ARTÍCULO ORIGINAL

Effect of Moisture and Soil Compaction on Tillage Operations

Efecto de la humedad y la compactación del suelo en operaciones de labranza

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ABSTRACT. In the present paper, soil tillage under different moisture and dry bulk density is discussed. An experimental installation called soil-bin was used to perform the measurement of vertical and draft forces over the tool. The soil used was classified as Oxisol, characterized by a high clay content and mechanical strength. The compaction in soil-bin is performed using a roller compactor and confirmed by measurement moisture and dry bulk density in all sections. The main results show a close dependence between physical soil condition and resulting forces. The maximum levels of forces were found for density and moisture in dry and compacted state. Meanwhile, maximum values of soil profile were obtained for low densities and moisture. Similarly, for medium content of moisture increases the amount of aggregates sized less than 10 mm.

Keywords: *Dry bulk density, tensometry, soil profile, soil-bin, aggregates.*

RESUMEN. En el presente trabajo se aborda la labranza de un suelo agrícola bajo diferentes condiciones de humedad y densidad del suelo. En el mismo se emplea una instalación experimental de pruebas o canal de suelo, el cual se acondicionó con los medios para la medición de las tensiones verticales y horizontales en el apero. El suelo empleado está clasificado como un Oxisol y se caracteriza por su alto contenido de arcilla y resistencia mecánica. La compactación del suelo del canal se realizó empleando un rodillo compactador, la misma se comprobó por medio de mediciones de humedad y densidad en las diferentes secciones. Los principales resultados muestran la dependencia existente entre el estado físico del suelo y las fuerzas resultantes. Las tensiones alcanzaron valores máximos para niveles de densidad y humedad de suelo seco y compactado. Por su parte, en el perfil del suelo se obtuvo valores máximos para bajas densidades con humedades medias. De igual forma para condiciones medias de humedad y densidad se obtuvo una mayor fragmentación con predominio de agregados menores a 10 mm.

Palabras clave*: Densidad, Tensometría, perfil de suelo, canal de suelo, agregado.*

INTRODUCTION

The soil physical conditions are strongly connected with the final structures of the aggregates resulting from tillage. Traction force in arable soils also is affected by soil physics parameters as soil moisture and compaction increasing the power consumption (Solhjou *et al*., 2013; Tagar *et al*., 2014; Tim Chamen *et al*., 2015). Tillage operation in a soil-bin condition plays an intermediate role between theoretical designs and field applications. Different soil-bin designs have been used for research on measuring dynamic forces during soil cutting. The magnitude of the force in longitudinal direction or draft force defines the energy required for the tillage operation. Several studies have correlated soil resistance with the draft force through testing different tool geometries using the draft force magnitude as a soil strength indicator (Lara Coba *et al*., 2011; Obermayr *et al*., 2011; Bravo *et al*., 2014; Hasimu; Chen, 2014). The determination of the critical speed related to soil deformation during high speed tillage was carried out using a soil-bin trolley (Kushwaha; Linke, 1996). To validate a continuous model a monorail soil-bin system was designed using silt and compacted clay soil. They found an increment in power, tool draft and soil pulverisation with increase in speed. Empirical equations to predict draft forces have been developed by Sahu; Raheman (2006). The draft forces for these models were measured in a soil-bin during tillage using a simple tillage-tool in a loam soil, taken as reference condition. Generally, the experiments in soil-bin lead to more consistent data, avoiding the variability of soil structure, keeping control over operational parameters and reducing the effects of climatological factors. Under soil-bin test in controlling condition the soil moisture and soil compaction can be manage to make in the soil different physical estates. Draft and vertical forces measured for all these conditions are used to compare the results with the model prediction (Mak *et al*., 2012; Chen *et al*., 2013). Also soil parameters related to the effect of the tool on soil loosing can be controlled and related to the soil condition.

The objective of the present research is to investigate the force variations and soil loosening indicators during tillage. A multi-blade tool was designed for non-inversion tillage and tested at several soil conditions in the Oxisol soil.

