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Influence of soil humidity level onto readings of cone penetrometers in compaction measurements

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Abstract: *Influence of soil humidity onto readings of cone penetrometers in compaction measurements.* The study presents results of soil compaction measurements on sandy clay with the use of four penetrometers differing in terms of geometrical dimensions of the measurement end piece. The investigation was conducted on sandy clay with the bulk density of 1.5 $g \cdot cm^{-3}$, at the humidity levels of 7.64 and 10.4%. Compaction was determined for the superficial layer of 1–7 cm. The conducted measurements demonstrated that penetrometers with a cone shaped end piece with the apex angle of 30°, in the conditions of identical bulk density of the soil, but once its humidity increased from 7.64 to 10.4%, demonstrated – on average – lower soil compaction by 35.5%; however, three out of four penetrometers demonstrated a compaction reduction by over 39 to 40.8%. In the same soil conditions, penetrometers with the apex angle of 60° rendered much higher readouts than penetrometers with K30 cones, whereas growth in soil humidity from 7.64 to 10.4% resulted in an average compaction reduction by 32.9%. The influence of soil humidity level onto its compaction turned out to be statistically significant in measurements with penetrometers with the cone base area of 1 and 3.33 cm^2 and the apex angle of 30°, as well as with penetrometers with the cone base area of 1, 2 and 3.33 cm^2 and the apex angle of 60°. A linear regression model was developed to demonstrate the relationship between soil compaction and humidity, measurement depth and penetrometer cone parameters.

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

INTRODUCTION

Soil density and humidity are among the most important factors allowing growth and cropping of plants [Buckman and Brady 1971, Jabłoński 1982, Krężel et al. 1999]. Moreover, humidity has significant influence onto the soil's susceptibility to densification [Soane et al. 1981, Etana and Håkansson 1994, Mosaddeghi et al. 2000]. According to Lejman and Owsiak [2001], the relationship between density and compaction may be described by a power function with the value of average absolute error up to 5% depending on the compaction measurement method. These soil properties are included in descriptions of investigation conditions, in overviews of changes caused by the influence of tools onto the soil [Lejman 2008, Buliński and Niemczyk 2009, 2015, Buliński et al. 2012, Buliński and Sergiel 2014, Powałka and Buliński 2014]. 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 [Lejman and Owsiak 2001, Sudduth et al. 2004, Brennenstuhl 2013, Fountas et al. 2013]. This diversity of measurement methods in different conditions of soil densification and humidity may lead to differences with respect to obtained values, making soil compaction figures obtained in this way difficult to compare. From the investigation conducted by Klonowski and Buliński [2016] it results that in soil conditions identical in terms of densification, density measurements performed with penetrometers differing in terms of size of the measurement cone may render completely different values. Moreover, no information is available regarding how the compaction measurement results performed in such soil conditions will differ in case of humidity change.

This investigation, constituting extension of the problem undertaken previously [Klonowski and Buliński 2016], is expected to provide information regarding the degree of influence of soil humidity change onto readings of cone penetrometers in soil compaction measurements.

MATERIAL AND METHODS

The investigation was carried out in a soil channel (10 × 2 × 1 m, length × × width × depth) filled with sandy clay, at two average humidity levels of the measurement layer 7.64 and 10.64%. A description of the investigation station is contained in previous publications of the authors [Waszkiewicz et al. 2009, Klonowski and Buliński 2015]. Before measurements, soil in the channel was scarified down to the depth of 30 cm and subsequently, after levelling of the surface, the soil was densified by rolling it over using a smooth cylinder with own weight of 360 kg at the speed of 0.2 $m \cdot s^{-1}$, which allowed average densification of the 0–20 cm measurement level at *Go* = = 1.5 $g \cdot cm^{-3}$. As in the authors' previous investigations [Klonowski and Buliński 2016], because of the highest and statistically significant differences in terms of compaction obtained during passage of the cone through the superficial layer, the analysis considered readings for the 0–7 cm profile.

Bulk density of the soil was determined by picking samples with an Eijkelkamp probe with a 100 cm^3 measuring cylinders. Soil compaction was measured using the Penetrologger cone penetrometer in compliance with the methodology described in Klonowski and Buliński [2016].

Measurements were performed using four end pieces with the cone apex angle of 30° (K30) and four end pieces with the cone apex angle of 60° (K60). Four repetitions were made for each measurement variant (base area × cone apex angle). Characteristic cone dimensions are specified in Table 1.

Identifications used in the descriptions consider the penetrometer dimensions – for example: penetrometer S1_K30 means that the penetrometer had a cone with the base diameter of 11.28 mm and apex angle of 30°.

