Research of soil compaction process in area of contact with a wheel mover

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Abstract. Practice of operating heavy wheeled machines (T-150K, K-700, K-701) and experimental data show that even if the average pressure of a wheel on soil is maintained, degree of its compaction increases. To explain this phenomenon, in our opinion, it is necessary to develop a mathematical model of interaction process of a deformable pneumatic with an elastic-plastic medium, which is considered to be soil subject to modern processing. Working parts of agricultural machines process a wide variety of materials, number of which is increasing, in addition, method of processing the same material is often changed in an effort to improve agricultural technology. This forces us to create new mechanisms for agriculture that were known before. Use of replaceable toothed working parts on flat-cut cultivators helps to reduce energy consumption and improve quality of non-moldboard soil cultivation. Article proposes a method for mathematical description of distribution of machine load over contact surface of a wheeled mover with deformable soil. At the same time, several assumptions and conditions were adopted, namely: volume of skeletal part of deformable soil element remains constant, independent of deformation; contact surface is a curve of two radii - in the load zone (Rl) and in the unloading zone (Ru), tire operating in driven mode has no skids; deformable soil is uniform in depth; wheel load is constant; tire radial stiffness along tread portion width is also constant in magnitude and direction; lateral pressure along deformable soil depth is small and is not taken into account in calculation.

1. Introduction
The principle of per-cultural universalization is based on the generality of the methods of sowing various row crops or methods of caring for them. For a long time, the development of agricultural technology and the mechanization of cultivation of row crops followed different paths. Numerous studies have
established that the constant use of non-moldboard methods of soil cultivation leads to a gradual differentiation of the arable layer, as a result of which the fertility of the upper part increases, and the lower one decreases. An important role in increasing row crops is played by reducing the time of inter-row cultivation, improving the quality of their implementation.

One of the most important mechanical processes, a change in soil density, plays a significant role in obtaining crop yield (figure 1).

Figure 1. Scheme of the consequences of the mechanical impact of agricultural machinery on the soil, affecting the yield of agricultural crops.

There are farms on the lands of which there are up to 20 large ravines, to combat them it would be necessary to build up to 80 different relatively simple special engineering structures.

Planar and furrow (linear) erosion, reaching 10...30 t/ha (and under the influence of rainfall - 75...120 t/ha) per year, carries away the fertile humus layer, nutrients (nitrogen, phosphorus, potassium, calcium) and water, often scarce and extremely necessary for obtaining high yields.

Erosion is exacerbated by the creation of large fields with tillage along the slopes. The dominance of tilled crops in cultivated crops (with their cultivation along the slope) and the practically absence of grass fields in crop rotations on slopes of more than 6° contribute to the development of all forms of erosion of chernozem. There are many farms in the chernozem zone where 60...75% of arable land has been disturbed by erosion. Anti-erosion measures are carried out to a small extent. Losses of agricultural products from erosion are estimated in millions of tons.

With the mechanical action of machines (mobile technical systems) on the soil, its physical state, the running systems, as a rule, compact it, and the working bodies of the tillage machines loosen it. When performing field work, the sequence of the impact of the running systems and working bodies can be different, however, the most common sequence is when the running systems go in front, and then the working bodies [1-3]. In addition to general criteria for agricultural machines, specific requirements are imposed on the entire range of breeding machines due to the technology of breeding work. It is also necessary to take into account the wide variety of requirements for the method of conducting field experiments. All this indicates that without conducting scientific research on the problems of mechanization in the processes of selection, variety testing and primary seed production, the development of the selection and seed production process is problematic [8]. Equipping seed farms with modern machines and equipment is one of the necessary conditions for increasing production volumes and ensuring high quality seed material.
2. Research purpose
To substantiate effective mechanized soil cultivation technologies in the conditions of slope agriculture, ensuring the preservation and increase of fertility, productivity and product quality with minimal labor costs.

