

SIMULATION OF CLAY SOIL DE-COMPACTION BY SUBSOILING PROCESS USING DISCRETE ELEMENT METHOD

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Abstract. High pressures on the soil surface by action of heavy machinery and tillage process cause soil compaction and hardpan layers formation. De-compaction is a energy demanding operation applied to break deeply compacted soil for agricultural uses. Three dimensional simulations of soil decompaction are presented based on a soil-tool interaction model implemented in DEMeter software. Formulation of soil-soil and soil-tool interaction are combined into an elastic-plastic particle based model for soil deformation and evaluated in different tension states among soil particles; The macromechanical input parameters include: adhesion, friction, Young’s modulus, Poisson’s coefficient, elastic limit, plastic limit and soil density. Compression triaxial tests and shear box tests were carried out in order to obtain the required mechanical properties for a tropical clay soil. Simulations of unconfined compression tests using different particle sizes and inter-particle tension were used to calibrate the model to experimental stress-strain curves. The performance of complex tillage tools geometries is tested with 3D simulations and evaluated based on the reaction force on the tool as a function of time and displacement. The results show qualitative and quantitative adjusts of real patter of soil behaviour.

1. INTRODUCTION

Tillage tool geometry is an important element on the integrate system for soil conservation practices. The quality of the implement to remain the crop residues on the soil surface, making limited disruption and keeping on the upper layer the organic matter is the way to avoid soil degradation by erosion, Carbon releasing and soil compaction. Mulch tillage, ridge tillage, zone tillage and no-tillage are some of the principal types of conservation tillage techniques, its purpose is to reduce tillage operation focus in economic and environment advantages, improving soil quality, time and energy reduction [1]. Several effects of conventional tillage based on soil inversion, as a moldboard plow, become soil more susceptible to erosion, reduce bio-organisms diversity and contribute to hardpan formation.

Spatial soil redistribution during tillage depend basically on particular characteristics of the implement used, this translocation increase for moldboard conducted in down slope

direction [2]. Soil physical and chemical degradation including soil compaction, organic matter losses and nitrogen deficiencies is more pronounced with conventional disk tillage than conservation tillage; evaluation of chisel plow, no tillage and flexible tillage showed the tillage system effect on soil quality indicator [3]. Enhance soil organic Carbon stabilization in tropical soil is affected mainly by tillage disturbance, consequence of to apply long term of soil preparation with ripping tools for sandy and clay soil, residue retention and reduction tillage decrease the organic Carbon decomposition[4]

Agricultural subsoiler is a tillage implement used to working in deep layer of soil, in the beginning designed to break up the hard soil layers and uniform compaction, the non-inversion property agree with low-till practices under conservation tillage criterion. As a result of transition from moldboard plow to vertical tools, many implements had been testing on different soil and crops plantation in order to minimize soil and mulch disturbance, soil properties and crop particularities need to be manages carefully to warranty positive effect from new tools geometries on tillage operation [5]. Soil type is considered the main factors for successful adoption of non-inversion, relatively well suited for clay soil, conservation tillage reduces the risk of hard seedbed formation, however for some sands with angular structures the tillage exclude air and water movement [6].

Between soil physical properties and tillage tools geometry exist a close relationship determining the proportion of soil disturbance during the process, optimization of tillage tools focusing in geometrical modification had been making on moldboard plough obtaining significantly draft reduction requirement [7, 8]. Field performance of implement for future application on soil-ecosystem had been evaluated in nineties decade, testing several variant of tool shape, speed and draft force, equipments for conservation tillage were evaluated at the farm level correlating energy and seedbed quality [9].

Data from field and soil lab experiment has been compute using mathematical models offering more accurate, faster and extended prognostic of soil behavior. Computational techniques as well as finite element methods (FEM), discrete element methods (DEM), artificial neural network (ANN) or computational fluid dynamics (CFD) are indistinctly used with different purposes allowing to pass from quasi-static to dynamic soil analysis on the rheological behavior of soil [10]. FEM models to simulate runoff process from agricultural land with reasonable good agreement between simulation and experimentally test predict the effect of water flow, topographic condition and crop parameters [11]. Considering the soil as a continuum medium, several constitutive models has been creates and improved focused on capturing the particular soil behavior, this models dependent mainly on elastic and plastic deformation. Modified Cam-Clay model was implemented with the object to derive time dependent effect taken accounts the effect of anisotropic and expansion of loading, affected by the principal stress redirection, the validation of the simulation was carried out using undrained shear box and creep test [12]. Draft forces simulation by FEM were conducted using different tools geometries on two and tree dimension with the aim to investigate the effect of cutting speed and cutting angles in draught force requirements during soil-tool interaction [13-18].

