Calibrating the Physical Properties of Corn and Wheat using the Discrete Element Method

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I met Dr. Ambrose when I took his class during the fall of 2018. I enjoyed learning about the physical properties of biological materials. Dr. Ambrose asked me if I would be interested in joining his research group to learn and work with using the discrete element method to analyze grain. I began working with a graduate student in his group, Zhengpu Chen, who showed me how to use EDEM and helped guide me throughout the process.

This is a report of experimental work done with live experiments and in EDEM.
Abstract

Discrete element method (DEM) is a powerful modeling tool widely used to simulate granular materials. Recently, discrete element methods have become popular in the modeling of the behavior of grain in post-harvest processing. The accuracy of the DEM simulations is greatly affected by the model input parameters. However, precisely quantifying the physical properties of the grain kernels to input as a model parameter remains a challenging task. In previous studies, new methods of determining the physical properties of corn and wheat kernels for DEM simulations were proposed to estimate the model parameter values. This study aims to evaluate the accuracy of the measured model parameters by comparing with the bulk material tests, i.e. bulk density test, angle of repose test, and tilting box test, with the corresponding DEM simulations. The simulation results were in good agreement with the experimental measurements. The validated input parameters were used to perform simulations on the change in angle of repose when a grain pile is moved, as to predict the angle of repose of the pile in a moving grain cart. The simulations indicated that the angle of repose of the moving pile is smaller than the original static angle of repose of the grains. This result will be useful to estimate the grain fill level in grain carts during harvesting and the quantity of grains in the grain cart as influenced by the movement and vibration in grain cart.

Keywords: Grain Kernel, Grain Handling, Discrete Element Method, Angle of Repose

1. Introduction

Flowing grain can sometimes be modeled like continuum fluid flow, however, this depends largely on the energy associated with the flow(Boac et al., 2014). Because the kernels are discrete
particles with varying properties, typical methods like finite element and finite volume analysis cannot be used, as they take into account the uniformity of a material or substance. To better analyze systems where discrete particles are used, the discrete element method was developed (Cundall and Strack, 1979). The method has been commonly used by the mining and pharmaceutical industry but is being increasingly seen by the grain industry as a way to model the properties and behaviors of grains throughout the harvest, post-harvest, and pre-processing stages. To conduct these DEM simulations, computer programs like EDEM, Rocky, LIGGHTS, etc are commonly used.

The DEM can monitor, calculate and analyze the particle-particle interactions during deformation, discontinuous movements, or during fracture. DEM enables the monitoring of particle interactions at each contact. In addition, the translational and rotational displacement are modeled particle by particle. Various contact models and force-velocity-displacement laws are applied used to predict these particle-particle interactions (O’Sullivan, 2011). Cundall and Strack (1979) proposed a simple spring-dashpot model from which many complex and accurate contact models were developed. In the Cundall and Strack model, the spring relates to the elastic deformation and the dashpot relates to the viscous dissipation. The contact models uses various particle properties such as size, shape, density, elastic modulus, coefficient of friction, and coefficient of restitution to accurately predict the particle-particle interaction and the particle positions as influenced by the interaction. However, the major challenge of DEM method is the need for accurate particle properties that is difficult to obtain for materials of biological origin. The physical properties of grain kernels vary based on the moisture content, variety, hybrid, growing location, weather conditions, etc. So, the major goal of this paper is to calibrate the physical properties of grains using DEM simulations. The objectives of this work are: i) to
calibrate the bulk density, static angle of repose of corn and wheat kernels, and ii) to study the effect of grain cart movement on angle of repose by simulating the angle of repose of grain kernels under vibration.

2. Methods

2.1 Lab Experiments

Experiments for bulk density test, angle of repose test, and tilting box test were conducted in the lab. The corn and wheat samples used in the tests were acquired from a farm located at Covington, Indiana. The moisture content for the corn was 14.7% wet basis and the moisture content for the wheat was 13.9% wet basis. The experimental procedures are explained below.

2.1.1 Bulk Density

A Winchester cup setup (Seedburo Equipment Co., Des Plaines, IL) was used to measure the bulk density, where a funnel with a sliding door was placed on a ring stand above a cup of a known volume. In these experiments, the volume of the cup used was one dry US pint or approximately 0.00057 m³. Before the experiment, the mass of the empty cup was recorded. The funnel was filled about two thirds of the way full of grain. The door at the bottom of the funnel was opened, allowing the grain to flow freely into the cup. The grain was allowed to overflow into a pan. A wooden stick was used to level off the cup, and then the cup was weighed with the grains. The mass of the empty cup was subtracted from the mass of the full cup to give us the mass of the grain. The mass of the grain was divided by the volume of the cup to get the bulk density of the grain, as shown in Equation 1,

\[ BD = \frac{m}{v} \]  (1)
where \( BD \) represents the bulk density in kg/m\(^3\), \( m \) represents the mass in kg, and \( v \) represents the volume of the cup in m\(^3\). The test was repeated three times for corn and wheat samples to obtain an average and standard deviation for the data set.

