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Tracing of the rapeseed movement by using the contrast point tracking method for DEM model verification

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Abstract. For designing the efficient storage and transport of rapeseed, it is necessary to follow the rules of bulk material, know its properties, and use appropriate equipment. The mentioned properties of bulk material are essential for simulating the numerical model and obtaining the parameters of the geometry particle tracing during the rapeseed manipulation. In order to determine the angle of repose and mechanical properties of rapeseed, the results of previous experiments were used. The aim of this paper was to propose the methodology for calculating the traces of individual particles using the contrast point method during a real test to calibrate and verify a numerical model of the same system as in a real test. RockyDEM software was used to create the numerical model of rapeseed. The numerical model was used to test the flow analysis of rapeseed particles. The experiment measuring rapeseed particle traces was performed using an assembled experimental device. The rapeseed particles and the contrast point particles were poured out from the device, and a camera recorded the process. In parallel with the real experiment, the angle of repose test was performed on the same device to verify the numerical model. The results showed that the methodology is suitable for the DEM model verification with an accuracy of 3.77 mm in the X-axis, 0.55 mm in the Y-axis and 1.7 mm in the Z-axis. This confirmed that the proposed method is suitable for determining the surface behaviour of bulk material to verify the DEM model.

Key words: rapeseed, discrete element methods, particle tracing, angle of repose test, contrast point.

INTRODUCTION

Modelling and simulation are methods often used in science, economics, engineering praxis, and many other fields of human activity. Computer simulation is one of the most commonly used methods in agriculture because of its low design and testing costs. To effectively manipulate and store rapeseed, following a specific set of rules and using special equipment is necessary. This equipment has to be designed in such a way as to allow seamless transportation and storage of rapeseed. The numeric simulation using discrete element methods (DEM) allows for creating a preview of particle tracking geometry (of rapeseed). However, in order to achieve the correct calibration of the numerical model, it is necessary to obtain the mechanical properties of the rapeseed. By using known parameters and properties, it is possible to create a computer model and determine the correlation between the experiments and the model (Zhou et al., 2002; Asaf et al., 2007; Chen et al., 2013). For the bulk matter's basic properties, it is necessary to determine the angle of repose as well as the external and internal friction angle of said bulk material (Amšiejus et al., 2014). The internal and external friction angle can be calculated using shear tests (Schwedes & Schulze, 1990; Ucgul et al., 2015; Kotrocz & Kerenyi, 2017). The tests are performed using a special shear device. The test was also used by Kuře et al. (2019), who created and verified a numerical DEM model of rapeseed.

Lei et al. (2021) verified the rapeseed's DEM model by comparing the motion characteristics and seeding performance during the simulation and the bench test. The results confirmed the possibility of using DEM to determine the final position of rapeseed during seeding. By analysing the movement of particulate matter, it is possible to verify whether the movement in the DEM model corresponds. One of the many methods of motion analysis is image processing.

Image processing can be a useful tool for tracing surface objects. It is possible to record the movement of particles for later analysis by using a camera (Hoffmann et al., 2014; Kříž et al., 2016). Zhang et al. (2006) proposed two types of analysis, soil mass motion analysis for tracking soil displacement and soil particle tracking analysis for unique soil particle translation and rotation tracking. They used a basic algorithm based on cross–correlations of the frames to determine the corresponding locations of the traced point in successive frames and thus measure the displacement values. Image processing for particle tracing using the contrast point method was applied by Hardy et al. (2017), who simulated the effect of raindrops on soil erosion by using fluorescent coating on the upper particles in a soilbox.

The aim of this paper is to propose and use the methodology for calculating the traces of individual particles of rapeseed using the contrast point method during a real test. To calibrate and verify a numerical model of the same system as in a real test. For additional verification will be used the angle of repose test.

MATERIALS AND METHODS

An experimental device for measuring the angle of repose was used to trace the rapeseed grains during the pouring process. The process was filmed and then processed by the optical contrast point method. Then a simulation model was created, corresponding with rapeseed grains in their parameters. For verification and added calibration of the simulation model, a test measuring the angle of repose was performed for the model and a real experiment.

