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PREDICTION OF PRE-COMPRESSION STRESS OF SOIL WITH UNIAXIAL TEST

Kinga Śnieg[a], Dariusz Błażejczak[a*]

[a] Department of Construction and Usage of Technical Devices,
West Pomeranian University of Technology in Szczecin

[*]*Corresponding author: e-mail: dariusz.blazejczak@zut.edu.pl*

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ABSTRACT

The paper presents a concept of determination of pre-compression stress. It assumes that the stress value is close to the unit pressure value which is indispensable to increase the initial degree of soil compaction. Thus, an attempt was made to develop an empirical model for predicting the value of stress at which the initial compaction of a soil sample increases by a determined value. Samples with the so-called intact structure (*NS*) and soil material in the form of loose mass were collected from subsoil, and they were used to form model samples. Both types of samples were uniaxially compressed. For the study, data on moisture and dry bulk density of model samples were used, as well as determined ratios (conversion factors) that present relations between the results of compaction of model samples and samples with the intact structure. It was reported that the pressure necessary for the increase of the initial compaction of the model samples with the value of +0.05 or +0.10 $g \cdot cm^{-3}$ were higher than the formation pressure respectively by 1.03-1.11 and 1.42-1.93 times. It was proved that for determination of the pre-compression stress of the NS samples models of linear regression for prediction the pressure needed to increase the initial compaction of the model sample by the value of +0.05 $g \cdot cm^{-3}$, combined with a coefficient calculated for the present state of the soil properties, can be applied.

Introduction

Excessive soil compaction which results from the impact of wheels of machines and agricultural vehicles is one of the most serious problem of modern agriculture (van den Akker et al., 2003). Soils, which are particularly susceptible to compaction are as follows: heavy clays, clays, and sandy loams (Krasowicz et al., 2011). Firstly, excessive compaction of subsoil is a threat because the effects of compaction of this layer are long-lasting and its liquidation through deep scarification is energy consuming and often ineffective (Szeptycki, 2003).

From the practical point of view, it would be significant to determine the scope of loads (unit pressure) made on the ground with moving mechanisms of tractors and agricultural machines that do not cause an increase of the soil compaction. Soil compaction particularly increases when the compressive strength limit which can be defined with the pre-compression stress, is exceeded. It is considered that knowing the value of the stress enables predicting the pre-compaction loading of soil with driving mechanisms (Horn and Fleige, 2003). A utilitarian meaning of the pre-compression stress causes that this parameter is the object of research in many centres in the world. However, complexity of the soil environment and constant changes of its properties cause that no standard method of determination of this parameter has been yet developed (Błażejczak, 2010). Therefore, it seems justified to search for another method of determination of the pre-compression stress of soil with reference to the ones developed so far.

Results of the research obtained during the Proctor tests and uniaxial test may be useful for developing a procedure of determination of admissible loads on soil (Błażejczak et al., 2018; Nawaz et al., 2013; Śnieg et al., 2018). These results enable determination of conditions in which soil is susceptible to excessive compaction and searching for relations that facilitate selection of predictors indispensable for predicting admissible stresses. Parameters which describe the conditions of the maximum susceptibility on its compaction, are results of research obtained with the Proctor apparatus in the form of the maximum density and optimum water content of compaction (Wagner et al., 1994, Aragón et al., 2000; Nhantumbo and Cambule, 2006; Tarkiewicz and Nosalewicz, 2005). The maximum value of dry bulk density obtained in the standard Proctor method is considered as the maximum possible to be obtained for given soil (Kumar et al., 2009). Śnieg et al., (2018) concluded that the value of the unit pressure on soil in the uniaxial test indispensable for formation of dry bulk density obtained in the Proctor unit significantly depends on the moisture and initial dry bulk density of a sample, and that it is enough to use multiple regression for description of this relation. Thus, one may assume that also in the uniaxial test, it is possible to predict values of the unit pressure that is identified with the pre-compression stress value on soil in order to produce its specific compression.

Objective, scope and methods of research

The objective of the research was to develop an empirical model for predicting the value of the pre-compression stress based on determination of the unit pressure on soil, that increases initial compaction of the soil sample by an assumed value. Taking into consideration a practical precision of determination of the dry bulk density it was assumed that the studies should be carried out for the value of increase of the sample compaction equal to +0.05 g·cm^{-3} (Wojtasik, 1995) or +0.10 g·cm^{-3} (Komornicki and Zasoński, 1965).

