ESTABLISHMENT AND CALIBRATION OF DISCRETE ELEMENT MODEL FOR COATED WHEAT SEED BASED ON STATIC AND DYNAMIC VERIFICATION TEST /

基于静动态验证试验的包衣小麦种子离散元模型标定与优化

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ABSTRACT

This study calibrated discrete element parameters for coated wheat seeds through static and dynamic validation tests. Using physical experiments, key parameters were measured, and a discrete element model was created. Optimal parameters were identified via the Plackett-Burman test, steepest ascent experiment, and Box-Behnken design. Validation tests showed that the relative error between the simulated and actual angle of repose was 1.31%, and the relative error in seeding uniformity and seed displacement uniformity was less than 5%. These findings provide theoretical support for optimizing seed dispenser structures in precision wheat sowing.

摘要

本研究基于静动态试验对包衣麦种参数进行离散元标定，采用物理试验测得其物性参数和接触参数，建立离散元模型；采用 PLACKETT-BURMAN 试验，最陡爬坡实验、BOX-BEHNKEN 试验获得显著影响因素的最佳参数组合，通过静态圆筒提升实验与动态排种器台架试验进行验证。结果表明，仿真休止角与实际休止角相对误差为 1.31%，播量一致性和排种均匀性的变异系数相对误差平均值均低于 5%，可为麦种精量化播种中排种器结构优化提供理论参考。

INTRODUCTION

Wheat is the second-largest grain crop globally and one of the primary staple crops in China. As an important wheat-producing area, Xinjiang's stable yield is of great significance to guarantee national food security (*Chen et al., 2019; Lang et al., 2016; Zhang et al., 2018*). According to statistics, the sown area of wheat in China reached 23518.5 thousand hectares in 2022 (*Nbo S, 2023*). The widespread adoption of mechanized wheat production technology and equipment has significantly reduced labour costs and increased production efficiency (*Li et al., 2024*).

Sowing is a crucial step in the mechanized production of wheat. As the core component of mechanized sowing, the performance of the seed metering device directly impacts the seeding quality of the wheat planter. The structure of the seed metering device is intricate and compact, and the interactions between wheat seeds, as well as between the seeds and the metering components, are complex. Traditional analysis methods cannot directly study the movement patterns of seeds and the seeding mechanism during this process, making it necessary to rely on computer simulations. The Discrete Element Method (DEM) is particularly well-suited for analysing the movement of granular materials (*Han et al., 2018; Zhang et al., 2022*). Applying DEM to the seed metering process of wheat seeds is an effective approach; however, the accuracy of the DEM model is highly dependent on the precision of the physical parameters calibrated between the seeds and the metering components. Therefore, calibrating the discrete element parameters for coated wheat seeds is of utmost importance. International scholars have undertaken significant work in calibrating particle parameters.

Liu et al. optimized and calibrated the discrete element simulation parameters of wheat using repose angles obtained from experiments and simulations, finding no significant difference between the simulated and experimental values (*Liu et al., 2016*).

Lu et al. conducted discrete element simulations of the friction angles (including two repose angles and a sliding friction angle) of rice seeds. They used the experimental results of the three friction angles of the seeds as correction indicators to obtain calibrated parameters, with a relative error of less than 2.75% compared to the physical test results (*Lu et al., 2018*). The reliability and accuracy of the discrete element simulation method have been corroborated through extensive bench and field experiments in recent years (*Zhi et al., 2021*). Since the seed metering device directly interacts with coated wheat seeds, and the coating process alters some contact parameters (*Hu et al., 2018*), the parameters used in existing DEMs are not sufficiently accurate for coated wheat seeds. Few scholars have employed coated wheat seed parameters for discrete element analysis in their seed metering device designs, leading to insufficient precision in the data for coated wheat seeds. This lack of precision hampers research on the seed metering mechanism and structural optimization for devices using coated wheat seeds, making it necessary to calibrate the parameters for these seeds.

To further enhance the accuracy of discrete element parameters for coated wheat seeds, physical experiments were conducted to determine their geometric characteristics, physical properties, and contact parameters. These data were used to establish a DEM that reflects the intrinsic parameters of the coated wheat seeds. The parameters were optimized using *Plackett-Burman* (PB) test, *steepest ascent* (SA) test, and *Box-Behnken design* (BBD) test. The accuracy of the model was validated by comparing simulation results with bench tests of the seed metering device. This provides reliable DEM parameters for studying the seeding mechanism and optimizing the structure of wheat seed metering devices.