METHODS

To measure the variation of tillage performance at different soil physical conditions, a longitudinal indoor soil-bin was used (Figure 1a). The effective working area was sized at 1.5 m width, 8.0 m length. The soil-bin was filled with Oxisol soil located in the occcidental region of the Cuban island. A multi-blade tool called cultivator was manufactured for the experiment. This tool was designed for operation in the upper layer of the soil (Figure 1c).

FIGURE 1. Trolley over railway (a), tool transducer (b) and tool dimensions (c).

Between the trolley and the tool was connected the transducer ring; the deformable device was set up at the centre work of the soil-bin. The system was mounted on steel wheels rolling over a steel railway; also a steel cable was used to connect the trolley to the gear reducer, getting a constant velocity of 3.6 km/h.

Focusing on the effect of changing soil moisture content and compaction level, the experiment was organised using a Central Composite design for these two elements. Soil water content and dry bulk density were combined at nine levels and four centre point replications. Table shows the planned experimental combinations.

During tillage tests at different soil conditions, the following response variables were measured: horizontal force on the tool, vertical forces on the tool, soil density changes after tillage, soil profiles after tillage, and soil particles sizes distribution.

Draft and vertical forces were measured by the transducer designed for 5 kN capacity and non-linearity at 0.02%. The system was driven by an embedded controller Data logger NIcRIO-9012 from National instruments, Austin, TX, USA. For signal condition a module NI 9237 for full and half bridge connections was used. This module includes bridge excitation, signal amplification, multiplexing and signal filtering according to the data range. To manage the system a virtual instrument of Lab-View program was designed and installed in a Compact HP 6000 laptop.

TABLE. Experimental points from Central Composite design

Points	*w*,%	r_{d}, g/cm^3
1	17.5	1.4
2	12.2	1.3
3	22.8	1.3
4	10	1.1
5	17.5	1.1
6	25	1.1
7	12.2	0.9
8	22.8	0.9
9	17.5	0.8

RESULTS AND DISCUSSION

Draft force response

The draft forces obtained from the tests at the soil conditions defined in Table are shown in Figure 2a. The nominal force of each test was determined as the force average obtained from 150 to 450 cm in the tool trajectory.

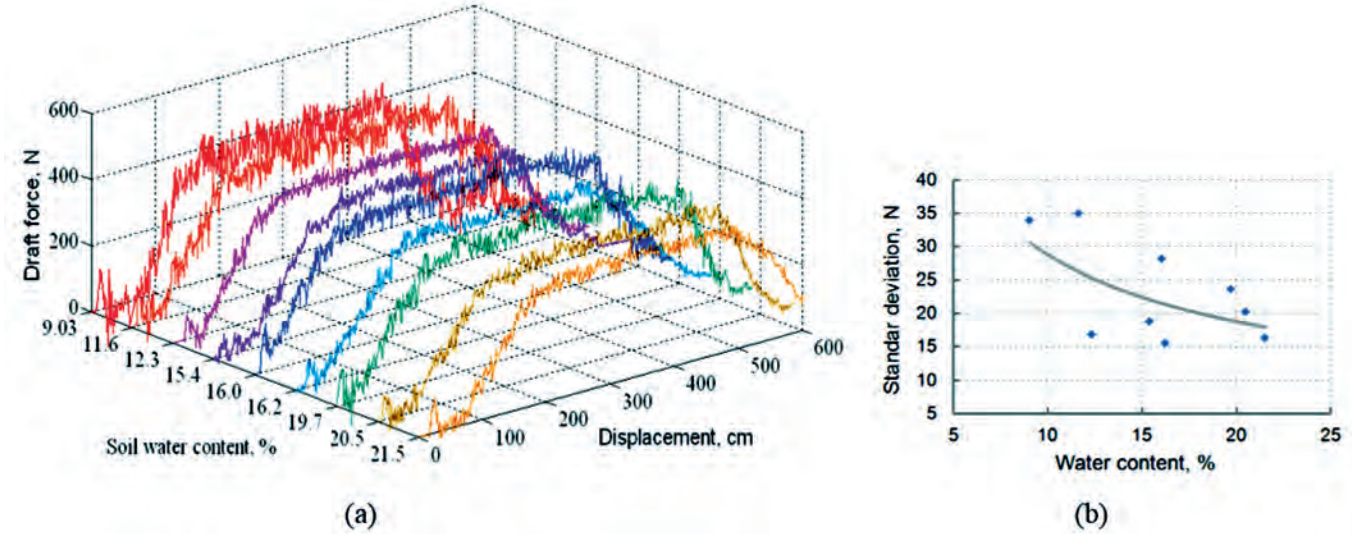

FIGURE 2. Horizontal forces from soil-bin tests (a) and standard error vs. soil water content (b).

