



TRACTORES Y MÁQUINAS AGRÍCOLAS TRACTORS AND AGRICULTURAL MACHINES

ARTÍCULO ORIGINAL

Simulación Numérica de la Interacción Suelo-Apero Mediante el Método de Elementos Discretos

Numerical Simulation of Soil-Tool Interaction by Discrete Element Method

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ABSTRACT. Discrete Element Method (DEM) was used to simulate the soil-tool interaction. The model is based on the action of normal, shear, cohesion and friction forces into the cohesive granular medium, calculated as a function of micro-mechanical properties. Macro-mechanical properties of soil-soil and soil-metal were used to determining the micro parameters on the model. In order simulate the tillage operations a soil virtual block was generated in hexagonal compacted array using 45 000 spherical particles forming a cohesive block. A soil-bin installation was conditioned to measuring the draft force in *hard-dry* and *soft-wet* soil condition to compare the results with simulation tests. The comparison showed a small under predicted behavior of the model for *soft-wet* soil; however the results become more accurate toward *hard-dry* soil conditions. The density changes during simulations and pressures distributions below the tillage tool path is showed, given a dynamic representation of soil internal tension and loosening after tillage operation.

Keywords: Tillage, modeling, draft force, density.

RESUMEN. El método de elementos discretos (DEM) fue utilizado para simular la interacción del suelo con la herramienta de labranza. El mismo se basa en la acción que ejercen las fuerzas normal, tangencial, cohesión y fricción en un medio granular cohesivo, a partir de su determinación a escala micro-mecánicas. Las propiedades macroscópicas que intervienen en el contacto suelo-suelo sirven como parámetros macros los cuales son usados para determinar los parámetros micros del modelo. Para la simulación de la labranza se realizó la generación virtual de un bloque de suelo con un total de 45 000 partículas esféricas, formando un bloque cohesivo. Para verificar los resultados de la simulación se acondicionó un canal de suelo para dos condiciones extremas: seco-endurecido y húmedo-suelto. Los resultados mostraron una tendencia del modelo a sobreestimar la magnitud de la fuerza de tiro para el suelo suelto y con alta humedad, Sin embargo el modelo resultó más preciso para la condición de alta densidad. Se obtuvieron además las distribuciones de densidad del suelo en las diferentes secciones del bloque virtual así como los resultados de la distribución de fuerzas en las capas comprimidas debido al paso de la herramienta de labranza.

Palabras clave: labranza, modelo, fuerza de tiro, densidad.

INTRODUCTION

Draft force prediction, clod sizes distribution and damages by erosion have been some of the motivation topics for modeling soil-tillage interaction. Data from field process and lab experiments are combined on mathematical models; supporting by the increment on informatics resources more accurate, fasters and extended prognostics are performed.

Computational techniques as well as finite element methods (FEM), discrete element methods (DEM), artificial neural network (ANN) and computational fluid dynamics (CFD) are indistinctly used with different purposes in soil simulation. Important approaching of rheological soil behavior is the result of transition from quasi-static to dynamic analysis (Karmakar & Kushwaha, 2006). Optimization for tillage

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tools focused on geometrical modification has been carried out on moldboard ploughs, obtaining significant draft force reduction required to move the tool through different soil conditions (Shrestha *et al.*, 2001; Godwin, 2007). Field performance of the implements for futures applications in soil-ecosystem were evaluated in the nineties decade, testing several variant of tools shapes and operations speed and getting the draft forces requirement. The most efficient tools designs were evaluated at farm level correlating the energy supply and seedbed quality (Perdok & Kouwenhoven, 1994). Prediction of draught requirements by ANN for three designs of moldboard plows, tested in sandy loam soil under different operating ranges and soil conditions, showed a good correlation in comparison with results obtaining from prediction equations (Roul *et al.*, 2009). Considering the soil as a continuum medium, several constitutive models have been created and improved. Modified Cam-Clay model was implemented focus on deriving time dependent effect, the model included soil anisotropic and creep behavior, as a result gyration and expansion of load affected the principal stress redirection, confirmation of simulation was made using un-drained shear and creep test (Ahmari & Ahmadi, 2009). Von-Mises yield criterion on perfectly plastic model was applied using Lagrangian method; including strain-softening and rate dependent, the authors present a numerical model for cone penetration into soft clay soil, the influence of stiffness index, in-situ stress anisotropy and roughness were theoretically correlated and compared with the cavity expansion theory (Liyanapathirana, 2009).

