Univerzitet u Beogradu
Poljoprivredni fakultet
Institut za poljoprivrednu tehniku
Naučni časopis
POLJOPRIVREDNA TEHNIKA
Godina XXXVIII
Broj 1, 2013.
Strane: 49 – 59

University of Belgrade
Faculty of Agriculture
Institute of Agricultural Engineering
Scientific Journal
AGRICULTURAL ENGINEERING
Year XXXVIII
No. 1, 2013.
pp: 49 – 59

UDK: 631.372:669-8

Originalni naučni rad
Original scientific paper

DISCRETE ELEMENT METHOD (DEM) MODELLING OF COHESIVE SOIL-TOOL INTERACTION

Krisztián Kotrocz[*], **Kornél Tamás**, **György Kerényi**

Budapest University of Technology and Economics, Faculty of Mechanical Engineering, Department of Machine and Industrial Product Design, Hungary

Abstract: The soil-tool interaction is an important role in modern agricultural researches. In this paper a cultivation tine tool was simulated in operation with the working speed of 1 m s^{-1} and working depth of 20 cm using discrete element method (DEM). The parallel bond model was used to demonstrate the cohesive behaviour of the soil. Three analyses were created with different material properties and during the simulations the draft force was measured to compare it with soil bin tests' results. After the soil-tool analyses three tri-axial tests were performed with the same material properties to measure the cohesion and the internal friction angle.

***Key words**: discrete element, DEM, parallel bond, cohesive soil, tool*

INTRODUCTION

Many articles have been published in recent decades to improve the design of the tillage tools. There are some analytical and numerical methods available to investigate the soil-tool interaction. The first analytical theories were developed in the 1970s and summarised by McKyes [1]. This method gives very accurate results but only with simple blades. If the shape of the tool is complex there will be an error in the calculations so numerical analyses are necessary to describe the dynamic behaviour of the soil. Finite Element Method (FEM) has been used since the early 1990s to model the soil-tool interaction [2-4]. In FEM models the soil is modelled as a homogeneous

---

[*] Corresponding author. E-mail: kotrocz.krisztian@gt3.bme.hu

The authors wish to acknowledge the instrumentation and the assistance on soil bin for the Hungarian Institute of Agricultural Engineering of Gödöllő.

isotropic material. While real soils consist of individual particles which slide and roll on each other during the cultivation process, their displacements are discontinuous so this material can not be modelled by FEM correctly.

There is another type of the numerical simulations the so-called Discrete Element Method (DEM) which was developed by Cundall and Strack [5]. In DEM each particle has its own displacements depending on the contacts with walls or other balls. Contact forces can be calculated from the material parameters (e.g.: stiffness) and the overlap of two elements. According to Newton's second law the motion of the particles can be determined in every calculation cycle. Therefore this method is the most suitable to model the soil mechanical behaviour, so many studies have been created in recent years [6-8].

In this work we created a 3D model to simulate the process of the cultivation tine tool and to calculate the average draft force. Different material properties were added to calibrate a model and all three simulated material was examined by tri-axial tests.

MATERIAL AND METHODS

To calibrate the material properties of the DEM model real in-situ or soil bin measurements' results are necessary. In the laboratory of the Hungarian Institute of Agricultural Engineering of Gödöllő some soil bin tests were performed to determine the draft force of the tillage tool with different draft speeds in the winter of 2009 [9]. First step was to create this tool's geometry in the 3D CAD system with the specific parameters. The tool has a sweep angle of $2\gamma = 57°$, a rake angle of $\beta = 20°$ and a width of 310 mm, which correspond with the data in [10].

In the DEM software it is possible to import 3D CAD geometry as walls, but only *.stl file format is supported. Therefore the simplified geometry of the tine tool needs to be converted to *.stl format with a CAD software. This STL-mesh is shown in Figure 1.