By realization of the objective of the study, answers to the following questions were searched for:

1. What is the relation between the values of unit pressure ($P_{\rho m+0.05}$ or $P_{\rho m+0.10}$) that increase the initial compaction of the model sample (ρ_{dm}) by the value of +0.05 g·cm^{-3} or +0.10 g·cm^{-3} with reference to the unit pressure (P_m) applied to form samples?
2. What is the relation between the values of unit pressure ($P_{\rho d+0,05}$ or $P_{\rho d+0,10}$), indispensable to increase the initial compaction of a soil sample with the so-called intact structure (*NS*) by the value of +0.05 g·cm^{-3} or +0.10 g·cm^{-3}, with reference to the unit pressure made on soil by wheels of vehicles and agricultural machines?
3. How can values of unit stresses indispensable for the increase of the initial compaction of the *NS* sample be predicted by the assumed value?

Regarding the fact that this paper is a continuation of earlier research (Śnieg et al., 2018) material for the research was obtained from the layer that is at the depth of 35-40 cm from the fields of the following rural areas: Nowy Przylep (*NP*), Obojno (*Ob*) and Ostoja (*Os*) – the Szczecin Lowland (Nizina Szczecińska). Soil material in the form of loose mass was collected therefrom in order to determine typical soil properties and to carry out the uniaxial test. A textural group was determined with Bouyoucos-Casagrande's method in Prószyński's modification. A pycnometer method was used for determination of the density of solid particles. Humus content was determined with Tiurin's method and soil reaction with the electrometrical method. The plastic limit was measured with the rolling method and the liquid limit with the use of Cassagrande's apparatus.

Soil material dried in free air, designed for the Proctor or uniaxial tests, was sieved through a sieve with 6 mm diameter meshes and then divided into 5 parts. Each part was moistened with a varied amount of water PN-88/B-04481 and placed in separate containers. The aim was to place the obtained levels of moisture within the range between moisture close to the optimum one, according to Proctor, and the plasticity limit, the values of which were determined in the previous research (Błażejczak et al., 2018). The amount of material per one container (level of moisture) was selected to be enough to form 12 model samples (3 densities x 4 iterations). The total number of samples for each object was 60 items. The uniaxial test of compression consisted in the initial compression of soil in steel rings to varied density, as in the paper of Śnieg et al. (2018), within the values observed in field conditions (Błażejczak and Dawidowski, 2013; Śnieg and Błażejczak, 2017). Internal diameter (D) and height of cylinders (H) were respectively 100 and 30 mm. Then, samples were subjected to secondary compaction with an electric press with continuous registration of the stress made and sample deformation. A punch with a diameter (*d*) 50 mm was applied.

Realization of the objective of the paper required creation of the data set obtained in samples with the so-called intact structure *(NS).* Within the years 2014-2017 during spring and fall cultivation treatment, samples were collected from the investigated objects from the layer 35-40 cm with cylinders of the same dimensions as the ones applied in model tests. These samples were subjected to the uniaxial test as in the model samples. Moreover, present water content (w_a) and dry bulk density (ρ_d) of samples were calculated. At the same time limitation was assumed that the final set of data will be formed by samples for which the scope of changes w_a and ρ_d will be close to density (ρ_m) and moisture (w_s) of model samples.

Research results and their analysis

Table 1 presents results of determination of own properties of the soil material. One may notice that the soil material with a varied textural group was used. The highest content of fractions: sand, dust and loamy included material collected respectively from the following objects: Ostoja (*Os*), Nowy Przylep (*NP*) and Obojno (*Ob*). Moreover, considerable differences between the objects regarding the content of humus and values of reaction and relative moisture occurred. It was found out that the material came from compact soils - difference between limits of liquidity and plasticity was higher than 1.0% moisture content

Table 1.
Average values of own properties of soils for the selected objects in the layer of 35-40 cm

