MEASUREMENT OF THE PHYSICAL PARAMETERS OF PEANUT SEEDS AND CALIBRATION OF THE DISCRETE ELEMENT PARAMETERS
/
花生籽粒物理参数测定与离散元参数标定

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ABSTRACT
This study measured the intrinsic and contact parameters through physical experiments to improve the accuracy of discrete element simulation analysis of peanut seeds. Discrete element models for five different peanut seed filling ball numbers were established. The simulation parameters were calibrated through a combination of physical and simulation experiments. Firstly, the Plackett-Burman test was used to screen the significance of simulation parameters. Then, the steepest climbing test was conducted to determine the optimal range of significance parameters using the relative error between the simulated and the physical experimental as the evaluation index. Finally, a response surface experiment with three factors and three levels was conducted using the angle of repose as the response value. The static and rolling friction coefficients among peanut seeds were set as 0.43 and 0.50 separately, and the rolling coefficient between peanut seeds and steel plate was set as 0.12. During verification experiments, the simulated angle of repose was 25.18°, with a relative error of 2.42% compared to the physical angle of repose, further verifying the reliability of the simulation model. The research group used different numbers of filling balls with optimal parameters in the angle of repose experiment. Then they evaluated the simulation time and the error value of the angle of repose between the simulated and physical experiment. The optimal number of filled balls was the Sphere 1178. The research results indicate that discrete element model of peanut seeds and calibration parameters are reliable. Based on the results of this research, an intelligent peanut precision sowing machine can be developed.

摘要
为了提高花生籽粒离散元仿真分析过程中的仿真精度，该研究通过物理试验测定了花生籽粒的本征参数和接触参数，建立了五种不同填充球数的花生籽粒的离散元模型，通过物理试验与仿真试验相结合的方式对仿真参数进行了标定。首先，采用 Plackett–Burman 试验对仿真参数进行显著性筛选。然后，以仿真堆积角与物理试验堆积角之间的相对误差为评价指标，进行最陡爬坡试验，确定了显著性参数的最优取值范围。最后，以堆积角为响应值，进行了三因素三水平的响应面试验，得到最优参数组合为：花生籽粒间的静摩擦系数 0.43、花生籽粒间滚动摩擦系数 0.50、花生籽粒-钢板滚动摩擦系数 0.12。并进行验证试验，得出仿真堆积角为 25.18，与物理堆积角之间的相对误差为 2.42%，进一步验证了仿真模型的可靠性。以最优参数进行不同填充球数的堆积试验，以仿真堆积角与物理实验堆积角的误差值和仿真时间为评价指标，得到最佳填充球数为 1178。研究结果表明该花生籽粒离散元模型及标定参数可靠，可为智能花生精量播种机具的研制提供依据。

INTRODUCTION
Peanut is a kind of important economic and oil crops and it has been widely cultivated in many countries and regions *(Chen et al., 2020; Wang et al., 2021; Wang et al., 2018; Xu et al., 2023)*. Peanut seeds have an oil content of 44% to 56% and are rich in protein and various vitamins, with high nutritional value. The core component of a peanut precision seeder is the seeder, which directly affects its performance *(Ding et al., 2022; Zhang et al., 2023)*. The influence of the physical parameters and distribution of agricultural materials on particle flow was fully considered in discrete element analysis *(Hao et al., 2023; Hou et al., 2020; Peng et al., 2018)*. It is particularly suitable for studying nonlinear problems such as the motion laws and mechanical characteristics changes of peanut seeds during seeding.

Qian et al., (2023), used the discrete element method to model different varieties of peanut seeds and obtained the differences between different types of peanuts, as well as the effects of variety differences and seeder speed on the seeding process.

