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DEM modelling of tillage tools in sand and verification of draft forces in the soil box

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Abstract. Soil resistance is still being important parameter during tillage. By reducing the soil resistance during processing, greater efficiency and cost reduction can be achieved. With the correct design of the shape of the tillage tools, reduction in the force required for tillage can be achieved. New tool designs must be tested in field conditions to determine the effect. Using DEM (Discrete element method) modelling, individual designs can be compared without the need for field tests. However, the accuracy of the model must first be verified on real tests. The paper deals with the creation of a mathematical model of sand, which is used for testing tillage tools in the soil box. The models are focused on tests of various shapes of wings on tillage tools. Draft forces are compared, and the correctness of the model is verified.

Key words: DEM, modelling, tillage tools, soil box, draft force.

INTRODUCTION

The construction of the usable mathematical model of bulk material depends on the correct setting and use of the correct method. The basic models can be divided into models without adhesive forces (Cundall & Strack, 1979; Walton, 1993), that correspond to materials without significant moisture (seed, sand, etc.) and into models with adhesive forces (Pasha et al., 2013; Pasha et al., 2014) that correspond to materials such as soil, wet sand, etc.

In agriculture, these materials can be modelled using the DEM method (Ucgul et al., 2014). This method is suitable for materials such as agricultural crops (Boac et al., 2014; Kanakabandi & Goswami, 2019) or for sand and soil (Shmulevich et al., 2007; Milkevych et al., 2018; Ucgul et al., 2018). These models usually do not respect the diversity of the soil environment and are limited to a maximum of two different types according to the simulation. The solution is usually performed in an EDEM environment. Using the model, it is possible to simulate the passage of the tool through the soil and then evaluate, for example, the forces acting on the tool or the behaviour of the soil itself (Ucgul et al., 2017; Ucgul & Saunders, 2020). However, the individual models must be verified experimentally. The validated model can then be used to investigate other tillage processes. By using the model, it is possible to predict the behaviour of the modelled material or the interaction between the tools and the material and immediately reject inappropriate designs. This can save work and money in designing real prototypes of new tools and equipment.

The Rocky DEM environment enables the creation of the mathematical models with respect to the action of adhesive forces and models without adhesive forces (Fonte et al., 2015). To set up the material model and its interaction with solids in solving the problem, it is necessary to set the boundary conditions, material model and kinematics of solids (Yan et al., 2015; Kuře, Hájková et al., 2019), that can be obtained from experimental results. For example, some Ucgul's DEM models of soil with interaction of agricultural tools were created according to Fielke's experimental results. It is possible to use results from field measurements such as soil resistance. When designing a soil model, a 1:1 scale tool model can be created for interactions. The parameters of the model can be set in any variances until the results of the model are comparable with the results of field tests. Subsequently, the model can be declared suitable.

The boundary conditions of the model are usually obtained using partial models and verified on the basis of real tests (Kuře, Chotěborskýet al., 2019) or field tests (Kešner et al., 2019). The modelling can be used in agriculture as a tool for the design of new tillage tools or innovation of new geometry and determining their properties in tillage. The model verification can be performed on real models of tillage tools in the soil box model (Kuře et al., 2020).

The 3D printing can be used to design new tool shapes. When used in a soil box model, individual tools can be changed easily and quickly. In the case of using a model printed on a 3D printer, the material properties must be also verified (Hnízdil et al., 2020). Especially if a tool model is created using the finite element method. Different types of sand are often used as a filler in soil boxes. Sand has very similar mechanical properties to a soil and is much easier to keep in a consistent condition compared to a soil.

The aim of this paper is to create a mathematical model of sand, which is used to testing of tillage tools in a soil box model. The model is tested on various shapes of wings, which are equipped on tillage tools. The model verification is performed based on a comparison of the draft force of the model and of the real test.

MATERIALS AND METHODS

To create the model, it is necessary to perform a set of measurements and obtain default settings. The basic settings of the model of silica sand were chosen on the basis of already known data (Schellart, 2000; Katinas et al., 2021) and own measurements. Each model must be verified on a real test to verify its authenticity. The sand model was verified for test in the soil box. The soil box is used for testing tillage tools. The soil box is designed for tools at a scale of 1:2. The tensile force is the main value obtained from tests. The soil box is designed for testing different geometries of tillage tools before full field tests.

