DISCRETE ELEMENT METHOD SIMULATION OF RICE GRAIN STACKING CHARACTERISTICS
/
水稻籽粒堆积特性离散元法模拟研究

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ABSTRACT
Accurately determining the angle of repose for irregular and dispersed agricultural grain materials requires a simulation model that effectively represents the actual grain shapes and utilizes numerical methods to analyze their stacking behavior. This study focuses on "Yongyou 15" rice grains, employing 3D raster scanning technology to obtain precise contour data. Through a reverse modeling process, a detailed 3D geometric model of the grains was developed, resulting in a discrete element model comprising 618 grains of varying diameters, created using granular polymer theory. Discrete element analysis software (EDEM) was integrated with MATLAB image processing to simulate the falling and stacking process of the rice grains within a stainless steel bottomless cylindrical tube. The contour of the grain heap was analyzed using linear fitting, followed by a micro-mechanical investigation of the grain heap structure. The analysis indicated that the pressure depression within the heap is caused by the oblique transmission of contact forces. The simulated angle of repose under experimental conditions was 31.29°±0.41°, differing by only 0.81% from the actual measured angle of 31.04°±0.21° obtained through physical stacking experiments. These results demonstrate that combining numerical simulations with image feature extraction is a reliable and efficient method for assessing the stacking properties of agricultural materials.

摘要
为了准确确定不规则、分散的农业物料籽粒的休止角，需要建立与真实物料形状高度相似的籽粒仿真模型，并采用数值方法对物料的堆积特性进行仿真研究。本研究以"甬尤 15 号"水稻籽粒材料为例，利用三维光栅扫描技术获取籽粒的轮廓数据，采用逆向建模过程生成籽粒的三维几何模型，基于颗粒-聚合物理论建立由 618 个不等径颗粒组成的水稻籽粒离散元模型。利用离散元分析软件 EDEM 和 MATLAB 图形图像处理技术，模拟了水稻籽粒在不锈钢无底圆柱形管中落料和堆积过程，并对堆积图像轮廓采取线性拟合，同时对籽粒堆微观力学结构进行研究，得到籽粒堆压力凹陷的原因，来自籽粒堆内部接触力的斜向传递特征。模拟试验条件得到休止角为 31.29°±0.41°，与实际堆积试验休止角 31.04°±0.21°对比，偏差为 0.81%。结果表明，数值模拟结合图像特征提取的方法对测量农业物料堆积特性有效可行。

INTRODUCTION
In agricultural engineering, grain materials play a critical role as the primary operational medium for agricultural machinery, influencing its efficiency and performance through their dynamic response behaviors and contact interactions. During the stacking process, grains exhibit complex motion states that reflect key properties such as flow, scattering, and friction. Analyzing the stacking behavior of these materials holds substantial scientific and engineering importance, providing essential insights and practical guidance for enhancing agricultural machinery operations.

With the continuous development of computer technology, the discrete element method (DEM) has become a widely used tool for simulating grain materials (*Zeng et al., 2021; Wen et al., 2020; Zhang et al., 2022; Wang et al., 2020; Hu et al., 2023*). *Shu et al. (2023)* focused on agricultural particle characteristics and calibrated DEM parameters for rapeseed discharge during combined harvesting, validating these parameters through cleaning platform experiments and CFD-DEM gas-solid coupling tests.

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Similarly, *Ma et al., (2020), Hao et al., (2021), Shi et al., (2020),* and *Zhang et al., (2020),* calibrated DEM parameters for various grains, including alfalfa seeds, sunflower seeds, flax seeds, and corn grains, providing essential reference data for agricultural material simulations. Accurate simulations of agricultural materials require calibration of both the intrinsic material properties and contact parameters (*Wu et al., 2020; Shi et al., 2019; Zhang et al., 2022*). Numerical methods not only serve as an efficient alternative to direct measurements but also allow predictions of grain behavior under specified stacking conditions. For instance, *Jia et al., (2014),* employed a discrete element stacking approach using nine filled spheres to model rice grains. However, the significant disparity between the model and actual grain shapes led to reduced simulation stability. *Zhang et al., (2020)*, explored the influence of varying the radii of filled spheres on grain dynamics, discovering that smaller radii yielded results closer to experimental observations. Recently, advancements in 3D scanning technology have facilitated reverse modeling of grain shapes and solid particle morphology with higher precision, offering a powerful tool for improving the accuracy of grain material simulations (*Lumay, Boschini & Traina, 2012*).

