

Article

Discrete Element Model of Oil Peony Seeds and the Calibration of Its Parameters

Hao Zhou ^{1,2,3,*}, Kangtai Li ¹, Zhiyu Qin ¹, Shengsheng Wang ^{1,2,3}, Xuezhen Wang ^{1,2,3}  and Fengyun Sun ¹

¹ College of Agricultural Equipment Engineering, Henan University of Science and Technology, Luoyang 471003, China

² Longmen Laboratory, Luoyang 471003, China

³ Henan Collaborative Creation Center for Advanced Manufacturing of Machinery and Equipment, Luoyang 471003, China

* Correspondence: zhouhao-2019@haust.edu.cn; Tel.: +86-0379-64877837

Abstract: Oil peony is an important oil crop that is primarily sown by using artificial methods at present. Its seeder encounters the problems of low efficiency of seeding that significantly limits the highly efficient mechanized production of high-quality peony oil. In this study, Fengdan white oil peony seeds were used as the research object and repose angle as the response value to establish a discrete element model (DEM) and parameter calibration. The range of parameters of oil peony seeds was first obtained through an experiment, and their repose angle was obtained by an inclinometer. A three-dimensional DEM of oil peony seeds was then established. The Plackett–Burman (PB) test was utilized to screen the parameters that had a significant influence on the repose angle, and the steepest ascent (SA) test was applied to determine their optimum range of testing. Following this, based on Box–Behnken (BBD) test results, a second-order regression model between the important parameters and the repose angle was constructed. Finally, the absolute minimum difference between simulated and measured repose angles was utilized as the objective of optimization to obtain the following optimum combination of parameters: The values of the seed–steel collision recovery coefficient (CRC), seed–seed static friction coefficient (SFC), seed–steel SFC, and seed–seed rolling friction coefficient (RFC) were 0.704, 0.324, 0.335, and 0.045, respectively. This optimal combination of parameters was confirmed through simulations, and the error between simulated and measured repose angles was only 0.67%, indicating that the calibrated DEM of oil peony seeds was reliable.

Keywords: oil peony seed; model building; parameter calibration; repose angle; simulation



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1. Introduction

China is the world's largest consumer of edible oils but produces only about 40% of its national requirement. Oil peony is an excellent oil crop, the quality and efficiency of cultivation of which is important for ensuring China's self-reliance in the production of edible oils [1–7]. At the same time, peony oil is as high as 92% in unsaturated fatty acid content, especially the alpha-linolenic acid content is over 42%, and is known as the world's best cooking oil. However, the problems of a low efficiency of seeding encountered by the peony seeder hinder the highly efficient mechanized production of high-quality peony oil. The DEM of oil peony seeds can be used to investigate the mechanism of interaction between seeds during the seeding process to improve their quality and efficiency [8].

The DEM has been extensively used for modeling and simulation-based analyses of agricultural materials, such as wheat, rice, corn, and soybean, in recent years [9–14]. Bai et al. obtained the range of parameters of cotton seeds through experimental measurements and used the minimum errors in the stacking and resting angles of cotton seeds as the objectives of the NSGA-II optimization algorithm to obtain the best combination of DEM parameters [15]. Zhong et al. obtained the DEM parameters of sugarcane by the high-speed photography and inclined plane method, and the range of values of the RFC, SFC, and

CRC [16]. Wang et al. established six models of sunflower seeds of varying precision by the polyhedron and multi-ball stuffing methods and obtained accurate parameters of the DEM of sunflower seeds by simulations to verify the repose angle [17]. Lu et al. proposed the ellipsoid modeling of wheat seeds and used the ellipsoid method and two multi-ball modeling methods to simulate and analyze their process of seeding. The results exhibited that the ellipsoid model had higher accuracy and stability compared to the multi-ball models [18]. Hu et al. established a DEM of cottonseed with a dynamic angle of reactivity as the test index [19]. Zhang et al. considered germinated American ginseng seeds as the object of research and calibrated their DEM parameters by the PB, SA, and BBD tests [20]. However, few studies in the literature have sought to establish DEM of oil peony seeds.

This study seeks to solve the problem of a lack of DEM parameters for the simulation-based optimization of the arrangement of the device for oil peony seeds. To this end, oil peony seeds were used as the object of research. The range of test values of their DEM parameters was obtained, their repose angle was measured, and these variables were used to establish a DEM. The calibration of DEM parameters was achieved through the PB, SA, and BBD tests. Following this, the minimization of the absolute difference between the simulated and measured repose angles was set as the final goal of optimization to obtain the best parameter combination of DEM. The accuracy of the calibrated DEM parameters was verified by contrasting simulated repose angles with measured ones. This can provide accurate DEM parameters for the optimal design of the arrangement device for oil peony seeds.

