SUELO

ARTÍCULO ORIGINAL

Influence of Soil Moisture and Dry Bulk Density on the Engineering Properties of an Oxisol Soil

Influencia de la humedad y la densidad en la variación de las propiedades ingenieriles de un suelo Oxisol

Dr.C. Elvis López Bravo[I], Dr.C. Miguel Herrera Suárez[I], Dr.C. Omar González Cueto[I], Dr. Engelbert Tijskens[II], Dr. Herman Ramon[II].

[I] Central University "Marta Abreu" of Las Villas, Faculty of Agricultural and Animal Sciences, Department of Agricultural Engineering, Villa Clara, Santa Clara, Cuba.
[II] Faculty of Bioscience Engineering, Division of Mechatronics, Biostatistics and Sensors (MeBioS), Department of Biosystems, Heverlee, Belgium.

ABSTRACT. Soil mechanical properties were experimentally determined by triaxial compression tests and modified shear tests. The experimental study was divided in the tests to determine properties related to the soil interface as Young's Modulus, cohesion and internal friction, conducted by compression triaxial tests; and those properties related to the interface soil-metal, such as soil-metal adhesion and external friction, conducted by the direct modified shear tests. Soils, however, are in constant changes related mainly to climatic, natural and external factors. All these changes modify the soil mechanical response. To capture the soil strength at different conditions, the mechanical properties above defined were obtained at a different content of water and dry bulk density. A multilevel factorial experimental design was used to combine the soil gravimeter water content w ranging from 16 to 32% with a dry bulk density r_d between 1 and 1,4 g/cm^3. As a result, a set of statistical regression equations was obtained for predicting the magnitude of the mechanical properties as a function of soil moisture and compaction level.

Keywords: *Tillage, triaxial test, elastic modulus, shear test; friction angle.*

RESUMEN. Las propiedades mecánicas del suelo se obtuvieron de forma experimental empleando ensayos de compresión triaxial y de corte directo modificado. El estudio estuvo dividido en la determinación de las propiedades relacionadas con la interfaz del suelo: Módulo de Young, cohesión y fricción interna; se determinaron además las propiedades relacionadas con la interfaz suelo-metal: adhesión y fricción externa. Considerando que los suelos están en constantes cambios relacionados a la influencia de factores externos,se emplearon valores variables de humedad y densidad del mismo. Con este fin, se realizó un diseño de experimento factorial combinando el contenido de agua del suelo de 16 a 32%, con una densidad aparente de 1 a 1,4 g/cm^3. Como resultado, se obtuvieron un conjunto de ecuaciones de regresión estadística para la predicción de la magnitud de las propiedades ingenieriles del suelo relacionadas con los niveles de humedad y la compactación del suelo.

Palabras clave: *labranza, ensayos triaxiales, módulo de elasticidad; ángulo de fricción.*

INTRODUCTION

Tillage operations should generate a favourable soil structure in terms of water, nutrients, oxygen, and temperature. However, soil behaviour changes according to factors such as soil type, moisture, bulk density, loading type, and loading rate (Ayers, 1987). Consequently, the variability in soil mechanical response makes it a difficult task to determine adequate parameters for tillage tools.

Soil mechanical response is characterised, in the first place, by the stress-strain relationship during soil deformation. Many internal and external factors, however, affect the way the soil is deformed under pressureThe stiffness and soil strength are the direct results of increasing parameters as cohesion, internal friction, Young's modulus and Poisson's ratio. All of these parameters are found to be dependent on the soil compaction (Mouazen *et al.*, 2002). Anincrementin bulk density results ahigher draught force and energy requirement during tillage.At the soil-tool interface, particle sliding takes place at a certain velocity, the friction between coarse grains of soil andthe tool steel surfaces cause, in a specific period of time, wear on thetool surface in contact with soil which reduces the quality of the tillage and consequently increments in the traction force (Bayhan, 2006; Graff *et al.*, 2007).

On the other hand, soil mechanical properties have been used indistinctly for FEM and DEM models as soil parameters for soil-tool interaction (Mouazen y Ramon, 2002; Abo-Elnor *et al.*, 2004; Cui *et al.*, 2007; Shmulevich *et al.*, 2007; Coetzee y Els, 2009). In general,soil simulations have been implemented with constant soil properties, focused, most of the time, on finding the effect of the model parameters, called micro-parameters, on the simulation results.