The material model and the physical input parameters were based on the numerical model from previous experiments (Kuře et al., 2019). The experiment aimed to create a numerical rapeseed model and verify it by comparing the static and dynamic friction in the real experiment and the model. Model calibration was made on a shear test using a shear device.

The rapeseed seeds (*Brassica napus*) of the Atora variety were used for the measurements. The used rapeseed properties were based on results from previous experiments (Kuře et al., 2019). The size of the rapeseeds was measured, which was 1.93 mm ± 0.214. The bulk density was 707 kg m^{-3} ± 5.469, and the moisture content was 3.5% ± 0.145. The moisture content of the rapeseed was verified by using the Memmert oven 100–800. The amount of the rapeseed was placed into the oven and dried to the moisture of 0%. From the weight difference before and after drying, the moisture was counted.

The experimental device for measuring the angle of repose

The device (Fig. 1) consisted of a camera (1), a tray (2), a cylinder (3), and construction (4), to which a cylinder was attached to a linear system. The cylinder was made of a transparent tube with an inner diameter of 100 mm, and an outer diameter of 110 mm. The cylinder was filled with particulate matter, which consisted of the rapeseed particles. After filling the cylinder with particles, the cylinder was lifted by a DC motor (5). The cylinder's lifted speed has been set at 0.00325 m s^{-1}. The speed depends on the gear ratio of the DC motor and the pitch of the thread. The speed mustn't be too high so that only the static behaviour of the substance is manifested. As the cylinder was lifted at a constant speed, its content (particulate matter) was spilt on the tray.

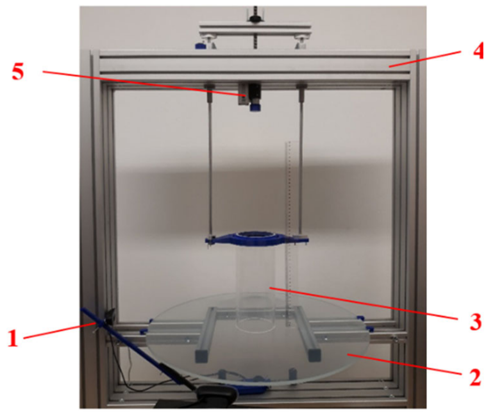

Figure 1. The equipment for measuring the angle of repose.

Tracing the particles by using the method of the contrast point

Polypropylene particles were chosen as contrast points for particle tracking. The polypropylene impact copolymers with the density of 900 kg m^{-3}, tensile stress at yield of 26 MPa, tensile strain at yield of 10% and the average size of 4.3×3.6×2.7 m was used. The cylinder of the experimental equipment was filled with particulate matter, which consisted of the rapeseed particles and nine polypropylene particles. Three polypropylene particles were placed at the approximate height of 80 mm at the centre of the camera's axis. Due to the spacing, the particles were approximately 20 mm apart. The other three particles were seated at the height of 120 mm. The last three particles were placed at the height of 160 mm. The cylinder was filled with rapeseed approximately at the high of 210 mm (Fig. 2).

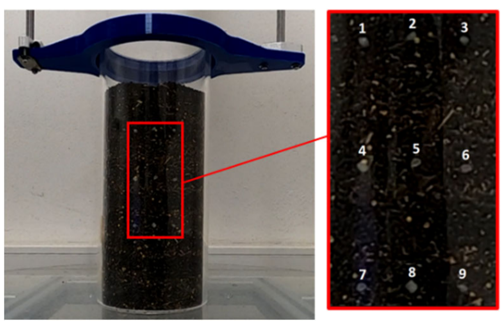

Figure 2. Single points of PP particles in rapeseed.

The used camera recorded the movement of polypropylene particles during the whole experiment. The record was evaluated using image analysis to determine the particle trajectory, visible throughout the entire recording duration. The camera was placed at the height of 80 mm above the level of the plate and recorded the entire course of the experiment from a distance of 360 mm. After recording, the video was saved in a MOV format.