The discrete element method (DEM) analyzes the macroscopic behavior of granular flows by iteratively calculating the motion dynamics of individual particles within the medium (*Ajayi & Sheehan, 2012*). In this research, DEM is utilized to simulate the formation process of a rice grain heap as it flows through a bottomless stainless steel cylinder. MATLAB is employed to process grain heap images, enabling the analysis of stacking properties such as the angle of repose and internal contact forces. This study introduces a numerical simulation and prediction approach for the stacking behavior of agricultural grains, offering key DEM model parameters for the development and optimization of rice sowing and harvesting machinery.

MATERIALS AND METHODS

Main structure and working principle

This research focuses on simulating the small-scale static stacking behavior of rice grains. Due to the low moisture content of the grains during the harvest season, adhesive forces are negligible. The displacement, force, and velocity of the grains during stacking are primarily influenced by the extent of overlap between the grains and the contact surfaces. The accuracy of the simulation outcomes largely depends on the selected contact model in the DEM. In this study, the Hertz-Mindlin mechanical model is adopted to simulate contact interactions during the stacking process, as depicted in Fig 1. This model simplifies the collision forces at contact points by decomposing them into normal and tangential components, which are represented using a parallel system of springs and dampers.

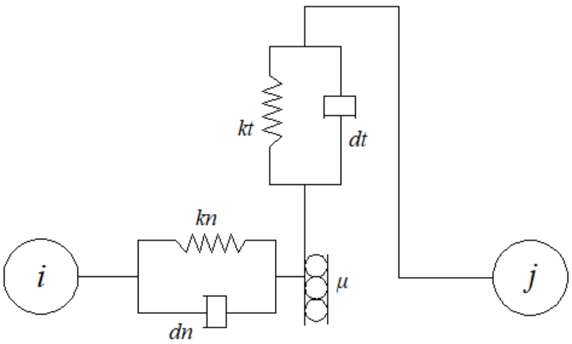


Fig. 1 – Hertz-Mindlin contact model

The model was applied to calculate the forces acting on a given granule i during the rice grain stacking process. These forces include the granule weight $m_i g$, the normal collision contact force F_n between granules, the normal damping force, the tangential collision force F_t, and the tangential damping force. Based on Newton's second law, the translational motion equation for each granule can be expressed as follows.

$$m_i \frac{dv_i}{dt} = m_i g + \sum_{j=1}^{n_i} \left(F_n + F_n^d + F_t + F_t^d \right) \tag{1}$$

Moreover, rice grains are also subject to the actions of tangential torque T_t and rolling friction torque Tr:

$$I_i \frac{d\omega_i}{dt} = \sum_{j=1}^{n_i} \left(T_t + T_r \right) \tag{2}$$

where m and I are the mass and rotational inertia of the granule, respectively; n_i represents the total number of granules in contact with the granule i; v represents the movement speed of the granule; ω_i is angular velocity; and t denotes time.

During the stacking process of rice grains, contact collisions occur either between grains or between grains and other objects. These collisions result in small elastic deformations at the contact points, generating a degree of overlap to counteract the forces involved. The tangential collision force F_t is constrained by Coulomb's friction force $\mu s F_n$ where μs represents the static friction coefficient. If the tangential collision force exceeds the Coulomb friction force, the grains will slide along the contact surface, and in such cases, F_t is primarily determined by $\mu s F_n$. Based on the equations provided in Table 1, rolling motion occurs during the stacking process due to the interplay between tangential torque and rolling friction torque. Rolling friction torque, which depends on the rolling friction coefficient μr, was incorporated into the model to account for its influence on the degree of resistance to grain rolling.