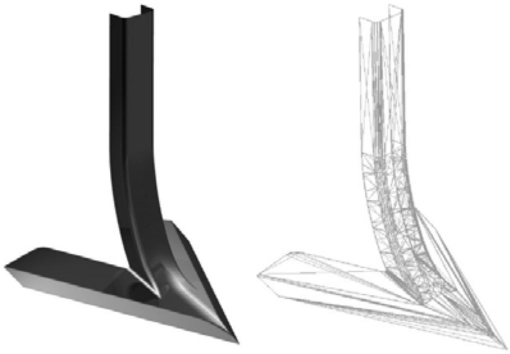

Figure 1. The 3D CAD geometry and the STL-mesh of the tine tool

To model the soil mass a box was created with the dimensions and mechanical parameters shown in Table 1. Within this box 5000 pieces of discrete elements were generated with the radius range from 2 to 5 mm. To fill the box and reach the porosity of

0.4, the radius of the balls were multiplied then many calculation cycles were carried out to approach the mechanical equilibrium state (see in Figure 2). This can be determined by monitoring the velocity of the balls or the mean unbalanced force during the simulation. In Figure 3 the velocity of a selected ball with identical number (ID) 1309 is shown. After 200 000 steps this value reduced to almost zero, so the system reached the equilibrium state.

Table 1. The geometrical parameters of the simulations

Geometrical parameters		
Walls (box and the shape of the tool)		
Length of the box	*1000*	*mm*
Height of the box	*700*	*mm*
Width of the box	*600*	*mm*
Working depth of the tool	*200*	*mm*
Balls		
Number of balls	*5000*	*-*
Radius	*12…30*	*mm*

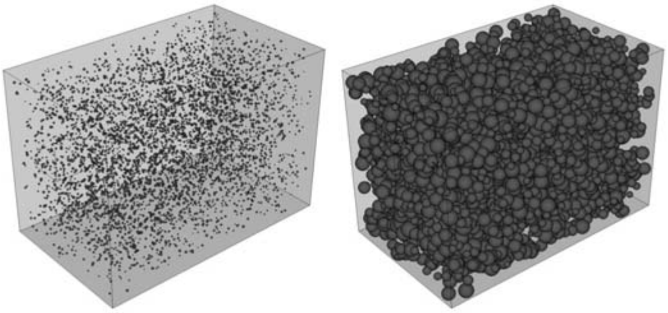

Figure 2. The 3D DEM model before (left) and after (right) increasing the ball's radii

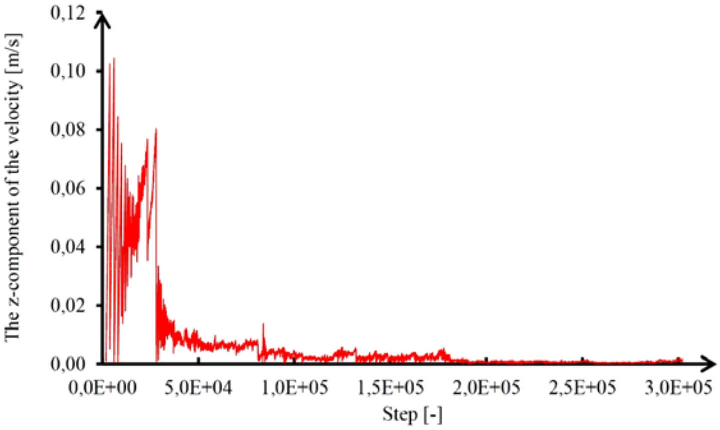

Figure 3. The velocity's z-component of the ball ID 1309

After importing the tool's geometry the mechanical parameters of the soil must be added to the model. The discrete elements can not be deformed, therefore it is important to define the contact properties of the balls correctly. To model the cohesive behaviour of the soil the so-called Parallel Bonds were added. This type of contact was developed by Potyondy and Cundall [11] and can be envisioned as a set of elastic springs with stiffness's in normal and shear direction. These springs act in parallel with the normal and shear direction of the contact as shown in the right side of Figure 4. Relative motion of the two contacting elements (displacement and rotation) causes a contact force and a moment to develop within the bond, respectively. To define the contact stiffness-, strength parameters and the so-called parallel bond radius must be added to the model. Over and above viscous damping and friction were defined between the balls as well as the mechanical parameters of the walls (e.g.: normal- and shear stiffness's, velocity etc.). These are listed in Table 2, separately for each of the three analyses (see Analysis 1, 2 and 3). All of the three calculations were completed with the time step of *dt* = 1×10E-6 sec.

