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BULK DENSITY AND TOTAL POROSITY ESTIMATION THROUGH PENETROMETER

Estimación de la densidad volumétrica y porosidad total usando el penetrómetro

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ABSTRACT. The bulk density and total porosity readings are highly correlated to penetration resistance values. The goal of this study was to find the regression equations that allow the estimation of bulk density and total porosity of soil using the penetration resistance values. The work was developed in Leachate Yellowish Ferralitic and Brown soil types. For each soil type were taken 24 lectures with the penetrometer apparatus at random procedures, between 5 and 35 cm deep and penetration resistance values between 130 and 750 N cm^{-2}. In each point before were determined also the soil humidity and bulk density. The real density was evaluated for each soil type and the total porosity estimated. The penetration resistance value was used as independent variable in the regression equation estimation. Through t test was evaluated the relation between the real observation and the estimation values. The results showed a highly significant linear relation between bulk density and penetration resistance procedures, as well as between them and the total porosity, for both soil types. In the four regression equations, the quality of the functional relation, evidence clears statistic equality, with a probability of 1. The determined equations allow also estimating compaction indices for both soil types, using national scales, express in g cm^{-3}.

RESUMEN. Las mediciones de densidad volumétrica y porosidad total están altamente correlacionadas con valores de resistencia a la penetración. El objetivo del presente estudio fue determinar las ecuaciones de regresión que permiten la estimación de la densidad volumétrica y porosidad total, a partir de las mediciones de resistencia a la penetración obtenida con el penetrómetro. El trabajo se desarrolló en suelos del tipo Ferralítico Amarillento Lixiviado y Pardo. Por cada tipo de suelo se tomaron 24 lecturas al azar con el penetrómetro, a profundidades de 5 a 35 cm y valores de resistencia a la penetración entre 130 y 750 N cm^{-2}. En cada punto de lectura se determinó, además, la humedad del suelo y la densidad volumétrica. La densidad real se determinó para cada tipo de suelo y la porosidad total fue estimada. El valor de resistencia a la penetración se tomó como variable independiente para determinar las ecuaciones de regresión. Mediante una prueba t se comprobó la relación entre los datos reales observados y los valores estimados. Los resultados mostraron una relación lineal altamente significativa entre la densidad volumétrica y la resistencia a la penetración y de ellos con la porosidad total del suelo en ambos tipos de suelos estudiados. En las cuatro ecuaciones de regresión obtenidas, la calidad de las relaciones funcionales, evidenció igualdad estadística, con una probabilidad igual a 1. Estas ecuaciones permiten, además, estimar índices de compactación en ambos tipos de suelos, usando escalas de evaluación nacionales, expresadas en g cm^{-3}.

Key words: soil compaction, compression, soil porosity, physical properties of soil, soil mechanics

Palabras clave: compactación del suelo, compresión, porosidad del suelo, propiedades físicas del suelo, mecánica de suelo

INTRODUCTION

Compaction is considered the main cause of degradation of agricultural soils (1). Its effect causes changes in soil structure, affects the behavior of physical properties and hinders the growth and development of plants (2-5). Compaction is also a precursor to the process of soil erosion and surface crusting (6). It is a compression process, which causes an increase in the soil mass per unit volume, due to the application of an external force, resulting in a decrease in the flow and water and gaseous exchange of the soil (7).

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Due to the textural and structural composition of the soils, the mass/volume ratio indices vary from one soil type to another. In this sense, soil texture is commonly related to volumetric density, total porosity or resistance to penetration; variables that refer in one way or another to said relationship (8,9).

Among the methods used to diagnose soil compaction are: the measurement of volumetric or apparent density; the resistance to penetration; total porosity; pore index and air and water permeability (7). Within these methods, the ones that are mostly used are the volumetric density and the resistance to penetration, whose results are expressed in g cm^{-3}, kg m^{-3} or mg m^{-3} and N cm^{-2} or MPa, respectively.

Volumetric density is one of the most widely used methods and represents, in many cases, the standard for evaluating the degree of compaction of a soil. For its use, greater expertise and time is needed than for the measurement of penetration resistance with a penetrometer. If the penetrometer is digital, then it provides a spectrum of values as it penetrates the soil layers (10,11), being one of the most used tools for this type of study (12-14).

At the global level, there are evaluation scales of soil compaction, expressed in N cm^{-2} or MPa, referring to indices of resistance to penetration (7). These scales, in most cases, define the value of 200 N cm^{-2} or 2 MPa as a critical value, from which problems of soil compaction are manifested; however, in Cuba, soil compaction evaluation scales are referred to g cm^{-3} (15), associated with the generalized use of the volumetric density method. Consequently, it is difficult to evaluate the results of resistance to penetration obtained with the penetrometer, limiting its use.

