CALCULATION OF A TRACK FORMATION PROCESS DURING WHEEL-GROUND INTERACTION
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РОЗРАХУНОК ПРОЦЕСУ УТВОРЕННЯ КОЛІЇ ПРИ ВЗАЄМОДІЇ КОЛЕСА ІЗ ҐРУНТОМ

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ABSTRACT

The article provides the mathematical model of formation of a track depth depending on the size of vertical loading of a machine-tractor unit wheel, the structural parameters of the wheel and the soil properties. Based on the developed mathematical model, the experimental data of wheel-soil interaction and the soil properties, the track formation process in the soil depending on the pressure created by the wheel in a zone of contact with soil is proved. The analysis of the process of forming the track allows us to conclude that the intensity of track formation decreases with the increase in the wheel-ground interaction time.

АБСТРАКТ

В статті розроблено математичну модель формування глибини колії в залежності від величини вертикального навантаження колеса машинно-тракторного агрегату, конструкційних параметрів колеса та параметрів агротехнологічного середовища. На основі розробленої математичної моделі, отриманих експериментальних даних взаємодії колеса із ґрунтом та параметрів агротехнологічного середовища обґрунтовано процес формування колії в ґрунті в залежності від тиску який створює колесо в зоні контакту з ґрунтом. Аналіз процесу формування колії дозволяє зробити висновок про зменшення інтенсивності формування колії із збільшенням часу взаємодії колеса із ґрунтом.

INTRODUCTION

Trends in the development of modern agricultural machinery are to increase the capacity and productivity of technical means, primarily characterized by an increase in the total weight of machine-tractor units (MTU). Increasing the weight of MTU increases the intensity of soil compaction by running systems and accelerates soil degradation processes (*Mueller et al., 2010*). Soil compaction is a worldwide problem that leads to increased soil density, reduced water volume and reduced porosity, impairs soil aeration and water permeability, disrupts plant nutrition metabolism (*Nawaz et al., 2013; De Lima, 2017*), leads to increased greenhouse gas emissions (*Usowicz and Lipiec, 2017*), and decreases soil productivity (*Mueller et al., 2010; Vereecken et al., 2015*). Interaction of a navigation system simultaneously with the soil compaction leads to the formation of a track. Especially intensive process of track formation is observed when performing operations of pre-sowing treatment, sowing, fertilizing, and chemical protection, carried out in the phase when the soil is artificially loosened after plowing and saturated with sufficient moisture. Changes in the relief of the ground surface and the presence of areas with different physical and mechanical characteristics degrade the quality of technological operations and negatively affect the operational performance of MTU. When moving on less compacted soil, the rolling resistance of the movers increases and there is an increase in the power consumption for movement. A number of studies (*Gray et al., 2016; Taghavifar and Mardani, 2016*) are devoted to the development of programs, the algorithm of which allows optimizing the movement of MTU on the field in order to reduce the possible overlaps of the paths of machines wheel movers, and as a consequence, reduce the negative impact on the soil. Understanding the processes of forming a track in the soil will further reduce the negative impact on the soil, improve the efficiency of MTA due to the optimal choice of existing equipment and the design of new technical means and engines.

In some studies (*Kurjenluoma et al., 2009*) the influence of the type of tires on the formation of a track and the formation of rolling resistance was determined using the regression analysis method. It was established that the depth of the track is correlated with the value of the wheel coupling with the soil and soil density indicators, a linear correlation of the depth of the track and rolling resistance was established. It was also noted that the bearing capacity of the soil both vertically and laterally depends largely on the relative strength and moisture content of the soil layers. Having carried out an experimental analysis of the factors influencing the track formation of driven (*Carman, 2002*) and driving (*Taghavifar and Mardani, 2016*) wheels, it was found that the main factor that affects soil compaction is the vertical load. In the studies (*Damanauskas and Janulevičius, 2015; Higa et al., 2015; Taghavifar and Mardani, 2016*) it is noted that in addition to the vertical load, the processes of compaction and deformation of the soil are influenced by the speed and parameters of the wheel movers. The results of the studies provide an understanding of the track formation process flow and compaction of the soil running systems. The obtained regression models are useful for modeling the corresponding parameters of soil interaction, but their wide application is limited by the parameters of similarity of the conditions under which these models are obtained.