Table 2. The mechanical parameters of the simulations

Mechanical parameters			
Walls (box and the shape of the tool)			
Normal stiffness		2×10^{30}	*N/m*
Shear stiffness		1×10^{30}	*N/m*
Speed of the tool (Draft speed)		*1*	*m/s*
Balls			
Friction coefficient		*0.5*	-
Density		*1850*	*kg/m*^{3}
Viscous damping coefficient		*0.7*	-
Parallel Bond normal stiffness	*Analysis 1*	4×10^{7}	*Pa/m*
Parallel Bond shear stiffness		2×10^{7}	*Pa/m*
Parallel Bond normal strength		2×10^{5}	*N/m*
Parallel Bond shear strength		1×10^{5}	*N/m*
Parallel Bond radius		*1*	-
Parallel Bond normal stiffness	*Analysis 2*	4×10^{6}	*Pa/m*
Parallel Bond shear stiffness		2×10^{6}	*Pa/m*
Parallel Bond normal strength		2×10^{4}	*N/m*
Parallel Bond shear strength		1×10^{4}	*N/m*
Parallel Bond radius		*1*	-
Parallel Bond normal stiffness	*Analysis 3*	4×10^{5}	*Pa/m*
Parallel Bond shear stiffness		2×10^{5}	*Pa/m*
Parallel Bond normal strength		2×10^{3}	*N/m*
Parallel Bond shear strength		1×10^{3}	*N/m*
Parallel Bond radius		*1*	-

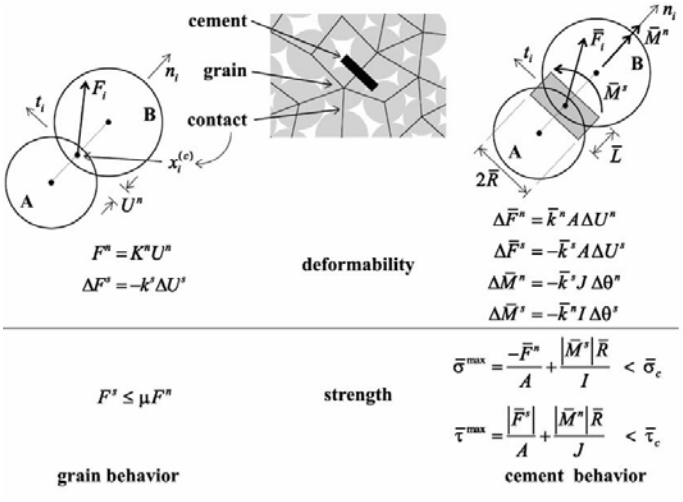

Figure 4. The Parallel Bond Model [11]

Parallel with these analyses three tri-axial tests were performed with DEM to measure the cohesion and the internal friction angle of the three types of soil which are described above. The theoretical background of the simulations is detailed in [1]. From the results of the tests (the first and third principal stresses) the Mohr-cycles and the Coulomb-lines can be drawn. The angle of the Coulomb-lines and the horizontal axis defines the internal friction angle, the intersection with vertical axis defines the cohesion. The confining stresses were 28 kPa, 34 kPa, 48 kPa and 54 kPa, respectively.

RESULTS AND DISCUSSION

The results of the three simulations are shown in Figure 5…9. First the effect of the tine tool was analysed. During the operation the tool forces the particles to move, so the displacements of the elements are much greater in front of- and above the cultivation tool than in the bottom of the box (see in the right side of Figure 6 where the magnitude of the displacement-vectors is proportional with the size of the arrows.).

