STRESS DISTRIBUTION AND SOIL COMPACTION CHANGES UNDER THE AGRICULTURAL TYRES*

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One of the major problems facing current agriculture is excessive soil compaction. The solution involves the rational selection of agricultural technology for a particular type of soil. The soil is in a complex stressed condition under the influence of pressure distributed in a certain contact area. The reason for excessive soil compaction is an increase in the mass of machines and the use of ballasts. Therefore, the research described in this article aims to determine the tensions that arise under the wheels of machines and how they influence soil compaction. A calculation scheme has been developed for the study of the stress-strain state of the soil under tractor drive. The equations obtained for the component of the stress state of the soil under the trail of the tractor wheel allow to determine the change in soil density at any point along the verticals and horizontals of the array. Furthermore, it describes the measurement of tractor wheels compacting the soil. Two devices were developed for field tests, which confirmed the correctness of theoretical calculations. Furthermore, the work considers the influence of two different types of tractor wheels and the change in soil compaction under twin tyre wheels in Ukrainian conditions.

soil compaction; agricultural machinery wheels; soil stress; agricultural machinery; tractor

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INTRODUCTION

Soil compaction is one of the main components of land degradation and is an issue for soil management (Batey, 2009; Naderi-Boldaji et al., 2017) and has resulted in a reduction in the yield of most agronomic crops throughout the world (Nawaz et al., 2013). Therefore, the protection of soils from excessive compaction due to machine wheels that work in the field is one of the modern challenges of agricultural production (Vilde et al., 2004; Alzoubi et al., 2018). Navaz et al. (2013) mention that the consequences of soil compaction are still underestimated, especially among farmers and practitioners. Furthermore, the issue of soil compaction is increasing over time, as pointed out by the study by Keller et al. (2019), which highlights the likelihood of already exceeding the acceptable agricultural machinery weights and, therefore, future agricultural operations must take into consideration the mechanical limits of the soil.

The pressure of the wheels and tracks reduces the porosity of the soil, nutrient cycling, water, and aeration, which leads to an uneven distribution of moisture, as well as changes in thermal conductivity and, consequently, a reduced soil fertility (Jiang et al., 2019; Keller et al., 2019; Williams et al., 2020). Therefore, the study of mechanical phenomena in the soil that occur due to the pressure of agricultural machines and tractors operating in fields is of significant practical importance (Dovzhyk et al., 2013).

Many scientists, such as Sivarajanab et al. (2018), Dame et al. (2019), Shahgholi et

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al. (2015) and Lamande and Schjonning (2017), have studied the process of soil compaction by machine wheels working in the field. Their research has enabled an understanding of the importance of this process and the main factors that affect the degree of soil compaction. Furthermore, it is essential to keep in mind that subsoil compaction persists for decades; therefore, it is important to reduce this risk (Damme et al., 2019). Kroulik et al. (2018) have provided recommendations about the use of trucks and machines in the field. Within their study, they investigated the process of motion of the technique in parts of the field, but did not describe the instruments they used for measurements: Such data could assist in determining the changes of soil compaction density after the work of the technique in the field. The tyre size, inflation, its load, and the use of twin wheels also significantly affect soil compaction and soil stress (Keller and Arvidsson, 2004; Arvidsson and Keller, 2007; Grecenko and Prikner, 2014). The methods of use and prediction of the effect of soil compaction by machinery have been described by Grečenko and Prikner (2014), Kučera et al. (2016) and Prikner et al. (2017).

One of the main phenomena that affect soil compaction is the towing and trajectory of the tractor, which is also often considered during the use of coupled drives (Nadykto et al. 2015; Melnik et al. 2017; Dovzhyk et al., 2019). However, these authors (Nadykto et al. 2015) did not specify how they determined soil compaction. In our opinion, the method of determining the soil compaction, particularly the device, plays a highly important role.