MATERIALS AND METHODS

Measurement of basic physical parameters

For the widely cultivated "Xindong 20" variety in southern Xinjiang, 10,000 plump, undamaged seeds were selected to determine the basic physical parameters of coated wheat seeds. These seeds were randomly divided into 10 groups, each containing 1,000 seeds. Each group was weighed using an electronic balance with an accuracy of 0.01 g to calculate the average weight and determine the thousand-seed weight (38.32 g). Additionally, 100 seeds were randomly selected from each group and measured with a calliper to obtain their characteristic dimensions (length L 6.17 mm × width W 3.31 mm × thickness T 2.86 mm), as illustrated in Fig.1.

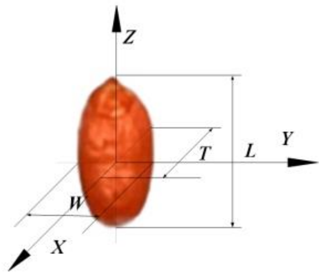


Fig. 1 - Schematic diagram of three-dimensional sizes

The volume of the coated wheat seeds was measured by the drainage method, and the density of the coated wheat seeds was calculated to be 1260 kg·m^{-3}.

Poisson's ratio and shear modulus

The Poisson's ratio is one of the important mechanical characteristics of coated wheat seeds. It was determined using a combination of theoretical definitions and experimental measurements (*Shi et al., 2018*).

The coated wheat seeds, being small and irregularly shaped, were subjected to a compression deformation test using an RCM-4002 universal testing machine (range: 0-2 kN) in the thickness direction, as shown in Figure 2. The seeds were placed on the lower pressing plate, and the upper pressing plate applied a load at a speed of 0.5 mm/s for 3 seconds. The test was repeated six times The Poisson's ratio of the coated wheat seeds was calculated to be 0.3 by measuring their length and thickness before and after the test.

To determine the elastic modulus, a compression test was performed using the same universal testing machine. The seeds were placed horizontally on the test bench, and a circular pressing plate applied a load along the thickness direction at a speed of 2 mm/min for 10 seconds, after which the machine was stopped. The compression force-displacement curve, as shown in Figure 3, was generated using the computer software's post-processing module. The test was repeated six times, and the average value was recorded.

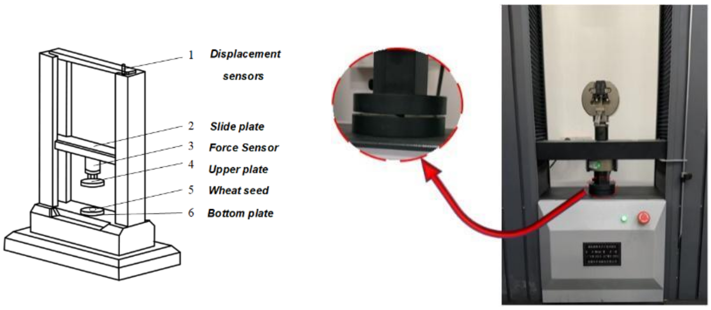
The contact area was determined as the projected area in the thickness direction. Due to the irregular shape of the seed, its contact area was calculated using SolidWorks by creating a 3D model based on the measured dimensions of the seed, resulting in a contact area of 3.02×10^{-6} m².

$$G = \frac{F / s}{2(1+\delta)(\Delta l / l)} \tag{1}$$

where:

G - the shear modulus of the coated wheat seed, Pa; F is the applied force, N, s is the contact area, m², δ - Poisson's ratio of coated wheat seed, dimensionless. Δl is the deformation, mm, and l is the sample height, mm.