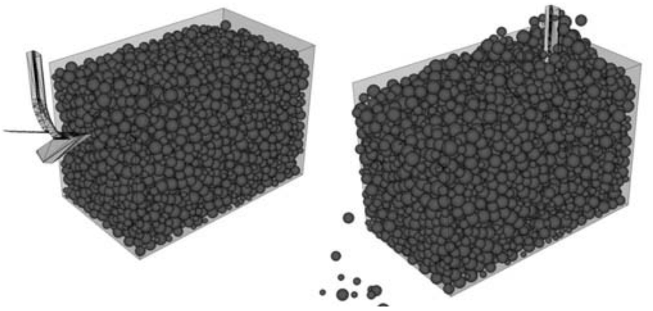

Figure 5. Screenshots from the start (left) and the end (right) of the third analysis

Near the tool the parallel bonds disappeared because the contact forces reached their maximum values which are defined with the contact stiffness's parameters. This result can be seen in the left side of Figure 6 where the parallel bonds were shown as black lines. But in Figure 5 there are some particles above and ahead of the tool which move together because of the remaining parallel bonds. This represents the cohesion between the elements so the simulations seem to be acceptable.

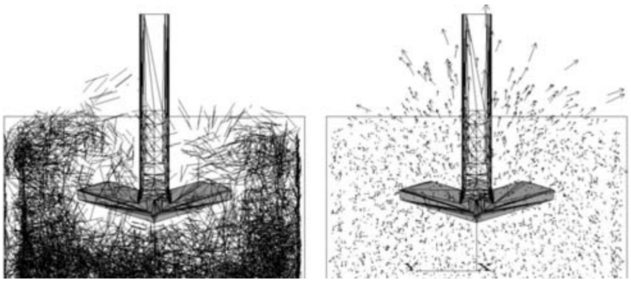

Figure 6. The Parallel Bonds (left) and the elements' displacements (right) in the third analysis

During all of the three analyses the draft force was measured, the values are shown in Figures 7-9. In the first steps the tine tool does not reach the soil-model completely, so only the values from the step nr. 100 000 were considered in the evaluation (these are represented as red, black and blue in the figures, respectively). The nature of the results is very similar to the results of the soil-bin tests [9], particularly in the second and third analysis. The values of the draft forces scatter widely which is corresponding with the real measurements' results. From this data the step-based average values were calculated. The average draft force of the first and the second simulation are approximately equal to the soil-bin test value (F=1170…1220 N) [9]. In the third analysis the mechanical parameters of the contacts are too small therefore we got a small value as draft force. (The values of the average draft forces are shown in the title of each figure.)

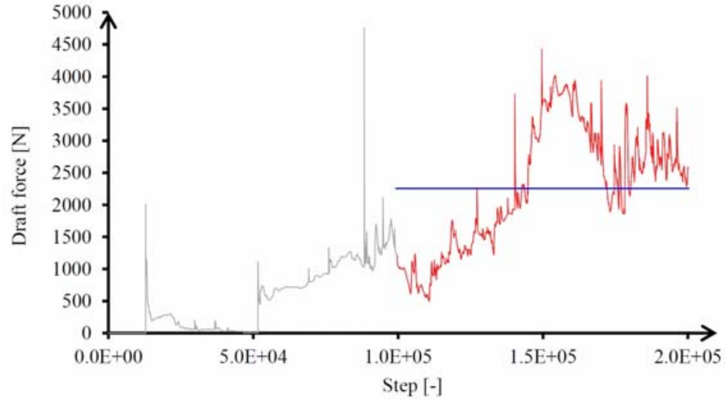

Figure 7. The result of the first analysis, draft force as the function of step (average value is 2257.3 N shown as blue)

