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Soil compaction changes in the area of wheel passage at different tyre pressure values

LESZEK SERGIEL[1], JERZY BULIŃSKI[2]
[1]Institute of Technology and Life Sciences, Masovian Research Centre in Kludzienko, Department of Plant Production Engineering
[2]Department of Agricultural and Forest Machinery, Warsaw University of Life Sciences – SGGW

Abstract: *Soil compaction changes in the area of wheel passage at different tyre pressure values.* The study presents results of an investigation regarding soil compaction under the rut caused by wheel passage and in adjacent lateral areas, at the depth of 10–35 cm. The investigation was carried out on sandy clay characterised with the humidity of 8–12–16%. Pressure values in the tyre of the wheel were 140–180–220 kPa. The conducted investigation demonstrated a statistically significant relation between soil compaction, tyre pressure and distance of the layer from the wheel-rut axis. The influence of soil humidity turned out to be statistically insignificant. Differences in terms of compaction of the soil situated in lateral layers, as compared with the layer under the wheel-rut, decreased with growth in tyre pressure. At the tyre pressure of 140 kPa, differences in average group values for all humidity levels were from 160 to 308% (on average 241%), at the pressure of 180 kPa, the differences were from 140 to 266% (on average 208%), whereas at the pressure of 220 kPa they were from 114 to 188% (on average: 208%) and they increased along with distance of the layer from the wheel-rut axis.

Key words: soil channel, tyre pressure, wheel-rut, compaction, soil humidity

INTRODUCTION

Soil compaction is one of the most important indicators of physical properties of the soil, indicating the forces connecting soil particles. In agricultural practice, soil compaction is usually measured with a cone penetrometer. Resistance of the penetrometer pushed into the soil provides similar information on conditions to be overcome by a root of a developing plant. It is assumed [Barley et al. 1965, Taylor et al. 1966, Unger and Kaspar 1994, Buchter et al. 2004 Beylich et al. 2010] that for most crops and soil fauna, compaction above 1.7––2.0 MPa, and in clayey soils even above 1 MPa [Farias 1994], is the threshold value above which development of plants is significantly hindered or completely stopped. Development of roots in a strongly compacted layer consumes more energy, which slows down and weakens plant development [Passioura 2002, Ferree and Streeter 2004]. During the investigations conducted by Buliński [2000] in field conditions on loamy sand, it was determined that the speed and kind of tractor unit and, thus, distribution of wheel loads, demonstrated greater influence onto soil compaction and rut depth than its density. One of numerous factors influencing soil compression during mechanised field works is pressure in the wheels of agricultural vehicles. Changes in wheel pressure, admissible by tyre manufacturers for field conditions, i.e. deformable areas, allow – on the one hand, lower degree of falling into the soil and result in wheel-rut shallowing, but on the other hand, they increase rolling resistance. Tyre pressure reduction by 28 kPa as compared with the pressure value recommended by the manufacturer resulted in increasing the rolling resistance by 5.01% and, after further pressure reduction by 55 kPa, the resistance increased by 9.96% [Elwaleed et al. 2006]. The investigation of Kurjenluoma et al. [2009] revealed that the kind of tyre also had significant influence onto the rolling resistance and depth of the resulting wheel-rut. Most investigations conducted so far focused on changes of soil compaction in the wheel-rut and influence of the tyre pressure onto soil densification and rolling resistance. It is not completely clarified how the soil compaction changes in the wheel-rut and in the area adjacent to the wheel-rut, or what is the influence onto coil compaction of tyre pressure changes at different soil humidity levels.

