Investigation of soil-sweep interaction in laboratory soil bin and modelling with discrete element method

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KEYWORDS

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ABSTRACT

Nowadays, it is important to preserve the moisture content of the soil which can be executed with cultivator tools. The objective of this study was the investigation of the energetic and working quality characteristics of sweep tools by soil bin experiments conducted in laboratory conditions and the simultaneous development of a discrete element model (DEM) validated by comparing the measured and the simulated values of draught forces. Three sweeps were analyzed differing in aspects of shape and size; the tool widths were 100, 230 and 300 mm, respectively. Experiments were conducted in the NARIC Institute of Agricultural Engineering soil bin facility filled with sandy soil with volumetric moisture content of 2% and 15%, at three different working speeds (0.5, 1, 2 m/s) at the working depth of 0.15 m. The improved DEM model contain a soil model consisting of discrete particles created within the Yade software and 3D laser scanned model of the sweep tools. Inserting the analyzed tool geometry into the simulation made it possible to investigate the characteristics of the tillage tools and also the effect of the different geometries appearing in the soil cutting forces. The investigation of the effect of the shape of the particles on the energy dissipation and studying the differences between the validated frictional and the cohesive soil models based on the soil bin test were the aim within this study.

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INTRODUCTION

Agriculture is an important part of our daily life and supplies food to the world's population. Therefore, appropriate soil conditions must be ensured for the crops grown. In order to increase productivity, there are several possibilities to influence the processes in the soil using different mechanical methods. One of the appropriate tools for this is the sweep tool that does not mix the soil, so the moisture content in the affected soil layer is not exposed to the surface and the soil does not dry out. This is especially important, because the aim of the loosening process with a sweep tool is the seedbed preparation, cutting plants' roots beside the reduction of moisture loss of the cultivated soil.

The development of computer technology put thorough investigation of soil-tool interaction within reach and made it possible to study certain areas of soil mechanics and analyze results which are difficult to achieve in experiments or solely with analytical methods, considering the complexity of the matter. Among the numerical methods, the FEM (finite element method) spread initially: both two- and three-dimensional models were developed. As the computing capacity increased, the calculation time was reduced, enabling the appearance of more complex numerical simulations such as the CFD (computational fluid dynamics), which is a proper technique to investigate the soil movement from a flow point perspective and the SPH (smooth particle hydrodynamics) method, which is suitable to analyze the soil loosening processes (Urbán et al. 2012; Zachár et al. 2016).

Nevertheless, it is difficult to use the FEM or the aforementioned other methods when researchers encounter problems in which the discrete nature of the particles of the material is crucial. In the case of these problematic areas, where the discrete nature of the granulated material is key, the DEM (discrete element method) can be a proper technique to use (Bagi 2007; Tamás 2016).

Initially, researchers mainly investigated the behavior of spherical particles, although in reality granular particles are generally non-spherical, therefore the utilization of particles with a more complex shape was needed. The internal structure of the granular material is transformed by the particles rolling down and interlocking, and thus the behavior of the set is greatly influenced by the shape of the particles, which can also be considered as an input parameter to be calibrated. Researchers also use ellipsoids, polyhedrons and clumps as particles. The shape of the material particles is responsible for the extent of the energy dissipation in the material set, so the examination of the effect of the particle shape has also played an important role in this research.

The previous models of soil-tool interaction mostly presumed friction in the soil, but because of its moisture content the soil also shows a cohesive behavior. By increasing the moisture content, the draught force is also increasing, so the introduction of cohesive models was necessary. The focus of this study was the examination of the soil-tool interaction: the main aim was to create a three dimensional DEM model simultaneously with the execution of a laboratory soil bin experiment. An another aim was to carry out the calibration process of the DEM model that was created, with particular emphasis on finding the most appropriate particle shape regarding its effect on the extent of energy dissipation of the interaction. The additional objective was to improve the micromechanical parameter set used in the DEM model of soil-sweep tool interaction by comparing laboratory and simulation results with the use of relative error method.