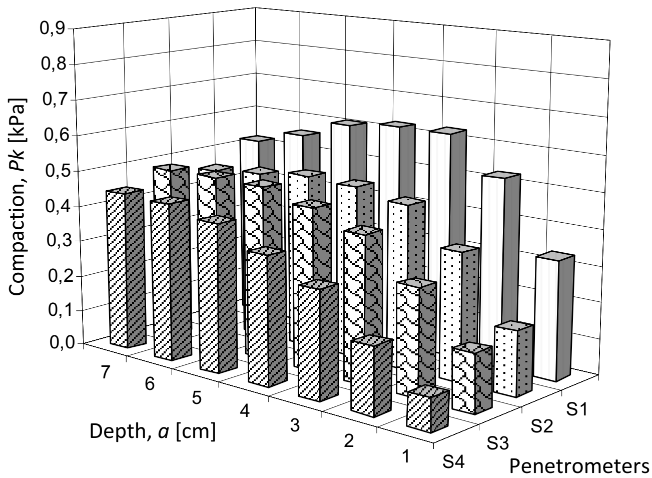
RESULTS

Results of soil compaction measurements with the use of penetrometers with the apex angle of 30° (K30) are presented in Figure 1.

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

Penetrometer	Cone base area [cm^2]	Cone base 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

a



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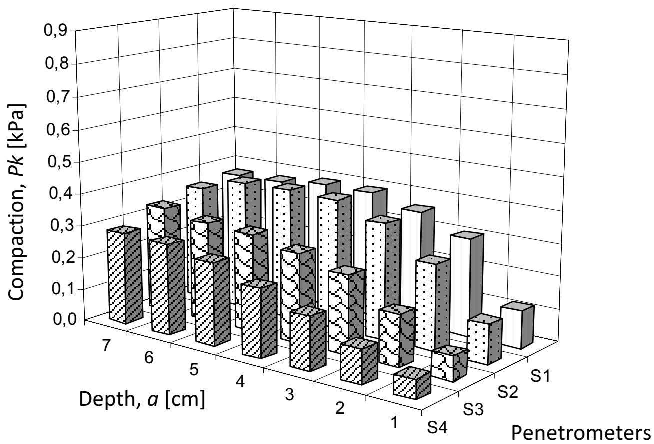

FIGURE 1. Soil compaction changes measured by penetrometers with a cone shaped end piece with the apex angle of 30° at soil humidity of 7.64% (a) and 10.4% (b)

A comparison of the presented graphs leads to the conclusion that there exists an opposite relationship between soil compaction values and cone sizes. At the humidity level of 7.64%, the highest readings were definitely obtained with penetrometer S1 – penetrometer with the smallest cone. Humidity increase did not render such unambiguous differences in the readings of particular cones, with penetrometers S1 and S2 cm rendering similar compaction values. Based on analysis of the measured values it can be concluded that after soil humidity increase from 7.64 to 10.4%, all penetrometers showed much lower compaction, with differences in readings covering the whole measurement depth. In the case of penetrometer S1, readings at the humidity level of 10.4% were lower, on average, by 0.212 MPa, i.e. 40.7% than at the humidity of 7.64%. Penetrometer S2 with a cone twice as large, showed lower soil compaction after humidity increase by, on average, 0.082 MPa, i.e. 21.2% – nearly two times less than penetrometer S1.

Based on comparison of readings of penetrometer S3 it can be seen that in case of soil with higher humidity the readings were lower, on average, by 0.154 MPa, i.e. by 40.7% – as in the case of measurements performed with penetrometer S1. Penetrometer with the largest cone shaped end piece, S4, showed a lower soil compaction value, on average, by 0.124 MPa, i.e. by over 39%, after humidity increase from 7.64 to 10.4%.

Considering all the penetrometers used in the investigation (S1 – S4) with the apex angle of 30°, one may conclude that in case of identical bulk density of the soil, a humidity increase by 40% resulted in a compaction decrease by, on average, 35.5%, with three, four penetrometers demonstrating compaction reduction by over 39 to 40.8%. The location, scattering and shape of distribution of the compaction values measured by cones with the apex angle of 30° at two soil humidity levels is presented in the graph in Figure 2.