MATERIAL, METHOD AND INVESTIGATION

The investigation was conducted in a soil channel [Waszkiewicz et al. 2009, Buliński et al. 2010] on soil identified based on granulometric composition as fine sand loam, with a floating particle content of 16.5% [PN-R-04033]. The investigation was performed at three soil humidity levels of 8–12–16%. Before each series of measurements, the soil was scarified with a set of chisel teeth down to the depth of 0.5 m, followed by levelling of the measurement section with a slat to an even level. Next, the measurement section was driven over four times (on the same trace) with a tractor wheel with a 7.50-16 ANP-5 tyre, at the constant speed of 0.82 $m \cdot s^{-1}$ and vertical load of 3,600 N (Fig. 1). Three tyre pressure levels were applied in the investigation (140–180–220 kPa). Soil compaction measurements were performed immediately after preparation of the soil and after being driven over with the wheel, at three places in the measurement section (located at the distance of about 1.5 m from one another) using a set of four penetrometers equipped with cone-shaped end pieces with the diameter of 20.27 mm and a apex angle of 30°, in compliance with ASAE [ASAE Standards 1993] norm.

The penetrometers were spaced at the distance of 100 mm from one another, perpendicularly to the wheel-rut

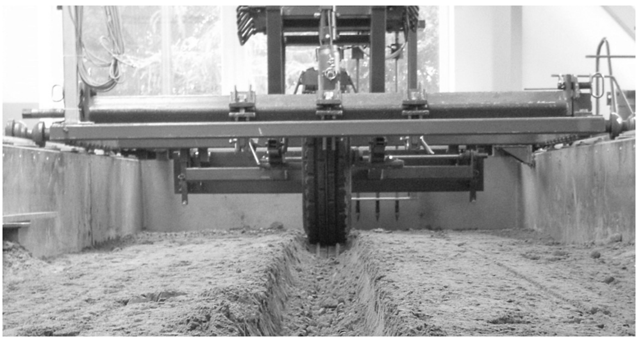

FIGURE 1. Measurement wheel and wheel-rut after driving along the channel

axis. The speed used to push them into the soil was constant at 0.03 m·s^{-1}. Thanks to this, for each measurement option (three pressure levels × three humidity levels × three repetitions), data concerning soil compaction for layers located at the distance of 5–15–25–35 cm at the left and right sides of the wheel-rut axis were obtained. Compaction was calculated by referring penetrometer resistance values to the area of base of the cone shaped end piece. The force used to push the penetrometers into the soil and penetration depth by the cone shaped end piece was registered using a DMCplus measurement and registration set manufactured by Hottinger Baldwin and a computer with the CATMAN 2.1 programme.

RESULTS

After preparation for measurements, average soil compaction values were 160.3 kPa for the series of measurements with the tyre pressure of 140 kPa, 161,7 kPa for measurements at the pressure of 80 kPa and 164.7 kPa for the measurements at the highest pressure of 220 kPa.

Taking into account own observations regarding soil compaction after a wheel-rut and figures from the literature [Buliński 2007] stating that the superficial layer of the area adjacent to the wheel-rut experiences numerous cracks and lateral displacements of the soil, average values recorded by probes at corresponding distances at the left and right sides of the wheel-rut, from the depth profile of 10–35 cm, were used for analysing the measurement results.

Analysis of soil compaction at the tyre pressure of 140 kPa (Fig. 2) leads to the observation that the greatest soil densification occurred in layers located at the smallest distance from the wheel-rut axis (*b* = 5 cm), with the greatest compaction changes obtained at the humidity level of 12%. In those layers, soil compaction in comparison with the condition before being driven over increased by about 3.3 times at the humidity of 8%,