Object	Textural group acc. to PTG/USDA (PTG 2009)	Content of fraction acc. to PTG/USDA (2009)			ρ_s	Reaction (in KCl)	Z_{pr}	P_L	L_L	w_{opt}	ρ_{ds}
		Sand	Silt	Clay							
		(%)			($g \cdot cm^{-3}$)	(pH)	(%)	(% w/w)			($g \cdot cm^{-3}$)
NP	*SL*	36.0	53.4	10.6	2.46	6.34	2.02	21.3	31.2	15.7	1.74
Ob	*L*	25.0	48.0	27.0	2.49	6.84	3.77	28.0	47.9	17.7	1.68
Os	*L*	45.0	40.3	14.7	2.66	5.13	0.61	18.4	27.6	13.1	1.88

Source: Śnieg et al., 2018

Symbols: *SL* – sandy loam, *L* – loam, ρ_s specific density, Z_{pr} – humus content, P_L – plastic limit, L_L – liquid limit, w_{opt} – optimum water content acc. to Proctor, ρ_{ds} – maximum density acc. to Proctor

Table 2 presents results of the tests on initial density (ρ_{dm}) and moisture (w_s) of the model samples and relations between the values of pressure $P_{\rho m+0.05}$ and $P_{\rho m+0.10}$ and unit pressure (P_m) applied for their formation. One may notice that stresses $P_{\rho m+0.05}$ indispensable to increase the initial compaction of the model sample (ρ_{dm}) by the value +0.05 $g \cdot cm^{-3}$ were higher than ca. 1.03 to 1.11 of the value P_m. Pressures $P_{\rho m+0.10}$ essential to increase the initial compaction of the model sample (ρ_{dm}) by the value +0.10 $g \cdot cm^{-3}$ were higher than ca. 1.42 to 1.93 of the value P_m. The average values of samples deformation $\Delta H_{+0.05}$ and $\Delta H_{+0.10}$, at which the increase of the value ρ_{dm} by +0.05 or +0.10 $g \cdot cm^{-3}$ was increased, were respectively ca. 1 and 2 mm. It should be mentioned also that according to the previous research results, the value of the pre-compression stress was close to the value P_m (Błażejczak, 2010). Taking into consideration the above-mentioned relations, as well as the fact that the obtained values $P_{\rho m+0.05}$ were close to $P_{\rho m+0.05}$ P_m, one may conclude that the value of the pre-compression stress of model samples should be determined at the deformation which is between 0.84 to 1.20 mm.

Table 2.
Initial parameters and results of uniaxial test of model samples

Object	w_s	ρ_{dm}	P_m	$P_{\rho m+0,05}$	$P_{\rho m+0,10}$	$\Delta H_{+0,05}$	$\Delta H_{+0,10}$
	(% w/w)	($g \cdot cm^{-3}$)	(kPa)			(mm)	
NP	16.3 – 21.1	1.38 – 1.62	66 – 257	73 - 276	126 – 474	0.89 – 1.15	1.78 – 2.01
Ob	17.5 – 27.2	1.28 – 1.52	49 – 377	54 - 396	87 – 564	0.99 – 1.20	1.94 – 2.22
Os	13.4 – 18.5	1.47 – 1.68	68 – 321	74 - 332	112 – 502	0.84 – 1.06	1.71 – 1.96

Symbols: w_s – water content, ρ_{dm} – dry bulk density, P_m – sample formation pressure, $P_{\rho m+0.05}$ – unit pressure on a sample at which density of ρ_{dm} +0.05 $g \cdot cm^{-3}$was obtained, $P_{\rho m+0.10}$ – unit pressure on a sample at which density of ρ_{dm} +0.10 $g \cdot cm^{-3}$ was obtained, $\Delta H_{+0,05}$ – deformation of a sample at which density of ρ_{dm} +0.05 $g \cdot cm^{-3}$was obtained, $\Delta H_{+0.10}$ – deformation of a sample at which density of ρ_{dm} +0.10 $g \cdot cm^{-3}$

