DYNAMICS OF DEEP LOOSENER LOADING DURING AGROTECHNICAL TILLAGE OPERATIONS

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Abstract. Modern agriculture requires introduction of rational, energy-saving and environmentally friendly agro-technologies. In recent years, special attention has been paid to the issues of preserving the fertility of agricultural land. One of the problems faced by farmers and agricultural enterprises is excessive soil compaction. This problem has arisen due to the steady tendency of increasing the weight of agricultural machinery, in connection with this negative impact of heavy machinery the subsoil layer is also compacted in addition to the arable layer. The depth of soil compaction depends on the tractor weight, frequency of passes, moisture, type and the condition of soil. Besides repeated passes of machines, soil compaction is also promoted by repeated plowing of soil to the same depth, which causes formation of so-called plow sole with hardness more than 3.5 MPa. Excessive soil compaction blocks the rise of soil moisture through capillaries from the depth of water-bearing layers. Soil compaction is felt by almost all agricultural crops through limitation of water supply to the root system of plants. One way to combat soil over-compaction is deep loosening or chiseling, sometimes referred to as vertical tillage. Also, soil loosening provides improved water and air regime. Under certain conditions, deep loosening can replace plowing. The paper studies the loading dynamics of deep loosening machines, which have been used for soil decompaction in tillage systems, which is of scientific and practical interest. To study the dynamics of deep loosener loading, a measuring and registration complex developed at the university was used. This complex allows to control in real time the load parameters of an agricultural machine without interfering with its design.

Key words: aggregate dynamics, soil compaction, deep loosener, tillage system, measuring complex.

Introduction

Farmers and scientists all over the world have been paying special attention to the problem of soil degradation for many years. Scientists from European countries and America have been dealing with this complex problem for decades. According to the research conducted by experts from Ohio State University, 85% of compaction occurs during the first pass. Researches of scientists have established that in the process of field works agricultural machinery leaves its traces on 40-80% of the processed area, and the turning lanes have even more passes and, consequently, even more compaction. A number of foreign authors studied the mechanism of influence of different types of tillage on soil productivity (Wang, X., Qi, J., et al.; Yadav, G. S., et al.; McGarry, D. et al.;) [1-4]. In Ukraine, the topic of soil compaction became relevant only after gaining independence. This is due to the fact that during these years agriculture has intensively developed and, accordingly, the presence of various modern agricultural machinery and high-power tractors on the fields has increased (M.A. Hamza, et al.; Bulgakov V., et al.;) [5; 6].

Modern tractors, grain carriers and combines have a special impact on soil compaction, and this is due to the tendency to increase their weight. The continuous tendency to increase the weight of machines for working in the fields has a negative effect not only on the arable layer, but also compacts the subsoil layer to a depth of over 1.0 m. Compaction of the upper 20 cm of the soil layer will also have a negative impact and lead to yield reduction. How deep the soil compaction will be formed depends on the moisture, soil type and condition, tractor weight, frequency of passes (Kohan A.; Diserens E., et al.) [7; 8].

Materials and methods

Many farms use crop cultivation technologies at their own discretion: they often do not observe crop rotation, violate agrotechnical requirements. Uncontrolled movement of tractors, combines and trucks on the field, especially in spring, when soil moisture is high, creates conditions for the formation of plow sole – a layer of soil with increased hardness. Early spring tillage of wet soil is very dangerous, as it leads to significant over-compaction (Janulevičius A., et al.; Medvedev V., et al.;) [9-11].

In order to preserve the soil structure and fertility, it is necessary to carry out application of organic fertilizers, constantly control the hardness and density.

Determination of soil hardness is carried out with the help of hardness testers at the depth of cultivation when performing this or that technological operation. Determination of hardness provides two options: the first is organoleptic, the second is hardness determination with the help of hardness testers such as hardness tester Revyakin (Fig. 1), when the hardness value is fixed on the decipherable hardness gram and the result is determined by calculations of soil hardness at a depth from 0 to 400mm.

Fig. 1. **Revyakin hardness tester for determining soil hardness**

When conducting research on the farm of Kharkiv region, measurements of soil hardness before the planned deep loosening were carried out (Table 1).

Table 1

Soil condition before cultivation

Soil condition	**Unit of measurement**	**Indicator**
Hardness in layers, cm.		
0-5	MPa	0.85
5-10	MPa	1.87
15-20	MPa	2.45
25-30	MPa	3.22
Soil humidity in layers, cm		
0-5	%	17.05
5-10	%	20.02
15-20	%	23.01
25-30	%	28.03

The farm is engaged in crop production and the soil cultivation systems used require periodic deep loosening to break the resulting plow sole to avoid soil compaction and improve the soil structure.

