ISNN 2083-1587; e-ISNN 2449-5999
2018,Vol. 22,No.3, pp.85-92
Agricultural Engineering
www.wir.ptir.org
DOI: 10.1515/agriceng-2018-0030

PREDICTING UNIT PRESSURE INDISPENDABLE FOR GENERATION OF SPECIFIC COMPACTION OF A SOIL SAMPLE

Kinga Śnieg, Dariusz Błażejczak*, Małgorzata Słowik

Department of Construction and Usage of Technical Devices, West Pomeranian University of Technology in Szczecin, Poland

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

ARTICLE INFO

Article history:
Received: July 2018
Received in the revised form: August 2018
Accepted: September 2018

Key words:
soil, compaction,
Proctor test,
uniaxial test

ABSTRACT

The objective of the research was to construct an empirical model for prediction of a unit pressure indispensable for generation of a specific compaction of soil samples. Soil material in the form of loose mass was collected from the soil layer deposited in the depth from 35 to 40 cm and then its typical properties were determined (textural group, density of solid particles, humus content, reaction, plastic and liquid limits) and in order to compact it in Proctor apparatus and in the uniaxial compression test. Results of both tests were used for construction of regression models reflecting the course of the unit strength ($P_{\rho d}$) necessary to generate compaction (ρ_{dj}) equal to the dry bulk density obtained in Proctor apparatus (ρ_{dp}), in relation to the sample moisture (ρ_{dm}). Searching for relations was restricted to the scope of moisure between an optimal one acc. to Proctor and the soil plastic limit. It was stated that the pressure value $P_{\rho dp}$ made on the soil sample in the uniaxial compression test depends significantly on w_s and $\rho_{dm,}$ and for description of this relation the use of multiple regression is sufficient. It was found out that for model samples with a textural group of silt loam and loam, differences in dry bulk density obtained in Proctor apparatus are approximately up to 0.15 $g{\cdot}cm^{-3}$.

Introduction

Excessive soil compaction which results from the impact of wheels of machines and agricultural vehicles is one of the most serious problems 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). First of all, excessive compaction of subsoil is dangerous because the effects of compaction of this layer are long-lasting and its liquidation through deep loosening is energy consuming and often ineffective (Szeptycki, 2003). A rational approach to counteracting this phenomenon requires evaluation of the present soil density and identification of conditions in which it takes place.

From a practical point of view, determination of the range of admissible loads (unit pressures) made on the ground with moving mechanisms of tractors and agricultural machines which do not cause the increase of the soil compaction would be significant. Soil compaction increases when the soil compaction strength, which can be defined with a pre-compaction stress, is exceeded. It is considered that knowing the value of the pre-compaction stress enables forecasting the loading of soil with driving mechanisms, exceeding of which poses a risk of the increase of its compaction (Horn and Fleige, 2003). An utilitarian meaning of the pre-compaction stress makes this parameter 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). Thus, it seems justified to search for another way of determination of admissible loads made on soil. Results of the research obtained during Proctor tests and uniaxial pressure test may be useful for development of such a procedure (Nawaz et al., 2013).

Błażejczak et al., (2018) stated that the value of uniaxial pressure made on the soil sample in the uniaxial compression test ($P_{\rho dp}$), indispensable for generation of compaction equal to bulk density obtained in Proctor apparatus (ρ_{dp}), depends significantly on the sample moisture (w_s). Regression equations were obtained in model samples with uniform initial bulk density (ρ_{dm}), thus authors found that the impact of the initial density of a sample on the predicted value of uniaxial pressure indispensable for generation of a specific state of soil compaction should be investigated. Searching for relations was carried out within the range of samples moisture resulting from Proctor's procedure; thus, from considerably low values of moisture, at which there is no threat of excessive compaction, to high soil moisture content, at which field works are impeded or impossible. Therefore, it seems to be justified to limit a discussion to the soil condition corresponding to soil moisture, within which field works are carried out and soil is susceptible to compaction. The scope between soil optimum moisture acc. to Proctor (w_{opt}) and its plactic limit (P_L) may be considered a moisture range.