A certain number of mathematical models *(Söhne, 1958; Smith, 2000; Défossez, 2002)* for predicting soil compaction and deformation were obtained as a result of improvements in the equations of M.J. Boussinesq (*Naveed et al., 2016*). However, the use of this type of models is only suitable for homogeneous soil and at loads not exceeding the elastic limit of the soil (*Nawaz et al, 2013*). Investigating the influence of the number of passes of wheeled vehicles on the depth of the track formation (*Vennik et al., 2019*), the comparison of experimental data of soil deformation based on the results of calculation using analytical models is performed. The authors noted the high coincidence of the results when using the SoilFlex model to predict the depth of the track formation when moving along the surface of the soil, but also noted the need to refine this model for use on other types of soils and when modeling multiple passes.

The SoilFlex model (*Keller et al, 2007*) implemented an algorithm that combined a wheel-soil contact model, a model for quantifying soil bulk deformation in the longitudinal and lateral directions, and a model for estimating soil deformation depth. In further studies, *Keller et al (2015)*, changes were made regarding the block, taking into account the influence of variable properties of soil structure on the process of deformation and stress propagation and the SoilFlex-LLWR model was obtained. SoilFlex models allow estimating the ultimate conditions of deformation and bearing capacity of the soil (*Lozano et al., 2013; Vennik et al., 2019*). The disadvantage of the SoilFlex and SoilFlex-LLWR models is the lack of a time function during which the soil is subjected to the appropriate loads. These shortcomings prevent the use of these models for the analysis of dynamic processes of interaction between the wheel and the ground.

Models based on the FEM – finite element method (*Hambleton and Drescher, 2009; González Cueto et al., 2016; Silva, 2018*) have been developed to predict soil deformation and track depth. The complexity of the practical use of such models is associated with the need to introduce a sufficiently large number of input experimental parameters. The considered FEM models of soil compaction are aimed at the combination of different soil properties in order to determine the General distribution of stresses and strains. These models do not allow determining the energy costs of soil deformation and require an algorithm to account for the time during which the contact interaction occurs.

For determining the indices of soil deformation and track formation, in some studies (*Mason et al, 2016; Vahedifard et al., 2016*) it was proposed to expand the known analytical model VTI (Vehicle Terrain Interface) by introducing algorithms for the estimation of the pressure of contact interaction of wheels with the soil and strength of soil index (taper index). The application of VTI models to obtain practical results, along with simplicity, requires sufficiently voluminous initial experimental studies of the relevant variables. In Mason's et al study (*Mason et al., 2016*), 2737 experimental measurements were performed to obtain a model capable of predicting the parameters of track formation. A composite database of more than 5,253 studies was used to model the mobility performance of wheeled vehicles when operating on dry sand (*Vahedifard et al., 2016*). Given the number of parameters affecting soil deformation, as well as the possible quantitative variations of these parameters, updating VTI models is a large-scale task in terms of performing the required number of experimental measurements.

The analysis indicates the importance of understanding the phenomena occurring during deformation and the formation of a track during the interaction of wheel travel systems with the soil. Existing models consider the state of the soil, which experiences loads and stress transfer that occur, but do not consider the dynamics of the process of track forming from the load of running systems on the soil. The available models obtained by means of regression analysis are rather limited by the conditions under which they were obtained. Forming a model that fully takes into account the processes that occur during the formation of the track will allow designing the parameters of the machine, considering the functionality of performing certain operations in accordance with the properties of the working environment in which the engine operates.

MATERIALS AND METHODS

A mathematical model of the dynamics of track formation under the action of MTU wheels has been developed on the basis of the mechanics laws, based on the power analysis of the MTU work and considering the soil properties and the contact interaction of the wheels with the soil.

