EVALUATING THE STRESS FIELD ON SWEEP DURING TILLAGE PROCESS APPLYING COUPLED FINITE–DISCRETE ELEMENT METHOD

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ABSTRACT

Agricultural production is based on proper tillage, where different types of cultivators are often used. The sweep is often applied among the several cultivator designs. The traditional design procedure of these tools is based on producing several prototypes and inspecting them during cost-demanding laboratory and field measurements. However, it is possible to reduce the number of necessary prototypes by utilizing numerical analyses.
Static yield and fatigue are possible mechanical failure modes of the sweep. By utilizing a one-way coupled finite-discrete element simulation method, it becomes possible to find the stress concentration areas during the linear motion of the tool in soil, which can cause the failures.
The geometry of a sweep was 3D scanned to get an accurate 3D surface model. The reaction forces between the soil and the sweep were calculated by the application of discrete element method (DEM) and the stress field was computed with the use of finite element method (FEM). The stress field was also estimated by assuming a homogenous distributed reaction force. The paper discusses the difference between the results of the two reaction force computing methods and the influence of using the coupled simulation.

INTRODUCTION

One of the principal influencing factors of agricultural productivity is the proper preparation of the soil, which is mainly performed by tillage machines. They plant seeds, destroy weeds, dig, overturn, loosen, aerate the top layer of the soil and compact its surface if needed. A modern tillage machine is usually composed of two components: the power and traction source (the tractor) and the appliance. The appliances are changeable and have several types of designs to be able to perform their specific task. They also have two main parts: the support frame and the tools, which interact with the soil. There are certain types of agricultural appliances, the cultivators, which stir and pulverize the soil and one of them is the *sweep* (or duck foot cultivator), a widely applied tool design.
The traditional way of design is based on analytical assumptions, experiences and measurements. After planning concepts, the manufacturers produce several prototypes for development purposes, then the various shapes and materials are tested in laboratory and in field measurements. The drawbacks of this method are the high costs and the length of the design time. However, these can be reduced with the application of numerical simulations. One of the most widespread numerical methods in engineering is the finite element methods (FEM) which is mainly applicable to model continua.
When the exact load distribution is unknown, FEM calculations often use assumptions, which leads to less accurate results. However, they can still give enough information for design purposes many times, as, according to Saint-Venant's Principle, the difference between two different, but statically equivalent loads become very small at sufficiently large distances from load. A typical case when the forces are hard to determine is, when the tool of the machines interact with granular materials, such as the soil-sweep interaction.
The discrete element method (DEM) is a developing numerical method, which excellently models discontinua. It is also able to compute the arising forces on tools. If the load values from the DEM simulation are used as input data, instead of the approximate forces, more accurate results can be obtained in the FEM simulations. For example, in our case, the stresses can be calculated accurately not only in the frame, but near the surface of the sweep as well. Hence, DEM was utilized in our study to model the mechanical behaviour of soil to compute the force distribution on the sweep precisely during its motion in soil. The forces were imported from the DEM simulation into the FEM simulation by a formerly developed one-way connection technique (Orosz et al. 2018). In comparison with the assumptional method, where the draft force would be dispersed on the surface of the sweep.

MATERIALS AND METHODS

As the parametric 3D model of the sweep was not available for us, we used reverse engineering methods to digitize its geometry. The body of the sweep was firstly

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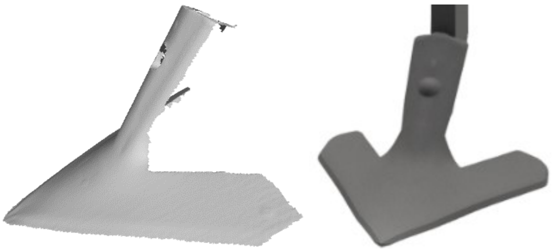
3D scanned, then was refined in more different computer aided design (CAD) software to produce suitable inputs for the DEM and FEM software.