### 2.1.2 Angle of Repose

For angle of repose measurement, an apparatus similar to the bulk density experiments was set up, with a funnel suspended over a pan. Grain was poured into the funnel at a rate that allowed the funnel to fill. After the pile was formed, a digital caliper was inserted into the center of the pile to find the peak height. The height of the pan was subtracted from the pile height, giving the height of the triangle formed by the height of the pile and the radius of the pile and pan. Using trigonometric relationships, the angle of repose was calculated using Equation 2,

\[
\theta = \tan^{-1}\left(\frac{h}{r}\right)
\]  

(2)

where \( \theta \) is the angle of repose, \( h \) is the height of the pile, and \( r \) is the radius of the pan. The test was also repeated three times for both wheat and corn kernels.

### 2.1.3 Tilting box test

The third experiment that was conducted was the tilting box test to measure the angle of slippage. This test was done using the apparatus shown in Figure 1. The box was filled with grain and leveled off with a wooden stick. The box was raised slowly until grain began to slide off of the top. Videos of the tests were recorded and was analyzed using a protractor app on a phone. To ensure false readings were not taken just when the first particle moved, the tilting box test was taken when the particles appeared to move in mass in the video. The test was repeated three times and the average and standard deviation for the angle was calculated.
2.2 DEM Simulations

Each of the above experiments was run as a simulation in EDEM software (DEM Solutions Ltd., Edinburgh, UK). For all of the simulations, the materials were developed based off of measurements taken across several kernels of both wheat and corn. The materials are made up of different variations of these particles, to make up for the variation that occurs in the particles themselves. The parameters that defined the particle-particle and particle-material interaction were taken from Horabik and Molenda (2016). The values of the parameters are shown in Table 1 and were used for all simulations. The shape of the particles simulated were made up of individual spheres representing the approximate shape of the grain. The geometries were created in EDEM using the built-in modeling tools.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Coefficient of Restitution</th>
<th>Coefficient of Static Friction</th>
<th>Coefficient of Rolling Friction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle-Particle (Corn-Corn)</td>
<td>0.254</td>
<td>0.23</td>
<td>0</td>
</tr>
<tr>
<td>Particle-Material (Corn-Steel)</td>
<td>0.612</td>
<td>0.138</td>
<td>0</td>
</tr>
<tr>
<td>Particle-Material</td>
<td>0.595</td>
<td>0.138</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 1: Grain kernel input parameters used in the DEM simulations.
For each simulation, a uniform time step, cell size and save interval was used for each grain. This was to normalize the simulations with respect to one another. The time step was selected to be 20% of the Rayleigh time step. This value was chosen, because too large of a time step causes the particle penetrate through the geometry, and too small of a time step can exponentially increase the run time for the simulation, which is unnecessary. The simulation setting parameters are shown below in Table 2.

<table>
<thead>
<tr>
<th>Grain type</th>
<th>Time Step (s)</th>
<th>Data Save Interval (s)</th>
<th>Simulation Grid (R min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Corn-Cup)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Particle-Particle (Wheat-Wheat)</td>
<td>0.5</td>
<td>0.51</td>
<td>0</td>
</tr>
<tr>
<td>Particle-Material (Wheat-Steel)</td>
<td>0.5</td>
<td>0.325</td>
<td>0</td>
</tr>
<tr>
<td>Particle-Material (Wheat-Cup)</td>
<td>0.4</td>
<td>0.1</td>
<td>0</td>
</tr>
</tbody>
</table>

The following sections discuss the simulation setups in EDEM. They were meant to mimic the real-life experiments, but due to the nature of the program, slight modifications were made. It was determined that the modifications have little effect on the grain flow behavior.

2.2.1 Bulk Density

The geometry for the bulk density simulation was based on the geometry of the experimental apparatus used in this study. The simulation setup of bulk density test in EDEM can be seen in Figure 2. This simulation was run with both corn and wheat. All of the geometry materials were set to steel. The dimensions of the cup were measured and used to create a cylinder
in EDEM. The height of the funnel above the cup was approximated, and the size of the orifice in EDEM was larger than the size in the experimental set-up. With a small orifice, it was common for the particles to interlock and clog at the hopper outlet, since the particles are made up of individual spheres and are not smooth like the real grain kernels. Slightly increasing the orifice diameter alleviated this problem. The door was opened within one second to simulate the quick opening of the door during experimental measurements. The leveling stick was set to move in a zig-zag pattern to sweep off the kernel above the cup. After the completion of the simulation, a “density sensor” was defined to obtain the bulk density.