When performing experimental studies, the MTU was used as part of a 4WD tractor Kyi-14102 with a total weight of 37.5 kN and a plow PRO-3 with a weight of 8.5 kN (Fig. 1). The weight on the rear axle of this MTU with a raised plow was 36.5 kN. To determine the maximum possible depth of the track, a rectangular section of the floor with a length of 150 m and a width of 100 m was previously plowed. After installing the appropriate pressure in the pneumatic chambers of the wheels, the MTU made some distance on freshly plowed soil while fixing the depth of the rear wheel track (Fig. 1). The average value of 10 measurements made at different points along the length of the experimental section was taken as the track depth. An experimental study of the change in the geometric parameters of the contact zone of the tractor tires with a change in the pressure in the pneumatic chamber of the wheel was performed. To find the contact area of the wheel with the ground, a geometric analysis of the wheel imprint on the ground was performed (*Golub et al., 2019*).

Fig. 1 - Measurement of the track depth after the MTU passed

To determine the soil properties, with the help of a manual penetrometer Datafield with a step of 25 mm, a change in the taper index of the fresh-cut soil profile was determined.

When performing theoretical calculations, it was taken the value of the tractor performance indices, soil properties in accordance with those under which experimental studies were carried out.

RESULTS

Under the weight of a tractor or self-propelled machine, the wheel deforms and sinks into the ground. During the rolling of the wheel, the soil in front of it is compacted by tightening the soil under the wheel. When the wheel compacts the soil, it is compressed from the initial height to the depth of the track, and then can be partially expanded to a certain height (this phenomenon may be slightly manifested only when moving on soils with a high content of organic matter). At the same time, a track is formed in the soil.

With an increase in the depth of the wheel into the ground, the resistance of the soil to the wheel penetration increases. To analyse the change in soil resistance as a function of depth, we make the following assumption: the resistance of the soil R as the wheel sinks into the soil is directly proportional to the depth of the wheel l into the soil.

So we can record $dR=kdl$.

Thus, the coefficient of proportionality k can be written as follows:

$$k=\frac{R-R_0}{l}\,. \tag{1}$$

where

k – the proportionality coefficient, [Pa/m]; R – soil resistance, [Pa]; R_0 – initial resistance of the soil, [Pa]; l – depth of immersion of the wheel in the ground, [m].

The penetration of tractor wheels into the ground will be determined by the following equation:

$$m\frac{d^2l}{dt^2}=mg-RS=mg-S\left(R_0+kl\right)\ \ldots \qquad \ldots\ldots\ldots\ldots\ldots..(2)$$

or

$$\frac{d^2l}{dt^2}=g-\frac{RS}{m}=g-\frac{S}{m}\left(R_0+kl\right) \tag{3}$$

where g – gravitational acceleration, [m/sec^2]; S – the contact area between wheel and soil, [m^2]; m – MTU weight per wheel, [kg].

We find the solution of the differential equation (3) in the form:

$$l=\frac{a}{b}+\frac{1}{b}\sqrt{a^2+2bC_1^2}\,\sin\left[\sqrt{b}\left(t+C_2\right)\right]. \tag{4}$$

Accept the initial conditions: $t=0,\ l=0.\ \dfrac{dl}{dt}=0$, $l=max$.

The constant integrations based on the initial conditions will be:

$$C_1^2=b\frac{l_{MAX}^2}{2}-al_{MAX}\ , \tag{5}$$

$$C_2=\frac{1}{\sqrt{b}}\arcsin\left(-\frac{a}{a-bl_{MAX}}\right). \tag{6}$$

We substitute the obtained integration results into equation (4) and perform the necessary transformations:

$$l=\frac{a}{b}\left\{1+\left(1-\frac{b}{a}l_{MAX}\right)\sin\left[t\sqrt{b}+\arcsin\left(-\frac{1}{1-\frac{b}{a}l_{MAX}}\right)\right]\right\},$$

Substituting the values $\dfrac{b}{a}=\dfrac{kS}{m}\dfrac{m}{mg-SR_0}=\dfrac{kS}{mg-SR_0}$, we have:

$$l=\frac{mg-SR_0}{kS}\left\{1+\left(\frac{mg-SR_0-kSl_{MAX}}{mg-SR_0}\right)\sin\left[t\sqrt{\frac{kS}{m}}+\arcsin\left(-\frac{mg-SR_0}{mg-SR_0-kSl_{MAX}}\right)\right]\right\} \tag{7}$$