Geometry

As the first step, the body of the sweep was 3D scanned by the application of NextEngine Laser Scanner, which resulted a triangular surface mesh in *stl* format. This raw mesh was processed improved with Autodesk Meshmixer. The DEM software requires an *stl* file, however, the FEM modelling was more effective by giving a parametric solid body as an input. Therefore, a solid body was created for the FEM program with the utilization of the Autodesk Inventor software. Furthermore, a support rod was added with a rivet, as it was not missing from the scan data. Figure 1 shows the difference between the raw scan data (a) and the processed and re-modelled solid geometry (b).



a) b)

Figure 1: Raw 3D Scan of The Sweep (a) and the 3D Solid Model (b)

To be able to import the edited geometry into the DEM simulations, the solid geometry was converted back to *stl* format. The result mesh was further optimized by MeshLab software to save computational time in the DEM simulation. The result is show on Figure 2.

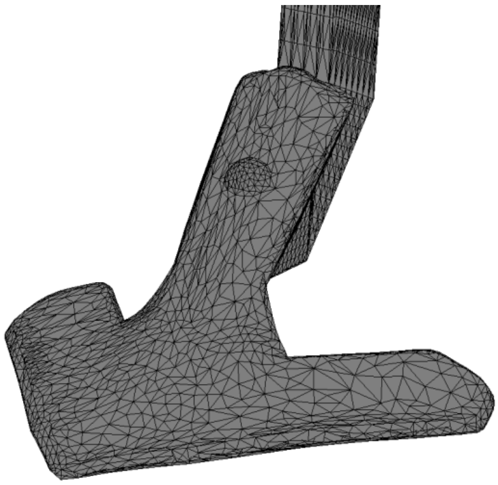


Figure 2: Optimized Surface Model of the Sweep Made from the Solid Model

Discrete element model

The discrete element method is a numerical technique, which is appropriate to model soils and the soil-tool interaction. The basics of DEM modelling were defined by Cundall and Strack (1979), and were improved by many other researchers. The method simulates materials with an assembly of particles, which have independent kinematical degrees of freedom. Interactions can arise and cease between these elements (Bagi 2007). The possible shapes of elements are various as well as the definition of interaction forces.

For developing the DEM model, the Yade open-source software (Šmilauer et al. (2015)) was used in our study, in which several different interaction models are available regarding the micromechanical relation between discrete particles. The software applies Newton’s and Euler’s law of motions with the central differences explicit time integration scheme. In this research, the so-called *CohFrictMat*, model (Šmilauer et al. (2015)) was used for soil, which involves normal and shear force, friction and cohesion between particles. The cohesion micro-parameter was used to model the mechanical effect of moisture content of the soil. For the sweep *FrictMat* model was used, which is similar to *CohFrictMat*, but has no cohesion. The applied micromechanical parameters, which were calibrated using soil bin tests, are listed in Table 1.

Table 1: Micromechanical Properties of DEM Simulation

	Soil	Sweep	Unit
Micro-Young	$5{\cdot}10^6$	$1{\cdot}10^{12}$	N/m^2
Poisson	0,4	0,3	-
Density	2600	7850	kg/m^3
Inter-particle friction angle	30	30	°
Normal cohesion	$1{,}76{\cdot}10^5$	-	Pa
Shear cohesion	$0{,}88{\cdot}10^5$	-	Pa
Rolling resistance	0,6	-	-
Twisting resistance	0,6	-	-

Instead of the simple spheres, so-called clumps were used in this study. They are composed of spheres, connected to one another and form an independent, discrete, perfectly rigid unit. The density was homogeneous within the clumps. To find the proper particle shape, several preliminary simulations were run, where the appropriate set of particle assembly for energy dissipation were studied. The results of these simulations were presented in a previous study (Tamás et al. 2018). The created model was calibrated with a previously conducted soil bin test, which was presented in detail in our previous work.