3. Research methodology
For deep flat-cut soil cultivation, in this case, it is advisable to have active needle discs driven from the power take-off shaft (PTO) of the tractor. They improve the quality of soil loosening, preserve stubble and mulch on the surface of the field, and reduce the traction resistance of the tool. They can be used both in single-operation machines (hoe, harrow) and in combined tillage machines. The estimation of the pressure distribution in contact of the tire with the ground is essentially suitable for a particular case, i.e. when the deformable layer has a rigid base [2]. For deep flat-cut soil cultivation, in this case, it is advisable to use active needle discs driven by the tractor PTO shaft. They improve the quality of soil loosening, preserve stubble and mulch on the surface of the field, and reduce the traction resistance of the implement. They can be used both in single-operation machines (hoe, harrow) and in combined tillage machines. Figure 2 shows the trajectory of the absolute movement of the tip of the needle of the active needle disk.

![Figure 2. The trajectory of the absolute movement of the tip of the needle of the active needle disk.](image)

Let us consider the trajectory (figure 2) of the absolute movement of the tip of the needle (point B) of the active needle disk. This point, moving rectilinearly and uniformly together with the machine at a speed $v_m$ and uniformly rotating with an angular speed $\omega$ relative to the axis $O'$, traces out a trajectory in the form of an elongated cycloid. Let us choose a coordinate system with the origin at point $O$, when the tip of the needle is located on the same vertical line with the axis of its rotation. In this case, the $OX$ axis will be directed vertically upward, the $OY$ axis – horizontally at a depth, and tillage with a needle disk in the direction of the machine movement [2,8].

4. Research body
Scientifically based minimal soil cultivations provide a reduction in energy costs due to a decrease in their number and depth. To improve the quality of plowing, the differentiated use of replaceable bodies is of great importance, providing the required turnover of the seam, its crumbling and effective weed control. If we assume that the wheel is a cylinder, the problem of pressure distribution over the contact surface will be flat.

Let us consider the process of soil deformation in the load zone (see figure 3).
The volume of soil $V_0 = bS_{ABCD}$ isolated before coming into contact with the wheel is characterized by pore volume $V_{Po}$, volume of the skeleton and the organic part $V_{To}$, moisture $W$ and density $\gamma$.

Where in

$$V_0 = V_{Po} + V_{To}. \quad (1)$$

At the same time, as follows from the design scheme,

$$V_0 = kbR_i^2 \sin \phi_{0l}. \quad (2)$$

where $k$ – coefficient that takes into account the depth of propagation of soil deformation; $b$ – width of the contact zone, equal to the width of the tread of the wheel.

It is assumed that $CD = AB = kR_i \sin \phi_{0l}$.

The coefficient $k$ can be determined experimentally or by calculation [6].

We select from the volume $V_0$ two elementary $v_1$ and $v_2$, each of which before deformation can be represented as

$$v_0 = \frac{1}{n} k b R_i^2 \sin \phi_{0l}. \quad (3)$$

where $n = \frac{1}{\Delta x_0} R_i \sin \phi_{0l} $, wherein $\Delta x_0 = 1$.

Using the relationship known from soil mechanics between the porosity coefficient $\varepsilon_0$, the volume of the solid (not changing volume) part $V_{To}$ nd the pore volume $V_{Po}$ [7]

$$\varepsilon_0 = V_{Po}/V_{To},$$

expression (1) can be written as

$$V_0 = V_{To}(\varepsilon_0 + 1). \quad (4)$$

Taking into account $\varepsilon_0$ the volume $v_o$ can be represented as

$$v_0 = \frac{V_{To}\Delta x_0}{R_i \sin \phi_{0l}}(\varepsilon_0 + 1). \quad (5)$$

The volume of the deformed part of the soil

$$\Delta v_1 = 1bR_i(\cos \phi + \Delta \phi) - \cos \phi_{0l}; \quad (6)$$

$$\Delta v_2 = 1bR_i(\cos \phi - \cos \phi_{0l}). \quad (7)$$

From equations (6) and (7) it follows that the change in volume depending on the contact angle is determined by the relation
\[ \Delta v = \Delta v_2 - \Delta v_1 = 1bR_l \sin \varphi \Delta \varphi. \]  

(8)

Since the length of the elementary arc of the contact is \( \Delta l = R_1 \Delta \varphi \), and \( \Delta l \sin \varphi = z_2 - z_1 = \Delta z \), then \( \Delta z = R_l \sin \varphi \Delta \varphi \).

