The study of soil mechanics and intensification of agriculture

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Abstract. In recent decades, in our country insufficient attention has been paid to the study of soil mechanics. Currently, there is a need to study the mechanical processes in the soil when it interacts with the working bodies of tillage machines and operating systems of mobile agricultural equipment. With existing technologies for cultivating crops, various machines pass through the field from 10 to 15 times. The tools used have a centuries-old history of development and improvement, both of individual types of working parts, and of technological tillage complexes as a whole. At the same time, the scientific basis for tillage has not yet been fully developed. The article explores soil mechanics and intensification of agriculture; saturating it with heavy machines, and increasing the energy saturation of tractors put forward new tasks that cannot be solved without the development of theoretical and applied research in the field of soil mechanics. Depending on the formulation of the tasks of the interaction of tillage organs and movers with soil, degenerate models can be used that contain only those rheological properties of the soil that define the main goal of the technological problem.

1. Introduction

Soil is a complex open dynamic system, which is both the result of the interaction of soil formation factors and the environment in which this process is currently ongoing.

The cycles of renewal of the main soil-forming agents are different: from several hours (gas and moisture exchange) to tens of thousands of years (formation of soil-forming rocks). The flow of material particles connects the landscape components, and the soil plays a key role in the process: the migration flow of elements passes through it, it reflects the material composition of valuable components and is a material expression of their geochemical connection. Soil is a subsystem of a more complex system, a biogeocenosis (according to V. N. Sukachev) or an elementary landscape (according to B. B. Polynov, the founder of landscape geochemistry). The total area of the tracks of the wheels and tracks of tractors,
and harvesting vehicles is 100-200% of the field. Turn strips are rolled by car wheels 6 – 20 times (only 10 – 15% of the field area is free from the influence of moving systems). Since the average pressure created by caterpillar tractors reaches 60 – 80 kPa, and by wheeled tractors, 85 – 165 kPa (maximum 320 – 560 kPa due to the uneven distribution of pressure on the supporting surfaces), the soil density in the arable and subsurface horizons increases.

Another source of mechanical soil compaction is the working parts of tillage machines. It was experimentally established that when a flat wedge moves at a depth of 110 mm, the pressures reach 300 – 600 kPa. The ploughshare and moldboard of plows can create pressures of about 800 – 1000 kPa. Contact pressure on the surface of the working parts of tillage machines is greater, which than leads to the formation of the desired tillage pan and compacted soil agglomerates [1,13, 27].

2. Research Methodology

In agriculture, cutting and turning a layer of soil with a plow is called plowing. Cutting and separating soil layers in the form of lumps or granular material with a pore volume significantly larger than before treatment or mechanical destruction are called loosening [2,5,17].

In the process of loosening soil is destroyed within a certain volume, the width of which on the surface of the field exceeds the width of the loosening element. The destruction zone is understood as a layer of soil where crack formation occurs, leading to an increase in its fluffiness and penetrability, which is the main task of loosening [3,24]. Technologically, soil loosening is a process of separating pieces and layers from the soil massif with a wedge-shaped tool, and in the physical sense, mechanical destruction of the soil massif. The main geometric dimensions and shape of the loosening zone depends on the physical and mechanical properties of the soil, the number and shape of the loosening elements, the position of the share blade relative to the cutting direction and the surface of the field. In irrigated agriculture, tools for soil loosening are arranged and operate on the principle of cutting with the separation of chips. But because of the variety of loosening elements (figure 1) there are also various cutting methods. In this case, cutting can be carried out with a straight or broken cutting edge with one or two faces. Depending on the arrangement of the working parts on the frame of the implement, there are various conditions for the cutting process: blocked, unblocked and free [4,6].

Soil density can be studied using methods of mechanics of a deformable continuous medium. Very often soil mechanics is identified with ground mechanics, because of the similar structure of soils and grounds. Both are a medium consisting of solid (mineral particles), liquid and gaseous phases [21,25, 29].

