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Impact of soil density on readings of cone penetrometers in soil compaction measurements

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Abstract: *Impact of soil density on readings of cone penetrometers in soil compaction measurements.* Research results have been presented, concerning soil compaction measurements using four probes, differing in terms of the geometric dimensions of the measuring tip. Research was conducted in sandy clay for three soil density levels, amounting to 1.36–1.43–1.50 $g \cdot cm^{-3}$ at humidity level of 7.64%. The research conducted that probes equipped with measurement cone tips with apex angle of 60° indicated higher compaction values in comparison with probes with cones 30°. At soil density of 1.36 $g \cdot cm^{-3}$, the differences in readings amounted on the average to 28%, at soil density of 1.43 $g \cdot cm^{-3}$ – 23%, and at density of 1.5 $g \cdot cm^{-3}$ – 28%. As for changes in soil compaction, probes with cone angle of 60° responded to changes in soil density in more uniform manner. A regression equation was determined, including correlations between soil compaction and its volumetric density, the field base area and the angle of the cone.

Key words: cone penetrometer, dimensions, soil density, soil compaction

INTRODUCTION

The soil, as the biologically active surface layer of the Earth, is the environment for growth and development of plants. A significant impact on plant growth is exerted by physical soil condition, including, in particular, its density and compaction, which determine its physical properties [Buckman and Brady 1971, Baranowski 1980, Jabłoński 1982, Sommer and Petelkau 1990, Krężel et al. 1999]. These parameters are also taken into account in assessment of research conditions, characteristics of changes caused by impact of tools on the soil [Lejman 2008, Buliński et al. 2012]. Soil compaction measurement is usually performed using cone penetrometers [Buliński and Sergiel 2014, Powałka and Buliński 2014], and a standard has been proposed by ASAE [1993], providing two cone sizes – smaller, of base area of 130 mm^2 (recommended for "hard", highly compacted soils) and larger, of base area of 323 mm^2 (for loose soils), of the same tip angle of 30°. The same standard recommends the penetrometer pressing speed of 30 $mm \cdot s^{-1}$. In practice, however, penetrometers of varying base area and tip cone angle values are used, driven [Idkowiak and Kordas 2004] or pressed into soil, using various methods (manually, mechanically), at various speeds (20–50 $mm \cdot s^{-1}$) [Fellenius and Eslami 2000, Lejman and Owsiak 2001, Sudduth et al. 2004, Brenenstuhl 2013, Fountas et al. 2013]. Such diversity in the soil compaction measurement methods provides non-comparable results. Taking this into account, the authors [Klonowski and Buliński 2015] conducted research using a penetrometer with eight different, replaceable cones, allowing for determination of an equation to describe the correlation between soil compaction and geometric parameters of the measurement cones:

$$Pk = -0.107 \times S + 0.0058 \times K + 0.0068 \times a$$

$$R^2 = 91.47\% \quad (1)$$

where:
S – area of the penetrometer cone base [cm^2];
K – penetrometer cone angle [°];
a – measurement depth [cm].

Research was conducted under laboratory conditions for the same soil density. The results of measurements conducted served as a basis for stating that differences in the values obtained by using different penetrometers were mainly due to different resistance in the cone moving through the surface layer – to the depth of 5 cm, which was under the greatest impact of compaction by the roller, while in the deeper layers, characterized by lesser compaction, discrepancies in penetrometer readings were less significant.

The correlation between soil density and its compaction was described by Knittel and Stanzel [1976] using the following equation:

$$BW = 2.48 \times 10^3 \times WG^{-1.93} \times rt^{7.24}$$

$$(r^2 = 0.72) \quad (2)$$

where:
BW – soil resistance [N·cm^{-2}];
WG – humidity [%];
rt – soil density [g·cm^{-3}].

Correlation (2) shows a positive correlation between soil compaction and density and a negative correlation with soil humidity. However, no information is available on how the results of soil compaction measurements, obtained using different penetrometers, would differ in the case of varying soil density.

The objective of the research project was to determine to what extent a change in soil density influences readings of cone penetrometers in soil compaction measurements depending on the dimensions of the penetrometer.