DaVinci Resolve (16.1.2) software environment was used to obtain paths of polypropylene particles from video records. It was done using the DaVinci Resolve function called Tracker. The contrasting point was bounded as an image (Fig. 3). Then the Tracker monitored image movement during the video playback. This movement eventually created the path of motion of the contrast point image.

Figure 3. Bounded contrast point.

The coordinate system was shifted, and the [0;0] value on X and Y-axis was moved to the cylinder's centre on it's wall (Z-axis was not concerned, because it was calculated later), i.e., to the height where the cylinder contacts the plate. It was done so that the gathered data could be later compared with data gained from Rocky DEM. The path coordinate data (X-axis and Y-axis) were exported to MS Excel and processed. The resolution of the recorded images was 1,080×1,920 pixels. The resolution was later recalculated to millimetres, so the value of the particle movement was known. The polypropylene particles' position on the Z-axis was obtained by calculations (1) and (2).

$$z = r \cdot cos\alpha \quad (1)$$

$$\sin \alpha = \frac{x}{r} \quad (2)$$

where x (m) is the position of the particle on the X-axis; r (m) is the diameter of the cone's cross–section; α (°) is the angle between the r and z curves, and z is the particle's position on the Z-axis.

The diameter r was variable due to the conical shape of the spilt rapeseed, so it was necessary to determine its value for each position on the Z-axis. It was obtained using graphical measurements in the mathematical application GeoGebra software environment (GeoGebra, 2019). Subsequently, all coordinate values were known. The coordinate values of the contrast particle's initial positions were selected and used to select particles in the numerical model.

The numerical model

The numerical model was created in Rocky DEM Particle Simulator (4.2.0) environment (Fonte et al., 2015). The angle of repose experiment (described in The angle of repose experiment) calibrated the numerical model of spilling rapeseed. The property of particle interaction was set up according to previous experiments (Kuře et al., 2019). Input parameters of the materials, their interactions, and physics are listed in (Table 1.). The particles were chosen to be spherical, and their size was set up to 2 mm, which corresponds to the average rapeseed diameter. The hysteretic linear spring model is the mathematical model chosen for the normal force component. The resulting contact force can be expressed by Eq. (2) for the convergence of two particles and separately by the equation for the retraction of two particles (Kruggel-Emden et al., 2007). The model is described in detail in (Katinas et al., 2019).

$$F_n = \begin{cases} -k_z \cdot \delta, & \dot{\delta} \geq 0 \\ -k_o \cdot (\delta - \delta_0), & \dot{\delta} < 0 \end{cases} \quad (3)$$

where $F_n(N)$ – normal force; $k_z(N \cdot m^{-1})$ – spring load stiffness; $k_o(N \cdot m^{-1})$ – spring relief stiffness; $\delta\ (m)$ – overlap; $\delta_0\ (m)$ – overlap during the retraction of particles; $\dot{\delta}\ (m \cdot s^{-1})$ – instantaneous normal velocity.

Table 1. Input parameters of the numerical model

Simulation physics:		Source
Normal force	Hysteretic linear spring	(Rocky DEM technical manual, 2020)
Tangential force	Linear spring coulomb limit	(Rocky DEM technical manual, 2020)
Adhesive force	None	(Rocky DEM technical manual, 2020)
Rolling Resistance	0.28	Selected
Gravity	9.81 m s^{-2}	Selected
Material interaction properties between particles:		
Static friction	0.33	Selected
Dynamic friction	0.3	Selected
Tangential stiffness ratio	0.8	Selected
Restitution coefficient	0.3	Selected
Material properties:		
Bulk density	707 kg m^{-2}	(Kuře et al., 2019)
Young's modules	2.66 Mpa	(Kuře et al., 2019)
Poisson's ratio	0.3	Selected
Partical size	2 mm	(Kuře et al., 2019)
Lifting velocity of the cylinder in the Y-axis	0.00325 m s^{-1}	Selected

The cylinder and tray models were imported to Rocky DEM. The cylinder model was filled with the model of particles (Fig. 4), and the retraction velocity was set up to 0.00325 m s^{-1}. Once the model was set up, a calculation was followed by a simulation of spilling the rapeseed.