In the field conditions, a relation between optimum moisture content of soil compaction and its plastic limit may be modified by various factors (Mosaddeghi et al., 2000). Mosaddeghi et al., (2009) found out that optimum moisture of compaction is similar to the optimum value of cultivation moisture content, understood as the water content at which strength of capillary connections between aggregates is minimal. Moreover, soil moisture, at which the best cultivation efficiency is obtained, may differ in relation to the applied tools and the working depth (Larson et al., 1994). In literature we may find various manners of determination of the optimum cultivation moisture, the scope of which is within the soil optimum moisture acc. to Proctor and the plastic limit (Mueller et al., 2003).

Objective, scope and methods of research

The aim of the research was to develop an empirical model for prediction of uniaxial compression indispensable for generation of a specific soil sample compaction in relation to its moisture and dry bulk density. It was assumed that the ranges of the values of soil properties determined in field studies and results of soil material compaction measurements with Proctor apparatus should be the basis for designing an experiment.

Answers to the following questions were searched for:

1. Does the initial compaction of a sample affects the determined uniaxial pressure ($P_{\rho dp}$) indispensable for generation in the uniaxial test of its bulk density (ρ_{dj}) with the value equal to the one obtained in Proctor apparatus (ρ_{dp})?

2. What is the scope of changes of soil density obtained in Proctor apparatus (ρ_{dp}) during compaction of soil material with the water content between optimum moisture (w_{opt}) and the plastic limit (P_L)?
3. How can we write down relations of the unit pressure ($P_{\rho dp}$) necessary to generate in the uniaxial test dry bulk density of a sample (ρ_{dj}) with the value equal to the one obtained in Proctor Apparatus (ρ_{dp}) from the initial state of a soil sample?

While selecting material for research an assumption that was taken into consideration was that its properties should be variable mainly with regard to the grain size distribution. Based on the analysis of information included in soil and agricultural maps and results of the previous research (Śnieg, Błażejczak 2017) fields of rural areas edges were selected for collecting the material: Nowy Przylep (*NP*), Obojno (*Ob*) and Ostoja (*Os*) – the Szczecin Lowland (Nizina Szczecińska). Studies were carried out in the layer at the depth of 35-40 cm i.e. below a working depth of applied cultivation tools, but in case of ploughing, in the zone of direct impact of tractor wheels on soil - wheels movement in a furrow. Soil material in the form of loose mass was collected therefrom in order to determine typical soil properties and to carry out compaction in Proctor apparatus and the uniaxial compression test. A textural group was determined with Bouyoucosa-Casagrande's method in Prószyński's modification. A pycnometer method was used for determination of the density of solid particles. The 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 Proctor tests or uniaxial compression test, 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 according to PN-88/B-04481 and placed in separate containers. The aim was to place the obtained levels of moisture within moisture close to the optimal one acc. to Proctor and the plastic limit, the values of which were determined in the previous research (Błażejczak et al., 2018). The amount of material for each container (moisture level) was selected so as to be sufficient for compression in Proctor apparatus and for forming 4 model samples which were then uniaxially compressed. Compaction in Proctor apparatus was carried out acc. to PN-88/B-04481 with the use of a cylinder with volume of 1000 cm3 with unit compaction energy which was 0.59 $J \cdot cm^3$ of soil. Uniaxial test performance consisted in initial soil compaction in steel rings (cylinders - fig. 1a) to varied densities within the limit of values observed in the 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 (figure 1b). A plate with a diameter (*d*) 50 mm was applied.

Knowledge of uniaxial test parameters and initial dry density of model samples enabled calculation of changes of dry bulk density under the plate in relation to the unit stress on the sample. At the same time, assumption was made, that sample compaction changes linearly along with the increase of the plate depth (Błażejczak et al., 2018). Secondary compaction of samples was carried out until the plate depth of 10 mm was obtained. In such a case, final compaction of each sample exceeded the value of the maximum bulk density obtained in Proctor test.

