Agronomy Research **17**(2), 551–558, 2019
https://doi.org/10.15159/AR.19.034

Discrete element simulation of rapeseed shear test

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Abstract. Suitable equipment are required for storage and transportation of rapeseed which are developed according to rules for bulk matters. It is one of reasons where bulk matter properties are important to the design. Bulk matter properties are important to known as angle of repose, internal friction, external friction, adhesivity force and other bulk properties. Experimental values of bulk properties are added to mathematical models. The model should be calibrated with adequate experiment. The shear test is one of popular calibration test for bulk matters so that be able done experiment and numerical model in one. The aim of this paper is simulation of rapeseed bulk properties during shear strain and flow and its evaluation and calibration with experimental tests. RockyDEM software was used for numerical simulation of rapeseed. Shear test, angle of repose, static and dynamic friction test were used to calibration of the numerical rapeseed model. Sensitivity of numerical model is discussed on the bulk properties.

Key words: oilseed, discrete element methods, angle of friction, shear test.

INTRODUCTION

Use of special equipment is necessary for rapeseed storage and manipulation. These equipment must be designed in a way to accommodate for seamless transportation and storage of the rapeseed. It is possible for a computer simulation to be made in order to lower the design and testing costs. Such simulation requires an accurate mathematical model. To achieve a correct calibration of the mathematical model, it is necessary to acquire rapeseed's mechanical properties. Fundamental bulk properties are angle of repose, internal and external friction. Angle of repose can be determined through experimental measurement (Zhou et al., 2002; Marigo & Stitt 2015). Shear test on a shear device is the most common method for obtain values of internal and external friction (Amšiejus et al., 2014).

Discrete element method (DEM) is a suiTable way of creating the model. Raji & Favier (2004), Wojtkowski et al. (2010) have already dealt with rapeseed modelling, particularly in the area of rapeseed's deformation and processing. High performance of modern computer technology allows for simulation of bulk matter of rapeseed in 1:1 real rapeseed to simulation ratio. This way, it is possible to achieve accurate results.

The aim of this paper is to create a mathematical model of rapeseed. Model calibration was made on a shear test using shear device. Modelling program RockyDEM was used for the simulation.

MATERIALS AND METHODS

Firstly, it was necessary to acquire rapeseed's basic properties such as size of individual grains, moisture and bulk density. The acquisition of parameters was subject of measurement and experimentation. Secondly, in order to determine the parameters of rapeseed it was necessary to specify its static and dynamic properties. These properties served as input values of the mathematical model. The obtained parameters were then evaluated, inserted to the mathematical model and a calculation was made.

A selected rapeseed sample was subjected to experimental measurement. The first step established the rapeseed grain properties according to (Kanakabandi & Goswami 2019). The diameter of 100 rapeseed grains was measured in order to determine the average grain size. Measured values were then analysed, further processed and finally used to create a histogram. Six measurements were made to specify the bulk density. A 400 mL volume container was filled with rapeseed sample. The weight of the rapeseed was then subtracted.

As (Çalişir et al., 2005; Wiacek & Molenda 2011) have already determined, rapeseed's moisture changes its properties fundamentally. Rapeseed's moisture must be preserved for the entire duration of the measuring process of its properties. The change in the bulk material's moisture affects its cohesive properties and leads to a different behaviour of the material. The moisture content was measured using moisture analyser OHAUS MB 25 (Hromasová et al., 2018). Five different rapeseed measurements were made. Individual samples were heated in the analyser to a temperature of 105 °C. During the test the sample was observed for weight loss. The calculation of moisture was made after the weight of the sample stabilized at a new value. Young's modulus for bulk matter of rapeseed was the next parameter. The test was performed on a tensile testing machine. Rapeseed sample was placed inside a cylindrical chamber with a diameter of 40 mm. Height of the bulk sample was 30 mm. The sample was deformed from 0 N to 10 N. The relative ratio of the volume change and the corresponding load was subsequently evaluated. The result was the Young's modulus.

