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Influence of geometrical penetrometer cone dimensions onto readings in soil compaction measurements

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Abstract: *Influence of geometrical penetrometer cone dimensions onto readings in soil compaction measurements*. An analysis of influence of the apex angle and diameter of the cone onto readings in soil compaction measurements is presented. The investigation was conducted in a soil channel, on sandy clay characterised with the humidity of 7.64% and bulk density of 1.36 g·cm^{-3}. The investigation demonstrated existence of a negative correlation between the cone base area and the measured value, and a positive correlation in the case of the apex angle. Differences between the average values of compaction determined with penetrometers with the apex angle of 30° changed depending base area by 11.5 to 18%, whereas in the case of penetrometers with the apex angle of 60° – from 6 to 28%. Change of the angle from 30 to 60°, depending on the cone base area, resulted in growth of average soil compaction readings by 18.4 to 30.2%.

Key words: cone penetrometer, soil compaction, method of measurement

INTRODUCTION

Next to density and porosity, soil compaction is one of its fundamental properties. Denoting the strength of mutual connections between particular soil particles, in agricultural practice it is assumed as a measure of soil condition as a result of various agricultural activities [Idkowiak and Kordas 2004], development conditions of plants' root systems [Lipiec et al. 2003, Buchter et al. 2004, Beylich et al. 2010] influence of the wheels of agricultural vehicles and machines on the soil while driving over the field [Buliński et al. 2011, Buliński and Sergiel 2013, Powałka and Buliński 2014], as well as for evaluating quality of the arable layer in the aspect of its protection against degradation as a result of uncontrolled, excessive densification and sealing. Thanks to measurement ease, possibility of quick and direct reading of the value, soil compaction is a parameter commonly determined with the use of various penetrometers equipped with cone shaped end pieces to specify characteristics of conducting field investigations. In fact, there is no uniform methodology for performing measurements and although the ASAE [1993] norm specifies two standards of cones with the identical apex angle of 30° – smaller one with the base area of 130 mm^2 (recommended for "hard" and very compact soils) and bigger one with the base area of 323 mm^2 and cone diameter of 20.27 mm (for loose soils). Moreover, the norm recommends the speed of pushing the penetrometer into the soil at 30 mm·s^{-1}. In investigation practice, penetrometers with different base areas and apex angles are used, hammered [Idkowiak and Kordas 2004] or pushed into the soil with various methods (manually, mechanically) at a different speed (20–50 mm·s^{-1}) [Fellenius and Eslami 2000, Lejman, Owsiak

2001, Sudduth et al. 2004, Fountas et al. 2013, Brennenstuhl 2014]. This diversity of measurement conditions may result in differences in the obtained values, which makes comparison of results, interpretation and drawing conclusions more difficult. What is more, field measurements are performed on soils and materials which differ in terms of composition and humidity – factors influencing the friction resistance level [Sun et al. 2012] and, thus, influencing the resistance encountered during passage of the penetrometer through the analysed layer. Although in the literature one can find investigations [Sudduth et al. 2004] whose authors obtained compaction values in specific conditions of performing measurements with a non-standard penetrometer (lack of statistical differences) comparable with values determined with penetrometers meeting the ASAE standard, the observations cannot be generalised and interpreted as guidelines for investigations related to soil compaction conducted in field conditions in various field conditions. Moreover, perception of the soil condition defined by the ASAE norm (hard – very compact – loose) at which a cone with the given diameter ought to be used, may differ. The general character of information in this respect gives room to interpretation regarding the principles governing performance of measurements and may lead to completely different interpretations of obtained results, and different conclusions.

The aim of the study was to evaluate the influence of the apex angle and cone base area in the penetrometer onto soil compaction measurement results.