Finally, using equation (1), the shear modulus of the coated wheat seed was calculated to be 4.93×10^{8} Pa.



a) Test schematic b) Physical test diagram

Fig. 2 - Compression test of coated wheat seed

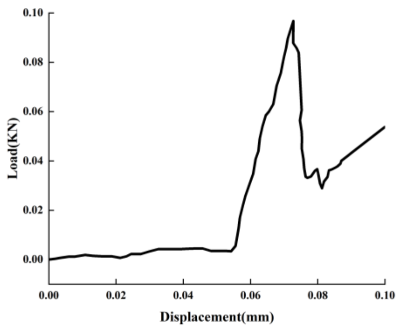
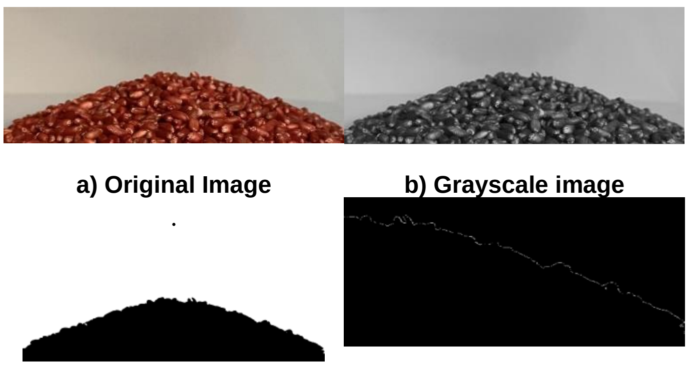


Fig. 3 - Compression-displacement curve

Angle of repose determination test

The repose angle was used as the standard parameter in this study, as its measurement accuracy directly influences the reliability of simulation parameter calibration. An acrylic cylinder with an inner diameter of 39 mm and a height of 120 mm was selected based on the material characteristics of the wheat seeds (*Wu et al., 2002*). The lower end of the cylinder was initially blocked with a baffle. Once the cylinder was completely filled with coated wheat seeds, the baffle was quickly removed, allowing the seeds to fall freely and form a conical pile. After the seeds settled, the slope of the pile was recorded as the repose angle.

A high-definition camera captured a frontal image of the seed pile. This image was processed using MATLAB software for grayscale conversion, binarization, and extraction of boundary pixels (*Ma et al., 2024*), as illustrated in Figure 4. The extracted boundary pixels were then fitted using the image digitization tool in Origin software to determine the single-sided repose angle of the coated wheat seeds, as shown in Figure 5. Here, H represents the horizontal pixel points, and R represents the vertical pixel points. After 10 repeated experiments, the average repose angle of the coated wheat seeds was found to be 31.14° in the physical tests.



a) Original Image b) Grayscale image

c) Binarized filling d) Edge extraction

Fig. 4 - Repose Angle Profile Extraction Process

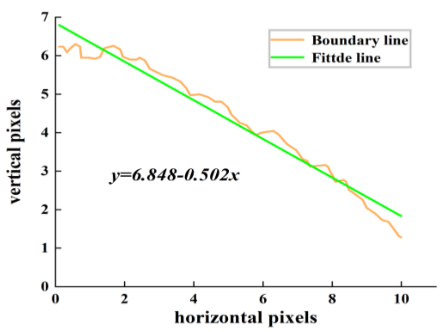


Fig. 5 - Seed single-sided angle of repose fitting image

Coefficient of static and rolling friction

In this experiment, a custom-built device was used to measure the friction coefficients between coated wheat seeds, as well as between the seeds and acrylic plates. The experimental setup is shown in the fig. 6. Coated wheat seeds were placed on an acrylic plate mounted on an iron base, and the static friction coefficient (SFC) was determined by measuring the angle at which the seeds began to slide as the inclined plane was raised (*Hao et al., 2021*). Double-sided tape was used to attach the coated wheat seeds to the acrylic plate, ensuring that the seed surfaces were aligned as accurately as possible. During the test, the coated wheat seeds were placed on the seed plate, and the testing procedure followed the same steps as previously described. After 30 repeated trials, the seed-seed SFC was found to range from 0.2 to 0.8, with an average of 0.60. The seed-acrylic SFC was found to range from 0.3 to 0.7, averaging 0.51. The rolling friction coefficient (RFC) was measured using the same approach. The seed-seed RFC was in the range of 0 to 0.1, with an average of 0.05, the seed-acrylic RFC was found to range from 0 to 0.1, with an average of 0.01.