The soil is in a complex stressed condition under the influence of pressure distributed in a certain contact area (Dovzhyk et al., 2013). It emits both normal stresses σ and tangents - τ. The calculation foundations must deal with significant loads that cause a large fluidity of the soil, its transition to a plastic state, subsidence, and protrusion to the sides and upwards. These processes are undesirable under the wheels and working parts of machines operating in fields. Therefore, the specific load on the soil is limited, as a rule, by the value to which the relationship between stress and deformation has a slight non-linearity. Therefore, in this case, the theory of a linearly deformed medium can be applied (Dovzhyk et al., 2016).

At the point of contact of the wheel with the wheel with the ground, the intensity of the pressure q, in which the width of the platform can be considered constant (Fig. 1), is transmitted from the soil to the ground, and the regularity of its change along the line of motion is irrelevant because the maximum pressure will be felt by each point of the formed trace.

Thus, there is a band of infinite length and width *2a* (Fig. 1), deformed in a distributed load. The stressed state at an arbitrary point of an array is described by nine stress components. They can be simplified by limiting the flat solution when taken into account that the soil in the direction of the *Oz* axis has no possibility of deformation (Fig. 1).

Considering the unit width strip cut out by two parallel cross sections (Fig. 2) parallel to each other, as a half-infinite plane, a known solution in polar coordinates was used (Dovzhyk et al., 2016) and the equation for stresses was written in the Cartesian coordinate system:

$$\sigma_x = \frac{q}{\pi}\left[\begin{array}{c} arcsin\frac{y-a}{\sqrt{x^2+(y-a)^2}} - arcsin\frac{y+a}{\sqrt{x^2+(y+a)^2}} + \\ + \frac{x(y-a)}{x^2+(y-a)^2} - \frac{x(y+a)}{x^2+(y+a)^2} \end{array}\right]; \quad (1)$$

$$\sigma_x = \frac{q}{\pi}\left[\begin{array}{c} arcsin\frac{y-a}{\sqrt{x^2+(y-a)^2}} - arcsin\frac{y+a}{\sqrt{x^2+(y+a)^2}} + \\ + \frac{x(y-a)}{x^2+(y-a)^2} - \frac{x(y+a)}{x^2+(y+a)^2} \end{array}\right]; \quad (2)$$

$$\sigma_x = \frac{q}{\pi}\left[\begin{array}{c} arcsin\frac{y-a}{\sqrt{x^2+(y-a)^2}} - arcsin\frac{y+a}{\sqrt{x^2+(y+a)^2}} + \\ + \frac{x(y-a)}{x^2+(y-a)^2} - \frac{x(y+a)}{x^2+(y+a)^2} \end{array}\right]; \quad (3)$$

The stresses at the sites perpendicular to the *Oz* axis are found by the condition that the deformation ε_z=0. Then according to the generalised Hooke's law:

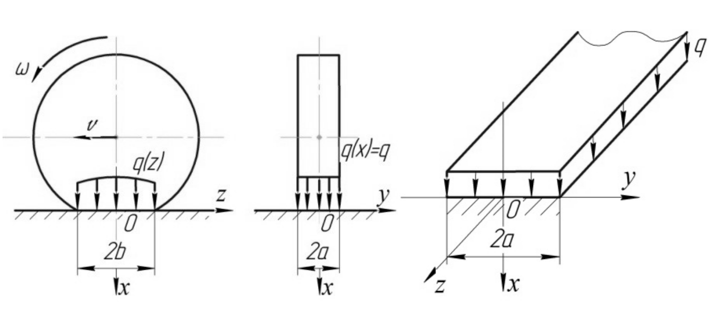


Fig. 1. The load on the ground from the wheel and the calculation scheme

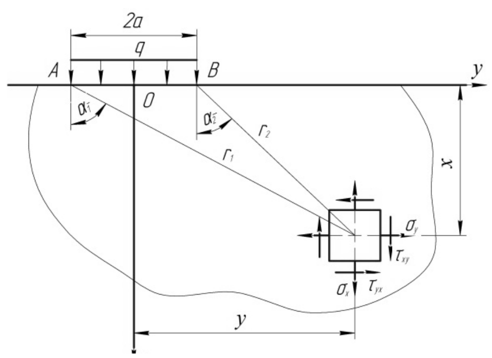


Fig. 2. Tension in the xOy plane.