MATERIAL AND METHODS

The investigation was carried out in a soil channel (10 × 2 × 1 m, length × × width × depth) filled with sandy clay with the humidity of 7.1–8.0% (on average 7.64%). Conducting the investigation in the channel allowed maintaining repeatability of soil conditions, required to compare particular measurement variants. Before each measurement, soil in the channel was scarified with a set of chisels down to the depth of 30 cm, and subsequently, after levelling of the surface, the soil was rolled over twice to densify it with a smooth cylinder with own weight of 360 kg at the speed of 0.2 $m \cdot s^{-1}$. Subsequently, at three randomly selected spots of the channel, soil samples were taken from the layers of 0–5, 5–10, 10–15 and 15–20 cm using an Eijkelkamp probe with a 100 cm^3 measuring cylinders, which were used to identify the bulk density.

Compaction measurements were performed using the Penetrologger cone penetrometer with electronic recording of the cone resistance force and measurement depth recording at every 1 cm. Compaction measurements were performed by pushing the penetrometer into the soil at the speed of 0.03 $m \cdot s^{-1}$. In order to eliminate so-called soil variability, measurements were performed along the channel, at diagonals of the grid of rectangles (0.4 × 0.6 m) marked on the soil surface (Fig. 1).

Measurements were performed using four end pieces with the apex angle of 30° (K30) and four end pieces with the apex angle of 60° (K60) (Fig. 2). Four repetitions were performed for each measurement variant (base area × cone

FIGURE 1. The Penetrologger cone penetrometer in the soil channel with marked places of compaction measurement places

FIGURE 2. Cone shaped end pieces of Penetrologger penetrometer (S – identification connected with the cone base area, *K* – cone apex angle)

apex angle). Characteristic cone dimensions are specified in Table 1.

Within the set of cone shaped end pieces of the penetrometer, the most similar to the ASAE standard was the end piece identified as S1K30 with the base diameter of 11.28 mm. Proportion of the base area of cone shaped end pieces with

TABLE 1. Characteristic dimensions of cone shaped end pieces of the penetrometer

Penetrometer	Cone base area [cm^2]	Cone diameter [mm]	Apex angle	
			30° (K30)	60° (K60)
			lateral area [mm^2]	lateral area [mm^2]
S1	1.0	11.28	386.1	199.9
S2	2.0	15.96	773.0	400.1
S3	3.33	20.60	1287.7	666.6
S4	5.0	25.23	1931.6	999.1

the apex angle of 30° (K30) to that of end pieces with the angle of 60° (K60) was constant at 1.93 : 1. Penetrometer symbols used in the description, e.g. S1K30, S4K60 denote, respectively: penetrometer with the cone base area of 1 cm^2 and cone apex angle of 30°, penetrometer with the cone base area of 5 cm^2 and apex angle of 60°.

RESULTS

Soil prepared for the investigations was characterised with the density of the measurement layer (0–0.20 cm) of 1.35––1.37 $g \cdot cm^{-3}$ (on average 1.36 $g \cdot cm^{-3}$). Average values of soil compaction, as determined by means of S1, S2, S3 and S4 penetrometers with the cone with the apex angle of 30° (K30) are presented in Figure 3.

Analysis of the values presented in Figure 3 leads to a conclusion that, irrespective of the cone size, all graphs indicate a similar character of soil compaction changes along with measurement depth. Maximum compaction values were shown by particular penetrometers in the layer of 5–9 cm, and compaction decreased along with depth growth. Soil compaction values determined with S1–S4 penetrometers in the layer of 0–20 cm may be described with fourth degree polynomials characterised with high degree of matching with the obtained measurement values (Table 2). Similar observations with respect to the model describing compaction changes in the soil profile were presented by Lejman and Owsiak [2001], who proposed third degree polynomial for sandy and loamy soil. The investigators used a penetrometer with a cone with the base area of 3 cm^2 and apex angle of 60°.