The dimensions of the box are height 500 mm, width 500 mm and length 1,500 mm. Silica sand with fraction 0.1–0.3 mm was used as filling of the box. The moisture content of silica sand was 0%. The subject of interest was the active length. The active length expresses the area, where the tool is already fully recessed and correspond to normal field work. The active length of the box depends on the used tool, its shape, and the length of the tool engagement. For tests was chosen tool with changeable wings. In the case of tillage tool with variable wings, the active length was 200 mm. The schema of the soil box is shown in Fig. 1. In figure is shown active length l_m (mm), draft force F (N) and variable depth of the tool d (mm). Tillage tools used in the soil box were printed on a 3D printer. Material used for printing was Pet-G. The advantage of plastic materials is fast and cheap production of many structural designs and their verification, in contrast to the expensive production of steel prototypes. Although plastic has a different value of interaction with particulate matter (e.g. Static Friction, Dynamic friction, Adhesive stiffness), when comparing design solutions that are made of a single material, changes in results (such as a decrease or increase in forces) will correlate with a metal tool.

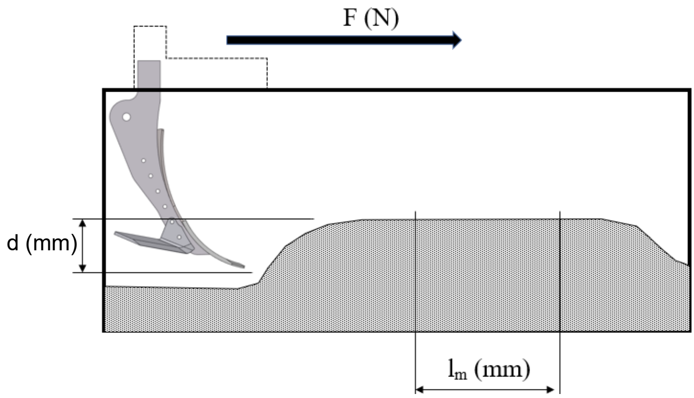

Figure 1. Schema of soil box (Kuře et al., 2020).

The verification of the model was performed on already obtained data within the measurement of individual wing geometries (Kuře et al., 2020). Data from the active length measurements at a depth of 10 cm were used. Measurement was performed for four different types of wings with the same width. Measured data were taken from (Kuře et al., 2020)

For the simulation were made geometry of the soil box, tillage tool and four types of wing. All of geometries were made in ratio 1:2 to origin tools. These models were imported into the Rocky DEM environment ('Rocky DEM Particle Simulator', 2018). Rocky DEM software is an environment for creating models using the DEM method. The positions of the geometries, velocities and movements of the models corresponding to the real measurement conditions were set. The entire length of the soil box was used in the model (in the original testing, the length of the box was shortened by a camera, which was placed inside the box). The velocity of tillage tool was set to 0.1 m s^{-1}. For each test, the tool with the appropriate wing shape was imported. Wing shapes are shown in Fig. 2.

The main prerequisite for the individual designs was the preservation of the projected area of the wings. Type 0 is the basic type of wing with an angle of inclination of 45°. For the Type 1 wing, the initial inclination was changed to 60° and for the Type 2 wing to 30°. For the last Type 3, the shape was designed using a curve. In all cases, the projected areas are preserved.

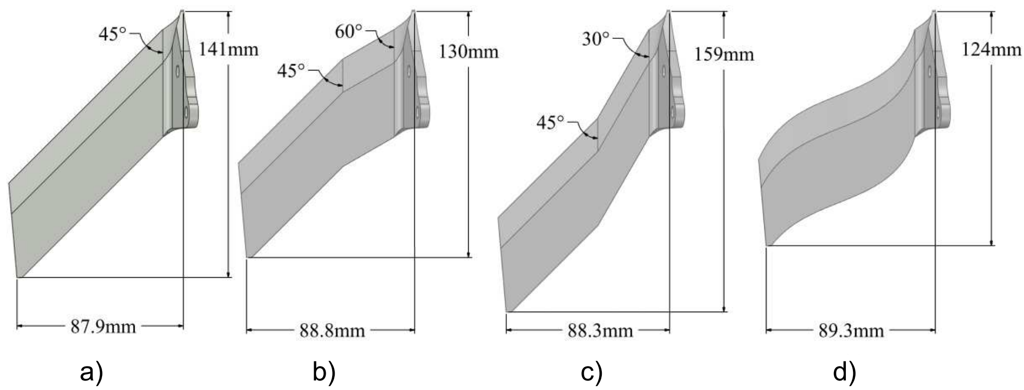

Figure 2. Schema of wings types: a) type 0 b) type 1 c) type 2 d) type 3.

