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Study of the mechanism of rut formation during wheel movement in the soil

Intensification of soil cultivation with the extensive use of agricultural machinery and multiple passes of machinery leads to soil over-compaction and degradation in conditions for growing agricultural crops. Wheeled machinery is the most widely used in modern agriculture. This study examines the stress state of the soil and the mechanism of rut formation during wheel movement in soil. For experimental studies, it is appropriate to represent the soil as a continuous deformable medium with properties of elasticity, viscosity, and plasticity. The research utilized the finite element method, employing the FEMAP with NX NASTRAN software complex, as well as the photoelasticity method with the PPU-7 polarization-projection unit. ED-6 epoxy resin hardened with methyltetrahydrophthalic anhydride was used as an optically sensitive material. It was established that when the wheel moves in the soil, the soil flow that runs into the wheel is divided into two parts. In the upper part, where tangential stresses predominate, the soil shifts and accumulates in front of the wheel in the form of a growth as a result of the bulldozer effect. Below this level, where normal stresses prevail, soil densification occurs, meaning that a certain compacted core is formed, and its particles gradually shift under the wheel.

***Keywords**: wheel; soil; stressed-deformed state; track.*

Topicality. The properties of the soil used for the cultivation of agricultural crops undergo changes during cultivation process, both due to the action of the working bodies of tillage tools and the impact of the machinery’s running wheels used for cultivation. The extend of this influence depends on the type of crops being grown. So, while up to 15 operations must be performed when growing grain crops, up to 25 operations are required when growing row crops. Multiple passes of equipment lead to soil compaction, primarily reducing the soil’s pore space. The number of agronomically valuable pores with a size of 100-300 microns decreases significantly. At the same time, the amount of moisture available for plants decreases and the amount of unavailable moisture in the micropores increases. The air capacity of the soil decreases, leading to decreased microflora activity and a slower decomposition rate of plant residues. The water permeability of the soil and its temperature regime are deteriorating. All this has the effect of reducing the yield of agricultural crops. Thus, for grain crops, this can result in a decrease of 10-15%, while root crops may experience a decrease of 20-30% in yield. This explains the need to study the impact of running systems of agricultural machinery on soil properties, and, first of all, on its density.

Analysis of the latest research and publications on which the authors rely. Many works of domestic and foreign scientists are devoted to the study of the impact of running systems of agricultural machinery on soil properties and the reduction of negative consequences. Thus, in work [1] it was established that, in addition to the above-described negative consequences of the influence of running systems, the length of roots and the root mass of plants decrease in the upper soil layer. Various methods have been developed to reduce the negative impact of agricultural machinery's running systems. The work [2] describes the following approaches to reduce pressure on the soil’s supporting surface during cultivation: the use of crawler tractors; use of arched or wide-profile low-pressure tires; rational selection of tire sizes; increase in tire sizes; use of pneumatic tracks; reducing soil trap heigh; decreasing the number of tire layers; using tandem wheels; wheel pairing; regulation of air pressure in tires; equipping agricultural machines with metal tracks and other methods. However, large costs for operation and repair due to the small resource and high cost of tracked machines make their use limited. Therefore, wheeled machinery remains the primary type of agricultural machinery used in soil cultivation.

There are several different approaches to assessing the influence of the running systems of wheeled agricultural machinery on soil properties. Thus, some researchers consider the soil as an elastic half-space that experiences either a concentrated force or a uniformly distributed load [3]. At the same time, the normal and tangential stresses arising in the soil from the action of these loads are determined on the basis of the well-known Flaman problem. The equation for the dependence of soil density on the acting normal and tangential stresses has the following form:

$$\rho = \rho_0 + b \ln(\sigma_m + c\,\tau_{max}), \tag{1}$$

where ρ_0 is the initial density value; σ_m is the average value of normal stresses; b and c are empirical coefficients.