Zhang et al., (2023), designed a seed tray for an air suction drum type hole seeder and simulated the suction and primary seeding processes using the DEM-CFD gas-solid coupling calculation method. They analyzed the seed movement trajectory and seeding performance in the seed-carrying area. Based on the adhesive particle model, *Yu et al., (2020)*, used the discrete element method to model and calibrate the parameters of the seeds of medicinal herbs. The precision seeder of the seeds of medicinal herbs was validated using the pass rate, miss rate, and replay rate of the seeder as experimental indicators. *Zhang et al., (2022)*, calibrated the discrete element parameters of mung bean seeds. They conducted simulation experiments on the seeder's performance with the seeding shaft's rotation speed as the experimental factor. *Shi et al., (2019)*, used the discrete element method to calibrate the discrete element parameters of sesame seeds and conducted simulation experiments on irregular hole seeders and field experiments. *Zhu et al., (2019)*, built a discrete element simulation platform for a wide seedling belt wheat spreader. They used the coefficient of variation of wheat grain lateral uniformity as an indicator to simulate and optimize the design of the spring seed board for the wheat-wide seedling belt spreader. *Chen et al., (2022)*, established a simulation model of the seed tube body of a precision seeder based on the discrete element method. They conducted seed-guiding performance simulation experiments with factors such as operating speed and the inclination angle of the delivery section end. *Li et al., (2020)*, performed discrete element modeling and parameter calibration on cotton seeds, established a simulation model of a rotary hole precision seeder and obtained the effects of the motion parameters of the seed wheel and the speed of the seeder on the seeding performance of the seeder. Some scholars have studied the flow performance of seeds during the seeding process *(Lu et al., 1997; Vu-Quoc et al., 2000; Wang et al., 1999)*. *Zhang et al., (2023)*, established a compacted straw cube discrete element model that includes flexible straw's elastic, plastic, and viscous mechanical properties. *Bembenek et al.,(2022)* found a discrete element model for material compaction in a roller press. Compared with the finite element method, the model established by the discrete element method is more applicable.

This research group chose Yiyuan peanut seeds as the research object because it is widely planted in Yiyuan County, Zibo, Shandong Province, China. Five different peanut seed models with other filling ball numbers were established by using the discrete element method. Besides, the group calibrated the simulation parameters of peanut seeds utilizing a combination of simulation and physical experiments. The Plackett−Burman experiment, steepest climbing experiment, and response surface experiment were carried sequentially to determine the simulation parameters of the optimal filling ball number peanut seed model. This study aims to provide a basis for the development of intelligent peanut precision sowing machines.

MATERIALS AND METHODS

A five-point sampling method was used to sample Yiyuan peanuts in the peanut planting area of Yiyuan to establish a three-dimensional model of peanut seeds accurately. After shelling treatment, 200 peanut seeds were randomly selected for triaxial size measurement. The experimental equipment is set with a digital vernier caliper with an accuracy of 0.01 mm, and the three-axis dimensions (length L × Wide B × Thick W), as shown in Fig. 1. By using an electronic balance with an accuracy of 0.01 g, the mass of each peanut seed was measured. The volume of peanut seeds was measured with a cylinder, whose accuracy is 0.2 mL. The moisture content of peanut seeds was collected by using oven drying method. Take the average of the measurement results and the data is shown in Table 1.

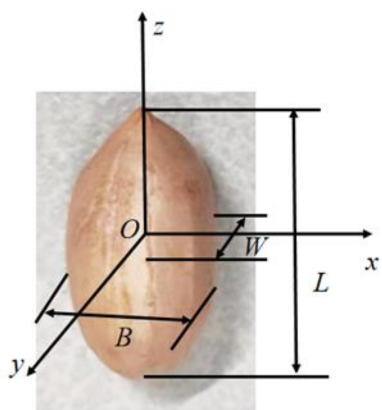

Fig. 1 - Three axis dimensions of the peanut seed

Table 1

Three axis dimensions of peanut seeds

Physical parameters	Value
Three axis dimensions (length *L* × Wide *B* × Thickness *W*)/mm	17.16×8.09×7.41
Mass/g	1.39
Density/(kg/cm^3)	1390
Moisture content/%	32.37