Shear test was performed on shear device. With the help of shear test it is possible to determine the coefficient of internal and external friction. The internal friction coefficient of bulk materials determines the frictional properties between the individual particles of the material. The coefficient of internal friction determines the frictional properties between the bulk material and the surface of foreign object. (Krc et al., 2016)

Shear device consists of two chambers and a top board. The internal dimensions of the chambers are 90 x 90 mm with the height of 30 mm. Rapeseed sample has been placed inside of the chambers and the upper chamber closed by the top board. See Table 1 for the load for the measurement. See Fig. 1 for the measurement scheme. After load of F_n (N), the upper chamber has been set to motion along horizontal axis at the speed of 1 mm s^{-1}. Tangential force F_s (N) acting on the upper chamber has been progressively subtracted during motion Δl (mm).

Table 1. Values of loads

Number of measures	1	2	3	4	5	6	7	8	9	10
Mass (g)	500	1,000	1,500	2,000	2,500	3,000	3,500	4,000	4,500	5,000

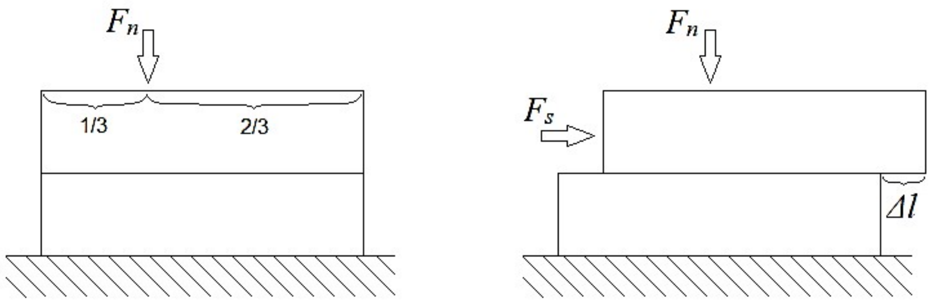

Figure 1. Share device principle.

From each measured force-displacement dependence, a transformation was made based on the stress-deformation dependence (1) (2). Tangential forces at the tearing point and maximal shear forces were subtracted in the overall course. After the construction of Mohr's circles (Fig. 2), a coefficient of static and dynamic friction was obtained.

$$\tau = \frac{F_s}{A} \tag{1}$$

where τ – tangential stress (Pa); F_s – tangential force (N); A – cross section area (m^2)

$$\sigma = \frac{F_n}{A} \tag{2}$$

whre σ – normal stress (Pa); F_n – normal force (N); A – cross section area (m^2)

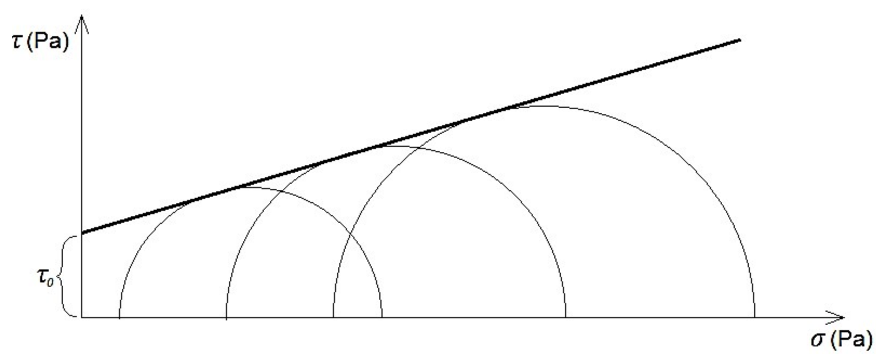

Figure 2. Mohr's circles.

Tangential stress τ (Pa) is given by the formula:

$$\tau = \tau_0 + \sigma \cdot \mathrm{tg}\varphi \tag{3}$$

where τ – tangential stress (Pa); τ_0 – initial tangential stress (Pa); σ – normal stress (Pa); φ – angle of internal friction (°).