2. Materials and Methods

2.1. Geometric Parameters of Oil Peony Seeds

The Fengdan white oil peony seeds tested for this study were planted in Luoyang, in Henan Province of China. The results of manual screening showed that they were undamaged, had no mildew, and had a water content of 7.3%.

A Vernier caliper (STWC Co., Shanghai, China) with an accuracy of 0.02 mm was used to measure the 3D sizes (i.e., H, B, T) of the above seed randomly selected (Figure 1). The measurement was repeated 500 times. Owing to their complex shapes and different sizes, the geometric model of the peony seeds was simplified to represent only ellipsoidal and flat seeds based on their measured dimensions [21]. The ratio of ellipsoidal seeds to flat seeds was 19:6.

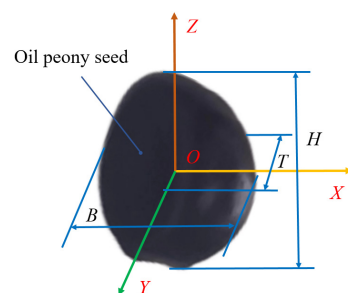


Figure 1. Schematic diagram of three-dimensional sizes.

2.2. Thousand Particle Weight and Density Measurements

Three groups of oil peony seeds were randomly selected, with 1000 seeds in each group, and were subjected to three repeated tests by using a small electronic balance. The average measured weight was 198.20 g. Because part of each seed floated in the water, they were gathered with gauze, and their volume was determined through the drainage method by using a 1 L cylinder.

2.3. Elastic Modulus

Twenty ellipsoidal and flat oil peony seeds were randomly selected, and compressed by using the TA.XTC-16 texture analyzer (BosinTouch Co., Shanghai, China) [22]. The oil peony

seeds were placed on the test platform of the texture analyzer, and their original dimensions along the direction of thickness were recorded for the compression test (Figure 2). A cylindrical probe with a radius of 10 mm was utilized to this end; its initial height was set to 10 mm, while its speeds of travel and loading were set to 0.5 mm/s and 0.25 mm/s, respectively. After loading, the probe speed movement and the pressure limit were 0.5 mm/s and 17,000 gf. The force–displacement data obtained during the compression test was utilized to calculate the elastic modulus of the seeds through Equation (1).

$$E = \frac{\sigma}{\varepsilon} = \frac{F \cdot L}{\Delta L \cdot S} \quad (1)$$

In the above, E is the elastic modulus of the oil peony seeds, Pa; F is the external force applied to the oil peony seeds, Pa; L is the deformation-induced displacement of the oil peony seeds, m; ΔL is their initial length, m; and S is their cross-sectional area, m².

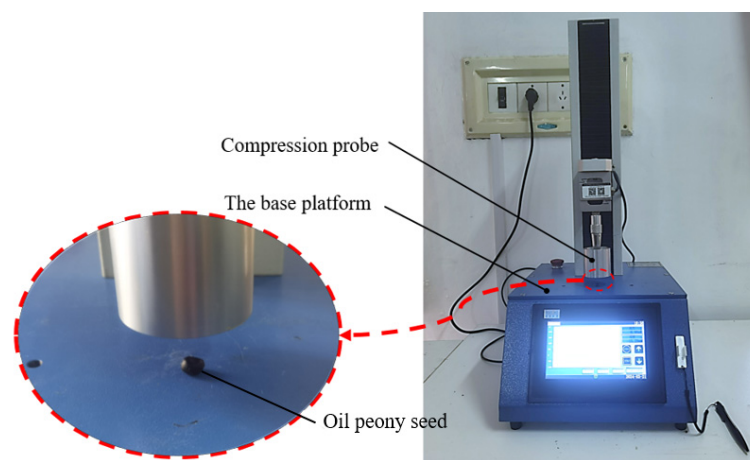


Figure 2. Compression test of oil peony seeds.

2.4. Poisson's Ratio

The compression test was carried out by using the cylindrical probe of the texture analyzer, and the Poisson ratio of the oil peony seeds was calculated [12]. Twenty oil peony seeds were randomly selected, and their transverse dimensions were recorded. Compression tests were carried out on seeds, respectively, and the test settings were the same as those detailed in Section 2.3. The axial and transverse sizes of the seeds after compression were used to calculate their Poisson's ratio according to Equation (2).

$$\mu = \left| \frac{\varepsilon_x}{\varepsilon_y} \right| = \frac{\Delta C / C}{\Delta H / H} \quad (2)$$

where μ is the Poisson's ratio of the oil peony seeds, ΔC is their transverse deformation, m, C is their initial transverse dimension, m, ΔH is the axial deformation of the oil peony seeds, m, and H is their initial axial dimension, m.