Analysis of the values presented in the value graph shows noticeable influence of soil humidity onto penetrometer readings, expressed as the difference in the location of data blocks. One may also claim that, except for one measurement

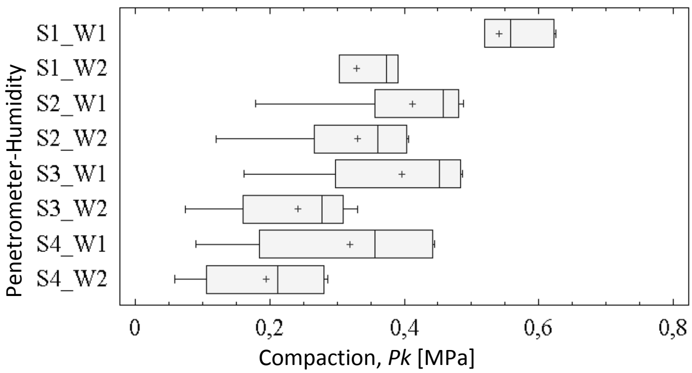

FIGURE 2. Soil compaction changes and their distribution in measurements by penetrometers with the apex angle of 30° at two soil humidity levels

variant (S1_W1), all the others are characterised with a clear left-sided asymmetry of data distribution and high scattering of measured values.

At both soil humidity levels, penetrometer S1 with a K30 cone showed the highest concentration of readings, and the value of scattering, especially in the case of the lower humidity level, increased along with dimensions of the cone shaped end piece. This phenomenon is not favourable, as in case of a high standard deviation, operating with a data set average value may lead to increase in the error rate and incorrect interpretations of penetrometer readings.

Results of the statistical analysis performed with the method of significance test of difference in average values of soil compaction measurements at two humidity levels, obtained with penetrometers with a 30° apex angle cone, are presented in Table 2.

Analysis results show that, in case of identical soil densification, humidity increase led to a statistically significant differentiation of measured values obtained from penetrometers S1 and S3 with a 30° cone shaped end piece. Differences in soil compaction values measured with penetrometers S2 and S4 at two humidity levels were smaller and statistically insignificant.

The influence of soil humidity onto readings of penetrometers with the apex angle of 60° (K60) in compaction measurements is presented in Figure 3.

A comparison of the above graphs leads to the conclusion that, in the same conditions, penetrometers with a cone shaped end piece with the apex angle of 60° (K60) demonstrated much higher compaction values than penetrometers with K30 cones. At the soil humidity of 7.64%, the highest measured values were those of penetrometer S1, whereas the lowest values were those of penetrometer S4. The other penetrometers recorded intermediate values. As it was the case with penetrometers with a smaller cone (K30), humidity growth resulted in a noticeable decrease in measured values, especially in the case of penetrometer S1. As with the K30 cone penetrometer,

TABLE 2. Statistical analysis of soil compaction measurement results performed by penetrometers with a 30° apex angle cone

Cone angle	Penetrometer	Soil humidity	Average compaction [MPa]	t_{cal}	*P*-value
30°	S1	W1	0.541286	3.9268*	0.002010
		W2	0.329143		
	S2	W1	0.412429	1.40844	0.184378
		W2	0.330571		
	S3	W1	0.396429	2.63386*	0.021819
		W2	0.242143		
	S4	W1	0.318714	2.01805	0.066512
		W2	0.194286		

*Statistically significant difference at the confidence level of 95%.