The draft force variation was found to be between 350 and 390 N. The force standard deviation increases in dry soil conditions as shown in Figure 2b, revealing the stiffness of the soil. This pattern was well observed in test 4 carried out at the smallest soil water content $w = 9.0\%$. In fact, the magnitude of the forces characterises the general state of soil strength and affected also by the soil compaction level. The soil pattern of deformation has been found to be related with the intensity of force oscillations. Other authors had explained the gradual building up of the draft force and the attainment of the dynamic stability of the force as a function of the surcharge over the soil by the action of the tool, eventually defined by the general soil strength (Hasimu; Chen, 2014; Tagar *et al.*, 2014)

The influence of water content and dry bulk density in draft force response is shown in Figure 3. For all values of soil moisture under study when the dry bulk density increases, the draft force increases too. However, this increase for higher soil moisture $w = 23\%$, is moderated in the range between 0.9 to 1.0 g/cm^3).

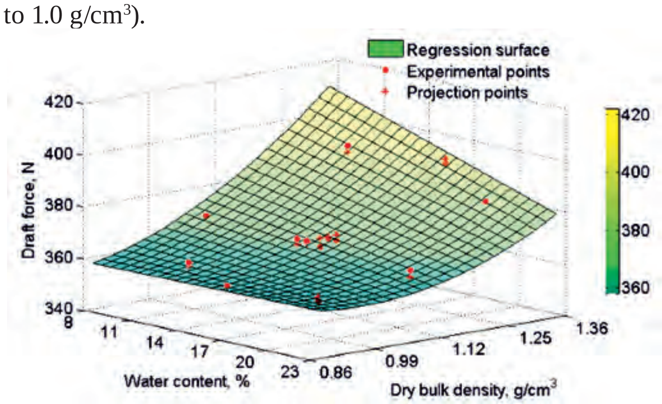

FIGURE 3. Drafts force response surface function of moisture and soil dry bulk density.

On the other hand, the influence of the soil water content is appreciable as the soil compaction increases ($r_d > 1.12$ g/cm^3). As the moisture increases the soil strength decreases. However, for smaller dry bulk densities, the influence of moisture is negligible. As was found by Sahu; Raheman (2006), the soil compaction is the main factor that contributes to the increase in draft force. The authors, in spite of including parameters as tillage depth, operation speed and tool shape decided to keep water content constant. However, in several researches a significant effect of the moisture content was found for tillage forces. In general, they have focused on finding the optimum water content for tillage, defined as workability state (Mueller *et al.*, 2003; Barzegar *et al.*, 2004; Mosaddeghi *et al.*, 2009). This condition is related with the minimal draft force needed to obtain the maximum soil loosening. The independent analysis of the draft force behaviour in the soil under study subject that the optimal water content can be placed between 14 to 23% and also beyond this point. To reduce the range of the optimum soil moisture, the loosening indicator discussed in next sections provides the entire information.

Vertical force response

The soil physical conditions defined by the different experimental tests also modify the reaction force measured in the vertical direction oriented in down sense. This vertical component is related with the pressure applied by the tool over the soil foot surface and the compaction in the surface below the tool travel, usually called plough-pan. As shown in Figure 4a, the reaction force magnitudes during the tests are found in the range of 76 to 97 N. The standard errors increase when the soil becomes drier, showing a similar pattern for the horizontal force in relation with the soil moisture (Figure 4b).