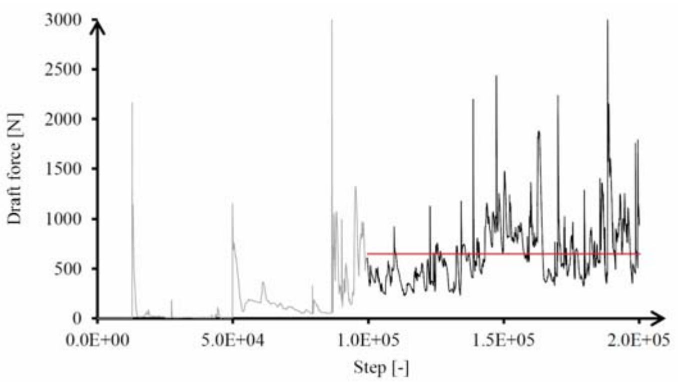

Figure 8. The result of the second analysis, draft force as the function of step (average value is 654.2 N shown as red)

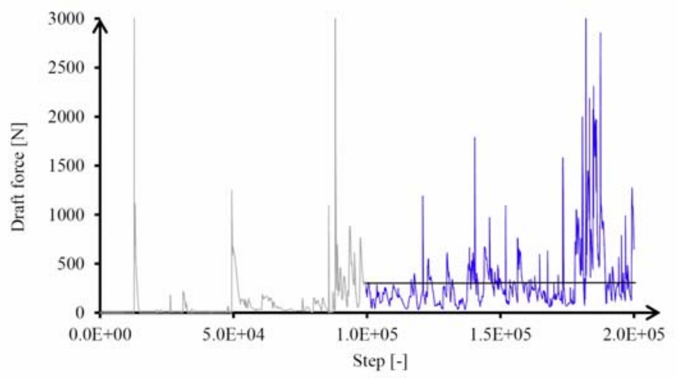

Figure 9. The result of the third analysis, draft force as the function of step (average value is 310.8 N shown as black)

The results of the tri-axial test are shown in Figure 10-12. In the diagrams the negative y-axis and the x-axis define the axial stress as the function of axial strain. In turn the positive y-axis and the x-axis define the shear stress as a function of axial stress. In this diagram the Mohr-cycles can be drawn and the internal friction angle and the cohesion can be calculated [1]. Table 3 contains exact values of these parameters.

The first soil has high cohesion (70.8 kPa) which causes the high values of the draft forces in the first simulation. But in the second and the third analysis the cohesion is about zero which means that we can not get any parallel bonds between the elements at the end of the second and the third soil-tool simulation. In Figure 5 there are some parallel bonds above the tine tool, so probably the cohesion will not be equal to zero, but it has a very small value. Therefore it is possible that some particles move together at the end of the simulations. In these analyses the parallel bond strengths are very small compared to the stiffness's, so increasing the value of the strength will cause that we will get a higher cohesion and higher draft force as results.

The internal friction angles are close to the real values (15…35°) [1].