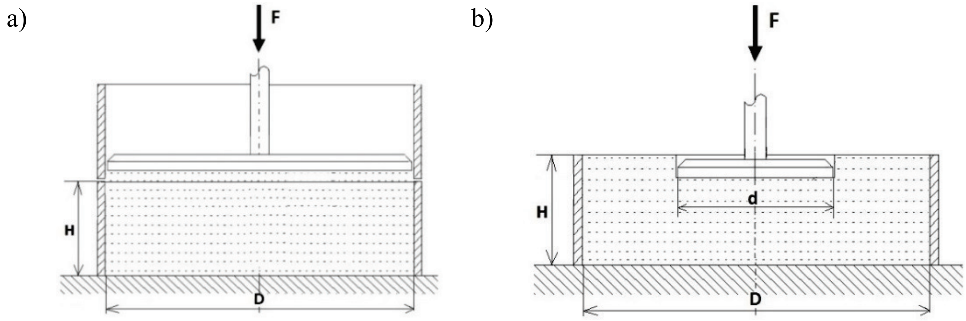

Figure 1. Stages of uniaxial samples compression test: a) formation, b) uniaxial deformation

Searching for an answer to the research question, the experiment was performed in two stages. In the first stage, samples were differentiated within each object with regard to dry bulk density. In the second stage, the condition of the produced samples was varied on account of moisture and dry bulk density and the obtained results were used for construction of a regression model for prediction of the unit compression necessary for production of compaction equal to bulk density obtained in Proctor apparatus. But, results of research on samples of the second stage were divided into two groups, i.e. basic for construction of models and validation which was used for assessment of the obtained equations. The level of significance of α=0.05 was obtained.

Results of research and their analysis

Table 1 presents results of determination of own properties of the soil material. One may notice that soil material with varied textural group was used. The highest content of fractions: sand, silt and loamy one included material collected respectively from the following objects: Ostoja (*Os*), Nowy Przylep (*NP*) and Obojno (*Ob*). Moreover, considerable differences between the objects with regard to the humus content and values of liquid and plastic limits occurred. It was found out that material came from compact soils - difference between liquid and plastic limits 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 USDA (PTG 2009)	Fraction content acc. to PTG (2009)			Specific density	Reaction (in KCI)	Humus content	P_L	L_L
		Sand	Silt	Loam					
			(%)		(g·cm^{-3})	(pH)	(%)	(% w/w)	
NP	*SL*	36.0	53.4	10.6	2.46	6.34	2.02	21.3	31.2
Ob	*L*	25.0	48.0	27.0	2.49	6.84	3.77	28.0	47.9
Os	*L*	45.0	40.3	14.7	2.66	5.13	0.61	18.4	27.6

Symbols of textural groups: *SL* – sandy loam, *L* – loam , P_L – plasticity limit , L_L – liquidity limit

According to the assumed course of the procedure, firstly, an answer to the question concerning the impact of initial density of the compressed sample on the determined value of unit pressures ($P_{\rho dp}$) necessary for production of compaction (ρ_{dj}) equal to the value obtained in Proctor apparatus (ρ_{dp}), was searched for. Outcomes of a comparison of the pressure value $P_{\rho dp}$ for varied initial densities of model samples (ρ_{dm}) at their identical water content (w_s) was placed in table 2. It was found out that these values did differ significantly – $p < 0.05$. Higher values of pressure $P_{\rho dp}$ for samples with a higher initial dry bulk density (ρ_d) may be justified with higher resistance of soil particles movement outside the zone of a direct impact of a plate and higher soil shearing strength by its edge.