THE SOIL BIN TEST

In order to create a DEM model, in the first step soil bin study was conducted (Figure 1). The measurements were carried out in the soil bin facility of NARIC Institute of Agricultural Engineering, Gödöllő, Hungary. The laboratory soil bin was filled with sandy soil with the following content: 93% of sand, 4.66% of silt and 2.06% of clay. The dry bulk density was calculated by the results of a previously conducted oedometer test, and was determined as 1424.12 kg/m^3. For the investigation of soil-tool interaction three different sweep geometry were used with the tool width (W) of 100, 230 and 300 mm, respectively, henceforward referring to them as small, medium and large sweep tools (Gürsoy et al. 2017). The experiment focused on the relation between draught force and working speed. Three different working speeds were used, in average 0.5, 1, 2 m/s. The soil bin study was made at the tool's working depth of 0.15 m.

a,

b,

Figure 1: The soil bin of the NARIC Institute of Agricultural Engineering a) the sweep tool in the soil and b) the soil loosening process

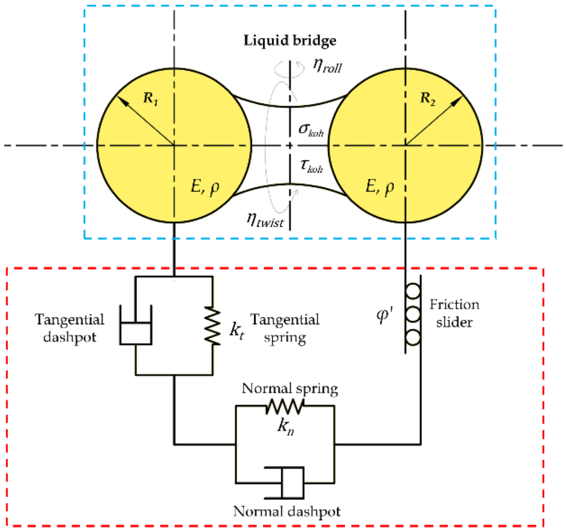

Figure 2: The friction and the cohesion connection in the utilized CohFrictMat contact model (Bourrier et al. 2013, Horváth 2017)

Primarily the relation between draught force and working speed was analyzed. Also another aim of this measurement was to study soil particles' displacements in a vertical direction, and the effect of soil moisture content.

Following the proper preparation of the sandy soil, the penetration resistance and volumetric moisture content measurements were conducted. In

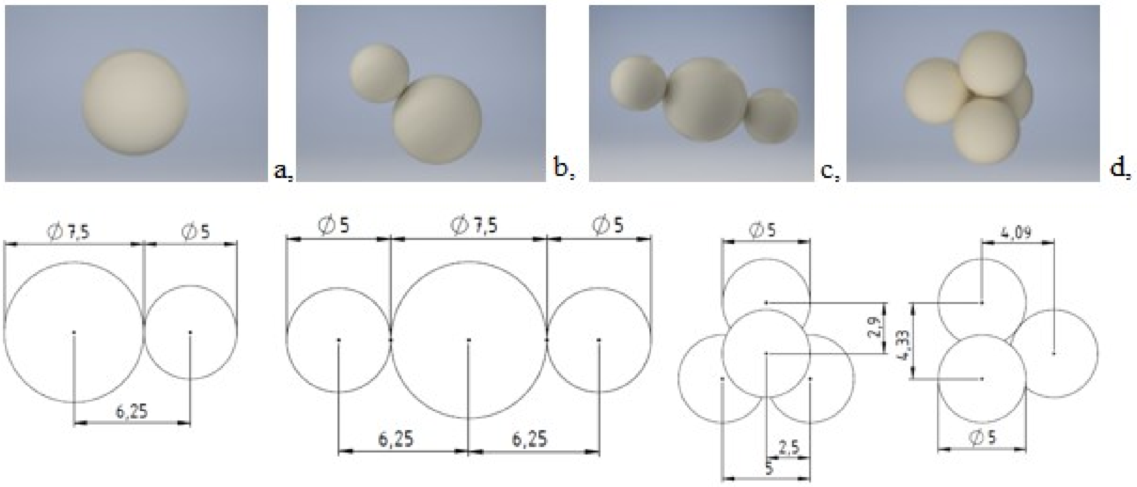

Figure 3: The created and used clumps in the model a) sphere, b) clump made of 2 spheres, c) clump made of 3 spheres, d) clump made of 4 spheres

case of dry soil, the volumetric moisture content of 2% was observed, and in case of wet soil a value of 15% was measured.