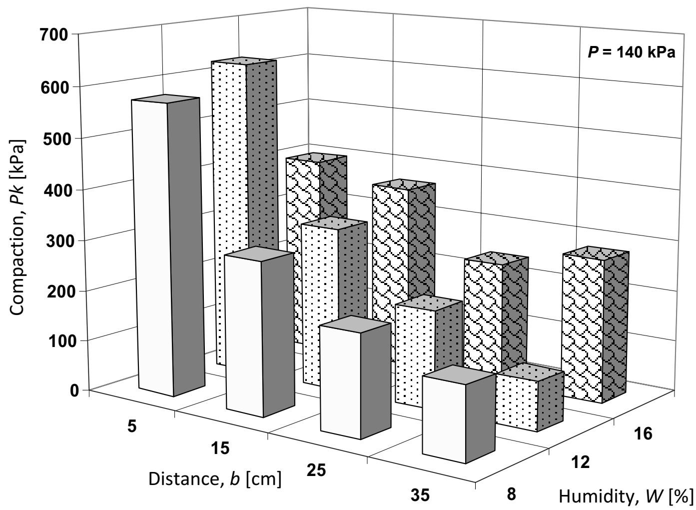

FIGURE 2. Soil compaction changes at the tyre pressure of 140 kPa

nearly four times at the humidity of 12% and about 2.4 times at the highest humidity of 16%.

At the humidity of 12%, average soil compaction in the profile at the depth of 10 to 35 cm was 624 kPa and was by 9% higher (573.1 kPa) than the value obtained at the humidity of 8%, and by over 56% higher (398 kPa) with respect to a corresponding measurement at soil humidity of 16%. The results confirm the authors' observations from preliminary investigations as well as data from the literature [Forssblad 1981] stating that for each kind of soil there is a certain humidity level at which the soil demonstrates highest susceptibility to compression, which results in the highest densification at the same pressure force. In all measurement variants, one may observe a negative correlation of compaction with distance of the given layer from the wheel-rut axis. The greatest and clearly oriented compaction decreases were obtained at the humidity levels of 8 and 12%. Corresponding values at those humidity levels did not exceed 50 kPa and they did not differ in a statistically relevant degree. At the highest humidity level (16%), changes of compaction also decreased with distance, but in an unstable manner, which may result from the buffer effect of water in the soil space, which hinders propagation of stresses from the layer of direct contact with the wheel deeper down and to the profile sides.

Increasing the tyre pressure to 180 kPa resulted in increased soil compaction in the layers located at 10 to 35 cm (Fig. 3) from the wheel-rut axis. Yet, as it was the case at lower humidity, as compared with the condition of the soil before being driven over, compaction of the layer located closest to the wheel-rut axis (b = 5 cm) after being driven over with a wheel characterised with the pressure of 180 kPa increased from 2.5 to around four times. One may notice that also in this case, at soil humidity of 12%, the densification in the layer located closest to the wheel-rut axis was considerably

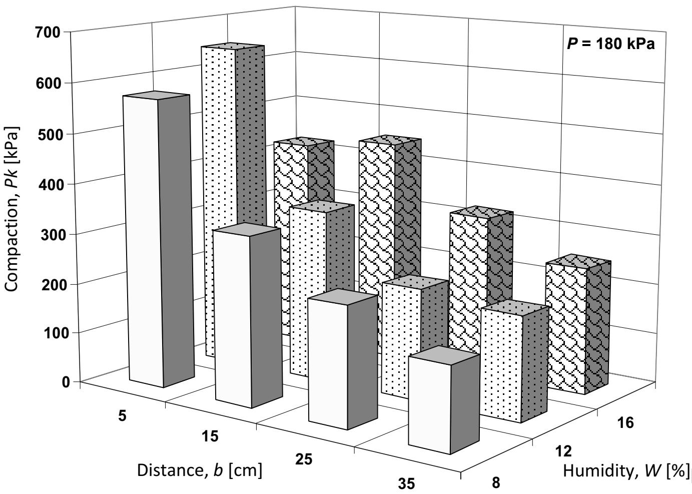

FIGURE 3. Soil compaction changes at the tyre pressure (P) of 180 kPa

higher than at the remaining two humidity levels.

Average soil compaction at the humidity level of 8% (572 kPa) was lower by 77 kPa, i.e. about 12%, whereas at the humidity level of 16% by over 226 kPa, i.e. nearly 35%. At the same time, as it was the case at the lowest pressure (140 kPa), there exists a negative correlation with distance of the layers from the wheel-rut axis, provided however that the layers closest to the axis were less densified than layers located 10 cm further away only at the highest moisture level. Similarly to the previous pressure variant, the values of soil compaction at the humidity level of 16% at the distances of 15, 25 and 35 cm from the wheel-rut axis were greater than corresponding values measured at lower humidity levels – by 46 to 114 kPa, i.e. by 22–34%.

