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DEM ANALYSIS OF THE SOIL-TOOL (SWEEP) INTERACTION

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ABSTRACT The main function of the field cultivator is to prepare a proper seedbed for the crop to be planted into, to bury crop residue in the soil, to control weeds, and to mix and incorporate the soil to ensure the growing crop has enough water and nutrients to grow well during the growing season. To achieve these goals, it is important to have a basic understanding of interaction between soil and tillage implements. The discrete element method (DEM) seems to be a promising approach for constructing a highfidelity model to describe the soil–implement interaction. Discrete Element Models were built in correspondence with the field tests. In the DEM, the interaction of the particles is treated as a dynamic process with states of equilibrium developing whenever the internal forces balance. In this paper we will introduce the methods of DEM approach used in developing a modell for the prediction of draught force on cultivator sweeps and the final porosity of the soil. A verified DEM is a cheap and useful tool in the development procedure of cultivators and can be used to research and analyse the performance of resulting prototype. There are some factors that we can determine such as the soil and the cultivator tools. The influences of cultivator sweep geometry was researched by the DEM and compared to results of soil bin tests to validate the sweep shares. With the results of the methodology it is possible to validate the optimal β angle of the sweep in a 2D model.

Keywords: Soil, Cultivator, DEM, Modeling, Tillage, Soil Bin, Forces, Optimization.

INTRODUCTION

The environment-friendly tillage methods get more importance nowadays, thanks to the economical production and the environment load of tillage and its harmful effects. One of the most important environment-friendly tools is the field mulch cultivator. During the last years I have studied the geometry of the cultivator tillages and measured the energy consumption in the soil bin with the most general sweep tools. I defined

Figure 1. The soil bin test

that most influencing for the energetic property is the tools inclined angel (β).

Before further soil bin study, FEM and field experiment, I studied the Discrete Element Method for recognizing the soil-tool interaction. The analysis of soil profiles and soil redistribution by tillage has progressed slowly due to its complexity which involves many factors, such as soil types and properties, types of tillage tools and their operational parameters.

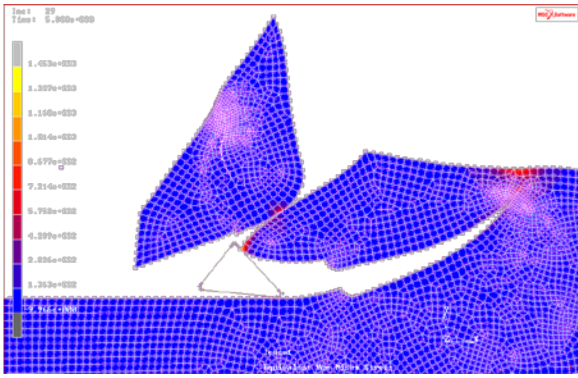


Figure 2. The VCCT method in FEM as the Soil-Tool Interaction in cohesive soil.

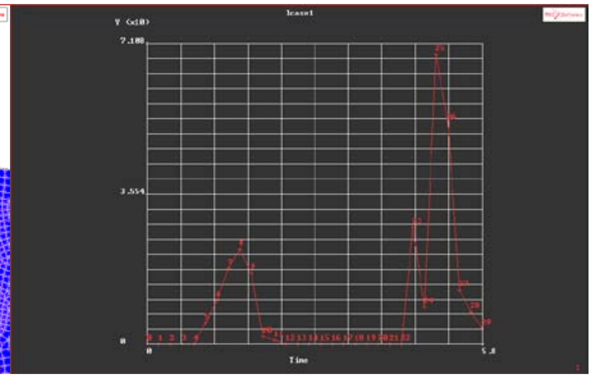


Figure 3. The Draft Force in the FEM analysis

The study of soil- tool interaction focuses on soil failure patterns and development of force prediction models for design optimization. The force-deformation relationships used in models developed to date have been considering soil as a system of discrete particles. Most of the models are based on quasi-static soil failure patterns. In recent years, efforts have been made to improve the conventional analytical and experimental models by numerical approaches. One of these approaches is my previous research the FEM analysis with using the VCCT Method.