2.5. Friction Coefficient

The friction coefficient of oil peony seeds was measured by the inclined plane method [23]. Seeds of similar thicknesses were selected and arranged densely on A4 printing paper to form a seed board (Figure 3). During the test, the seed was set on the device used to measure the friction coefficient (or was fixed on the seed plate on the device). The angle of inclination of the test platform was then gradually increased manually until the seed tended to slide (or roll) downward along the incline and then stopped moving. The angle θ of the test platform was subsequently recorded. Oil peony seeds are mainly divided into two categories with ellipsoidal and flat shapes, where the former are prone to rolling. To ensure the accuracy of the experimental data, 10 flat, randomly selected oil peony seeds

were used for three repeated tests of the FSC, and ten ellipsoidal seeds were used for three repeated tests of RFC. The friction coefficient, calculated using Equation (3), was represented by its average value.

$$f = \tan\theta \quad (3)$$

where f is the friction coefficient of oil peony seeds and θ is the angle of inclination of the inclined plane.

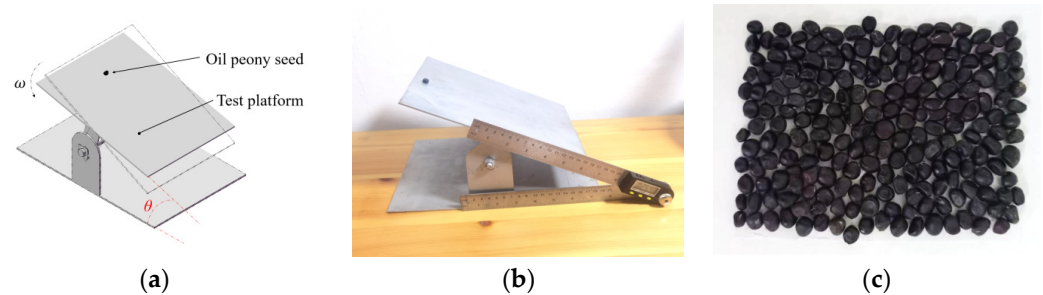


Figure 3. Determination of the friction coefficient. (a) Schematic diagram of the device used to measure the friction coefficient. (b) Photograph of the device. (c) Seed board.

2.6. Collision Recovery Coefficient

The CRC from collisions between oil peony seeds and between seeds and contact material was determined by the vertical drop test (Figure 4) [24]. Coordinate paper was provided on the far left of the measuring device, with the vertical distance H between the seed hole and the contact material set at 300 mm. Fifty oil peony seeds were randomly selected for the measurements, which were taken by using a high-speed camera (Olympus Corporation, Tokyo, Japan) after the seeds had freely fallen in the seed hole and bounced off the contact material. Due to the irregularity of the outline of the oil peony seeds, we chose 20 seeds that had vertically sprung back up after collision and recorded their greatest height. According to its physical definition, the CRC between the peony seed and the contact material is the ratio of its relative velocity of separation after collision and its relative approaching velocity before collision [25–27]. Because the velocity of the contact material before and after the collision was zero, Equation (4) can be used to calculate the CRC.

$$\varepsilon = \frac{v'}{v} = \sqrt{\frac{h}{H}} \quad (4)$$

where ε is the collision recovery coefficient, H is its initial height, m, and h is the height to which the seed rebounded, m.

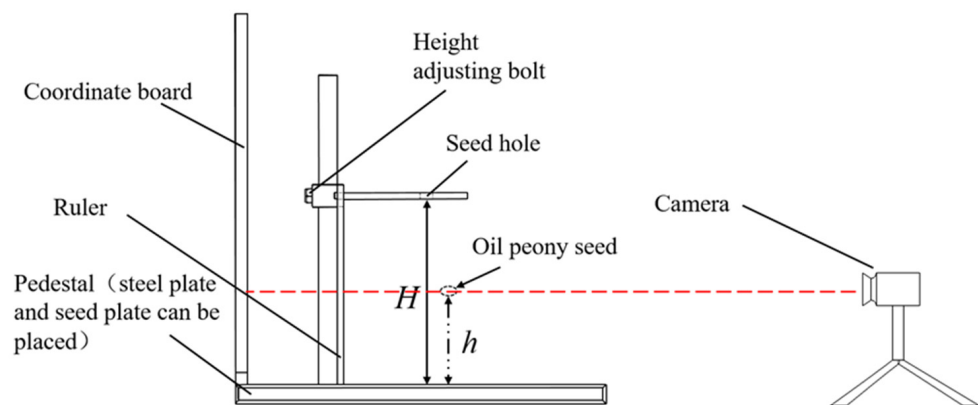


Figure 4. Schematic diagram of recovery coefficient test principle.

2.7. Repose Angle

Using an inclinometer (model DT-1) to measure the repose angle of oil peony seeds (Figure 5). The device was placed on a horizontal test bench. The lifting platform was placed inside the material tank, which was then filled with seeds. The handle was used to lift the lifting platform to the top of the material tank slowly and at a constant speed, such that the seeds left on the lifting platform formed a repose angle.

