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Effect of compacting soil on changes in its strength

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Abstract: *Effect of compacting soil on changes in its strength.* There are presented results of field investigations on the change in strength of soil compacted by passages of tractor Ursus 4512, that created total specific wheel pressures of 137, 353, 614, and 1,237 kPa in the rut, corresponding to 1, 2, 4, and 8 passages over the same track. Soil strength in the surface layer (0–5 cm) that directly contacted the wheel tyre was considerably lower (from 21% to about 37%) than in the layer beneath (5–10 cm). The biggest differences in soil density and the related soil strength were found between pressure variants 137 and 353 kPa as well as 353 and 614 kPa. Practically, it means that biggest changes in the loosened soil subjected to tractor wheel pressures occurs up to the fourth passage.

Key words: soil, density, strength, agricultural tractor

INTRODUCTION

The strength of soil is its significant property, especially of the arable layer [Świętochowski et al. 1993]. This property determines the binding force of particular soil particles. In agricultural practice, the soil strength is usually measured with a probe equipped with the conical end of cone tip angle 30 or 60°, that is driven in soil to a certain depth at constant speed. Resistance of probe driven in soil can provide information on the conditions that must be overcome by the root of growing plant. A series of investigations point out at limited increment of roots' bulk and the rate of their development in strongly compacted soils [Buliński and Niemczyk 2010, Buliński et al. 2011], especially during drought periods of limited water and nutrients availability from deeper layers [Raper et al. 2005]. For majority of cultivated plants and soil fauna, the soil strength that exceeds 1.7–2.0 MPa [Barley et al. 1965, Unger and Kaspar 1994, Taylor et al. 1996, Buchter et al. 2004, Beylich et al. 2010], and in clay soils even 1.0 MPa [Farias 1994] is the limit, above which their development is rapidly or totally stopped. It is evident from investigations [Copas et al. 2009] that under field conditions, depending on operations applied, the soil strength exceeded 1.5 MPa in the layer of depth 0.25–0.30 m and 3.0 MPa in the layer of depth 0.3–0.4 m, where majority of plant roots is accommodated. The roots need higher energy inputs to overcome a strongly compacted layer; it slows down and weakens the roots development; a decrease in roots bulk increment can exceed even 50% [Atwell 1993, Lipiec et al. 2003]. According to Lipiec and Stępniewski [1995], there is a relationship between the soil density and intensity of nutrient uptake by plants; it is mainly connected with changes in water-air relations in the layer, where the plant roots develop. This situation is particularly important under conditions of adverse climatic factors (prolonged water shortage) in weak soils of deteriorated structure.

According to Unger and Kaspar [1994], the soil strength of 2 MPa (measured with a cone penetrometer) corresponds to maximal soil density, at which majority of cultivated plants develop and uptake the nutrients. Soil density above this value leads to excessive mechanical resistance against the roots, that change direction of penetration [Materechera et al. 1991] and become deformed; the rate of their bulk increment is decreased. A change in direction of roots development is also connected with a change in configuration and structure of pores; very small pores arranged horizontally predominate. Negative effects of these changes were confirmed by Munkholm [2000]. In strongly compacted layer the roots developed horizontally, according to arrangement of pores, until they reached the layers with pores arranged vertically. The change in configuration and structure of pores limits the range of roots, the possibility of better utilization of nutrients; affecting the yield [Lipiec et al. 1991]. The yield reduction in excessively compacted soils can result also from the limited infiltration of water and its poor availability to plants [Radford et al. 2001].

In practical agriculture, the main reason for the increased soil density expressed by bulk density and strength are mainly the wheel pressures during multiple passages over the field [Powałka 2007, Buliński and Sergiel 2013]. Grečenko reported [2003] that after from two to four wheel passages, the wheel – ground contact area and specific pressure values were close to the values that would occur on a hard surface. The range of compaction usually exceeds the depth of loosening operations applied. At axle load of 100 kN, which commonly occurs in tractor outfits, the range of soil compaction amounts to 50 cm [Håkansson and Reeder 1994]. Therefore, depth is one of important parameters that shape the soil density values caused by the wheel of agricultural vehicles.