Table 2.
Results of comparison of uniaxial pressures ($P_{\rho dp}$) necessary for production of compaction in uniaxial test (ρ_{dj}) equal to the value obtained in Proctor apparatus (ρ_{dp}) for varied initial dry bulk density of a model soil sample (ρ_{dm})

Object	w_s (% w/w)	ρ_{dm} (g·cm^{-3})	$\rho_{dj} = \rho_{dp}$ (g·cm^{-3})	$P_{\rho dp}$ (kPa)	Value p (for $P_{\rho dp}$)
NP	18.0 (0.1)	1.27 (0.03) 1.48 (0.02)	1.71	317 (25) 487 (10)	< 0.001
Ob	23.3 (0.3)	1.29 (0.02) 1.42 (0.02)	1.58	291 (5) 675 (21)	< 0.001
Os	15.7 (0.1)	1.48 (0.02) 1.67 (0.01)	1.85	332 (3) 432 (14)	< 0.001

Symbols: w_s – sample moisture, ρ_{dm} – initial dry bulk density of a model sample, p – probability level; Notice: the brackets include the standard deviation value

Table 3 includes the results of Proctor tests and unit compression test for a considered scope of soil moisture, i.e. approximately between optimal moisture (w_{opt}) and plastic limit (P_L – Tab. 1). The range of values of densities obtained in Proctor apparatus (ρ_{dp}) within the moisture of w_{opt} and P_L may be considered as significant, because it exceeds 0.1 g·cm^{-3}. For the investigated objects *NP*, *Ob* and *Os* this scope was respectively: 1.61 – 1.73, 1.52 – 1.67 and 1.74-1.88 g·cm^{-3}. It may be also noticed (Table 3) that the determined values of the unit pressures $P_{\rho dp}$ and $P_{\rho ds}$ indispensable for generation of densities respectively ρ_{dp} and ρ_{ds} are similar.

Table 3.
Input parameters and results of Proctor test and uniaxial pressure of model samples

Object	w_s *(% w/w)*	ρ_{dm} *(g·cm^{-3})*	w_{opt} *(% w/w)*	ρ_{ds} *(g·cm^{-3})*	ρ_{dp} *(g·cm^{-3})*	$P_{\rho dp}$ *(kPa)*	$P_{\rho ds}$ *(kPa)*
NP	16.3 – 21.5	1.36 – 1.60	15.7	1.74	1.61 – 1.73	159 - 685	175 - 706
Ob	18.0 – 27.3	1.27 – 1.51	17.7	1.68	1.52 – 1.67	135 - 695	182 - 712
Os	13.7 – 18.4	1.46 – 1.71	13.1	1.88	1.74 – 1.88	148 - 803	192 - 805

Symbols: w_{opt} – optimal moisture acc. to Proctor, ρ_{ds} – maximum bulk density acc. to Proctor, ρ_{dp} – bulk density obtained for particular values of moisture (w_s), $P_{\rho ds}$ – unit pressure on a sample, at which density equal to the maximum density (ρ_{ds}) determined in Proctor test was obtained; remaining symbols see table 2

Searching for an answer to the third research question, using the samples produced in the second stage of the experiment, the properties of which (w_s, ρ_{dm}) were presented in table 3, a multiple regression was used. When assessing independent variables of the obtained models (Table 4) it was stated that pressure $P_{\rho dp}$ necessary for generation of $\rho_{dj} = \rho_{dp}$ depends significantly on moisture (w_s) and dry bulk density (ρ_{dm}) of a sample. The obtained equations are significant (p<0.001) and well adjusted for measurement points - coefficient of determination (R^2) was within 0.92 to 0.97. Regression equations were subjected to assessment with cases included in the validation set. The calculated average values of relative errors of prediction (δ_p), understood as a difference of values measured and predicted divided into measured values were lower than 6% which should be considered as a very good result for the needs of estimation of pressure $P_{\rho dp}$. Taking into consideration a statistical evaluation of the obtained equations and values of prediction errors, it should be recognized that application of multiple regression equations for prediction of pressure values $P_{\rho dp}$ is justified. Analysis of the values of regression equations coefficients makes us notice that their similar values were obtained for objects *NP* and *Ob*, which can be justified with similar properties of samples (Tab. 3) and different properties of *Os* object such as sand and humus fraction content (Tab. 1) which could have influenced registration of compaction resistance.