After importing the geometries, it was necessary to set the DEM model of the particulate matter (silica sand). The shape of the particle was chosen as a sphere. The shape of the sphere can be used to simplify the shape of the sand and speed up the calculations. The basis of the model was set according to Table 1. Initial values of material model were obtained experimentally (Bulk density was determined by weighing material of known volume). The parameters having a great influence on the change of results were determined. These parameters were used in the subsequent design of experiment (DoE) analysis. The principle of DoE was in the selection of input parameters significantly influencing the results of the model. The values of these parameters were systematically set to extreme values and, based on the change of the result, adjusted to the optimal setting. The individual combinations of settings are listed in Table 3 below. The Young Modulus of silica sand was included in the DoE analysis due to the large variance of the measurement results.

Table 1. Settings of material model of silica sand

Material			Particles	
Bulk Density (kg m^{-3})	Young Modulus (MPa)	Poisson's ratio (-)	Size (mm)	Rolling Resistance (-)
1533	DoE	0.3	10	DoE

In the case of setting interactions, the sand / sand and sand / tool relationship had to be set. The individual settings were measured on sand shear tests. Based on these tests, the values for static and dynamic friction were determined. Friction between sand and tool (Pet-G material) was included in the DoE analysis. The remaining values were left in the original model settings. The basic settings for model interactions are listed in Table 2.

Table 2. Settings of interactions between sand / sand and sand / PetG

Relation	Static Friction (-)	Dynamic Friction (-)	Tangential stiffness r. (-)	Restitution coef. (-)
Sand / Sand	0.7	0.6	1	0.3
Sand / Pet-G	DoE	DoE	1	0.3

The total number of particles used in the one model was 97,072. Simulated time of one model was 12 seconds. The Timestep for saving data was set to 0.05 seconds. The Internal Timestep of solver was $2.93764.10^{-5}$ seconds. The model was optimized to save time in the calculation. The optimization included the shape and size of the DEM particles. The calculations were performed on an Nvidia Tesla P100 graphics card. The calculation time for one model was 1 hour.

The model was calibrated according to the test using the first type of tillage tool (model contained wing type 0). Gradually, the input parameters were set according to the DoE analysis and the model calculations were performed. The resulting draft force of model was determined and compared with the results of real tests. In case of differences in results, parameters were adjusted and calculation was performed again. The procedure is shown in Fig. 3.

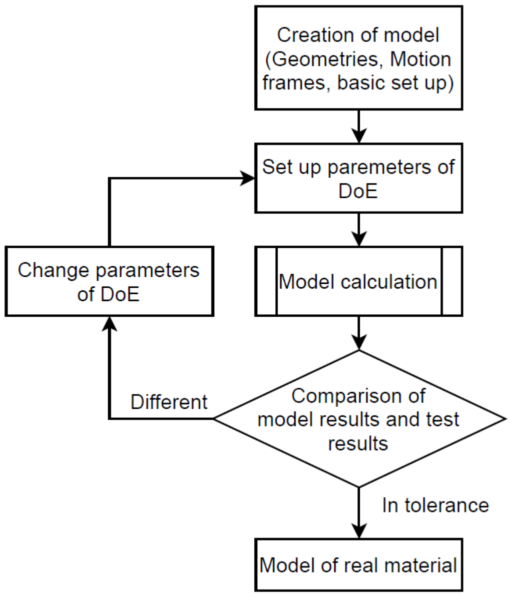

Figure 3. Scheme of the model creation process.

The results were analyzed from individual model settings. The force in the Z axis was determined, which was compared with the measured values. The comparison was determined for the active working part (active tool depth). The average value of force in this working part was compared with the measured data. The model setting that corresponded to the best match between the compared values was also used for the other three types of tools (with different wings). Subsequently, the individual results were evaluated and compared.

RESULTS AND DISCUSSION

For each model, the parameters according to DoE were changed and the results were compared. The aim was to set the individual parameters so that the resulting model corresponded to real tests. Table 3 lists the individual parameters that were used for each model. Each model was set individually and after the calculation the output data (draft force) were evaluated. The output data are listed in the table in the last column and corresponds to the settings in the relevant row. The best match was achieved when setting up model 17. The results show that it is possible to rely on material models designed for other types of computational tasks such as for example wear (Katinas et al., 2021).