In this study, the application of relatively small particle size was an aim in order to get accurate forces on the surface of the sweep tool geometry, which were later exported to the FEM simulation. The length and the width of the modelled soil bin were 0.6 m, based on the work of Milkevych et al. (2018). It had to be filled with particles up to the height of 0.25 m., To accomplish this, firstly a loose pack of particles were generated with the desired shape and size distribution, then they fell freely under the influence of gravity. The unnecessary particles were deleted after the settling process. The spheres' radii of the prepared clumps were between 2.72-4.82 mm, and the soil bin contained about 100 000 particles.

The geometry of the sweep and the soil bin were modelled by triangular surface elements (facets). These particles have no width, mass and inertia and are defined by the position of their three vertices. However, they can interact with clumps and record the arising forces on them. The facets of the sweep were directly specified by the imported *stl* file. The sweep moved with a prescribed constant velocity during the simulation, and the arising forces on every facet were exported sequentially in text files with a specific format. The average of the sweep forces was also computed between the adequate sweep positions, when it was fully immersed in the soil. The draft force was also computed by the summarization of adequate components of facet-forces. The DEM simulation is shown in Figure 3.

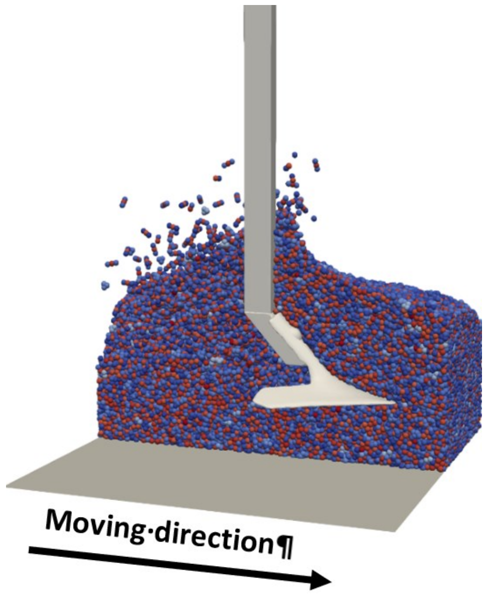


Figure 3: The Simulation of the DEM Model of Soil-Sweep Interaction. (the Particles are Coloured Randomly)

Finite element model

Finite element method (FEM) (Zienkiewicz 1971) is a numerical method, which discretizes differential equations in space. It is mainly used to model continuum materials. The typical problem areas are structural analysis, heat transfer, fluid flow and electrodynamic processes.

FEM also models materials with limited number of elements like the DEM, however, the mechanical degrees of freedom of FEM elements are not independent: they are defined by common nodes and form a 1, 2 or 3-dimensional mesh

This feature makes DEM more suitable to describe bulk materials, and FEM to model continua.

The FEM simulation was performed in the static structural module of ANSYS Workbench 19.2 Student Edition. As the strains were relatively small and the material of the sweep was steel, linear material model and solver was utilized.

The geometry was cut into four separate bodies to make meshing and boundary condition definition easier (Figure 4): first is the sweep tool, the other three are the different segments of the support rod. The sweep is modelled with quadratic tetrahedron elements and the rod segments are made up of quadratic hexahedron (brick) elements. In reality, the middle rod segment is fixed to the other parts of the tillage machine. For that reason, the displacements and rotations of nodes on the surface of the middle rod segment were fixed in all dimensions. Between the rod and the sweep, a bonded type contact connection was used.