This paper goals at reviewing the existing methods of tillage tool modeling and exploring the use of Discrete Element Method to deal with a specific particle bonding. The previous experimental and finite element studies have shown the influence of both soil initial conditions and sweep operating conditions on cutting forces. Most of these finite element analysis are limited to small blade displacements, to reduce element distortion and useing the Virtual Crack Closure Technique we have to set the initial crack point.

In this study a dynamic two dimensional DEM of soil-tool interaction was carried out to investigate the effect of cutting speed, the angle (β) of cutting forces and the influences of the soil parameters. This method does not depend on the displacements and unnecessary to define the mechanical propertys of the rupture.

History

Soil cutting process has been studied by many researchers. The conventional analytical method has been used to develop two- and three-dimensional models based on Terzaghi's passive earth pressure theory (Terzaghi, 1943). On the basis of general use and successes of the FEA methods, some previous researchers (Liu Yan, Zhi-Min, Xie Xiao-Mi, Kuswaha, Kerényi etc.) began adopting the adjustment to describe the soil-tool interaction.

The 3D theories of the soil cutting with FEM were researched by Yong and Hanna. In this theory they postulated the cutting process as a quasi static question. They created a 2D model, in which they validated with shearing experiment the non-linearity of the soil properties (Mohr-Coulomb-theory), they computed with hyperbola function the received displacement- shearing tension diagram.

The 3D models of LIU YAN, ZHI-MIN are similar to the 2D models, because of the quasi static task.

CHI and KUSWAHA researched the straight and wedge shape tools with FEM. They consider the soil as non-linear elasticity material. They determinated the touching elasticity modulus as a hyperbolic function.

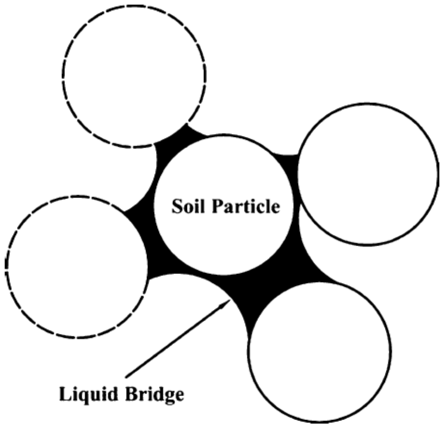
The Discrete Element Method

DEM is a discontinuous numerical method based on molecular dynamics. It was developed and applied for analyzing rock mechanics by Cundall in 1971. It overcomes some of the disadvantages of Continuum Mechanics Method (CMM) such as Finite Element Analysis, which ignores individual unit characteristics, and relies on the highly simplified mechanical equations excessively. DEM represents great superiorities to CMM in analyzing discrete materials. Considering soil as a multiphase compound, it is discrete by nature. The soil which is cut or separated by soil engaging components is much more discrete, therefore DEM is an ideal method to analyze large discontinuous deformations of soil. Cohesive soils are very common we come across in agricultural operations and constructions. The analysis of the dynamic mechanical behavior of cohesive soils subjected to external forces is very important in designing and optimizing the tillage tools. Cohesive soil contains water, and the presence of water can produce cohesion between soil particles, which makes the mechanical structure of these soils much more complex. In order to simulate and analyze the mechanical behavior of cohesive soil accurately, it is necessary to establish a DEM mechanical model of cohesive soil by considering the effects of water on the mechanical behavior of cohesive soil. We could simulate this cohesion in the PFC2D Discrete Element Program, because it allows particles to be bonded together at contacts.

MODEL DESCRIPTION

The Parallel-Bond Model

The parallel-bond model describes the constitutive behavior of a finite-sized piece of cementatious material deposited between two balls. The two balls are treated as either spheres or cylinders. These bonds establish an elastic interaction between particles that acts in parallel with the slip or contact-bond models thus, the existence of a parallel bond does not preclude the possibility of slip. Parallel bonds can transmit both forces and moments between particles, while contact bonds can only transmit forces acting at the contact point. Thus, parallel bonds may contribute to the resultant force and moment acting on the two bonded particles.