MATERIAL AND METHODS

The investigations were carried out in a soil bin of dimensions of 10 × 2 × 1 m (length × width × depth), filled with sandy clay of humidity ranging from 7.1 to 8.0% (average of 7.64%). A description of the site has been included in earlier publications [Waszkiewicz et al. 2009, Klonowski Buliński 2016]. Before taking measurements, soil in the channel was aerated to the depth of 30 cm, and then, after evening out the surface, it was compacted using a smooth roller of mass of 360 kg, moving at speed of 0.2 m·s^{-1}. In this manner, three levels of compaction were obtained in layer 0–20 cm, of average volumetric density: Go_1 = 1.36, Go_2 = 1.43, Go_3 = = 1.50 g·cm^{-3}. Volumetric density of the soil was determined by collecting samples using an Eijelkelkamp probe with cylinders of volume of 100 cm^3.

For each soil density level, soil compaction was measured with the use of Penetrologger cone penetrometer [Klonowski and Buliński 2016].

Measurements were performed using four cone tips with apex angle 30° (K30) and four cone tips with apex angle 60° (K60). The cones used in research were components of a typical study kit of Eijelkelkamp company, used by many research institutions. For each measurement variant (base area × cone tip angle), four repetitions were performed. Characteristic cone dimensions have been presented in Table 1.

TABLE 1. Characteristic dimensions of the penetrometer cone tip

Probe	Cone base area [cm^2]	Cone base diameter [mm]	Tip 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	1 287.7	666.6
S4	5.0	25.23	1 931.6	999.1

In the set of cone tips used, the one closest to the ASAE standard dimensions was the tip marked as S1 of base diameter of 11.28 mm. The proportion of the lateral area of cone tips with angle of 30° in comparison with tips with angle of 60° was constant and amounted to 1.93 : 1. The designations used in descriptions take into account the penetrometer dimensions. For instance: penetrometer S1K30 means that the cone base diameter was 11.28 mm and the tip angle was 30°.

When processing the measurement results, Statgraphics Plus and Statistica 12 software was used.

RESULTS

Analysis of measurement values obtained for penetrometers with cones of 30° and 60° indicated that at different soil density levels, soil compaction charts in the layer of 0–20 cm were characterized by very similar changes (Fig. 1).

After the initial strong increase in soil compaction to the depth of 5–7 cm, a significant decrease in penetrometer resistance can be noted. These changes reflected the cone crossing through the surface layer, in which, in all measurement variants, the compaction impact of the embankment was the highest. In deeper layers, compaction decreased quickly to reach the level close to the initial value, that is, prior to compacting, and the values of readings for individual penetrometers did not vary significantly. These results confirm the earlier observations of the authors [Klonowski and Buliński 2016] that the highest and statistically significant differences in compaction levels measured by individual penetrometers were associated mainly with varying resistances of passage of the cone through the surface layer. Due to the above, the analysis of penetrometer readings for various soil compaction levels were based on the highest values, that is, for the layer of 1–7 cm.

Average soil compaction values determined using penetrometer S1K30 and S1K60 for three compactness levels have been presented in Figure 2.