On the other hand, the use of the penetrometer does not allow knowing the values of volumetric density that the soil presents, information necessary to calculate the quantities of chemical elements present in it, in kg ha^{-1}, as well as the volumes of water and fertilizers needed to the crops.

The objective of the present study was to determine the two regression equations that allow the estimation of the volumetric density and the total porosity, from the measurements of resistance to penetration obtained with the penetrometer.

MATERIALS AND METHODS

Place Location

The work was carried out in Soils Ferralitic Yellowish Leached (FRAL) and Pardo (P) (16), from the province Pinar del Río, Cuba, located at coordinates 209.9 N; 276.2 E and 303.8 N; 248.9 E, respectively; Acrisol and Cambisol in WRB (17). At the time of the study, both soils were fallow, the first type is dedicated to the cultivation of tobacco under cloth and the second to pastures and fodder.

Methods and procedures

24 readings were taken at random, for each type of soil, with the hand penetrometer, analog conical type of the firm EIJKELKAMP, at values of resistance to penetration (Rpenet) between 130 and 750 N cm^{-2}, at depths from 5 cm up to 35 cm. At each evaluation point with the penetrometer, samples were taken to determine soil moisture, according to the proposed method (18) and the volumetric density, also referred to as bulk density (Da), following the Cuban standard (19). The real density or specific gravity (Dr) was determined for each type of soil according to the Cuban standard (20), from a sample composed of each type of soil. The total porosity (Pt) was calculated from the volumetric density and the real density, according to the Cuban norm (21). The mechanical composition of the soil was determined by the hydrometer method (18), using the composite sample taken by each type of soil, the textural class (16) being subsequently defined.

Statistical analysis

First, the strength of the linear relationship between the variables was studied, determining the correlation matrices and the significance of the coefficients for the two types of soil. The sample size needed to find a significant relationship between variables with a significance level of 0.05 and a power of 90 % was determined according to the formula described (22), for a correlation coefficient of 0.90.

With the values of Da, Pt and Rpenet, regression curves were developed between Da vs Rpenet and Pt vs Rpenet for each type of soil, using Rpenet as an independent variable. The confidence intervals were calculated for the regression coefficients, estimated to determine between which values would oscillate in case of estimating the equations, with multiple samples of equal size, taken from the same population. The predictive capacity of the determined equations was evaluated from the coefficient of determination. To verify normality, the Shapiro Wilk test was applied to the residues. The comparison between the actual data observed and the estimated values with the equations found was made by means of a t Test for related samples. The data was processed with the statistical program SPSS 15.0.

RESULTS AND DISCUSSION

Table 1 shows the results of penetration resistance readings (Rpenet) that were performed with the penetrometer, the volumetric density (Da) and the estimated values of total porosity (Pt) for each type of soil, Ferralitic Yellowish Leached (FRAL) and Brown (P).

The value of the Dr for the soil type FRAL was 2.53 g cm^{-3} and for the soil P of 2.39 g cm^{-3}. The textural class of the FRAL soil type was classified as sandy Loam, with a composition of 65.4 % sand, 20.2 % silt and 8.7 % clay, while soil type P was classified as loamous clay. , composed of 43.0 % sand, 14.3 % silt and 42.7 % clay.

The sample needed to guarantee a power of 90 % and a significance of 0.05 for a correlation of 0.90 according to the formula used was of size five. However, in the present investigation 24 observations were taken for the FRAL soil type and 23 for the P.

During the analysis it was observed that readings of resistance to penetration greater than 700 N cm^{-2} generated non-compliance with the theoretical assumptions of the regression analysis and increased estimation errors, such was the case of an observation in soil type P, eliminated from the analysis without affecting the partial and final results of the study. This behavior is in correspondence with that recommended by the manufacturer of the penetrometer, which guarantees the reliability of the equipment at reading ranges between 200 and 700 N cm^{-2}.