From the equation $\varepsilon_z = \frac{1}{E}\left[\sigma_z - \mu(\sigma_x + \sigma_y\right] = 0$ we find:

$$\sigma_x = \frac{q}{\pi}\left[\begin{array}{c} arcsin\frac{y-a}{\sqrt{x^2+(y-a)^2}} - arcsin\frac{y+a}{\sqrt{x^2+(y+a)^2}} + \\ + \frac{x(y-a)}{x^2+(y-a)^2} - \frac{x(y+a)}{x^2+(y+a)^2} \end{array}\right]; \quad (4)$$

where μ is the coefficient of transverse deformation for the soil;
E is a module of longitudinal elasticity.

Voltage σ_z is one of the three main stresses because in planes perpendicular to the axis Oz, there are no shear forces and $\tau_{xz} = \tau_{yz} = 0$. By virtue of the law of parity of tangential stresses $\tau_{zx} = \tau_{xz} = 0$; $\tau_{zy} = \tau = 0$. Thus, all components of the stress state are determined.

Relative volume change at an arbitrary point of the array:

$$\theta = (1 - 2\mu)\left(\sigma_x + \sigma_y + \sigma_z\right)/E \quad (5)$$

Now, the relative change in soil compaction caused by a change in its volume can be calculated:

$$p/p_0 = 1/(1 - \theta) \quad (6)$$

The p_0 is the compaction of the soil in the non-elastic state.

To date, there is no general equipment for field testing to measure soil compaction under the wheels of working tractors as necessary for our purposes. There are instruments that allow to measure the hardness of the soil; however, this research is focused on changes in the voltage in the soil during the collision of the tractor wheel and residual stresses after the tractor wheel passes through the experimental path. It is through stresses that it is easiest to find out how the density of the soil will change directly during the field experiment.

This research attempts to look into the problem of stress distribution and soil compaction changes under the wheels of a working vehicle. The results and conclusions from this work can be used during the planning of future work and the selection of working tractors in the field.

MATERIALS AND METHODS

For field trials, a special device was developed to determine stresses in the soil of a stressed state at the volumetric and plane level. This device was developed at Sumy National Agrarian University as a pilot sample for experimental research. The authors received a patent valid for Ukraine for the device for the determination of the volumetric stress state - MPK G01N 33/24 (Solarov et al. 2016).

A device to measure the voltages of a stressed volumetric state (Fig. 3) is a hollow rod of 1 rectangular cross section; at one of its corners, three sensing elements are mounted. They are intended to measure stresses in three mutually perpendicular directions as according to Dovzhyk et al. (2013). Each of the sensitive elements is a rectangular cross section cantilever beam with dimensions $b \times h$ (Fig. 3), attached to body 2 at one end, and its free end car-

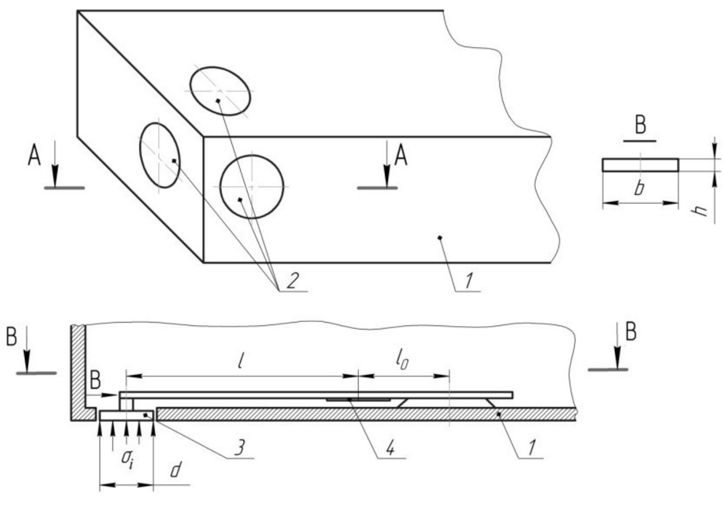


Fig. 3. Diagram of the device for measuring volumetric stresses

Fig. 4. Plating device for measuring the stressed state of the plane: 1 - tensor station; 2 - device. Voltmeter and strain gauge RV7-22A, produced in Russia (Special cable bureau)

ries a washer 3 with diameter d in contact with the ground. A strain gauge 4 bonded by isolated conductors that extend through the inner cavity of housing 2 to the surface, with a strain gauge device, is glued at a distance of working length l in the stretched zone of the beam (Fig. 3).