Several studies by FEM have been conducted using simples and complexes geometries of tools projected in two and three dimensions, with the objective of determining the effect of cutting speed and blade angles related to draft force variation during soil-tool interaction (Mouazen & Neményi, 1999; Mootaz *et al.*, 2003; Abo-Elnor *et al.*, 2004; Sahu & Rahman, 2006; Gebregziabher *et al.*, 2007; Davoudi *et al.*, 2008).

Several studies have been carried out to simulating the soil behavior in Cuban soil focus in tillage operation and soil management. The methodology to determine from mechanical soil test the parameters needed to fill the FEM model was used to predicting the result of soil tensional state (Herrera, 2001). The parameters of the model for soil tool interaction was determined and proof the accurate of elastic-plastics formulation obtaining best results using a Drucker-Prager model (Herrera *et al.*, 2008). Triaxial compression test and shear test have been simulated in different Cuban soils to predict the soil behavior related to compaction by the action of the inflate wheel pressures and transporting load (Gonzalez *et al.*, 2007; Gonzalez *et al.*, 2009).

Discrete medium is widely applied for simulation of dynamic process, having an extend field in soils engineering applications. The principal vantage over continuum methods is the capacity to represent the interaction among particles happen in granular medium (Tadesse, 2004). Many contact models can be included depending on how each element interacts

with each other, these contacts models rules the behavior of the overall medium, the micro-properties parameters for the model will be deduced from soil mechanical properties. The rheological simulation can result on an accurate prognostic about soil behavior and draft force requirements.

The goal for the present study is to simulate the soil-tool interaction to predicting the draft forces and soil particles behavior in tillage operations by mean of macro-scale model implemented on Discrete Element Method.

METHODS

Model description. Classical DEM model proposed by Cundall and Strack (Cundall & Strack, 1979), is used to compute the interaction between soil particles and tillage tool, two kinds of contacts were implemented: soil-soil and soil-tool, for both calculations the same contact scheme is applied, changing only cause of mechanical properties which are obtained from regression equation according to the specifics soil physical desire condition (López, 2011). The macroscopic parameters included in the model bring a physic-mechanical characterization of the soil namely: Elastic Young's modulus (E), Poisson ratio (ν), cohesion (c), adhesion (c_a), internal friction (ϕ) and metal-soil friction (δ). The model dealing with normal, shear, gravity, cohesion and friction forces (Figure 1).

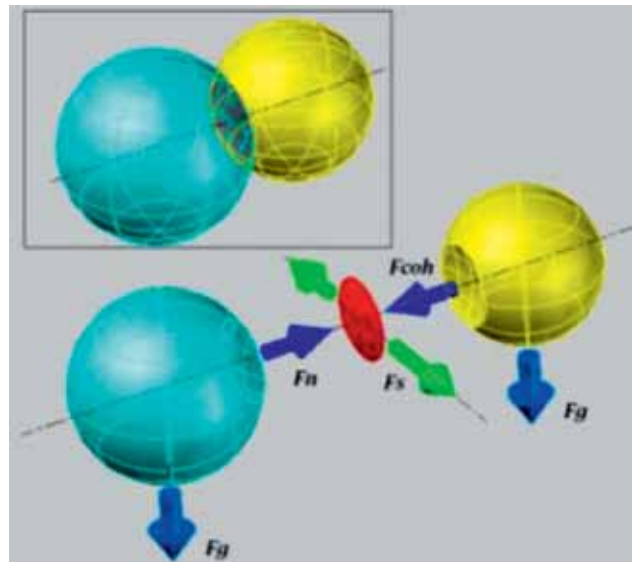


FIGURE 1. Force system applied for simple contact point between two particles. F_f : Friction force, F_{coh} : Cohesion force, F_n : Normal force, F_s : Shear force, F_g : Gravity force.