Table 1

The forces and moments experienced by the grain in motion

Force and moment		Unit	Formula derivation
Normal force	Contact force	F_n	$F_n = \frac{4}{3}E^*\left(R^*\right)^{1/2}\delta_n^{3/2}$
	Damp force	F_n^d	$F_n^d = -2\sqrt{\frac{5}{6}}\cdot\frac{\ln e}{\sqrt{\ln^2 e+\pi^2}}\cdot\sqrt{S_n m^*}v_n^{rel}$
Tangential force	Contact force	F_t	$F_t = -S_n\delta_t$
	Damp force	F_t^d	$F_t^d = -2\sqrt{\frac{5}{6}}\cdot\frac{\ln e}{\sqrt{\ln^2 e+\pi^2}}\cdot\sqrt{S_t m^*}v_t^{rel}$
Frictional force	Torque	T_t	$T_t = R_i\times\left(F_t+F_t^d\right)$
	rolling friction torque	T_r	$T_r = -\mu_r F_n R_i\hat{\omega}$

where E^* is equivalent elastic modulus; R^* is equivalent granule radius; δ_n and δ_t denote normal and tangential overlaps, respectively; S_n and S_t represent normal and tangential stiffness, respectively; e is recovery coefficient; v_n^{rel} and v_t^{rel} are normal and tangential relative velocity, respectively; m^* is equivalent mass; $\hat{\omega}$ is the unit angular velocity of the object at contact point; μ_r is rolling friction factor.

Modeling of Rice Grains

Rice grains possess a complex geometry with significant variations in curvature, making it challenging for traditional modeling techniques to accurately capture their physical characteristics. Advanced digital imaging and CT scanning technologies have been utilized in discrete element modeling to achieve more precise material representations (*Du et al., 2012*). This study focused on the "Yongyou 15" rice variety, employing 3,500 unthreshed and unsorted grains to construct a detailed 3D model (*Yu et al., 2014*). A 3D laser scanner was used to obtain point cloud data of the grains, as illustrated in Figure 2a. This data was processed to reconstruct a 3D solid model of the grains, as shown in Figure 2b. The finalized 3D model was imported into EDEM software, where the particle properties were configured with a smoothing value of 8 and a minimum grain radius of 0.2. Using the software's automatic packing module, a discrete element model consisting of 618 grains with varying diameters was successfully developed, depicted in Figure 2c.

a) Point cloud data *b) 3D model* *c) Discrete element model*

Fig. 2 - Three- dimensional model of rice grain

Modeling of contact geometry parameters and model stacking

This research examines rice grains and utilizes the discrete element method (DEM) to simulate their stacking behavior. A bottomless stainless-steel cylindrical tube is employed to guide the material flow, with simulation parameters determined based on relevant studies, as summarized in Table 2.

Table 2

Material parameters used in simulation

Parameters	Value
Poisson's ratio of rice grain	0.25
Shear modulus of rice grain / MPa	86.5
Density of rice grain / (kg·m^{-3})	1086
Poisson's ratio of stainless steel	0.29
Shear modulus of stainless steel / MPa	75000
Density of stainless steel / (kg·m^{-3})	7800
Coefficient of restitution between rice grains	0.81
Coefficient of static friction between rice grains	0.35
Coefficient of restitution between rice grain and stainless steel	0.40
Coefficient of rolling friction between rice grains	0.01
Coefficient of static friction between rice grain and stainless steel	0.56
Coefficient of rolling friction between rice grain and stainless steel	0.02

The dimensions of the stainless-steel cylindrical tube were determined based on the size of the rice grains. Specifically, the tube diameter was set to be 4–5 times the maximum grain diameter, with a height-to-diameter ratio of 3:1. Given the average rice grain length of 7.6 mm, a tube with a diameter of 40 mm and a height of 120 mm was selected. Using the Geometry module in the EDEM software, a discrete element model of the cylindrical tube was created with these specifications and appropriate material properties. This model was used to simulate the dropping and stacking of rice grains both within the cylindrical tube and on a stainless-steel plate. The Particle Factory module in EDEM, positioned above the tube, dynamically generated three-dimensional models of rice grains that fell into the tube. Once the tube was filled with these grain models, it was slowly lifted vertically away from the plate, enabling the grains to form a heap on the plate.