Table 4.
Regression equations for prediction of unit stress ($P_{\rho dp}$) indispensable for production of compaction (ρ_{dj}) equal to dry bulk density (ρ_{dp}) obtained in Proctor apparatus and their statistical evaluation

Object	Equation	Statistical assessment of the equation		δ_p
		p	R^2	(%)
NP	$P_{\rho dp} = - 71.9\ w_s + 723.4\ \rho_{dm} + 782.8$	<0.0001	0.92	5.6 (3.6)
Ob	$P_{\rho dp} = - 70.8\ w_s + 675.2\ \rho_{dm} + 1102.0$	<0.0001	0.92	4.4 (2.7)
Os	$P_{\rho dp} = - 79.9\ w_s + 416.7\ \rho_{dm} + 994.4$	<0.0001	0.97	4.7 (3.4)

Symbols: R^2 – determination coefficient, δ_p – relative error of prediction; remaining symbols see table 2: Notice: brackets include the value of standard deviation

Equations of regression (table 4) were obtained on produced samples in laboratory conditions, namely on material with lower strength than soil with a natural structure, which is proved by, inter alia, research results presented by Horn and Lebert (1994). Thus, the results obtained in this paper should be verified in the future in field conditions i.e. on samples with the so-called intact structure.

Conclusions

1. Initial compaction of a soil sample influences the determined value of unit pressures necessary for production in the uniaxial compaction test of the equal value bulk density obtained in Proctor apparatus.

2. A difference in the maximum and minimum value of dry bulk density obtained in Proctor apparatus for soil material with granulation of silt loam or loam and its moisture within the optimum moisture and plastic limit, is between 0.12 and 0.15 $g \cdot cm^{-3}$.
3. For description of a relation unit pressure, necessary for generation in uniaxial test of compaction equal to the value of dry bulk density obtained in Proctor apparatus from the initial bulk density and samples moisture within optimal moisture and plastic limit, a multiple regression may be used. It is proved by high statistical assessment of the obtained regression equations ($R^2 \geq 0.92$, $p < 0.001$) and low values of relative errors of variable dependent prediction ($\delta_p \leq 6\%$).

References

Błażejczak, D. (2010). *Prognozowanie naprężenia granicznego w warstwie podornej gleb ugniatanych kołami pojazdów rolniczych.* Wyd. ZUT w Szczecinie. ISBN 978-83-7663-050-2.

Błażejczak, D., Dawidowski, J.B. (2013). Problem wykorzystania gęstości objętościowej gleby w ocenie jej zagęszczenia. *Journal of Research and Applications in Agricultural Engineering*, *Vol. 58*(1), 17-20.

Błażejczak, D., Śnieg, K., Słowik, M. (2018). Comparison of Proctor and uniaxial compression tests for selected soils. *Agricultural Engineering*, *Vol. 22, No 1*, 5-13.

Horn R., Fleige, H. (2003). A method for assesing the impact of load on mechanical stability and on physical properties of soils. *Soil & Tillage Research, 73*, 89-99.

Horn R., Lebert M. (1994). *Soil Compactability and Compressibility.* In: Soil Compaction in Crop Production, Soane B.D. and Ouwerkerk (Eds.), Elsevier Science B.V. s. 45-66. ISBN: 9780444882868.

Krasowicz S., Oleszek W., Horabik J., Dębicki R., Jankowiak J., Stuczyński T., Jadczyszyn J. (2011). Racjonalne gospodarowanie środowiskiem glebowym Polski. *Polish Journal of Agronomy*, *7*, 43-58.

Larson, W.E., Eynard, A., Hadas, A., Lipiec, J., (1994). Control and Avoidance of Soil Compaction in Practice. In: *Soil Compaction in Crop Production.* 597-601.