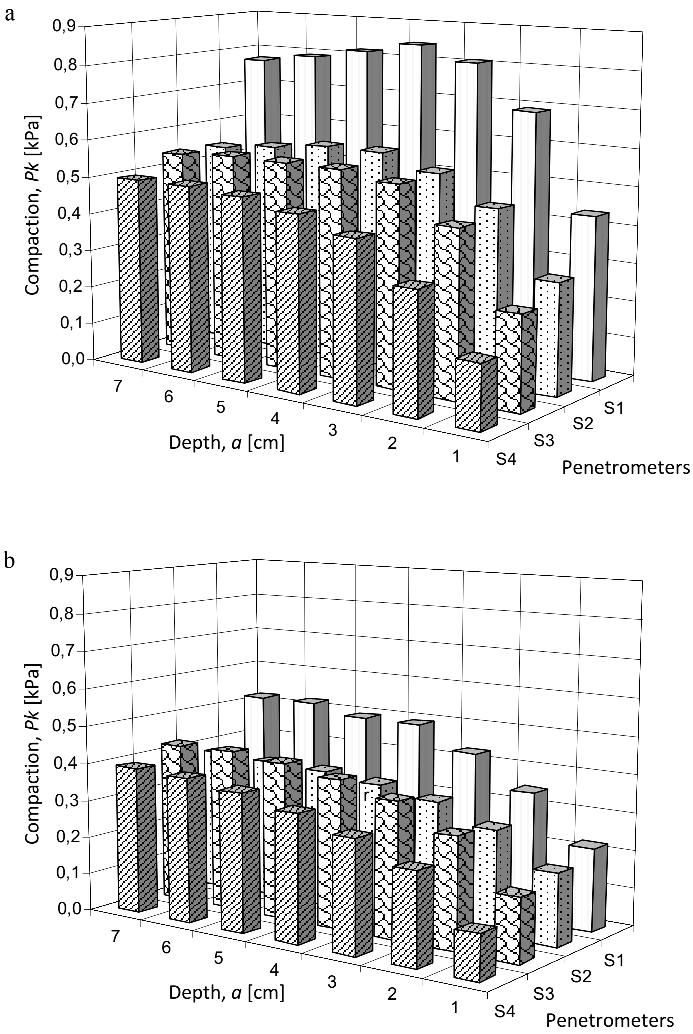

FIGURE 3. Soil compaction changes measured by penetrometers with a cone shaped end piece with the apex angle of 60° at soil humidity of 7.64% (a) and 10.4% (b)

differences in readings between penetrometers S2 and S3 were not clearly oriented at higher humidity.

A comparison of readings of particular penetrometers leads to the conclusion that, after soil humidity increase, compaction values measured with penetrometer S1 were lower, on average, by 0.307 MPa, i.e. 42.2%. As far as the other penetrometers are concerned, reading differences were smaller. On more humid soil (10.4%), compaction values measured with penetrometer S2 were lower, on average, by 0.18 MPa, i.e. 35.8%, whereas respective values for penetrometer S3 were 0.34 MPa, i.e. 28%, and for penetrometer S4: 0.102 MPa, which reflected reduction of the readings by 25.5%.

Considering readings of all penetrometers with the apex angle of 60°, one may claim that growth in soil humidity from 7.64 to 10.4% on soil with uniform bulk density resulted in average compaction reduction by 32.9%; the reduction is on a similar level as in the case of measurements performed with K30 cone penetrometers.

The location, dispersion and shape of distribution of the compaction values measured by cones with the apex angle of 60° at two soil humidity levels is presented in the graph in Figure 4.

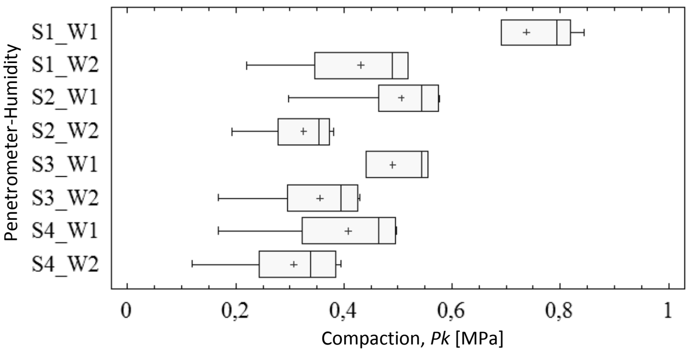

FIGURE 4. Soil compaction changes and their distribution in measurements by penetrometers with the apex angle of 60° at two soil humidity levels

Analysis of values presented in the figure leads to the conclusion that – as in the case of measurements performed at lower soil humidity – penetrometer S1 showed the highest soil compaction value at both humidity levels, and the influence of soil humidity on its readings was the greatest. Another similarity is the left-sided asymmetry in distribution of the property, without extreme, right-sided observations. Asymmetrical distribution of data confirms the thesis that resistance encountered by the cone shaped end piece of the penetrometer during passage through the top soil layer is decisive for the degree of differences among the readings of particular penetrometers.

Results of the statistical analysis of soil compaction measurements at two humidity levels, obtained with penetrometers with a 60° apex angle cone (K60), are presented in Table 3.

Results presented in the table allow the conclusion that, after change in soil humidity, soil compaction values measured with penetrometers S1, S2 and S3 with a K60 cone shaped end piece changed in a statistically significant manner, whereas differences in soil compaction measured with penetrometer S4 were smaller and statistically insignificant. This observation confirms the need to develop appropriate recalculation coefficients in order to be able to obtain comparable results of the compaction measurements with the use of penetrometers equipped with different cone shaped end pieces.

In order to determine the likelihood of particular independent factors (soil humidity, cone base diameter, cone apex angle) becoming the reason of differences between the observed group average values of soil compaction, the variance

TABLE 3. Statistical analysis of soil compaction measurement results performed by penetrometers with a 60° apex angle cone

Cone angle	Penetrometer	Soil humidity	Average compaction [MPa]	*t*-statistic	*P*-value
60°	S1	W1	0.737429	4.49779*	0.000729
		W2	0.430571		
	S2	W1	0.506857	3.94308*	0.001952
		W2	0.325714		
	S3	W1	0.490286	2.40787*	0.033041
		W2	0.355714		
	S4	W1	0.408492	1.71363	0.112286
		W2	0.306571		

*Statistically significant difference at the confidence level of 95%.

analysis was performed for all the measurement results. Results of the analysis performed with the method of sum of square values of type III are presented in Table 4.