Therefore, \( \Delta v = 1b\Delta z \).

Assuming that

\[ v_1 = v_{p_1} + v_{T_1}; \]

\[ v_2 = v_{p_2} + v_{T_2}, \]

where

\[ v_{T_1} = V_{T_0} \Delta x_0 / (R_1 \sin \varphi_0), \]

we calculate \( v_1 \) and \( v_2 \) and, subtracting the first value from the second, we find

\[ \Delta v = \frac{V_{T_0} \Delta x_0}{R_1 \sin \varphi_0} (\varepsilon_1 - \varepsilon_2). \]  

(9)

Then the change in the deformation of the soil under the wheel

\[ \Delta z = kR_l \sin \varphi_0 \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_0 + 1}, \]  

(10)

Denoting \( \varepsilon_1 - \varepsilon_2 = \Delta \varepsilon \) and passing to the differential form, equation (10) can be written as follows:

\[ d\varepsilon = \frac{\varepsilon_0 + 1}{kR_l \sin \varphi_0} dz. \]  

(11)

The solution of the last equation, taking into account the initial conditions, establishes the dependence of the average value of the porosity coefficient of the compressible soil volume on the deformation

\[ \varepsilon = \varepsilon_0 - \frac{(\varepsilon_0 + 1)z_0}{kR_0(1 + \Delta / z_p)} \sin \varphi_0, \]  

(12)

Thus, the porosity of the soil after the wheel has passed decreases in proportion to the depth of the track. In this case, an increase in the radius of curvature of the front part of the contact arc will be a factor that reduces the effect on the pore volume. Since according to [5],

\[ R_1 = R_0 \left( 1 + \frac{\Delta}{z_p} \right), \]

where \( R_0 \) - constructive radius of the wheel; \( \Delta \) - tire deformation; \( z_p \) - complete soil deformation,

\[ \varepsilon = \varepsilon_0 - \frac{(\varepsilon_0 + 1)z_0}{kR_0(1 + \Delta / z_p)} \sin \varphi_0, \]  

(13)

where \( z_0 \) - residual track depth.

From the obtained expression, it follows that in order to reduce the impact on the soil, it is necessary to increase the design radius of the wheel, reduce the pressure and reduce the rigidity. The obtained analytical relationship between the parameters of the wheel and the soil during their interaction, firstly, makes it possible to qualitatively assess the effect of the wheel propeller on the soil, and secondly, it serves as a real basis for calculating the distribution diagram of the load components (normal and tangential) over the contact surface.

5. Conclusion

The main factor holding back the further growth of crop yields during layer-by-layer cultivation is the destruction of stubble, a decrease in the fertility of the lower part of the arable layer due to the lack of turnover of the layer and its removal to the surface.
As a result of compaction, the physical condition of the soil deteriorates, and under some conditions of loosening it improves. The intensification of work on the creation of new varieties of agricultural crops requires proper material and technical support, and first of all, for the implementation of field and laboratory technological processes in selection and primary seed production.

The article describes a mechanized soil-protective technological process and technical means for the cultivation of agricultural crops on slope erosion-hazardous lands. The methodology for improving agricultural machines for work on slope erosion-hazardous lands has been clarified. The methods of increasing the stability of the movement of agricultural machines on the slopes to improve the quality of technological operations are substantiated. The operating mode of the active needle disk is described.

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