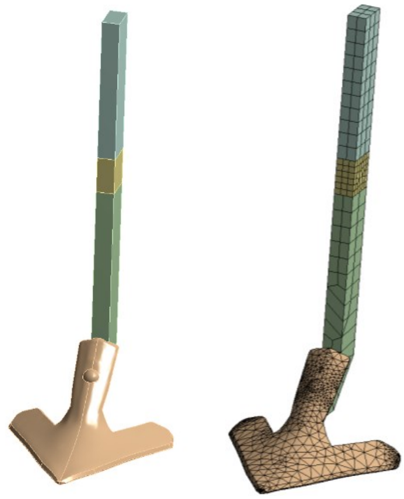


Figure 4: The Part with the 4 Bodies

The external forces were imported from the DEM simulation via a text file and were mapped to the surface of the sweep tool. The material properties are shown on Table 2. During the simulations, the von Mises equivalent stresses and the deformations have been computed.

Table 2: Material Properties of the Sweep in FEM Simulation

Density	7850 kg/m^3
Young's Modulus	200 000 MPa
Poisson	0,3

RESULTS

Figure 5 shows the draft force on the sweep as a function of its displacement. Initially (at 0 m displacement), the tip of the sweep only touches the side of the soil bin, so the force is zero. After the beginning of the simulation, the sweep starts to penetrate the soil and the draft force starts to raise. The tool is 250 mm long in the moving direction, from which the support rod takes 45 mm. Therefore, at slightly after 0.2 m displacement, the growth of the force stops. At the displacement of 0,25 m, the sweep completely penetrates the soil. At 0,6 m displacement, it starts to leave the soil, until 0,85 m, when its entire body escapes. Because of that, the force is expected to remain constant form 0,25 m until 0,6 m, then reach zero at 0,85 m after a mellow decrease.
However, Figure 5 shows a difference: at about 0,5 m, the force starts to raise drastically and drops suddenly to zero slightly after 0,8 m. This phenomenon is caused by the jamming of soil particles between the sweep and the wall of the soil bin, when the sweep approaches the end of the box. This just happens in the simulation and does not occur in real working conditions.

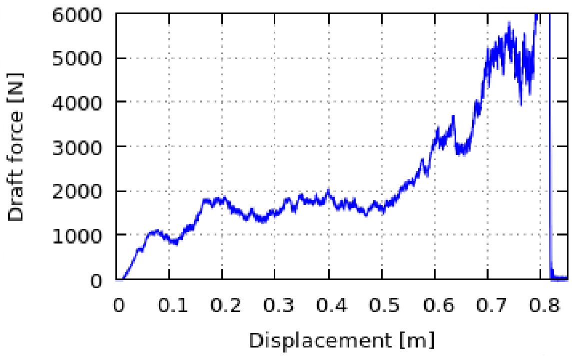


Figure 5: Draft Force as a Function of Displacement

The FEM simulations were made with the same sweep geometry, material definition, and boundary condition. The difference between them is the time, when the loads were exported from the DEM simulation. In the first case (Figure 6), only the tip of the sweep penetrates the soil, and the tool displacement is 0,05 m in the DEM model. The loads are imported from a text file. The maximum von Mises equivalent stress was 104 MPa at the middle of the sweep. The total deformation was 0,99 mm at the tip of the sweep.

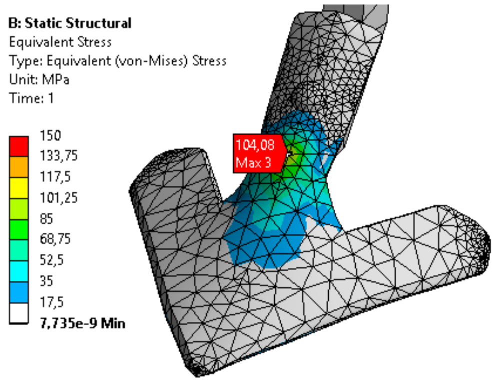


Figure 6: Von Mises Stress on the Sweep at the Displacement of 0,05 m (momentary DEM forces)

In the second case, at 0,4 m displacement, the entire body of the sweep is moving in the soil. The displacements on the sweep are visible at the Figure 7. The total deformation was 1,65 mm at the tip of the sweep.