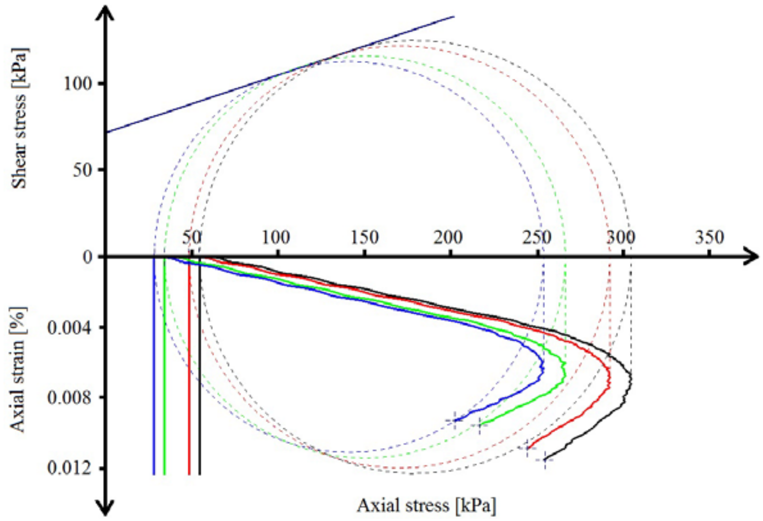

Figure 10. The result of the first tri-axial analysis

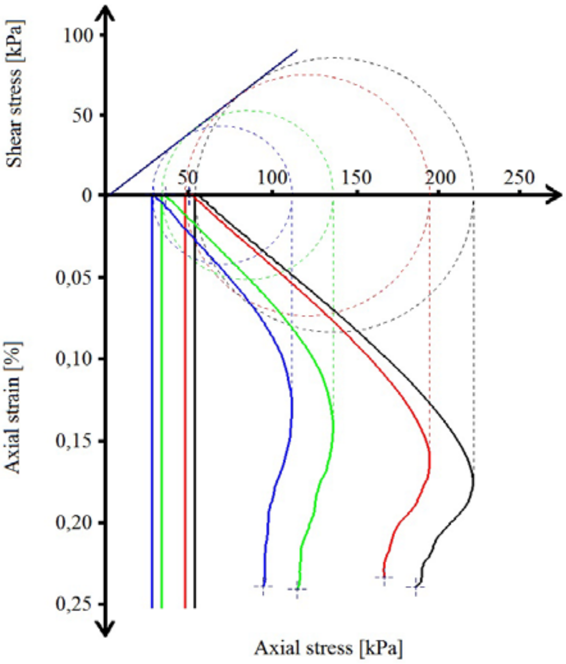

Figure 11. The result of the second tri-axial analysis

Table 3. The results of the tri-axial tests

	Cohesion		Internal friction angle	
Analysis 1	*70,8*	*kPa*	*18,4*	°
Analysis 2	*0*	*kPa*	*38,1*	°
Analysis 3	*0*	*kPa*	*37,8*	°

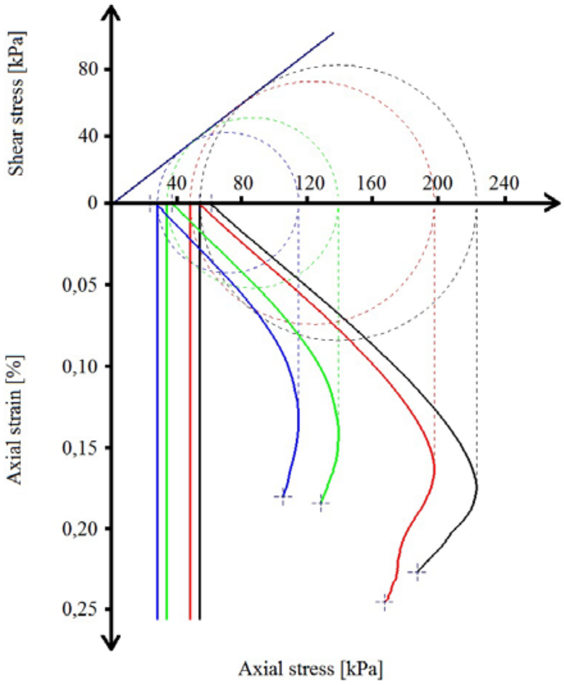

Figure 12. The result of the third tri-axial analysis

CONCLUSIONS

We created a 3D discrete element model to simulate the soil-tool interaction during the operation. Three analyses were carried out, each with the working speed of v=1 m/s and working depth of 20 cm. The soil's cohesive behaviour was modelled by parallel bonds. The displacements of the particles are appropriate and the soil's loosening and cutting process can be well simulated with the developed model even with complex tool shapes. Therefore these simulations are suitable to substitute the expensive soil bin or in-situ measurements.

To verify the results real soil bin tests and tri-axial DEM analyses were performed. Comparing to the soil bin results we can determine that the tendency of the draft forces is the same. The values scatter widely, but with well calibrated material parameters the magnitude of the average draft force is acceptable.