Based on the obtained measurement values it can be concluded that, despite identical preparation of soil in the channel, compaction values determined with the use of penetrometers with particular stone shaped end pieces differ significantly. The highest value of soil profile

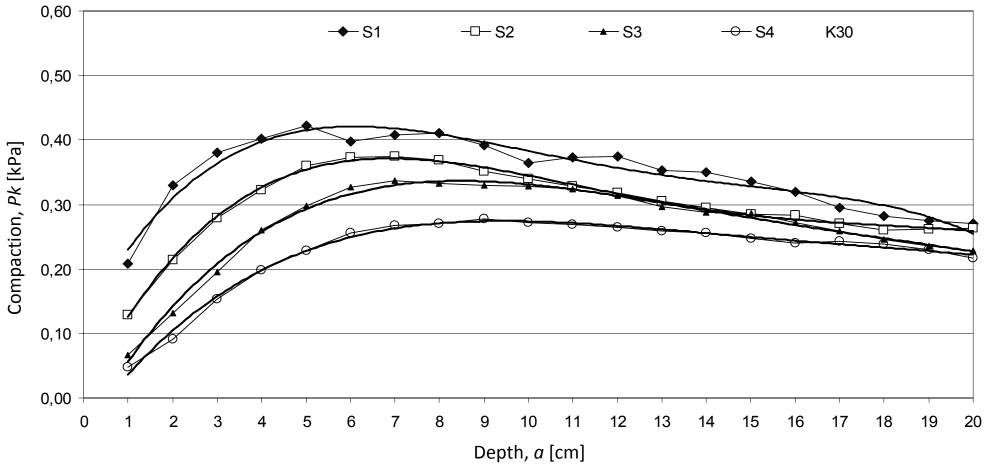

FIGURE 3. Soil compaction changes measured with S1 – S4 penetrometers with the apex angle of 30° (K30) with fourth degree polynomial approximation

TABLE 2. Equations for compaction, determined by penetrometers with the apex angle of 30°

Equations for K30 penetrometers	R^2
$Pk_{S1} = 0.1207 - 2E\text{-}05a^4 + 0.001a^3 - 0.0181a^2 + 0.1268a$	0.941
$Pk_{S2} = 0.0058 - 1E\text{-}05a^4 + 0.0008a^3 - 0.0172a^2 + 0.1366a$	0.995
$Pk_{S3} = -0.0512 - 8E\text{-}06a^4 + 0.0005a^3 - 0.01272a^2 + 0.12a$	0.992
$Pk_{S4} = -0.0475 - 6E\text{-}06a^4 + 0.0004a^3 - 0.0095a^2 + 0.0933a$	0.993

was obtained in the measurements performed by a penetrometer with the smallest cone S1 with the base area of 1 cm^2, whereas penetrometers with higher base areas recorded lower compaction values, suggesting existence of an opposite correlation between reading values and cone base area. A comparative specification of average soil compaction figures obtained with the use of particular penetrometers is presented in Figure 4.

Analysis of compaction changes presented in the figure indicates that the greatest differences in the readings of particular penetrometers concerned the superficial layer of 0–5 cm. As compared with penetrometer S2, penetrometer S1 recorded a compaction value higher by about 64% at the depth of 1 cm, and the difference decreased to about 17% at the depth of 5 cm. In comparison with the compaction value obtained by penetrometer S3, the differences were higher by, respectively, 210% immediately at the surface and 41% at the depth of 5 cm, whereas in comparison with penetrometer S4, compaction differences in the subsurface profile layer were, respectively, 335 and 84%. Along with growth in the cone base area, differences between the readings of particular penetrometers were decreasing. Penetrometer S2 demonstrated higher compaction of the subsurface layer than penetrometer S3 – by about 90% at the depth of 1 cm and about 20% at the depth of 5 cm, whereas in comparison with penetrometer S4 the values were higher by, respectively,

