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MODELING THE SOIL HETEROGENEITY IN THE DISCRETE ELEMENT MODEL OF SOIL-SWEEP INTERACTION

Kornél Tamás*, Márton F. Tóth†

* Department of Machine and Product Design
Budapest University of Technology and Economics (BME), Faculty of Mechanical Engineering
Bertalan Lajos street 4-6. Building MG300, H-1111 Budapest, Hungary
e-mail: tamas.kornel@gt3.bme.hu, web page: http://www.gt3.bme.hu/en/

† Department of Machine and Product Design
Budapest University of Technology and Economics (BME), Faculty of Mechanical Engineering
Bertalan Lajos street 4-6. Building MG300, H-1111 Budapest, Hungary
e-mail: t.marton95@gmail.com

ABSTRACT

In agriculture the analyse of soil compaction in soil-tool interaction has a significant role. The equipments of agricultural farms are getting bigger and more complicated and it has huge importance to optimize the tillage methods. Two of most frequently investigated factors are the tool's mixing-effect and the draught force on the tool; these results are important for agronomical experts to design tillage tools and cultivation processes. Discrete element method (DEM) is one of the numerical methods to model soil's behaviour and soil-tool interaction. Aim of this study is to develop a 3D DEM model for clay soil and analyse the behaviour of soil-model regarding to non-homogeneous soil condition of agricultural fields. Simulation results will be compared with field test measurements for cone penetration tests. In this paper effects of particle's shape and micromechanical properties will be investigated and simulations will be compared using special particles, so-called clumps in model. Clumps are aggregations that are set of spheres. This study investigates the effect of using clumps instead spheres in simulations and it will be attempted to model the thixotropic behaviour of soil with special kind of particles. Non-homogeneous property and varied compaction of field soil will be modelled with more layers, keep to be comparable the simulation results with field tests. Measurements were set for more moisture content; study investigates appropriate set of micromechanical parameters to simulate the effect of water.

1 INTRODUCTION

In agriculture the role of research about precision plant cultivation is getting bigger and many digital technologies have a great importance in this field. A lot of technologies and methods are used in agriculture and food industry and have some special fields, such as numerical simulations; these used to analyze and improve harvest and food process methods. Another frequently researched area is the analyzing of soil-tool interaction with tests and simulations. Many papers can be found connected to this research, such as in [1, 2, 3] where the mostly and successfully used numerical technique was the discrete element method (DEM).

The [1] study focused on the dynamical behavior of soil and it was analyzed with measurements and simulations. In this research the DEM model included only spherical particles with more distributions of radius. In simulations parallel-bond model was applied and the experiments were soil-bin tests with a sweep tool. Soil-bin tests appeared in [2], and this paper presented a DEM model for soil-tool interaction. This study used only spherical particles with equal radii. In soil model were applied 3 layers with different parameters to model inhomogeneous soil conditions. For calibration were used cone penetration models and tillage data, the calibrated parameters were the particle and bond stiffness. The successful model was used to investigate the influence of tillage-depth for draught force and loosening-efficiency. The paper [3] presents a study about sensitivity analysis. Research focused on soil-thrown effect and draught force while soil-sweep interaction. The influence of micro properties, such particle and bond elasticity, damping coefficient, etc. were investigated and DEM simulations with spherical particles were compared with soil-bin tests. The most sensitive parameter was the Young's modulus according to results of paper. Similar study can be found in [8], paper investigated the role of parallel bond model and viscous damping parameter in a soil-sweep DEM model. Conclusion of research showed, the bond radius has an important role in modeling of soil moisture content and the viscous damping need to be decreased at higher speeds in model to keep it comparable with measurements.

The most of studies was able to investigate soil-bin tests and publications focused mainly on this art of measurements; respectively soil models use always spherical particles. Although, in some cases the DEM models were able to simulate complex fluid mechanics behavior of soil and the soil-tool mixing-effect. On the other hand, in agriculture it has a high importance to make in-situ tests on agricultural fields and develop soil models which can be compared with in-situ results. These measurements usually require high costs and the evaluation of test results are often difficult due to the inhomogeneous structure of soil. The aim of this study is analyzing the results of field tests and improving a 3D DEM model to simulate the heterogeneity of agricultural soil and developed model serves a preparation of investigating of soil-tool interaction. On the one hand, the motivation of this research is the trying to reduce draught force of agricultural processes, because it could require high draught power which means more costs for farmers and more load for cultivator machines. On the other hand, this research can be useful to investigate the soil-degradation phenomenon.