A similar approach was used in [4]. The soil is consideredg as a semi-infinite plane loaded with a uniformly distributed load of intensity q and length 2a, and all nine components of the stress state tensor are determined. When determining the stresses, the coordinates of the points are expressed through the parameter a and, after reducing the results by the amount q, the ratio of the stress values σ_x/q is obtained; σ_x/q; σ_y/q; σ_z/q; τ_{xy}/q, which will be common for any load cases, regardless of the values of a and q. Next, a stress matrix in the soil is constructed for the right side of the half-space, symmetrical about the Ox axis. The relative change in soil volume at any given arbitrary point (that is, the change in soil density) is calculated using the formula:

$$\theta = (1 - 2\mu)(\sigma_x + \sigma_y + \sigma_z)/E, \tag{2}$$

where μ is Poisson's ratio; E is the modulus of elasticity.

Another approach is demonstrated, for example, by Naveed M., who in study [5] showed that in structured soils stresses are transmitted through a chain of soil aggregates, with the strength of this chain depending on aggregate size. At the same time, at moderate stress values, this nature of stress transfer was preserved, while at vertical stress values of 620 kPa, the soil aggregates were destroyed and the elastic nature of stress transfer prevailed, which corresponds to the well-known Boussinesq model for material elasticity. To experimentally determine stress values in the soil, a tractor-trailer combination was utilized in study [6]. The trailer included a fully loaded slurry tank and was equipped with three axles. During the experiment the front axle of the trailer was hydraulically raised, resulting in a load of approximately 70 kN on the tractor's rear axle and approximately 68 kN on the middle and rear axles of the trailer. The results of this study demonstrate that a soil load of approximately 70 kN can cause vertical stresses of approximately 300, 100, and 45 kPa at soil depths of 0.3, 0.6, and 0.9 m, respectively. The maximum stresses observed in the tire-soil contact area reached approximately 345 kPa, indicating that the soil aggregates did not collapse. Thus, turf-podzolic soil should be considered as a polydisperse discrete medium that undergoes deformation and has rheological properties.

According to the considered approaches to soil modeling, the methods of determining the depth of the rut also vary. For instance, in study [7], which investigates the rolling of an elastic wheel on a deformable surface, the main factor influencing the depth of the track is the vertical component of the load G. The properties of the soil are practically not taken into account.

In the study [8, 9] on the interaction of tractor wheels with the soil, the rheological properties of the soil are taken into account. A rheological model of an elastoplastic (Maxwellian) body is used and the rut depth is determined by the formula:

$$h = \sqrt[3]{\frac{(mg)^2}{k^2 b^2 D}} \sqrt[3]{\left[\frac{1+(T_r\omega_0)^2}{1+(2T_r\omega_0)^2}\right]^2}, \tag{3}$$

where mg is the vertical load; T_r is relaxation time; ω_0 is angular speed of the wheel.

According to the accepted understanding [10], when a wheel rolls on the ground in a plane perpendicular to its axis and passes through the middle of its axis, a compacted zone appears, i.e., the so-called core, is formed, deviating from the vertical axis in the direction of the wheel's movement. But at the same time, soil compaction is mainly caused by its vertical displacements.

Subsequently, the sealing zone gradually moves beneath the wheel due to its rotation. This is evidenced by the results of studies conducted by Koichiro Fukami [11], Khwantri Saengprachatanarug [12, 13] and others, who have studied the movement of soil particles during wheel motion. For instance, in the study [12], the research setup consisted of a soil container and a rigid wheel mounted on a cart. The thickness of the soil layer was set at 600 mm. The test wheel had a diameter of 300 mm, width of 410 mm, and covered with a 5 mm thick layer of rubber. It weighted 217 N. During the test, the wheel was gradually lowered onto the ground surface without rotation, followed by wheel rotation and movement on the soil surface. The following parameters were measured during the experiment: the wheel rotation angle, the distance of the movement, penetration depth into the ground, the dynamics of the load, the torque on the wheel shaft, the reaction of the soil and the line of its application, as well as normal and tangential stresses applied to the contact surface. The trajectory of particle movement was determined (Fig. 1). It was observed that when a soil particle was positioned in front of the wheel, it moved forward and upward. As it approached the wheel, the particle turned to move forward and down. The direction of motion was then reversed and downward, and the particle reached its bottom position at the moment when the wheel was directly above the particle. After the wheel passed, the particle moved back and upward, and its motion finally stopped.