This study used a CNY-1 inclined plane instrument to measure the friction coefficient between peanut and peanut seeds (the steel plate). When calculating the static friction coefficient between peanut seeds, 30 were bonded to form a peanut seed plate Fig. (2a) and connected to the testing plane. The inclined plane meter was rotated until the peanut seeds were observed to slide. The angle on the digital inclinometer was recorded Fig. (2b), and the static friction coefficient between peanut seeds was calculated with Formula (1). When the peanut seeds start rolling, stop rotating and record the angle on the digital inclinometer. Formula (2) helped to calculate the rolling friction coefficient between the peanut seeds. Each experiment was repeated ten times, and the average value was taken as the final value. According to Formula (1), the static friction coefficient between peanut seeds is 0.39~0.61, and the static friction coefficient between peanut seeds and steel plate is 0.43~0.63. According to Formula (2), the rolling friction coefficient between peanut seeds is 0.42~0.60, and the rolling friction coefficient between peanut seeds and steel plate is 0.11~0.32.

$$\mu_1 = \tan\alpha_1 \tag{1}$$

In the Formula: μ_1 is the static friction coefficient, α_1 is the critical angle for the static friction coefficient, (°).

$$\mu_2 = \tan\alpha_2 \tag{2}$$

In the Formula: μ_2 is the static friction coefficient, α_2 is the critical angle for the static friction coefficient, (°).

Fig. 2 - Sketch for measuring friction coefficient of peanut seeds
(a) Seed board; (b) Friction coefficient testing device

The angle of repose is an essential parameter for testing the accuracy of parameters. The angle of repose of peanut seeds was determined by the hollow cylinder method. During the experiment, a hollow cylinder with an inner diameter of 80 mm and a height of 150 mm was used. After all peanut seeds were utterly stationary on the bottom plate, a high-definition camera was used to take a frontal image of the seed pile. Fig. 3 is the sketch of angle of repose physical test. Matlab was used to grayscale and binarize seed stacking images, extract image boundary pixels, and fit boundary pixels. Through multiple repeated experiments, the average angle of repose of peanut seeds was obtained to be 24.57°.

Fig. 3 - Angle of repose physical test

There is no slip contact force among particles or between particles and surfaces. Mutual forces control the behavior between particles. Therefore, the Hertz-Mindlin (no slip) model *(Lei et al., 2023; Wang et al., 2023)* was chosen as the particle contact model using Altair EDEM 2022 Software, as shown in Fig. 4.

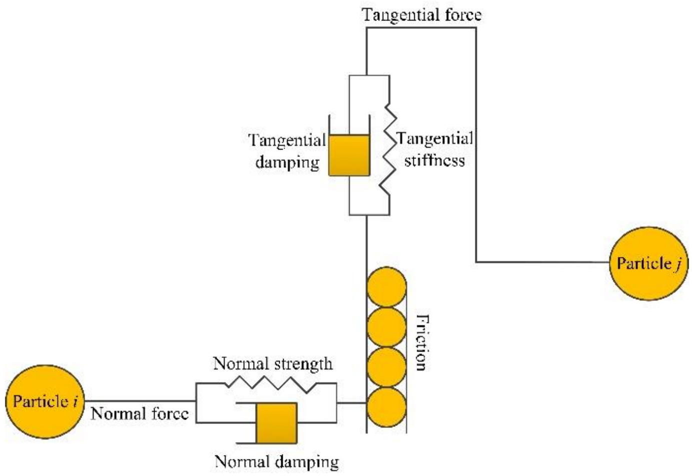

Fig. 4 - Particle to particle contact model

In the Formula, the particle dynamics equations define the translational and rotational motion of particles, which can be expressed as:

$$m_i \ddot{v} = m_i g + \sum_{j=1}^{n} F_n + F_n^d + F_t + F_t^d \tag{3}$$

In the Formula: m_i is the mass of particle i, $\ddot{v}$ is the acceleration of the particle center of mass, g is the acceleration of gravity, F_n, F_t are the normal force and tangential force, respectively, F_n^d, F_t^d are the normal damping and tangential damping. The definition of normal force is as follows:

$$F_n = \frac{4}{3} E^* (R^*)^{\frac{1}{2}} \delta_n^{\frac{3}{2}} \tag{4}$$

In the Formula: E^* is the equivalent elastic modulus, R^* is the equivalent radius, and δ_n is the normal overlap.