2 MATERIAL AND METHODS

2.1 FIELD EXPERIMENTS

The field tests were set at three different moisture content before tillage in a clay-sandy soil, on the placement of Hungarian Institute of Agricultural Engineering (NARIC). First penetrate measurements were set at ten randomly chosen points on agricultural field (Fig.1). The second

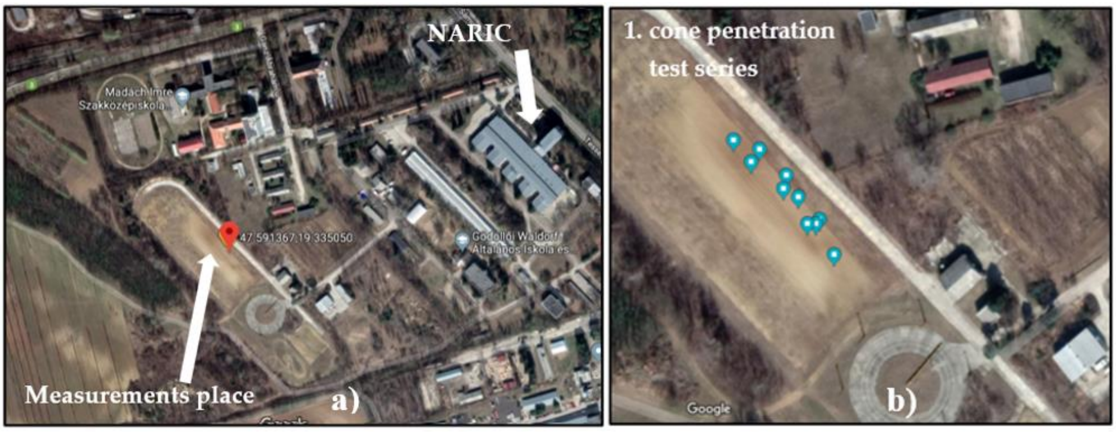

Figure 1: **a**) Placement of field experiments, **b**) first series of cone penetration test [10]

cone penetration test series were set on same placement with same experiment's number, at another time. The third test series was set at same place, it included only 3 measurements. For measurements was used a penetrometer, this device measures the vertical resistant force and the volumetric moisture content of soil. It is available as a complete set suitable for measurements up to a depth of 80 cm. The cone penetrometer itself consists of a penetrologger housing with GPS and a control panel. The logger is contained in a water-resistant housing with electrically insulated grips. Cone is screwed onto the bottom end of a bipartite probing rod. Depending on the application and the expected resistance to penetration different cones can be attached. The cones supplied have 60º top angle and various projected areas. At field tests was used a cone with 60º top angle and 1 cm^2 area. The resistant force is divided by projected area of conehead and averaging all measurements at each test series, so, can be given a curve that express stress values, the Cone Penetration Resistance (CPR) of soil. As could be observed, there are large deviations from average but values can define one exact curve. The test results are compared at different moisture contents, it shows Fig. 2. The penetrometer recorded the soil moisture content at all measurements, at first series was the soil driest, at second series soil contained the most moisture and the third test showed a medial moisture content, as can be seen in Table 1.

Table 1: moisture content at each cone penetration measurement

	Moisture content, V/V%										Mean values
1. Test series:	9	6	5	4	9	7	7	8	4	7	**6.6**
2. Test series:	24	21	23	21	20	21	23	22	24	22	**22.1**
3. Test series:	13	14	13								**13.3**