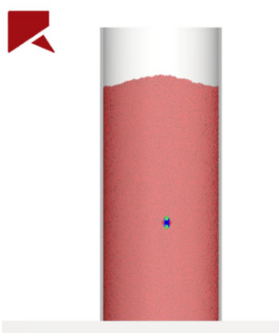

Figure 4. The cylinder model was filled with the model of particles.

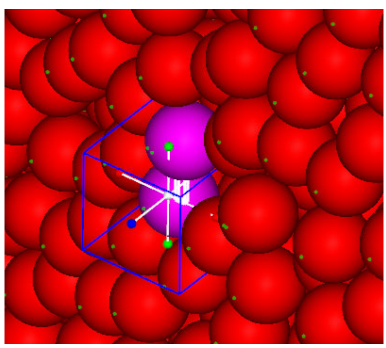

Figure 5. Two nearest particles correspond to the initial position of contrast points from the real test.

After the simulation, particle paths could be detected. According to the initial position of the particles from the real experiment, two particles from the simulation were selected. The model particles' positions were the closest to the position that corresponded to the position of the particles from the real experiment (Fig. 5). Each particle was marked, and its path was exported for the entire simulation course.

The angle of repose experiment

The measurement of the angle of repose experiment was used to verify the model of the particle tracing experiment. GeoGebra (2019) software environment was used to obtain said angles. Defining a horizontal line was the first step in measuring the angle of repose. A horizontal line was created by using two marginal points on the bottom of the cylinder. These points are visible in Fig. 6 as the point 'S' and 'T'. The horizontal line is parallel to the bottom of the pile and is used as the adjacent side of the angle of repose. To count the angle of repose, it was also necessary to make the hypotenuse lines. Both sides of the pile's surface profile formed the hypotenuse lines. That formed the pile's profile into two right triangles from which the angles could be calculated. The angle between the surface lines of the pile and the horizontal line are the angles of repose, that is indicated in the Fig. 6.

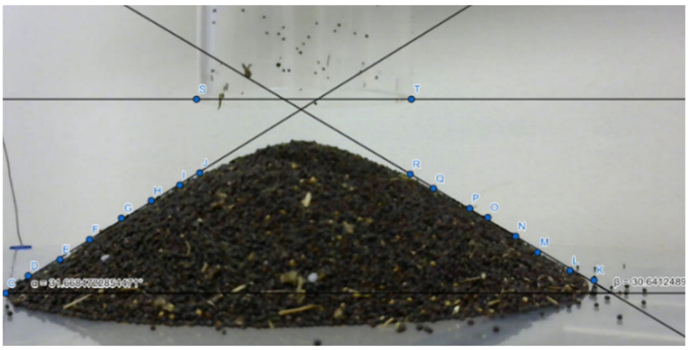

Figure 6. Measuring the angle of repose on the real system.

Subsequently, the script supported by the RockyDEM environment was used to determine the angle of repose. The pile was divided into 36 individual slices utilising the script (Fig. 7). Each slice was divided into separate sectors from the centre of the pile (Fig. 8). For each sector, a particle with the highest Y-axis value was identified. A line was created for each slice using linear regression, and its direction determined the given angle.

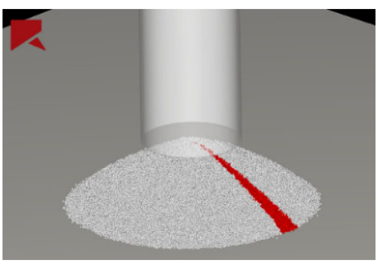

Figure 7. A circular section set aside for determining the angle of repose.

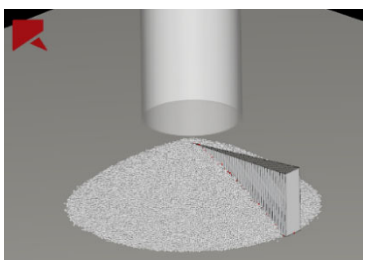

Figure 8. Division of a circular segment into sectors.