Related with the limitation to apply FEM to simulate the granulated medium, DEM is applied to resolve the dynamic process showing a extend field for soil application. Particles interaction on DEM shows a close similitude with soil mechanical contacts take place between real grains, this contacts also exist and can be calculated between tool and soil, many

contacts models rules the behavior of overall simulation depending on the nature of the element that interact with others, the overlapping among elements is the key for contact resolution, geometrical information is provided from two element in contact obtaining velocity and position vectors, tangential and normal forces is computed and contact forces for all particles in each time step [19]. Methodology to obtain the micro mechanical input parameters for DEM based on in situ field tests, showing a well correlation before optimization between real and simulation deformation curve [20]. Simulation of soil-tool interaction with high rate of plastic deformation was modeled using wide cutting-blade and soil particles conformed by clumps of two disks with cohesion forces, DEM result were evaluated for two dimension different blade shapes, the effect of soil flow in from of the blade was related with horizontal and vertical forces [21].

The objective of this work is to implement a DEM model in order to simulate the draft force requirements during soil tool interaction for decompaction and non inversion tillage on different physical condition in a tropical clay soil.

2. MATERIALS AND METHODS

2.1 Model description

Classical DEM model proposed by Cundall and Strack [19] was used to compute the interaction between soil particles and tillage tool, two kinds of contacts were implemented : soil-soil and soil-tool, for both calculation was applied the same contact scheme varied only on mechanical properties input. The model dealing with the system forces composed by: normal, shear, gravity, adhesion and friction force (Fig. 1), the friction force is applied only during sliding when shear force is bigger than Coulomb friction criterion.

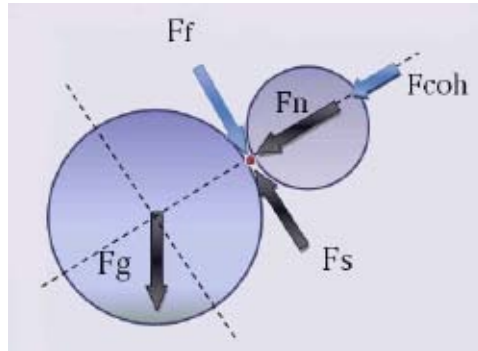


Figure1: Force system applied for simple contact point between two particles. **Ff:** Friction Force, **Fcoh:** Cohesion force, **Fn:** Normal Force, **Fs:** Shear Force, **Fg:** Gravity Force.

Based on soil macro-properties the micro-properties were dynamic calculated using the geometrical parameters obtained from particles interaction in each time step.

Force in normal direction is calculated by:

$$Fn = kn\Delta u_n + \eta_n (\Delta u_n / \Delta t) \quad (1)$$

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

Equation for normal spring [22] enclose the relationship among elastic properties and dimensional data as:

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

Where E_{ab} is the equivalent Young's modulus of the two contact elements, \tilde{A}_{int} is the interior area of the contact and D_{eq}^{ab} is the equivalent distant between objects, another part of the equation is the relation between poisson's ratio ν and fitting parameters [23].

Force in tangential direction is calculated by:

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

Where ks is the shear spring, Δu_s is the variation of tangential overlapping and η_s is the viscous damping in tangential direction.

Value of ks depend of kn , obtained by:

$$ks = kn \left(\frac{1 - \alpha_k \nu}{1 + \nu} \right) \quad (4)$$

Viscous damping in normal and tangential direction is determined by:

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

Where β is viscous damping coefficient; m_a and m_b were the mass of two objects in contact.