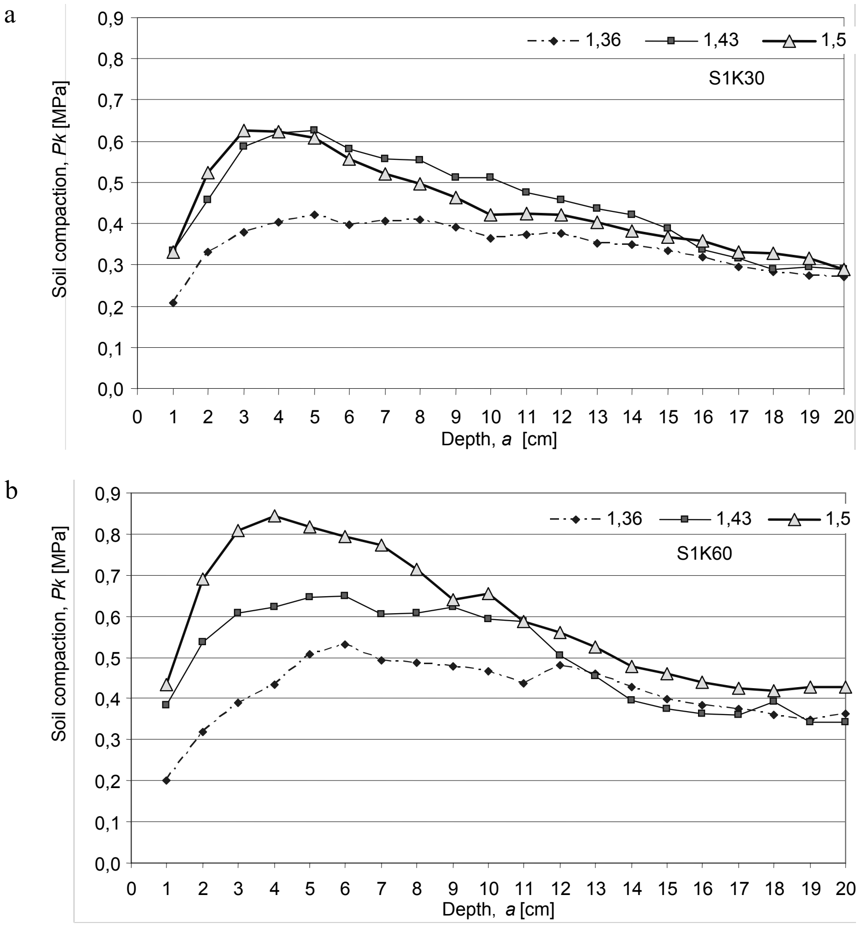

FIGURE 1. Changes in soil compaction for three levels of its density *Go* = 1.36, 1.43, 1.50 g·cm^{-3} measured with penetrometer S1 with cone angle of 30° (a) and 60° (b), (penetrometer designations as in Table 1)

Analysis of the values obtained indicates that penetrometer S1K60 responded much more strongly to changes in soil density in comparison with penetrometer S1 with a tip with angle of 30° (K30). After a change in soil density from 1.36 (level Go_1) do 1.43 g·cm^{-3} (level Go_2), the average soil compaction in the analyzed layer, measured with penetrometer S1K30 increased by 0.173 MPa (that is, about 47%). Upon further increase in soil density to 1.50 g·cm^{-3} (level Go_3), the average compaction of the layer changed only by about 0.004 MPa (that is, about 0.7%), which can be considered to be a minor change within the error limit. Measurements of the same layer, performed using a penetrometer with cone of 60° (S1K60) showed a more uniform, gradually increasing change in compaction, amounting to 0.169 MPa (that is 41%), after compacting the soil to the level of Go_2 and 0.158 MPa (that is 27.3%) upon compaction change to

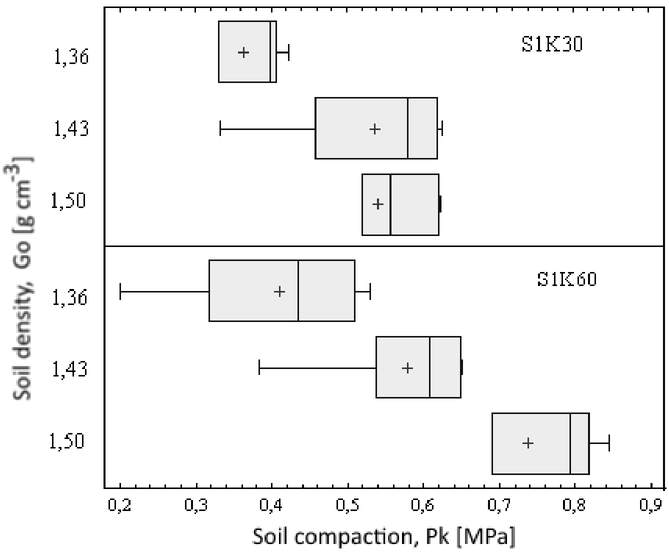

FIGURE 2. Changes in average soil compaction at three compactness levels, determined by penetrometers S1 with varying cone tips (penetrometer designations as in Table 1)

Go_3. It can thus be hypothesized that for the soil density levels applied, penetrometers equipped with a cone tip with opening angle of 60° (K60) would reflect the changes in compaction due to increased volumetric density more precisely. The measurement results obtained indicate that at varying soil density values (1.36–1.43–1.50 g·cm^{-3}), the average soil compaction values for the layer under concern measured by penetrometer S1K60 were greater than indicated by S1K30 respectively by 12.8%–7.7% and 36.2%. Statistical analysis of all results for the layer of 1–7 cm, performed using the multiple range tests and Tukey's method HSD showed that the average compaction values, determined using penetrometer S1 with tip K30 and K60 differed in a statistically significant manner only at the highest level of soil density (1.50 g·cm^{-3}), that is, Go_3.