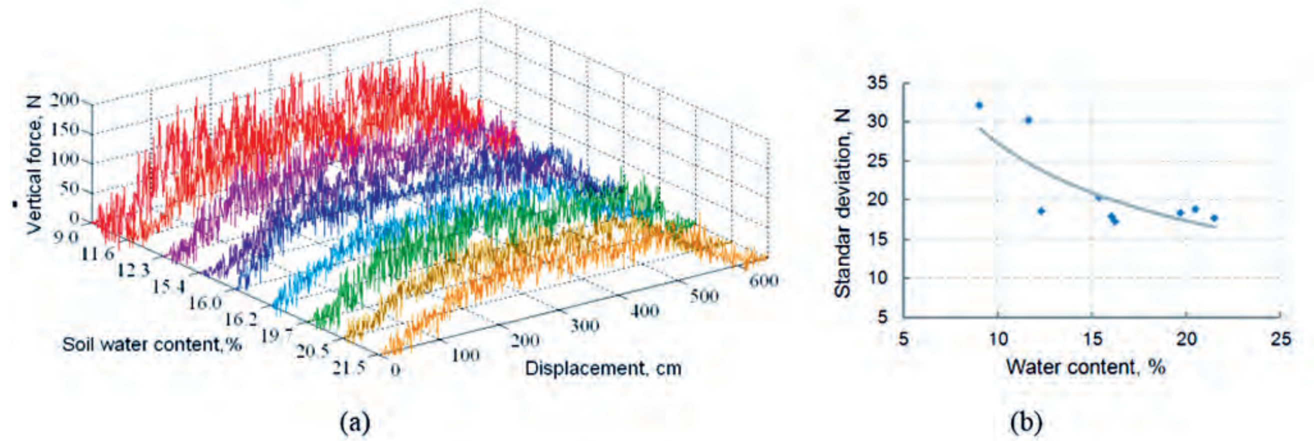

FIGURE 4. Vertical forces from soil-bin tests (a) and the standard deviation vs water content (b).

Vertical force response surfaces as a function of dry bulk density and moisture content are shown in Figure 5. As it was expected, the force increases with soil become denser and decreases with water content. These results are in accordance with the variation in soil strength parameters like cohesion, friction and soil elasticity. The susceptibility of the soil to compaction, however, is related to factors as content of clay and the critical water content (Saffih-Hdadi *et al*., 2009).

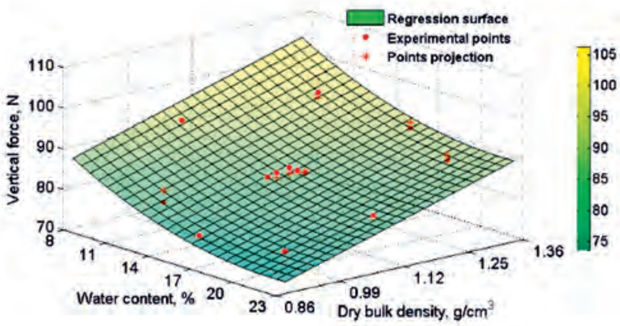

FIGURE 5. Vertical force functions of water content and dry bulk density.

Soil loosening indicators

As indicators of soil loosening variations in the initial dry bulk density, soil profile and particle size distribution by the tillage operation were measured during each different test in the soil-bin. The final dry bulk density was obtained from the disturbed soil (Figure 6a), according to the procedure explained in section 2.4.

The soil profile was measured after soil tillage by the profilometer method as shown in Figure 6b, and the soil texture classification was carried out by sieving using four different mesh sizes (Figure 6c).

The variation of the dry bulk density through the different experimental points is showed versus water content in Figure 7a.

For all combination of water content and dry bulk density tested, the loosening effect during the tillage is denoted by smaller values of final dry bulk density (red bar). As the soil water content increases, the proportional variation of dry bulk density Dr_d respect to its initial value also increases as is shown in Figure 7b. However, for the experimental points with water content beyond 15% the variation tents to be constant. According with the results discussed in section 2.6.4, as the water content increases a reduction of inter-particle bond resistance take places, maximising the grain fragmentation during soil-tool interaction. The results are in line with those found by Arvidsson *et al.* (2004), the authors concluded that tillage operation at specific water content before soil plastic limit provides a large proportion of small aggregates, and also reduces the energy demanded for tillage. The soil profile, measured after tillage was found strongly connected with the variation of dry bulk density as shown in Figure 8.