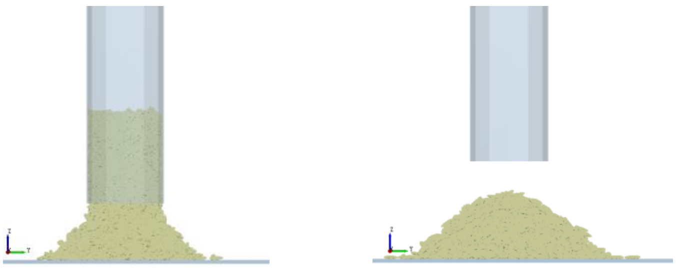


Fig. 3 – Stacking simulation of rice grain

When simulating the stacking process of a 3D rice grain model using a bottomless stainless-steel cylindrical tube, several key factors must be taken into account. These include the shape and properties of the grain model, such as static friction, rolling friction, and the restitution coefficient, as well as the specifications of the cylindrical tube. Additionally, the lifting speed of the tube plays a crucial role in determining the formation of the grain heap. To prevent the heap from spreading excessively, which could affect the accuracy of the repose angle measurements, a slower lifting speed is employed to maintain the heap's stability. A lifting speed of 1 mm/s was chosen to minimize edge diffusion and preserve the structural integrity of the heap.

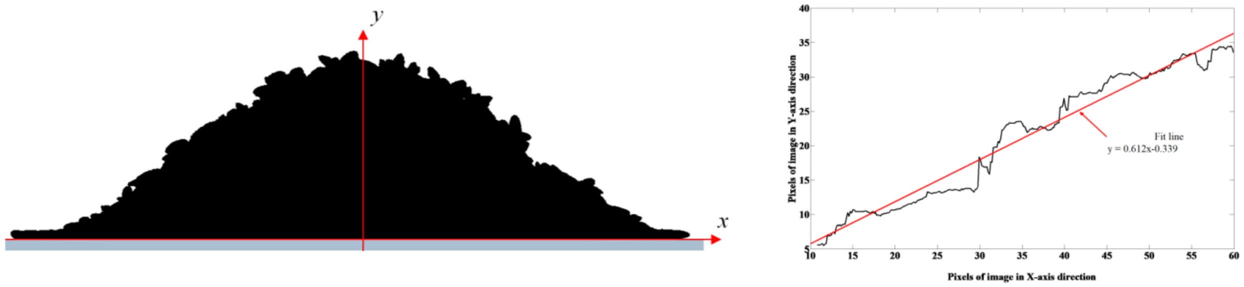
Measurement of the Repose Angle

After generating the 3D model of the rice grain heap, the angle of repose is calculated using image processing techniques. In this process, the x and y coordinates correspond to pixel values, which do not have physical units. The rice heap image is symmetrically divided into left and right halves, as shown in Figure 4a.

MATLAB image processing tools are then employed to extract and binarize the boundary contours of the heap on one side. These contours, detected in grayscale as illustrated in Figure 4b, are analyzed to identify the slope boundary of the grain heap. The boundary is subsequently fitted linearly, and the resulting equation is used to calculate the slope, denoted as k. The final angle of repose is then determined using Equation (3).

$$\theta = \frac{\arctan|k| \times 180^{\circ}}{\pi} \tag{3}$$

In this study, the stacking angle of rice grains, denoted as θ, is numerically measured using the slope (k). Given that the stacking process of rice grains exhibits a degree of randomness, accurate measurement of the repose angle requires careful analysis. The angle of repose was measured using image processing along both the x and y axes, with measurements taken five times in each direction, as illustrated in Figure 4. This approach ensures a reliable and precise determination of the stacking angle.