The mathematical model is designed in the same way as the shear device and therefore it is possible to observe only the tangential force F_s (N) in the x axis acting on the chamber. RockyDEM software was used to create the mathematical model. Model of the shear device was created using SpaceClaim modelling software, which is a part of Ansys. The model was saved as .stl file and then imported to RockyDEM. (Fig. 3). For the input parameters required for simulation setup see Table 2. These parameters were gathered in previous experiments. After setting up the parameters, the mathematical model was calculated.

Table 2. Input parameters in RockyDEM

Parameter	Value
Particle parameters	
Bulk density	707 kg m^{-3}
Bulk Young's modulus	2.66 MPa
Bulk Poisson's ratio	0.3 (-)
Boundary parameters	
Density	2,700 kg m^{-3}
Young's modulus	70 GPa
Poisson's ratio	0.3 (-)
Material interaction between particle and particle	
Static friction	K (-)
Dynamic friction	0.75 (-)
Tangential stiffness ratio	0.8 (-)
Restitution Coefficient	0.3 (-)
Material interaction between particle and boundary	
Static friction	0.34 (-)
Dynamic friction	0.43 (-)
Tangential stiffness ratio	0.8 (-)
Restitution Coefficient	0.3 (-)

Model verification was made through comparison of experimental results from the shear test and the results of the mathematical module. Output parameters were set once more and another calculation was made. Parameter setting was focused on Static friction, dynamic friction and stiffness. The individual changes were compared based on the adjustment of individual input quantities. It has been found that static friction has the highest effect on the test. To find the optimal parameters, Design of Experiment was followed. Variable K in Table 2 indicates the search parameter.

For normal loads of 500 g, 1,000 g and 2,000 g, simulations with static friction of 0.12, 0.21 and 0.33 were calculated. The results were compared according to individual parameters. The comparison was based on the *T-test* probability in MS Excel 2016.

Parameters that have been selected for the compare of displacement force curves are presented in Fig. 3. Fmax is the maximum value of displacement force curve. Alpha (α) is angle of slope (gradient) displacement force curve. Displacement energy is marked E. Displacement energy is area under displacement force curve.

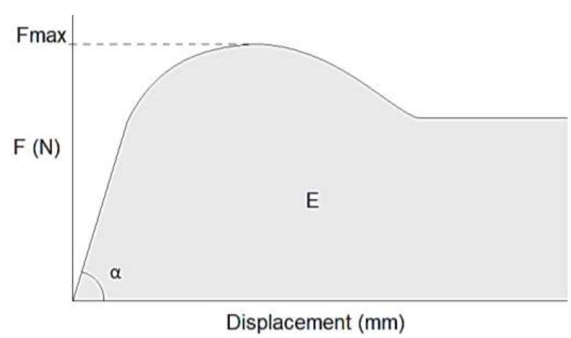

Figure 3. Necessary parameters to compare displacement force curves.

Two computational devices were used for the calculations. The first device was used for preprocessing and post processing: Intel® Xeon® Processor E5-1680 v4, 20MB Cache, 3.40 GHz. The second device was used for solver: HPE NVIDIA Tesla P100 PCIe 16GB Computational Accelerator graphic card.

RESULTS AND DISCUSSION

For the measured rapeseed grain diameter, bulk density and moisture see Table 3. Grain size corresponds to a normal distribution. Measured grain size at the given moisture is comparable to (Çalişir et al., 2005) The value of bulk density; however, was measured higher, but contrary to (Wiacek & Molenda, 2011) the bulk density was lower.

Table 3. Table of measured rapeseed properties

	Value
Size	1.93 mm ± 0.214
Bulk density	707 kg m^{-3} ± 5.469
Moisture	3.5% ± 0.145

Coefficients of static and dynamic friction was calculated of measured tangential stress and normal stress. Results are shown at Fig. 4, a) and b). Coefficient of static friction is 0.29 with $R^2 = 0.97$, coefficient of dynamic friction is 0.76 with $R^2 = 0.99$. Value of bulk Young's modulus is 2.66 MPa.