The investigations aimed at determination of relationships between the values of specific pressures caused by the wheels of agricultural tractor and soil density and the connected soil strength.

MATERIAL AND METHODS

The investigations were performer under field conditions on soil determined as clayish sand of the following size distribution: 47% (1–0.1 mm), 34% (0.1––0.02 mm) and 19% (<0.02 mm). The measuring lengths were prepared for investigations by loosening them to a depth of 35 cm followed by surface leveling.

During measurements the average soil moisture content in the profile 0––30 cm amounted to 8.9–10.4% by weight (on the average 9.6%, σ = 0.39).

The arable layer was compacted with tractor Ursus 4512 by performing its passages over the same track on the loosened field surface. Basic specification of the tractor is presented in Table 1.

Basing on measurements of the tyre – soil contact area for front and rear tyres during subsequent passages over the same track and the wheel loading determined by weighing, the total specific

TABLE 1. Basic specification of tractor used in investigations

Item		Unit	Tractor Ursus 4512
Weight		kN	31.77
Axle load	front	kN	12.28
	rear		19.49
Size of tyres	front	inch	7.50-16
	rear		13.6/12-36
Tyre inflation pressure	front	kPa	210
	rear		120

wheel pressures were calculated. After execution of one, two, four and eight compacting passages in the place of wheel track overlapping, the total pressures amounted to: 137, 353, 614, and 1,237 kPa, respectively.

The soil density was measured with the use of Eijelkelkamp probe for taking undisturbed samples; it was equipped with cylindrical containers of volume 100 cm^3 and height 5 cm. After each series of passages the probe was vertically driven in soil in the middle of wheel track to a depth of 30 cm; the measurements were repeated three times at randomly selected places along the track. Therefore, there were obtained the soil bulk density values for particular levels determined as 2.5, 7.5, 12.5, 22.5, and 27.5 cm, that corresponded to the centres of layers, where soil samples were taken from. The investigations were carried out at loosened soil density ranging from 1,021 kg·m^{-3} in the surface layer (0–5 cm) to 1,244 kg·m^{-3} – in the deepest layer (25–30 cm) – on the average 1,158 kg·m^{-3}.

The soil strength was determined for particular compaction variants with the use of a two-probe set with the conical end of tip angle 30° and the cone base cross section 20.27 mm [ASAE Standards 1993]. The probes were driven in soil in the wheel tracks at distance of 50 mm to the right and left from the track axle, to depth 300 mm at constant speed 0.03 m·s^{-1}. The probe resistance was recorded in the range 0–300 mm and every 1 mm, with accuracy up to 5 N. The measurements for each soil compacting variants (wheel pressures) were repeated three times.

RESULTS OF INVESTIGATIONS

Changes in average soil density in the track are presented in Figure 1 for particular total wheel pressure values at particular depths. Soil density of not compacted soil (initial value) is designated as “0”.

Considering the presented value one can find that the soil density systematically increases along with the pressures applied. Taking into consideration the natural increase in soil density in the profile, connected with its self-contained consolidation (pressure “0”) one can find, that the highest changes in density resulted from the pressures occur to a depth of 10 cm. An increase in density of this layer exceeded 40%, may be because of small self-condensation of these