Table 1. Values of penetration resistance, volumetric density and total porosity for each observation and type of soil under study

Observation	Soil FRAL			Soil P		
	Rpenet (N cm^{-2})	Da (G cm^{-3})	Pt (%)	Rpenet (N cm^{-2})	Da (G cm^{-3})	Pt (%)
1	220	1,50	40,6	130	1,38	42,3
2	240	1,52	39,7	175	1,38	42,1
3	245	1,53	39,7	200	1,40	41,6
4	260	1,54	39,3	225	1,40	41,3
5	270	1,55	38,9	275	1,41	41,2
6	320	1,55	38,8	275	1,43	40,2
7	320	1,55	38,7	275	1,44	39,8
8	320	1,56	38,4	300	1,44	39,6
9	350	1,59	37,2	300	1,45	39,4
10	370	1,59	37,2	300	1,45	39,3
11	400	1,59	37,1	300	1,46	39,1
12	425	1,60	36,7	325	1,47	38,6
13	450	1,61	36,4	350	1,47	38,4
14	465	1,62	36,1	375	1,48	38,0
15	480	1,62	36,0	400	1,50	37,4
16	500	1,65	34,9	450	1,50	37,1
17	520	1,66	34,5	550	1,51	36,7
18	540	1,66	34,3	575	1,53	36,1
19	560	1,67	34,1	600	1,53	36,0
20	620	1,67	33,9	628	1,54	35,5
21	630	1,68	33,4	650	1,55	35,2
22	650	1,69	33,1	675	1,59	33,5
23	680	1,70	32,9	700	1,60	33,2
24	700	1,72	32,1	750	1,70	28,9

Rpenet: resistance to penetration Da: volumetric density Pt: total porosity

The correlation coefficients between the variables Da and Pt with Rpenet for soil type FRAL and P are highly significant in both cases, positive with Da and negative with Pt (Table 2).

Table 2. Pearson correlation coefficients between Da with Rpenet and Pt with Rpenet

Type of soil	Coefficients	Rpenet. Da	Rpenet.Pt
FRAL	Pearson correlation	0,987**	-0,990**
	Bilateral significance	< 0,001	< 0,001
	N	24	24
P	Pearson correlation	0,973**	-0,974**
	Bilateral significance	<0,001	<0,001
	N	23	23

The linear models obtained have a high predictive capacity of the total variability, it is explained in the case of the Da, 97.5 % for the soil type FRAL and 94.6 % for the soil P and in the case of the total porosity 98 % and 94.9, respectively (Tables 3, 4, 5 and 6).

The regression coefficients are highly significant and the confidence intervals have a reduced amplitude, which does not indicate large changes in case of replacing the sample with another of equal size obtained from the same population (Tables 7, 8, 9 and 10).

The regression equations, for both types of soil, which relates Rpenet to Da and Pt, as dependent variables, are presented together with the dispersion diagram of the observations made and the trend line in Figure 1 for the type FRAL and in Figure 2 for type P. In all cases, the coefficients of determination R_2 are greater than 0.94.

In both soil types, the results show a highly significant linear correlation between the volumetric density and penetration resistance method, as well as between the penetration resistance and the total porosity for both types of soils. These results suggest the validity of the use of the penetrometer as an estimator of Da and Pt.

Table 3. Summary of the Da vs Rpenet model on FRAL soil

Model	R	R square	R squared corrected	Typical error of the estimate
1	0,987[a]	0,975	0,973	0,01030

a. Predictor variables: (Constant). Penetration resistance

Table 4. Summary of the Pt vs Rpenet model on FRAL soil

Model	R	R square	R squared corrected	Typical error of the estimate
1	0,990[a]	0,981	0,980	0,35639

a. Predictor variables: (Constant). Penetration resistance

Table 5. Summary of the Da vs Rpenet model on ground P

Model	R	R square	R squared corrected	Typical error of the estimate
1	0,973[a]	0,946	0,943	0,01496

a. Predictor variables: (Constant). Penetration resistance

Table 6. Summary of the Pt vs Rpenet model on P floor

Model	R	R square	R squared corrected	Typical error of the estimate
1	0,974[a]	0,949	0,947	0,60246

a. Predictor variables: (Constant). Penetration resistance

Table 7. Regression coefficients and confidence intervals for Da vs Rpenet on FRAL soil

Model	Coefficients non-standardized		Typified coefficients	t	Significance	Confidence interval 95% for B	
	B	Typical error	Beta			Inferior limit	Superior limit
(Constant)	1,427	0,007		215,8	0,000	1,414	1,441
Rpenet	0,00041	0,000	0,987	28,9	0,000	0,00038	0,00044

B: non-standardized regression coefficient of the predictor variable

Table 8. Regression coefficients and confidence intervals for Pt vs Rpenet on FRAL soil

Model	Coefficients non-standardized		Typified coefficients	t	Significance	Confidence interval 95% for B	
	B	Typic error	Beta			Inferior limit	Superior limit
(Constant)	43,640	0,229		190,8	0,000	43,166	44,114
Rpenet	-0,016	0,000	-0,990	-33,3	0,000	-0,017	-0,015

