Seedbed preparation of the upper soil layer

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Abstract. Increasing crop yields is the most important condition for intensifying agricultural production. High quality of various technological operations of soil preparation can significantly increase yields. It is especially important to prepare soil before seeding, it forms a habitat for plants, ensures uniform seeding in depth. Using heavy machines in agriculture, surface and subsurface soil layers undergo mechanical deformation with inevitable deterioration of its physical and biological properties. Density of surface and subsurface horizons increases, number of pores with a size of 0.2 ... 10 microns decreases, which determine soil moisture content. Productivity of cultivated plants is influenced by effective fertility of not only surface layer, but also machines and tractors. Many studies have established that soil deformation during movement of cultivator hoe or wedge consists of two stages. At the first stage, soil particles located in close proximity to the hoe are displaced forward, forcing the layers in front to compress, when stresses in soil reach their limit values, a shift occurs at some distance from the toe of the hoe. At the second stage, soil begins to intensively move forward and upward and move along surface of working body. In this regard, resistance of soil to movement of individual parts of working body will be different. The article describes research that helps to determine ground unevenness. One of the possible measures to prevent compaction of the subsurface is presented - improving technology of preparing upper surface soil layer.

1. Introduction

One of the possible measures to prevent the compaction of the subsurface is to improve the technology of preparing the surface layer of the soil. Research on models showed that when creating and maintaining the optimal bulk density and structural composition in the prepared layer of the studied chernozem soil

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(taking into account the requirements of vertical differentiation of agronomic parameters), to a certain extent, it was possible to optimize the mode of accumulation and consumption of moisture, air exchange between the soil and the atmosphere, and accelerate the emergence of seedlings, improve the phenological indicators of plants, increase the yield by at least 20% compared to the reference.

The use of the damping properties of loose soil is provided for in order to reduce or prevent the spread of mechanical deformation along the soil profile in depth. The speed of movement of the units was the same - 6.3 ... 6.5 km/h. Observation of the change in soil density for a depth of up to 60 cm revealed different deformation of its layers, depending on the intensity of loosening and the pressure of the tillage machines (see table). The density of the upper layers after shallow plowing becomes less than before preparing. The density of subsurface layers under the influence of the mass of machine-tractor units increases, and the more it is, the heavier the tractor is. The weight of the MTZ-50 tractor is about 3 tons, the DT-75M tractor is about 7 tons; the pressure on the soil of the first one exceeds 0.1 MPa, for the second one it is almost half less.

2. Research results and discussion

Various formulas [1, 2, 4-7] for determining soil resistance are known. We have calculated the total resistance of the tine through its components, depending on the nature of the loading of the tine elements (blade, hoe wings, stand).

![Figure 1. Soil load scheme.](image)

Considering that the soil has internal bonds between individual particles, it can be considered a deformable elastic-viscous medium with a predominance of elastic properties. Therefore, we have applied the provisions of the theory of elasticity with a sufficient degree of accuracy. The process of soil deformation can be represented as a trajectory in the multidimensional space of principal stresses of principal deformations and time. The destruction condition is determined by some quasi-surface in the same multidimensional space. Therefore, destruction can be achieved with different energy consumption (different energy intensity of soil loosening). With more rational technologies, volumetric deformations are minimal, with more energy-intensive technologies, the proportion of volumetric deformations is large.

The peculiarity of the mechanical behavior of real materials is represented by the equation of state. The behavior of soils during shear (figure 2.3) with different rates shows that the time factor (deformation rate) significantly affects the ultimate shear resistance τₜ and thus proves once again the need for a rheological approach to the study of soil deformation.
To calculate the resistance of the soil to the movement of the cutting edge of the cultivator tine, the plane problem of the theory of elasticity in polar coordinates was solved. The normal pressure on the edges is determined in the same way as for a flat wedge [1]. Therefore, consider the deformation of the soil by one wing of the tine but normal to the blade. The total resistance of the cutting edge of the entire tine was found as the sum of the projections of the resistance forces of the wings on the direction of movement.