This device can hardly be used without disturbing the structure of the soil, so a cylindrical device was developed (Fig. 5).

The device (Fig. 5) was placed in the soil without disturbing its structure. This was achieved using a specially designed screw drill for the diameter of the device. The correctness of the experiment was confirmed by theoretical calculations. The studies were carried out at various stages and in different experimental areas of the field.

The appearance of the strain gauge is shown in Fig. 4. The main element of the tensile measurement device is the 4-shoulder circuit in which one of the shoulders is a strain gauge.

The imbalance of a bridge measured by a numerical voltmeter is proportional to the change in the resistance of the strain gauge ΔR. This imbalance is compared to the mechanical stresses σ_i acting on the surface of the beam loaded with force σ_i at the end of the console. The values of the device voltmeter are directly related to the measured voltage σ_i, while testing.

Determining the dimensions of the working element of the device (cantilever beam) is made on the basis of the maximum pressure (voltage) $\sigma_{imax} = q = 0.35$ MPa. The beam material - duralumin D16 (elastic modulus of the first kind E = 0.7 105 MPa; yield limit σ_T=290 MPa).

Taking ρ, q/cm^2 constructively the diameter of the contact element d = 10 mm and the length of the console l = 80 mm, one can use to find the pressure force on the contact element:

$$P = q \cdot \frac{\pi d^2}{4} = 0.35 \cdot \frac{3.14 \cdot 10^2}{4} = 27.475 \text{ N} \quad (7)$$

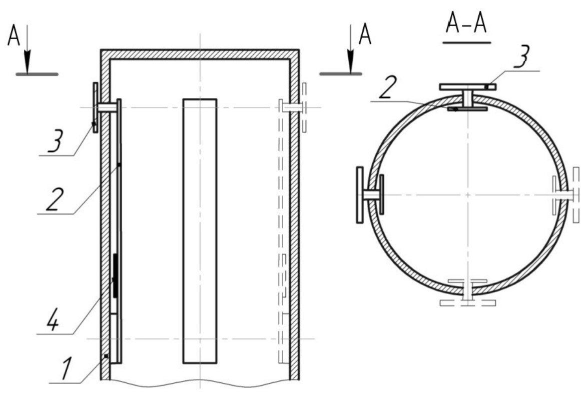


Fig. 5. Device for measuring the stresses of a plane

and bending moment in a dangerous section:

$$M = P(l + l_0) = 27.475(30 + 20) = 3022.25 \text{ Nmm} \quad (8)$$

where = 30 mm - the distance from the center of the strain gauge to the support.

Permissible stress for beam material is:

$$[\sigma] = \frac{\sigma_b}{n} = \frac{290}{2} = 145 \text{ MPa} \quad (9)$$

where n = 2 - the strength coefficient.

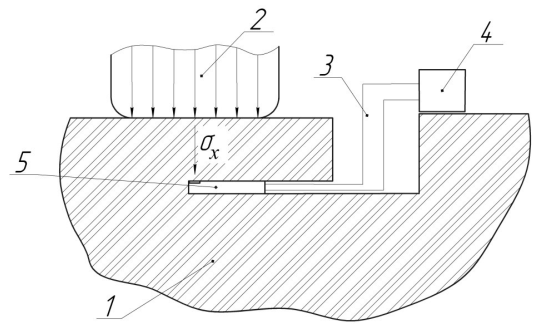
From the flexural strength, we find the necessary moment of resistance to the beam cross section:

$$W = \frac{M}{[\sigma]} = \frac{3022.25}{145} = 20.8[\sigma] = \frac{\sigma_b}{n} = \frac{290}{2} = 145 \text{ MPa}, 4 \text{ mm}^3 \quad (10)$$

At the height of the section h = 3.0 mm and width b = 6.46 mm.