![Figure 1. Mechanical effects of agricultural machinery on soil, affecting crop yields.](image-url)
One of the most important mechanical processes—changing the density of soil—plays a significant role in producing crops (figure 1). During the work of plows, the soil density in such lumps is 1.24 times higher than in the same layer before treatment, and the hardness of the soil of the furrow bottom is 1.5-2.0 times higher than before the passage of the machine.

To identify the comparability of factors of soil density and crop productivity, a mathematical model is presented (1):

\[
Q = 1 - [a_1(\rho_{opt} - \rho) + a_2(\rho_{opt} - \rho)^2 + \cdots + a_n(\rho_{opt} - \rho)^n] 
\]

Where \(Q\) is the yield in fractions of the maximum obtained at the optimum soil density; \(a_1, ..., a_n\) are empirical coefficients characterizing the responsiveness of a crop to a change in soil density; \(\rho_{opt}\) - optimum soil density, \(\text{g/cm}^3\); and \(\rho\) is the current density of the soil.

Combining the two facts — the effect of soil density on productivity and the increase in variability of soil density as a result of exposure to movers of mobile agricultural machines and implements — we arrive at the following conclusion. Even if the average soil density is optimal, a decrease in yield is inevitable due to variability of soil density in the upper root layer [7,8,15,30].

The stress state of the soil element in front of the working part or under the undercarriage system in the mechanics of continuous media is characterized by the stress tensor, and the deformation state by the strain tensor [9,12,26].

In the vicinity of a point in space (soil element), the energy of deformation of the soil element:

\[
\Pi = \frac{1}{2} \sigma_{ij}\varepsilon_{ij} = \Pi_D + \Pi_v 
\]

Where \(\sigma_{ij}, \varepsilon_{ij}\) are the components of the stress tensor, strain; \(\Pi_D, \Pi_v\) are deviatorial energy (changes in the soil element), spherical (changes in the volume of the soil element constituting the spherical stress tensor).

The ratio of energy spent on changing the volume and energy spent on changing the shape of the soil element has the form:

\[
\frac{\Pi_v}{\Pi_D} = 1/[2[+3(I_2/I_1)^2]] 
\]

Where are \(I_2, I_1\) the second and first versions of the stress tensor.

It follows that the stress field created by the working part and the undercarriage system in the soil always leads to deformation of a certain volume of soil (since \(I_1 \neq 0, \Pi_v/\Pi_D\) cannot be equal to zero in the entire deformable region).

From what has been said, one can formulate a corollary, which is the central working hypothesis of soil mechanics: any action of a working part or running system increases the soil density in a certain volume [11,14,16,31].

The geometry of a working part or mover, and the kinematics of their movement determine the nature of the stress and strain fields. The energy of volume change leads to soil compaction by a working part or mover. The energy intensity of soil cultivation depends on the form of the working part and the kinematics of its movement [18, 23,28].

The study of the fields of deformations and stresses caused in the soil by the action of a working part allows us to choose stress-deformable states in which the compaction effects are minimal [10,19,22]. The boundary conditions that provide the stress and strain fields required from a technological point of view reflect the geometry of a working part or mover, and the initial conditions reflect their kinematics.

As a result of this, it becomes possible to create methods for calculating and designing working parts of tillage machines and movers, providing both a reduction in energy costs for tillage and the creation of conditions leading to the preservation of soil fertility. The state of soil density and changes in soil deformation are determined by continuous relationships between certain mechanical (stresses,
deformations and their derivatives with respect to time) and thermodynamic variables, called soil state equations [20,29].

3. Results and discussion
In the general case, equations of state describe the processes of transition and transformation of energy within the medium under consideration, including both the mechanical and thermal forms of energy. If we assume that all the mechanical work spent on soil deformation by the working part goes into heat, then the soil temperature would rise by only a fraction of a degree.

