Disk shredder workflow

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Abstract. Tillage is the most energy-intensive process and should be aimed at the accumulation of humus and the formation of a fertile soil layer. Therefore, the development of resource-saving technological processes and technical means to stop the progressive degradation of soil from wind, water erosion and reduce operating costs is relevant. The most gentle cultivation of the soil with less energy costs allows you to perform disk implements. The cultivator working process is examined from the point of view of the power characteristics of the disk-soil. Soil cultivation is systemic in nature and is based on zonal conditions, as it should be soil-protective, energy-saving, economically viable and environmentally friendly. Fulfillment of these requirements is connected with the right choice and optimal combination of used machines. Analytical expressions are obtained that establish the dependence of the horizontal and vertical components of the drag force of a disk tillage implement as a function of the volume of the cut soil layer. The use of the research results will help industrial enterprises of agricultural machinery in the design of new tillage machines for agriculture, which will reduce the cost of manufacturing prototypes and testing them for traction resistance and quality of soil cultivation.

1. Introduction

Soil cultivation is an important aspect of crop cultivation and it affects yields. The choice of a soil tillage system is based on zonal conditions and should be soil-protective, energy-saving, economically viable and environmentally friendly. Fulfillment of these requirements is connected with the right choice and optimal combination of used machines [1, 2, 3].

2. Problem Statement

According to the Ministry of Natural Resources of the Russian Federation in Omsk region there are more than 3 million hectares of land, predisposed to the development of erosion and deflationary processes. Erosion processes are most pronounced in steppe and southern forest-steppe zones. For the last ten years there was a decrease in gross humus reserves in arable soils to 10-15 % of the original, especially in the south.

Planks, cultivators and deep loosening machines are used to till such soils, but the working process of these machines is energy intensive. Therefore, the development of resource-saving technological processes and technical means to stop the progressive degradation of soil from wind, water erosion and reduce operating costs is relevant.

3. Research Questions

Soil cultivation is systemic in nature and is based on zonal conditions, as it should be soil-protective, energy-saving, economically viable and environmentally friendly. Fulfillment of these requirements is connected with the right choice and optimal combination of used machines [4, 5].
Based on the data from the Soil Institute named after V. V. Dokuchayev [6], the northern boundary of the erosion-hazardous territory passed south of Omsk and Novosibirsk. However, at present we have information about the manifestation of wind erosion outside the northern boundary, which was established in 1960: dust storms in 1969 and some subsequent years occurred north of Omsk and Novosibirsk.

Over the past 40 years, areas of arable land subject to wind erosion have increased more than 2.2 times. Annual losses of humus are 0.45 on poorly eroded soils, 0.7 on medium eroded soils and 1.1 t/ha on strongly eroded soils [7, 9]. In this situation, anti-erosion and resource-saving soil treatment is required, which should take into account the contamination of fields, type, particle size distribution, water resistance of structure and density of soils. Fulfilling these requirements will ensure moisture conservation, increase field fertility and save money.

4. Purpose of the Study
There are several methods of soil tillage: minimum, no-milling, zero, classical (ploughing) and multi-degree tillage.

It is established that minimum tillage to a depth of 15 cm allows one to solve a number of problems: to prevent water and wind erosion, to increase the accumulation of productive moisture in the soil through the conservation of stubble residue and mulch from straw on the surface of the field. Such a protective cover is universal and ensures moisture preservation during the whole vegetation period. It protects the soil from overheating (the surface of uncovered soil in our conditions in hot days is heated up to 60 degrees), promotes the activation of soil microflora, is the basis for the renewal of the fertile layer and increase crop yields and fertility restoration. At the same time, no uneven distribution of plant residues on the soil surface should be allowed. Excess straw inhibits the growth and development of spring crops, as it lowers soil temperature and leads to overwetting in spring. Uncovered straw areas, on the other hand, warm up quickly and dry out. The optimum amount of plant residue per hectare should be 3-5 tons dry matter.

Meteorologists have called the last ten years the hottest on the planet in the history of meteorological observations. Thus, in autumn 2005 the productive moisture in the soil of some regions of the south of the Omsk region was more than half of the usual reserves. The amount of available moisture was different and significantly depended on the methods of basic soil tillage.