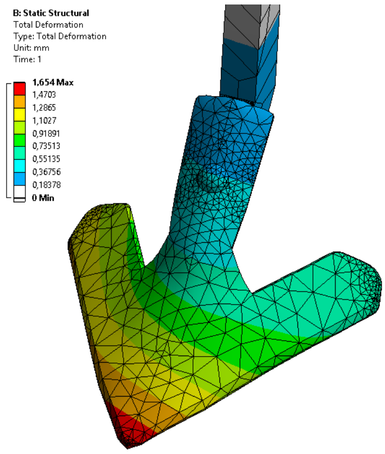


Figure 7: Displacements on the sweep, at the DEM displacements of 0,4 m

The peak von Mises equivalent stress was also at the middle of the sweep, in the indicated area, (Figure 8) and its value was 158 MPa, which was definitely higher, than in the former case.

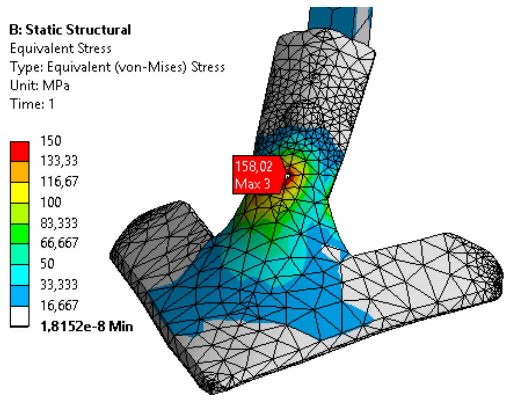


Figure 8: Von Mises Stress on the Sweep at the Displacement of 0,4 m (momentary DEM forces)

In the third FEM simulation case (Figure 9) the assumption method and our coupled method were compared. In this case, the whole sweep is inside the material in the DEM simulation. The draft force was computed by the DEM simulation and had a magnitude of 1700 N. This force was homogenously distributed on the surface. The peak equivalent stress was on the same area, with the value of 126 MPa. The total deformation was 1,45 mm at the tip of the sweep.

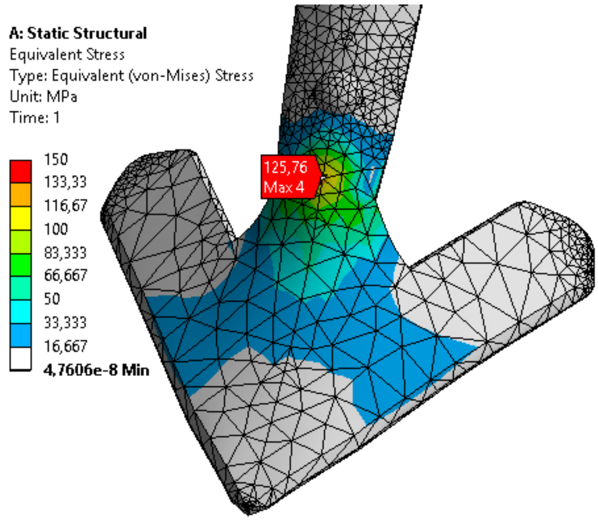


Figure 9: Von Mises Stress on the Sweep at the Average DEM forces (Uniformly Distributed Draft Force)

In the Figure 10, the results of the new method are visible. The case is the same as on the Figure 9, the difference between them is that in this case the load is not a uniformly distributed force, they are imported from the DEM simulation. The peak von Mises equivalent stress was at the same spot, with the value of 118 MPa. The total deformation was 1,23 mm in the tip of the sweep.