![Figure 2: Bulk density geometry set up for DEM simulation.](image)

### 2.2.2 Angle of Repose

The geometry for the angle of repose experiment was also modeled based on the geometry used for experimental measurements. The simulation setup used in this study is presented in Figure 3. This simulation was run with both corn and wheat, and the material for all the geometries was set to steel. Similar to the bulk density test simulation, the diameter of the orifice was increased to avoid the interlocking problem that was discussed above. In the simulation, a door was used at the
outlet of the hopper to hold the particles in the funnel. This was necessary to acquire a more controlled flow instead of a few particles coming through at a time. When the particles flowed through individually, they had the tendency to miss the pan. Allowing the particles to congregate in the funnel first created a steady flow out, which helped develop a pile and minimized the number of particles missing the pan. In EDEM software’s “Analyst” module, a protractor tool was used to measure the angle of the pile from the top of the pan to the pile.

![Figure 3: Angle of repose geometry set up used in DEM simulations.](image)

### 2.2.3 Tilting box test

To conduct the tilting box test experiment, a box was first created to match the geometry similar to the experimental setup, as shown in Figure 4. This experiment was conducted on both corn and wheat. The material of the box was set to “Cup” which has the properties of a plastic. The grain was generated above the box and allowed to fall in. Once the box was filled, it was set to rotate about an axis along the edge of the box. Using the frame-by-frame feature in EDEM “Analyst”, it was easy to determine when the particles began to slip. By setting the particles to be represented by velocity vectors, the number of particles in relative motion could be easily seen. When the top level of grains had a velocity greater than 0.165 m/s This value was determined by
examining the grain in the surrounding box. The velocity of grain at the farthest edge of the box was around this velocity the entire motion, so any value greater than this would indicate slippage. Once enough grain reached that velocity, the point where this occurred was determined to be the angle where the grain would slide against itself. The angle was measured in “Analyst” using the protractor tool.

2.2.4 Angle of Repose under Vibration

Simulation of corn and wheat angle of repose under vibration was conducted using EDEM software. This simulation was conducted once the other properties mentioned above had a good agreement with the simulation results. The material of the geometry was defined as steel. The simulation from the angle of repose experiment was exported to a new simulation, with the final time step in the angle of repose experiment set as time zero. A sinusoidal translation was added to the pan, where it would oscillate back and forth once in a 10-second interval. The displacement of the pan was set to 50 mm, and the frequency at 0.1 Hz. This created a slow, sinusoidal motion of the pan. After the simulation was completed, the protractor tool was used to
determine the geometry of the triangle. The new angles of repose were subtracted off of the original angle of repose to determine the change.

3. Results

3.1 Bulk Density

The results of the bulk density experiments are shown in Table 3. It could be observed that the DEM simulations predicted the bulk density of grain kernels with reasonable accuracy. There was a larger variation in the experimentally measured bulk density of corn compared with the wheat kernels, which also help explain the larger percent error between the experimental and simulated bulk density of corn kernels.

Table 3: Experimental and simulated bulk density of corn and wheat kernels.

<table>
<thead>
<tr>
<th>Grain</th>
<th>Simulation result (kg/m³)</th>
<th>Experimental result (Average) (kg/m³)</th>
<th>Standard deviation of experimental result</th>
<th>Percent error between predicted and measured values (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>806.50</td>
<td>767.20</td>
<td>3.18</td>
<td>5.12</td>
</tr>
<tr>
<td>Wheat</td>
<td>730.54</td>
<td>739.66</td>
<td>1.92</td>
<td>1.23</td>
</tr>
</tbody>
</table>

3.2 Angle of Repose

The results for the angle of repose are shown in Table 4. A large difference between the experimental and simulated results was observed for the angle of repose test. Even with a much larger variation, it could be seen that the trend was similar to the bulk density experiments. There was a larger variation in the experimentally measured angle of repose of corn, and less for wheat, which translates to a larger percent difference for corn than wheat. The variation could also be due to the differences between the setups for the live experiment and the simulation, however, some of these differences are present in the bulk density experiments.
Table 4: Experimental and simulated angle of repose of corn and wheat kernels.