(a)Stacking diagram at y-axis perspective

(b) Unilateral stacking diagram in x axis direction

Fig. 4 –Stacking results of rice grains in different directions

Using the same method, the repose angles of the rice heap from five repeated simulations were measured as 30.71°, 31.47°, 31.05°, 31.93°, and 31.27°. The average angle of repose was calculated to be 31.29°, with a standard deviation of 0.41°. Thus, the angle of repose obtained from the discrete element method simulation for the rice grains is 31.29° ± 0.41°.

Verification test of stacking

To validate the accuracy of the angle of repose prediction method, natural stacking tests were conducted using real rice grains, a stainless-steel cylinder, and the necessary equipment. Since grain moisture content significantly affects its physical properties, the rice grains were conditioned to a moisture content range of 16%-20% to closely align with the simulation conditions, based on physical and mechanical parameters from literature on the collision mechanics of harvested grains. The specifications of the stainless-steel cylinder were set to match those used in the simulation. To ensure consistency between the simulated and experimental conditions, post-processing tools in EDEM software were used to count the number of grains in the cylinder, which amounted to 3,500 grains with a total mass of 101.15 grams.

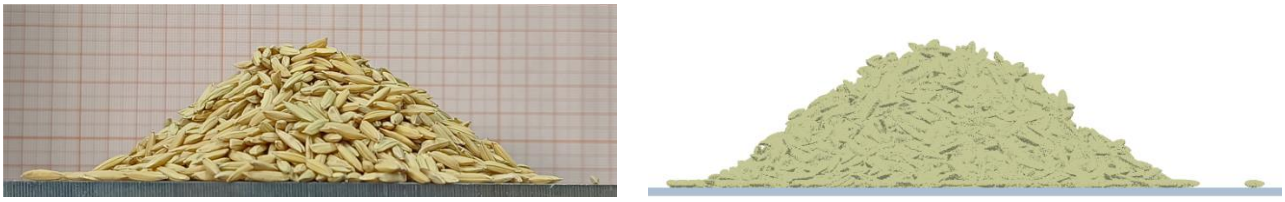
Fig. 5 – Physical stacking test

Angle of repose of rice grains was measured with the conventional method several times in different directions in the test, so as to obtain the bottom diameter d and height h of grain stack and take their averages. The actual test angle of repose θ′ was calculated by Equation (4).

$$\theta' = \arctan(\frac{2h}{d}) \tag{4}$$

where θ' is the measured angle of repose of rice grains; h and d are the stacking height and diameter of rice grains, respectively.

The experimental procedure to measure the natural angle of repose involved filling the cylinder with rice grains, which were then lifted using a microcomputer-controlled electronic universal testing machine at a constant speed of 1 mm/s, in alignment with the simulation conditions. After the rice grains had settled and the heap's slope surface stabilized, the angle of repose and related measurements were recorded. This process was repeated five times, resulting in the following natural repose angles: 30.82°, 31.21°, 31.16°, 31.25°, and 30.74°. The average natural angle of repose was calculated as 31.04°, with a standard deviation of 0.21°, yielding a final repose angle of 31.04° ± 0.21°.



a. Verification test b. Simulation test

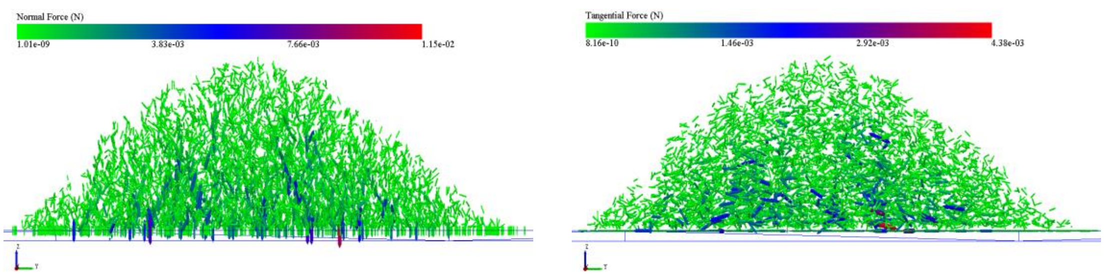
Fig. 6 – Simulation and experimental comparison of natural stacking angle of repose of rice grains