Mosaddeghi, M.R., Hajabbasi, M.A., Hemmat, A., Afyuni, M. (2000). Soil compactibility as affected by soil moisture content and farmyard manure in central Iran. *Soil & Tillage Research*, *55*, 87-97.

Mosaddeghi, M.R., Morshedizad, M., Mahboubi, A.A., Dexter, A.R., Schulin, R. (2009). Laboratory evaluation of a model for soil crumbling for prediction of the optimum soil water content for tillage. *Soil & Tillage Research*, *105*, 242-250.

Mueller, L., Schindler, U., Fausey, N.R., Lal, R. (2003). Comparison of methods for estimating maximum soil water content for optimum workability. *Soil & Tillage Research*, *72*, 9-20.

Nawaz, M., F., Bourrié, G., Trolard, F. (2013). Soil compaction impact and modelling. A review. *Agronomy for Sustainable Development, 33*, 291-309.

PN-88/B-04481 (1988). Grunty budowlane. Badania próbek gruntu.

Polskie Towarzystwo Gleboznawcze (2009). Klasyfikacja uziarnienia gleb i utworów mineralnych – PTG 2008. *Roczniki Gleboznawcze*, *60*(2), 5-16.

Szeptycki, A. (2003). Wpływ ciężkich maszyn rolniczych na fizykomechaniczne właściwości gleby. *Journal of Research and Application in Agricultural Engineering*, *Vol. 48*(3), 5-9.

Śnieg, K., Błażejczak, D. (2017). Evaluation of subsoil compaction of plastic soils. *Agricultural Engineering*, *Vol 21, No 1*, 85-94.

Van den Akker, J. J. H., Arvidsson, J., Horn, R. (2003). Introduction to the special issue on experiences with the impact and prevention of subsoil compaction in the European Union. *Soil & Tillage Research*, *73*, 1-8.

Kinga Śnieg, Dariusz Błażejczak, Małgorzata Słowik

PROGNOZOWANIE NACISKU JEDNOSTKOWEGO NIEZBĘDNEGO DO WYTWORZENIA OKREŚLONEGO ZAGĘSZCZENIA PRÓBKI GLEBOWEJ

Streszczenie. Celem badań było zbudowanie modelu empirycznego do prognozowania nacisku jednostkowego niezbędnego do wytworzenia określonego zagęszczenia próbki gleby. Z warstwy gleby leżącej na głębokości od 35 do 40 cm pobrano materiał glebowy w postaci luźnej masy, a następnie oznaczono jego typowe cechy własne (skład granulometryczny, gęstość fazy stałej, zawartość próchnicy, odczyn, granice plastyczności i płynności) i przeprowadzono testy zagęszczania w aparacie Proctora oraz jednoosiowego ściskania. Wyniki obu testów wykorzystano do budowy modeli regresji odwzorowujących przebieg nacisku jednostkowego ($P_{\rho dp}$), niezbędnego do wytworzenia w teście jednoosiowym zagęszczenia (ρ_{dj}) równoważnego gęstości objętościowej uzyskiwanej w aparacie Proctora (ρ_{dp}), w zależności od wilgotności (w_s) i początkowej gęstości objętościowej szkieletu próbki modelowej (ρ_{dm}). Poszukiwanie zależności ograniczono do zakresu wilgotności pomiędzy optymalną wg Proctora a granicą plastyczności gleby. Stwierdzono, że wartość nacisku $P_{\rho dp}$ wywieranego na próbkę gleby w teście jednoosiowego ściskania zależy istotnie od w_s i $\rho_{dm,}$ a do opisu tej zależności wystarczające jest zastosowanie regresji wielorakiej. Uzyskano, że dla próbek modelowych o składach granulometrycznych pył gliniasty i glina zwykła, różnice gęstości objętościowych szkieletu uzyskiwanych w aparacie Proctora wynoszą do około 0,15 g·cm^{-3}.

Słowa kluczowe: gleba, zagęszczanie, test Proctora, test jednoosiowy