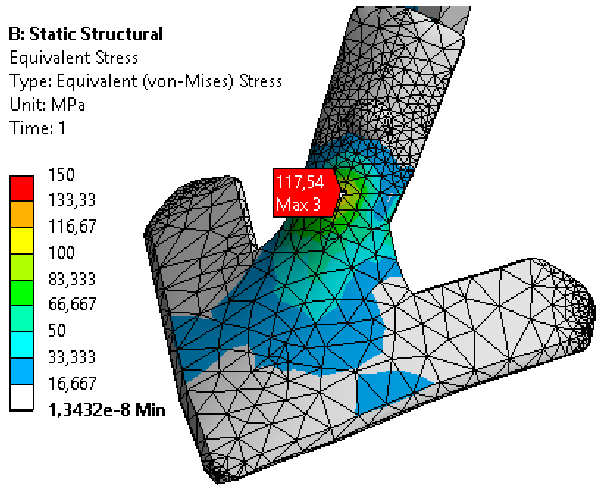


Figure 10: Von Mises Stress at the Average DEM Forces (Averaged DEM Forces)

The von Mises equivalent stress values of all simulations can be seen in Figure 11. The results are the most accurate between 0,25 and 0,5 m sweep positions, as before 0,25 m, the sweep is not completely penetrating the soil. On the other hand, after 0,5 m, the stress suddenly increases as the jamming of particles occur between the rod and the wall of the soil bin. It is clearly visible, that the stresses, which uses momentary DEM forces are higher in most cases than the assumption method, where the results computed with the aid of draft forces.

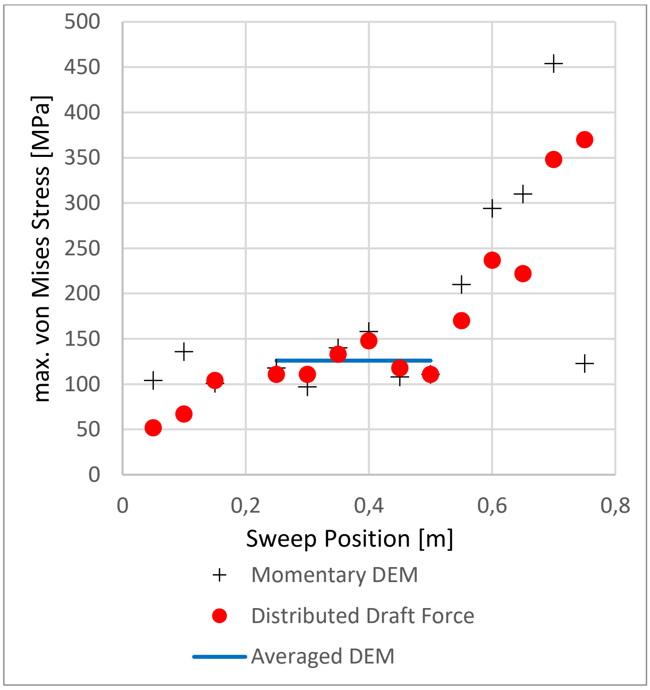


Figure 11: von Mises Stresses as a Function of Sweep Positions

SUMMARY AND CONCLUSIONS

In our study, three force distribution definition methods were compared in the case of FEM simulation of stresses of a sweep during its linear motion in soil. The first one was based on the draft force and used an assumption: it was distributed homogenously on the surface of the tool. The other two applied DEM simulations to compute the arising forces on the segments of the sweep surface model: momentary and time-averaged values were exported. Compared to the assumption method, the stress field was almost identical in case of averaged DEM forces, but was higher when applying momentary loads. This leads to the conclusions, that in case of FEM simulation of a tool that interacts with a granular material:

- If a proper assumption is made regarding the force distribution on a tool, it can evaluate the average stresses
- Averaged forces from DEM simulations are also can be used to compute average stress distribution and to validate the force assumptions
- Importing momentary forces from DEM simulations are able to compute momentary peak stresses in the tool

The results prove the importance and benefits of coupled FEM-DEM simulations.
The method has the opportunities for further development. The abrasive wear was not taken into consideration in this research, in the future, we should pay attention to this failure form, as it is a common failure.
The connection was a one-way connection which is accurate enough in case of small displacements. But for large displacements, a two-way connection is required between FEM and DEM simulations.

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