Substituting in the resulting equation (7) the value of the pressure from the wheel $P=\dfrac{mg}{S}$, we have:

$$l=\frac{P-R_0}{k}\left\{1-\left(1-\frac{kl_{MAX}}{P-R_0}\right)\sin\left[\arcsin\left(\frac{1}{1-\frac{kl_{MAX}}{P-R_0}}\right)-t\sqrt{\frac{kg}{P}}\right]\right\} \tag{8}$$

The obtained solution (8) of the differential equation (3) makes it possible simulating the dynamic processes of soil deformation in the formation of a track depending on the parameters of wheel-soil interaction. When performing the simulation using the dependence (8), it is necessary to take into account that the sine is an odd function the graph of which is symmetric with respect to the origin, so when performing the simulation, we choose the first period in which the sine function is in the positive half-period.

Soil properties and parameters of interaction between the wheel and the support surface were obtained in the field, when performing studies of the MTU at different pressures in the pneumatic chamber of the wheel tire (Table1).

Table 1

The values of the parameters of the interaction of the wheels with the ground

Index	Un.	Symbol	The value of the cell pressure, kPa		
			0.18	**0.18**	**0.18**
MTA weight given to the rear wheel (tractor Kyi-14102 + plow PRO)	kg	m_T	1825	1825	1825
The initial soil resistance	Pa	R_0	11000		
The coefficient of proportionality of soil resistance	Pa/m	k	2742831	2524858	2234227
The pressure on the ground in the contact patch	Pa/m^2	P	92523	114764	127880
The length of the contact patch	m		0.45	0.39	0.35
The maximum track depth	m	l_{MAX}	0.123	0.139	0.151
The MTU speed	km/h		8.2	5.4	3.6
The time of interaction of the wheels with the ground at a given speed	sec	t	0.3	0.195	0.35

Experimental dependences of the influence of pressure in the pneumatic chamber of the wheel tire on the change of the contact area of the wheel with the support surface and on the track depth are obtained (Fig. 2).

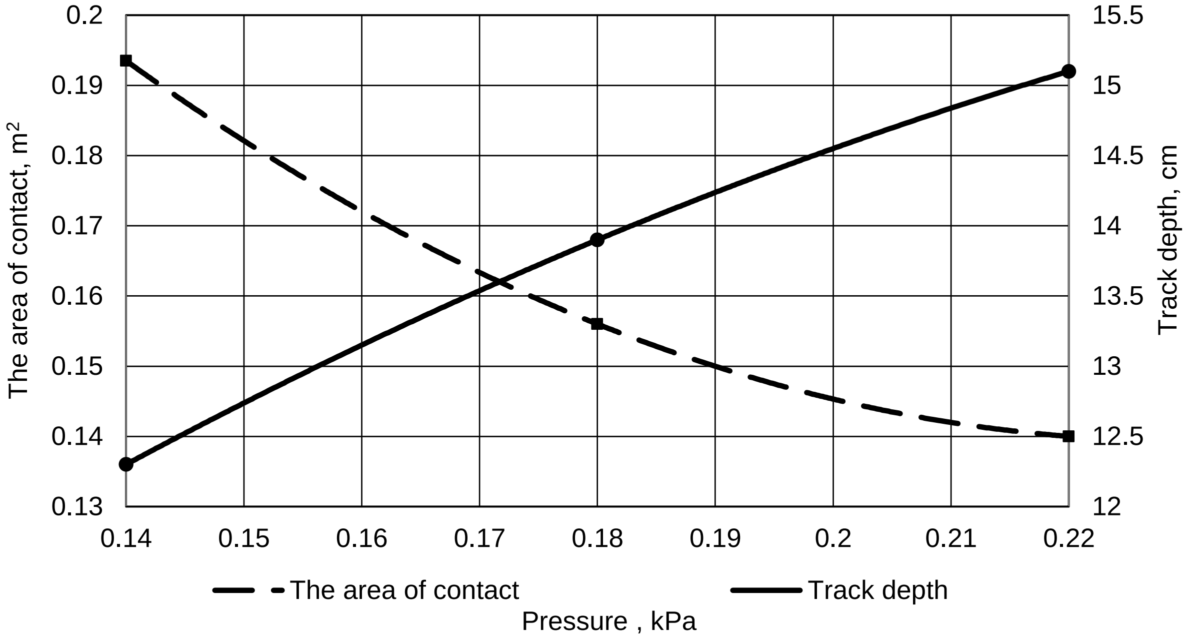

Fig. 2 - The effect of pressure in the pneumatic chamber of the wheel on the contact area of the wheel with the soil and the track depth