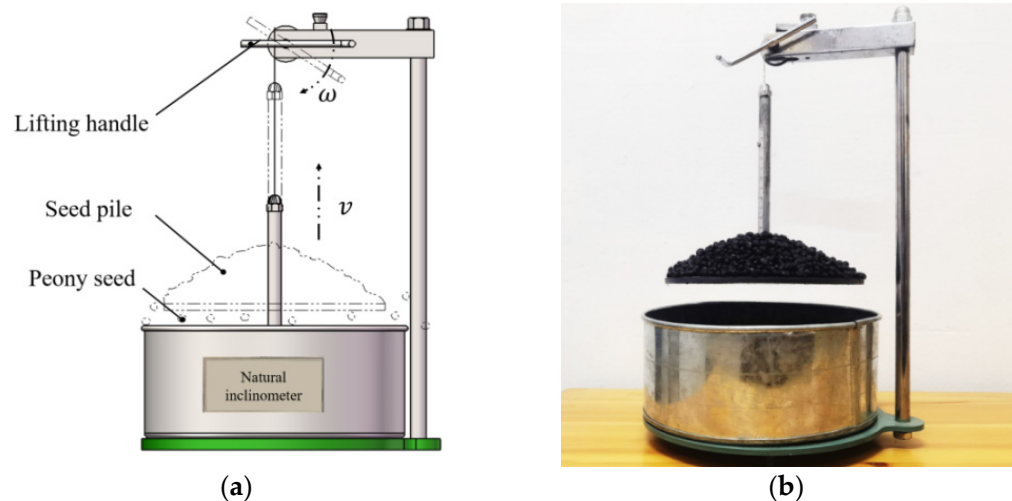


Figure 5. Determination of the repose angle. (a) Test principle. (b) Actual test.

Three tests were conducted, and a high-speed camera was utilized to photograph images of the seed pile (Figure 6a). MATLAB was used to process the images in grayscale, binarize them (Figure 6b), extract their boundaries, and linearly fit them (Figure 6c) [28,29].

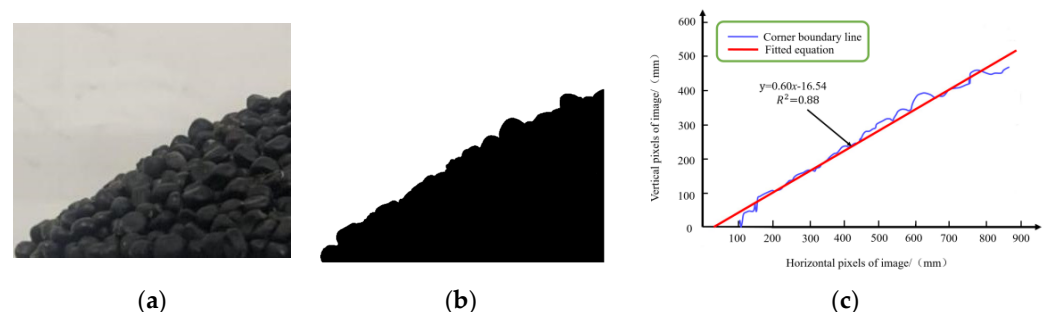


Figure 6. Measurement of the repose angle and image processing: (a) Photograph of seed pile; (b) binarized image; (c) curve fitted to a model.

2.8. Model Construction and Simulation

Based on their measured average sizes, three-dimensional modeling software was utilized to establish representative three-dimensional models of the flat and ellipsoid oil peony seeds and applied the Hertz–Mindlin (no slip) contact model to build their DEM (Figure 7). Simulations of the ellipsoidal and flat seeds, at a ratio of 19:6, in the material tank were conducted, where the number of seeds was 10,000. When the particles of the seeds had attained a stable state, the disk-lifting platform was moved to the top of the material tank at a speed of 0.1 m/s along the Z-axis, and the seed particles on it fell under the action of gravity. The seeds that eventually remained on the platform created a stable repose angle (Figure 8).

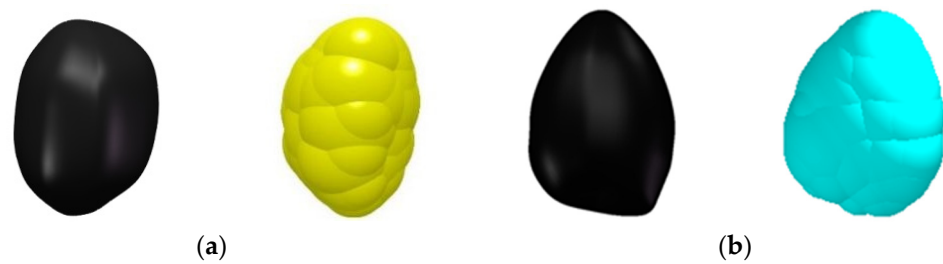


Figure 7. The three-dimensional model used for simulations of the seed particles. (a) Flat oil peony seeds. (b) Ellipsoidal oil peony seeds.