The layer of soil, cultivated by the edge of the wing of the tine, can be represented with sufficient accuracy as a semi-infinite plate (figure 1). Then the stresses arising in the soil are

\[
\sigma_{rr} = \frac{1}{r} \frac{\partial \Phi}{\partial r} + \frac{1}{r^2} \frac{\partial^2 \Phi}{\partial \theta^2},
\]

\[
\sigma_{\theta \theta} = \frac{\partial^2 \Phi}{\partial r^2};
\]

\[
\sigma_{r \theta} = -\frac{\partial}{\partial r} \left( \frac{1}{r} \frac{\partial \Phi}{\partial \theta} \right),
\]

where \(\sigma_{rr}, \sigma_{\theta \theta}, \sigma_{r \theta}\) – are the main stresses, respectively, acting along the radial line and tangential; \(\Phi(r, \theta)\) – are the Airy function in polar coordinates [8, 9].

The change in soil pressure along the length of the wedge blade should be noted [4]. Therefore, for the cutting edge of the tine (the blade of the paw and the adjoining part of the wing for the sharpening width), we assume, with some approximation, a linear distribution of the load acting on the straight edge of the semi-infinite plate, and the mass forces equal to zero due to the relatively small depth of preparation. Then the purely radial stress distribution in the soil layer will be obtained, and even relative to the measured polar angle \(\theta\) Airy function:

\[
\Phi(r, \theta) = Ar \sin \theta,
\]

where \(A\) is a constant; \(r\) is the distance to the point at which the stress is determined.

According to the assumptions made, \(\sigma_{\theta \theta} = 0\) and \(\sigma_{r \theta} = 0\), and the joint solution of (1) and (2) gives

\[
\sigma_{rr} = \frac{rA}{r} \cos \theta.
\]

When determining the constant \(A\) in equation (3), consider the equilibrium condition of the soil layer between the external \(dR_k\), and internal forces, which we find through the stress \(\sigma_{rr}\), and the cross-sectional area of the elementary volume of a semi-infinite plate (or soil layer) \(dA_1 = rd\theta t\) (\(t\) is the thickness of the semi-infinite plate), \(dR_h = \sigma_{rr} \cos \theta dA_1\).
Considering that the tine mainly acts on the soil lying above the edge, the stress \(\sigma_{rr}\) is considered in the layers bounded by the \(X_1\) and \(X_2\) axes, the limits of integration are from 0 to \(\pi/2\).

Then

\[
R_{k_1} = \int_0^{\pi/2} \sigma_{rr} \cos \theta \, r \, t \, d\theta.
\]

From expressions (3) and (4) we find

\[
A = 2R_{k_1}/(\pi t).
\]

Substituting the values of \(A\) into equation (3), we obtain the soil resistance to the movement of the tine edge along the normal to the blade:

\[
R_{k_1} = rt\pi/(4 \cos \theta).
\]

Soil resistance to movement of the entire edge

\[
R_{k_1} = \frac{\sigma_{rr}rt\pi}{2 \cos \theta \cos \gamma},
\]

where \(\gamma\) is half of the tine aperture angle.

In the zone of application of the force \(R_{k_1}\), the stresses are infinitely large, and therefore plastic deformations are inevitable in the immediate vicinity of it. However, at some distance from the place of application of force [9], according to the principle of locality, formula (6) can be suitable for practical calculations. In addition, the shift of the soil layer occurs at a distance \(l'\) from the tine blade at \(\theta = 0\) [3]. Therefore, it is advisable to refer the limiting values to this area and consider the resistance \(R_k\) depending on the stress \(\sigma_{rr}\) arising in the zone of maximum stresses at the moment of shear, i.e.

\[
\sigma_{rr} = \sigma_{comp},
\]

where \(\sigma_{comp}\) is the compressive stress for a specific type of soil and working conditions.