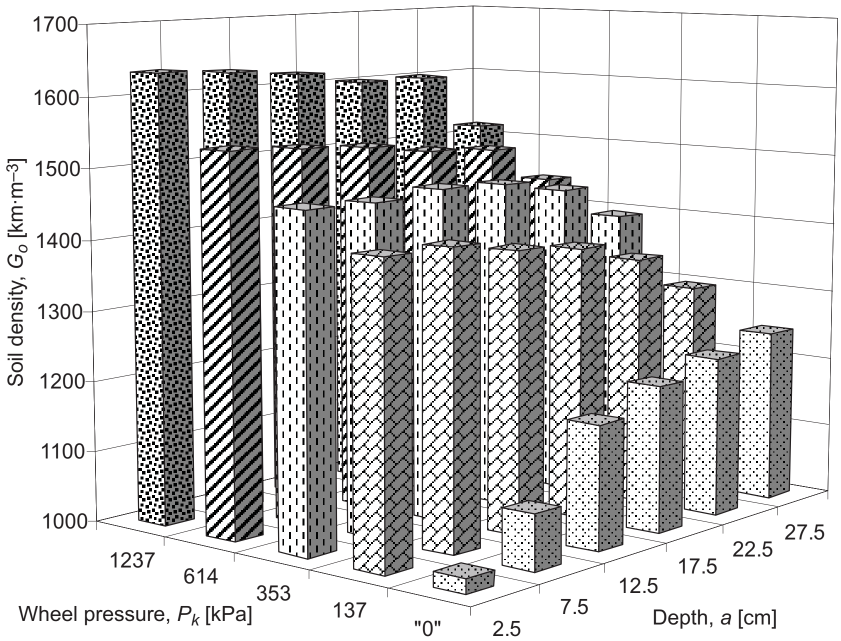

FIGURE 1. Soil density in the track for particular wheel pressure values

layers resulted from their small thickness; at the same time, these layers were most affected by the pressures.

Changes in average soil density in the entire considered profile under the track at particular pressures are presented in Figure 2.

It is evident from comparison of values presented in Figure 1 that differences between soil density values in particular

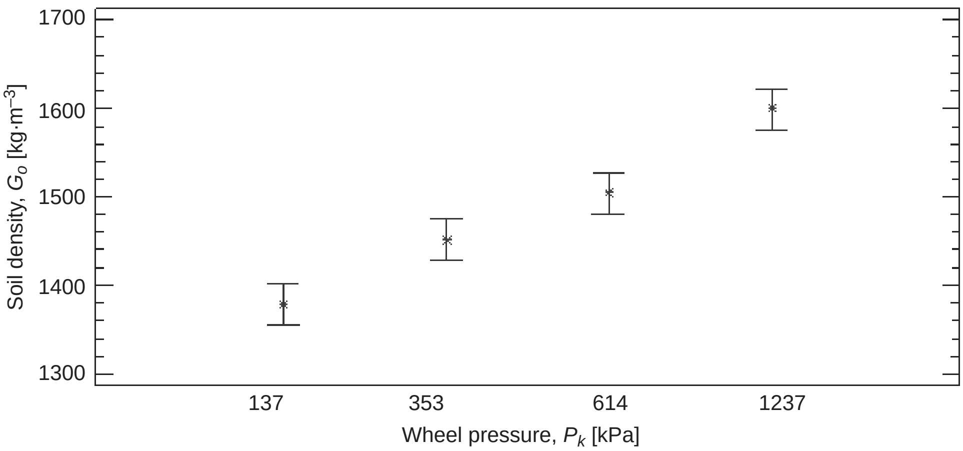

FIGURE 2. Average soil density values in the profile under track in particular measuring variants with confidence interval according to 95% HSD Tukey method

pressure variants range from about 3.7 to 6.3%. The ranges of values for confidence level 95% (Fig. 2) point out at small variability of the parameter; the bigger differences in average values occur between density at pressures 137 and 353 kPa as well as 614 and 1,237 kPa, while differences in soil density at pressures 353 and 613 kPa were distinctly lower. In order to confirm significance of differences between particular density levels, the variance analysis of measuring values was executed (Table 2).

The obtained values of statistics showed the significance of differences between soil density levels; it allows for assumption that the levels of total pressures were selected correctly.

The results of soil strength measurements for particular density levels are presented in Figure 3.