Changes in compaction measured by S2K30 were similar to those measured using S1K30 (Fig. 3).

Upon soil density increase from 1.36 to 1.43 g·cm^{-3} (from Go_1 to Go_2), soil compaction increased by 0.12 MPa, that is, more than 41%, while further density increase to 1.50 g·cm^{-3} (to Go_3) did not result in increased of soil compaction (<1%), which confirms the observations made when making measurements with penetrometer S1K30. In the measurement variant with tip K60, changes in soil compaction were more visible and progressing along with density increase throughout the entire measurement range. Changes in soil density from Go_1 to Go_2 and further to Go_3 led to increase in soil compaction, respectively, by 0.107 MPa (29%) and 0.030 MPa, that is 6.2%. In comparison with penetrometer S2K30, compaction measured with

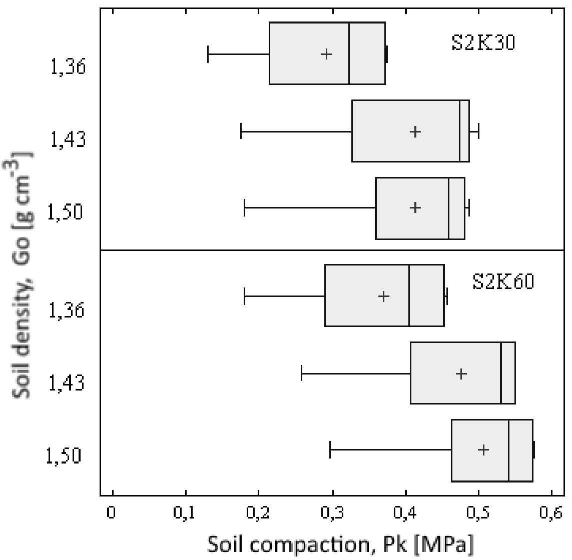

FIGURE 3. Changes in average soil compaction at three compactness levels, determined using S2 penetrometers with varying cone tips (penetrometer designations as in Table 1)

penetrometer S2K60 at density values of 1.36, 1.43 and 1.50 g·cm^{-3} were greater, on the average, by 26.3, 15.4 and 22.5%, respectively.

Statistical analysis of results of measurements performed using penetrometers S2 showed that despite some differences in soil compaction levels, these were not statistically significant for soil density levels (Go_1–Go_2–Go_3) or for the cone tips (K30 and K60).

Examining the results of measurements performed using penetrometers S3 (Fig. 4), it can be noted that at this diameter of the working tip base, both at the cone opening angle K30 and K60, the changes recorded in the average compaction level in the soil layer examined increase systematically and incrementally along with increase of its volumetric density.

Measurements performed using penetrometer S3K30 indicated that after increasing soil density from 1.36 to 1.43 g·cm^{-3}, the average compaction of the layer of 1–7 cm increased by 0.096 MPa, that is 41%. This result is similar to compaction results obtained using penetrometer S2K30. Further increase in soil density (to Go_3 = 1.5 g·cm^{-3}) led to increased compaction of the layer by 0.069 MPa, that is, by more than 21%, which, in comparison with the readings obtained by using penetrometer S2K30, constitutes a significant difference. The measurement values of soil compaction obtained using penetrometer S3 with a cone tip with opening angle of 60° (S3K60) showed a similar pattern of changes upon density increase. Changes in soil density from 1.36 to 1.43 and then to 1.5 g·cm^{-3} (Go_1, Go_2, Go_3) led to increase in its compaction by 0.093 and 0.091 MPa, which corresponded with percentage changes by 30.5 and 22.7%, respectively.