Device calibration (Fig. 4) was carried out in the Laboratory of Materials Mechanics and Structures with a load on the contact element to gain appropriate performance of the device to a particular stress relative to a specific type of soil (Pytka, 2009; Lazzarin, 2015). For each value $\sigma_i = \frac{P}{F} = \frac{4P}{\pi d^2}$, the corresponding readings of the numerical voltmeter V were removed. The results of the calculations and measurements are shown in Table 1.

The device for measuring the stresses of a plane stressed state also consists of the case 1 of the device



(a)

(b)

Fig. 6. Placement of the device in the soil (a - schematic illustration; b - hole in the soil to place the device)

Table 1. Strain gauge correction data

Mass (m, kg)	Power (P, H)	Tension (, MPa)	The indicators of a numerical voltmeter (V)
0.2	1.962	0.025	14
0.4	3.924	0.050	24
0.6	5.886	0.075	43

Table 2. Dependence of change in yield on changes in soil compaction

Soil compaction (g/cm3)	Number of plants (pieces)	Number of productive stems (pieces)	Weight of 1000 grains (g)	Yield (quintal/ hectare)
Wheat				
0.9	340	480	25	46
1.0	260	460	32	44
1.1	240	440	25	40
Oat				
0.9	250	560	33	44.2
1.0	225	500	32	38.3
1.1	175	440	30	32.2
Barley				
0.9	225	500	46	37.0
1.0	175	480	49	25.5
1.1	163	340	45	25.7

(Fig. 5) made from a steel pipe . Inside the case, two sensitive elements are mounted at an angle . To increase the accuracy and reliability of the measurements, we can add two more diametrically opposite elements (shown by the dotted line).

Each element consists of a cantilever beam 2, at the end of which a pin 3 is attached, and in the location where the beam is fixed on its stretched fibres is the glued strain gauge 4, which is connected to the strain gauge and the numerical voltmeter (Fig. 5). All sensing element parameters are the same as in the device to measure volumetric stress (Fig. 3).

Fig. 6 shows the arrangement of the device in the soil: 1 – soil; 2 - wheel; 3 - electrical conductors; 4 - tensor station; 5 - instruments for measuring stresses.

RESULTS AND DISCUSSION

One of the most popular ways of combating soil compaction is through the use of twin tyres or tracks, increasing the contact area with the ground mover. It is important to remember that some indicators of changes in soil compaction have different effects on different crops; therefore, it is essential to choose the most appropriate technique for each culture.

Table 2 shows how the change in soil compaction density affects crop yield. It illustrates that the change in soil affects agricultural crop productivity. Having access to these data will make it easier for engineers and agronomists to select equipment to process certain agricultural crops. The main task is to choose the right tyres and the ability to use dual wheels to minimise soil compaction and process crops simultaneously. Modern tractors allow for changing wheels, setting parameters and wheel configuration with different tyres.

To verify the theoretical data obtained, the determination of stresses and changes in soil compaction under the wheels of a CASE-340 Magnum tractor (Fig. 7) was performed in the field of LLC «Mikhailovka», in the village of Mikhailovka, Lebedin district, Sumy region, Ukraine. The base of the field was a black clay ground (Chernozems). According to the international classification of the World Reference Base for Soil Resources, Chernozems have a thick humus layer, calcium carbonates are present in the lower layers. The upper part of the chernozem on which the field studies were conducted has a lumpy-granular structure. Soil moisture during field research was 14% (the ratio of the total mass of the selected soil sample to the mass of water in the soil). Soil moisture was determined in the laboratory by weighing selected soil samples during experiments and after complete drying.

Table 3. Operating parameters of the tractor

Parameter	CASE 340 Magnum
Traction class	3
Speed of movement, km/h.	40
Model of the engine	FPT Cursor 9 / Tier II
Engine displacement, l	8.7
Engine power, hp	340
– tractor length, mm	6100
– tractor width, mm	3100
– tractor height, mm	3500
Tractor weight, kg	3900
Front Wheel Tyres	9x20
Rear tyres	15x38
Specific ground pressure from the front wheels, MPa	0.08

The basic operating parameters of the tractor CASE 340 Magnum can be seen in Table 3.