Considering the presented values one can find a characteristic pattern of soil density values regardless of the pressures. Soil density in the surface layer (0–5 cm), that directly contacted the

TABLE 2. Variance analysis of soil density in measuring variants

Source of variability	Sum of squares	Degrees of freedom	Mean square	F	P
Between groups	156,548.0	3	52,182.7	34.37	0.0000
Within groups	30,365.6	20	1,518.28	×	×
Total	186,914.0	23	×	×	×

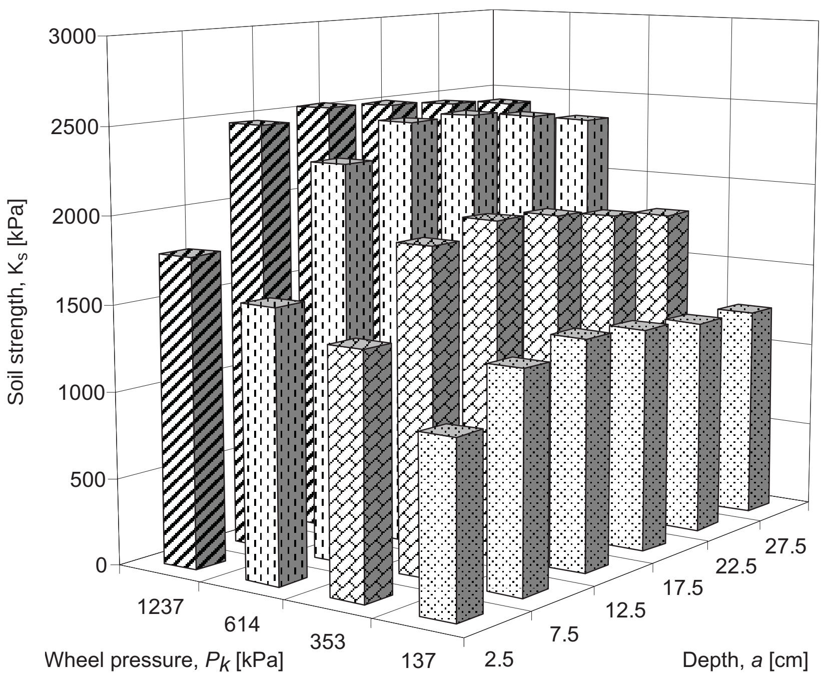

FIGURE 3. Soil strength changes resulted from compacting by wheel pressures

wheel tyre, was considerably lower (from 21 to about 37%) than in the layer beneath (5–10 cm).

It may result from the action of tyre tread ribs that cause a multidirectional displacement of soil in the surface layer during movement of wheel. The deeper layer (10–15 cm) was characterized by highest strength, which decreased in the deepest layer (>15 cm). These results point out that the range of strongest effects of the wheel pressures was limited, as a result of filtration resistance (water and air) under conditions of carried out measurements at depth below 15 cm.

Analyzing average values of profile strength under the track (Fig. 4) at various pressures one can find that the highest differences in soil density and the connected soil strength were obtained between pressure variants 137 and 353 kPa as well as between 353 and 614 kPa. It practically means, that the strongest changes in loosened soil under pressures of tractor wheels occur up to the forth passage. Less significant differences in average soil strength were found at total wheel pressures of 614 and 1,237 kPa, that corresponded to four and eight passages of tractor.

Fairly wide confidence intervals for average values are connected with the scatter of measuring values, which may be affected by loosening of soil surface layer by the tyre tread. The analysis of measuring values performed by multiple comparison method LSD (Table 3) confirmed significant differences between the strength mean groups at pressures up to 614 kPa, while differences at pressures 614 and 1,234 kPa were insignificant.

The test showed also that the calculated difference for soil strength recorded at pressures 353 and 614 kPa slightly exceeded the limit value. These pressures values corresponded to two and four passages over the same track, respectively.