Based on the research of M. Vavilov Poltava State Research Station where the advantages of deep loosening in crop cultivation were confirmed, it was decided to use deep loosening machines to improve the soil structure and increase yields. It also becomes relevant to determine the method of basic soil cultivation, which in the system of the agrotechnical process will contribute to the maximum moisture accumulation by the soil, revealing by hybrids and varieties of their genetic potential (Kohan A.) [7].

To combat the negative phenomenon of soil compaction, deep loosening and chiseling are used. After deep loosening treatment, up to 75% of crop residues remain on the surface of the field, which protects the soil from wind erosion, reduces moisture evaporation, and deep loosening and mixing of crop residues with the surface layer of soil increases its ability to absorb moisture several times (Kozicz J.) [12].

Of all the various soil tillage implements, chisel ploughs and deep loosening ploughs are subjected to the greatest stress. The smallest changes in soil properties during a technological operation can have a significant impact on the quality of work. At the same time, however, tillage has a number of well-known advantages. Reduction of expenditures on fuel and lubricants and reduction of energy intensity of basic tillage is one of the significant advantages of deep tillage. However, the energy intensity of deep tillage is compared with moldboard plowing, the use of which in farms is decreasing. In connection with the above, it is necessary to study the real loads on deep loosening tools during this complex agrotechnical operation.

Fig. 2. **John Deere 9470R + Gaspardo DIABLO-700 tillage machine**

Traction resistance of tillage implements that perform soil loosening at different depths and their dependence on various parameters can be represented by an analytical expression similar to the rational formula of V.P. Goryachkin (Vetohyn, V.) [13]:

$$R = fG + kS_k + \varepsilon S_k V^2 \quad (1)$$

where f – coefficient of resistance to implement movement in the furrow;
G – weight of the implement, N;
k – specific resistance of soil, $N \cdot m^{-2}$;
S_K – cross-sectional area of the loosened part of the formation, m^2;
ε – coefficient depending on the shape of working tools, soil properties and formation size;
V – operating speed, $m \cdot s^{-1}$.

At the same time, the proposed methodology for determining the traction resistance does not take into account the parameters of soil composition. N.V. Shchuchkin proposed a method that is based on the determination of the coefficient of specific resistance of soil depending on hardness and the coefficient of friction of soil against steel (external friction). The rational formula (Vetohyn, V.) [13] was the prototype.

$$R = fG + mxab, \quad (2)$$

where f – coefficient of soil friction against steel;
G – weight of the tillage tool, N;
m – coefficient expressing the ratio of specific resistance to soil hardness;
x – hardness of the arable soil layer, Pa;
a – depth of soil cultivation, m;
b – width of the deep loosener bit, m.

To carry out the calculations, we will study the two-mass dynamic system of the soil cultivation unit, simulating our soil cultivation unit (Artiomov M.) [14], with four degrees of freedom: ξ and η – respectively, longitudinal and transverse coordinates of the centre of mass of the tillage aggregate for connecting the deep loosener; ψ_1 – course angle of the tractor frame deviation in relation to the axis OX; ψ_2 – angle of rotation of the deep loosener with respect to the axis of attachment to the tractor. To describe the motion of the dynamic model of the machine we will use the Lagrange equation of the 2nd kind.

To solve the problem, let us measure accelerations at two control points, which are functions of time on the interval (0, t). The coordinates of points M_1 and M_2, where the sensors are installed, are known. The coordinates of points M_1 and M_2 are also known relative to the coordinate system (XY), rigidly connected with the moving, relative to the stationary coordinate system, machine-tractor unit. Let us denote the components of accelerations at these points as follows: point M_1 – ax_1, a_{y1}, point M_2 – ax_2, a_{y2}. Once the accelerations have been measured, the relationship of the acceleration components $\vec{a}_1 = a_{x1}\vec{e}_x + a_{y1}\vec{e}_y$ and $\vec{a}_2 = a_{x2}\vec{e}_x + a_{y2}\vec{e}_y$ to the generalized coordinates ξ and η must be established. In the case of plane-parallel motion of a dynamical system, the acceleration of any point M can be represented as the geometric sum of three accelerations.

$$\vec{a}_{\mathrm{m}} = \vec{a}_o + \vec{a}_b + \vec{a}_c \tag{3}$$

where $\vec{a}_o$ – acceleration at the point,
$\vec{a}_b$ – acceleration of rotation,
$\vec{a}_c$ – centrifugal acceleration.