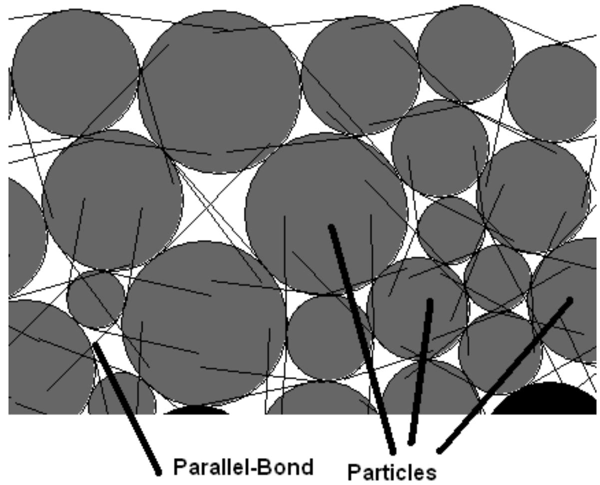


Figure 5. The finite-sized piece of cementatious material

Figure 4. Liquid bridges between soil particles.

The DEM appears to be a pertinent complementary tool for the study of unsaturated soil mechanics. More precisely, discrete methods should convey a new insight into the discussion about the controversial concept of generalized effective stress by relating basic physical aspects to classical phenomenological views.

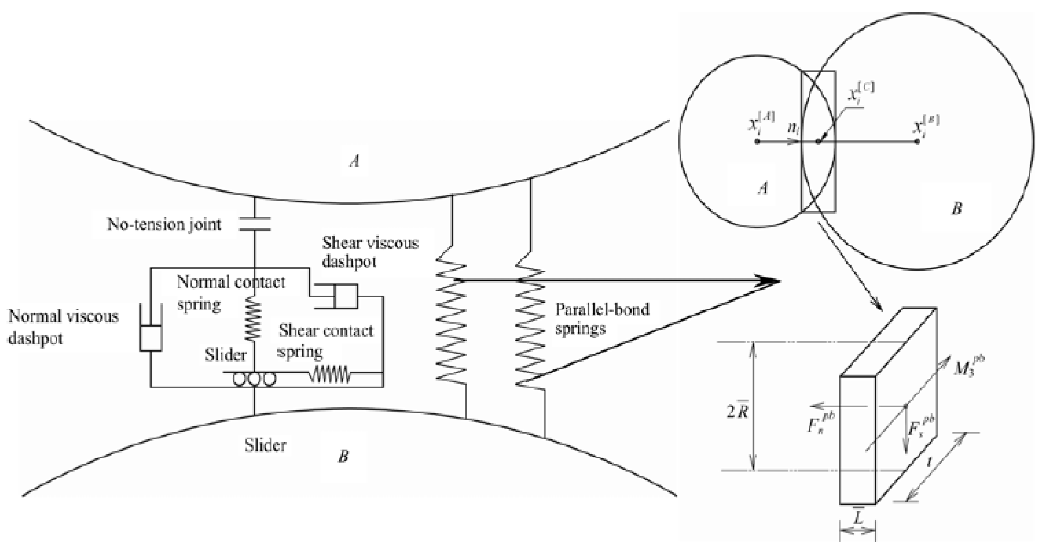


Figure 6. The nonlinear mechanical model of contact between soil particles.

A parallel bond can be envisioned as a set of elastic springs with constant normal and shear stiffnesses, uniformly distributed over either a circular or rectangular cross section lying on the contact plane and centered at the contact point. These springs act in parallel with the point-contact springs that are used to model particle stiffness at a point, and whose constitutive behavior. Relative motion at the contact (occurring after the parallel bond has been created) causes a force and a moment to develop within the bond material as a result of the parallel-bond stiffnesses. This force and moment act on the two bonded particles and can be related to maximum normal and shear stresses acting within the bond material at the bond periphery. If either of these maximum stresses exceeds its corresponding bond strength, the parallel bond breaks. A parallel bond is defined by the following five parameters: normal and shear stiffness $k\ n$ and ks [stress/displacement]; normal and shear strength σc and τc [stress]; and bond radius R.