In stationary experiments (R.S. Shakirov) systematic ploughing without mineral fertilizers in 10 years reduced the total humus content by 0.3%. The soil of an arable layer was reconsolidated, the plough sole is clearly visible on the soil section. Replacement of ploughing by flat-cutting treatment with preliminary shelling and leaving of crushed straw in the field resulted in increase of humus content by 0.5-0.6%, improvement of water resistance of soil structure, compaction, activation of humus formation processes in 10 years. The process of humus formation intensifies at the bottom - 35 t/ha of green mass. Replacement of ploughing by plane loosening with preliminary husking allows one to save 40-45% of fuel and lubricants [8, 10, 11].

Thus, on well-cultivated, weakly clogged soils with density not exceeding 1.3 g/cm3 (preferably 1.1-1.2 g/cm3) it is expedient to replace plowing with small loosening by shredders, heavy disk harrows, stubble cultivators. It is very effective on chernozems, especially carbonate and typical soils, which have high water resistance of structure, optimal density of addition, sufficient porosity of aeration, good water permeability. In areas, subject to wind erosion, cultivation is carried out by disk shredders with a flat disk and stubble cultivators.

On soils with the density higher than 1.3 g/cm3, it is necessary to carry out flat loosening to the depth of the arable layer with preliminary shelling or ploughing without dumps.

Heavy soils heavily clogged with perennial weeds should be used multigrade ploughing with techniques of ploughing without ploughing and surface treatment, which should be periodically interrupted by ploughing for black soil zones not exposed to wind erosion. On soils exposed to wind erosion, ploughing is not acceptable, it can cause increased erosion, so herbicide spraying is recommended for weed control.
Usually the surface treatment is done in two sessions. The first one is immediately after the previous crop has been cleaned. The second one - after the root weeds germinate, in a mutually perpendicular direction.

The quality of the treatment of soils exposed to wind erosion with disk tools is estimated by the following indicators:
- deviation of the average actual depth of soil tillage from the set one no more than 1.5 cm.
- levelling of the field surface: the height of the ridges shall not exceed 5 cm, and the length of the profile on the section of 10 m shall not be less than 10.5 m.

The quality of the soil cultivation with the disc implements depends on many factors, of which the main ones are: angle of attack, working depth and machine speed. The angle of attack influences the loosening quality of the soil and the working width of the implement, and when it is increased the better loosening of the soil layer is observed. At small angles of attack and high speed, the holes in the soil are loosened, which contributes to water accumulation.

There are many descriptions of the work of disk working tools - disk knife, which performs cutting of layer, spherical or conical disk, which performs cutting and moving of layer to the side at a certain angle of attack [1, 4, 5, 6, 7, 12, 13, 14, 15]. All these descriptions are based on V.P. Goryachkin's formula [2], which was derived for the plough, not for the disk taper workflow, so it can be presented as follows.

5. Research Methods
When the plough is running (Figure 1) at the maximum possible depth of 120 mm with an angle of attack \( \alpha > 0 \), the working surface will not be the entire buried part of the ABCD spherical disc (Figure 1, b), but only the part of the BCD disc (Figure 1, b), since the discs come with some overlap (Figure 1, a).

The disk sphere radius is 600 mm, however, BCD segment (Figure 1, c) is so small that the sphere in further calculations can be replaced by a plane passing through points B, C, D. It will allow one to find out a physical picture of interaction of working bodies of the shredder (harrow) with soil and to receive more exact analytical expressions establishing dependence of resistance to work in the parametrical form (in function of volume of volume of a cut layer of soil).

The horizontal component of resistance force of the shinner can be considered as a sum of resistance force of cutting \( W_{\text{cut}}(h, H) \) [3], which is the function of thickness of the cut layer of soil \( h \) and the height of the soil layer \( h \) before disk, and resistance force of \( W_{\text{mov}}(H) \) to movement of the soil layer before the disk:

\[
P_{\text{h1V}} = W_{\text{cut}}(h, H) + W_{\text{mov}}(H).
\]

The vertical component of the force of resistance of the plough can also be considered as the sum of the two components:

\[
P_{\text{v1V}} = W_{\text{vk}}(h, H) + W_{\text{vs}}(H),
\]
where \( W_{vk}(h, H) \) – vertical force of the circular knife; 
\( W_{vs}(H) \) – vertical force of the spherical surface of the disc.

To determine the resistance force \( W_{cut}(h, H) \) of the soil shearing off, we will adopt the calculation scheme (Figure 2, a).