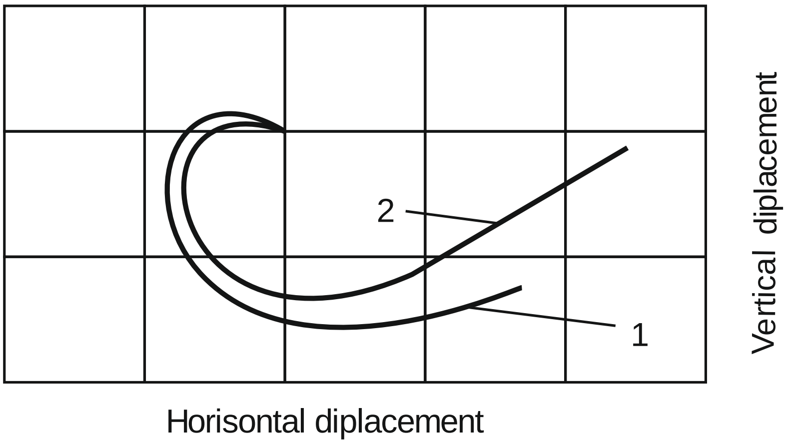

Fig. 1. Trajectories of loci movement of soil particles: 1 – in studies of Khwantri Saengprachatanarug; 2 – in the research of Koichiro Fukami

The purpose of the study was to analyze the stress-strain state of the soil while the wheel moves within it and to investigate the impact of this state and the factors that influence the formation of ruts.

Research materials and methods. Considering the analysis of the existing methods of research of the wheels interaction with the soil, it can be concluded that the method that is most adequate for experimental research is the one that allows the representation of the soil as a continuous deformed medium that has the properties of elasticity, viscosity and plasticity. This assumption makes it possible to use experimental and analytical methods to determine stresses, deformations, and changes in soil density depending on the values and directions of the applied forces, parameters of the wheel movement and its geometric shapes (Al-Hazaali, 2017 [14], Kovbasa, 2006 [15]]). Experimental and theoretical studies conducted by Wang X. L., 2020 [16] showed that an increase in normal stresses in the soil leads to an increase in soil density. At the same time, the magnitude of this density increase depends on the amount of applied loads and soil moisture.

It is known that when a wheel moves in the soil in the direction of its movement, a rise or fold of the soil occurs in front of the wheel. This phenomenon is called the bulldozer effect (S. Higa, 2019 [17], Y. Du, 2018 [18]), because something similar happens in front of the bulldozer blade when it works with the soil. It was decided to conduct qualitative studies of the stress state of the soil under the action of a horizontal force. The finite element method was employed using the FEMAP with NX NASTRAN software package. Elastic material was chosen as the material and it was determined that the choice of material type and the magnitude of the load did not alter the qualitative pattern of stress distribution.

In order to evaluate the stress distribution under such a load, the study also employed the photoelasticity method. This method involves the use of transparent materials that exhibit optical anisotropy and the associated birefringence when subjected to applied mechanism loads. In the research, the PPU-7 polarization-projection device was used, along with ED-6 epoxy resin hardened with methyltetrahydrophthalic anhydride, which had an optical constant $\sigma_0^{1,0}$= 1.88 MPa as the optically sensitive material. During the research, a special stand was used, where a plate made of the optically sensitive material was loaded with a horizontal force of 1000 N. The amount of applied force was measured using a universal dynamometer (UDM). As a result, isochrome (Fig. 4) and isocline patterns were obtained, which made it possible to determine the values of normal and tangential stresses.