Increasing the tyre pressure to 220 kPa changed the character of compaction changes both with respect to particular humidity levels and distances of layer location (Fig. 4). Analysis of the values presented in the figure allows observation of significant diversification in compaction changes, particularly in the lateral layers located further away from the wheel-rut axis. As in the case of the previous pressure variants, the highest soil densification was obtained in the layer closest to the wheel-rut axis (*b* = 5 cm) at the humidity of 12%, whereas differences between soil compaction values obtained at the remaining humidity levels were similar as in the variant with the lower pressure of 180 kPa. One may also notice that in the highest tyre pressure, the compressive effect of the wheel onto the sides increased considerably in comparison with the previous variants (Figs. 2 and 3).

In the layers located at the distance of 15 cm from the wheel-rut axis, soil compaction was only slightly lower than in the layers located immediately under the wheel-rut (*b* = 5 cm). At the humidity level of 8%, the difference was 16%, whereas at the humidity level of 12%

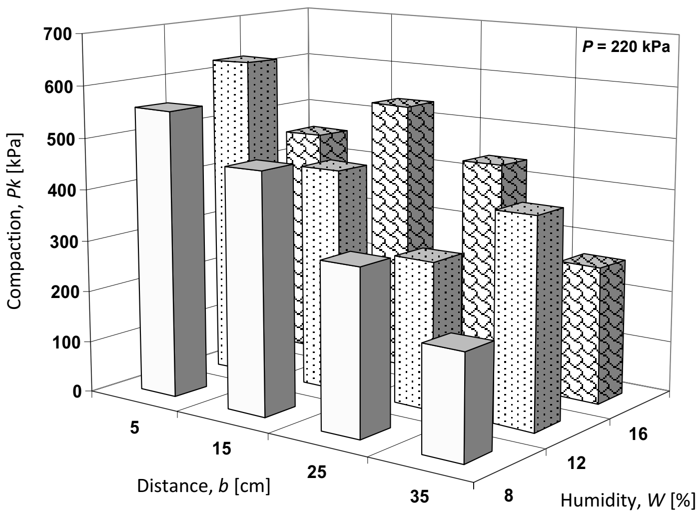

FIGURE 4. Soil compaction changes at the tyre pressure (*P*) of 220 kPa

– the difference was about 30%. In the case of the highest humidity level, layers located at a greater distance (*b* = 15) demonstrated compaction by about 17% greater than the layers located immediately under the wheel-rut (*b* = 5 cm). Moreover, the obtained values suggest that the relation between compaction and distance of a layer from the wheel-rut axis was the opposite only at the lowest soil humidity level. At higher humidity levels and tyre pressure of 220 kPa, the relationship was not very evident. This observation is particularly relevant to readings of the penetrometers for layers located at the distance of 35 cm from the axis, at the humidity level of 12%. As values presented in the figure constitute average group values from six measurements (two measurements × three spots in the section) and no significant differences were found between particular repetitions during the analysis, this compaction deviation (for *b* = 35 cm) may not be considered an error. This variability of measurement results may have resulted from higher values of stress in the soil under the influence of dislocation of layers deeper down the profile under a much more pumped and harder tyre. One must also consider that the analysed soil constitutes a site which is not completely comparable with field conditions where such elements are found as natural cohesion of particles, differences in their dimensions, presence of natural organic components including plant roots, etc. This observation concerns higher compaction of layers located at the distance of 15 cm from the wheel-rut axis, at soil humidity levels of 12 and 16%, as described above.

After comparison of the average values obtained for particular levels of independent variables (Fig. 5), one may notice an evident and oriented influence of pressure changes onto the measured soil compaction values.