The soil responsesto physical conditions change dramatically along different patterns known as elastic, elastic-plastic, plastic, and viscous. This behaviour is hard to reproduce by a single mathematical model. Additionally, is difficult to think about soil deformation patterns, without a variation in moisture and bulk density.Considering the complexity in soil behaviour the objective of the present work is obtain the relationship existing between the engineering soil mechanical properties with water content and dry bulk density.

METHODS

The samples of soil were collected at the central region of Cuban Island. Soil texture and physical properties were obtained by combination of soil sieve and hydrometer tests (Archer y Marks, 1985).The soil was classified as Oxisol according to the international classification based on soil taxonomy (ASTM-D2487). In view of its granulometric composition according to the so-called soil textural triangle, the soil was considered as clay. The soil mechanical properties related to soil-soil interaction, more specifically, the internal friction, soil cohesion, soil adhesion, Young's modulus, and Poisson's ratio were studied by means of the Standard Triaxial Compression Test (ASTM-D2850). A multilevel full factorial experimental design was used to obtain the influence of the soil gravimetric water content (w) and dry bulk density (r_d) on the behaviour of mentioned mechanical properties. The content of water was planned to vary in five levels: 16, 20, 24, 28 and 32%, and dry bulk density in three levels: 1; 1,2 and 1,4 g/cm^3.

The external properties of the soil called soil adhesion (c_a) and soil external friction (δ) were obtained by direct shear tests with respect to a steel surface. Soil specimens were sized at 70 mm diameter and 16 mm height by means of the procedure of mixing and remoulding according to the standard (ASTM-D3080). In order to determine the influence of the water content and dry bulk density with respect to adhesion and external friction behaviour, in a way similar to the triaxial compression test.

RESULTS AND DISCUSSION

Elastic Young's Modulus

Through the entire experimental region a strong linkage of soil elastic modulus with water content and dry bulk density was found. The magnitude of Young's modulus was obtained between 10 to 100 MPa (Figure 1).

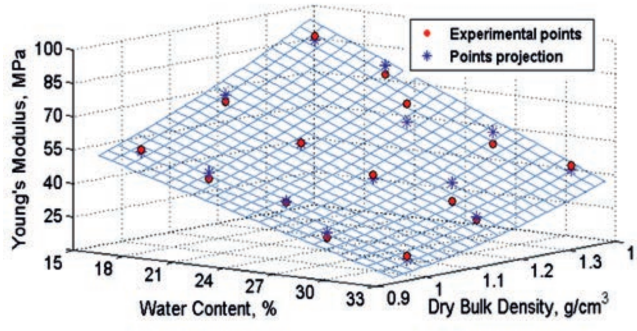

FIGURE 1. Variation of Young's modulus.

The statistical model to predict Young's modulus *E*as a function of water content and dry bulk density is written as:

$$E = a + bwr_d + cr_d^2 \quad (1)$$

where:

E = Young'smodulus [MPa];

a = 32.1 [MPa];

b = -2.33 [Nm/g];

c = 57.2 [Nm^4/kg^2].

The model was fitted with an adjusted coefficient of multiple determination,*Adj.* R^2=0,95 and standard deviation of the regression was*RMSE* = 4,2 MPa. Young's modulus describes a quadratic relationship with respect to dry bulk density as is shown in Figure 1. The interaction between independent variables was also considered important in the model accordingly with Equation (1). The water content, on the other hand, gave a linear reduction of Young's modulus by increasing moisture content. At low moisture the water binds the particles of clay,enhancing the effective soilstrength, by this process, when the soil is drying out clay becomes very stiff. The non-linear behaviour of soil elasticity as a function of dry bulk density was also found by Mouazen *et al.* (2002). At the same time, an study carried out in a soil classify as RhodicFerrasol by Cueto (2011) showed close results in Young's modulus magnitudes.

Soil cohesion

For an specific soil, the predominant factors that affecting soil cohesion are the index of compaction and soil moisture, as a result of the chemical and physical phenomena taking place in the soil (McKyes, 1989).The cohesion as function of the dry bulk density and soil moisture is shown in Figure 2.

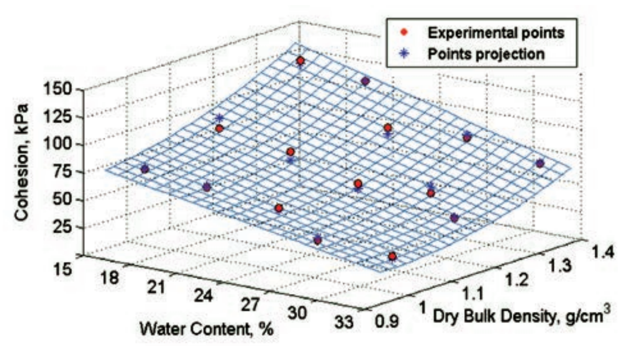

FIGURE 2. Variation of soil cohesion.