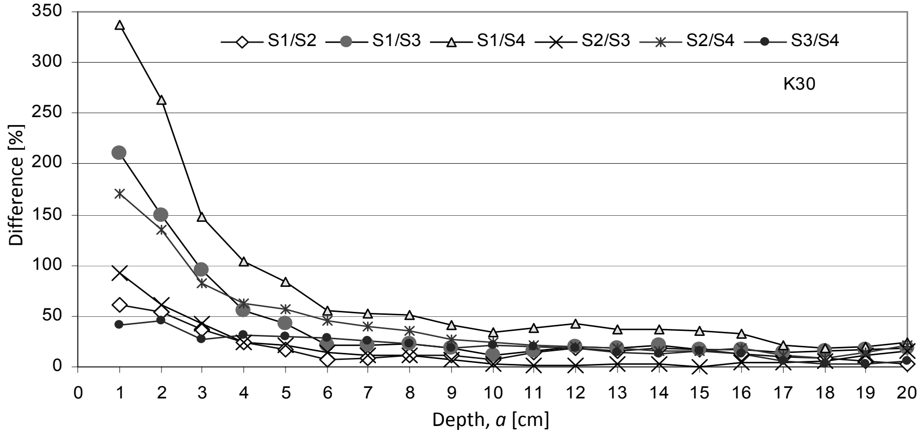

FIGURE 4. Percentage differences between readings of particular penetrometers (K30) in the investigated soil profile

170 and 57%. The smallest differences among the readings were determined between penetrometers S3 and S4 which, for the most compacted superficial layer, were from 45 to 30%, respectively. Taking all four penetrometers into consideration, the difference in readings between them in the 0–5 cm layer was on average 87%, in the 5–10 cm layer it was on average 23%, in the 10–15 cm layer – 18%, and in the 15–20 cm layer – 12%.

Results of soil compaction measurements performed with the use of a penetrometer with cones with a different base area (S1 – S4) and apex angle of 60° (K60) are presented in Figure 5.

Analysing the course of soil compaction changes, one may notice that – similarly to penetrometers with the cone apex angle of 30° – the highest soil compaction value was observed in the 6–9-cm layer. Along with depth growth, differences in readings between penetrometers S1, S2 and S3 were decreasing significantly, whereas the probe with the largest cone base area (S4) demonstrated considerably lower soil compaction throughout the measurement range. As it was in the case of K30 cone probes, the measurement values obtained by penetrometers with the K60 angle may be described with fourth degree polynomials, well matched to the measurement values (Table 3).

Presented in Figure 5 courses of soil compaction changes depending on

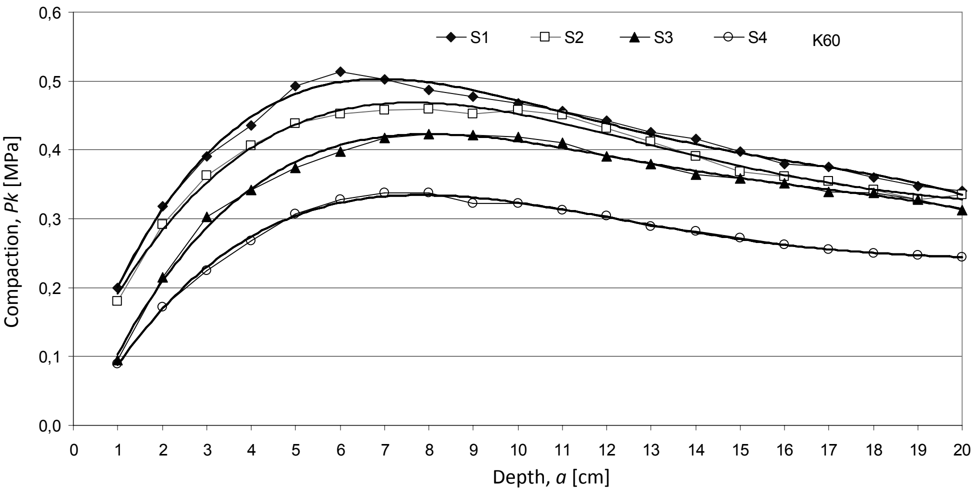

FIGURE 5. Soil compaction (P_k) changes in the function of depth (a) measured with penetrometers S1 – S4 with the apex angle of 60° (K60) with fourth degree polynomial approximation