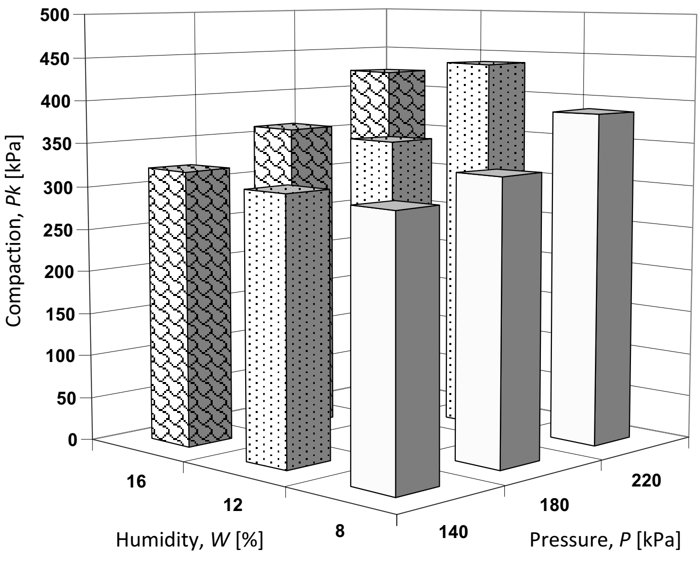

FIGURE 5. Average soil compaction values at particular levels of tyre pressure and soil humidity

The influence of soil humidity at particular pressure variants, especially in the layers located at the greatest distance, may be considered insignificant or ambiguous. At the tyre pressure of 220 kPa, average group soil compaction levels were by 17–23% higher than respective values obtained at the pressure of 180 kPa, and by 27–42% higher than respective values obtained at the lowest pressure, i.e. 140 kPa.

In order to verify whether the analysed variables could be the reason of differences between the observed group average values, the variance analysis was conducted for the whole measurement material. Results of the analysis performed with the method of sum of square values of type III are presented in Table 1.

The obtained statistical values indicate that, among the analysed factors, the influence of humidity onto soil compaction changes at individual tyre pressure values turned out to be statistically insignificant ($P > 0.05$), whereas both the values of applied pressures and distance between location of the soil layer from the wheel-rut axis significantly differentiated the average group soil compaction values (Table 2).

Results of the statistical analysis gave grounds to development of a regression equation relating soil compaction (*Pk*) with the significant factors, i.e. distance from the wheel-rut axis (*b*) and tyre pressure (*P*), as follows:

$$Pk = 337.462 + 1.3147 \times \mathrm{P} - 10.789 \times b \quad (1)$$

TABLE 1. Results of the variance analysis of the measurement material

Source	Sum of Squares	Degree of freedom	Mean Square	*F*-ratio	*P*-value
Distance, *b*	546 395.00	3	182 132.00	31.71	0.0000
Humidity, *W*	6 754.34	2	3 377.17	0.59	0.5621
Pressure, *P*	68 465.30	2	34 232.60	5.96	0.0070
Rest	160 805.00	28	–	–	–
Total	782 419.00	35	–	–	–

TABLE 2. Regression analysis for soil compaction (dependent variable Pk)

Parameter	Estimate	Standard error	t-statistic	*P*-value	
Constant	337.462	74.7985	4.51162	0.0001	
P	1.31472	0.389491	3.37549	0.0019	
b	–10.789	1.13778	–9.48249	0.0000	
Variance analysis for the model					
Source	Sum of Squares	Degree of freedom	Mean Square	*F*-ratio	*P*-value
Model	590 181.0	2	295 090.00	50.66	0.0000
Rest	192 238.0	33	5 825.41		
Total	782 419.0	35			

for which: R^2 = 75.4%; *SEE standard* = 76.324; *MAE* = 60.254.