Table 3 presents results of determination of water content (w_a) and dry bulk density (ρ_d) of the *NS* samples which were subjected to the uniaxial test identically as the model samples. One may notice that scopes of changes of the determined values w_a and ρ_d were close to the values of parameters of model samples (w_s, ρ_{dm}) placed in 2. Similar scopes of changes of the values of stresses $P_{\rho d+0.05}$ and $P_{\rho d+0.10}$ and deformation of samples $\Delta H_{+0.05}$ and $\Delta H_{+0.10}$ were like the values obtained in the investigated model samples (table 2). One may also notice that the values $P_{\rho d+0.05}$ and $P_{\rho d+0.10}$ are often higher than the determined average unit stresses on soil by wheels of vehicles and agricultural machines (Walczyk, 1995; Jurga, 2009; Filipovic et al., 2016). With reference to the investigated layer of soil, which is at the depth of 35-40 cm, values of $P_{\rho d+0.10}$ should be considered as particularly diverging - the so-called beyond the range of the discussion. It results from the fact that along with the increase of depth, the values of stresses on the soil surface decrease (Pytka, 2005). For example, according to Filipovic et al., (2016) registered stresses at the depth of 30 cm constitute approximately 37% of the value registered at the depth of 10 cm. Thus, exceeding the value of pre-compression stress in the considered layer will be possible if the average unit stress on soil by a wheel will be considerably higher than the pre-compression stress. Taking the above into consideration, further discussions were carried out with reference to the unit stresses indispensable to increase the soil compaction by the value of 0.05 g·cm^{-3}.

Table 3.
Initial parameters and results of uniaxial test of samples with intact structure (NS)

Object	w_a	ρ_d	$P_{\rho d+0.05}$	$P_{\rho d+0.10}$	$\Delta H_{+0.05}$	$\Delta H_{+0.10}$
	(% w/w)		(g·cm^{-3})	(kPa)		(mm)
NP	18.9 – 21.6	1.36 – 1.59	75 - 371	124 – 530	0.84 – 1.10	1.70 – 2.06
Ob	18.0 – 26.5	1.35 – 1.58	50 - 488	115 – 714	0.92 – 1.04	1.80 – 1.94
Os	13.4 – 17.1	1.53 – 1.75	86 - 282	170 – 539	0.79 – 0.89	1.59 – 1.74

Symbols: w_a – water content, ρ_d – dry bulk density, $P_{\rho d+0.05}$ – unit pressure on *NS* sample, at which density of ρ_d +0.05 g·cm^{-3} obtained, $P_{\rho d+0.10}$ – unit pressure on *NS* sample, at which density of ρ_d +0,10 g·cm^{-3}obtained; other symbols see table 2.

Searching for the method of predicting the unit pressure indispensable to increase the initial compaction of *NS* samples by the value of 0.05 g·cm^{-3} were made in stages. Data on *NS* samples were divided into two subsets i.e. *NS1* that serves for developing models and *NS2* which was used for verification.

In the first stage, data on values w_s and ρ_{dm} of model samples (Table 2) were used to construct multiple regression equations for predicting the values of $P_{\rho m+0.05}$. The obtained models (Table 4) were highly significant ($p<0.001$) and well-adjusted to measurement points - coefficient of determination (R^2) was within 0.89 to 0.91.

Then, in the second stage, relations between unit pressure values $P_{\rho d1+0.05}$, measured on *NS1* samples and values $P_{\rho m+0.05}$, calculating the quotients (conversion factors) $q = P_{\rho d1+0.05}/P_{\rho m+0.05}$ were investigated but values $P_{\rho m+0.05}$ were determined with the regression equations (Table 4) assuming $w_s = w_a$ and $\rho_{dm} = \rho_d$. One may notice that the average values of $P_{\rho d1+0.05}$ measured on the model samples were higher from ca. 1.00 to 1.15 times than the predicted values $P_{\rho m+0.05}$, which complies with the results of Horn and Lebert (1994) who say that samples with the so-called intact structure show bigger strength than the ones produced in laboratory conditions.

In the third stage a possibility of predicting unit pressure values ($P_{\rho d2+0.05}$) necessary to increase the initial compaction of *NS* samples by the value of 0.05 $g \cdot cm^{-3}$ was verified with the use of equations presented in table 4 using subset *NS2*. It was concluded that predicting stresses $P_{\rho d2+0.05}$ with equations of the form of

$$P_{\rho d2+0.05} = (a \cdot w_s + b \cdot \rho_{dm} + c) \cdot q, \tag{1}$$

i.e. with the use of the obtained regression equation models for predicting $P_{\rho m+0.05}$ and conversion factor q which increases the value of the predict by the result of the calculated quotient is flawed considerably. It is proved by calculated considerably high values of a relative error of the predict (δ_p) obtained for samples from the checking set *(NS2)* i.e. from 41 to 84% which resulted from big distribution of the value of the quotient q, whose standard deviations were within 0.27 to 0.69. Error δ_p was calculated as a quotient of the values measured and predicted divided into the measured value.