Based on the transformations performed on the measured parameters of the machine and equation (3), we obtain the following system of equations

$$\Delta a_x = -\Delta_2 \ddot{\psi}_1 + \Delta_1 \dot{\psi}_1^{\,2}, \tag{4}$$

$$\Delta a_y = -\Delta_1 \ddot{\psi}_1 - \Delta_2 \dot{\psi}_1^{\,2}, \tag{5}$$

where, respectively, in equations (4) and (5), we introduce the notations

$$\Delta a_x = a_{x1} - a_{x2}, \quad \Delta a_y = a_{y1} - a_{y2},$$

$$\Delta_1 = r_2 \cos\alpha_2 - r_1 \cos\alpha_1, \quad \Delta_2 = r_2 \sin\alpha_2 + r_1 \sin\alpha_1. \tag{6}$$

After substituting all components of accelerations and parameters of the machine, carrying out simplifications, we obtain a linearized system of equations, which will allow us to carry out the determination of the dynamics of force characteristics of the deep loosener.

$$\begin{cases} m\ddot{\xi} = T - W_1 - W_2 - R_X + R_Y\psi_2; \\ m\ddot{\eta} + m_1 b_1 \ddot{\psi}_1 + m_2 b_2 \ddot{\psi}_2 = (T - W_1 - W_2)\psi_1 - R_X\psi_2 - R_Y; \\ m_1 b_1 \ddot{\eta} + 2J_1\ddot{\psi}_1 + C(\psi_1 - \psi_2) = 0; \\ m_2 b_2 \ddot{\eta} + 2J_2\ddot{\psi}_2 - C(\psi_1 - \psi_2) = R_Y l - R_X l \psi_2; \end{cases} \tag{7}$$

To obtain a correct result, we will use the definition of the resistance force of the deep loosener working organ (Leshchenko S. et al.) [15], where normal forces, friction forces, machine speed and some other factors are taken into account.

$$R = \sum(N_H + N_R + N_W) + \sum\left[fG + f_1(N_H + N_R + N_W) + 2f_L(R_{HB} + R_{LR} + R_{LW})\right] + \\ + \left(K + \varepsilon_B V^2 + \varepsilon_W V^2\right)(Bh_R + Sh_B + Sh_W), \tag{8}$$

where N_H – horizontal components of forces acting on the bit, N;
N_R, N_W – resistance of rack and wing movement, respectively frontal resistance, N;
fG – friction force on the furrow bottom, N;
$f_1 (N_H + N_R + N_W)$ – horizontal component of friction forces from normal forces, N;
$2f_L (R_{HB} + R_{LR} + R_{LW})$ – horizontal and lateral components of friction forces on the side surfaces of the bit, rack and wings respectively, N;
K – coefficient characterizing the ability of the ground to resist deformation;
ε_B, ε_W – coefficients depending on the shape of the bit working surface i wings, properties and size of the ground section deformed by the corresponding elements;
$(Bh_R + Sh_B + Sh_W)$ – sum of active areas of rack, bit and wings, m^2.

After substituting equation (8) into the system of equations (7) and the program of the measuring and registration complex, control trials were carried out on the field with grain stubble.

Results and discussion

Recently, various measuring complexes have started to be used, which do not require intervention in the design of the machines and can obtain information about the acting loads in remote mode [16].

Sensors of the measuring and recording complex (Artiomov M. et al.) [16] were installed on the tractor on the left front and on the right rear on the frame. The length on which the measurements were made was 460 m. The speed of the machine movement was 8.5...9.6 km·h^{-1}, the depth of the soil tillage was 45 cm. The results of the accelerometer measurements were recorded in the computer memory for further processing. The most informative part of the graph of longitudinal accelerations (x-axis) of the tractor, showing the dynamics depending on time, is shown in Fig. 3.

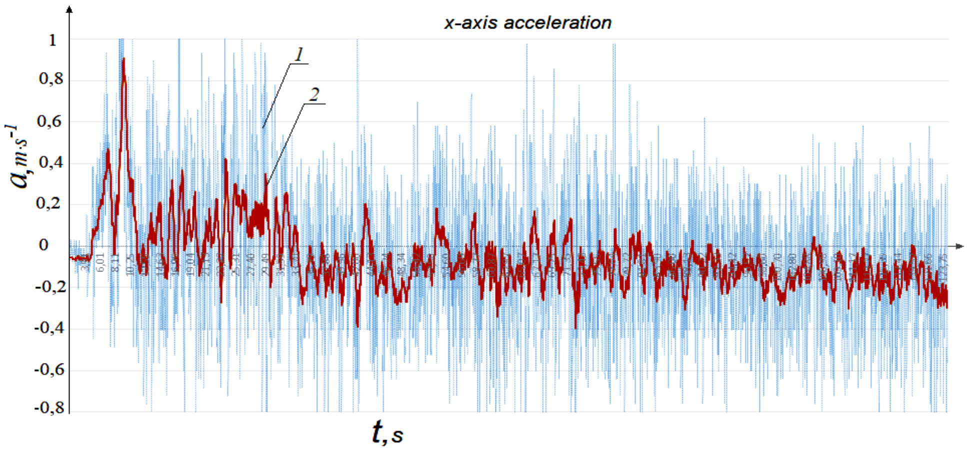

Fig. 3. **Dependence of longitudinal acceleration of tillage machine John Deere 9470R + Gaspardo DIABLO-700 as a function of time (*x*-axis):**
1 – actual signal; 2 – signal that has passed through the filter

The graph shows an array of data from measuring the dynamics of accelerations along the x-axis in the direction of the aggregate movement. The dynamics of accelerations (3), which have passed through the filter, is highlighted separately, because the sensors perform measurements at a rate of 50 measurements per second.