The statistical model to predict soil internal cohesion as a function of water content and dry bulk density is written as:

$$c = a + bwr_d + cr_d^2 + dr_d \qquad (2)$$

where:
c = soilcohesion [kPa];
a = 220,7 [kPa];
b = -2,7 [Nm/kg];
c = 211 [kN·mm^4/g^2];
d = -317 [Nm/kg].

The model was fitted with an adjusted coefficient of multiple determination,*Adj.* R^2=0,96. The standard deviation of the regression was*RMSE* = 4,6 kPa.A quadratic increase with respect to dry bulk density characterises the cohesion for all values of soil moisture.At the same time, cohesion decreases linearly when soil water content increases.Inthe range of soil moisture under study (w = 16 to 32%), the soil cohesion raises an average of 50 kPa for all values of dry bulk densities tested. This behaviour subjects the soil tendency to obtain hither values of cohesion in dry-compacted condition (c> 120 kPa) in contrast with the values found under wet-loose conditions (c < 30 kPa). Similar results have been reported by Horn and Fleige (2003), the authors linked the soil strength with soil suction, texture, structure, and applied stress.

Soil adhesion

As shown in Figure 3, a small linear increase was found in soil adhesion with respect to dry bulk density with an average variation of 2,1 kPa for specific water content. This result suggests a weak dependence of soil adhesion on soil compaction. The predominant factor is the water content in a quadratic relation. Beyond 23% of water content the adhesion rapidly increases.

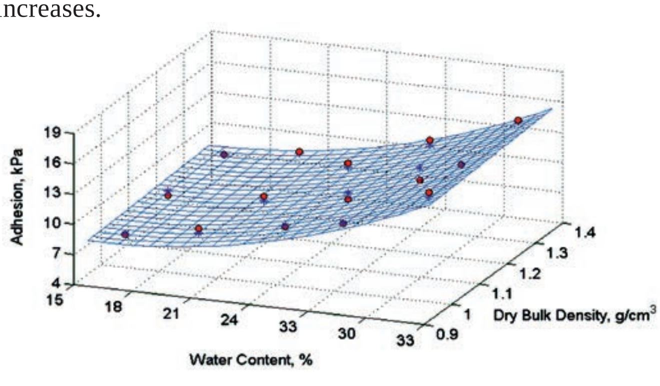

FIGURE 3. Variation of soil adhesion.

The statistical model resulting from multiple regression analysis is written as:

$$c_a = a + bw + cr_d + dw^2 \qquad (3)$$

where:
c_a= Soil-metal adhesion [kPa];
a = 12,12 [kPa];
b = -0,7807 [kPa];
c = 1,28 [Nm/kg];
d = 0,02537 [kPa].

The model was fitted with an adjusted coefficient of multiple determination, *Adj.* R^2= 0,96. A standard deviation of regression *RMSE = 0,*4 kPa was obtained.The relationship between soil adhesion and moisture in several Cuban soil was studied by Garcia de la Figal (1978), the author reported the quality of clay soils to acquire high values of adhesion in contact with plastic and steel at specific water content, that behaviour was found weak for sandy soils. The values obtained in the present study corroborate the results reported by Rodriguez (1999) in a Vertisol soil with 50% of clay.

Soil internal friction

The variation of internal friction angle to respect of water content and dry bulk density is shown in Figure 4.

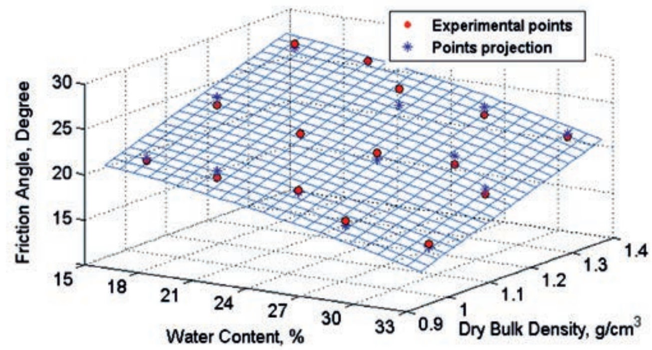

FIGURE 4. Variation of internal friction.