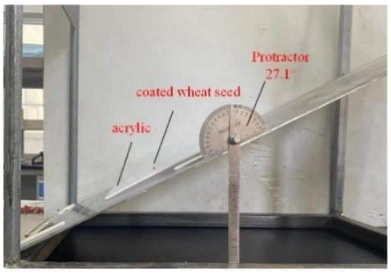


Fig. 6 - Friction coefficients test

Collision recovery coefficient (CRC)

Newton's law of collision was used to calculate the CRC. A 200 mm graduated ruler was placed vertically on the acrylic board, with the graduated side facing the camera. To minimize experimental error due to air resistance, the coated wheat seeds were released from a height H of 120 mm above the material board (*Teng et al., 2007; Zhou et al., 2021*). The seeds bounced off the acrylic board, and the entire collision and motion process was recorded using the slow-motion video feature on a Huawei Mate50, set to 240 frames per second. Each frame of the video was analysed to record the height h corresponding to the highest rebound point. The experiment was repeated six times. The acrylic board was then replaced with a seed-coated board, and the experiment was repeated six times using the same procedure. The coefficient of restitution was calculated using the following formula:

$$e = \frac{v_1}{v_0} = \frac{\sqrt{2gh}}{\sqrt{2gH}} = \sqrt{\frac{h}{H}} \tag{2}$$

where: e - the collision response factor, dimensionless; v_1 - the instantaneous velocity normal to the collision, mm s^{-1}; v_0 - the instantaneous velocity before the collision, mm s^{-1}; h - the maximum bounce height, mm; H - the seed release height, mm.

According to equation (2), the seed-seed and seed-acrylic CRC were calculated to be 0.48 and 0.54.

Establishment of discrete element model

Based on the measured physical dimensions of the coated wheat seeds, a 3D model was created using SolidWorks. The completed seed model was then converted to STL format and imported into EDEM. Research by scholars has shown that minor differences in the shape outline do not significantly impact simulation results (*Horabik et al., 2016; Shi et al., 2022*). Therefore, this model uses single-sphere particles for the Generate Particle function. The physical appearance, physical model, and DEM of the coated wheat seeds are shown in Figure 7. The material in contact with the coated wheat seeds is an acrylic board, the parameters of which have been determined by reference to the literature (*Boac et al., 2014*). The Poisson's ratio of Acrylic is 0.40, the shear modulus is 1.6×109 Pa, and the density is 1385 kg m^{-3}.

In the simulation of the repose angle of coated wheat seeds, a simulation tool model was established based on the actual dimensions of the experimental tools. A virtual particle factory was created above the acrylic cylinder, where particles were allowed to fall freely to the bottom of the cylinder, generating a total of 3,000 coated wheat seeds. Once the particles stabilized, the baffle was quickly removed, and the particles formed a stable pile on the base, as shown in Figure 8. The Hertz-Mindlin (no slip) contact model embedded in EDEM software was used, in line with the physical characteristics of the coated wheat seeds as granular materials.

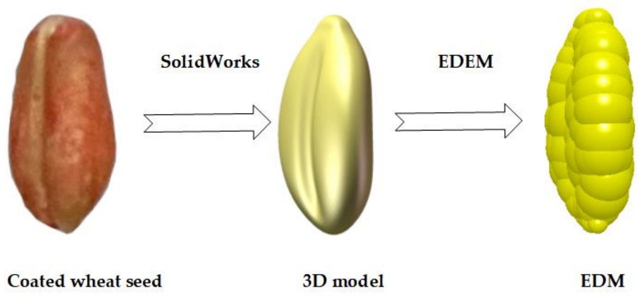


Fig. 7 - Discrete element modeling process

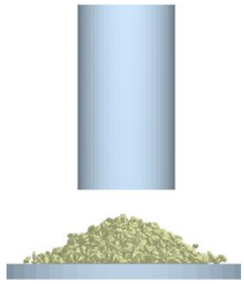


Fig. 8 - Repose angle simulation test

RESULTS

Plackett–Burman (PB) Test

Using the repose angle of the coated wheat seeds as the response value, the PB module in Design-Expert 13.0 software was employed for experimental design to identify the significant factors affecting the repose angle (*Jia et al., 2014*). Given that the minimum number of factors for the experiment was 11, and with 8 real parameters considered, the remaining 3 factors were filled with virtual parameters. Each parameter was set at two levels, high and low, coded as +1 and -1, as shown in Table 1.