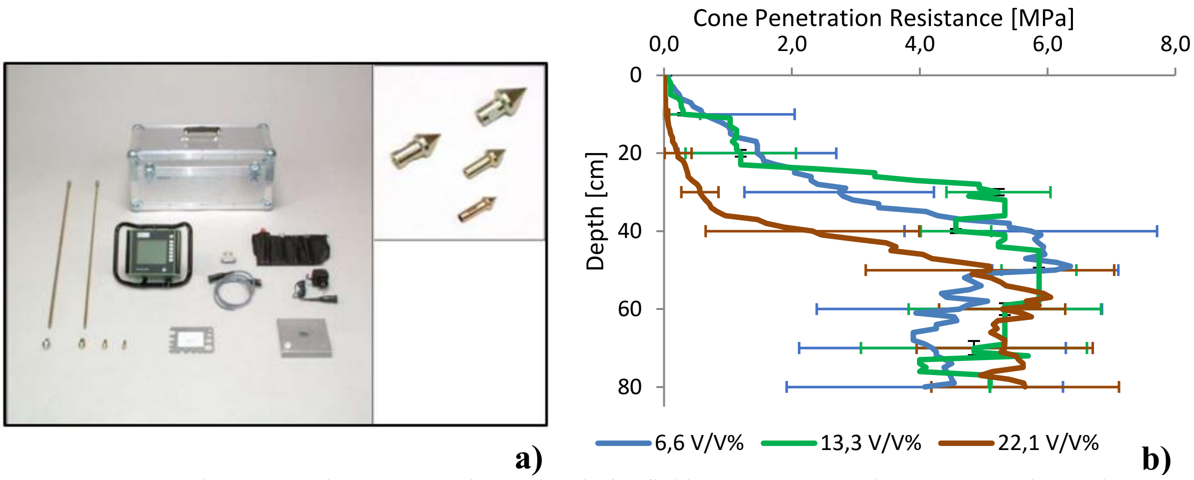

Figure 2: **a)** complete penetrologger set and cone heads for field tests **b)** averaged cone penetration resistance of soil at different moisture contents with standard deviations

It can be seen on Fig. 2, drier soils have larger resistance, similar to [4], and the peak at each curve is given between 50 and 60 cm deep from the top of soil. Cone resistance depends on soil compaction, bulk density, moisture content; and higher resistance is associated with higher bulk density [5,6]. Test results will be used for further simulations with soil model and have high role in calibration process. After each cone penetration test, began the tillage process with a tractor, as can be seen on Fig. 3. For this process was used a cultivator sweep tool, and during tillage the draught force was recorded with a 50 Hz sample frequency. The distances of measurements were between 60-90 meter, the average velocity was 9.1 km h^{-1} and the work-

Figure 3: **a)** cultivator tools, the piece in the middle was used for tillage experiments **b)** the tractor

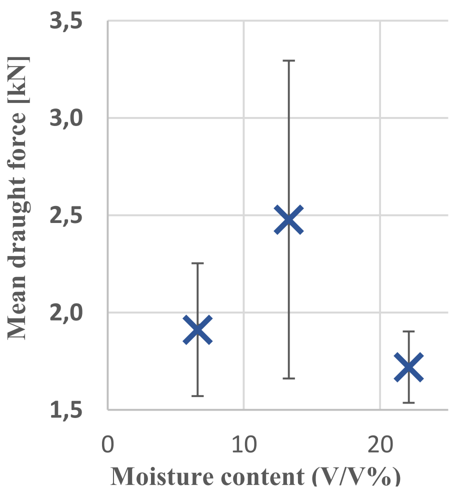

Figure 4: Mean draught force with standard deviations by tillage at each moisture content

depth was at each experiment 10-15 cm. Fig. 4 shows, soil with medium moisture content (13.3 V/V%) produced the highest draught force, and the smallest mean force was observed by the soil with the highest moisture content (22.1 V/V%). Results are similar to cone resistant experiments, where the driest and medial moisture content soil produced largest resistant and the soil with less wet shows the smallest cone penetration resistance (CPR) until 50 cm depth.

2.2 DISCRETE ELEMENT MODEL

For the simulation of soil behavior was used DEM and applied YADE DEM software. The DEM is able to model some effect of soil-tool interaction but there are some numerical parameters which need to calibrate a model. The most frequently used method for that is the