B: non-standardized regression coefficient of the predictor variable

Table 9. Regression coefficients and confidence intervals for Da vs Rpenet on the ground P

Model	Coefficients non-standardized		Typified coefficients	t	Significance	Confidence interval 95% for B	
	B	Typic error	Beta			Inferior limit	Superior limit
(Constant)	1,336	0,008		170,1	0,000	1,320	1,353
Rpenet	0,00035	0,000	0,973	19,2	0,000	0,00031	0,00038

B: non-standardized regression coefficient of the predictor variable

Table 10. Regression coefficients and confidence intervals for Pt vs Rpenet on ground P

Model	Coefficients non-standardized		Typified coefficients	t	Significance	Confidence interval 95% for B	
	B	Typic error	Beta			Inferior limit	Superior limit
(Constant)	44,095	0,316		139,4	0,000	43,437	44,753
Rpenet	-0,015	0,001	-0,974	-19,9	0,000	-0,016	-0,013

B: non-standardized regression coefficient of the predictor variable

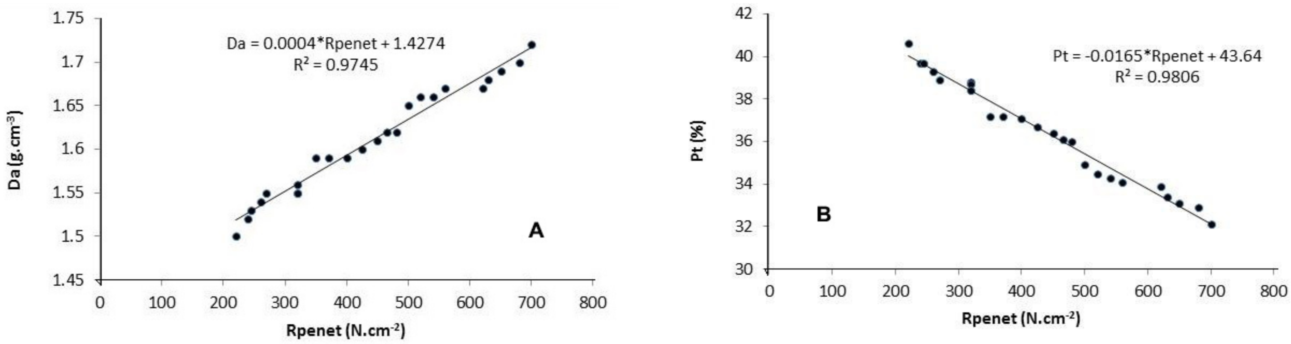

Figure 1. Trend line and regression equation that relates Da and Rpenet (A) and Pt and Rpenet (B) for the FRAL soil

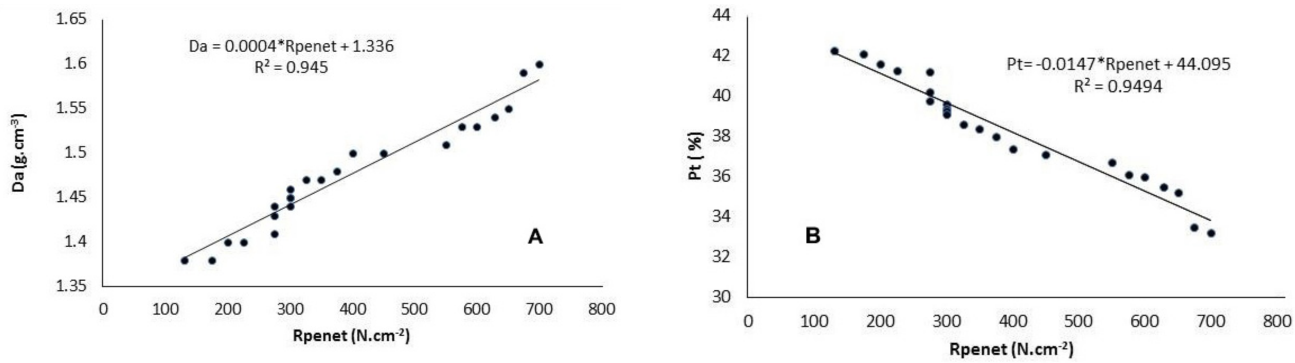

Figure 2. Trend line and regression equation that relates Da and Rpenet (A) and Pt and Rpenet (B) for soil P

The regression equations that allow the estimation of Da and Pt for the FRAL soil type are: Da=1,427+0,0004 Rpenet; R_2 = 0.97 and Pt = 43.64 - 0.0165 Rpenet; with an R_2 = 0.98. For the soil P the regression equations are: Da = 1,336 + 0,0003 Rpenet; with an R_2 = 0.95 and Pt = 44.1 - 0.015 Rpenet; with an R_2 = 0.95. To determine the value of Da and Pt, in all the equations, Rpenet must be replaced by the value of the reading obtained with the penetrometer, expressed in N cm^{-2}. These equations allow; In addition, estimate compaction rates in both soil types, using national assessment scales, expressed in g cm^{-3}.