On the basis of the obtained mathematical model (8) and the data of Table 1, the simulation of soil deformation in the formation of a track depending on the pressure in the pneumatic chamber of the wheel is shown in (Fig. 3).

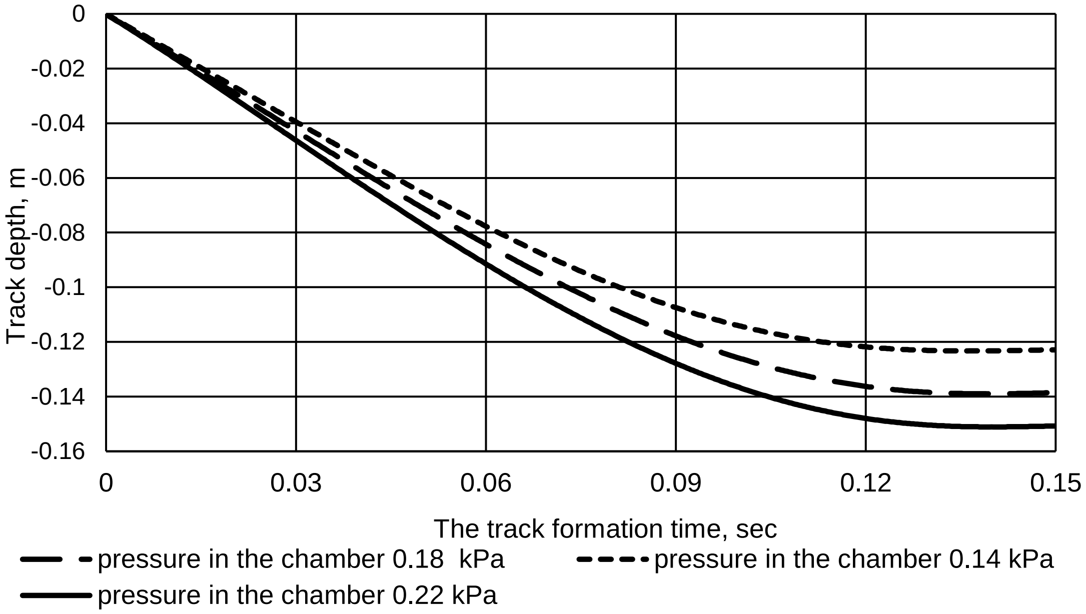

Fig. 3 - Dynamics of the soil deformation process in the formation of the track in interaction with the wheel at different pressures in the pneumatic chamber of the tire

The contact interaction of the wheel with the ground during the formation of the track occurs in the contact plane, which in the longitudinal section has a sinusoidal shape. The sinusoidal shape in the longitudinal section plane is affected by the contact pressure in the wheel - soil contact zone, the maximum track depth and properties of soil environment, as well as the time of contact interaction.