$$F_n^d = -2\sqrt{\frac{5}{6}} \frac{\ln\gamma}{(\ln\gamma)^2 + \pi^2} \sqrt{S_n m^*} v_n^{'} \tag{5}$$

In the Formula: γ is the recovery coefficient, S_n is the normal stiffness, m^* is the equivalent mass, and $v_n^{'}$ is the relative normal velocity.

$$F_t = -S_n \delta_t \tag{6}$$

In the Formula: δ_t is the tangential overlap.

$$F_t^d = -2\sqrt{\frac{5}{6}} \frac{\ln\gamma}{(\ln\gamma)^2 + \pi^2} \sqrt{S_t m^*} v_t^{'} \tag{7}$$

In the Formula: S_t is the tangential stiffness, $v_t^{'}$ is the relative tangential velocity.

$$I_i \dot{\omega} = \sum_{j=1}^{n} T_t + T_r \tag{8}$$

$$T_t = R_i (F_t + F_t^d) \tag{9}$$

In the Formula: I_i is the moment of inertia of particle i, $\dot{\omega}$ is the angular acceleration, T_t is the tangential moment, T_r is the rolling friction torque, and R_i is the distance from the center of mass i to the contact point.

$$T_r = -\beta R_r |F_n| \frac{\omega'}{|\omega'|} \tag{10}$$

In the Formula: β is the dynamic friction coefficient, R_r is the effective rolling contact radius, and ω' is the relative angular velocity of two contact particles.

This research established a geometric model of peanut seeds by using 3D modeling software, and then converted the peanut seed model into. * stp format. Next, the files were imported into Altair EDEM 2022. To make the surface of peanut seeds smoother, multiple sets of particles were simulated and modeled, with the number of filled spheres set to five types: Sphere 368, Sphere 607, Sphere 1176, Sphere 2823, and Sphere 9772, as shown in Fig. 5.

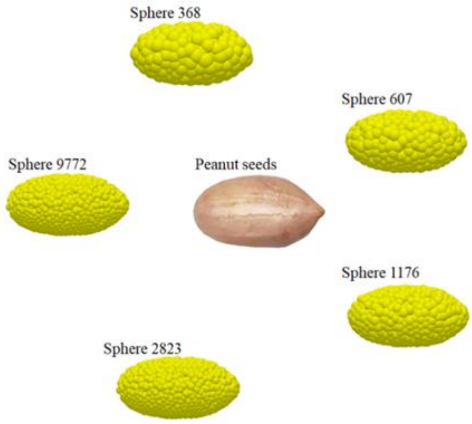

Fig. 5 - Peanut grain combination model

The Hertz-Mindlin (no slip) model was selected for peanut seeds in the simulation experiment. The research group established a virtual particle factory above the hollow cylinder to generate peanut seeds. The seed particles were generated dynamically at a rate of 2000/s, resulting in 450 peanuts. To consider both the reliability and efficiency of the simulation results, the size of the generated seed particles was fixed. The total simulation time is 2 seconds, the Rayleigh time step is 25%, the data storage interval is 0.01 seconds, and the grid size is three times the minimum particle radius. The simulation process is shown in Fig. 6.

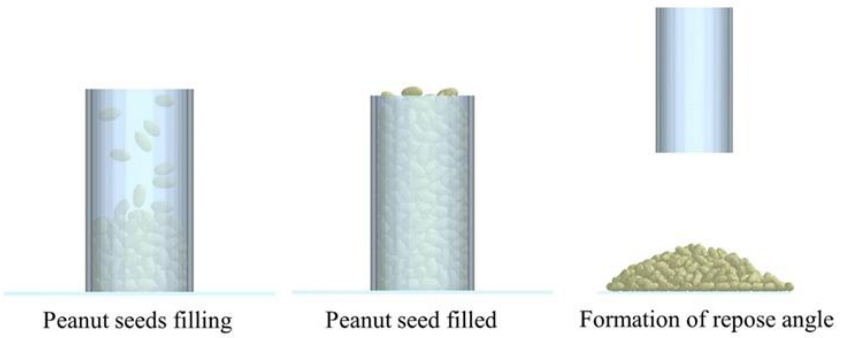

Fig. 6 - Discrete element simulation of the hollow cylinder method

There are numerous discrete element simulation parameters for peanut seeds. To accurately identify parameters and ranges with significant effects in simulation parameters, take the peanut grain model of the Sphere 607 as an example. The significance of each parameter was obtained using the Plackett-Burman test. The optimum of significant influence parameters was determined by the steepest climb test. The optimal parameter combination was determined by the Box-Behnken test. The experimental results were performed response surface analysis, using the angle of repose obtained from physical experiments as the experimental indicator to determine the optimal parameter combination.