The graph presenting matching of the model to actual values is presented in Figure 6. Presented scattering of points corresponds with the matching of about 75% and presents the level of explanation of the dependent variable by the model's predictors. This level is typical of most empirical investigations in the soil conditions with the use of equipment, and may be considered satisfactory. One ought to mention that the above relationship was obtained in soil conditions close to homogeneity, allowing repetitions in the same or maximally similar measurement conditions. In natural conditions, it would be very difficult, if not impossible.

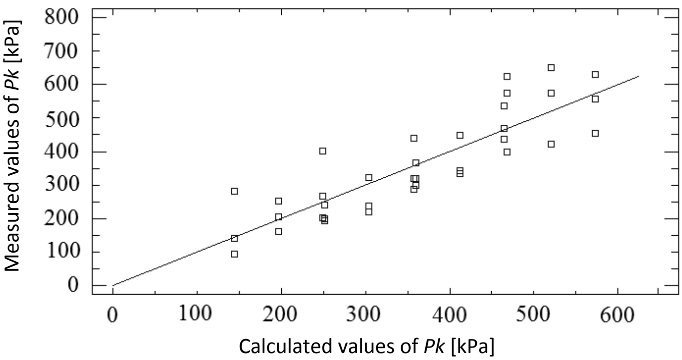

FIGURE 6. Comparison (*Pk*) of measured values with values calculated pursuant to equation (1)

CONCLUSIONS

The investigation conducted in the conditions of a soil channel allows drawing the following conclusions.

1. Soil compaction under the wheel-rut and in lateral layers was considerably dependent on pressure in the wheel tyre and horizontal layer location distance, whereas soil humidity did not have a statistically significant influence.
2. Differences with respect to compaction of soil located in lateral layers as compared with the layer under the wheel-rut were reduced along with growth in tyre pressure. At the tyre pressure of 140 kPa, differences in average group values of all humidity levels were from 160 to 308% (on average 241%), at the pressure of 180 kPa they were from 140 to 266% (on average 208%), at the pressure of 220 kPa they were from 114 to 188% (on average 208%) and increased along with distance of the layer's location.
3. At all tyre pressure levels, on soils with the humidity levels of 8 and 12%, layers located under the wheel-rut were more densified than in the lateral layers. On soils with the humidity level of 16%, at tyre pressures of 180 and 220 kPa, soil compaction values for the soil located immediately under the wheel-rut (*b* = 5 cm) were lower by, 6 and 18%, respectively, than the

compaction values for the layer located at a greater distance (b = 10 cm).

4. At soil humidity levels of 12 and 16% and the tyre pressure of 220 kPa, changes in the compaction of layers located at a greater difference from the axis (10–35 cm) were not oriented.
5. At the tyre pressure of 220 kPa, average group soil compaction values were higher by 17–23% than respective values obtained at the pressure of 180 kPa and by 27% to 42% higher than respective values obtained at the lowest pressure, i.e. 140 kPa.

REFERENCES

ASAE Standards 1993: Soil Cone Penetrometer. Standards Engineering Practices Data. 40-th edition American Society of Agricultural Engineers. St. Joseph. Mi. USA. 657. .

BARLEY K.P., FARRELL D.A., GREACEN E.L. 1965: The influence of soil strength on the penetration of a loam by plant roots. Australian Journal of Soil Research 3: 69–79.

BEYLICH A., OBERHOLZER H.R., SCHRADER S., HÖPER H., WILKE B.M. 2010: Evaluation of soil compaction effects on soil biota and soil biological processes in soils. Soil and Tillage Re-search 109: 133–143.

BUCHTER B., HAUSLER S., SCHULIN R., WEISSKOPF P., TOBIAS S. 2004: Definition und Erfassung von Bodenschadverdichtungen Positionspapier der BGS-Plattform Bodenschutz. BGS Dokument 13.

BULIŃSKI J. 2000: Wpływ prędkości ruchu i rodzaju agregatu ciągnikowego na zagęszczanie gleby kołami. Inżynieria Rolnicza 6 (17), 111–117.