The statistical model to predict internal friction as a function of water content and dry bulk density is written as:

$$\phi = ar_d + bw^2 + c \qquad (4)$$

where:
ϕ = internal friction angle [°];
a = 16,6 [cm^3/g];
b = -0;008 [°];
c = 6;2 [°].

The model was fitted with an adjusted coefficient of multiple determination *Adj.* R^2= 0,94, the standard deviation of the regression was obtained at *RMSE* = 0,82°.Soil moisture and compaction level change the internal friction response as shown in the Figure 4. With the increase in soil water content the friction was reduced until it reached a minimum value for lower dry bulk density, describing a non-linear behaviour. As previously discussed, soil softening and bond dissolution risewith water increases. Inversely, increasing soil compaction the internal friction also linearly rises, probably caused by the augmentation in the actual area of contact and the number of contact points. During sliding, thesoil grains are fragmented into new smaller grains affecting the soilinternal friction. The increase in moisture content is accompanied by a decrease in the solid fraction in the soil. According to McKyes (1989),as the solid fraction decreases and moisture content increases, theinterlocking and long-range forces between small particles, and the strength parameters i.e. friction and cohesion also decrease.

Soil-metal friction

Soil external friction related to the soil-steel interface was determined from the modified direct shear tests. The variation of soil-steel angle of friction to respect of moisture and compaction is shown in Figure 5.

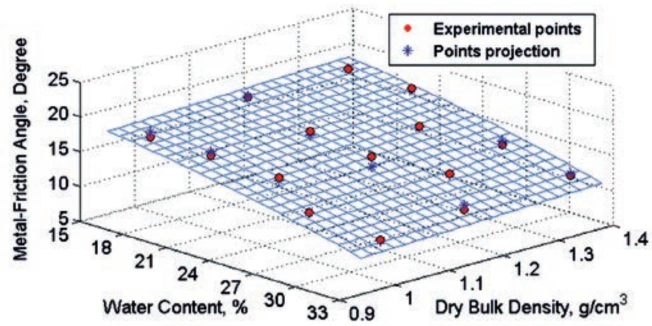

FIGURE 5. Surface response of soil-metal friction.

The statistical model to predict the angle of soil external friction as a function of water content and dry bulk density can be written as:

$$\delta = a + br_d + cw^2 \quad (5)$$

where:

δ=Soil-steel angle of friction [°];

a = 15,8 [°];

b = 3,03 [cm³/g];

c = -0,009 [°].

The model was fitted with an adjusted coefficient of multiple determination,*Adj.* R^2= 0,94 and standard deviation of the regression was *RMSE* = 0,21°. The soil external friction wasmainly affected by the water content as shown in Figure 5. Starting from dry conditions, the soil-steel friction diminishes in a quadratic way as water content increases. Dry bulk density was found as a secondary factor in the behaviour of the soil-steel friction. From loose to compacted soil only 2,1º of average variation was observed.The results of metal-friction variation obtained in the present study show the main effect of the water content as was reported by Suarez (2006). In this study however, the value of the angle change between 10° to 32°.

CONCLUSIONS

- The variation of Young's modulus showed a non-linear relationship with dry bulk density, increasing from 52 to 93 MPa at a minimum water content *w* = 16%. Theelastic property decreases with increasing water content until reaching a value of 18 MPa for *w* = 32%. Soil cohesion increased linearly with the water content, and its response was quadratic with dry bulk density. Both variables exert a significant influence on the rise in soil cohesion. Soil adhesion, however, shows a small linear increase with dry bulk density and was affected mainly by water content above 24%. The soil internal friction rangedfrom 14° to 28° has a quadratic relationship with water content and a linear relationship with soil compaction. Different patterns of behaviour characterized soil external friction. This property is strongly influenced by the water content, decreasing quadraticallyfor all levels of dry bulk density. A smalllinear increase is obtained by the action of soil compaction. In general, soil-metal friction angle shows a variation from 16,1° to 19,9°.For each soil mechanical property under study a regression equation was obtained to calculate its magnitude with an adjusted coefficient of multiple determination*Adj.* R^2 from 0,94 to 0,97. The statistic coefficients were determined at 95% confidence limit.

REFERENCES

ABO-ELNOR, M.; R. HAMILTON & J. T. BOYLE: "Simulation of soil-blade interaction for sandy soil using advanced 3D finite element analysis", *Soil and Tillage Research*, 75 (1): 61-73, 2004.

ARCHER, J. R. & M. J. MARKS: "Techniques for Measuring Soil Physical Properties", *ADAS Reference Book*: 22,130, 1985.