The parameter range of the Plackett-Burman test is based on the results of physical experiments, with the simulated angle of repose of peanut seeds as the response value. The Plackett-Burman test is used to screen out parameters that have a significant impact on the response value. The range of values for the experimental parameters, including Poisson's ratio and shear modulus of peanut seeds, collision recovery coefficient between peanut seeds, and collision recovery coefficient between peanut seeds and steel plates, were determined by referring to relevant literature *(Hao et al., 2021; Lu et al., 2016; Wan et al., 2022; Wang. 2017; Zhang et al., 2018)*. The remaining parameters were measured through physical experiments. Encode the minimum and maximum values of the experimental parameters in Table 2 as -1 and+1, respectively. The encoded value of -1 represents the low level of the parameter, and +1 represents the high level of the parameter. After each set of simulation experiments, the angle of repose of peanut seed was measured by using the same method as measuring the angle of repose in physical experiments.

Table 2

Plackett-Burman test parameters table

No.	Test parameters	Levels		
		Low(-1)	Middle (0)	High(+1)
A	Peanut seeds Poisson's ratio	0.3	0.4	0.5
B	Shear modulus of peanut seeds/MPa	5.0	6.0	7.0
C	The collision recovery coefficient between peanut seeds	0.45	0.6	0.75
D	Peanut seeds steel plate collision recovery coefficient	0.470	0.485	0.500
E	Static friction coefficient between peanut seeds	0.39	0.5	0.61
F	Peanut seeds steel plate static friction coefficient	0.43	0.53	0.63
G	Rolling friction coefficient between peanut seeds	0.42	0.51	0.6
H	Rolling friction coefficient between peanut seeds and steel plate	0.11	0.22	0.32

Based on the Plackett-Burman experiment, perform the steepest climb test on the selected significance parameters. The relative error between the simulation experiment angle of repose and the physical experiment angle of repose was used as the evaluation index, the optimal range of simulation experiment parameters was determined. Other non-significant parameters were measured by using physical experiments to determine the average values.

In the steepest climbing test of peanut seeds, the 3rd level was taken as the center point (0), while the 2nd and 4th levels were taken as the low level (-1) and high level (1), respectively. The angle of repose was used as the response value and a Box-Behnken experiment with significance parameters was conducted to determine the optimal parameters for peanut seeds. The horizontal coding of peanut seeds is shown in Table 3.

Table 3

Levels coding table of factor

Levels	Parameters		
	E	*G*	*H*
-1	0.39	0.42	0.11
0	0.45	0.47	0.17
+1	0.5	0.51	0.22

In order to verify the accuracy of the contact parameters obtained from calibration experiments, it is necessary to further analyze the impact of different particle filling numbers on simulation accuracy (angle of repose, simulation time) and use the relative error between simulation experiment angle of repose and physical experiment angle of repose as the evaluation index to determine the optimal filling number.

RESULTS

Due to the multiple influencing factors of the angle of repose test, it is necessary to determine the significance of each factor's impact on the angle of repose test through the Plackett-Burman test. This research used the Plackett-Burman module to screen the contact parameters of peanut seeds (collision recovery coefficient between peanut seeds, static friction coefficient, rolling friction coefficient, collision recovery coefficient between peanut seeds and steel plate, static friction coefficient, rolling friction coefficient, Poisson's ratio and density of peanut seeds) based on the response value of peanut seed stacking angle. Each parameter is set at three levels, high (1) and low (-1), for 12 experiments. Each experiment was repeated three times, and the average value was taken. The experimental plan and results are shown in Table 4.