To reduce the negative impact of wheeled tractors on the soil, a 'dual system' of wheels was used. This approach reduces the specific pressure on the soil and soil compaction by 1.5 to 2.0 folds. In this case, the width of the track increases and the traction ability of the tractor increases permeability and stability. There is also an increase in the load-carrying capacity of the tractor, which subsequently increases its productivity.

To obtain precise values during the field experiment, the device was calibrated in the laboratory before the experiment for the appropriate soil type. The received data (as a result of calibration) are entered in Table 3. The data in the table show that the load cell is working correctly and that there is a linear relationship between the load of the device and the reading of the voltmeter. Thus, the voltage of the beam material of the device is also linear with respect to the load. This table shows what the voltage will be at certain voltmeter readings. The data obtained are used during the field experiment.

With correctly selected air pressure in the twin wheels tyres, the total weight of the machine is distributed over a large area in terms of the contact area of the tyre with the soil. The consequence of this is a lack of deep traces of the wheels and a lack of soil redevelopment. In addition, traction effort increases because of the better adhesion of the tread protectors to the soil.

The determination of the contact area of the tractor wheels with the soil was carried out using household chalk (Fig. 7). A measurement of the area of contact patch was performed before each experiment. The contact patch area of the front wheel of the tractor CASE 340 was 1,869 cm^2, and the rear was 3,074 cm^2. Fig. 7a shows the contact area of the wheel with the soil in red. Fig. 7b shows how with the use of chalk the spots of contact of the wheel with the soil were created.

The soil was pre-compacted before determining the contact area of the wheel by approximately 5-8%, primarily to determine a clear ground and wheel contact area in order to clearly see the contact border of the wheel and soil. The tyre pressure is the most intense in the contact wheel area. Therefore, no plowing, deep loosening, or deep harrowing was carried out before determining the area of contact between the tyre and the soil. During the studies, the pressure of the tyre does not matter; the soil compaction process itself is affected by the tyre and the soil contact area. However, the tractor tyre pressure was 2 bar, which is recommended by the manufacturer.

The specific pressure on the soil was determined by the formula:

$$q = \frac{m_T}{2B_F l_F + 2B_R l_R} = 0.05 \text{ MPa}, \qquad (11)$$

where - operating mass of the tractor, - width of rim of the tyre of the front and rear wheels, - length of the supporting part of the front and rear wheels. This formula is used to determine the specific pressure of a tractor with a conventional wheelbase. In our case, the actual specific pressure will be twice as low compared to when using dual propulsion.

The specific of this work compared to Riggert et al. (2016) is that in our study the process of

(a) (b)

Fig. 7. Determination of the contact patch of the propeller with the ground (the red colour shows the area of contact of the wheel with the soil)

Table 4. Results of soil compaction measurements under tractor wheels

Soil depth (mm)	Initial soil density (g/mm^3)	CASE-340 (basic equipment) (g/mm^3)	CASE-340 (twin tyres) (g/mm^3)
0	1,1317	1,1384	1,1348
240	1,1316	1,1355	1,1340
480	1,1318	1,1340	1,1328
720	1,1317	1,1331	1,1321
960	1,1317	1,1330	1,1320
1200	1,1314	1,1329	1,1319
1440	1,1316	1,1327	1,1319

soil compaction was examined directly on the field and with different types of machines, both with and without twin wheels, providing better data verification. Furthermore, this study was carried out under static and dynamic loads in the soil, as described in more detail in Solarov (2016).

The method developed in this study for determining stresses in the soil and changing soil compaction after exposure to equipment wheels is more universal compared to the works of other researchers such as Naderi-Boldaji et al. (2017). It allows the determination of the stress in three projections σ_x, σ_y, σ_z (such as visible Fig. 2, showing tension in the *xOy* plane). Furthermore, it enables a deeper understanding of the compaction process. This information can contribute significantly to the quantification of the economic and ecological costs of compaction, as mentioned by Keller et al. (2019).