Considering a semi-infinite plate, we took its thickness \(t\) equal to the length of one wing of the tine. Expressing \(t\) in terms of the tine grip width \(B\) and the tine opening angle \(\gamma\), and substituting these values into equation (6), we obtain

\[
R_k = \frac{\sigma_{comp}l'B\pi ctg\gamma}{4},
\]

where \(l' = 0.8a \, ctg \psi (u_t - u_s \cos \beta)/(u_s \cos \beta)\); \(a\) – preparation depth; \(\psi\)– soil shearing angle; \(u_t\) – forward speed of the tine movement; \(u_s\) – speed of soil movement along the surface of the tine; \(\beta\) – angle of the wing of the tine, at which the soil crumbling occurs.

Equation (7) does not contain all the indicators characterizing the physical and mechanical properties of the soil. Obviously, all this information should be carried by \(\sigma_{comp}\) for a given type of soil. Therefore, we studied the resistance of soil samples to compression by the method of fractional factorial experiment. The following factors were investigated: soil hardness \(c\), moisture \(\omega\) and loading rate \(v\) (figure 2, 3).

Experiments have shown that the values of the ultimate stresses for shear, separation and compression do not depend on the size of soil samples, the cross-sectional area of which is more than 40…50 cm².

To establish the uniform strength of the samples under study, they were loaded in three different directions, and then the ultimate compressive stress was determined. Experiments have shown that the compressive stresses for samples of unequal hardness, moisture content and at different loading rates change depending on the orientation of the sample with respect to the collapse load. As a result, an empirical dependence was obtained

\[
\sigma_{comp} = 0.57 \cdot 10^{-3}e^{1.625c^{0.1925} \omega^{1.804}} \times (50.4 \cdot 10^{-4}v + 0.048).
\]
Additional studies have shown that it is possible to use formula (8) for the analysis of loamy and sandy loam chernozems with a change in humidity within 10…30 %, hardness – 0.5…2.0 MPa, loading rate – 3…4 m/s.

To determine the resistance of the soil to the movement of the wings of the tine \( R_t \) and the stand \( R_{st} \), a well-known technique was used [7, 10].

The force of soil resistance to the movement of the wings of the tine \( R_t \) =

\[
R_t = \left( \frac{a_l v_l \sin \beta}{\sin(\beta + \psi)} \right) - \left[ \cos \psi \sin(\beta + \psi) \right] \tan \varphi_1 \cos \beta + a_l b g \cos^2 \beta \tan \varphi_1 \sin \gamma + \sigma_{comp} B b \sin \beta + a^2 B pg \tan \varphi_2 \cot \psi, \tag{9}
\]

where \( l \) – length of the tine blade; \( \rho \) – soil density; \( \varphi_1 \) – angle of external friction of the soil against the tine; \( b \) – width of the wing of the tine; \( g \) – acceleration of gravity; \( \varphi_2 \) – angle of internal friction of the soil.

Table 1. Soil density, g/cm³, depending on the methods of its preparation.

| Preparation sequence | Soil layer, cm | 0...1 | 10...20 | 20...30 | 30...40 | 40...50 | 50...60 | 60...60 |
|----------------------|----------------|-------|---------|---------|---------|---------|---------|---------|
| Before preparation   | 1.02           | 1.32  | 1.27    | 1.42    | 1.44    | 1.52    | 1.46    |
| After shallow ploughing with a unit of a tractor: |               |       |         |         |         |         |         |         |
| MTZ-50               | 1.02           | 1.30  | 1.29    | 1.42    | 1.44    | 1.52    | 1.46    |
| 1.07                 | 1.24           | 1.27  | 1.42    | 1.44    | 1.54    | 1.47    |
| DT-75M               | 1.04           | 1.19  | 1.30    | 1.44    | 1.54    | 1.66    | 1.54    |
| After plowing the shallow plowed field with a unit of a DT-75M tractor, with a unit of a tractor: |               |       |         |         |         |         |         |         |
| MTZ-50               | 1.16           | 1.21  | 1.32    | 1.44    | 1.48    | 1.56    | 1.49    |
| 1.15                 | 1.18           | 1.28  | 1.43    | 1.47    | 1.54    | 1.48    |
| DT-75M               | 1.17           | 1.22  | 1.43    | 1.50    | 1.61    | 1.69    | 1.60    |
| 1.16                 | 1.18           | 1.30  | 1.44    | 1.54    | 1.66    | 1.54    |
| After plowing a not shallow plowed field | 1.15 | 1.21 | 1.33 | 1.49 | 1.54 | 1.50 |