The specific wheel pressure values are directly connected with the soil strength, since they create stresses, change structure and arrangement of soil spaces; this leads to changes in soil density and the resulted soil strength expressed by cone penetrometer resistance. In the carried out investigations the soil density and strength measurements were executed

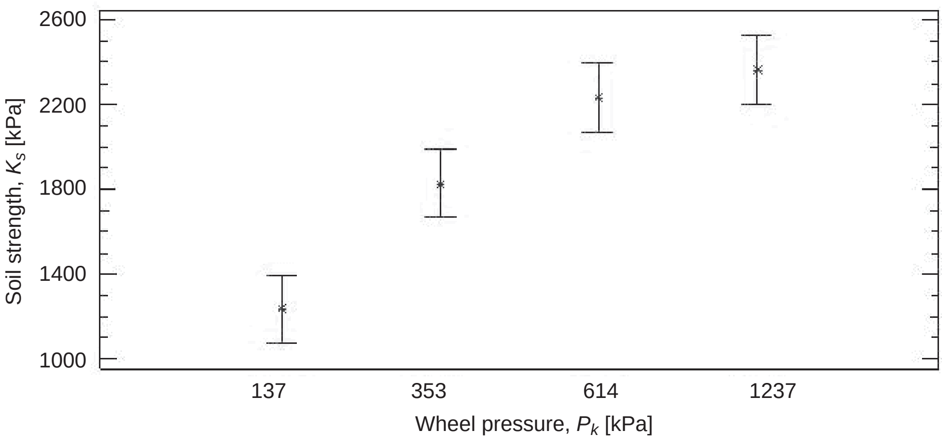

FIGURE 4. Changes in average soil strength in investigated profile as influenced by specific pressures

TABLE 3. Test of multiple comparisons for strength in particular measuring variants

Source	Mean	Contrast	Calculated difference	Limit value
Pk 137	1,234.49	$Ks_{Pk137} - Ks_{Pk\ 353}$	–591.82*	323.489
		$Ks_{Pk137} - Ks_{Pk\ 614}$	–999.345*	
		$Ks_{Pk137} - Ks_{Pk\ 1237}$	–1128.38*	
Pk 353	1,826.31	$Ks_{Pk353} - Ks_{Pk\ 614}$	–407.525*	
		$Ks_{Pk353} - Ks_{Pk\ 1237}$	–536.562*	
Pk 614	2,233.83	$Ks_{Pk614} - Ks_{Pk\ 1237}$	–129.037*	
Pk 1237	2,362.87			

*Statistically significant difference.

under the same field conditions and values of these parameters involved the same factors (moisture content, stress values, duration of stress, depth of layer etc.). Changes in soil strength in connection with soil density expressed by bulk density and with depth of layer can be determined with regression equation of the form:

$$K_s = -6177.44 + 5.1164 \times \times G_o + 33.4241 \times a \qquad (1)$$

where:
K_s – soil strength, kPa;
G_o – soil bulk density, kg·m^{-3};
a – depth of measurement, cm.

Correlation coefficient for the above equation amounted to $R^2 = 77.16\%$.

Comparison between the values calculated with the use of equation (1) and the corresponding measuring values is presented in Figure 5.