In the case of the dry sandy soil, vertical penetration resistance was about 1.12 MPa, and in wet sandy soil it fluctuated around 0.72 MPa. The initial soil profile was then recorded.

Along the measuring section the draught force was monitored, the time required to take the measuring section and the working speed. The sweep, with a rigid tine, was mounted with supports to the tool's draught force with calibrated strain gauges.

The soil profiles formed after the measurements were also recorded using a laser scanner. These were suitable for comparison with the initial soil profile to conclude how the analyzed tool geometries differ in lifting and mixing the soil at a given speed and how far the ground is lifted vertically by them. As the soil particles can only move upwards during the loosening process influenced by sweep tools, therefore a volume increase can be observed in the cultivated layer of the soil.

GENERAL INFORMATION OF DEM MODELING

For developing the DEM model, the Yade open-source software (Šmilauer et al. 2015) was used, in which several different contact models were available regarding the mechanical relation between discrete particles, including FrictMat (frictional) and CohFrictMat (frictional and cohesive) models (Figure 2).

The applied software performs a collision detection to analyze the interactions between the particles involved in the simulation and uses timestep, after which all particles can change their mutual positions. As a first step of the process, the software sets the forces to default, then updates the bindings. After that detects the impact and then calculate the forces based on the displacements. Then speed and position of particles are updated. Running various motors, recording data, and increasing the time step are the following steps.

Geometrical model of soil particles

Within the Yade software, the particles created in this study are so called clumps, composed of spheres (Figure 3). They are connected to one another and form an independent, discrete, perfectly rigid unit.

Also the clumps forming the set are rigid bodies and can't suffer deformations. In the simulations, different set of particles were examined handling them as input parameters (Coetzee 2016). These different particle shapes (clumps) can be seen on Figure 3. There were several preliminary simulations where the appropriate set of particle

Figure 4: a) The scanning process with the NextEngine 3D Laser Scanner, b) the geometry of the sweeps with different width (W) used in the soil bin experiment (large-W:100mm, medium-W:230mm, small-W:100mm)

assembly for energy dissipation were studied. The particle assembly used in the final soil model was consisting of the following ratio of the given clumps: b: 5%; c: 90%; d is 5% see on Figure 3. Clump particles were designed previously, as a template but the particle assembly was generated in two steps. In the first step the assembly was created with the use of spherical particles in uniform distribution with radius of 20-24 mm. Then in the next step these particles were transformed to clumps with the use of the template data. Therefore, the result of these clump generation process was the clump assembly, where the volume of the clumps were the same as the spheres were generated previously. Finally, the spheres' radius of the prepared clumps were between 10.88-19.26 mm. The particle density was set as 2600 kg/m^3. The density was homogeneous within the clumps. The particle assembly (as the model of soil) was settled with the utilization of the local damping of 0.8 for faster sedimentation. The settling process was finished when the unbalanced force was lower than 0.001. This local damp was set as zero in the soil-sweep simulations later where the CohFrictMat contact model was utilized.

Geometrical models of sweep tools

The sweeps were scanned using a 3D laser scanner in the Virtual Laboratory of Budapest University of Technology and Economics, Department of Machine and Product Design with the utilization of NextEngine 3D Laser Scanner (Figure 4) to create a simulation environment that is as close as possible to reality (Figure 5).