Simulation and analysis in cohesive soil by DEM

The dynamic behavior of cohesive soils during the loosening process by a cultivator sweep was simulated by using the above established DEM mechanical model of cohesive soil via PFC2D. The initialization of the interaction between the tool and cohesive soils is the complete model. The model is composed of different sizes of discrete particles. The parallel bonds produce cohesive forces between discrete particles, so parts of discrete particles are conglomerated and form particle aggregate clusters after the tillage process. The complete model is formed by bonding of elements in wide sizes. This structure of the model is similar to that of the actual cohesive soils.

Table 1. Model parameters

Parameter in DEM	Value
Bulk density (kg/m^3)	2000
Particle shape	Ball
Normal spring coefficient (K_n) [N/m]	1,00E+07
Tangential spring constant (K_s) [N/m]	1,00E+07
Coulomb damping (μ_g)	0,9
Friction coefficient between particles (μ)	0,2
damp viscous normal	1,9
damp viscous shear	1,9
Particle radius	0,06-0,1
Friction coefficient between particle and the sweep tool	0,6
Void ratio	0,75
Parallel-Bond (heavy soil)	
pb_rad	1
pb_kn	1,00E+06
pb_ks	1,00E+06
pb_nstren	3,00E+05
pb_sstren	3,00E+05
Parallel-Bond (loose soil)	
pb_rad	0,7
pb_kn	1,00E+06
pb_ks	1,00E+06
pb_nstren	8,00E+04
pb_sstren	8,00E+04
Time step of the calculation (Δt) (s)	4.0×10^{-5}

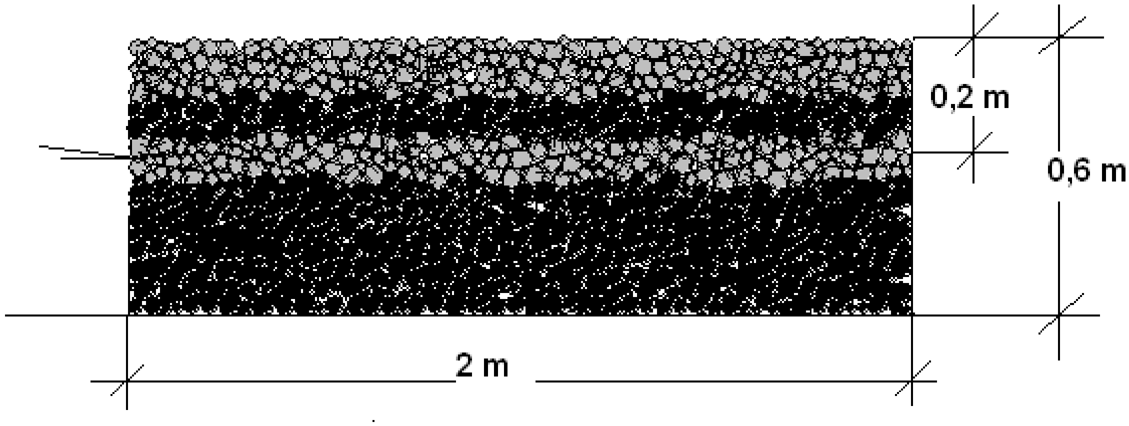


Figure 7. Geometric parameters of the 2D model

The distance between the lines is equal to two times the parallel-bond radius _R and the two lines have lengths equal to the distance between the centers of the two bonded particles. Parallel bonds near the tool decrease significantly and even disappear with time going. The reason is that the parallel bonds break (if the parallel bonds break, they will disappear) with the rupture and separation of the soil particle aggregate clusters. The disturbance of cohesive soil increase and more soil bonded particle rupture and separation with the tool moving. In this Figure, the parallel-bond force distribution is depicted as two parallel lines (for which black line thickness represents the bond forces) through each parallel-bond location and oriented in the direction of the bond force, with a thickness proportional to force magnitude.