Research results and discussion. As a result of the research using the finite element method, a picture of the distribution of equivalent Mises stresses in the material was obtained, which is shown in Fig. 2. The maximum values of equivalent stresses are observed at the upper point of load application. In the horizontal and vertical directions from this point, the stresses decrease, while in the horizontal direction it is much slower. The graph illustrating the distribution of equivalent stresses in the horizontal plane is shown in Fig. 2.

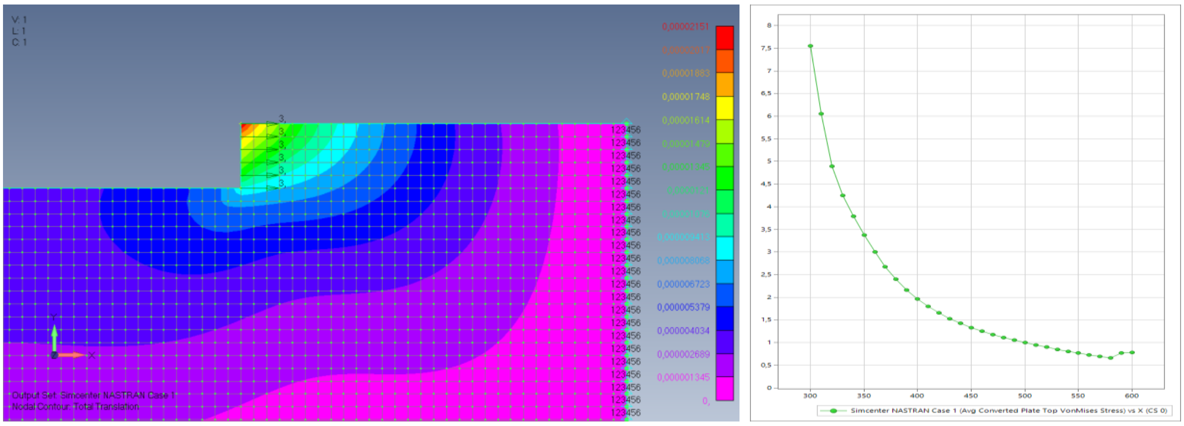

Fig. 2. Equivalent stresses in the horizontal plane

Research by the photoelasticity method was conducted at three levels of the plate: near the upper face, in the middle of the plate, and near the lower face. The values of normal stresses σ_x and σ_y were determined using the formulas:

$$\sigma_{xn} = \sigma_{x0} - \sum_{i=1}^{n} (\Delta\tau_{xy})_i \frac{\Delta x_i}{\Delta y}; \tag{4}$$

$$\sigma_{yk} = \sigma_{y0} - \sum_{r=1}^{k} (\Delta\tau_{xy})_r \frac{\Delta y_r}{\Delta x} + \gamma \sum_{r=1}^{k} \Delta y_r, \tag{5}$$

where n and k are the number of control points along the x and y axes, respectively; σ_{x0} and σ_{y0} are known values of σ_x and σ_y at the starting point of integration; Δx_i and Δy_r are intervals along the x and y axes through which measurements were performed; Δx and Δy are distances between parallel auxiliary sections along the x and y axes, respectively; $\gamma \sum_{r=1}^{k} \Delta y_r$ is the product of the volume weight by the length of the integration segment (taking into account if the model works under its own weight).

To calculate the tangential stresses, experimentally found values of the principal stress difference $\sigma_1 - \sigma_2$ and isocline parameters were used. The values of tangential stresses were calculated according to the formula:

$$\tau_{xy} = \frac{\sigma_1 - \sigma_2}{2} sin2\alpha \tag{6}$$

Figure 4 shows the distribution graphs of tangential and normal stresses. The tangential stresses reach their greatest value near the surface of the plate, and the lower the section, the smaller the tangential stresses. Normal stresses increase as we move away from the point of load application and then gradually decrease.