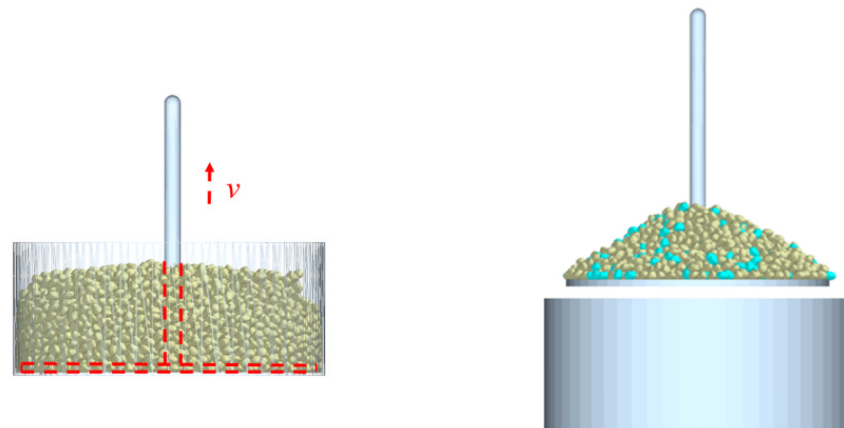


Figure 8. The simulation process of the angle repose.

3. Results and Discussion

3.1. Laboratory Test Results

Related parameters of oil peony seed use (Table 1) were measured in the third part of this study.

Table 1. Related parameters of oil peony seeds.

Parameters	Unit	Value
3D sizes of seed ($H \times B \times T$)	mm	$8.92 \times 7.15 \times 6.22$
Weight of seed	g	0.198
Volume of seed	cm ³	0.201
Poisson's ratio of seed		0.3
Elastic modulus of seed	MPa	9.21×10^6
Seed–seed CRC		0.7
Seed–steel CRC		0.78
Seed–seed SFC		0.36
Seed–steel SFC		0.38
Seed–seed RFC		0.05
Seed–steel RFC		0.053
Repose Angle	°	30.3

3.2. Plackett–Burman (PB) Test

Design-Expert 13 software was utilized to design the PB test. The repose angle was used as the test index, and parameters that had a significant influence on it were screened out [30]. Eight test parameters were selected in this experiment. Their ranges of values were chosen according to the results (Table 2). The scheme and results of the PB test (Table 3). Each group of simulations was repeated three times to obtain the average repose angle.

Table 2. Parameters of PB test.

Symbol	Parameters	Unit	Low Level (−1)	High Level (+1)
M_1	Poisson's ratio of seed	MPa	0.21	0.42
M_2	Elastic modulus of seed		6.10	13.00
M_3	Seed–seed CRC		0.10	0.90
M_4	Seed–steel CRC		0.67	0.83
M_5	Seed–seed SFC		0.29	0.46
M_6	Seed–steel SFC		0.32	0.46
M_7	Seed–seed RFC		0.04	0.08
M_8	Seed–steel RFC		0.04	0.07

Table 3. Design and results of PB test.

No.	M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8	Repose Angle $\theta/^\circ$
1	0.21	13.00	0.90	0.67	0.46	0.46	0.08	0.04	37.6°
2	0.42	6.10	0.10	0.67	0.46	0.32	0.08	0.07	37.1°
3	0.42	13.00	0.10	0.83	0.46	0.46	0.04	0.04	32.9°
4	0.42	6.10	0.90	0.83	0.46	0.32	0.04	0.04	29.8°
5	0.21	6.10	0.10	0.83	0.29	0.46	0.08	0.04	33.2°
6	0.42	13.00	0.90	0.67	0.29	0.32	0.08	0.04	34.2°
7	0.21	13.00	0.90	0.83	0.29	0.32	0.04	0.07	27.9°
8	0.21	13.00	0.10	0.83	0.46	0.32	0.08	0.07	34.5°
9	0.42	13.00	0.10	0.67	0.29	0.46	0.04	0.07	34.1°
10	0.21	6.10	0.90	0.67	0.46	0.46	0.04	0.07	33.6°
11	0.42	6.10	0.90	0.83	0.29	0.46	0.08	0.07	32.3°
12	0.21	6.10	0.10	0.67	0.29	0.32	0.04	0.04	27.7°

An analysis of the results of the PB test was provided (Table 4). It showed that M_7 had an extremely significant influence on the repose angle. Parameters M_4 , M_5 , and M_6 had a significant influence on it, whereas other parameters of the simulation did not significantly influence the repose angle. Therefore, only M_4 – M_7 were used for the SA and BBD tests.