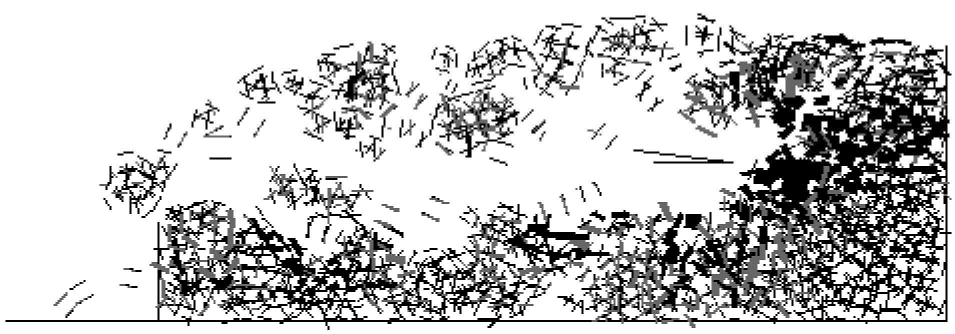


Figure 8. The parallel bond fields, that generate clods.

Moment is represented by varying the thickness of the two lines, to show the difference forces that would be present at those locations to produce the equivalent moment. The reason is that the parallel-bond forces disappear if the corresponding parallel bonds break. The phenomenon is resulted from the crushes between bonded soil particles and the sweep tool and between soil clusters themselves. The crushes make the overlaps between the contact particles increase, and these overlaps will produce compression between particles. The relative tension will be destroyed if the compression appears.

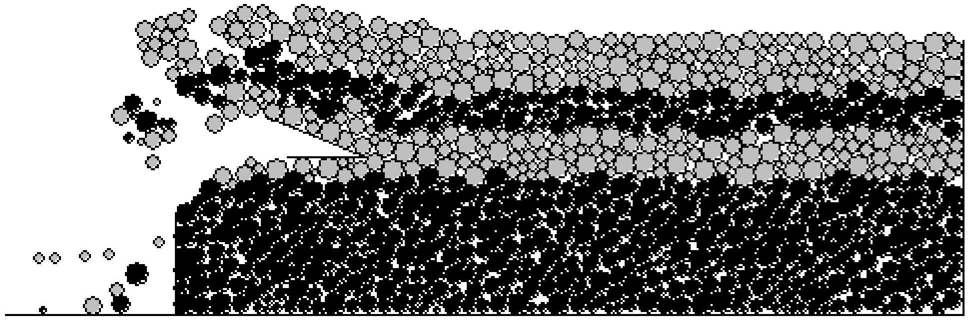


Figure 9. Loosening and clod generation

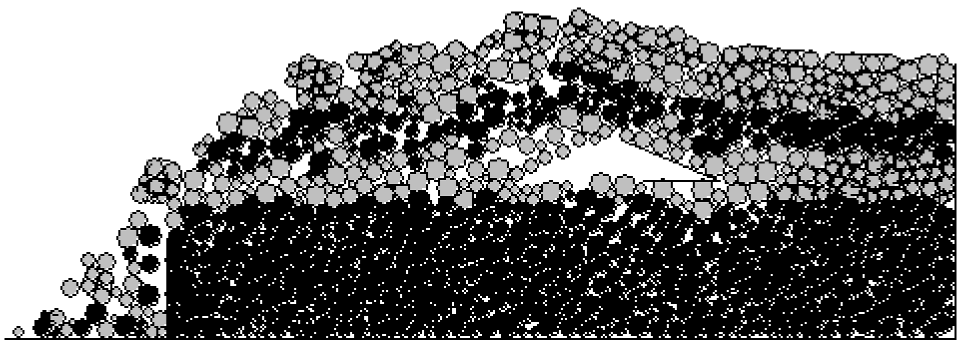


Figure 10. The effect of tool after 12 sec.

RESEARCH RESULTS

The β angel and speed influences in the heavy soil.