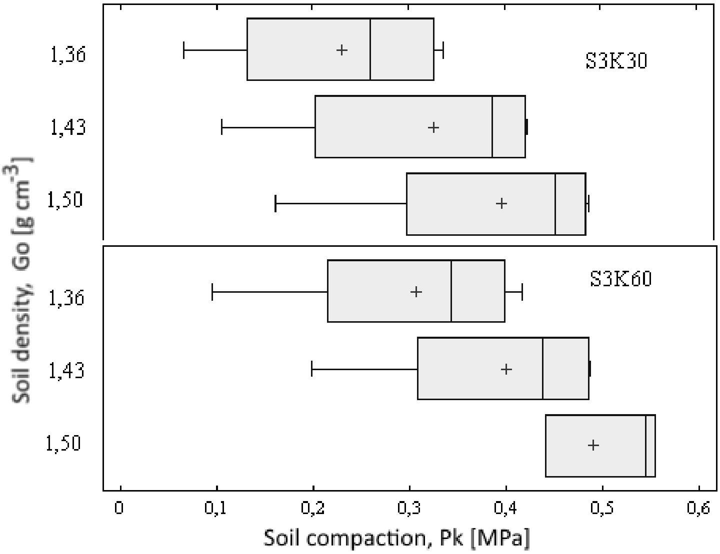

FIGURE 4. Changes in average soil compaction at three compactness levels, determined using penetrometers S3 with different cone tips (penetrometer designations as in Table 1)

Probe S3 with cone tip K60, under the same conditions of performance of measurements at soil density of 1.36, 1.43 and 1.50 g·cm^{-3}, showed higher compaction levels in comparison with penetrometer with tip K30, by 32.7, 22.2 and 23.7%, respectively.

A comparison of individual group average soil compaction values, obtained using S3 penetrometers, revealed no significant differentiation of readings both for volumetric density and for the opening angle of the cone tip.

Changes in soil compaction measured with penetrometer S4 (Fig. 5) with tip K30 were very similar to those observed in measurements performed using S3.

The gradual increase in density from Go_1 to Go_2 and to Go_3 corresponded with increase in compaction by 0.075 and 0.066 MPa, respectively, that is by 42 and 26%, respectively. In measurements conducted using penetrometer S4 with cone tip K60, changes in soil compaction for the same soil volumetric density levels were also greater for soil density increase from Go_1 to Go_2 in comparison with Go_2 to Go_3, amounting to 0.12 and 0.038 MPa, respectively, which corresponded with increase by 50 and 10.4%. On the basis of comparison of the soil compaction values, it can be concluded that penetrometer S4, equipped with tip K60, like in the previously examined variants, showed higher values under the same soil conditions as the penetrometer with tip angle of 30° (K30), on the average, by 39.1% at soil density Go_1, 46.9%, at soil density Go_2 and 28.3% at soil density Go_3. Analysis of overall results obtained using penetrometers S4 indicated that also in this measurement variant, differences between group averages were statistically insignificant both between individual density values and the cone sizes (K30 and K60).

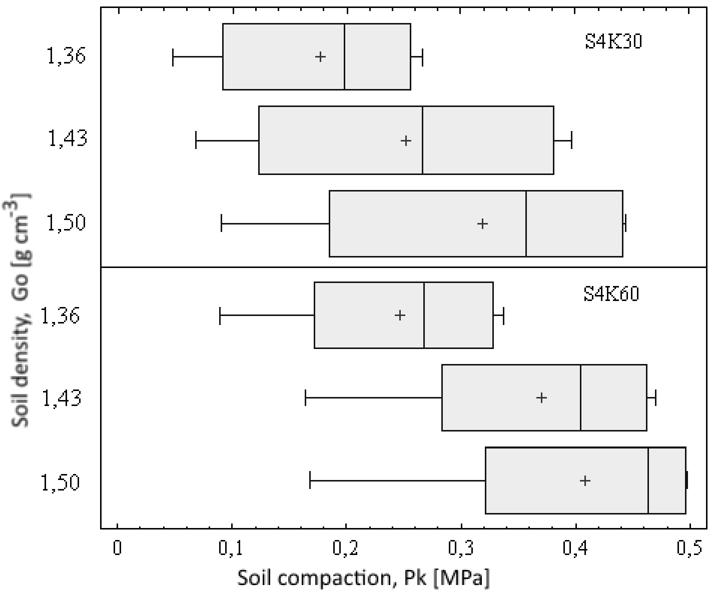

FIGURE 5. Changes in average soil compaction at three compactness levels, determined using penetrometers S4 with different cone tips (penetrometer designations as in Table 1)