Table 4. Analysis of the significance of parameters according to the PB test.

Parameter	Effect	Sum of Squares	Contribution/%	<i>p</i> -Value	Significance
M_1	0.98	2.90	2.69	0.2205	
M_2	1.25	4.69	4.34	0.1447	
M_3	−0.68	1.40	1.30	0.3622	
M_4	−2.28	15.64	14.48	0.0372	*
M_5	2.68	21.60	20.00	0.0245	*
M_6	2.08	13.02	12.06	0.0468	*
M_7	3.82	43.70	40.46	0.0093	**
M_8	0.68	1.40	1.30	0.3622	

Influence from low to high: *, **.

3.3. Steepest Ascent (SA) Test

To further explore the realistic range of values of the important parameters (i.e., M_4 , M_5 , M_6 , and M_7), the SA test was devised and carried out. The values of all non-significant parameters in the test were set to their averages. The design scheme and results of the SA test were listed (Table 5). They showed that the error between the simulated and measured repose angles was the smallest in test No. 2, indicating that the optimal ranges of values of M_4 , M_5 , M_6 , and M_7 were 0.67–0.75, 0.29–0.375, 0.32–0.39, and 0.04–0.06, respectively. The follow-up BBD test was carried out by these ranges of values for the parameters.

Table 5. Design and results of the SA test.

No.	M_4	M_5	M_6	M_7	Repose Angle $\theta/^\circ$
1	0.67	0.29	0.32	0.04	28.7°
2	0.71	0.3325	0.355	0.05	31.2°
3	0.75	0.375	0.39	0.06	34.5°
4	0.79	0.4175	0.425	0.07	36.3°
5	0.83	0.46	0.46	0.08	38.1°

3.4. Box–Behnken (BBD) Test

The BBD test was used to examine how the seed–steel CRC (M_4), seed–seed SFC (M_5), seed–steel SFC (M_6), and seed–seed RFC (M_7) affect the repose angle (θ). The coding table for the test factors was provided (Table 6), while the test design and results were presented (Table 7). Multiple regression analysis was performed on the obtained data to obtain the regression equation of test factors M_4 , M_5 , M_6 , and M_7 with respect to test index θ :

$$\begin{aligned} \theta = & -332.73 + 642.55M_4 + 20.47M_5 + 401.72M_6 + 2279.01M_7 + 58.82M_4M_5 - 285.71M_4M_6 \\ & -1687.50M_4M_7 + 134.45M_5M_6 + 705.88M_5M_7 - 785.71M_6M_7 - 341.15M_4^2 - 198.39M_5^2 \\ & -261.90M_6^2 - 9583.33M_7^2 \end{aligned} \quad (5)$$

The variance analysis of the test results (Table 8) was apparent that M_4 , M_5 , M_6 , M_7 , M_4^2 , and M_7^2 had extremely significant effects on the repose angle, M_4M_6 , M_4M_7 , M_5^2 , and M_6^2 had significant effects on it, while M_5M_6 , M_5M_7 , and M_6M_7 had no significant influence on the repose angle. The regression model of fitting of the repose angle showed that the results were significant and fitted well with the model. The coefficient of determination R^2 of the regression equation, revised coefficient, and variation coefficient were 0.9487, 0.8973, and 1.07%, respectively.

Table 6. Test factor codes for the BBD test.

Codes	Factors			
	M_4	M_5	M_6	M_7
−1	0.67	0.29	0.32	0.04
0	0.71	0.3325	0.355	0.05
1	0.75	0.375	0.39	0.06

Table 7. Design and results of BBD test.

No.	M_4	M_5	M_6	M_7	Repose Angle ($^\circ$)/ θ
1	0.67	0.29	0.355	0.05	31°
2	0.75	0.29	0.355	0.05	29.9°
3	0.67	0.375	0.355	0.05	31.4°
4	0.75	0.375	0.355	0.05	30.7°
5	0.71	0.3325	0.32	0.04	28.8°
6	0.71	0.3325	0.39	0.04	30.8°
7	0.71	0.3325	0.32	0.06	30.5°
8	0.71	0.3325	0.39	0.06	31.4°
9	0.67	0.3325	0.355	0.04	28.8°
10	0.75	0.3325	0.355	0.04	29.7°
11	0.67	0.3325	0.355	0.06	31.7°
12	0.75	0.3325	0.355	0.06	29.9°
13	0.71	0.29	0.32	0.05	29.5°
14	0.71	0.375	0.32	0.05	30.9°
15	0.71	0.29	0.39	0.05	30.4°
16	0.71	0.375	0.39	0.05	32.6°
17	0.67	0.3325	0.32	0.05	30.1°
18	0.75	0.3325	0.32	0.05	30.3°
19	0.67	0.3325	0.39	0.05	32°

Table 7. Cont.

