} + R \mathbf{t}}} = \frac{R \dot{R}}{r} \]

\[ \rho \mathbf{D} = \rho \mathbf{D} - \dot{u} \]

\[ \rho \mathbf{D} \mathbf{u} = -\sigma_r - p_a \]

\[ D \]

\[ \sigma_r, \sigma_r^* \]

\[ \rho, \rho' \]

\[ \mathbf{D}, \mathbf{D} \]
\[ D = \frac{\ddot{u}}{b \dot{r}^2} \sigma_r^* = -\frac{\rho \dot{u}}{b \dot{r}^2} - p_a \]

\[ r + u^\# \sigma_r = \rho \left( R \ddot{R} + \dot{R} \right) \int_r^b \frac{rdr}{\psi_r + R \dot{t}} - \rho \left( \ddot{R} \dot{t} + \dot{R} \ddot{t} \right) \int_r^b \frac{rdr}{\psi_r + R + \dot{t}^2} \]

\[ + \frac{\rho}{b \dot{r}^2} \ddot{R} \int_r^b \frac{rdr}{r^2 + \mu} \left[ \psi \left( r + u^\# \right) \right] + p_a \cdot r^\# \]

\[ p_a - p_a = \ddot{\rho} \cdot \phi \left( v^2 b^2 \right) \cdot x \cdot \frac{T^2}{\beta} + \int \frac{p_a \cdot \phi \left( v^2 b^2 \right)}{b} \left( v - \frac{\dot{\beta}}{\dot{\beta}} a^\# a^\# - a^\# a^\# \right) \]

\[ + \phi \left( v/b^2 \right) \cdot \left( v \cdot p_a + \frac{\tau_a}{\mu} \right) \]

\[ F = \pi \left( \bar{\beta} + \mu \cdot \bar{\beta} \right) \int (p - p_a) \cdot x \cdot \theta \beta \sqrt{\bar{\beta} + \theta \beta} dx \]

\[ F = \pi \left( \bar{\beta} + \mu \cdot \theta \beta \right) \cdot \left( A + B \rho \frac{L^2}{\theta \beta} + \rho \cdot C \frac{L^2}{\theta \beta} \right) \cdot h \]
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:

\[
A = \pi \cdot \frac{\tan \beta}{\mu} \left[ \frac{\pi}{\nu} + \frac{\tau}{\nu \mu} \right] \cdot \left( a' - \nu \right)
\]

\[
B = \frac{\pi \cdot \tan \beta}{b \left( \nu - \nu \right)} \left[ \frac{\nu}{\nu} \cdot (a' - \nu) + b (\nu - \nu) a' - (a' - \nu) \right]
\]

\[
C = \frac{\pi \cdot \tan \beta}{b \nu} (a' - \nu) \cdot a = \left( a' - \nu \right)
\]

\[
[m + m_{np}(h)] \cdot \dot{L} = -\pi \left( \frac{1}{\mu} + \frac{\mu \cdot \cot \beta}{\nu} \right) \left( A + B \rho \cdot \dot{L} \right) \cdot \dot{L} + k \cdot \left( L - V \cdot t \right)
\]

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.

Fig. 4. Change in displacement \( s \) of the subsoiler ploughshare \( L(t) \) (m) on time \( t \) (sec). \( k_0 = 50 \text{ H/m} \) and \( b_1 = \rho_0 / \rho_1 \).
\[ L(t) = b_1 \rho_0 / \rho_1 \]

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

\[ P(t) = k_0 (V_0 t - L) \]

Figures 6–7 show the dependences of elastic force \( P(t) \) 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), for \( k_0 = 50 \) N/m

Fig. 7. Change in elastic force \( P(t) \) on time \( t \) (sec), for \( k_0 = 500 \) N/m
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.

References