The experimental studies were carried out according to the following set up:

1. Determination of the main stresses in the soil when moving the wheel at the experimental site of the CASE 340 tractor with the help of the MPK G01N 33/24 ['Device for measuring stresses in the ground under a vehicle wheel'] at different depths.

2. Determination of stress during repeated hits of the CASE 340 tractor on the test site.

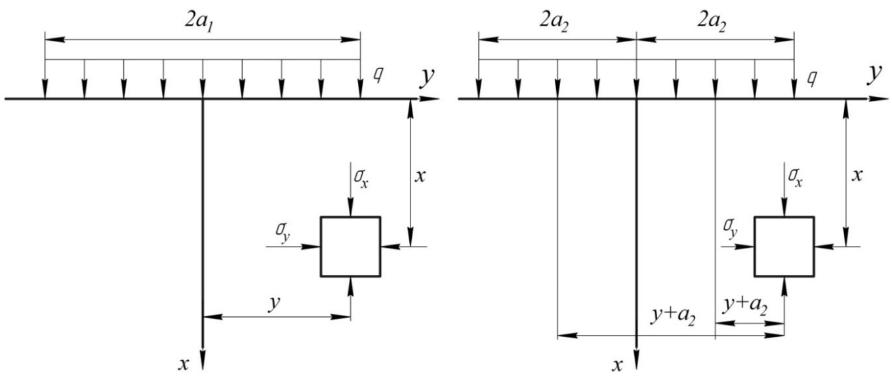
3. Analysis of the reliability of the experimental data obtained.

The theoretical values of the stresses were determined using the formulas (1; 2; 3), which can also be used in the case of dual wheels according to one of the two schemes (Fig. 8). Both schemes give the same result if .

After conducting the experimental tests and obtaining the stresses values under the tractor wheels, the formulas of Sivarajanab et al. (2018) and Shahgholi and Abuali (2015) were used to determine changes in soil compaction. The results are shown in Table 4. The results of the experimental tests are shown in Fig. 9. In Fig. 9, the red curve on the graph indicates the experimental results using basic equipment, the blue curve shows the experimental results with twin tyres, and the green curve shows the initial soil density. It shows that when operating a tractor with twin tyres, the stresses remain significant even at depths of up to 720 mm.

Before the experiment, the density of the soil at each depth was measured separately. This allowed the accurate determination of the change in the soil density after driving the tractor wheel over the experimental section of the field. The data in Table 4 show exactly how soil density changes when driving a tractor with a basic configuration when using twin tyres in relation to the initial soil density. Differences are visible between basic equipment and twin tyres, clearly showing a lower stress effect in the case of twin tyres. After experiments with the tractor using the

Fig. 8. Schemes for determining tensions in the case of twin tyres



basic configuration and using twin tyres, the average plant germination rates per square metre were calculated. The crop (wheat) was sown in the field using a 15 cm row spacing, with the distance between the plants 2.5 cm. In the field where the tractor with basic equipment was sued, the average number of plants per square metre was 203 plants. In the area where twin tires were used it was 262 plants.

For example, in the study of Alzoubi et al. (2018), the compressive effect of tractor wheels on the field have shown how the next passageways of machinery affect soil compaction. In our opinion, a detailed description of the highly technical measuring equipment, which allows data to be obtained in the field, is particularly significant.

The results obtained in the experimental studies are somewhat similar to those of Lamande and Schjonning (2017). The authors of the article quite clearly described their work, but in our opinion, the device developed within our study represents a tool that enables the obtention of clearer results. First, in our opinion, the authors do not fully acknowledge the integrity of the soil when placing a rubber band under the wheels of the trailer, which can cause an error in the results. Or potentially similar to the results find out by Keller and Arvidsson (2016), however, in their case, their main focus was on a prediction of vertical stress distribution, with using long rubber tracks (using data from Keller et al. (2002) and Arvidsson et al. (2011). Even in this case, there might be potential for an error of the result caused by the rubber band. Therefore, our aim was to develop a device that is placed in the ground without violating its structure. One of the drawbacks of the device is that its use is quite complicated and requires a very high accuracy during the experiment. The tractor driver must move evenly and clearly across the test place above the unit.