The micro parameters for the model are dynamic calculated from equations that working with geometrical elements and macro-properties of the particles in contact at each time step using. The force in normal direction is calculated by:

$$F_n = k_n \cdot \Delta u_n + \eta_n (\Delta u_n / \Delta t) \quad (1)$$

Where k_n mean the normal spring, Δu_n is the variation of normal overlapping, η_n is the viscous damping and Δt is the time step variation.

The equation to calculate normal spring encloses the relationship between elastic properties and dimensional parameters, it is written, as:

$$kn = \frac{E_{ab} \cdot A_{int}}{D_{eq}} \left[\frac{1 + \alpha_k}{\beta_k (1 + \nu) + \gamma_k (1 - \alpha_k)} \right] \quad (2)$$

Where E_{ab} is the equivalent Young's modulus of the two contact materials, A_{int} is the interior area of the contact and D_{eq} is the equivalent distance between the two objects, the other part of the equation is the relationship between poisson's ratio ν with loading path coefficient α_k , softening factor β_k and interaction range γ_k (Hentz *et al.*, 2004).

The force in tangential direction is calculated by:

$$Fs = k_s \cdot \Delta u_s + \eta_s (\Delta u_s / \Delta t) \quad (3)$$

Where k_s is the shear spring, Δu_s is the variation of tangential overlapping and η_s represents the viscous damping in tangential direction. The value of k_s depends on k_n , been obtained by:

$$k_s = k_n \left(\frac{1 - \alpha_k \cdot \nu}{1 + \nu} \right) \quad (4)$$

The viscous damping in normal and tangential direction is determined by:

$$\eta = \beta \cdot 2 \cdot \sqrt{\frac{m_a \cdot m_b}{m_a + m_b}} \quad (5)$$

Where β is the viscous damping coefficient; m_a and m_b are the

mass of the two objects in contact.

Inter-particles cohesion force acts when overlap increases over the soil Cauchy strain obtaining a attraction force which keeping the particles together. The relation between micro-friction and micro-cohesion is captured by interpolation procedure obtaining the following power relationship (Utili & Nova, 2008):

$$\phi c = \frac{c (\tan \phi \mu)^{k4}}{k3} \quad (6)$$

Where c is the cohesion between two objects in contact from lab experiment, $\phi \mu$ is micro-friction coefficient, $k3$ and $k4$ are two material constants related with porosity and particles sizes distribution in the simulated medium.

Soil block generation

Soil block at 650 x 400 x 300 mm was generated filling a rectangular box with 45 000 spherical particles (Figure 2a). The hexagonal compacted spatial array was used as the methods to get the efficient distribute of particles. The whole particles were submitted to free fall into the mentioned box, the second step was pressing from the top to the bottom. The horizontal press (red color plane) is moved at constant velocity at 0,2 m/min reducing the space into the container and getting the desire specimen density (Figure 2b). Sizes of particles were distributed on three different layers with radius at 8-10; 6-5 and 3-4 mm at the top, center, and bottom respectively.