Table 3. Settings of interactions between sand / sand and sand / Pet-G

	Set Up				Results
Number of DoE	Young Modulus (MPa)	Rolling Resistance (-)	Static Friction (-)	Dynamic Friction (-)	*F in active l. (N)*
1	8	no	0.5	0.5	*375.4*
2	6	no	0.5	0.5	*344.6*
3	4	no	0.5	0.5	*330.4*
4	2	no	0.5	0.5	*256.1*
5	2	0.15	0.5	0.5	*66.5*
6	2	0.17	0.5	0.5	*70.6*
7	2	0.2	0.5	0.5	*78.6*
8	1.9	0.15	0.5	0.5	*66.5*
9	1.9	0.17	0.5	0.5	*70.9*
10	1.9	0.17	0.5	0.3	*64.4*
11	1.9	0.17	0.4	0.3	*63.8*
12	2	0.15	0.4	0.3	*61.4*
13	2	0.14	0.4	0.3	*59.5*
14	1.9	0.14	0.4	0.3	*58.2*
15	1.8	0.14	0.4	0.3	*58.6*
16	1.8	0.12	0.4	0.3	*55.1*
17	**1.7**	**0.14**	**0.4**	**0.3**	***56.2***
18	1.7	0.12	0.4	0.3	*54.7*

Fig. 4 graphically shows a simulation of the passage of a tool with wings of type 0. The particles are marked according to depth.

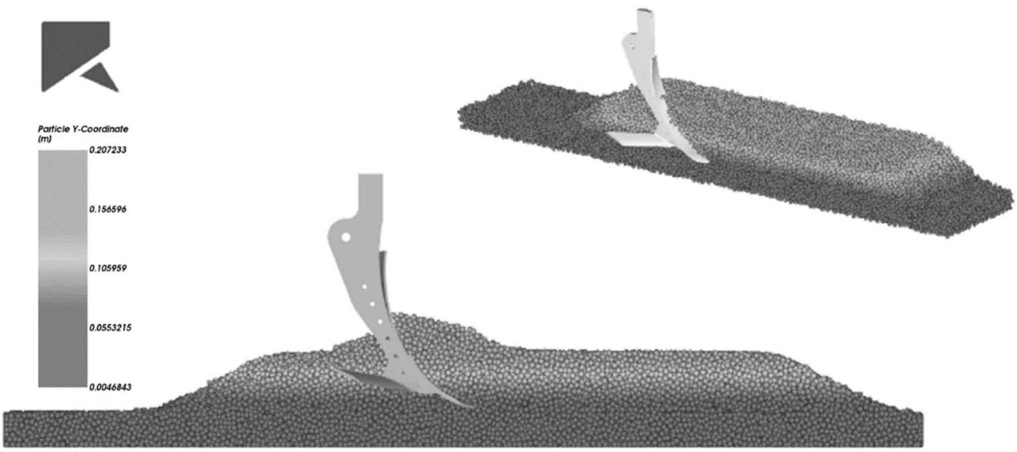

Figure 4. Graphical results of model from Rocky DEM.

The evaluation of the data from the model is shown in Fig. 5. The course of the draft force was determined from the model. Only the part corresponding to the active length (where the force is constant) was selected. The average force from this part was compared with the already measured results for the given type of tillage tool.

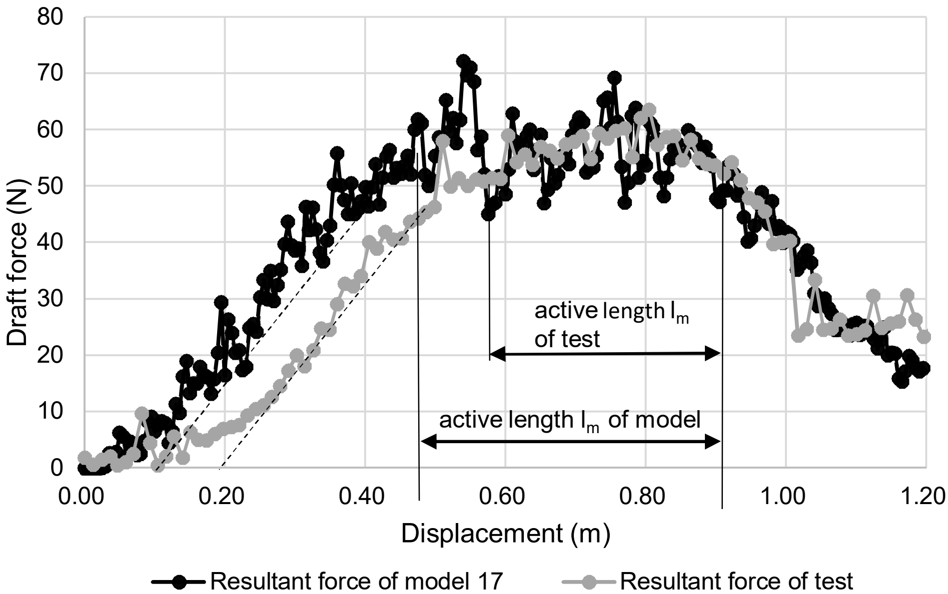

Figure 5. Comparison of model results with measured values.