Cohesion force only act during compression in normal direction, adding its value to the total force summation of the contact. The attraction between objects increase together increment of overlapping, resulting on a equilibrium point where repulsion and attraction forces sum is zero forming a bilateral bond, to break this inter-particles bond the overlapping need to become lower than Cauchy strain of soil where the effect of adhesion force is cancelled. Force of cohesion [21] is obtained by:

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

Where c is macro cohesion between two objects in contact obtained by lab test, $\phi \mu$ is micro-friction coefficient, $k3$ and $k4$ are adjusted parameters related with statistical regression particular for soil material.

2.2 Virtual model implementation

Graphical interface and mathematical model formulation was implemented using the facilities of DEMeter Software developed by research particles group from KULeuven University, Belgium. Simulation was divided in two step: Fixed model with triaxial test and soil-tool dynamic interaction.

The influence of particles sizes was evaluated simulating a triaxial unconfined compression test, spherical particles with radius at 0.6, 1.8 and 2.3 mm form a cylindrical specimen with 50 mm diameter and 100 mm high, joined by cohesion forces, this sample was obtained pressing the hole particles into the void cylindrical cavity. Constant press velocity at 1m/min was used for all simulation applied on top of the sample (Fig. 2a).

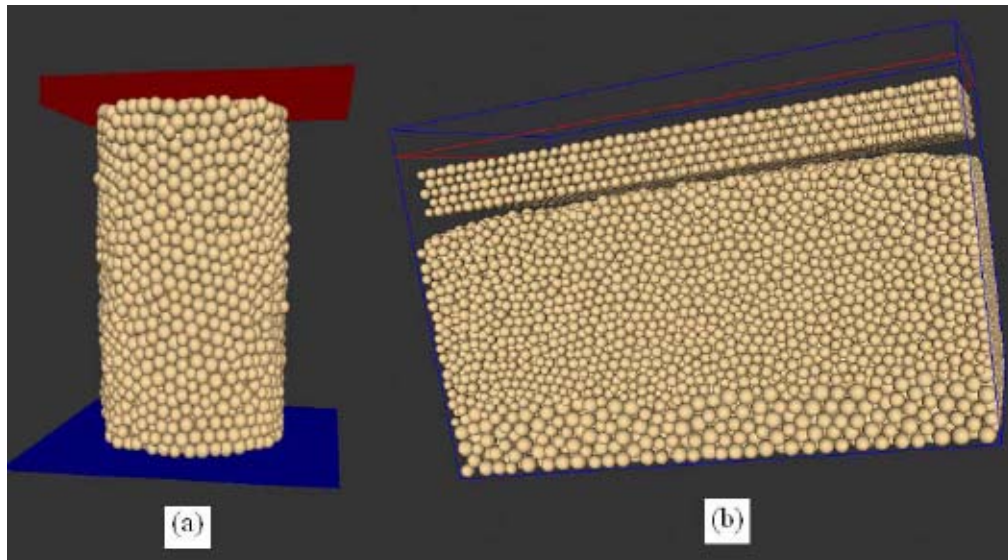


Figure 2: Sample for unconfined compression test simulation (a); construction procedure for virtual block of soil.

The second step was the construction of virtual block of soil formed by 40,000 spherical particles generated in hexagonal compacted array and submitted to free fall inside the 650 x 400 x 300mm rectangular box (Fig. 2b). Size particles were distributed in three different layers with radius in the bottom between 8-10 mm, center of 6 – 5 mm and top 4.5-4 mm. All simulation was running with constant velocity of 2 m/min.

Tillage tools were designed reproducing four different geometries of subsoilers (Fig. 3), The scale of 3:1 to respect of real dimensions was used. Non soil inversion was adopted to select the geometrical parameters.