The mechanical behavior of real materials is represented by the equation of state. Shear behavior of soils (figure 2) under different speeds shows that the time factor (strain rate) significantly affects the ultimate \( \tau_s \) shear resistance and thereby proves once again the need for a rheological approach to the study of soil deformation.

Figure 2 shows the effect of the deformation speed on the ultimate soil shear resistance at a density of soil samples of 2 g/cm\(^3\) (solid lines) and 1.7 g/cm\(^3\) (dashed lines) taking into account their moisture content.

![Figure 2](image)

**Figure 2.** Influence of the deformation speed on the ultimate soil resistance to shear at a density of soil samples of 2 g/cm\(^3\) (solid lines) and 1.7 g/cm\(^3\) (dashed), taking into account their humidity.

An analysis of the results of studies of the patterns of soil deformation in time as media that are closest in properties to soils shows that under prolonged (static) loading, soils exhibit inelastic properties. Similar properties are also manifested when cutting soils. In studies on the dynamic loading of soils (load duration 2 * 10\(^{-3}\) s), they also behave as inelastic bodies, and exhibit viscous and plastic properties. Under the influence of tillage tools, in the soil not only elastic properties are manifested, but also viscous and plastic, and in this case the load action time is 0.001-0.5 s.

Indeed, with a specific heat capacity of dry soil of 170 – 210 J/(g*deg), all the work spent by the plow on processing 1 kg of soil (with a specific resistance of 100 kPa and a density of 2.0 g/cm\(^3\)) converted to heat will change the temperature of soil by 0.0689 °C. Therefore, in soil mechanics, the equations of state of the soil can be reduced to the ratio of only mechanical variables, since the conditions of soil deformation are almost isothermal.

Thus, the representation of the relationship between stress and strain during shear deformations depends on the problem statement, and on the goal of the final study of the interaction of tillage organs with soil [1,13]. The use of two degenerate soil models (elastic-viscous and viscoplastic) is a consequence of the permissible simplification of the rheological model in each specific task. A feature and positive property of the rheological model that we have developed is the relationship between the
volume and shear deformations of the soil element, since the ultimate shear resistance depends on the normal stresses acting on the shear site.

In accordance with the full rheological model of the soil, it is possible to determine the change in its shape made by the working part, which is expressed by the function of both deformation and its speed: 
\[ \tau = \psi(y) \text{ and } \tau = \varphi(dy/dt). \]

With large changes of \( G_1 \), the function \( \tau = \psi(y) \) can be neglected. Then the equation of motion of the working part with an elastic bond (reduced to the point of application of the resultant on the working part) in projection onto the X axis will have the following form:

\[ d^2x/dt^2 + \omega_0^2x = \lambda(dx/dt) \] (4)

Where the right-hand side is the reaction of the soil in time during its deformation, \( \omega_0 \) is the frequency of the natural oscillations of the suspension.

For large values of \( \lambda \), this equation describes relaxation oscillations. Such oscillations are characterized by the fact that they consist of slowly and rapidly proceeding stages, i.e. from the stages of energy storage by an elastic bond in the first phase of deformation and its fast discharge in the second phase.

In the general case, the interaction of the working part with the soil can be described by the following equation:

\[ d^2x/dt^2 + \omega_0^2x = \alpha_1f_1(x, dx/dt) + \alpha_2f_2(x, dx/dt) + \cdots \] (5)

With a small value of the parameter \( \alpha \), i.e. with a large reduced mass of the working part and soil mass attached to the working part, self-oscillations of the suspension system becomes possible.

4. Conclusion
When using rotary machines, along with the geometry and thickness of the cut layer, the direction of rotation of the working parts and their kinematics are of great importance.

From the point of view of the mechanics of the technological impact of tillage organs on the soil, the least energy-intensive process is the rotation of the working bodies with soil chips being thrown back. In this case, the flow of mechanical energy dissipates little in space, since there is a load-free back wall of the deformable soil block.

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6