Note that in the numerator it is indicated at a preparation depth of 5...6 cm, in the denominator – 14...16 cm.
Figure 3. Analysis of the density of the subsurface soil layers.

Analysis of the density of the subsurface soil layers at a depth of 30...60 cm, where its change is more clearly traced when preparing the upper surface layer under the influence of machine-tractor units, shows that when plowing with a heavy tractor (traction class 3) a deeply shallow plowed (14...16 cm) field, the subsurface layers are compacted less than when plowing of a shallower plowed one (5...6 cm) with the same tractor. A lighter tractor (traction class 1.4) compresses the soil less when shallow plowing than a heavy one. The highest yield (30.6 t/ha) of green mass (oats, peas, sunflower) was obtained on a plot plowed with a DT-75M tractor, after shallow plow to a depth of 14...16 cm with a unit of a MTZ-50 tractor.

The proposed method of preparing the topsoil as one of the measures to prevent overconsolidation of the subsoil layers ensures the improvement or preservation of physical conditions favorable for plants, excluding the propagation of mechanical deformations in depth due to the damping property of loose soil, capable of "dampening" the pressure of the undercarriages of tractors and agricultural machines. In chernozems, units of medium and large sizes (larger than 3 mm) are formed not under the action of in-soil mechanisms - sequential physical, mechanical and chemical consolidation, but as a result of crushing under the action of root systems, volumetric changes, mainly mechanical preparation. The latter applies equally to the density of the soil composition, the range of change of which, depending on the tools used and the preparation methods, is very wide: for the studied chernozem – 0.9...1.5 g/cm³ (low level - immediately after plowing and harrowing, high - after repeated rolling by the wheels of tractors of traction classes 3-5).

These proposals can be realized by improving preparation technologies and creating machines of fundamentally new designs. The possibilities of the first direction are limited, since multiple passes of different tools will be required, which is undesirable. In addition, with the existing tools, it is practically difficult to ideally break up the soil in the seed layer and at the same time reduce the density in the under-seed layers. For these reasons, we give preference to the second direction.

3. Conclusion
In agricultural production, soil preparation occupies a significant volume and is considered the most energy-intensive technology, including a number of technological operations, one of which is
cultivation. Cultivation is carried out with tine cultivators designed to loosen the soil and destroy weeds. With poor-quality cultivation, up to half of the sown seeds lose their germination. Traction resistance is significantly increased on cultivators with blunt tines. The technical condition of the cultivator tines determines both the unevenness of the cultivation depth and the contamination of the soil. That is why the problem of increasing the resource of the working bodies of tillage machines is very urgent. A well-structured chernozem soil can practically be brought to the required ratio of structural components and bulk density, using our own resources, without resorting to additional means (structure-forming agents), using only loosening-compacting working bodies of various designs and taking into account the preparation conditions. To optimize the structural composition and bulk density, it is most effective to use a combined machine that processes the soil, sows seeds and applies fertilizers in one pass. Analysis of the work of the known combined machines showed that none of them can cope with this task. For its implementation, most likely, it is necessary to use other technological processes or select the most successful combination of passive and active working bodies of tillage machines. Tilling the soil should only slightly reduce the density of its lower layers. The root layer cannot be intensively loosened, as this can lead to its subsidence during the formation and development of the root system, which is unacceptable.

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