TABLE 3. Equations for compaction, determined by penetrometers with the apex angle of 60°

Equations for K60 penetrometers	R^2
$Pk_{S1} = 0.0533 - 2E\text{-}05a^4 + 0.0011a^3 - 0.0215a^2 + 0.1685a$	0.992
$Pk_{S2} = 0.0736 - 9E\text{-}06a^4 + 0.0006a^3 - 0.0147a^2 + 0.1315a$	0.999
$Pk_{S3} = -0.0307 - 1E\text{-}05a^4 + 0.0008a^3 - 0.0175a^2 + 0.1513a$	0.994
$Pk_{S4} = -0.0151 - 9E\text{-}06a^4 + 0.0006a^3 - 0.0129a^2 + 0.1155a$	0.996

measurement depth had a similar character and they confirm the previously made observation that use of different cone shaped end pieces differing in terms of dimensions and shape has influence onto the measurement values obtained. Yet, differences between the readings of particular penetrometers were not as high as in the case of measurements performed with penetrometers with the cone apex angle smaller by one half (Fig. 6).

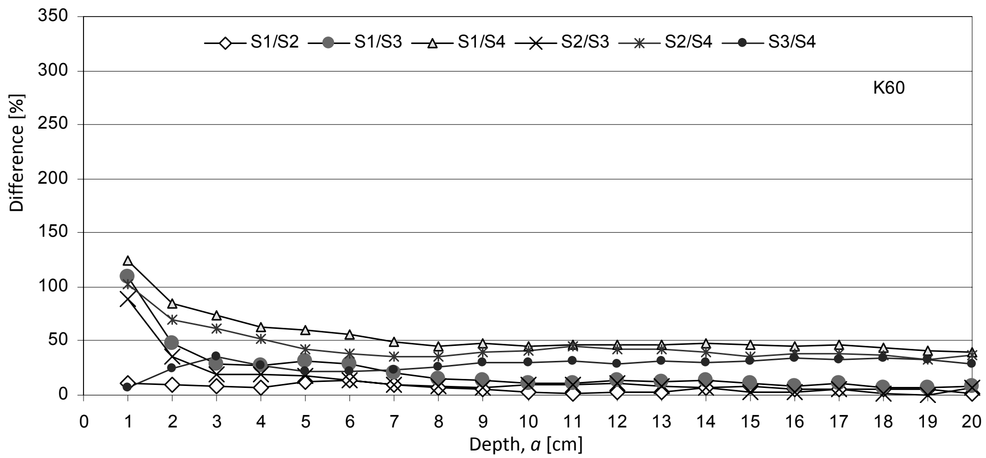

FIGURE 6. Percentage differences between readings of particular penetrometers (K60) in the investigated soil profile

For the sake of comparison, the graph intentionally uses the same range of scale as for the penetrometers with the apex angle of 30°. Analysis of the values presented in the figure leads to the conclusion that – as in the case of the penetrometers with K30 cones – the greatest differences among the readings concerned the superficial layer. Soil compaction values in the superficial layer, as determined by penetrometer S1, were by 9–12% higher than respective values obtained by penetrometer S2 whose cone base area is twice as large. Along with growth in depth, the difference was gradually decreasing to about 1.5% at the depth of 20 cm. As compared with penetrometer S3 with the cone base area larger by over three times, superficial layer compaction levels obtained by penetrometer S1 were by 31–109% higher, whereas differences of above ten percent occurred down to the depth of about 15 cm following which, in the deepest layer, they decreased to the range of 8–10%. In comparison with the penetrometer with the largest cone base area (S4), compaction values obtained by penetrometer S1 in the superficial layer were higher by 60–120%, whereas in the remaining part of the profile, the difference did not change considerably with depth and fell within the range of 40–48%. Taking into account all measurements, readings for the superficial layer differed among particular penetrometers on average by about 44%, whereas for the remaining layers of the investigated profile (5–10, 10–15 and 15–20 cm), average reading differentiation was from 21 to 24%.