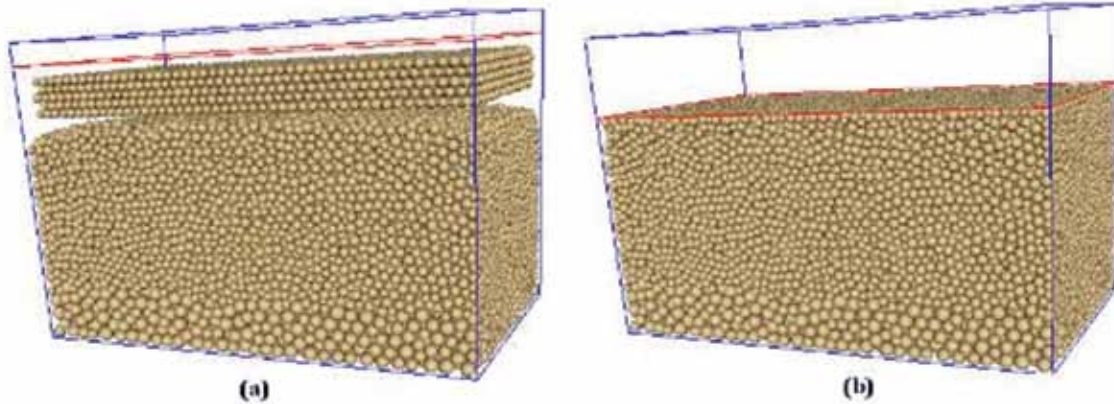


FIGURE 2. Soil virtual block generation, Particles free fall (a) and compression (b).

The soil block was generated in three different physical condition by mean of modifies in water contents (u) and soil bulk densities (γ). The conditions obtained by simulation represent soft-wet ($r = 1,1 \text{ g/cm}^3$, $u = 30\%$), friable

($r = 1,2 \text{ g/cm}^3$, $u = 18\%$) and hard-dry soil ($r = 1,4 \text{ g/cm}^3$, $u = 10\%$). The parameters used for each simulation is showing in Table1.

TABLE 1. Macro-parameters for different soil conditions

Depth, cm	Gs	PL	LL	PI	Sand	Silt	Clay
15	2.6	18.6	63.5	44.9	7	27	66
30	2.64	28.6	78.9	50.3	6	29	66
50	2.62	17.2	67.9	50.7	8	29	63

Soil Bin test

In order to compare the draft forces obtained by simulation in *soft-wet* and *hard-dry* soil conditions a 1,5 per 8 m soil-bin was conditioned, filled by Vertisol soil, the same material used to carry out the lab test explained above

(Figure 3a). The force reactions in longitudinal and vertical direction are measured by an extended orthogonal ring transducer fixed and calibrated between tool and trolley (Figure 3b). The CrioData acquisition system was configured using the LabView application and running in a HP laptop, taking 200 samples per second along the measurement time.



FIGURE 3. Soil-bin installation (a). Tool, transducer and trolley coupling (b).

RESULTS AND DISCUSSION

Comparison between soil-bin and simulation test

The average draft force obtained during the soil-bin test in *soft-wet* condition represented by the dash blue line in Figure 4, shows the small under-prediction quality of the model for relative low range of force demanding system. The draft force measured by the measuring system (red color line) in the lab condition was bigger than the force obtained in simulation test. Nevertheless the error of 97 N is an acceptable value considering the spatial huge variation of soil physical properties and the corresponding over-dimension of tiller in agricultural practices. On the other hand 1,41 kN draft force average measured in *hard-dry* soil condition (green dash line), shows more close force prediction by the model exhibiting a standard error of 34 N.

One of the reasons why draft force decrease is the particle packing which affects the strength of the simulated soil. The cylindrical shapes for all particles and a limited sizes distribution increase the empties spaces into the virtual block of soil, it is coherent with soil porosity, however in real soil large

amount of small particles are filled a considerable intergranular spaces what increase the soil stiffness. For hard-soil the overlap become larger and bulk density also increase obtaining a proportional pore homogenization and a consequently strength increment.

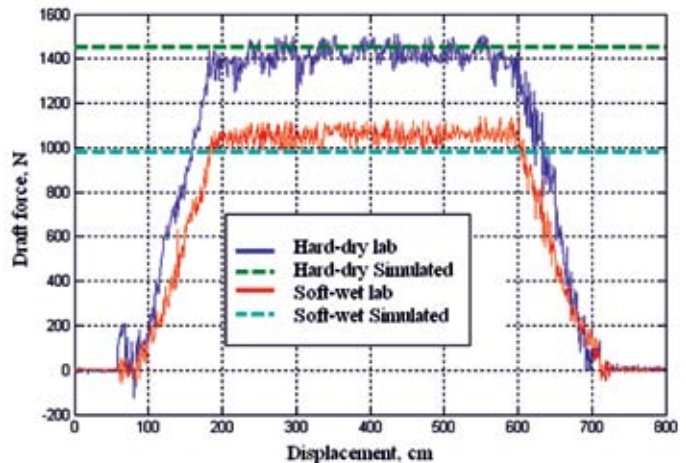


FIGURE 4. Draft forces measured in soil-bin and simulated test.