Fig. 5 shows a comparison of the measured force in the active length during real tests and the course of the draft force obtained from the model. The data of force from active length in the graph corresponds to the results of model number 17. The optimal results were achieved. The large scatter of force in the active part was caused by the size of the model particles. This size was chosen to optimize the time in the calculation. However, the result is not otherwise affected. It is also evident in the graph that the increase and decrease of the force measured in the real test correspond to the results obtained from the model. The active length during the measurement was reduced by 0.1 m due to the placement of the camera in the box. Nevertheless, the slopes of the increasing force are the same. It was possible to reduce the active length. When increasing the active length and maintaining the conditions (same depth, material, etc.), the average value of the force always stabilizes (Kešner et al., 2019). For this reason, it is not necessary to examine the whole course but only steady values.

After obtaining the optimal setting, it was necessary to compare other types of wing geometries. The same setting was selected (according to model 17) and models for individual geometries were calculated. The behaviour of the model in interaction with the tool must be the same even if the ambient condition changes as the speed of the tool or tool shape (Shmulevich et al., 2007). The resulting draft forces were compared with the measured data. The comparison is shown in Fig. 6.

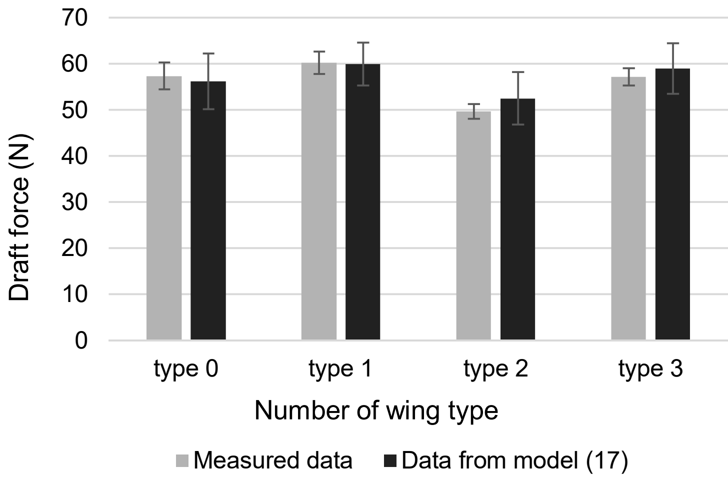

Figure 6. Comparison of measured draft force and model draft force.

The graph shows the individual average forces measured in the active length for both real tests and the model. Individual results were evaluated using statistical methods. An *F-test* was performed to determine the consensus of the variances of the individual results. In all cases, the result p-value was less than 0.05. The hypothesis of equality of variances was rejected. For this reason, an unpaired *T-test* for different variances was used to determine the concordance of the results. *P-values* of *T-tests* are shown in Table 4. In all cases except wings type 2, statistical consensus was achieved.

Table 4. *T-test* results for individual draft forces

	Wings type 0	Wings type 1	Wings type 2	Wings type 3
Measured force (N)	57.3 ± 2.9	60.2 ± 2.4	49.7 ± 1.6	57.1 ± 1.8
Model force (N)	56.2 ± 6.1	59.9 ± 4.6	52.5 ± 5.6	58.9 ± 5.5
p-value of *T-test* (> 0.05)	0.38	0.75	$0.2e10^{-3}$	0.14

From the data according to the graph (Fig. 6) the results for individual geometries correspond to individual models. The smallest measured draft force was found for a tillage tool with wings type 3. The largest draft force was found for a tillage tool with wings type 2. These dependences were same for individual models.

It seems that the DEM, after the correct setting, corresponds very well to the real conditions. Therefore, it is possible to obtain the additional information from the results, which simply cannot be obtained by measurement. The examples could be all forces and moments on the geometry, position of the centre of gravity, position of the forces, etc. This information can be combined with the FEM model of the machine and optimize or innovate individual parts or the whole machines for agriculture.

CONCLUSIONS

The DEM model of the silica sand for filling the soil box was created. The created model was verified for various geometries. The draft force was compared for verification. This parameter is suitable for the model verification for the purpose of determining the force effects. In all cases (with the same DEM model settings) relatively identical results were obtained. These results were compared using statistical methods. In most cases, a consensus of the results was found. It was found that with the correct setting of the DEM model, results corresponding to real conditions can be obtained. The model settings described in this paper can be used for a silica sand with zero moisture content and a fraction of 0.1–0.3 mm.

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