Fig. 6 compares the natural and simulated rice grain heaps, showing that while the overall stacking forms are similar, there is a slight difference in the smoothness of the slope surface. This variation can be attributed to the simulation's use of uniform geometric dimensions for the rice grains, while in reality, even after screening, individual grains exhibit minor irregularities. Additionally, the simulated angle of repose is slightly higher than the natural one. This discrepancy arises because the simulation model employs multi-sphere aggregates, which increase the contact area between adjacent grains, thus enhancing friction and reducing the flowability of the grains. The error between the simulated and natural angles of repose is 0.80%, indicating that the material parameters used in the discrete element method, along with the image processing techniques, provide a reasonably accurate simulation of the stacking behavior of rice grains.

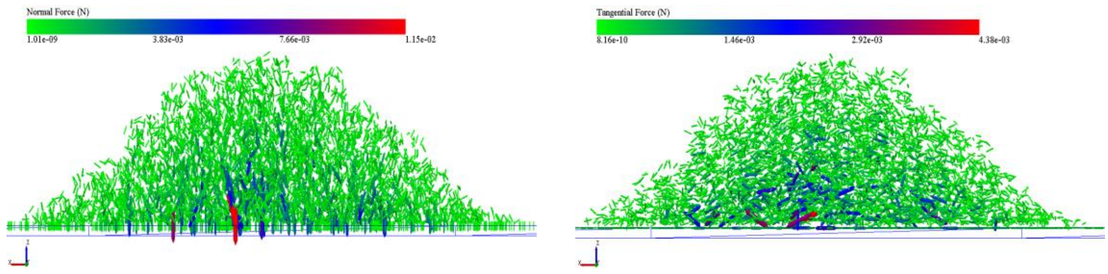
Analysis of Contact Forces in Grain Heap

To gain a deeper understanding of the stacking characteristics of rice grains, the contact force chains within the grain heap were visualized by hiding the geometric body and particle models.

This approach allowed for a clearer examination of the micro-mechanical structure of the heap. Figure 7 illustrates the distribution of contact forces within the grain heap, where the magnitude of the forces is represented by different colors. Stronger forces are depicted as strong force chains, while weaker ones are identified as weak force chains. Given the nearly symmetrical structure of the grain heap, statistical analysis was performed on the contact forces in just one-half of the heap.



a) -x Normal force b) -x Tangential force



c) -y Normal force d) -y Tangential force

Fig. 7 – Contact force under grains heap

Overall, the strong force chains are primarily distributed from the mid-lower layers to the base of the grain heap. These chains display an uneven spatial distribution, being relatively sparse but exerting significant localized forces. The peak values of the strong force chains are concentrated at the points where the grains contact the base of the heap. In contrast, weak force chains are more numerous and dispersed throughout the entire heap, especially in the surface and upper to mid-layers, where their spatial distribution is more uniform. Due to the weight of the grains, the contact forces in the superficial layers are generally smaller, while those within the heap are larger. The contact forces form an anisotropic, tree-like chain structure that mirrors the overall shape of the grain heap. Notably, strong force chains extend from the center to the periphery, creating an arch-like force chain structure. This behavior likely arises from several factors during the stacking process, particularly the random spatial and temporal distribution of individual grains. Consequently, the contacts between grains are mostly random, causing the transmission of gravitational loads within the heap to deviate from the direction of the primary vertical force chains.

CONCLUSIONS

The discrete element method (DEM) was used to simulate the stacking process of rice grains, and the resulting stacking image was processed using image processing technology. The angle of repose of the grain material, determined from the simulated heap, was 31.29°. This value was in close agreement with the experimental result of 31.04°, yielding a deviation of only 0.81%. This demonstrates that the angle of repose of grain material can be accurately measured under simulation conditions using this method. Through the analysis of the distribution patterns of the principal force chains within the rice grain heap and the observed anisotropy in normal contact forces between the grains, the underlying cause of the pressure distribution within the heap was clarified. The oblique transmission of contact forces within the grain mass forms an arch-like structural force chain pattern, which is characteristic of the internal mechanics of the heap.

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