The research results presented illustrate variability of readings of individual penetrometers at varying soil compaction levels, indicated by volumetric density. In the cases analyzed (except for measurement variant with penetrometer S1 – Fig. 2), no statistically significant differences were obtained for group average values of soil compaction at the compactness levels applied. Soil compaction values obtained in all measurement variants indicate clearly higher values obtained from measurements using probes with cone tips of opening angle of K60. In practical applications, under the conditions of the production field, characterized by substantial variability, differences in soil compaction may turn out to be much greater and statistically significant. The above conclusions are supported by the breakdown of all measurement results, obtained for different soil density values (Fig. 6).

Analyzing the values, presented in Figure 6, one can note that with increasing density of the soil increases its compaction.

The least sensitive to soil density changes were penetrometers S4 with the greatest cone base area. In comparison with these, penetrometers S3, for the same soil density change ranges, gave readings higher on the average by 16 to 27%, penetrometers S2 – from 27 to 56%, and penetrometers S1 – from 75 to 83%. Penetrometers with cone tip of 60° provided higher readings throughout the entire measurement range.

A comparison of average values of readings for individual penetrometers, obtained for the entire soil compactness range (Fig. 7) indicates that the measurement values of soil compaction decreased

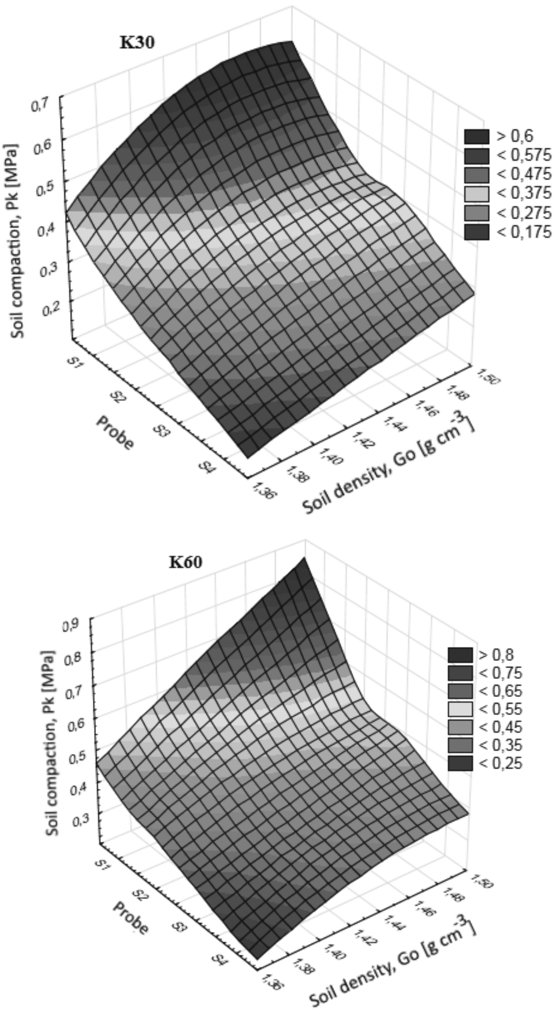

FIGURE 6. Changes in average soil compaction read by different penetrometers depending on soil compactness

along with increase in the penetrometer cone base area. At the same time, average readings of penetrometers with cone tip K60 were higher by 20–21–25–37%, respectively, than those received by penetrometers equipped with cone tip K30.

Statistical analysis of measurement results, conducted using the multiple range test method by Tukey HSD 95%, indicated that there are statistically significant differences (Fig. 7) between average soil compaction values (Fig. 8).

Although out of 28 comparison variants, only 7 (that is 25%) differ in a significant manner; however, taking into account the natural soil variation in the field (mosaicity, dry soil particles, uneven surface tilling), a comparison of readings of these penetrometers may give entirely different results.