The obtained test values of P (<0.05) indicate that in the conditions of conducted investigation, each of the analysed independent factors had significant influence onto the measured soil compaction values at the level of confidence of 0.95%.

The analysis results gave ground to determine a regression equation describing the relations between soil compaction and independent factors. Results of the multi-variable regression analysis are presented in Table 5.

Based on the analysis results, soil compaction (*Pk*) may be related to independent factors (measurement depth – *a*, penetrometer cone angle – *K*, cone base area – *S*, soil humidity – *W*, by means of a linear regression model in the following form:

$$Pk = 0.5508 + 0.0406 \times a + 0.0039 \times K - 0.0458 \times S - 0.03727 \times W$$

for which: R^2 = 75.5%, *SEE standard* = 0.0816, *MAE* = 0.0615.

TABLE 4. Variance analysis for soil compaction (Pk)

Source	Sum of squares	Degrees of freedom	Mean square	$F_{\alpha=0.05}$	*P*
a	1.04086	6	0.173477	51.55	0.0000
K	0.19671	1	0.19671	58.45	0.0000
S	0.600558	3	0.200186	59.49	0.0000
W	0.197554	1	0.197554	58.71	0.0000
Rest	0.336519	100	0.00336519	–	–
Total	2.91078	111	–	–	–

a – measurement depth [cm], *K* – cone apex angle [°], *S* – cone base area [cm^2], W – soil humidity.

TABLE 5. Multi-variable regression analysis for soil compaction (dependent variable *Pk*)

Parameter	Estimate	Standard error	*t*-statistic	*P*-value
Constant	0.550801	0.0837373	6.57773	0.0000
a	0.040567	0.00385707	10.5176	0.0000
K	0.00395119	0.000727296	5.43271	0.0000
S	–0.0457619	0.00514371	–8.89667	0.0000
W	–0.0372736	0.00684627	–5.44436	0.0000

Units of particular variables of the equation as indicated in Table 4.

The above equation, based on group average values for soil compaction, may be considered for the scope of conducted investigation, i.e. with the use of cone penetrometers with the *S* and *K* parameters as above, on sandy clay with the average humidity from 7.64 to 10.4%, bulk density of 1.5 $g \cdot cm^{-3}$ and prepared for measurements performed in laboratory conditions. If the scope of applying the relationship was to be extended, this would require performance of respective field investigations, on different soils, taking into account their variability, both in terms of humidity, densification and spatial differentiation typical of natural formations.

CONCLUSIONS

The investigations and analyses performed allow drawing of the following conclusions.

1. In the conditions of uniform soil densification, humidity growth resulted in reduced compaction readings, with change values depending on the geometrical dimensions of cones of the penetrometers used in the investigation.
2. In most of the measurement variants, both the values of soil compaction and changes after humidity increase were negatively correlated with the penetrometer cone sizes.
3. In the case of penetrometers with a cone shaped end piece with the apex angle of 30°, after soil humidity increase from 7.64 to 10.4%, the compaction value shown was lower by 21.2 to 40.7%, and on average by 35.5%, whereas in the same soil conditions, compaction measured with penetrometers with a cone shaped end piece with the apex angle of 60° was lower by 25.5 to 42%, and on average by 32.9%.
4. Measurement values obtained with penetrometer S1 with a K30 cone at both soil humidity levels were characterised with the greatest concentration. Scattering of measurement values obtained by particular penetrometers, especially at lower soil humidity, increased along with dimensions of the cone shaped end piece.

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Streszczenie: *Wpływ wilgotności 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 przy jej zagęszczeniu 1,5 $g \cdot cm^{-3}$ i dwóch wilgotnościach 7,64 oraz 10,4%. Wzrost wilgotności gleby skutkował zmniejszeniem się wartości wskazań sond i w większości wariantów pomiarowych wartości zmian zależały od wymiarów geometrycznych stożków sond użytych w badaniach. Równocześnie, wraz ze zmianą wymiarów końcówki stożkowej zwiększało się rozproszenie wartości pomiarowych. Sondy z końcówką stożkową o kącie wierzchołkowym 30°, po zwiększeniu wilgotności gleby z 7,64 do 10,4% wykazywały mniejszą zwięzłość średnio o 35,5%, natomiast w tych samych warunkach glebowych zwięzłość mierzona sondami ze stożkami o kącie rozwarcia 60° była mniejsza średnio o 32,9%.

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