The statistical evaluation

Statistical methods *F*-Test: Two-Sample for Variances and subsequently *t*-Test: Two-Sample Assuming Equal Variances were used to compare the measurement results and the results obtained by simulations in RockyDEM. The variances and the expected values for the individual X, Y, and Z-axis between the measurement and the simulation were determined using these methods. Hypotheses about the conformity of the variances and the conformity of the Equal Variances were established. The level of significance was set up to a value of $\alpha = 0.05$. This value was the border value of the *p*-value from the *F*-Test and *t*-Test that confirmed their hypotheses. (Svatošová & Kába, 2013).

RESULTS AND DISCUSSION

The angle of repose test

After the experimental phase, captured images of the pile were evaluated. The resulting average angle of repose equals 30.51° ± 1.50°. See (Fig. 9) for the measured data. The graph contains the individual average data for each slice (Fig. 8) with relative deviation. The horizontal line marks the average angle of repose. The chart shows that a systematic error was made during the measuring. Image deflection has occurred during the rotation of the camera. Systematic error is a sine function. A slight tilt of the camera may have caused the error. Another possibility is that the centre of the cylinder was not attached exactly to the axis. From a statistical point of view, this error has no significant effect on the average value of the entire measurement. In comparison to Izli et al. (2009) the angle is greater. However, a grain with a different humidity was chosen in our case.

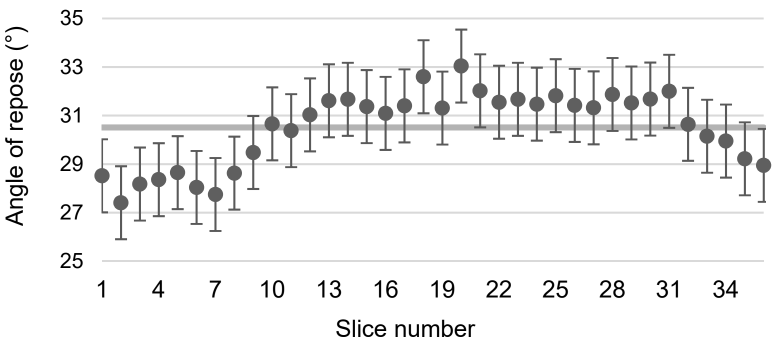

Figure 9. Graph of measured Angle of repose of pile of rapeseed after the real experiment.

Once the data evaluation was complete using RockyDEM rapeseed model script, an image containing the results was exported. The resulting angle of repose from the model equals 30.06° ± 0.5°. See Fig. 10 for the results. The part on the left shows the evaluation of angle of repose measurement. The result is an approximation of the maximum Y-axis values for the individual sectors. The part on the right shows the evaluation of the individual angles of repose, similar to Fig. 9. By considering the relative error, it can be said that the measured data and the data from the model correlate, and the error is in tolerance value.

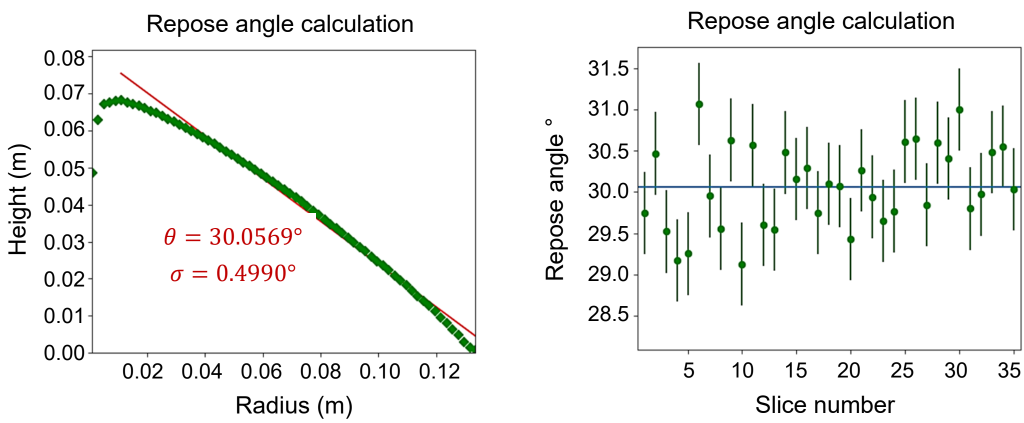

Figure 10. Graph of measured Angle of repose of pile of rapeseed model from RockyDEM.