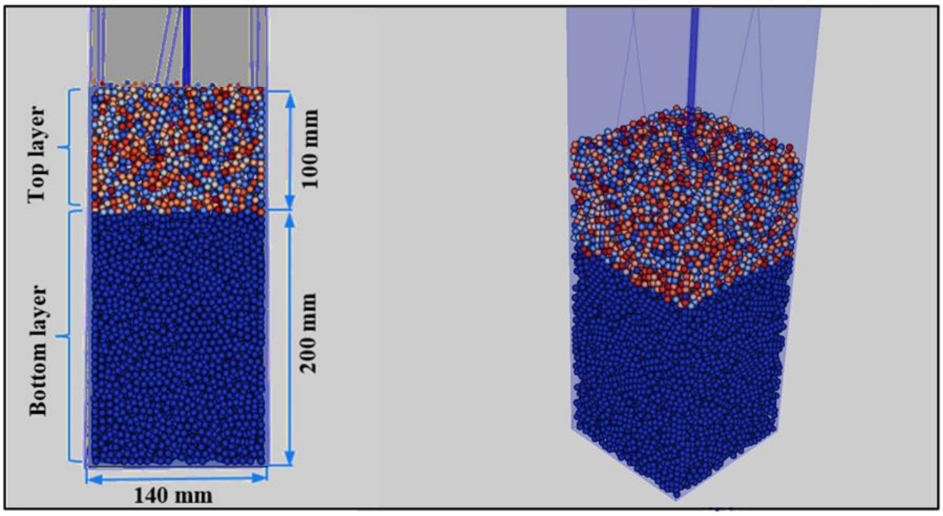

Figure 5: the two layers of soil DEM model and the rod with conehead

parameter sensitivity analysis. The most sensitive parameters in soil models usually are the Young's modulus [3], normal and shear cohesion, and the friction. But its notable, many studies were developed using only spherical particles and parallel-bond model in simulations. Other techniques to find appropriate parameters are systematic methods and optimization processes [2,7]. In this paper, the energy dissipation was modeled with particle's shapes using clumps. Three types of clumps were applied in model with different portions, these can be seen on Fig. 6. Finding appropriate microparameters a sensitivity analysis was applied, based on mentioned and similar studies. The 3D discrete element model was set up for conical tests, and it was developed with 2 layers. Previous paper [4] used same technique to model soil with different layers, but there were 3 layers in one penetrometer. For conical simulations was set up a 140×140×1000 mm box and the cone model was used with 1.5 cm^2 projected area and 60° cone angle. Speed of penetrometer was at each case 0.1 m s^{-1}. Other parameters of model are showed in Table 2.

The soil model consisted three types of clumps, as can be seen on Fig.6: so-called dyad by two, peanut by three and stick by four spheres. Particle distribution was set with these clumps with 5-5-90% ratio and the greatest size of these elements was between 13.9- and 24.1-mm. Damping between particles was not applied.

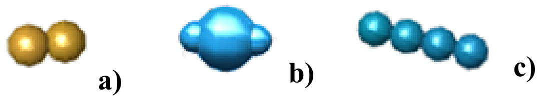

Figure 6: clumps built by spheres; **a)** dyad, **b)** peanut and **c)** stick elements

Soil model for cone penetration test included 9700 elements and it reached 0.3 m height. The cone moved 0.3 m deep in soil model with the mentioned constant speed and only vertical force was recorded during simulation. Regarding to inhomogeneous structure and compaction of field soil DEM model was divided along vertical two layers: top layer was set with 0.1 m and the bottom layer with 0.2 m. It was possible to set up different soil parameters for each layer and it was one device to the effective calibration. The two layers in model and the cone are visualized on Fig. 5.

Table 2: physical properties of soil for cone penetrate model

Parameters	Unit	Value
Particle density, ρ_p	kg m^{-3}	2700
Young modulus, E_Y	Pa	$5\cdot 10^6$
Particle friction, μ_p	-	Calibrated
Wall friction angle, μ_w	deg	40
Cohesion, σ, τ	Pa	Calibrated
Poisson ratio, ν_p	-	0.4

3. RESULTS

As seen the results of cone field tests it would be required to make more soil layers in DEM model and add different parameters. At first simulations the cohesion of top and bottom layers was modified and the other parameters were still constants. The previous results showed, it is considerable to set up higher cohesion at bottom layer, and the cohesion values could be selected in range from 10^3 to $\mathbf{5\cdot 10^6}$ Pa according to previous simulations and based other studies. During simulations normal and shear cohesions were set as equal. Particle friction will be usually expressed as friction angle; it was the other varied property.