**Figure 2.** Calculated schemes of interaction with soil of working bodies of disk tillage machines:

a - calculated scheme of cutting of soil with a knife of a shredder (harrow);
b - calculated scheme of moving of the soil layer with a sphere of a disk

The disk knife of the BC swinner cuts the soil layer to a depth of \( h \). The soil in front of the knife is considered to be a homogeneous mass that cracks at some angle of slide \( \psi_s \) to the horizontal plane.

The unit width of the chipping mass of the soil is influenced by the weight \( G \) of the soil, conditional loading with the intensity \( q \), normal reaction \( N_k \) of the knife, normal reaction of the soil \( N \), the friction force of the soil against the disc knife \( F_k \), the friction force \( F_s \) of the soil against the soil and the adhesion force of the soil \( F_{ad} \).

In the course of work, all geometric dimensions of the system under consideration are a function of the variable \( h \) thickness of the soil to be cut.

A vertical load \( Q \), equivalent to a uniformly distributed load, is applied to the crumbling soil mass:

\[
Q = q \cdot AC \cdot 1 = qh \frac{tg \delta_k + tg \psi_s}{tg \delta_k \cdot tg \psi_s}.
\]

Soil weight \( G \) is equal to:

\[
G = \frac{\gamma_s h^2}{2} \frac{tg \delta_k + tg \psi_s}{tg \delta_k \cdot tg \psi_s},
\]

where \( \gamma_s \) – volume weight of the soil.

Clutch force:

\[
F_{ad} = AB \cdot 1 \cdot C = \frac{Ch}{sin \psi_s},
\]

where \( C \) – adhesion coefficient.

To determine the force \( N_0 \) of the normal knife pressure on the soil we will make the equilibrium equation:

\[
\sum X = 0; \quad F_{ad} \cos \psi_s + F_s \cos \psi_s + N \sin \psi_s - F_k \cos \delta_k - N_k \sin \delta_k = 0;
\]

\[
\sum Y = 0; \quad -Q - G - (F_{ad} + F_s) \sin \psi_s + N \cos \psi_s - F_k \sin \delta_k + N_k \cos \delta_k = 0;
\]

\[
F_s = Ntg \psi_s; \quad F_k = Ntg \varphi_{met}.
\]

where \( \varphi_s \) – soil friction angle;
\( \varphi_{met} \) – ground angle against metal
As a result of solving the resulting system of equations, we find:

\[
N_k = \left[ \frac{\gamma_h^2 + qh + C_h}{\left(\operatorname{tg} \varphi + \operatorname{tg} \psi \right) \left(\operatorname{ctg} \varphi + \operatorname{ctg} \delta_k \right)} \right] \left(\operatorname{ctg} \varphi + \operatorname{ctg} \delta_k \right) \left(\operatorname{ctg} \delta_k - \operatorname{tg} \varphi_{\text{met}} + \operatorname{tg} \varphi_{\text{met}} \operatorname{ctg} \delta_k + 1 \right) \sin \delta_k.
\]  

(1)

Ground resistance to cutting for the entire width of the blade is determined by the expression:

\[
W_{\text{cut}}(h, H) = B(N_k \sin \delta_k + F_k \cos \delta_k).
\]

Ground resistance to cutting for the entire width of the blade is determined by the expression:

\[
W_{\text{sl}}(h, H) = B(N_k \sin \delta_k + F_k \sin \delta_k).
\]

To determine the resistance of the soil layer, we will accept the calculation scheme (Figure 2, b).

The soil in front of the disk is considered as a homogeneous array, sliding at an angle \( \psi' \). The disk is conditionally replaced by a plane located on a chord to a disk surface.

The following forces act on the soil mass: soil weight \( G' \), normal reaction of the blade side \( N_{\text{sl}} \), normal reaction of the moldboard \( N_{\text{mb}} \), force of the soil layer \( F_{\text{sl}} \) and ground friction force against the moldboard \( F_{\text{mb}} \).