The cone base (poured pile) in the model is 269 mm long. The base of the pile at the time of pouring was 293 mm long. Fig. 11 shows the proportional comparison between the poured pile and the rapeseed pile of the model. Because an angle of repose test verified the model's accuracy, it was possible to use the model to trace individual particles.

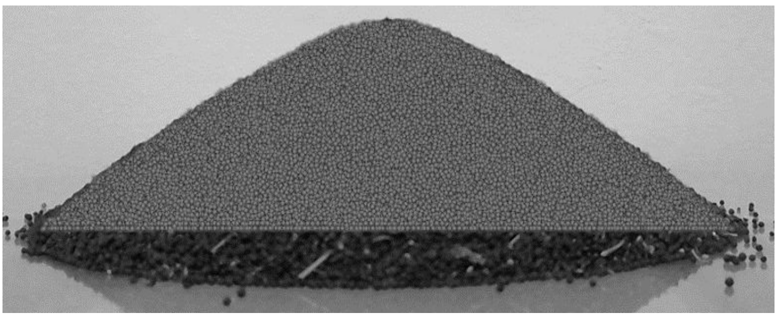

Figure 11. Comparison of rapeseed pile model and real test.

Results of the contrast point tracing

The data obtained and recalculated from DaVinci Resolve were compared with the data obtained from the model in Rocky DEM. To each particle traced in the real experiment were found two particles in the model, and their X, Y, and Z coordinates were exported to MS Excel. Fig. 12 compares the contrast point traces from the model and real test on the Y-axis and X-axis, and Fig. 13 shows the chart comparing the contrast point traces from the model and real test on the Y-axis and Z-axis. Fig. 12 and Fig. 13 show the trace the particle number 1. Seven out of nine particles could be traced from the measurements. For others, the trace failed due to poor visibility from the video due to particle overlap.

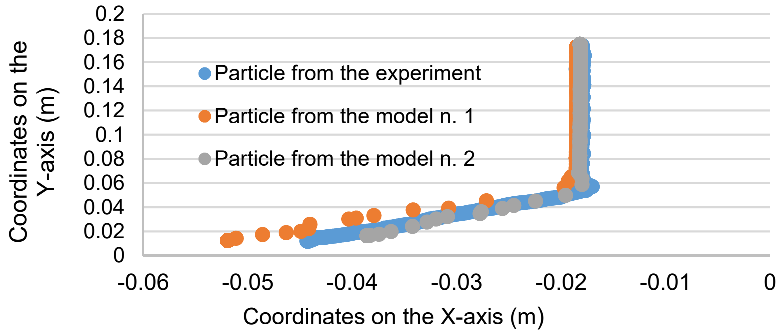

Figure 12. Comparison of contrast point traces from model and real test on X and Y-axis.

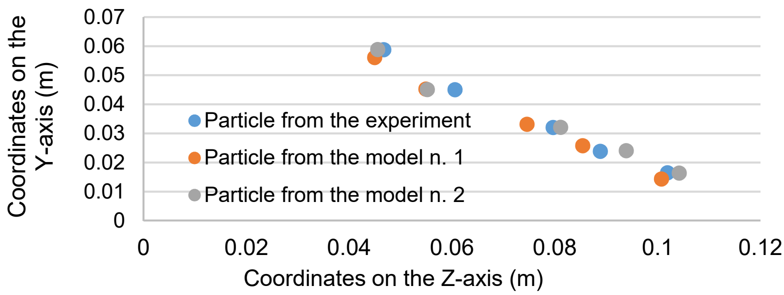

Figure 13. Comparison of contrast point traces from model and real test on Z and Y-axis.