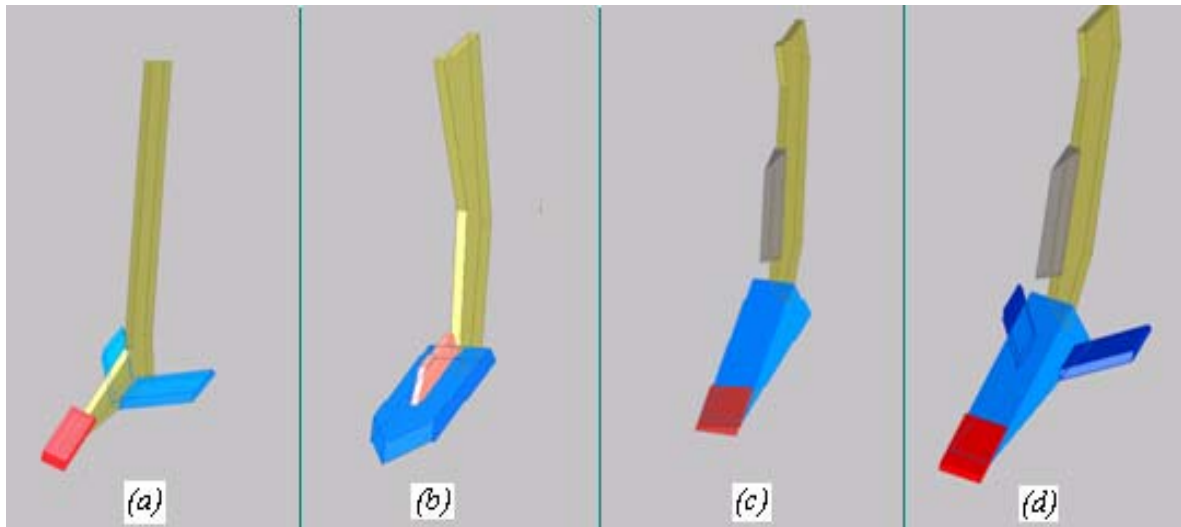


Figure 3: Tillage- tools shape. Cultivator (a); chisel subsoiler (b), knife subsoiler (c), combined subsoiler (d).

Simulation of soil-cultivator was running in three soil stage combinations; different water contents and soil bulk densities were using to obtain soft-wet soil (30 % water content and 1.1 g/cm^3), friable soil (18 % water content and 1.2 g/cm^3) and hard-dry soil (10 % water content and 1.4 g/cm^3). Chisel subsoiler and knife subsoiler were running in the same hard-dry soil condition to compare the draft force demanding in both cases. For the last soil-tillage simulation was added the lateral cutting knife forming a combined subsoiler (Fig. 3 d), forces demanded in hard-dry soil and soft soil with hardpan at the bottom were plotting.

2.3 Lab experiment and soil selection

Triaxial undrained compression test and shear box test were carried out in order to obtain the mechanical properties selected as macro-properties in DEM model. Elastic Young's Modulus, internal friction, metal interface friction, cohesion and adhesion of soil were calculated as a function of dry bulk density and gravimetric water content measured as a percentage of dry weight. Physical properties and granulometric composition (Table 1) show the high content of clay for the three principal layers becomes soil a cohesive material, the uniformity constitution on the hole depth allow to classify as a Vertisol according to the international classification based on the soil taxonomy.

Table 1: Vertisol soil properties. PL, LL and PI are the plastic limit, liquid limit and plastic index in %. Gs, specific gravity.

<i>Depth, cm</i>	<i>Gs</i>	<i>PL</i>	<i>LL</i>	<i>PI</i>	<i>Sand</i>	<i>Silt</i>	<i>Clay</i>
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

Three level of soil dry bulk density (γ) were selected to capture the variability of soil compaction, values at 1.0, 1.2 and 1.4 $g\ cm^{-3}$ represent loosen, medium and compacted soil. Five experimental point were using to measure the influence of water content (wet) at 15, 18, 20, 25, 35 %. Factorial experimental design to predicting the behavior of above five dependent variables with respect of dray bulk density and soil moisture was preformed resulting on 60 randomized runs for triaxial and shear test, pressures at 50, 70 and 100 kPa were applied in each test to get the relation between normal stress and shear stress at failure. Multiple regression statistical analysis showed a predictable behavior of selected soil mechanical properties, statistical equation (table 2)allow to calculate the prognostic properties values with more than 94% of confidence level. The statistical equations were using by the DEM model to initialize the macro-mechanical properties input according to desire physical soil condition.

Table 2: Regression equation for soil mechanical properties.