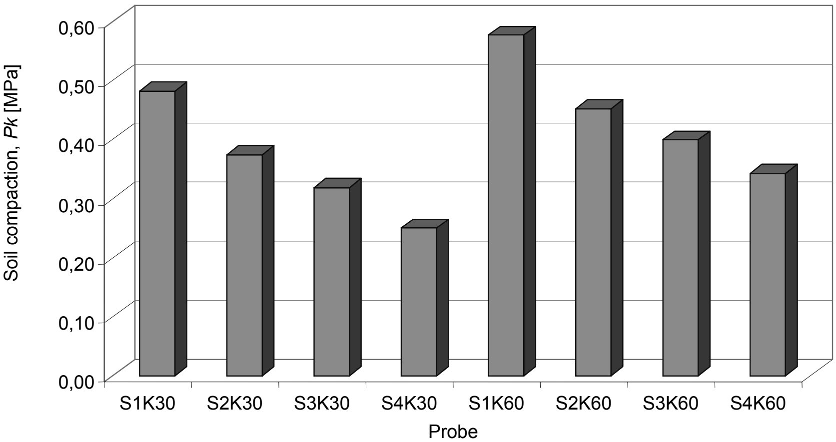

FIGURE 7. Average soil compaction values obtained by different penetrometers throughout the entire soil compactness range (penetrometer designations as in Table 1)

	S1K30	S2K30	S3K30	S4K30	S1K60	S2K60	S3K60	S4K60
S1K30								
S2K30								
S3K30					X	X		
S4K30					X	X	X	
S1K60								
S2K60								
S3K60					X			
S4K60					X			

FIGURE 8. Matrix of significance of differences in average compaction values determined using different penetrometers for the range of measurement applied (penetrometer designations as in Table 1)

Analysis of overall average group compaction values indicated that in measurements performed at varying levels of soil density of 1.36–1.43–1.5 g·cm^{-3}, penetrometers with cone tip K60 (60°) showed compaction higher by 12.8–46.9% (on the average, 26%) in comparison with penetrometers with cone tip K30 (30°). At the same time, measurement results indicate that despite the even change in soil density, compaction increments read by different penetrometers were not similar. At density increase from 1.36 to 1.43 g·cm^{-3} (from Go_1 to Go_2) in the case of probes with tip K30, the change in average group compaction amounted to 42.8% on the average. Upon further density increase to 1.5 g·cm^{-3} (from Go_2 to Go_3), change in soil compaction was almost four times lower, amounting to 11.8%, and the average values for penetrometers S1 and S2 were close to 0.

Changes in average soil compaction values, determined using penetrometers with tip K60, amounted to 37.5 and 16.7%, respectively, which also confirms this trend of lower readings upon soil density increase.

In order to determine the probability of differences between group average values by various independent factors (soil density, cone base area, cone tip angle), a variance analysis was conducted. The results of variance analysis using the sum of squares method type III have been presented in a Table 2.

The units of individual variables in the equation are as described in Table 2.

Assessment of the equation coefficient indicates that the parameter with the highest statistically significant impact on soil compaction is its density. In the scope of research conducted, the most substantial changes in measurement values of soil compaction were associated with a change in the cone base area. Increase in the cone base area by 1 cm^2 (from 1 to 4 cm^2) leads to decreasing of the soil compaction measurement result by 0.22 MPa, at the constant values of the remaining parameters (cone diameter, soil density). On the other hand, upon change of the cone tip angle by 30° (from 30 to 60°), compaction increases only by 0.09 MPa.

TABLE 2. Variance analysis for soil compaction (*Pk*)

Source	Sum of squares	Degrees of freedom	Average square	$F_{\alpha=0.05}$	*p*
Go	0.130015	2	0.0650074	58.02	0.000
S	0.17531	3	0.0584367	52.15	0.000
K	0.0448935	1	0.0448935	40.07	0.000
Rest	0.0190478	17	0.00112046	–	–
Total	0.369266	23	–	–	–

where: *Go* – soil density [g·cm^{-3}], *S* – cone base area [cm^2], *K* – cone tip angle [°].

The result of this analysis allow for stating that at test value $p < 0.05$, each of the factors applied (*Go*, *S*, *K*) had significant impact on soil compaction at confidence coefficient of $1 - \alpha = 95\%$. The results of this analysis served as a basis for determination of a regression equation, describing the correlation between soil compaction and the penetrometer parameters and soil density in the following format:

$$P_k = -1.382 + 1.262 \times Go + 0.003 \times K - 0.055 \times S \quad (3)$$

where:
$R^2 = 89.7\%$;
$SEE = 0.0467$;
$MAE = 0.02865$.