Tillage simulation for different soil conditions

The comparison among draft forces results from *soft-wet*, *friable* and *hard-dry* conditions obtained from tillage simulations with cultivator tool (Figure 5), shows an increment respect one another. The smaller draft force belong to *soft-wet* condition as was expected, the content of water and soil bulk density affect all macro-mechanical properties and consequently the micro-properties in the model, however the predominant effect is attributable of high moisture. Inversely the higher force magnitude was reached on *hard-dry* soil condition as a consequence of the increment in soil stiffness.

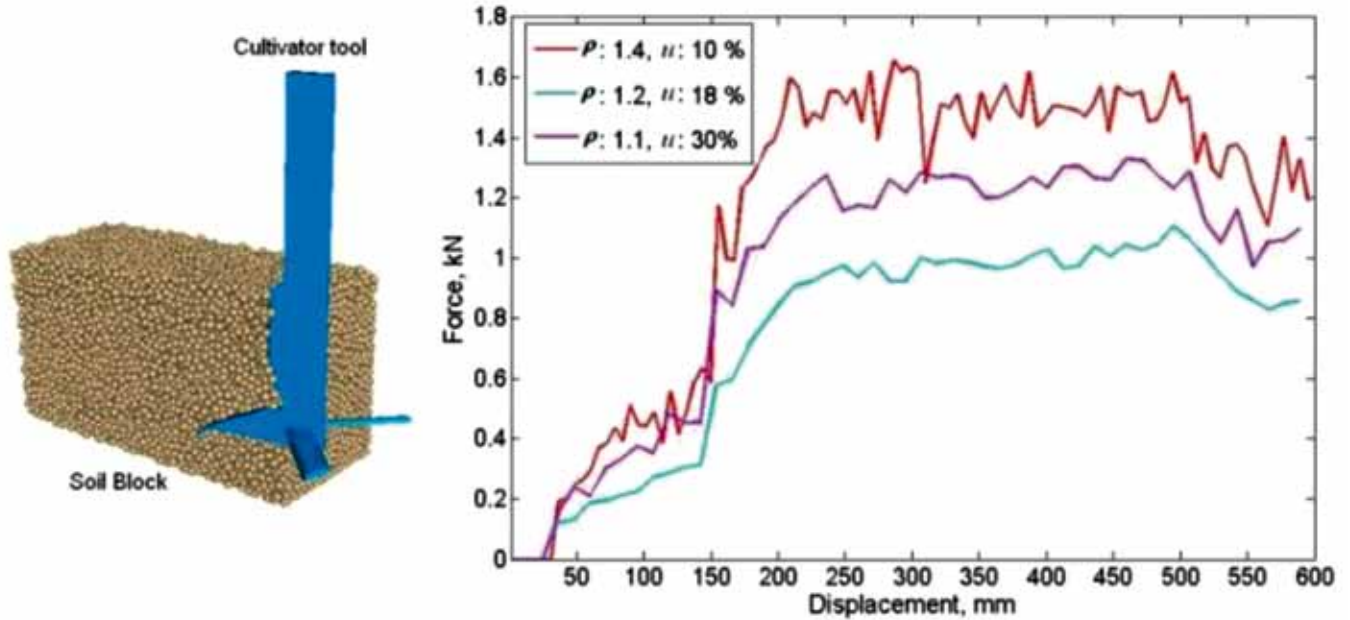


FIGURE 5. Draft force measures in different soil physical conditions.

Particles compression and decompression take places during movement of the tool through the soil, as a result the fluctuation forces pater with different proportion for each soil conditions appear, the amount of bonds broken up at the same time determine the minimum and maximum values of the force. The fluctuation force on *hard-dry* condition is also larger than two other treatments, caused by more fragility among particles. Patter of plastic flow characterizes the soil

movement on *soft-wet* condition, while fragile pater is more representative on *hard-dry* soil followed by larger number of clods formation.