The presented distribution of points around the straight line reflects degree

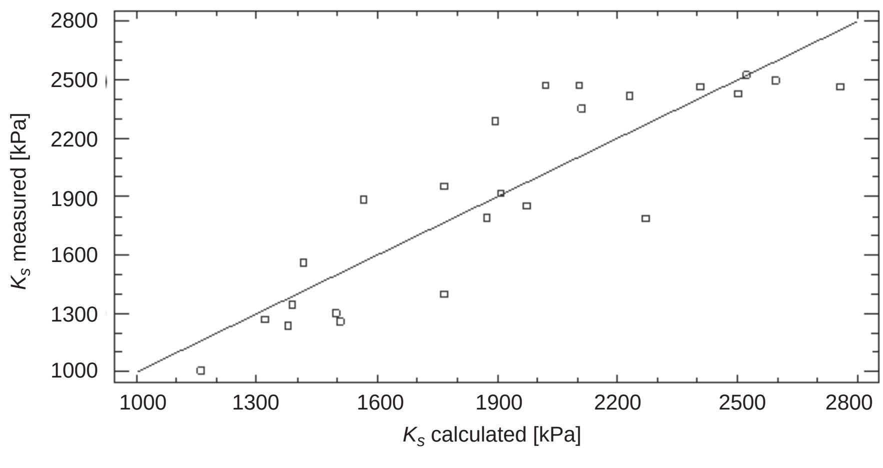

FIGURE 5. Comparison between values of strength (K_s) calculated with equation and measurement values

of equation fitting to the measured value. This distribution is characterized by determination coefficient (77.16%); it can be considered as satisfactory, although in the range of strength (1,600–2,200 kPa) there occur bigger differences between the calculated and measured values. The scatter of points may result also from the effect of other factors (e.g. external ones); the researchers had no influence on them, thus, they were not considered in the equation.

The carried out investigations showed that direct connecting the soil density and soil strength is difficult and not much satisfactory and should be secured with many conditions that limit application range of the developed model. Depending on the used model, the best fitting amounted to R^2 = 50% that corresponded to correlation coefficient determining interrelation of variables r = –0.708. The levels of these coefficients values situated themselves at the border of unsatisfactory and weak ones.

CONCLUSIONS

The carried out investigations on the effect of soil compacting by the wheel pressures on the soil strength enabled to formulate the following conclusions:

1. The highest changes in soil bulk density under the wheel pressures (that exceeded 40% in relation to the initial state) were found to a depth of 10 cm.
2. Soil strength in the surface layer (0–5 cm) that directly contacted the wheel tyre was considerably lower (from 21 to about 37%) than in the layer beneath (5–10 cm).
3. The highest differences in soil density and the connected soil strength were obtained between pressure variants 137 and 353 kPa as well as between 353 and 614 kPa. It practically means, that the strongest changes in loosened soil under pressures of tractor wheels occur up to the forth passage.
4. There was obtained the regression equation connecting the soil strength, soil bulk density and depth of measurement of fitting degree R^2 = 77.16%.
5. Direct connecting the soil density and soil strength should be secured with many conditions that limit application range of the developed model. In the case of carried out investigations, this direct connecting turned out to be not much satisfactory. Depending on the used model, the best fitting amounted to R^2 = 50% that corresponded to correlation coefficient determining interrelation of variables r = –0.708.

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Streszczenie: *Wpływ zagęszczania gleby na zmiany jej zwięzłości.* W pracy dokonano analizy wyników badań związanych z wpływem zagęszczenia gleby naciskami kół ciągnika. Stosowano cztery poziomy jednostkowych nacisków kół

odpowiadających 1-, 2-, 4-, 8-krotnym przejazdom ciągnika tym samym śladem. Mierzono gęstość i zwięzłość gleby w koleinie przejazdów. Przeprowadzone pomiary wykazały, że zwięzłość gleby w warstwie powierzchniowej (0–5 cm), bezpośrednio stykającej się z oponą koła, była znacznie mniejsza (od 21 do ok. 37%) niż w położonej bezpośrednio pod nią (5–10 cm). Najsilniejsze zmiany w spulchnionej glebie poddanej naciskom miały miejsce do czwartego przejazdu ciągnika. Bezpośrednie powiązanie gęstości gleby z jej zwięzłością musi być obwarowane wieloma zastrzeżeniami ograniczającymi zakres stosowania opracowanego modelu. W przypadku wykonanych badań bezpośrednie powiązanie zwięzłości z gęstością gleby okazało się mało zadawalające. W zależności od użytego modelu największe dopasowanie wynosiło R^2 = 50%, co odpowiadało współczynnikowi korelacji określającej współzależność zmiennych r = –0,708.

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