At the next parameter sensitivity test the effect of particle friction was investigated. In this model both layers had constant $5\cdot 10^4$ Pa cohesion and the friction coefficient has varied in both layers. It can be observed, with higher friction coefficient the cone resistance profile is similar to drier soil, and with low particle friction coefficient the results of simulations are closer to higher moisture content, so, the curve of model results is getting steeper. As can be seen on Fig. 7. the set #1.3 and #1.4 had the best match with driest soil and #1.1 and #1.2 were the closest to the soil with most moisture content. Parameter set #1.3 was closest to soil with medium moisture content at top section, and the set #1.5 passed to this soil at deeper section. It was observed, friction values had significant influence to cone index and the increasing of CPR was almost proportional with increase of friction coeficient. At the next simulation series, the cohesion of layers was varied with constant frictions; parameters are showed in Table 4. Best matches were achieved due to different cohesion at case of dry soil with set of #2.1 and #2.2. It can be seen on Fig. 8., that influence of particle friction is same as in earlier parameter series, curves shifted to higher cone resistance while increase friction. Interestingly, with change of cohesion's size ratio between layers there was not large deviation between layer's resistance. It is supposed, the influence of larger cohesion at bottom layer appears in top of soil, so cone resistance does not decrease instead lower cohesion at top layer. So, with change of cohesion's ratio, CPR profiles shifted almost parallel and profile curves were get steeper and followed worse test results than previous parameter set.