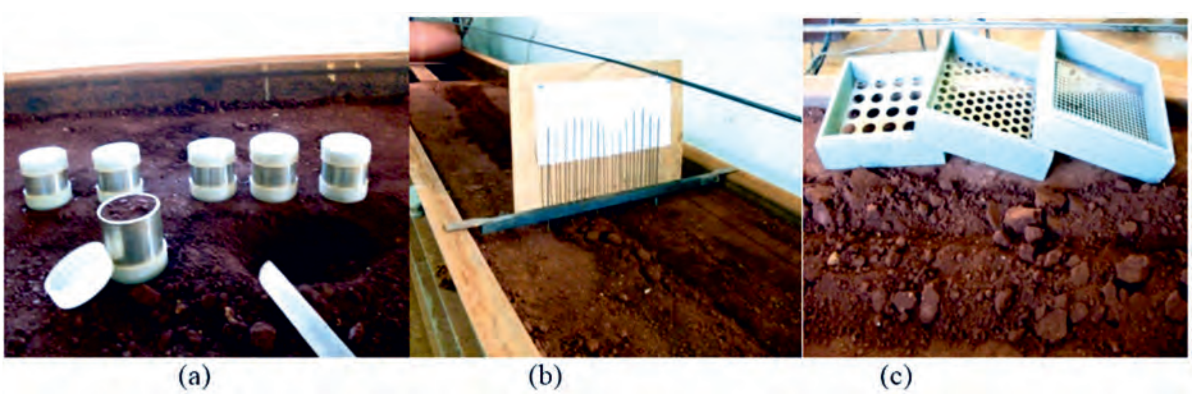

FIGURE 6. Parameters measured for all tests in soil bin.

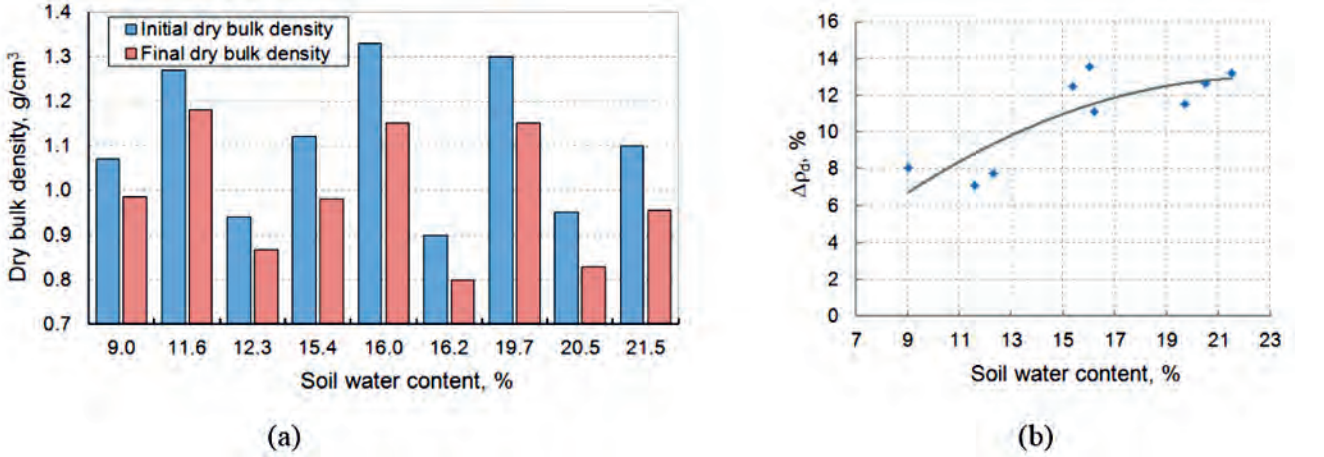

FIGURE 7. Initial and final dry bulk density (a), and dry bulk density variation after tillage.