BULIŃSKI J. 2007: Soil displacement caused by the wheels of agricultural tractors. Annals of Warsaw Agricultural University, Agriculture (Agricultural Engineering) 50: 9–14.

BULIŃSKI J., KLONOWSKI J., SERGIEL L. 2010: Wykorzystanie kanału glebowego do badań zespołów roboczych narzędzi i mechanizmów jezdnych. Inżynieria Rolnicza 1 (119): 93–98.

ELWALEED A.K., YAHYA A., ZOHADIE M., AHMAD D., KHEIRALLA A.F. 2006: Effect of inflation pressure on motion resistance ratio of a high-lug agricultural tyre. Journal of Terramechanics 43: 69–84.

FARIAS N.E. 1994: Physical of Soils. Editorial Trillas, Mexico.

FERREE D.C., STREETER J.G. 2004: Response of container-grown grapevines to soil compaction. Hortscience 39: 1250–1254.

FORSSBLAD L. 1981: Vibratory soil and rock fill compaction. Dynapac Maskin AB, Solna, Sweden.

KURJENLUOMA J., ALAKUKKU L., AHOKAS J. 2009: Rolling resistance and rut formation by implement tyres on tilled clay soil. Journal of Terramechanics 46: 267–275.

PASSIOURA J.B. 2002: Soil conditions and plant growth. Plant, Cell & Environment 25: 311–318.

PN-R-04033. Gleby i utwory mineralne. Podział na frakcje i grupy granulometryczne.

TAYLOR H.M., ROBERSON G.M., PARKER J.J. 1966: Soil strength–root penetration relations for medium coarse-textured soil materials. Soil Science 102: 18–22.

UNGER P.W., KASPAR T.C. 1994: Soil compaction and root growth: a review. Agronomy Journal 86: 759–766.

WASZKIEWICZ CZ., KLONOWSKI J., GŁUCH J. 2009. Effect of plough body on the quality of ploughing. Annals of Warsaw University of Life Sciences – SGGW, Agriculture (Agricultural and Forest Engineering) 54: 5–9.

Streszczenie: *Zmiany zwięzłości gleby w strefie przejazdu koła przy różnym ciśnieniu w oponie.* Przedstawiono wyniki badań zwięzłości gleby pod koleiną przejazdu koła i w bocznych strefach przylegających, na głębokości 10–35 cm. Badania wykonano na glinie piaszczystej o wilgotności 8–12–16%. Stosowane ciśnienia w oponie koła wynosiły 140–180–220 kPa. Przeprowadzone badania wykazały statystycznie istotną zależność między zwięzłością gleby a ciśnieniem w oponie i odległością położenia warstwy w stosunku do osi koleiny. Wpływ wilgotności gleby okazał się nieistotny statystycznie. Różnice w zwięzłości gleby położonej w warstwach bocznych, w stosunku do warstwy pod koleiną, zmniejszały się wraz ze wzrostem ciśnienia w oponie. Przy ciśnieniu w oponie 140 kPa różnice w wartościach średnich grupowych wszystkich poziomów wilgotności wynosiły od 160 do 308% (średnio 241%), przy ciśnieniu 180 kPa wynosiły od 140 do 266% (średnio 208%), przy ciśnieniu 220 kPa wynosiły od 114 do 188% (średnio 208%) i zwiększały się wraz z odległością położenia warstwy od osi koleiny.

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Authors' addresses:
Leszek Sergiel
Instytut Technologiczno-Przyrodniczy
w Falentach
Mazowiecki Ośrodek Badawczy w Kłudzienku
Zakład Inżynierii Produkcji Roślinnej
05-825 Grodzisk Mazowiecki, Kłudzienko 7
Poland
e-mail: l.sergiel@itp.edu.pl

Jerzy Buliński
Wydział Inżynierii Produkcji SGGW
Katedra Maszyn Rolniczych i Leśnych
02-787 Warszawa, ul. Nowoursynowska 166
Poland
e-mail: jbulinski@wp.pl