Table 4.

Regression equations for predicting unit pressure $P_{\rho m+0.05}$ indispensable for generation of model sample compaction equal to ρ_{dm} increased by 0.05 $g \cdot cm^{-3}$ and their statistical assessment and values of conversion factors q and average error of predict of unit pressure $P_{\rho d2+0.05}$ of samples of subset NS2

Object	Equation	Statistical assessment of the equation		N_{NS1}/N_{NS2}	q	δ_p
		p	R^2		(-)	(%)
NP	$P_{\rho dp} = - 24.1\ w_s + 593.7\ \rho_{dm} + 236.3$	<0.001	0.89	37/30	1.15 (0.33)	58
Ob	$P_{\rho m+0.05} = - 37.9 w_s + 853.0 \rho_{dm} - 125.9$	<0.001	0.91	43/28	1.14 (0.69)	84
Os	$P_{\rho m+0.05} = - 20.0 w_s + 458.8 \rho_{dm} - 256.1$	<0.001	0.90	40/29	1.02 (0.27)	41

Symbols: p - probability, R^2 – coefficient of determination, N_{NS1} and N_{NS2} – number of samples, q – value of quotient $P_{\rho d1+0,05}$ / $P_{\rho m+0,05}$, δ_p – relative error of predict $P_{\rho d2+0,05}$, remaining symbols see tab.2; Notice: brackets include the value of standard deviation

Due to unsatisfactory results of predicting the value of $P_{\rho d2+0.05}$, with multiple regression equations and values of quotients q (table 4) further works were aimed at a search for linear regression equations (Table 5). Equations were selected for a narrow range of variability of dry bulk density of model samples, i.e. value ρ_{dm} ±0.05 $g \cdot cm^{-3}$ which is justified in the light of Wojtasik's research (1995). Values w_s were predictors. The obtained models were highly significant ($p<0.001$) and well adjusted for measurement points – coefficient of determination (R^2) was within 0.91 to 0.98. One may notice that the obtained (Table 5) values of quotients q ($P_{\rho d1+0.05}/P_{\rho m+0.05}$) were varied within objects and decreased along with the increase of samples compaction. Predicting of pressures $P_{\rho d2+0.05}$ with regression equations presented in table 5 with the calculated quotient q were considerably flawed with error taking into consideration variability of the soil environment. The average values of error δ_p, obtained for samples of the checking set *(NS2)* were within 7 to 26%. Values of standard deviations of quotients *q* were within 0.04 to 0.22.

Table 5.

Regression equations for predicting unit pressure ($P_{\rho m+0.05}$) indispensable for production of compaction of the model sample equal to ρ_{dm} increased by 0.05 g·cm^{-3} and their statistical assessment and values of conversion factors q and the average predict error of unit pressure $P_{\rho d2+0,05}$ of the subset samples NS2

Object	Scope ρ_{dm} (g·cm^{-3})	Equation	Statistical assessment of the equation *p*	*R*^{2}	N_{NS1}/N_{NS2}	*q* (-)	δ_p (%)
NP	(1.35-1.45)	$P_{\rho m+0.05} = -14.37w_s + 395.8$	<0.001	0.92	11/10	1.27 (0.17)	19
	<1.45-1.55)	$P_{\rho m+0.05} = -32.30w_s + 811.5$	<0.001	0.96	12/8	1.24 (0.21)	17
	<1.55-1.65)	$P_{\rho m+0.05} = -58.58w_s + 1392.6$	<0.001	0.94	14/12	1.10 (0.04)	12
Ob	(1.30-1.40)	$P_{\rho m+0.05} = -15.86w_s + 484.6$	<0.001	0.98	16/8	1.36 (0.11)	26
	<1.40-1.50)	$P_{\rho m+0.05} = -25.66w_s + 803.2$	<0.001	0.93	14/9	1.24 (0.19)	18
	<1.50-1.60)	$P_{\rho m+0.05} = -36.25w_s + 1076.3$	<0.001	0.97	13/11	1.07 (0.22)	14
Os	(1.40-1.50)	$P_{\rho m+0.05} = -16.24w_s + 356.6$	<0.001	0.91	14/11	1.29 (0.09)	22
	<1.50-1.60)	$P_{\rho m+0.05} = -24.41w_s + 507.8$	<0.001	0.91	12/8	1.14 (0.17)	12
	<1.60-1.70)	$P_{\rho m+0.05} = -60.76w_s + 1177.7$	<0.001	0.98	14/10	1.04 (0.08)	7