The statistical evaluation

The results of statistical verification are seen in Table 2. These results show that seven traced particles out of nine were compared in each axis separately. The particle number refers to the order of the traced particle, according to Fig. 2. The *F*-Test column shows the resulting *p*-values that had values higher than the significance level of 0.05. This confirmed the hypothesis of equality of variances. The *t*-Test (the Equal Variances confirmation) column shows the resulting *p*-values that had values higher than the significance level of 0.05, except for particle 2 in X-axis. All comparisons were statistically significant except for particle 2 in X-axis. The average deviation was 3.77 m in X-axis, 0.55 mm in Y-axis and 1.7 mm in Z-axis.

Table 2. The results of statistical verification

Number of particle	Axis	*F*-Test	*t*-Test	Result
1	X	0.436	0.692	significant
	Y	0.486	0.991	significant
	Z	0.444	0.920	significant
2	X	0.071	0.017	insignificant
	Y	0.492	0.999	significant
	Z	0.427	0.870	significant
4	X	0.414	0.807	significant
	Y	0.498	0.975	significant
	Z	0.230	0.987	significant
5	X	0.105	0.287	significant
	Y	0.454	0.998	significant
	Z	0.326	0.995	significant
6	X	0.221	0.529	significant
	Y	0.310	0.999	significant
	Z	0.451	0.457	significant
8	X	0.329	0.079	significant
	Y	0.499	0.079	significant
	Z	0.484	0.074	significant
9	X	0.232	0.295	significant
	Y	0.232	0.992	significant
	Z	0.177	0.854	significant

DISCUSSION

The loose (particulate matter) consists of particles of various shapes and sizes but of the same loose particulate bulk density. Essentially, the particles create a statistical set, and therefore it is complicated to predict the matter's behaviour. Studying and monitoring the bulk material makes it possible to get an idea that helps predict the material's behaviour. However, the movement of a single particle can cause a domino effect of the entire mass of the matter. It is why tracing the particulate matter is difficult to measure and gain quality parameters.

The proposed method proved to be an affordable method for individual particulate matter movement surface monitoring. The video of particle movement is possible post-process with video processing software DaVinci Resolve. The method has been used, for example, by Hardy et al. (2017). However, they used fluorescent coating, so the light contrast was obtained, and data were post-processed by using Spyder (Scientific PYthon Development EnviRonment) script.

In order to preserve the maximal accuracy of the model, it is important to know not only the internal states of the system that is being examined but also take into consideration the external conditions affecting the system's behaviour. Incorrect entry values, poor computer model, or inappropriate selection of methods can lead to incorrect and misleading results. The length of the calculation, which is conditioned by the number and shape of the individual particulate particles, poses another risk. The more complex and numerous the material, the more time (multiplicatively) is needed to calculate the model. It is necessary to optimise the model parameters as well as the number of modelled particles and, at the same time, achieve sufficient model accuracy based on correlation verification with the real experiment (Wojtkowski et al., 2010).

The discrete element method can be used in the description of particulate particles, such as rapeseed. The given parameters are for moisture content of 6 % and the actual grain size of rapeseed. The possible change of boundary conditions must be considered when using a model with different grain ratios (Bravo et al., 2014).

CONCLUSION

This paper aimed to create the methodology for performing particle tracing using an optical contrast point method. The results obtained from the real test were statistically compared with the simulation and showed their statistical significance for all particles, except for one in one axis. The main conclusions can be summarised as follows:

- The proposed methodology is suitable for the verification of the DEM model.
- The trace of real particles from the original place is related to the average trace of the two nearest particles from the numerical model. The final position of traced particles was in the nearby area.
- The numerical model with relevant parameters can be used to predict the particulate matter movement with an accuracy of 3.77 mm in X-axis, 0.55 mm in Y-axis and 1.7 mm in Z-axis.

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