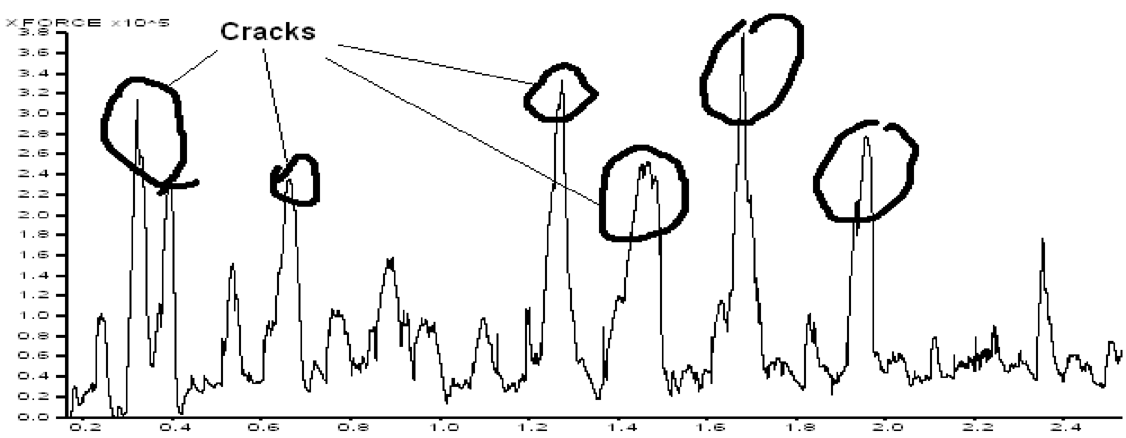


Figure 11. Draft force (N). Speed: 0,6 m/s. Result of a shear process, with the cracks marked.

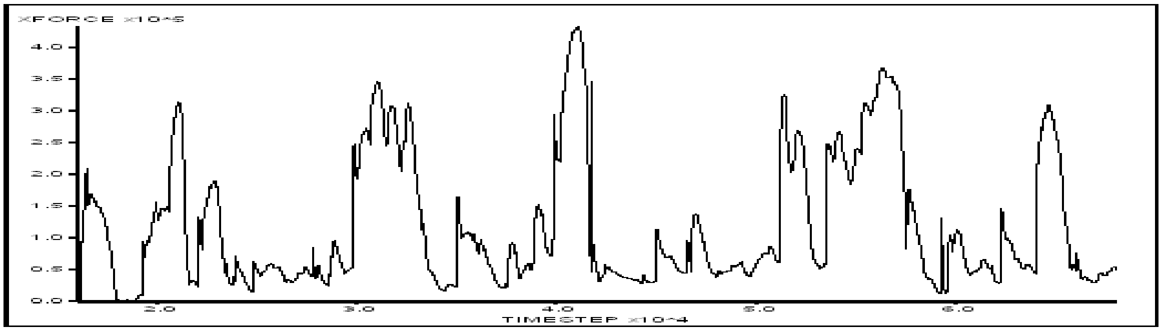


Figure 12. Draft force (N). Speed: 2,6 m/s. Result of a shear process.

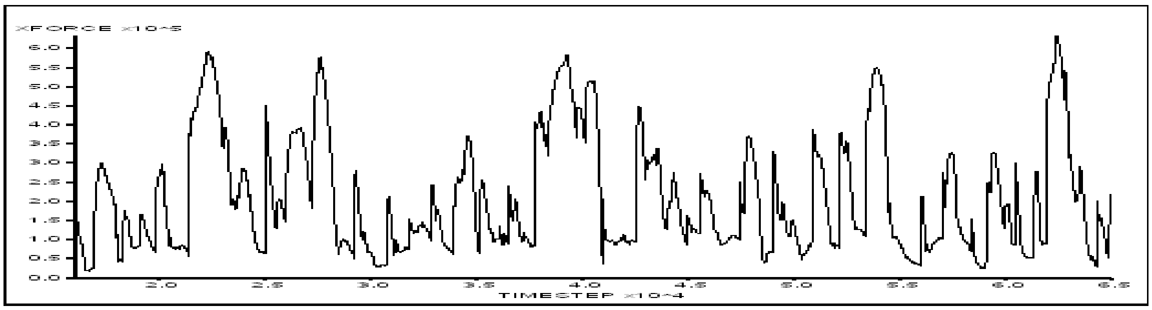


Figure 13. Draft force (N). Speed: 4,6 m/s. Result of a shear process.