Table 4

Plackett−Burman trial protocol and results

No.	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*	Angle of repose *θ* / °
1	-1	-1	-1	-1	-1	-1	-1	-1	24.47
2	-1	-1	-1	1	-1	1	1	-1	25.32
3	1	-1	-1	-1	1	-1	1	1	29.58
4	1	1	-1	1	1	1	-1	-1	28.54
5	-1	1	1	1	-1	-1	-1	1	26.51
6	1	-1	1	1	1	-1	-1	-1	26.83
7	1	1	-1	-1	-1	1	-1	1	25.04
8	1	-1	1	1	-1	1	1	1	27.11

No.	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*	Angle of repose *θ* / °
9	-1	1	1	-1	1	1	1	-1	28.15
10	-1	1	-1	1	1	-1	1	1	27.69
11	1	1	1	-1	-1	-1	1	-1	24.62
12	-1	-1	1	-1	1	1	-1	1	27.78

Table 5

Significance analysis of Plackett-Burman test parameters

Parameter	Effect	Mean square sum	Influence ratio / %	Significance order
A	0.32	0.30	1.00	6
B	-0.11	0.034	0.11	7
C	0.077	0.018	0.059	8
D	0.41	0.50	1.68	4
E	2.60	20.28	67.61	1
F	0.36	0.38	1.27	5
G	0.53	0.85	2.84	3
H	0.95	2.69	8.96	2

According to Table 5, after conducting significance screening through the Plackett -Burman test, it can be concluded that E, G, and H have a significant impact on the peanut grain stacking angle test, with the significance order being E>H>G, A, B, C, D, and F have a relatively low contribution rate to the peanut grain angle of repose experiment, so E, G, and H are selected as the experimental factors for the steepest climbing experiment.

After completing the Plackett-Burman test screening, the steepest climbing test was conducted, and the test results are shown in Table 6. As E, G, and H increase, the stacking angle of peanut seeds in the simulation experiment gradually increases. Comparing the simulation stacking test results with the physical ones, the error shows a trend of first decreasing and then increasing. Due to the relative minimum mistake in Experiment 2, Experiment 2 was chosen as the center level, and Experiment 1 and Experiment 3 are considered low and high levels, respectively.

Table 6

Results of steepest climbing test

No.	*E*	*G*	*H*	Angle of repose *θ*/ °	Relative error *S* / %
1	0.39	0.42	0.11	23.15	5.78
2	0.45	0.47	0.17	25.42	3.46
3	0.50	0.51	0.22	27.53	10.75
4	0.56	0.56	0.27	28.59	14.06
5	0.61	0.60	0.32	30.48	19.39

The static friction coefficient E, rolling friction coefficient G, and rolling friction coefficient between peanut seeds and steel plate H were used as experimental factors, and the simulated angle of repose was used as an indicator to conduct a response surface experiment with three factors and three levels. The investigation was performed 17 times, and the design and results of the response surface experiment are shown in Table 7.

Table 7

Test design and results

No.	*E*	*F*	*G*	Angle of repose *θ* / °
1	-1	0	1	32.47
2	0	-1	-1	21.15
3	-1	0	-1	27.22
4	0	0	0	29.13
5	0	-1	1	25.36
6	0	0	0	27.84
7	0	0	0	28.92
8	1	0	-1	26.88
9	0	1	-1	24.85
10	-1	1	0	31.23
11	-1	-1	0	33.95

No.	*E*	*F*	*G*	Angle of repose *θ* / °
12	1	-1	0	28.11
13	0	1	1	26.27
14	0	0	0	29.74
15	1	0	1	27.86
16	1	-	0	31.41
17	0	0	0	29.89

Table 8

Analysis of variance of the angle of repose

Source	Freedom	Mean square	*F* value	*P* value
Model	9	16.42	23.98	0.0002**
E	1	14.07	20.55	0.0027**
G	1	3.37	4.92	0.0621
H	1	17.58	25.68	0.0015**
EG	1	9.06	13.23	0.0083**
EH	1	4.56	6.66	0.0365*
GH	1	1.95	2.84	0.1357
E^2	1	41.40	60.46	0.0001**
G^2	1	4.77	6.97	0.0334*
H^2	1	55.54	81.12	<0.0001**
Residual	7	0.68		
Lack of fit	3	0.71	1.07	0.4545
Pure error	4	0.66		
Cor Total	16			