Parameters	Unit	Equations	a	b	c	d	R, %
Young's Modulus	Mpa	$E = a + b*\gamma + c*wet^2 - d*wet$	82.1	89.8	0.15	10.3	95.2
Shear strength	kPa	$T = a - b*wet + c*\gamma + d*wet^2$	216	229	164	3.9	94.6
Soil cohesion	kPa	$coh = a + b*\gamma + c*wet^2 - d*wet$	105	115	0.2	12.3	96.3
Soil adhesion	kPa	$adh = a + b*\gamma + c*wet$	-13	8.5	42	-	96.7
Soil friction	kPa	$fs = a + b*wet - c*\gamma + d*\gamma^2$	22.1	0.5	37.5	16.4	94.3
Metal friction	kPa	$fm = a + b*\ln(wet)$	-23.6	12.9			

3. RESULTS AND DISCUSSION

3.1 Triaxial unconfined compression test

The increment in the amount of particles in the same sample dimensions for unconfined triaxial test simulation, reduce the force oscillation effect during vertical wall displacement due to the increment on the contact area, particles accommodation in the void spaces reduce tension during compression increase, the magnitude of this reduction depend on the value getting for the overlapping become lower for small particles sizes, however small particles radius increase computation time due to the needed to reduce time step. Volumetric relation between sample dimensions and particles radius at 0.6 mm suggest 1:5000 units. Moreover the proximity of median soil granular distribution of the sample with minimum size particle tested suggest the optimum value proportional of minimum grain formed after soil failure.

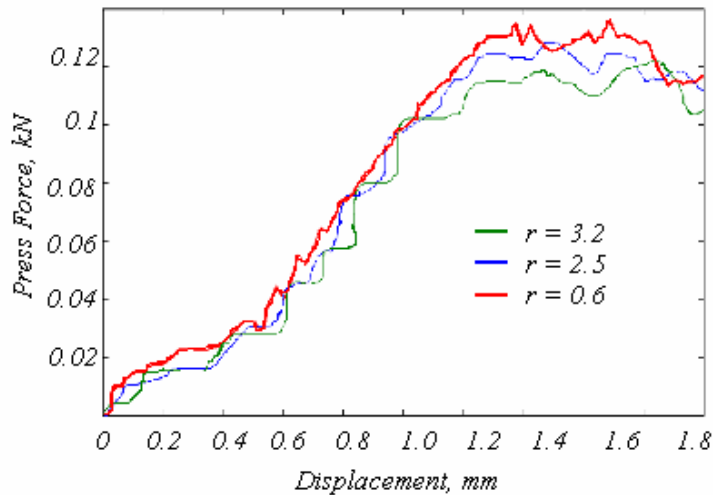


Figure 4: Variation of deformation curve for different particles radius during simulation

3.2 Cultivator on three soil condition

Comparison among draft forces on cultivation process (Fig. 5) for soft-wet, friable and hard-dry soil show the average increment of 0.25 kN for each soil condition. Smaller values of resultant forces correspond with soft-wet condition on soil as a result of reduction in soil cohesion and friction coefficient. Inversely the higher forces values were reached for hard-dry soil condition according to the increment on mechanical stiffness of the soil.