<table>
<thead>
<tr>
<th>Grain</th>
<th>Simulation result (degrees)</th>
<th>Experimental result (degrees)</th>
<th>Standard deviation of experimental Result</th>
<th>Percent error between measured and predicted values (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>30.63</td>
<td>21.81</td>
<td>0.68</td>
<td>40.44</td>
</tr>
<tr>
<td>Wheat</td>
<td>28.07</td>
<td>20.91</td>
<td>0.19</td>
<td>34.27</td>
</tr>
</tbody>
</table>

3.3 Tilting box test

The results for the tilting box test are shown in Table 5. There was a large difference between the experimental and simulated results. But the variation between the live and experimental results was lesser than the bulk density or angle of repose measurements. Because of the way that the angle of slippage was measured from the live experiments, there could be some slight distortion of the angle due to the angle the video was taken. To minimize this, assuring the camera is perpendicular to the box may improve the results.

Table 5: Experimental and simulated tilting box tests for corn and wheat kernels.

<table>
<thead>
<tr>
<th>Grain</th>
<th>Simulation result (degrees)</th>
<th>Experimental result (Average) (degrees)</th>
<th>Standard deviation of experimental measurement</th>
<th>Percent error between experimental and simulated values (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>44.15</td>
<td>34.00</td>
<td>3.61</td>
<td>29.85</td>
</tr>
<tr>
<td>Wheat</td>
<td>34.22</td>
<td>38.67</td>
<td>3.51</td>
<td>11.50</td>
</tr>
</tbody>
</table>

3.4 Angle of Repose under Vibration

The results for the angle of repose under vibration are shown below in Table 6 for both grains. It could be observed that there was a decrease in angle of repose under vibration. The larger change in the angle of repose for corn could be because of more settling occurred with the
corn than with the wheat. As there is larger pore space between the corn kernels than wheat kernels. The porosity of wheat is (on average) 0.30 (Babić et. al. 2011) and the porosity of corn is (on average) 0.39 (Babić et. al. 2013). Looking at the simulations, not many particles fall off of the pile, so most of the change would be caused by settling within the pile. This simulation indicates that, during harvest and when grains are filled in grain carts, during movement of grain carts grains would tend to settle first before sliding that leads to a change in angle of repose. As shown in Table 6, the conical pile of corn had a large change in volume, while the conical pile of wheat only had a slight change. By the volume of a pile changing, it would be possible to fit more grain into a grain cart, lowering the amount of time, and trips required by the operator to unload onto a truck or wagons, increasing the efficiency of transporting the grain.

Table 6: Angle of repose of corn and wheat kernels under vibration (simulation values used).

<table>
<thead>
<tr>
<th>Grain</th>
<th>Angle of Repose before vibration</th>
<th>Angle of Repose after vibration (degrees)</th>
<th>Change from static angle of repose</th>
<th>Volume of Conical pile before vibration (mm³)</th>
<th>Volume of conical pile after vibration (mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>30.63</td>
<td>22.95</td>
<td>-7.68</td>
<td>2.71 x 10⁵</td>
<td>1.94 x 10⁵</td>
</tr>
<tr>
<td>Wheat</td>
<td>28.07</td>
<td>27.80</td>
<td>-0.27</td>
<td>2.44 x 10⁵</td>
<td>2.41 x 10⁵</td>
</tr>
</tbody>
</table>

**Conclusion**

This study confirmed that DEM simulations of grain particles would provide a reasonable approximation for analyzing grain handling systems using the discrete element method. Some of the simulated properties were more accurate indicating that particle properties play a major role in bulk grain characteristics. Across all experiments, the difference between the measured and experimental were always larger for the corn than for the wheat. This shows that
while DEM programs like EDEM may not prove 100% accurate to live experiments, the behavior between simulations is consistent, and it is necessary to determine the parameters to accurately replicate the live and electronic systems. For future work, there are several changes and improvements that need to be made to improve the accuracy of predictions. For the bulk density simulations, the motion of the leveling stick could be improved to ensure that three strokes are used to level the cup off. For the static angle of repose estimations, it will be important to ensure that the setup used for simulations matches exactly to the experimental measurement setup with this study indicating that a small difference could affect the results. For the tilting box tests, as discussed in Results section, it would be best to get an experimental set up where the camera is perpendicular to the box to ensure that there is no distortion in the image that will cause some error in interpretation. For the angle of repose under vibration measurements, it would be better to determine the actual frequency of a grain cart or wagon would rock or move back and forth while traveling through the field, as well as introducing a more complex motion than just moving side to side would help improve the predictions.

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References