Variation on particles bulk density calculated from seven parallels blocks (Figure 6a), arranged in longitudinal direction after tillage simulation shows a different pater of increment (Figure 6b).

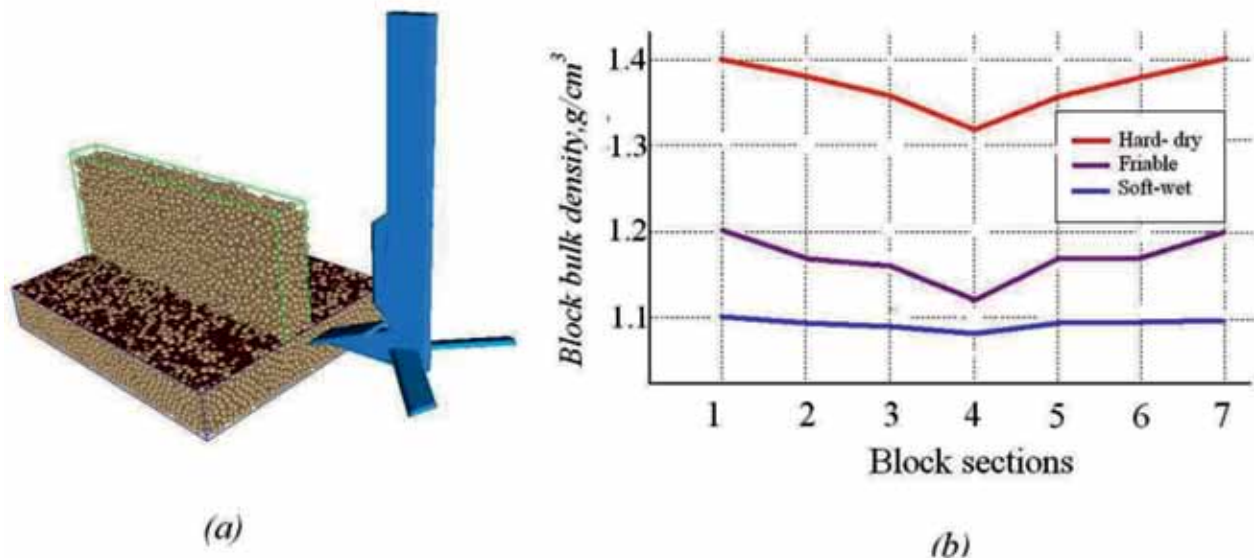


FIGURE 6. Soil bulk density changes.

In *hard-dry* soil condition bulk density decrease mainly at the center of the section (Figure 6b), by the action of the main body of the tool, for the section above lateral blades bulk density remain with discrete reduction. That behavior is also showed for simulation in *friable* soil condition, though more uniform density was obtained along transversal section of the tool meaning a rising in the soil loosening index. Under *wet-soil* condition the action of the lateral blades become nil, only small amount of particles loosening were found at the wedge

position section of the tool while the other part of the block remain undisturbed.

Graphical representation of particles forces on the horizontal plane below the tool path in the trajectory of 600mm from left to right obtained in the simulation of *dry-hard* and *friable* soil condition highlight the bigger particles tension register in the most compacted soil (Figure 7a), the amount of particles submitted to pressure also grown up and some picks are obtaining at the current tool position.