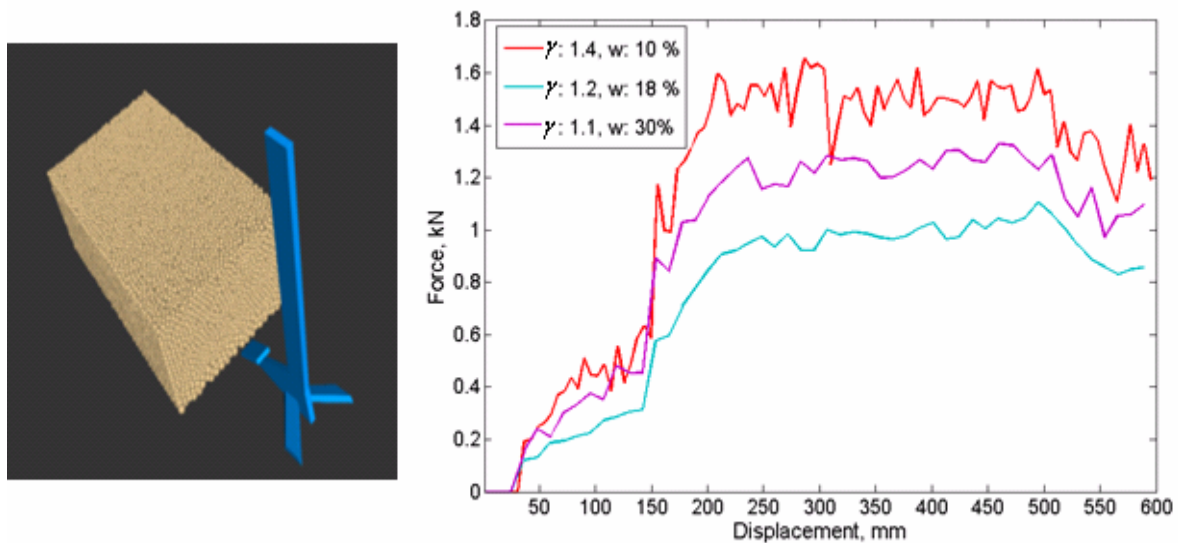


Figure:5 Displacement of cultivator tool on soft, medium and hard soil condition.

The increment in force fluctuation for hard-dry soil was observed, that behavior can be attributed to the relationship between high values of inter-particles bond and the amount of particles bond broken at the same time, however smooth curve is obtained in opposite condition tended to be linear during 200mm to 500 mm of displacement. Plastic flow characterizes the soil movement pattern on wet condition while fragile pattern was more

representative on hard soil distinguished by clods formation and keeps the shape of the tool into the soil.

3.3 Subsoilers soil simulation

The draft forces needed to move the tools through the soil in hard-dry condition during simulation (Fig. 6) show a close values for tools without lateral knife (Fig. 7a, 7b), however small increment for knife subsoiler denote the influence of cutting angels, this parameter is different in both cases. Forces values obtained from the simulation have consistence with the result obtained by Sahu, R. K. & Raheman, H. (2006a) empirical equation to predict tillage draft for narrow tools according soil condition.

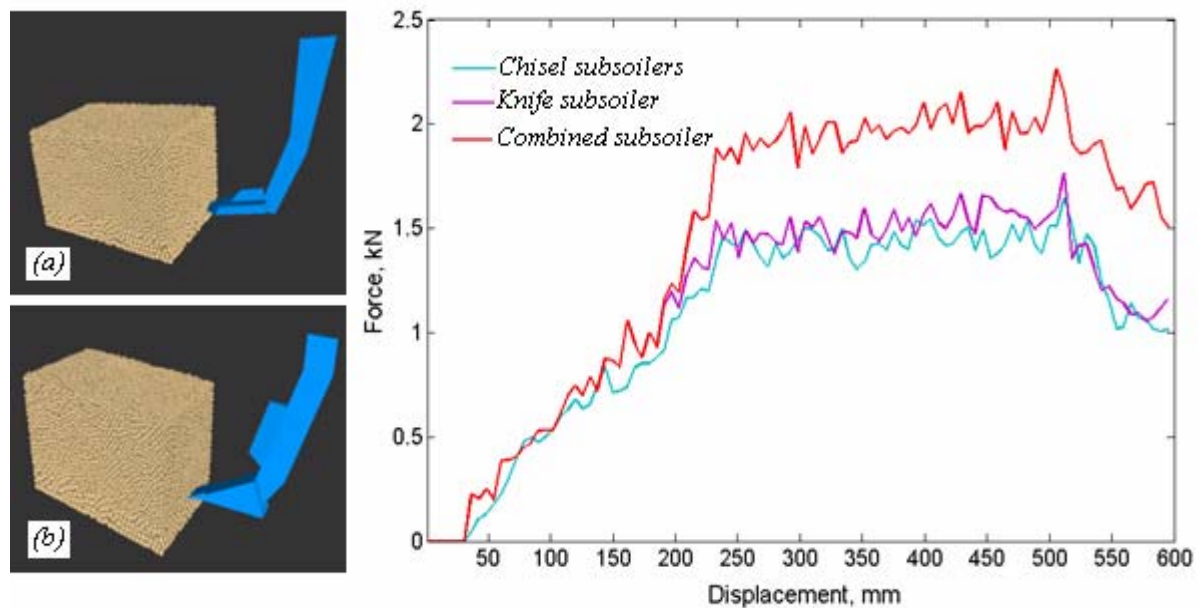


Figure 6: Draft force for subsoiling with different tools geometries on hard soil condition.