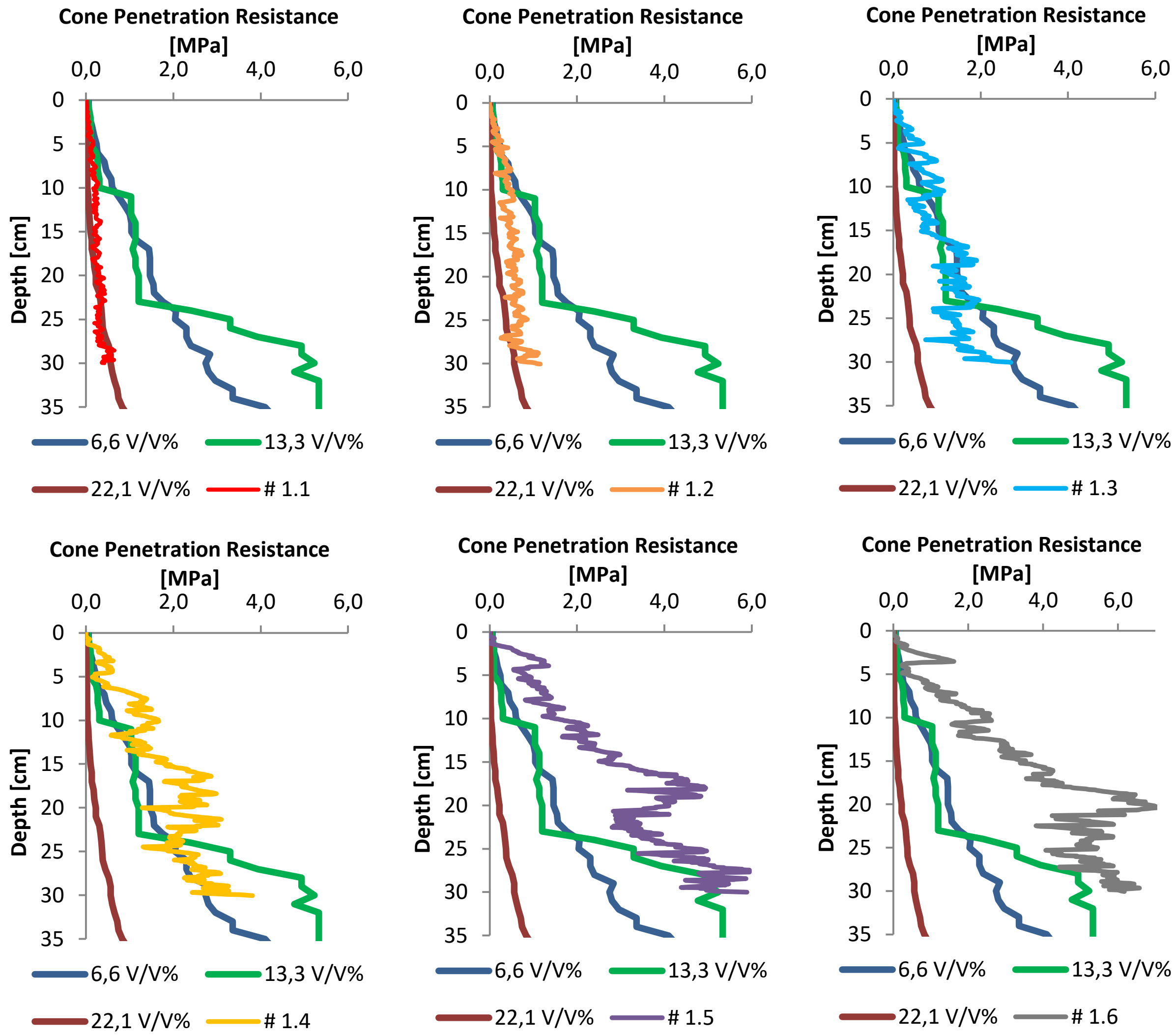

Figure 7: simulation and test results compared at first parameter series

Table 3: Parameter set of soil for cone penetrate model at first parameter sensitivity test

Parameter set	Friction angle	Cohesion at each layer
	deg	Pa
#1.1	10	
#1.2	15	
#1.3	25	$5 \cdot 10^4$
#1.4	30	
#1.5	40	
#1.6	45	

Higher cohesion at bottom layer laid to higher cone penetration resistant, as Fig. 8. shows in left and middle charts. By parameter set #2.5 and #2.6 results are not totally consistent with trend of second parameter series, but the curves shifted next to higher penetration resistance as effect of higher friction.

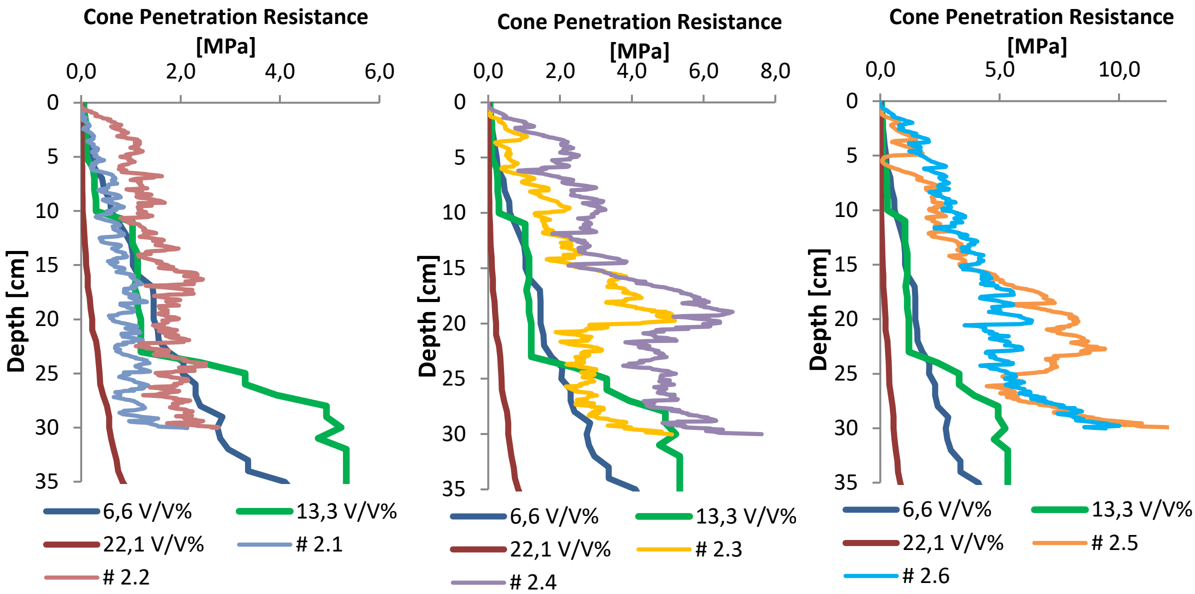

Figure 8: simulation and test results compared at second parameter series

Table 4: Parameter set of soil for cone penetration model at second parameter sensitivity analises