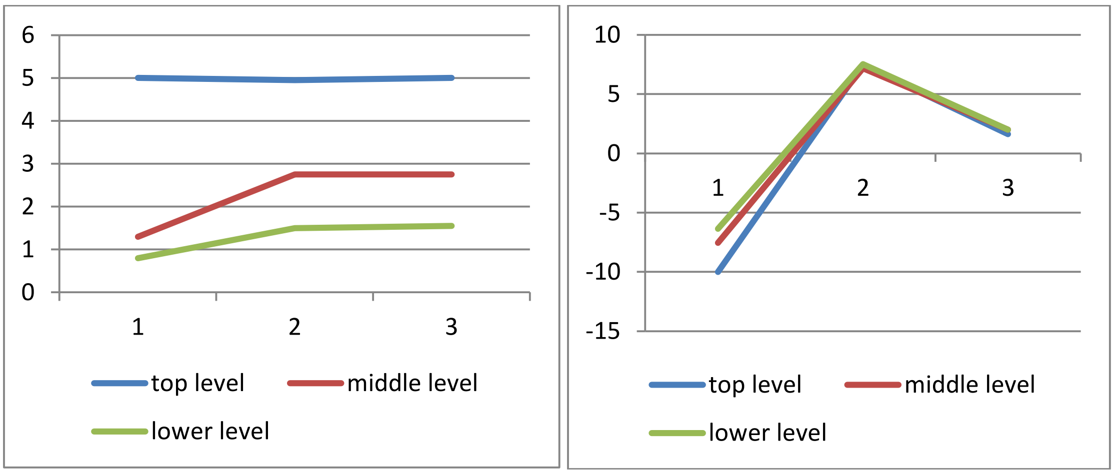

Fig. 4. Distribution of tangential and normal stresses

Conclusions and prospects for further research. In summary, it can be stated that when the wheel moves in the ground, the soil flow that runs into the wheel is divided into two parts. In the upper part, where tangential stresses predominate, the soil shifts and accumulates in front of the wheel in the form of a growth. Below this level, where normal stresses prevail, soil compaction occurs, resulting in the formation of a compacted core. Research conducted by Koichiro Fukami [13] and Khwantri Saengprachatanarug [14, 15] have demonstrated that these compacted soil particles gradually move under the wheel. It is obvious that the speed of the wheel also affects the formation and depth of the rut, although further research is needed to examine the impact of this factor.

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Дослідження механізму утворення колії при русі колеса в ґрунті

Інтенсифікація обробітку ґрунту з широким застосуванням сільськогосподарської техніки і багаторазові проходження техніки призводять до переущільнення ґрунту і погіршення умов вирощування сільськогосподарських культур. Найбільш широко в сучасній агротехніці використовується колісна техніка. В роботі досліджується напружений стан ґрунту і механізм утворення колії при русі колеса в ґрунті. Для експериментальних досліджень доцільним є представлення ґрунту як суцільного деформованого середовища, що має властивості пружності, в'язкості і пластичності. При дослідженнях застосовувалися метод скінчених елементів за допомогою програмного комплексу FEMAP with NX NASTRAN та метод фотопружності з використанням поляризаційно-проекційної установки ППУ-7. В якості оптично чутливого матеріалу використовувались епоксидна смола ЕД-6 отверджена метилтетрагідрофталевим ангідридом. Встановлено, що при русі колеса в ґрунті ґрунтовий потік, який набігає на колесо розділяється на дві частини. У верхній частині де переважають дотичні напруження відбувається зсув ґрунту і його накопичення перед колесом у вигляді наросту внаслідок бульдозерного ефекту. Нижче цього рівня, там де переважають нормальні напруження відбувається ущільнення ґрунту, тобто утворюється певне ущільнене ядро, частинки якого поступово переміщуються під колесо.

Ключові слова: колесо; ґрунт; напружено-деформований стан; колія.

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