The obtained discrepancies in measurement values for the superficial layer influenced evaluation of the average soil compaction throughout the analysed profile. A comparison of average soil compaction values in particular measurement variants, performed with the Multiple Range Tests 95.0 percent Tukey HSD, is presented in Table 4. The test values for penetrometers with the apex angle of 30° (K30), presented in the table, indicate lack of statistically significant differentiation between average compaction values obtained by penetrometers S1 and S2, S2 and S3 as well as S3 and S4, for which the measurement differences were from 12 to 18%. Much higher discrepancies were obtained by comparing average compaction values for the profile, as determined by penetrometers S1 and S3 as well as S1 and S4, where the differences were 29, 8 and 53% respectively, and were statistically significant.

Once the apex angle of the cone was increased to 60° (K60), a similar system of relations was obtained; average soil compaction values in the analysed layer, as determined by penetrometers S1 and S2 (difference 22.7%) and penetrometers S2 and S3 (difference 11.4%), did not differ in a statistically significant way. Penetrometer S3 rendered readings which were higher on average by 36%, whereas penetrometer S4 rendered readings which were higher by almost 76% than values obtained by penetrometer S1. These were significant differences. Significant differences also occurred between compaction values determined by penetrometers S2, S3 and S4 – reading differences were, respectively, 43 and 28%.

TABLE 4. Multiple Range Tests for compaction values in the measurement variants with S1 – S4 cones with the apex angle of 30° (K30) and 60° (K60)

Source		Average	Contrast	Calculation difference	Threshold value
K30	S1	0.3473	S1 – S2	0.0483	0.05199
			S1 – S3	*0.0797	
			S1 – S4	*0.1209	
	S2	0.2990	S2 – S3	0.0314	
			S2 – S4	*0.0726	
	S3	0.2677	S3 – S4	0.0412	
	S4	0.2265			
K60	S1	0.4113	S1 – S2	0.0247	0.05976
			S1 – S3	*0.0624	
			S1 – S4	*0.1398	
	S2	0.3887	S2 – S3	0.0377	
			S2 – S4	*0.1151	
	S3	0.3489	S3 – S4	*0.0774	
	S4	0.2715			

*Statistically significant difference.

A comparative specification of average soil compaction values in the investigated profile, obtained by penetrometers with end pieces characterised with a different apex angle (K30 and K60), is presented in Figure 7.