Table 2. The influence of the speed.

Draft-Force (N)		
Speed m/s	Cohesive Soil	Loosened Soil
0,6	3,10E+05	8,44E+04
2,6	4,34E+05	2,70E+05
4,6	5,90E+05	4,67E+05

During the simulated tillage process by a cultivator sweep, soil evolves from the extrusion between soil clumps, the humping ahead of the tillage tool, and the climb along the surface of the sweep, to the rupture and separation of cohesive soil cluster.

Table 3. The influence of the incline angels.

Draft-Force (N) (speed 2,6 m/s)	
β-Angle	Cohesive Soil
5°	4,13E+05
15°	4,34E+05
30°	4,90E+05

Large displacement and rotation take place between contact particles in the clusters when the collision between the clusters and the sweep and between clusters themselves happen.

When the maximum normal stress exceeds the normal bond strength, or the maximum shear stress exceeds the shear bond strength, the parallel bonds between the contact particles within the particles rupture. In the tillage process, the resulted clusters break and divide into smaller clusters or discrete particles that seems a sin the real time research. That means, the clusters rupture and separate into more discrete particles with the tool tillage.

Figure 14. Soil-Tool Interaction in cohesive soil

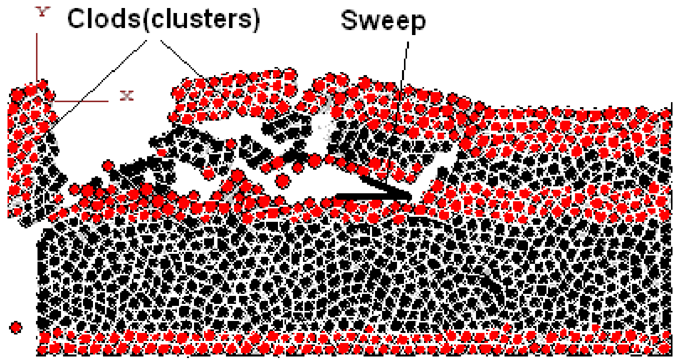


Figure 15. Soil-Tool Interaction by DEM model

Some clods after the work of the sweep also can be seen in this Figure. Parallel bonds between particles are displayed as two lines (white) connecting the particles. The above analysis showed that the phenomena, the compression, rupture and separation of the clusters in the model during the simulation process, are very similar to those of the actual cohesive soils subjected to the external forces.

CONCLUSIONS

The two- dimensional discrete element analyses carried out to simulate soil-tool interaction and the effect of soil properties and the tool inclined angle on predicted cutting forces was studied. The parallel-bond contact was used to describe the behavior of the cohesive soil (discontinuous) during soil-tool interface process. A series of models were analysed with various soil properties, speed and inclined angles using two-dimensional models. The results showed the significant effect of the tool incline angles and working speed on cutting forces in 20 cm depth.

Therefore, in this study we did the analysis in the full length, not to the second and third cracks or not only to the first fracture (in quasi static), this result could be the draft force in virtual reality. Results calculated from the DEM model support the following conclusions:

1. The DEM model proved to be an appropriate tool in development and analysis of the performance of cultivator sweeps in particular and soil loosening processes in general.

2. Total draught force calculated by the DEM model for different sweep geometrical types.

3. The DEM mechanical model of cohesive soil with parallel bonds between particles was established by considering the capillary and the dynamic viscous forces induced by the presence of water, along with the contact forces and the forces of friction between soil particles by the conventional DEM model.

4. The mechanical behavior of cohesive soils during the tillage process by a sweep was simulated. It can be seen from the simulation, the parallel bonds in the model made the discrete particles bond into clusters initially, and then these clusters were broken into smaller clusters or discrete particles during the process.

5. The result of soil-tool interaction in 3D is not considered by the DEM mechanical model of cohesive soil in this paper, which needs to be study in the future.

It can be concluded that the discrete element method can be used for simulating the soil cutting processes in non-homogeneous soils and investigation of soil loosening and sweep performance. The model can be used in development procedures of soil loosening tools, reducing the number of soil bin and field test.

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