*Notes: * indicates significant (P<0.05), ** indicates highly significant (P<0.01)*

The analysis of variance and significance of the experimental results is shown in Table 8, and the determination coefficient R^2 is 0.9686. The variance model is close to 1, indicating that the regression model is highly significant, and the loss of fit term P is greater than 0.05. The coefficient of variation is 2.92%, meaning that the experiment has good reliability. The binary regression equation is:

$$\theta=29.10-1.33E+0.65G+1.48H+1.50EG-1.07EH-0.70GH+3.14E^2-1.06G^2-3.63H^2 \tag{11}$$

The optimal value parameters were found by optimizing Equation (11) with the physical experiment angle of repose as the objective. The static friction coefficient E between peanut seeds, rolling friction coefficient G between peanut seeds, and rolling friction coefficient H between peanut seeds and steel plate were 0.43, 0.50, and 0.12, respectively. By reintroducing the parameters into the discrete element method for repose angle simulation experiments, it was found that the simulated angle of repose was 25.18°, with a relative error of 2.42% compared to the physical angle of repose test. The relative error is relatively small, and the experiment shows that the established peanut seeds angle of repose and regression model are better.

Angle of repose simulation experiments were carried out for five models with Sphere 368, Sphere 607, Sphere 1176, Sphere 2823 and Sphere 9772 filled balls based on the optimal value parameters. Compare the simulation test results with the physical angle of repose and obtain the relative error. The test results are shown in Table 9.

Table 9

Simulation test results of angle of repose with different ball numbers

Number of balls / piece	Simulation time / min	Simulated angle of repose *θ* / °	Relative error S_1 / %
Sphere 368	30	27.08	10.21
Sphere 607	50	26.15	6.43
Sphere 1176	80	25.43	3.50
Sphere 2823	260	25.11	2.20
Sphere 9772	530	24.87	1.22

As the number of the balls increases, the relative error between simulated and physical angles of repose gradually decreases, and the simulation time gradually increases. When the number of hops is between Sphere 607 and Sphere 1176, the angle of repose error is 6.43% and 3.50%, respectively. The accuracy of the angle of repose slowly decreases with the number of balls, and the simulation time gradually increases with the number of hops. Therefore, after careful consideration, it is more reasonable to choose a model with Sphere 1176 balls as the simulation model.

CONCLUSIONS

1) The basic physical parameters of peanut seeds, including external dimensions, mass, density, and moisture content, were determined through physical experiments. The static friction coefficient and rolling friction coefficient between peanut seeds and steel plate were measured using the CNY-1 inclined plane instrument. From this research, several conclusions can be gotten.

2) Based on the intrinsic and contact parameters of peanut seeds determined by physical experiments and references to relevant literature, the Plackett-Burman experiment was conducted to screen out parameters that significantly impact the angle of repose. Conduct the steepest climbing test using the relative error between the simulated angle of repose and the physical testing angle of repose as the evaluation index. The optimal range of significance parameters has been determined: the static friction coefficient between peanut seeds is 0.39~0.61, the rolling friction coefficient between peanut seeds is 0.42~0.60, and the rolling friction coefficient between peanut seeds and steel plate is 0.11~0.32. Then, the response surface experiment was conducted with the angle of repose as the response value. The experimental results showed the optimal parameter combination: the static friction coefficient between peanut seeds was 0.43, the rolling friction coefficient between peanut seeds was 0.50, and the rolling friction coefficient between peanut seeds and steel plate was 0.12. Besides, by using the optimal parameter combination as the experimental parameters, simulation angle of repose tests were conducted on five models with a filling ball number of the Sphere 368, Sphere 607, Sphere 1176, Sphere 2823, and Sphere 9772, and the model with a filling ball number of the Sphere 1176 was determined as the optimal simulation model.

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