No.	M_4	M_5	M_6	M_7	Repose Angle ($^{\circ}$)/ θ
20	0.75	0.3325	0.39	0.05	30.6 $^{\circ}$
21	0.71	0.29	0.355	0.04	29.1 $^{\circ}$
22	0.71	0.375	0.355	0.04	29.5 $^{\circ}$
23	0.71	0.29	0.355	0.06	30.5 $^{\circ}$
24	0.71	0.375	0.355	0.06	32.1 $^{\circ}$
25	0.71	0.3325	0.355	0.05	31.8 $^{\circ}$
26	0.71	0.3325	0.355	0.05	31.6 $^{\circ}$
27	0.71	0.3325	0.355	0.05	31.4 $^{\circ}$
28	0.71	0.3325	0.355	0.05	31.4 $^{\circ}$
29	0.71	0.3325	0.355	0.05	31.8 $^{\circ}$

Table 8. Variance analysis of the results of the BBD test.

Source	Sum of Squares	df	Mean Square	F-Value	p-Value	Significance
Model	27.73	14	1.98	18.48	<0.0001	**
M_4	1.27	1	1.27	11.82	0.0040	**
M_5	3.85	1	3.85	35.94	<0.0001	**
M_6	4.94	1	4.94	46.09	<0.0001	**
M_7	7.36	1	7.36	68.69	<0.0001	**
M_4M_5	0.400	1	0.400	0.3731	0.5511	
M_4M_6	0.6400	1	0.6400	5.97	0.0284	*
M_4M_7	1.82	1	1.82	17.00	0.0010	*
M_5M_6	0.1600	1	0.1600	1.49	0.2420	
M_5M_7	0.3600	1	0.3600	3.36	0.0882	
M_6M_7	0.3025	1	0.3025	2.82	0.1152	
M_4^2	1.93	1	1.93	18.03	0.0008	**
M_5^2	0.8329	1	0.8329	7.77	0.0145	*
M_6^2	0.6677	1	0.6677	6.23	0.0257	*
M_7^2	5.96	1	5.96	55.57	<0.0001	**
Residual	1.50	14	0.1072			
Lack of fit	1.34	10	0.1341	3.35	0.1275	
Pure error	0.1600	4	0.0400			
Sum	29.23	28				

Influence from low to high: *, **.

3.5. Interactive Effects Analysis of Regression Model

According to the results of the variance analysis (Table 8), the interaction terms M_4M_6 and M_4M_7 had a significant impact on the repose angle ($p < 0.05$). The response surfaces of interactions between M_4M_6 and M_4M_7 were drawn by using parameters other than the fixed interaction terms at the central level (Figure 9). The effect of interaction between these parameters is intuitively clear from it. When M_5 and M_7 were at the central level, the repose angle gradually increased with M_4 and M_6 . When M_5 and M_6 were centered horizontally, the repose angle gradually increased with M_4 and M_7 .

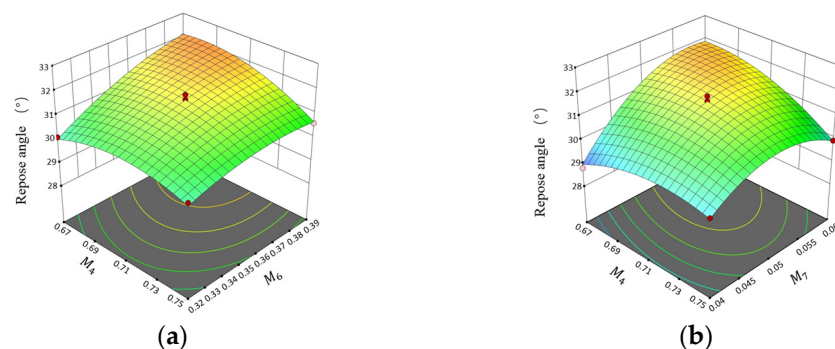


Figure 9. Response surface of the interaction between factors on the repose angle: (a) M_4M_6 interaction; (b) M_4M_7 interaction.