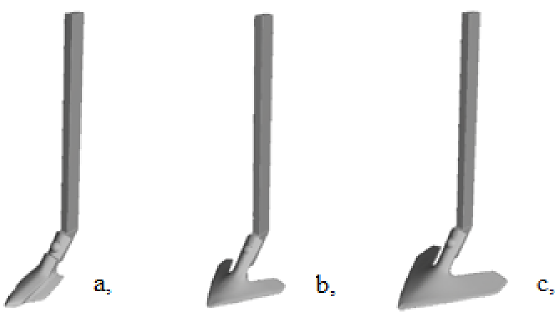

Figure 5: The final geometry of the tools used in the simulations a) small-sweep tool (W:100 mm) b) medium-sweep tool (W:230 mm) c) large-sweep tool (W:300 mm) W=Width

The shape of the cracks in the soil is partly influenced by the tool geometry, so it is important to insert into the simulations the realistic shape of the sweeps used in the measurements. To easily insert the tool geometries into the simulations, the scanned files were previously edited with Autodesk Meshmixer (2017) and the holes in the mesh were filled and the triangle count was reduced than exported as STereoLitography (STL) file format.

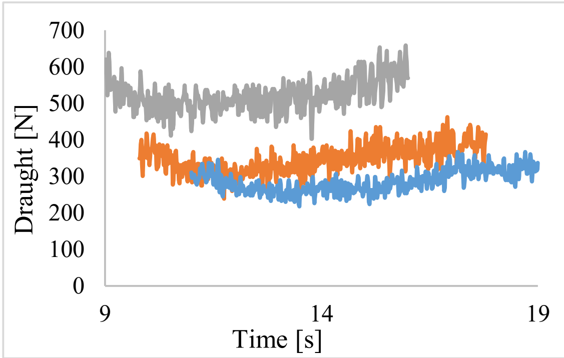

Figure 6: Comparison of the different tool geometries, at moisture content of 2% and speed of 2 m/s grey/upper curves – large sweep tool, orange/middle curves – medium sweep tool, blue/lower curves – small sweep tool

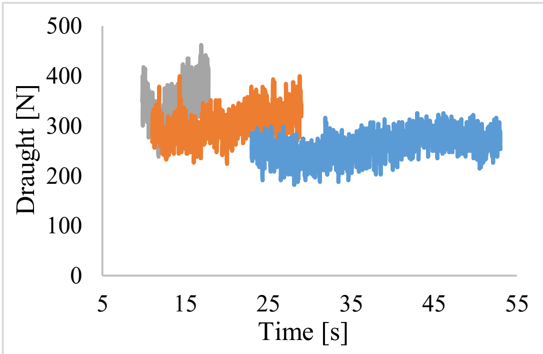

Figure 7: Comparison of different speeds, in moisture content of 2% with the medium sweep tool grey/upper curves – 2 m/s, orange/middle curves – 1 m/s, blue/lower curves – 0.5 m/s

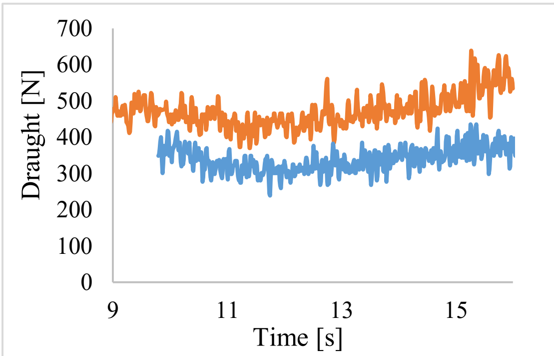

Figure 8: Comparison of different moisture contents at speed of 2 m/s with the medium sweep tool orange/upper curves – moisture content of 15%, blue/lower curves – moisture content of 2%

The scanned files were completed with the shank (Figure 5) was created by Dassault Systems Solidworks (2014) software. The sweep models were applied at 0.15 m working depth under the surface of the particle assembly.

RESULTS OF THE SOIL BIN TEST

The sweep tool creates a compaction, deformation zone in the soil and surface lifting during the soil cutting, and the resistance of the sweep tool is periodically variable at each breaking surface, the cutting resistance decreases dramatically, and after the subsequent compaction work, it starts to grow again. This is also illustrated by the diagrams showing the measurement results the draught forces fluctuate around a mean value (Tamás 2018).