The analysis of the obtained dependences showed that at different wheel pressures on the soil, the time to reach the maximum depth of the track formation is almost unchanged and is about 0.13 s. The nature of the obtained dependences of the track formation dynamics allows concluding that the intensity of the track formation decreases with increasing the interaction time. At a tire pressure of 0.14 kPa, at an interval of 0.03 seconds from the beginning of contact, the depth of deformation of the track is 3.95 cm; in the interval 0.03 - 0.06 seconds, the soil deformation was 3.82 cm, which is 3.29% less than in the previous interval; in the interval 0.06 - 0.09 sec, the soil deformation is 2.95 cm, which is 22.8% less than the deformation in the previous interval; in the interval 0.09 - 0.13 sec, the soil deformation was 1.57 cm. At a pressure of 0.18 kPa deformation for the first 0.03 sec is 4.27 cm; in the range 0.03 - 0.06 sec, the deformation was 4.16 cm, which is 2.58% less than in the previous interval; in the interval 0.06 - 0.09 sec, the deformation of the soil was 3.33 cm, namely 19.95% less than in the previous interval; in the range 0.09 - 0.13 sec, the deformation of the soil was 2.1 cm. At a pressure of 0.22 kPa, the deformation over the first 0.03 sec was 4.62 cm; in the range 0.03 - 0.06 sec – 4.53 cm, which is 1.94% less than in the previous interval; in the range 0.06 - 0.09 sec, the soil deformation was 3.62 cm, which is 20.08% less than in the previous interval; in the range 0.09 - 0.13 sec, the soil deformation was 2.27 cm. With greater pressure in the wheel-soil contact zone, an increase in the intensity of the track depth formation is observed. In the interval from the beginning of the wheel contact with the soil to 0.03 sec at a pressure in the tire chamber of 0.22 kPa, the soil deformation is 4.62 cm, which is 8.19% more than the deformation at a pressure in the chamber of 0,18 kPa and 16.96% more than at a pressure of 0.14 kPa.

It should also be noted that the time of track formation (Fig. 3) is considerably shorter than the time of wheel - ground contact interaction (table 1). The obtained results allow us to assert that for these conditions of soil interaction at a pressure in the wheel chamber of 0.22 kPa and a contact zone length of 0.35 m, the movement speed up to 9.69 km/h does not affect the formation of the track depth, for a pressure of 0.18 kPa, this speed is 10.8 km/h, for a pressure of 0.14 kPa, the speed is 12.46 km/h.

As a result of the conducted researches the mathematical model of dynamics of a track depth formation at the interaction of a MTU wheel with soil is developed. A mathematical model establishes a relationship between the parameters of the MTU, soil properties, the geometric engagement of the wheel with the ground. The obtained model of the track formation dynamics is suitable for modelling the effects on track depth the parameters of soil, parameters of the pneumatic tire wheel of the MTU, the vertical load on the wheel.

The obtained results allow checking the design solutions in the development of new machines, assembling the MTU depending on the soil properties, optimizing the modes of the MTU operation.

In carrying out further research, it is advisable to improve the obtained mathematical model of the formation of the MTU track depth by clarifying the influence of the pneumatic tire properties on the parameters of interaction with the soil. This will make it possible to more fully characterize the processes of interaction between the wheel movers and the soil and will allow obtaining dependencies that will increase the accuracy of mathematical modeling of the movers' impact on the soil during the operation of the MTU.

CONCLUSIONS

The studies established the relationship between the operational and structural parameters of MTU engines and the soil properties. On the basis of the mass per MTU wheel, geometric parameters of the contact zone of the wheel with the support surface, the coefficient of resistance of the soil, deformation and the track depth, a differential equation is obtained to determine the depth of the track formation. The solution of the obtained equation allows determining the dynamics of the formation of soil paths depending on the resistance of the soil, the area of contact interaction of the wheel with the support surface and the vertical load.

The simulation of the influence of pressure in the wheel pneumatic chamber, for certain agrotechnological conditions, showed that the formation of the track occurs within 0.13 seconds of the wheel - ground contact interaction and does not depend on the pressure in the wheel. It should be noted that with increasing pressure in the contact zone with the soil, there is an increase in the intensity of the depth of the track formation. It should also be noted that the intensity of the track formation decreases with increasing time, so at a tire pressure of 0.14 kPa, from the beginning of contact and for the first 0.03 seconds, the depth of track deformation is 3.95 cm, for the next 0.03 seconds, the deformation is 3.82 cm, which is 3.29% less than the previous one, for the next 0.03 seconds, the deformation of the soil is 2.95 cm, which is 22.8% less than the previous one, for the last 0.03 seconds, the deformation of the soil is 1.57 cm; speed up to 9.69 km does not affect the formation of the track depth. The obtained results allow us to determine the dynamics of a track formation in the soil during the movement of the MTU.

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