The Shapiro Wilk test applied to the residuals demonstrated the fulfillment of the assumption of normality required for the least squares regression (Table 11).

Table 12 shows the result of the paired comparison, between the real values of the dependent variable and the predicted ones. For both soil types, equality was evidenced, with a probability equal to 1 in a t test for related samples.

The values obtained from Da and Pt, for both soils, are in correspondence with previously published results (3,4). For Cuba, average or ideal Da values are reported in clay soils of 1.10 g cm^{-3}, in free soils of 1.35 g cm^{-3} and in sandy soils of 1.5 g cm^{-3} (15).

In another of the scales of assessment mostly applied in the country and integrated into the system for the calculation of the productive potential of soils, “AGRO 24”, and that does not distinguish the textural class, is considered a compacted soil, when it has values higher than 1.4 Mg m^{-3} (23). Similarly, the optimum range of volumetric density was reported for most crops, values equal to or less than 1.4 Mg m^{-3}; while for organic soils, values equal to or less than 1.0 Mg m^{-3} (7).

A soil compaction value of 1.31 g cm^{-3} in sandy Loam soil under maize cultivation, in a humid tropical environment, was considered as optimal (24). Meanwhile, in Rhodic Eutrudox soil, in Brazil, under no-tillage system and minimum tillage with barbed plow, values of 3.5 and 3.0 MPa were reported as critical values of penetration resistance, respectively, values higher than 2 MPa, which are commonly reported as critical using conventional tillage (14).

Table 12. Results of the t-Test for related samples

Type of soil	Estimated Dependent Variable	Probability in the t test
P	Da	1,00
	Pt	1,00
FRAL	Da	1,00
	Pt	1,00

In relation to total porosity, the values obtained during the study and previously shown correspond to values reported by other authors in similar types of soils (15,23). For the FRAL soil type the average value of Pt used in the estimation equation was 43.6 % and for the soil P of 44.1.

If we take into account that theoretically, the soil is made up of 50 % solid materials, 45 % mineral and 5 % organic and the other 50 % is occupied by porous spaces, where air and water accumulate (7); to the extent that the total porosity value falls below 50 %, the manifestation of soil compression problems and impacts on the flow and water and gaseous exchange of the soil must be greater, but this is not always the case, this definition is dependent on the texture and structure of the soil, which varies from one type of soil to another (5-8).

For Cuba, it was reported, for soils with a sandy Loam textural class and with values of total porosity between 40-45 %, good aeration and good drainage; however, for soils with textural clay loamy, these porosity values are evaluated as low aeration and with very poor drainage (16).

Other authors also reported different levels of affectation for similar values of total soil porosity depending on its texture (5-8,25).

Table 11. Shapiro Wilks test results

Type of soils	Dependent variable	Residues		
		[Min- Max]	Typical deviation	Probability in the Shapiro Wilk test
P	Da	[-0,022; 0,023]	0,014	0,110
	Pt	[-0,820; 1,140]	0,590	0,060
FRAL	Da	[-0,018; 0,018]	0,010	0,460
	Pt	[-0,680; 0,580]	0,340	0,360

CONCLUSIONS

- There is a highly significant linear relationship between the volumetric density of the soil and the resistance to penetration and of them with the total porosity of the soil, in both types of soil studied.
- Given the relationships between the variables studied, the regression equations for estimating Da and Pt in a leached yellowish Ferralitic soil are: Da=1,427+0,0004 Rpenet; R2=0.97 and Pt=43.64-0.0165 Rpenet; R_2=0.98 and for Brown soil, the regression equations are: Da=1.336+0.0003 Rpenet; R_2=0.95 and Pt=44.1-0.015 Rpenet; R_2=0.95.
- In the four equations, the quality of the functional relationships found and evaluated with test t, shows statistical equality, with a probability equal to 1.

RECOMMENDATIONS

Conduct similar studies in other types of soils, to continue relating the use of the penetrometer with the traditional methods used in Cuba and to develop compaction evaluation scales for Cuban soils, according to textural classes, expressed in N cm^{-2} and MPa.

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