Comparing the sweep tool geometries, at the same moisture content, the large sweep had the highest required draught force, followed by the medium sweep, while in case of the small sweep the smallest draught forces were measured on average (Figure 6). This was expected, given the size of the sweep's contact surfaces with the soil. Increasing the working speed (Figure 7) of the sweep tool increases the amount of energy transferred to the soil and thus the draught force, which determines how much force is needed to move the sweep horizontally in the soil in the given conditions. The draught force was higher at moisture content of 15%, than 2% (Figure 8) independent of the sweeps' widths.

The soil profiles were recorded at speed of 2 m/s. When the 2% moisture content in dry soil condition was measured the draught force and the surface vertical lifting were lower (Figure 9) than in moisture content of 15% (Figure 10), where the cohesion was higher and was effected by the liquid bridges between soil particles. When comparing the effect of the three different sweep tool geometry on profiles, it can be made the conclusion that the width of the deformation zone was the largest in the case of the large sweep and the smallest in the case of the small sweep (Figures 9-10). While examining the resulted soil profiles after the tillage process, it can be concluded that in case of wet soil the traces of the compacting tool is better preserved in the soil surface.

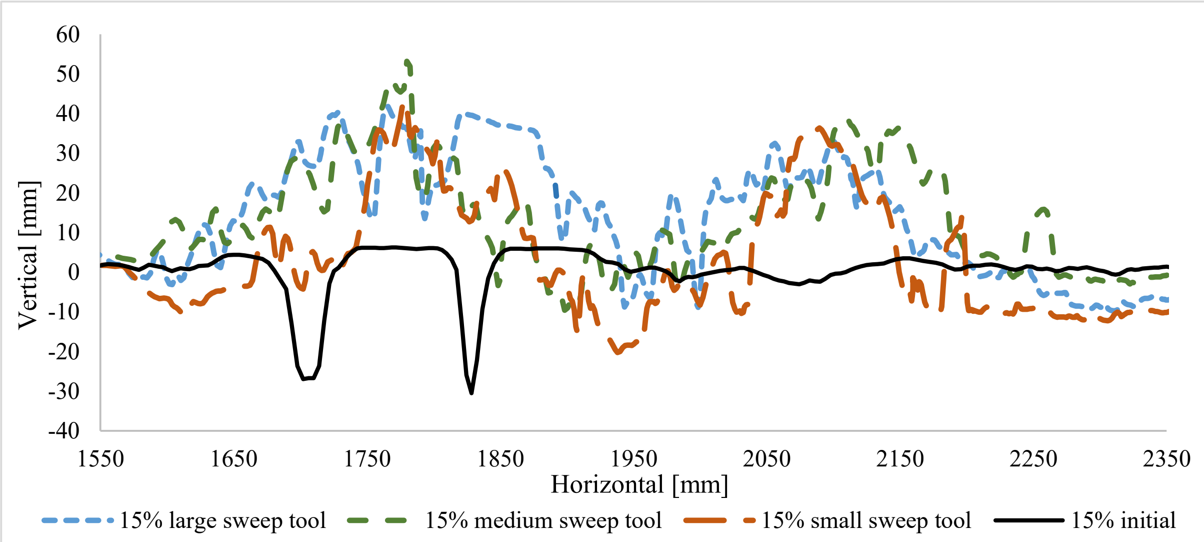

Figure 9: Soil profiles at the moisture content of 2%

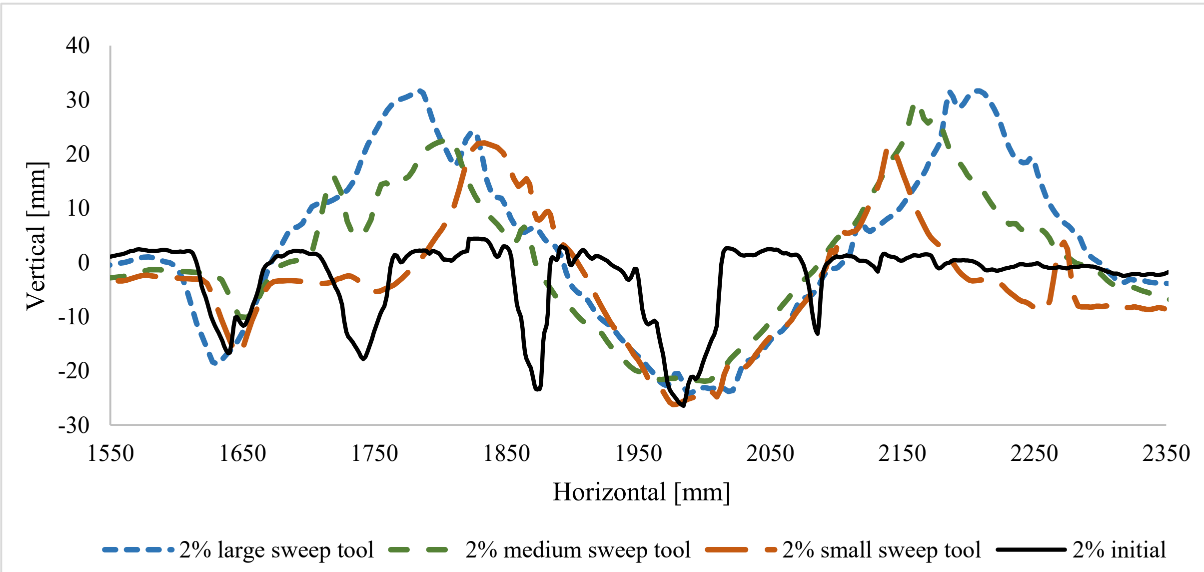

Figure 10: Soil profiles at the moisture content of 15%

RESULTS OF THE DEM SIMULATIONS

In the simulation model, the length of the soil bin was 2 m, its width and height were both 1 m. The validated parameter set, which were based on the experiences of the preliminary simulations and used during the validation process are summarized in Table 1.

Table 1: The utilized parameter set in DEM model

Parameter	Value
Young's modulus [Pa]	$2*10^5$
Rolling friction(etaroll)	0.001
Poisson ratio	0.4
Friction angle [°]	30
Density [Kg/m^3]	2600
Cohesion in normal direction (σ) [Pa]	$2*10^3$
Cohesion in shear direction (τ) [Pa]	$1*10^3$
Number of elements	20 000
Local damping	0.0
Timestep [s]	0.1*PWaveTimeStep()

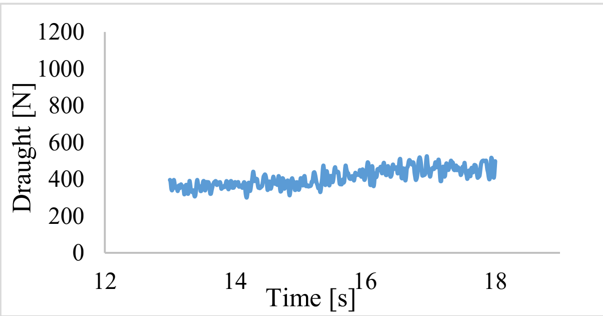

Figure 11: The measured draught forces with the medium tool at working speed of 2 m/s, at moisture content of 2%

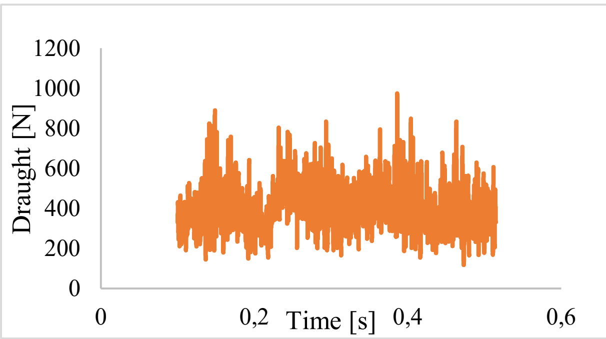

Figure 12: The simulated draught forces with the medium tool at working speed of 2 m/s, in the friction model

The applicability of the DEM model to the estimation of the draught force of the different sweep tools was validated by comparing the results of the soil bin experiments and the simulations (Figures 11-14). The resulting deviation of the draught force was