3.6. Parameter Optimization and Verification Test

To obtain the optimal combination of the test indices influencing oil peony seeds, the second-order regression model was optimized, and Equation (6) was obtained by eliminating the non-significant items in Equation (5). Following this, the objective function and the constraint function were established by using single-objective multi-parameter optimization based on the absolute minimum difference between simulated and measured repose angles as the final goal of optimization, as shown in Equation (7). The optimal parameter combination is as follows: M_4 , M_5 , M_6 , and M_7 were 0.704, 0.324, 0.335, and 0.045, respectively. The mean values of the parameters that were not significant were utilized from the above tests (i.e., the Poisson's ratio of seeds, the elastic modulus of seeds, seed–seed CRC, and seed–steel RFC was 0.30, 7.21 MPa, 0.70, and 0.053, respectively).

$$\theta = -360.28 + 662.11M_4 + 145.26M_5 + 407.14M_6 + 2234.79M_7 - 285.71M_4M_6 - 1687.50M_4M_7 - 341.15M_4^2 - 198.39M_5^2 - 261.90M_6^2 - 9583.33M_7^2 \quad (6)$$

$$\begin{cases} \min |\theta(M_4, M_5, M_6, M_7) - 30.3| \\ 0.67 \leq M_4 \leq 0.75 \\ 0.29 \leq M_5 \leq 0.375 \\ 0.32 \leq M_6 \leq 0.39 \\ 0.4 \leq M_7 \leq 0.6 \end{cases} \quad (7)$$

The optimal parameter combination obtained above was simulated to verify its accuracy. The repose angles obtained in three repeated simulations were 30.1° , 30.5° , and 31° , with an average value of 30.5° . The error between the simulated (Figure 10b) and measured repose angles (Figure 10a) was only 0.67%, indicating that the parameters of the calibrated DEM were reliable.

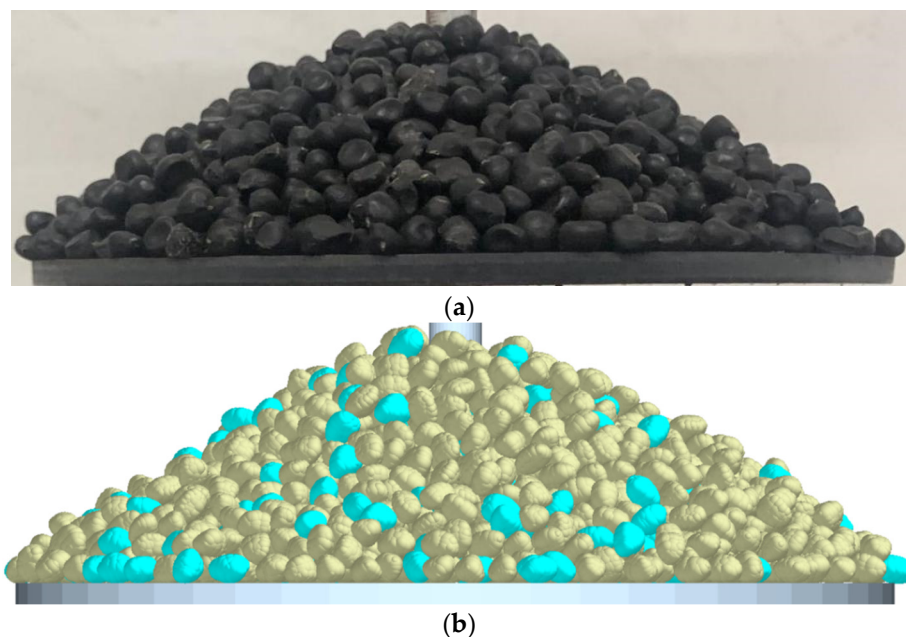


Figure 10. Test results: (a) Measured repose angle. (b) Simulated repose angle.

4. Conclusions

In this paper, a DEM of oil peony seeds was developed, and the range of values of each of its parameters was obtained based on empirical measurements as well as the PB, SA, and BBD tests. The accuracy of the DEM was subsequently verified through verification tests. The following conclusions can be drawn:

- (1) The ranges of values of each parameter of oil peony seeds in measurements obtained in the test were as follows: The Poisson's ratio was 0.21–0.42 (average, 0.3), elastic modulus

- was 6.1–13 MPa (average, 9.21 MPa), coefficient of recovery from seed–steel collision was 0.67–0.83 (average, 0.78), coefficient of static friction was 0.32–0.46 (average, 0.38), and coefficient of rolling friction was 0.04–0.07 (average, 0.053). The seed–seed recovery coefficient was 0.10–0.90 (average, 0.70), the coefficient of static friction was 0.29–0.46 (average, 0.36), and the coefficient of rolling friction was 0.04–0.08 (average 0.05);
- (2) The seed–steel CRC (M_4), seed–seed SFC (M_5), seed–steel SFC (M_6), and seed–seed RFC (M_7) significantly affect the repose angle of the oil peony seeds. The optimal parameter combination M_4 , M_5 , M_6 , and M_7 was 0.704, 0.324, 0.335, and 0.045, respectively;
 - (3) The results of tests to verify the optimum parameter combination yielded an error of only 0.67% between the simulated and the measured pose angles. This showed that values of the parameters of the proposed DEM of oil peony seeds were reliable, and that it can be used to simulate and optimize the design of the seed discharge device.

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