Parameter set	Cohesion at top layer	Cohesion at bottom layer	Friction angle
	Pa	Pa	deg
# 2.1	$5 \cdot 10^5$	$5 \cdot 10^4$	20
# 2.2	$5 \cdot 10^4$	$5 \cdot 10^5$	
# 2.3	$5 \cdot 10^5$	$5 \cdot 10^4$	35
# 2.4	$5 \cdot 10^4$	$5 \cdot 10^5$	
# 2.5	$5 \cdot 10^5$	$5 \cdot 10^4$	45
# 2.6	$5 \cdot 10^4$	$5 \cdot 10^5$	

At another parameter sensitivity analise at all set of properties was the cohesion at the bottom layer higher, regarding to earlier results. The effect of particle friction coefficient was same as the other penetration simulations and it could be observed, the lower cohesion at top layer and the higher cohesion at bottom layer led to gently sloped curves, when difference was enough between cohesions. So some of these results followed better the deeper section of soil's cone resistance, but at most of these simulation results CPR was extremly overestimated along full depth instead very low cohesion in top layer and low friction value. At some parameter sets could be observed a peak of curve like at set #1.5 and #1.6. These peaks appeared obviously only by high friction value and between 15 and 20 cm depth of soil.

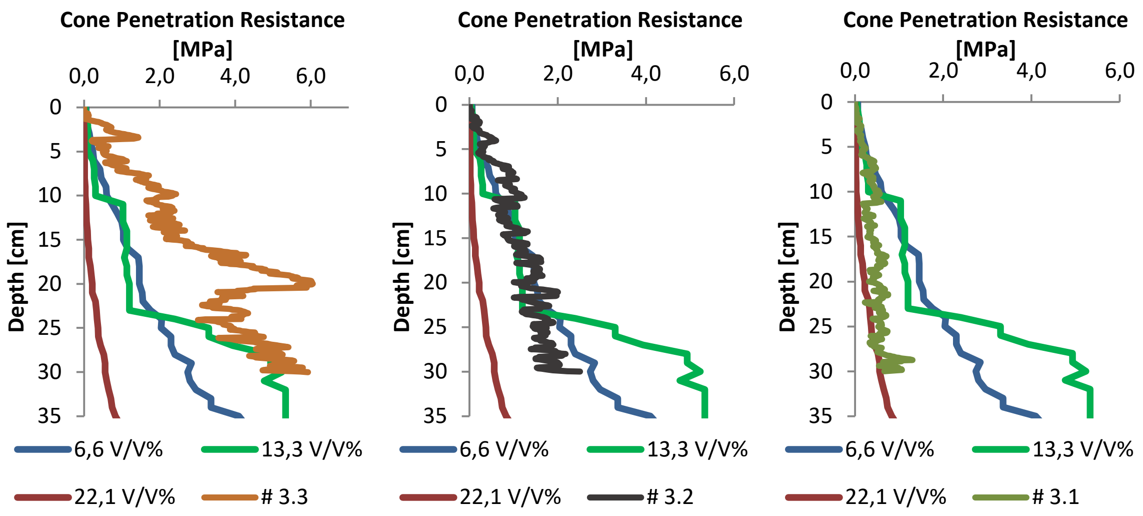

Figure 9: simulation and test results compared at third parameter series

Table 5: Parameter set of soil for cone penetration model at third parameter sensitivity analises

Parameter set	Friction angle at top layer	Friction angle at bottom layer	Cohesion
	deg	deg	Pa
# 3.1	10	15	
# 3.2	10	25	$5 \cdot 10^4$
# 3.3	10	40	

Fig. 9. shows the results of simulations with third parameter series. As can be seen in Table 5., the friction was a constant and low value at top layer, but friction in bottom layer was increased, while constant and equal cohesions were applied at each layer. The profiles and behavior of cone resistance were similar to first series, but the match at deeper soil'layers was better with these parameters. As can be seen set #3.3 it follows only deep section of soil CPR with medium moisture content and instead low friction it exceeds the CPR of top layer. One simulation was set over and above with medial top layer friction (25°) and higher friction coefficient (40°) at the bottom layer.