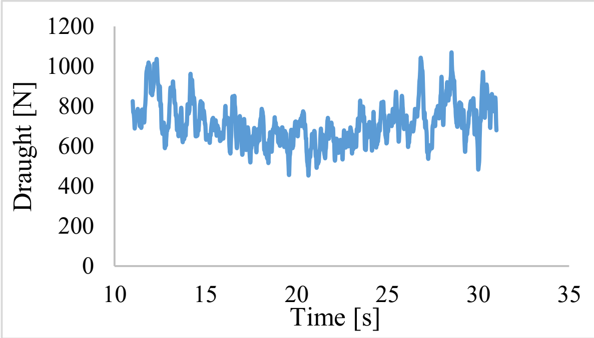

Figure 13: The measured draught forces with the medium tool at working speed of 2 m/s, at moisture content of 15%

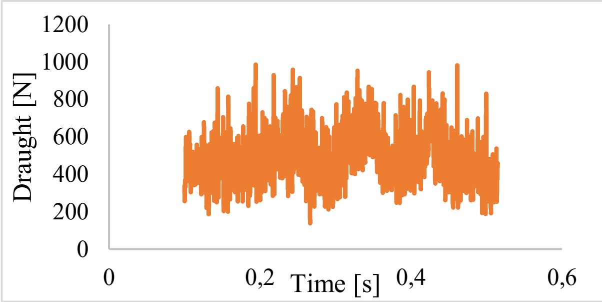

Figure 14: The simulated draught forces with the medium tool at working speed of 2 m/s, in the cohesion model

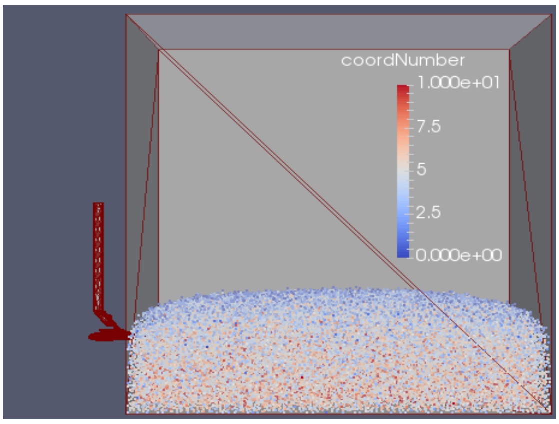

Figure 15: The soil domain in the improved DEM model of soil-sweep interaction. Working depth: 0.15 m. (The colour of particles indicates the coordination number.)

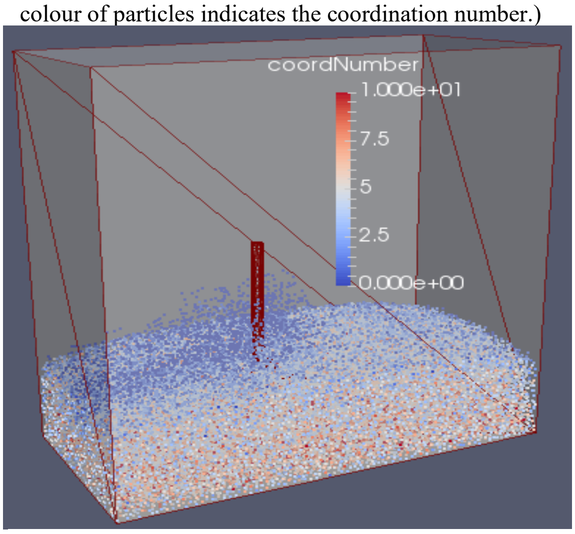

Figure 16: The simulation of the DEM model of soil-sweep interaction. (The colour of particles indicates the coordination number.)

large compared to the measured values, but the trend of the graphs was comparable (Figures 11-14).

Comparison of laboratory measurements and simulation results with the aim of validating the DEM model was carried out with the utilization of the method of the relative error between the measured and the simulated values (Figures 17-18).