The coefficient of static and dynamic friction are dependent on moisture content. The coefficient of static friction is approaching to results in (Çalişir et al., 2005; Wiacek & Molenda 2011).

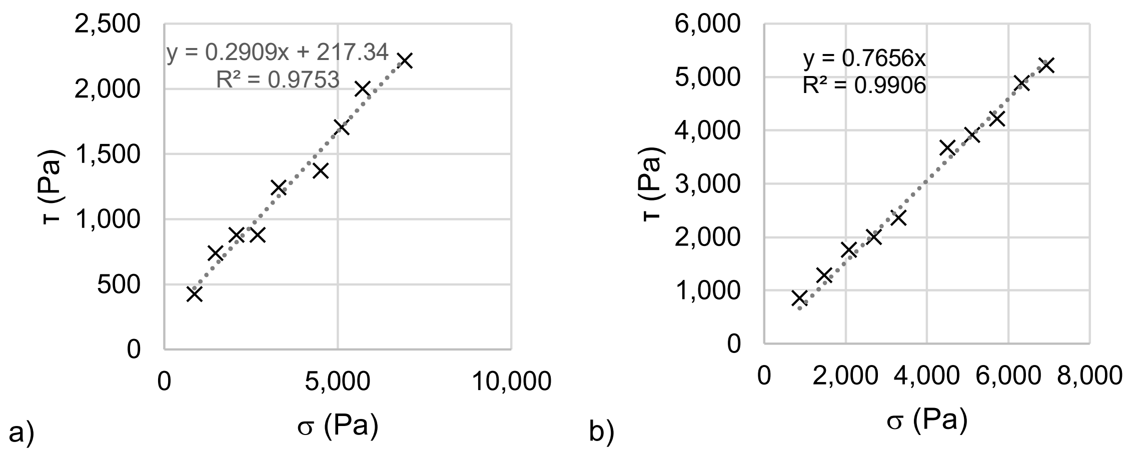

Figure 4. a) The static friction between particle and particle; b) The dynamic friction between particle and particle.

Mathematical model was performed according to Table 2 above. Values were determined by experimental measurements. Poisson ratio and restitution coefficient were left at the default values recommended by the technical manual of Rocky DEM. Tangential stiffness ratio was determined by the DoE when it reached optimal values depending on the model's result. Static friction was set to: 0.12, 0.21 and 0.33.

The final simulation is graphically presented by Rocky DEM (Fig. 5). The simulation shows the particle displacement caused by the top chamber displacement in the horizontal axis.

Fmax, energy and angle α were obtained from measured values and results of simulations. Values are presented in Table 4, 5 and 6.

P values obtained from the *T-tests* were compared and presented in Table 7. The highest value probabilities are bold. These probabilities are significant of model values with real experiment.

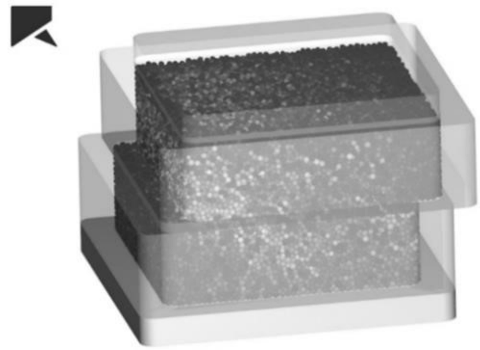

Figure 5. The simulation of share test in Rocky DEM.

Significant value of static friction for relation between computed model and real experiment was determined for value 0.33. However, maximum displacement force of the model with static friction 0.21 is more appropriate in this case.