The resulted curve with these properties was very similar to set of #3.3 but it overestimated the deeper section of CPR too. To compare objectively the model and test penetrate results, it was considerable to calculate relative error (RE) between simulated and test values [9]. Its calculation form was given as:

$$\mathrm{RE} = \frac{1}{n} \cdot \sum_{1}^{n} \frac{CPR_{DEM} - CPR_{Test}}{CPR_{Test}} \cdot 100\ (\%) \tag{1}$$

RE was calculated with use of trend-line values by model results and it was averaged at top and bottom layer and along full depth. Mean values are represented in Table 6.

Table 6: parameter set with the least mean relative errors between model and test results

Moisture content	Parameter set	Mean RE at top layer	Mean RE at bottom layer	Mean RE at full layer
V/V%		%	%	%
6.6	# 1.4	59.1	9,4	**27.0**
	# 2.2	46.8	9.9	**22.9**
	# 3.2	57.5	30.9	**40.3**
13.3	# 1.2	34.1	62.8	**52.7**
	# 2.1	64.4	40.4	**49.9**
	# 3.2	115.9	28.6	**59.6**
22.1	# 1.1	394.2	71.1	**163.4**

4. CONCLUSIONS

The 3D DEM model for cone penetration tests was successfully developed and with the variation of parameters were given several cone penetration test results. The comparation of simulations and test results were successful and some of these parameter sets were able to model the soil behavior. According to mentioned results of simulations, the range of friction coefficient and cohesion values is compliance to investigate appropriate model for the analyzed agriculture soil. In some cases, the mean problem was generally the overestimation by top layer and underestimation by bottom layer between test and model values. At first parameter series it succeeds to adjust the steep of curves respectively by dry and mostly wet soil using friction coefficient value as variable. At second series it was concluded, using different cohesion at each layer resulted very steep CPR curves, because bottom layer with higher cohesion influences top layer, so, it seemed difficult to calibrate appropriately using different cohesion. At third parameter series friction value was varied at each layer and these sets resulted also good matches but it was failed to follow the soil with medial moisture content and relative error by soil with most wet content stayed relatively high. It could be observed; the relative errors were highest always at top layer and the largest error appeared by soil with most moisture content. By driest soil least RE was for full depth 23%, by 13.3 V/V% moisture content it was 50% and by 22.1% it reached 163%. For calibration of models using cohesion as variable was one opportunity but friction coefficient seemed more effective to get an appropriate soil model, and it seemed not necessary to apply more layers at each case. Although, in favor to get better matches its considerable to set up simulations with another thick of layers. The analyzed soil model can be a good preparation of further simulations of soil-tool interaction.

5. ACKNOWLEDGEMENT

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REFERENCES

[1] Milkevych, V., Munkholm, L.J., Y Chen, Y., Nyord, T. *Modelling approach for soil displacement in tillage using discrete element method.* Soil and Tillage Research 183, 60-71 (2018)

[2] Zeng, Z., Chen, Y., Zhang, X. *Modelling the interaction of a deep tillage tool with heterogeneous soil.* Computers and electronics in agriculture 143, 130-138 (2017)

[3] Sadek, A., Chen, Y. *Feasibility of using PFC3D to simulate soil flow resulting from a simple soil-engaging tool.* Transactions of the ASABE 58 (4), 987-996 (2015)

[4] Sadek, M.A., Tekeste, M., Naderi, M. *Calibration of soil compaction behavior using Discrete Element Method (DEM).* ASABE Annual International Meeting, 1 (2017)

[5] Lipiec, J., Hatano, R. *Quantification of compaction effects on soil physical properties and crop growth*. Geoderma 116 (1-2), 107-136 (2003)

[6] Tekeste, M.Z., Raper, R.L. Schwab, E. *Soil Drying Effects on Soil Strength and Depth of Hardpan Layers as Determined from Cone Index Data.* Agricultural Engineering International: the CIGR Ejournal, X, 1-17. (2008)

[7] Asaf, Z., Rubinstein, D., Shmulevich, I., *Determination of discrete element model parameters required for soil tillage.* Soil & Tillage Research 92 227-242 (2007)

[8] Tamás, K. *The role of bond and damping in the discrete element model of soil-sweep interaction.* Biosystem engineering 169 57-70 (2018)

[9] Sadek, M. A., Ying Chen, and Jude Liu., *Simulating shear behavior of a sandy soil under different soil conditions*. Journal of Terramechanics 48.6: 451-458. (2011)

[10] www.google.com/maps , June 2019