In the tri-axial tests we got the same results. The first soil has high cohesion, therefore with these material parameters soils with high moisture can be simulated. In the second and third tri-axial analysis the cohesion is about zero so sandy soils can be modelled correctly. The values of the internal friction angle are corresponding too with real measurements.

BIBLIOGRAPHY

[1] McKyes, E. (1985): *Soil Cutting and Tillage*. Elsevier, New York.

[2] Chi, L., Kushwaha, R. L. (1990): A non-linear 3-D finite element analysis of soil failure with tillage tools. *Journal of Terramechanincs*, 27(4), 343-366.

[3] Abo-Elnor M., Hamilton, R., Boyle, J. T. (2003): 3D Dynamic analysis of soil-tool interaction using the finite element method. *Journal of Terramechanics*, 40, 51-62.

[4] Abu-Hamdeh, Nidal H., Reeder, Randall C. (2003): A nonlinear 3D finite element analysis of the soil forces acting on a disk plow. *Soil & Tillage Research* 74, 115-124.

[5] Cundall, P. A., Strack, O. D. L. (1979): Discrete numerical model for granular assemblies. *Geotechnique*, 29(1), 47-65.

[6] Zhang, R., Li, Z. (2006): Simulation on mechanical behavior of cohesive soil by Distinct Element Method. *Journal of Terramechanics*, 43, 303-316.

[7] Shmulevich, I. (2010): State of the art modeling of soil-tillage interaction using discrete element method. *Soil & Tillage Research*, 111, 41-53.

[8] Tsuji, T., Nakagawa, Y., Matsumoto, N., Kadono, Y., Takayama, T., Tanaka, T. (2012): 3-D DEM simulation of cohesive soil-pushing behavior by bulldozer blade. *Journal of Terramechanincs*, 49, 37-47.

[9] Hudoba, Z., Deákvári, J., Elek, J. (2010): Talajművelő szerszámok kopóelemeinek talajvályúban történő vizsgálata. *Report, Hungarian Institute of Agricultural Engineering of Gödöllő*, Hungary, Gödöllő (in hungarian).

[10] Szendrő, P. (2000): Mezőgazdasági gépszerkezettan. *Mezőgazdasági Szaktudás Kiadó*, Budapest (in hungarian).

[11] Potyondy, D. O., Cundall, C. A. (2004): A bonded-particel model for rock. *International Journal of Rock Mechanics & Mining Sciences*, 41, 1329-1364.

MODELIRANJE KOHEZIVNE INTERAKCIJE IZMEĐU ZEMLJIŠTA I ORUĐA METODOM DISKRETNIH ELEMENATA

Krisztián Kotrocz, Kornél Tamás, György Kerényi

Univerzitet tehnologije i ekonomije u Budimpešti, Mašinski fakultet,
Institut za mašine i industrijske proizvode, Mađarska

Sažetak: Interakcija između zemljišta i oruđa ima važnu ulogu u savremenim poljoprivrednim istraživanjima. U ovom radu je prikazana simulacija rada noža radnog organa za obradu zemljišta čija je radna brzina 1 m s^{-1} a radna dubina 20 cm korišćenjem modeliranja metodom diskretnih elemenata (DEM). Korišten je paralelan model da bi se pokazalo kohezivno ponašanje zemljišta. Napravljene su tri analize sa različitim materijalnim osobinama i tokom simulacije merena je vučna sila da bi se uporedila sa rezultatima testova u zemljišnom bazenu. Posle analize zemljište – oruđe, izvedena su tri tro-aksijalna testa sa istim osobinama materijala u cilju merenja kohezije i ugla unutrašnjeg trenja.

***Ključne reči**: diskretni elementi, DEM, paralelni spoj, kohezija zemljišta, oruđe*

Prijavljen: *Submitted:*	10.03.2013.
Ispravljen: *Revised:*	
Prihvaćen: *Accepted:*	23.03.2013.