The energy demanded on soil decompaction increase related with the tool geometry, for combined subsoiler (Fig 7a) that increment correspond with the addition of lateral knife, moreover the work done for this tool is bigger than the other in the specific disturbed area denoting advantage in term of specific draught demanding.

No significant differences were found in the simulation of hardpan and hard soil decompaction process. Identically tool geometry in two different soil unhealthy conditions for plant production result on approximated the same draft force to pass the subsoiler through the soil. From the force demanding point of view hardpan decompaction meaning the same thing that hard soil tillage, the force needed to work above hardpan decreases according to stiffness reduction making easy the seed bed preparation but tine pressure on the bottom compresses the soil below resulting on hardpan reinforcement

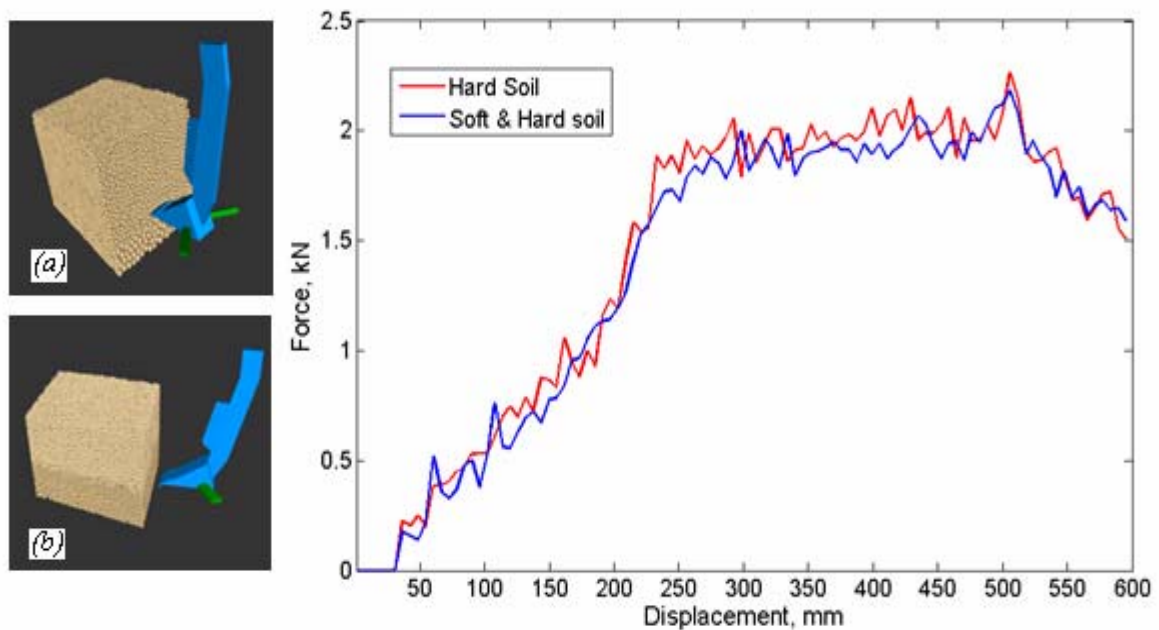


Figure 7. Decompanction of simple hard soil and two layers soil bulk densities.

4. Conclusion

- Triaxial compression test and direct box shear, combined in experimental soil condition, provide a set of statistical equation able to predict the basic soil mechanical properties needed to implement the computation model for soil tillage simulation.
- Granular nature of soil allows simulating by Discrete Element Model tillage operation, making possible to measure the draft forces and soil loosening patter in different physical condition of cohesive soil
- Small particles radius reduce the oscillation force effect during simulation of unconfined triaxial compression test, however the small particles sizes need the reduction in the time step with the consequently increment on computational cost.
- Soil tillage simulation by cultivator tool in soft, friable and hard soil condition showed the dependence of draught force on dry bulk density and water content, for the case of hard dry soil maximum values of force was measured.
- Geometry changes in the subsoiler design implied variation on draft forces, however the use of lateral knife increase the area of soil disruption without proportional increment on force demand.
- Scarification treatment to break up the hardpan demands the approximate same energy to till a fully compacted soil, however further investigation in lab and field condition to measure the draft forces and soil behavior is needed to validate the tillage simulation.

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