The geometric dimensions of the soil mass are considered as variables which are a function of the soil layer height:

\[
\begin{align*}
PL &= H \frac{\sin(\delta_0 - \varphi)}{\sin(\varphi + \psi') \sin \delta_0}; \\
h_1 &= H \frac{1 - \operatorname{ctg} \delta_0 \operatorname{tg} \varphi}{1 + \operatorname{tg} \varphi \operatorname{ctg} \psi} ; \\
h_2 &= H \frac{\sin(\delta_0 - \varphi) \sin(\delta_0 + \psi')}{\sin(\varphi + \psi') \sin \delta_0}.
\end{align*}
\]

The weight of the \( G' \) soil is equal to:

\[
G' = \frac{\gamma'_H^2}{2} \frac{\sin(\delta_0 - \varphi) \sin(\delta_0 + \psi')}{\sin(\varphi + \psi')}.
\]

where \( \gamma'_s \) – soil volume in the formation.

The weight of the soil \( G'_1 \) is equal to:

\[
G'_1 = \frac{\gamma'_H^2 \left(1 - \operatorname{ctg} \delta_0 \operatorname{tg} \varphi_{\text{met}} \right) \sin(\delta_0 - \varphi)}{2 \left(1 + \operatorname{tg} \varphi' \operatorname{ctg} \psi_{\text{met}} \right) \sin \varphi \sin \delta_0}.
\]

For the determination of normal reaction of moldboard \( N_{\text{mb}} \) waste heap and normal reaction of soil \( N_1 \), we will make equilibrium equation:

\[
\begin{align*}
\sum X_1 &= 0; \quad F_{\text{sl}} \cos \psi' + N_1 \sin \psi' - N_{\text{mb}} \sin \delta_0 - F_{\text{mb}} \cos \delta_0 = 0; \\
\sum Y_1 &= 0; \quad -F_{\text{sl}} \sin \psi' + N_1 \cos \psi' - G' + N_{\text{mb}} \cos \delta_0 - F_{\text{mb}} \sin \delta_0 = 0; \\
F_{\text{sl}} &= N_1 \operatorname{tg} \varphi; \quad F_{\text{mb}} = N_{\text{mb}} \operatorname{tg} \varphi_{\text{met}}.
\end{align*}
\]

In solving the system of equations, we will determine:
\[ N_1 = \frac{\gamma' H^2}{2} \sin(\delta_0 - \varphi) \sin(\delta_0 + \psi) \]
\[ \frac{\sin^2 \delta_0 \sin(\varphi + \psi) \cos \psi}{(1 - \tan \varphi \tan \psi) + (\tan \varphi + \tan \psi) \cot(\varphi_{\text{net}} + \delta_0)}; \]
\[ N_{mb} = \frac{\gamma' H^2}{2} \sin(\delta_0 - \varphi) \sin(\delta_0 + \psi) \]
\[ \frac{\sin^2 \delta_0 \sin(\varphi + \psi) \cos \psi}{\cot(\psi + \varphi)(\tan \varphi_{\text{net}} + \tan \delta_0) + (1 - \tan \varphi_{\text{net}} \tan \delta_0)}. \]

The resistance force of the soil layer is equal to the entire width of the blade:
\[ W_{\text{mov}}(H) = B(N_{\text{mb}} \sin \delta_0 + F_{\text{mb}} \cos \delta_0). \]
The vertical component of reservoir resistance force per blade weight is determined by expression:
\[ W_{\text{vs}}(H) = B(N_{\text{mb}} \cos \delta_0 - F_{\text{mb}} \sin \delta_0). \]

After determining the normal reaction of \( N_1 \), it is possible to determine the load \( q \) on the rock mass:
\[ q = \gamma' H + \frac{F_{\text{mb}} \sin \delta_0}{AC \cdot B}. \]

In the obtained expressions the value \( H \) is a function of the volume of the cut soil:
\[ H = \sqrt{\frac{2V_3 \sin \varphi_{\delta} \sin \delta_0}{B \sin(\delta_0 - \varphi_{\delta})}} = \sqrt{\frac{2V_3}{B(\cot \varphi_{\delta} - \cot \delta_0)}}. \]

6. Findings
Thus, the obtained analytical expressions allow one to establish the dependence of horizontal \( P_{01G} \) and vertical \( P_{01V} \), which are the resistance forces of the disc tillage tool in the functions of the volume of the cut soil layer.

7. Conclusion
Analytical expressions are obtained that establish the dependence of the horizontal and vertical components of the drag force of a disk tillage implementation as a function of the volume of the cut soil layer. The use of the research results will help industrial enterprises of agricultural machinery in the design of new tillage machines for agriculture, which will reduce the cost of manufacturing prototypes and testing them for traction resistance and quality of soil cultivation.

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