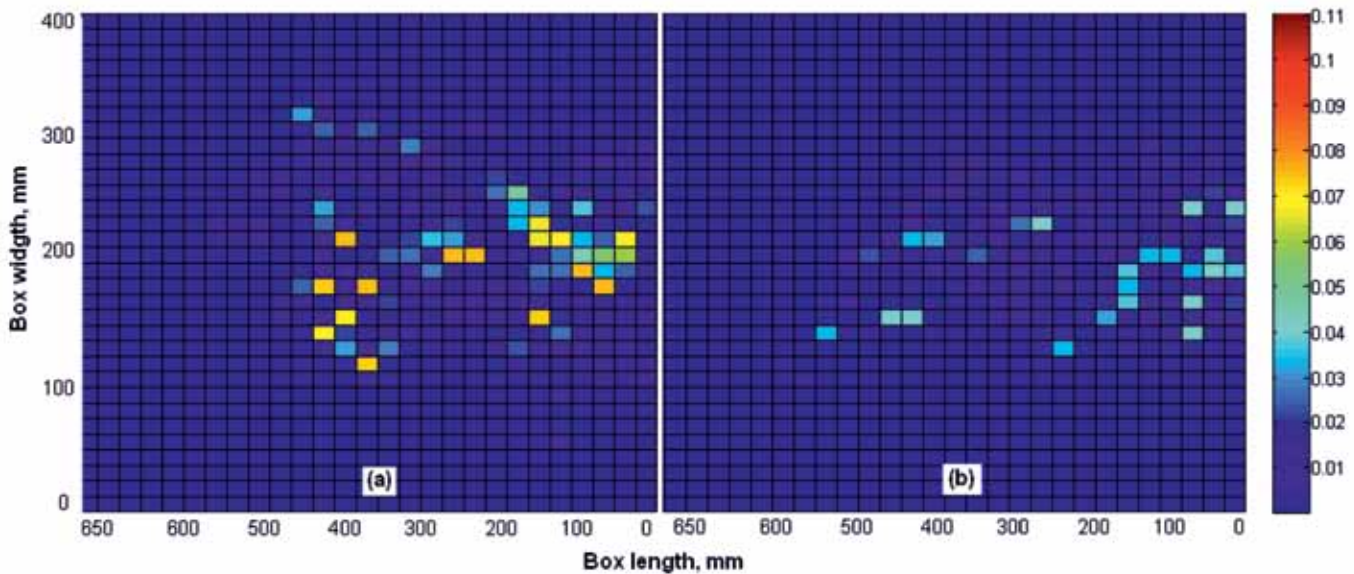


FIGURE 7. Force on particles below to the tool path.

Less forces values and quite reduction in pressured area characterize the resultant forces for soil in *friable* conditions (Figure 7b). Accordingly the bigger particles force the consequent increment on internal tension and plow pan formation.

CONCLUSIONS

- The discrete element method provides the fundamental formulation and geometrical tools to implementing the particles contacts in a macro-scale representation, deriving from soil macro-properties the micro properties for the model.
- The experimental measurements in a soil-bin using a tool designed according to agricultural treatments of soil cultivation allow determining the draft forces requirement for a tool in tillage operations submitted to different conditions of moistures and bulk densities.
- Comparison between tillage draft forces obtained from soil-bin and discrete simulation in *soft-wet* ($\rho = 1,1 \text{ g/cm}^3$, $u = 30\%$), and *hard-dry* ($\rho = 1,4, \text{ g/cm}^3$, $u = 10\%$) soil conditions showed an adequate prediction forces with standard error at 97 and 34 N respectively, the model

tended to under-predict the magnitude of the force in *soft-wet* condition attributable to larger amount of pores wish reduces the soil strength.

- By mean of soil tillage simulation by cultivator tool in *soft-wet*, *friable* and *hard-dry* soil conditions can be evaluated the variation of draft forces, the results obtained by simulation are consistent with the soil physical conditions giving a criteria of soil fragility and plasticity according to the pattern of force-displacement curve.
- Soil loosening depending on the position of the implement shows a maximum level in *friable* ($\rho = 1,2 \text{ g/cm}^3$, $u = 18\%$) soil, the bulk density level off from 1,2 to $1,12 \text{ g/cm}^3$ at the center of the tool decreasing gradually toward both sides, a different pattern was found in *soft-wet* soil where the bulk density decrease slightly only at the center tool path
- Particles forces distribution obtained in the plane below to the path of the tool in the simulated soil block show rising values for *dry-hard* soil, denoting maximum pressures at the current tool position, also the tension surface increase in comparison with *friable* soil condition becoming this area prone to plow pan formation.

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