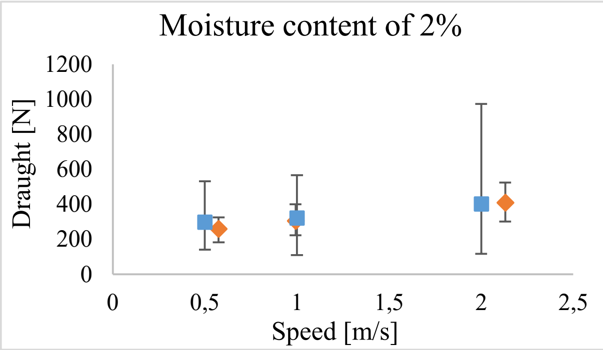

Figure 17: The measured ◆ and simulated ■ draught forces and their standard deviation with the medium tool at the moisture content of 2 %

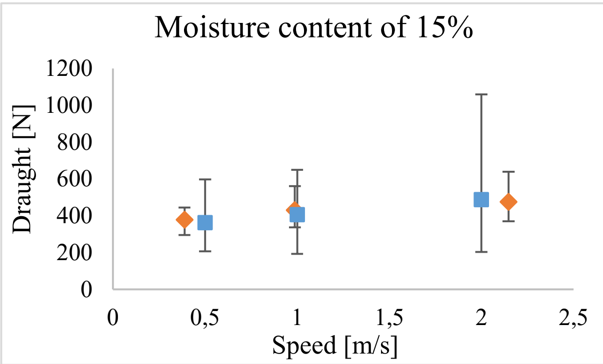

Figure 18: The measured ◆ and simulated ■ draught forces and their standard deviation with the medium tool at the moisture content of 15 %

The relative error was determined by the following formula:

$$RE = \frac{100}{n} \sum \left| \frac{S-M}{M} \right| \quad (1)$$

where RE: relative error [%], n: number of data, S: simulated value, M: measured value.

Table 2: Relative errors of sweep tools (negative sign indicates the underestimation)

Speed [m/s]	0.5	1	2
Small sweep tool			
		Friction	
Relative error [%]	*17.52*	*4.23*	*15.92*
		Cohesion	
Relative error [%]	*5.25*	*-2.70*	*7.36*
Medium sweep tool			
		Friction	
Relative error [%]	*14.30*	*5.82*	*-1.73*
		Cohesion	
Relative error [%]	*-3.82*	*-5.82*	*2.47*
Large sweep tool			
		Friction	
Relative error [%]	*-1.75*	*-5.49*	*-2.84*
		Cohesion	
Relative error [%]	*-24.65*	*-28.82*	*-24.59*

Based on the calculated relative errors (Table 2.), it can be concluded that the CohFrictMat model overestimated the draught force results of the measurements conducted in case of wet sandy soil regarding the small and medium sweeps, while underestimation occurred in case of the large sweep. The solutions to reduce the draught force overestimation at the utilization of lower tool's surface area and the underestimation at higher tool's surface area could be the inaccurate parameter set of bonds, or inaccurate shape of the utilized clumps.

Since the calibration process was performed on a medium sweep with a working speed of 2 m/s, the lowest relative error value was also achieved at this setting (RE=1.73%). Concerning the small sweep, the simulations with the cohesion model resulted in minor differences, and in regard to the large sweep, simulations with the friction model were the most effective. In further tasks, parameter sensitivity studies shall be made for reducing the effect of the size of the utilized clumps on the fluctuation of draught forces. Thus, research should be done in qualitative aspect where the bonds' effects on the occurrence of fractures resulted by micro cracks in the assembly have to be investigated, where the micro crack means the bond breakage. Moreover, an accurate further study need, where the displaced and redistributed soil profiles are investigated to verify the appropriate displacement in the particle assembly.

CONCLUSIONS

A DEM model was developed in this research, which is suitable to utilize of the optimization of the geometry of sweep tools used in tillage. In the developed soil-sweep DEM model it could be taken into account the soil's moisture content the particles' shape, the tool's geometry, and working speed, as well in the given working depth. Adequate input parameters were also selected and verified. However further development of the model is necessary by further examination of the effect of the Young's modulus settings or more appropriate clumps' geometry and size could be a way to improve the model. Therefore, better approximation of the actual draught forces could be realized with the applying of the simulation method. In addition, the aim of future research can also be to modelling the plant residues and roots in the improved soil model beside the particles' angular shape.

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