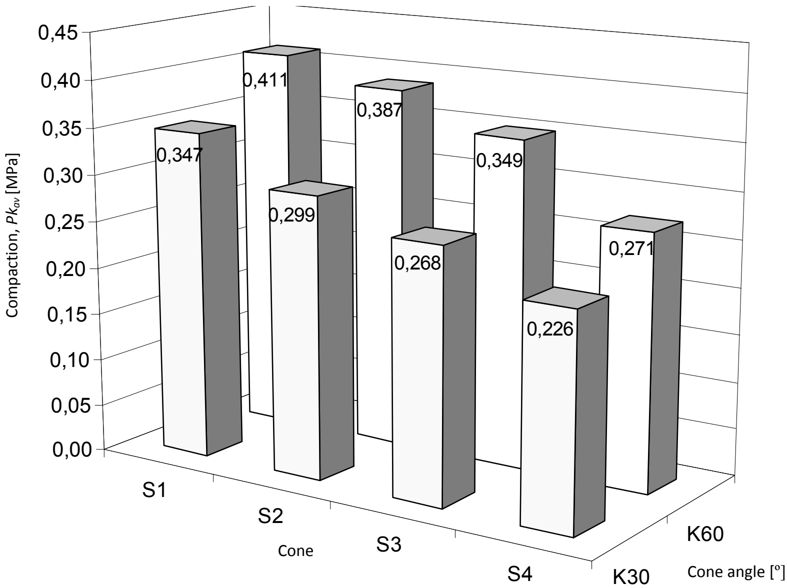

FIGURE 7. Average compaction values (Pk_{av}) of the soil layer investigated by penetrometers with a different cone apex angle

Values presented in the figure clearly indicate considerable influence of the cone apex angle onto obtained soil compaction values. Increase in the cone apex angle from 30 to 60° in case of measurement with penetrometer S1 with the cone base area of 1 cm^2 resulted in increase in the average soil compaction value in the profile by 18.4%, in the case of penetrometer S2 (2 cm^2) by 29.4%, S3 (3.33 cm^2) by 30.2%, whereas in the case of measurements with penetrometer S4 (5 cm^2), the readings increased by about 20%. Except for values obtained by penetrometer S4 – the remaining readings for different cone angles differed in a statistically significant manner.

To be able to compare investigation results, all of the measurement values obtained with the use of two sets of cone shaped end pieces (two apex angles × × four cone base areas) were subjected to statistical analysis. The obtained statistical values demonstrated significant influence of both the cone base area and of the apex angle (Table 5) onto soil compaction readings. It must be reserved, however, that the analysis results concern values obtained for an assumed range of conditions in the soil channel (humidity, bulk density, etc.). In order to increase the scope of comparability of the results of soil investigations carried out with cone shaped penetrometers, the investigation area ought to be extended, taking into account – among others – kind of

TABLE 5. Variance analysis for soil compaction (*Pk*) – sum of squares type III

Source of variation	Sum of squares	Degrees of freedom	Mean square	F_{emp}	*P*
S	0.38284	3	0.12761	213.71	0.0000
K	0.20114	1	0.20114	336.84	0.0000
a	0.62640	19	0.03297	55.21	0.0000
Rest	0.08121	136	0.00060	–	–
Total	1.2916	159	–	–	–

soil, humidity, densification at the time of measurement.

Results of the analysis determining the influence of particular factors onto soil compaction demonstrated significance for each of them at the 95% level of confidence. The results gave grounds for development of a multi-variable regression analysis connecting soil compaction (*Pk*) with measurement depth (*a*), cone base area (*S*) and apex angle (*K*). Analysis results are presented in Table 6.

Results of the conducted analysis allow determination a multi-variable linear regression equation showing the relationship between compaction and three independent variables – in the following form:

$$Pk = -0.0107 \times S + 0.0058 \times K + 0.0068 \times a$$

where:

S – penetrometer cone base area [cm^2];
K – penetrometer cone apex angle [°];
a – measurement depth [cm].

The following coefficient values were obtained for the above equation: R^2 91.47%; adjusted R^2 (for degrees of freedom) 91.36%; estimation standard error 0.0982; total error 0.0799.

Relatively high values of the equation coefficients (R^2, *SEE*, *MAE*) indicate good matching of the model to values obtained in the assumed soil conditions. However, one ought to remember that transferring the above equation into the conditions of a real field, characterised

TABLE 6. Regression analysis for soil compaction (dependent variable *Pk*)

Independent variables	Model coefficients	Standard error	t_α	*P*	
S	0.0107	0.004596	2.3279	0.0212	
K	0.0058	0.000354	16.4973	0.0000	
a	0.0068	0.001207	5.6097	0.0000	
Variance analysis for the model					
Source	sum of squares	degrees of freedom	mean square	*F*	*P*
Model	16.222	3	5.40734	561.05	0.0000
Rest	1.51314	157	0.00964	–	–
Total	17.7352	160	–	–	–

with a different structure and granulometric composition of the soil, humidity and possible influence of other factors which – due to obvious reasons – are not taken into consideration in laboratory conditions (presence of stones, soil organisms, natural cohesion of soil particles, etc.), requires caution and, as mentioned above, ought to be preceded with appropriate investigations with a properly selected scope. Investigations conducted in the soil channel obviously differ from natural conditions, but allow collection of relatively well controlled and comparable results in particular measurement repetitions.