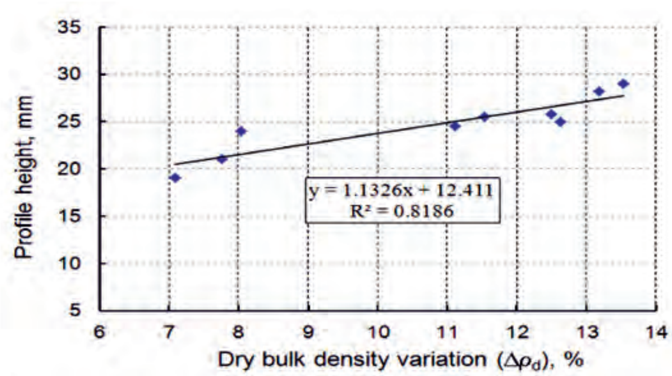

FIGURE 8. Soil profiles behaviour concerning dry bulk density variation.

In the analysis, the variation of the profile height reached after each test was established as a function of the dry bulk density variation. The relationship shows a linear increase in the height of the soil profile with increasing Dr_d. The behaviour of the soil corresponds with the volumetric changes taking place in the soil granular structure during soil loosening.

Soil aggregates distribution

The soil was classified in four groups of sizes to calculate their proportion in the soil disrupted by tillage. For the analysis three points were selected to represent the extremes and the centre of the experimental region called *dry-hard* (w = 11.6%, r_d = 1.27 g/cm^3), *medium* (w = 15.4%, r_d = 1.12 g/cm^3) and *wet-loose* (w = 20.5%, r_d = 0.95 g/cm^3). The particle distribution in the three conditions is shown in Figure 9.

The increment in the size of the aggregates for the scale of a_s < 10 mm is an indicator of better seed bed preparation. Inversely, the amount of aggregates in the scale of a_s > 50 mm shows an incomplete loosening of soil. For the *medium* soil condition, the smaller grain of soil represents more than 50% of the sample. In contrast, the *dry-hard* soil condition contains aggregates more than 10% bigger than 50 mm. Finally in soil at *wet-loose* state the number of smaller particles results slightly lower than *medium* one. As the soil becomes compacted, the aggregated size in the scale of a_s between 20 and 50 increases. However for the medium moisture the maximum proportion of a_s < 10 mm is obtained. Then, considering that the draft forces obtained in section 4.6.1, slightly decrease as the moisture increase, the optimum water content for tillage this kind of soil can be placed close to w = 15.4%.

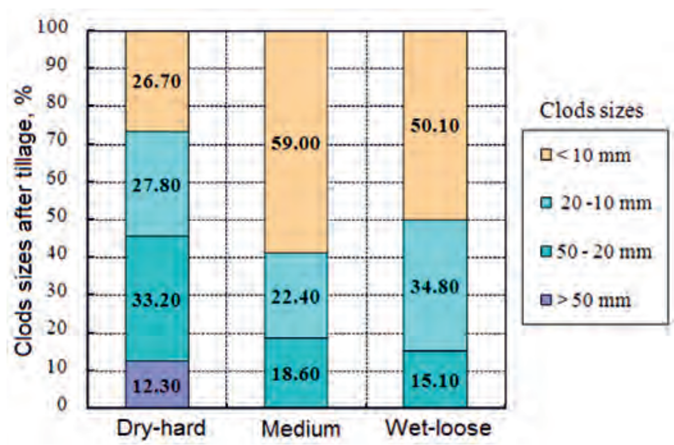

FIGURE 9. Aggregate sizes at different soil state after tillage tests.

CONCLUSIONS

- The draft force increased with the increment in soil compaction especially for dry bulk density beyond 1.1 g/cm^3. The effect of soil water content, was negligible for lower soil compaction, however, as the soil bulk density increases the draft force fall under the effect of the water content.
- The magnitude of the vertical force was found to vary between 76 and 97 N. The pressure exerted on the soil bottom increases along with the dry bulk density. Inversely, for all levels of compaction, the water content reduces the magnitude of the force in the vertical direction.
- By tillage operations, soil bulk density changes proportionally to the initial soil compaction. This variation also is affected by the water content. The height of soil profile

measured in the transversal section of disturbed soil after tillage showed a linear correlation with the variation of dry bulk density.

- The proportion of the aggregates with sizes less than 10 mm measured after tillage in three different soil conditions, called *dry-hard*, *medium* and *wet-loose*, vary with the soil state. As soil compaction increases the aggregates size after tillage also increase.

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