ASTM-D2487: *Test Method for Classification of Soils for Engineering Purposes. Annual Book of ASTM Standards, Vol 04.08,* West Conshohocken, United State, Vig. 1980.

ASTM-D2850: *Standard Test Method for Confined Compressive Strength of Soil. Book of Standards. Committee D-18,* West Conshohocken, United State, Vig. 1990.

ASTM-D3080: *Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions. Book of Standards. Committee D-18,* West Conshohocken, United State, Vig. 1998.

AYERS, P. D.: "Moisture and bulk density effects on soil shear strength parameters for coarse grained soils.", *Transactions of the Asae*, 31 (2): 1282-7, 1987.

BAYHAN, Y.: "Reduction of wear vía hardfacing of chiesel plougshare", *Tribology International*, 39: 570-574, 2006.

COETZEE, C. J. y D. N. J. ELS: "Calibration of granular material parameters for DEM modelling and numerical verification by blade–granular material interaction", *Journal of Terramechanics*, in press: 2009.

CUI, K.; P. DE´FOSSEZ y R. GUY: "A new approach for modelling vertical stress distribution at the soil/tyre interface to predict the compaction of cultivated soils by using the PAXIS code", *Soil & Tillage Research*, 95: 277-2, 2007.

GARCÍA DE LA FIGAL, A.: "Estudio de las propiedades tecnológicas mas importantes de los suelos cubanos", *Revista Ciencias Técnicas Agropecuarias*, 3 (2): 61-77, 1978.

GONZÁLEZ, O.: *Modelación de la Compactación Provocada por el Tráfico de Neumáticos de los Vehículos Agrícolas en Suelos en Condiciones de Laboratorio*, 209pp., Tesis (en opción al grado científico de Doctor en Ciencias Técnicas Agropecuarias), Universidad Agraria de La Habana, Centro de Mecanizacion Agropecuaria, La Habana, 2011.

GRAFF, L. J.; R. C. ROBERGE y T. G. CROWE: Wear of Ripper Point Hardsurfacing. En:2007 ASABE/CSBE North Central Intersectional Conference, October 12-13, pp. 10, North Dakota State University. Fargo, North Dakota, USA. Paper Number: RRV-07120, 2007.

HORN, R. y H. FLEIGE: “A method for assessing the impact of load on mechanical stability and on physical properties of soils”, *Soil and Tillage Research*, 73 (1-2): 89-99, 2003.

MCKYES, E.: *Agricultural Engineering Soil Mechanics,* Amsterdam: (ed.) ElsevierSciences, Amsterdam, 1989.

MOUAZEN, A. M. y H. RAMON: “A numerical-statistical hybrid modelling scheme for evaluation of draught requirements of a subsoiler cutting a sandy loam soil, as affected by moisture content, bulk density and depth”, *Soil and Tillage Research*, 63 (3-4): 155-165, 2002.

MOUAZEN, A. M.; H. RAMON y J. D. BAERDEMAEKER: “Effects of Bulk Density and Moisture Content on Selected Mechanical Properties of Sandy Loam Soil”, *Biosystems Engineering*, 83 (2): 217-224, 2002.

RODRÍGUEZ, M.: *Fundamentación de un sistema de rodajes por semiesteras en las cosechadoras cubanas de caña de azúcar para trabajar en suelos de mal drenaje*, 100pp., Tesis (en opción al grado científico de Doctor en Ciencias Técnicas) Universidad Central “Marta Abreu”, Departamento de Mecanizacion Agropecuaria, Santa Clara, Cuba, 1999.

SHMULEVICH, I.; Z. ASAF y D. RUBINSTEIN: “Interaction between soil and a wide cutting blade using the discrete element method”, *Soil and Tillage Research*, 97 (1): 37-50, 2007.

SUÁREZ, M. H.: *Simulación del comportamiento mecánico de los suelos ferralíticos rojos mediante el método de elementos finitos* 205pp., Tesis (en opción al grado científico de Doctor en Ciencias Técnicas Agropecuarias), Universidad Agraria de La Habana, Centro de Mecanizacion Agropecuaria, La Habana, 2006.

Recibido: 15 de julio de 2013.
Aprobado: 20 de marzo de 2014.

Elvis Lopez Bravo, Profesor, Central University “Marta Abreu” of Las Villas, Faculty of Agricultural and Animal Sciences, Department of Agricultural Engineering, Villa Clara, Santa Clara, Cuba, E-mail: elvislb@uclv.edu.cu