Symbols: R^2 – coefficient of determination of linear regression, remaining symbols see table 4.

Conclusions

1. Pressure indispensable to increase the initial compaction of the model sample with the value of +0.05 or +0.10 g·cm^{-3} were higher than the formation pressure (P_m) respectively by 1.03-1.11 and 1.42-1.93 times.
2. Predicting the values of pre-compression stress in the subsoil of the investigated soil based on the information on the unit pressure ($P_{\rho d+0.10}$), necessary to increase the initial compaction of the sample by the value of +0.10 g·cm^{-3} is not justified. The calculated values of $P_{\rho d+0.10}$ were often higher than the determined average unit stresses made on soil by wheels of vehicles and farming machines which is contrary to the theory of distribution of stresses in soil.
3. In order to search for a manner of predicting the value of pre-compression stress in a subsoil of the investigated soil, it is justified to use information on unit pressure ($P_{\rho m+0.05}$), necessary to increase the initial compaction of a sample by the value of +0.05

g·cm^{-3}. The calculated values of $P_{\rho m+0.05}$ were like the stresses of formation of model samples which corresponds approximately to the pre-compression stress value.

4. For predicting the value of unit stresses, indispensable to increase the initial compaction of the soil sample with the intact structure by the value of +0.05 g·cm^{-3}, namely, approximately to the pre-compression stress value, models of linear regression can be used for predicting $P_{\rho m+0.05}$ of the model sample and the conversion factor q calculated for the present condition.

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PROGNOZOWANIE NAPRĘŻENIA GRANICZNEGO GLEBY Z WYKORZYSTANIEM TESTU JEDNOOSIOWEGO

Streszczenie. Przedstawiono koncepcję wyznaczania naprężenia granicznego opartą na założeniu, że wartość tego naprężenia jest zbliżona do wartości nacisku jednostkowego, niezbędnego do zwiększenia początkowego stanu zagęszczenia gleby. W tym celu podjęto próbę opracowania modelu empirycznego do prognozowania wartości nacisku, przy którym następuje zwiększenie początkowego zagęszczenia próbki glebowej o określoną wartość. Z warstwy podornej gleby pobrano próbki o tzw. nienaruszonej strukturze (*NS*) oraz materiał glebowy w postaci luźnej masy, z którego formowano próbki modelowe. Oba rodzaje próbek odkształcano jednoosiowo. Do opracowania modelu wykorzystano dane o wilgotności i gęstości objętościowej próbek modelowych oraz wyznaczone współczynniki (przeliczniki), przedstawiające relacje pomiędzy wynikami ugniatania próbek modelowych i próbek o nienaruszonej strukturze. Stwierdzono, że naciski niezbędne do zwiększenia początkowego zagęszczenia próbki modelowej o wartości +0,05 lub +0,10 $g \cdot cm^{-3}$ były większe od nacisku formowania odpowiednio o 1,03-1,11 oraz 1,42-1,93 razy. Wykazano, że do wyznaczania wartości naprężenia granicznego próbek *NS* można wykorzystać modele regresji liniowej do prognozowania nacisku jednostkowego niezbędnego do zwiększenia początkowego zagęszczenia próbki modelowej o wartość +0,05 $g \cdot cm^{-3}$ oraz obliczony dla aktualnego stanu gleby przelicznik.

Słowa kluczowe: gleba, warstwa podorna, test jednoosiowy, naprężenie graniczne

Identification data Authors:

Kinga Śnieg *ORCID: 0000-0002-2350-7985*
Dariusz Błażejczak *ORCID: 0000-0002-2532-5704*