As experience shows by using devices to measure stresses, the latter version is easier to make and more convenient in practical work. On the whole, the results obtained confirmed the theoretical data received earlier (Dovzhyk et al., 2013). The device developed is unique and useful for soil compaction research. In the future, further plans are to improve the existing device, namely its modernisation in the direction of compactness, since its use in the field is still quite difficult.

CONCLUSION

The results of this research make it possible to fully determine the tensions that arise under the wheels of a working machine and how the compaction of the soil is affected. This work shows that when operating a tractor with twin tyres, the stresses remain significant even at depths of up to 720 mm. Having access to these data will make it easier for engineers and agronomists to select equipment to process certain agricultural crops. The effect of a kinematic mismatch of the radius of the twin wheels was also described in this article. This knowledge allows the correct tyre pressure to be chosen, allowing the load on the wheels and the soil to be distributed more evenly.

Furthermore, the use of twin wheels has a significant positive impact on crop production. The use of twin wheels with appropriately selected pressures allows one to increase the adhesive properties of the ground wheel and reduce slippage. Fuel consumption under these conditions could be reduced by 1.5 folds in the case of heavy work, such as plowing or harrowing.

Furthermore, the soil was much less compacted in layers where dual wheels were used, the plants sprouted 22% more effectively, and the yields increased by approximately 20%. It is important to note that yields can increase by up to 30% with correct tractor alignment and rational selection of the tyre type according to the specifics of the crop.

Soil compaction often results in a reduction in the yield of most agronomic crops and therefore it is essential to cope with this challenge. Our device makes it possible to determine soil stress in agricultural enterprises and combine specific data on soil compaction

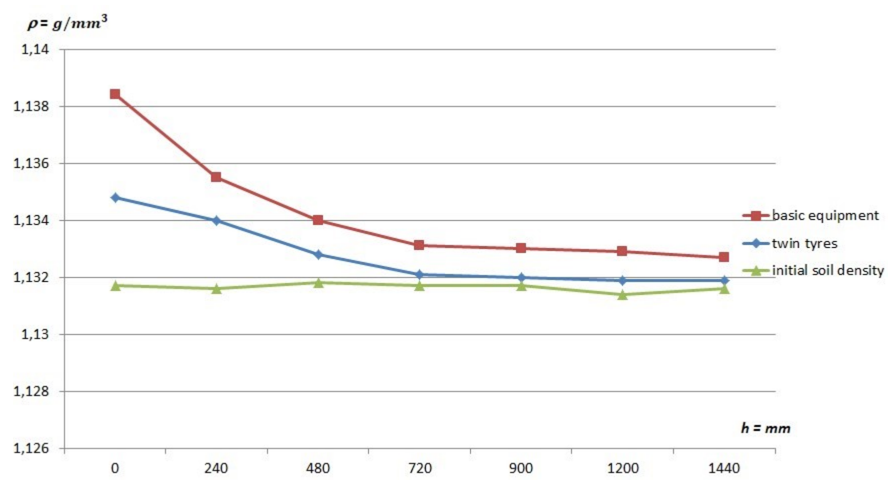


Fig. 9. Changes of soil compaction under the wheels of the tractor CASE-340

under the wheels of working machinery in a practical manner. Designed and patented instruments can be developed from promising prototypes for further research on soil compaction and stress distribution.

PATENTS

Patent 110621 Ukraine. MPK G01N 33/24 Device for measuring stresses in the ground under a vehicle's wheel / Solarov O., Dovzhyk M. Ya., Tatianchenko B.Ya., Plavinsky V.I. - No. a201405318; 19.05.2014; published 25.10.2016, bulletin № 20. Available online: http://uapatents.com/5-110621-pristrijj-dlya-vimiryuvannya-napruzhen-u-runti-pid-rushiehm-transportnogo-zasobu.html

AUTHOR CONTRIBUTIONS

Conceived the research idea M.D., O.S.; conceptualization O.S. and H.R.; methodology O.K., O.T. O.S. and H.R.; analysed the data and wrote the paper O.S., .V.R. and H.R.; writing—review and editing H.R., O.S., O.T.; funding acquisition H. R.

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CONFLICTS OF INTEREST

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