The equation (3), based on average group values of soil compaction, can be confirmed for the scope of research conducted, that is, using cone penetrometers with the assumed working parameters *S* and *K*, in sandy clay of average humidity of 7.64%, volumetric density of 1.36–1.5 g·cm^{-3}, prepared for measurements under laboratory conditions.

SUMMARY

The measurements conducted were aimed at determining of the extent, in which soil compaction measurement results for different soil compactness values would change, if performed using a cone penetrometer with various cone tops. Finding the answer to this question would, on the one hand, allow for better adjustment of the cone tip to the field conditions; on the other hand, it would bring us closer to the ability to compare research results obtained using various penetrometers. In the light of the available literature, this problem remains unsolved. Research was intentionally conducted under laboratory conditions in order to ensure repetitive soil conditions in terms of structure uniformity, compactness and humidity.

The research conducted showed that under the same soil conditions, results of measurements using penetrometers S1-4 with K30 and K60 tips differed significantly. Increase in soil density led to an increase in its compaction, however, the pace of these changes depended on the diameter and tip angle of the cone. Penetrometers equipped with measurement cones of opening angle of 60° showed higher compaction values in comparison with penetrometers with cone angle of 30°. In a decisive majority of all cases, the difference in readings of both types of cone tips increased along with the cone base diameter. At soil density of 1.36 $g\cdot cm^{-3}$, differences in readings ranged between 12.8 and 39% (on the average 28%), while at density of 1.43 $g\cdot cm^{-3}$, these differences ranged from 7.7 to 46.9% (on the average, 23%) and at density of 1.5 $g\cdot cm^{-3}$ – from 22.5 to 36.2% (on the average, 28%). It can also be noted that penetrometers with cone K60 responded to compaction changes more uniformly in terms of increase in the measured value. It can thus be assumed that upon the soil compaction levels applied, the penetrometers equipped with cone tips of opening angle of 60° (K60) reflected its condition caused by changes in volumetric density more accurately. Under the test conditions applied, all variables (cone angle and diameter and soil density) exerted statistically significant impact on the compaction value measured. The regression equation developed includes correlations between the two variables, taking into account the limitations resulting from the humidity applied, the soil compaction range, as well as lack of variability typical for a natural field. A parameter, which is characterized by the highest statistically significant impact on compaction is soil density. In the context of the research conducted, the highest changes in measurement values of soil compaction were associated with a change in the cone area. It can be hypothesized that an equally significant component is soil humidity, which acts on the cone surface like a “lubricant”, and the soil particles move along the cone surface during measurement. However, broadening of the scope of research would be required to take this variable into account.

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Streszczenie: *Wpływ gęstości gleby na wskazania sond stożkowych w pomiarach zwięzłości.* Przedstawiono wyniki badań zwięzłości gleby wykonane na glinie piaszczystej z wykorzystaniem czterech sond różniących się geometrycznymi wymiarami końcówki pomiarowej. Badania przeprowadzono na glinie piaszczystej dla trzech poziomów jej zagęszczenia wynoszących 1,36–1,43––1,50 $g \cdot cm^{-3}$, przy wilgotności 7,64%. Uzyskane wyniki wykazały, że sondy wyposażone w stożek pomiarowy o kącie rozwarcia 60° wykazywały większe wartości zwięzłości niż w tych samych warunkach sondy ze stożkiem 30°. Przy gęstości gleby 1,36 $g \cdot cm^{-3}$ różnice te wynosiły średnio 28%, przy gęstości 1,43 $g \cdot cm^{-3}$ 23%, a przy gęstości 1,5 $g \cdot cm^{-3}$ – 28%. Sondy ze stożkiem wierzchołkowym 60° reagowały na zmiany zagęszczenia gleby bardziej równomiernie niż sondy ze stożkiem 30°, w rozumieniu przyrostu mierzonej wartości. W przyjętych warunkach badań wszystkie czynniki zmienne (kąt i średnica stożka oraz gęstość gleby) miały wpływ statystycznie istotny na mierzone wartości zwięzłości. Wyznaczono równanie regresyjne obejmuje zależności między zwięzłością gleby a jej gęstością objętościową, polem podstawy stożka i kątem wierzchołkowym stożka.

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