The paper presents the results of the dynamics of the machine loading during agrotechnical operation. Such a method gives an opportunity to see the process of loading of working organs of an agricultural machine in contrast to the conducted loading calculations [2; 3; 5; 7] on the basis of statistical data on agricultural machines and aggregates. In work [15] calculation of parameters of a deep loosener on quality of soil tillage is carried out, but there is no description of what loads it will experience when working as a part of an aggregate.

According to the results of these calculations on the basis of statistical data (R_S) and measurements of the registration-measuring complex (R_D) we have built a graph of dynamics of the resistance force of the deep loosener depending on time (Fig. 4).

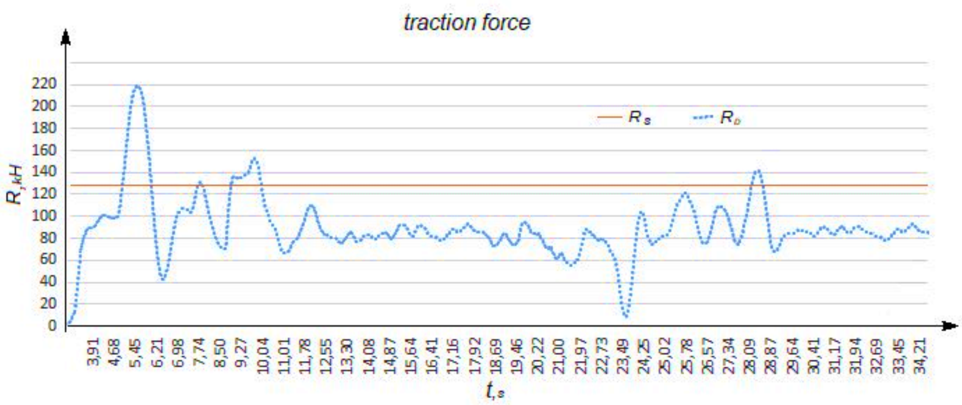

Fig. 4 **Dynamics of change in the resistance force of the deep loosener:**
R_s – theoretical drag force; R_D – experimental drag force

The graph shows the dynamics of the resistance force of the deep loosener at the moment from the beginning of the agrotechnical operation to the steady motion mode. The beginning of the graph clearly demonstrates the process of transition from one state (rest) to the state of uniform motion, more vividly demonstrating the dynamics of loading. At the initial moment the dynamic resistance is higher than the theoretically calculated, practically by 60%, and then after stabilization of movement fluctuates within 78...95 kN, which corresponds to 55...70% of the theoretically calculated value. Statistical processing of the acceleration graph of the machine was carried out with the help of MATLAB 7.0 software package.

Conclusions

1. In order to replace the traditional soil cultivation technology, which uses ploughing, it is necessary to use technological processes of soil cultivation and cultivation of crops with the purpose of wider introduction of soil-protective energy-saving and environmentally friendly agro-technologies. Technologies of deep loosening contribute to the preservation of the top fertile layer and reduce energy consumption.
2. It is established that at the beginning of the aggregate work the dynamic resistance is higher than the theoretically calculated statistical resistance, practically by 60%, and then after stabilization of movement fluctuates within 78...95 kN, which corresponds to 55...70% of the calculated, that allows to choose the optimum speed mode of the aggregate work, provide optimum use of the tractor traction force, reduce fuel consumption per unit of the executed work.
3. Calculation of dynamics of resistance forces of the deep loosener, which takes into account the friction force, normal forces, speed of the machine movement, with the help of the measuring and registration complex, allowed to carry out measurements without interference in the design of the machine in real time during the technological operation.

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Author contributions

Conceptualization, N. Artiomov; methodology, A. Anikeev; software, A. Kaluzhnij, validation, M. Tsiganenko; formal analysis, N. Artiomov and A. Anikeev; investigation, M. Tsiganenko; data curation, A. Kaluzhnij; writing – original draft preparation, N. Artiomov; writing – review and editing, A. Anikeev and M. Tsiganenko; visualization, A. Kaluzhnij, Oleg Pushkarenko. All authors have read and agreed to the published version of the manuscript.

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