SUMMARY

Relations between soil compaction in the channel, measured with a cone penetrometer, the cone base area and the apex angle may be described with a fourth degree exponential function. Compaction changes within the analysed soil profile, as identified by particular penetrometers differing in terms of shape and dimensions of the working area – irrespective of the cone size – demonstrated a similar course with the measurement depth. Differences within the obtained values, as demonstrated by particular penetrometers, resulted mainly from different resistance values encountered during passage of the cone through the superficial layer – down to the depth of 5 cm, at which the compacting effect of the cylinder was the strongest; on the other hand, in deeper located layers, characterised with lower compaction (Figs 3 and 5), discrepancies in penetrometer readings were no longer so significant. In the evaluation of the whole soil profile, the highest compaction value was demonstrated by penetrometer S1K60, i.e. the one with the smallest cone base area and the angle of 60° (Pk_{av} = 0.411 MPa), whereas the lowest average soil compaction in the profile was demonstrated by penetrometer S4K30 with the largest cone base area and the angle of 30° (Pk_{av} = 0.226 MPa). Thus, measurement values increased along with the base area and apex angle of the cone. Differences between average compaction values determined by penetrometers with the cone apex angle of 30° changed depending on the cone base area by from 11.5 to 18%, and in the case of penetrometers with the angle of 60° they equalled 6 to 28%. Change of the angle from 30 to 60°, depending on the cone base area, resulted in growth in readings of average soil compaction by from 18.4 to 30.2%.

Presented measurement results concern specific conditions created in the soil channel. In field practice, superficial compaction occurs upon a single drive of an agricultural aggregate with low unit wheel pressure onto the soil, immediately after the scarification procedure. Subsequently, as a result of soil deposition and influence of natural external factors, its structure is densified, while compaction of the scarified soil layer increases and equalises. Performance of measurements with such diversified penetrometers may lead to completely different conclusions. A practical example which causing justified doubts may be evaluation of soil condition in the aspect of fulfilment of conditions required for proper development of plants' root systems. Numerous literature sources [Buchter et al. 2004, Beylich et al. 2010]

provide relatively precise values (within the range of 0.3 MPa) concerning threshold resistance posed by various soils to the roots, above which development of the roots is rapidly stopped. Considering encountered discrepancies, use of different cone penetrometers for soil compaction measurements, with the possibility to achieve comparability of results, would require development of models associating parameters concerning measurement conditions and the cone with the penetrometer's readings.

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Streszczenie: *Wpływ geometrycznych parametrów stożka penetrometru na wartości wskazań w pomiarach zwięzłości gleby.* W pracy przedstawiono analizę zmian zwięzłości gleby mierzonej sondą z końcówkami stożkowymi o różnej powierzchni pola podstawy i kącie wierzchołkowym. Badania wykonano w warunkach laboratoryjnych, na glinie piaszczystej przy wilgotności 7,64% i gęstości objętościowej 1,36 $g \cdot cm^{-3}$. Analiza statystyczna całości wyników pomiarowych otrzymanych dwoma zestawami końcówek pomiarowych (dwa kąty wierzchołkowe × cztery pola podstawy stożka) wykazała istotny wpływ na wskazania zwięzłości gleby zarówno wielkości podstawy stożka, jak i kąta wierzchołkowego. Otrzymano ujemną korelację wartości wskazań sondy z polem podstawy stożka a dodatnią z kątem wierzchołkowym.

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