Table 4. Maximum force values of displacement forces, where S is simulation and SF is static friction

Normal load (g)	Fmax of experiment (N)	Fmax of S with SF 0.12 (N)	Fmax of S with SF 0.21 (N)	Fmax of S with SF 0.33 (N)
500	7.136584	4.635929	5.86799	6.987178
1000	10.0887	7.589752	9.539528	11.03859
2000	16.48494	14.10927	16.97077	20.01202

Table 5. Displacement energies of real experiment and simulations, where S is simulation and SF is static friction

Normal load (g)	Energy of experiment (N)	Energy of S with SF 0.12 (N)	Energy of S with SF 0.21 (N)	Energy of S with SF 0.33 (N)
500	58.25351784	39.49571125	47.77675263	54.73861092
1000	88.69717097	63.95716466	76.82710536	86.53662208
2000	141.9680287	115.7666934	138.7238772	156.3169611

Table 6. Angles α of slope of real experiment and simulations, where S is simulation and SF is static friction

Normal load (g)	Angle α of experiment (N)	Angle α of S with SF 0.12 (N)	Angle α of S with SF 0.21 (N)	Angle α of S with SF 0.33 (N)
500	87.8188913	86.42270722	86.86175238	87.28090587
1000	88.13814944	87.82255397	88.07203203	88.19160679
2000	88.44819378	88.86840589	88.97115811	89.01425526

Table 7. Probability of *T-test* between simulation and real experiment

Static friction in simulation	P value for maximum displacement force	P value for displacement energy	P value for angle of slope displacement force
0.12	0.565523618	0.523194	0.609584
0.21	**0.922420412**	0.825847	0.814835
0.33	0.777313268	**0.944186**	**0.963068**

In Fig. 6, the displacement force of real experiment as continuous line and displacement force of simulations as dashed and dotted lines are presented. Displacement force of simulation with static friction 0.21 shows similar run of curve for real experiment in the initial phase than displacement force of simulation, but the simulation with static friction 0.33 shows better run overall.

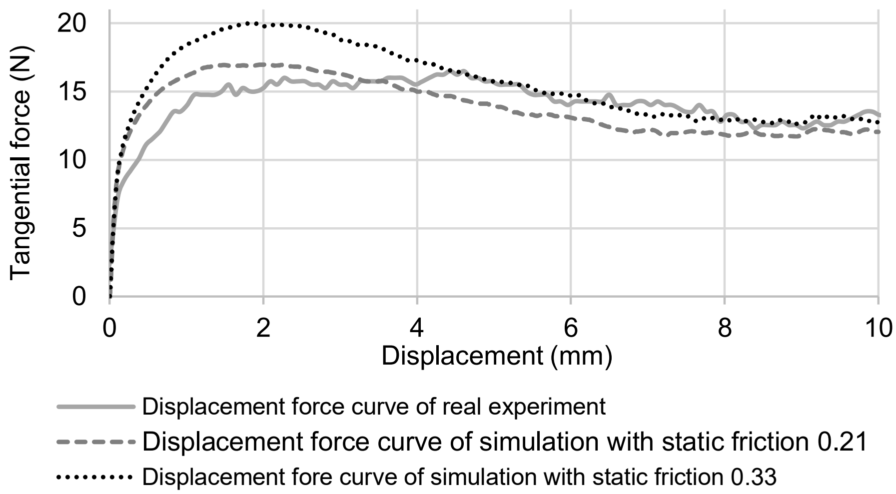

Figure 6. Results of shear tests with normal load of 2,000 g.

The model contains 87,054 particles. The calculation of 10.2 second of simulation need 2.4 hours computation time at the Tesla P100. Time-consumption of simulation of the same time interval is 20.8 hours at the Xeon E5-1680 processor. For the final sensitivity setting of the model was needed 424 hours of calculating.

CONCLUSIONS

The use of this modelling technique is according expanding and it is being exploited in many application. Discrete element method can be used to describe granular problems of rape seed. Parameters are given for moisture content 3.5% and real size of rapeseed grains. For models with a different grain ratio, it may be necessary to change the boundary conditions. When designing a mathematical model of rapeseed, it is important to discuss the purpose of model and use appropriate settings.

ACKNOWLEDGEMENTS. Supported by Internal grant agency of Faculty of Engineering, Czech University of Life Sciences in Prague with name: Influence of input parameters of agricultural bulk matter on the accuracy of solution using discrete element methods.

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