A total of 12 experiments were conducted. After the simulation of the repose angle of the seeds was completed, the simulated repose angle was measured using the same method as in the physical experiments, with the results shown in Table 2.

Table 1

PB test measure range table

Symbol	Parameters	Unit	Low level (-1)	Hight level (+1)
X_1	Poisson's ratio of seed		0.14	0.46
X_2	Shear modulus of seed	MPa	1.5	10
X_3	Seed-seed CRC		0.2	0.6
X_4	Seed- acrylic CRC		0.4	0.7
X_5	Seed-seed SFC		0.2	0.8
X_6	Seed- acrylic SFC		0.3	0.7
X_7	Seed-seed RFC		0	0.1
X_8	Seed- acrylic RFC		0	0.1
X_9、X_{10}、X_{11}	Virtual parameters		-	-

Table 2

PB test protocol and results

No.	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	Repose angle θ/°
1	1	1	-1	1	1	1	-1	-1	-1	1	1	24.96
2	-1	1	1	-1	1	1	1	-1	-1	-1	1	29.04
3	-1	1	1	1	-1	-1	-1	1	-1	1	1	16.23
4	1	-1	1	1	1	-1	-1	-1	1	-1	1	23.87
5	1	-1	-1	-1	1	-1	1	1	-1	1	1	28.11
6	-1	-1	-1	1	-1	1	1	-1	1	1	1	26.12
7	1	1	-1	-1	-1	1	-1	1	1	-1	1	17.35
8	-1	1	-1	1	1	-1	1	1	1	-1	-1	25.31
9	1	-1	1	1	-1	1	1	1	-1	-1	-1	33.04
10	-1	-1	1	-1	1	1	-1	1	1	1	-1	25.66
11	1	1	1	-1	-1	-1	1	-1	1	1	-1	22.54
12	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	17.15

The test results were analysed by ANOVA using Design-Expert 13.0 software to obtain the significant results of each simulation parameter as shown in Table 3. As can be seen from Table 3, the $P<0.01$ for seed-seed RFC (X_7) is extremely significant on the particle simulation rest angle; the $P<0.05$ for seed-seed SFC (X_5) and seed-acrylic SFC (X_6) is significant on the particle simulation rest angle; and the remaining experimental parameters with $P>0.05$ are not significant on the particle simulation rest angle.

Steepest ascent (SA) Test

Based on the results in Table 3, X_5, X_6, and X_7 were selected as the significant factors for the steepest ascent experiment (*Ma et al., 2020*), while the other non-significant parameters were assigned the average values from the physical experiments. Specifically, the Poisson's ratio of coated wheat seeds was 0.3, shear modulus was taken as 4.93 × 10^8 Pa, seed-seed CRC was 0.48, seed-acrylic CRC was 0.54, and seed-acrylic RFC was 0.01.

Table 3

Analysis of the significance of parameters according to the PB test

Parameters	Effect	Sum of Squares	Contribution / %	p-Value	Significance
X_1	1.7267	8.9441	3.076	0.209	
X_2	-3.0867	28.5825	9.83	0.0651	
X_3	1.8967	10.792	3.7116	0.1781	
X_4	1.6133	7.8085	2.6855	0.233	
X_5	4.0867	50.1025	17.2311	0.0326	*
X_6	3.8267	43.9301	15.1083	0.0385	*
X_7	6.49	126.36	43.4575	0.0093	**
X_8	0.3367	0.34	0.1169	0.7762	

*Note: * indicates a significant impact ($0.01<P<0.05$) ; ** indicates that the effect is extremely significant ($P≤0.01$).*

Table 4

Design and results of the SA test

No.	X_5	X_6	X_7	Repose angle θ/°	Relative error /%
1	0.20	0.30	0	0	100
2	0.35	0.40	0.03	19.53	37.28
3	0.50	0.50	0.06	26.23	15.77
4	0.65	0.60	0.09	29.67	4.72
5	0.80	0.70	0.12	33.15	6.45

From the results in Table 4, it is evident that the relative error was minimized at experiment 4, determining that the optimal range lies around this point. Therefore, No. 4 was selected as the centre point, with No. 3 and No. 5 serving as the low and high levels, respectively, for the subsequent BBD.

Box–Behnken (BBD) test

Based on the BBD principle and the results of the PB and SA tests, the significant parameters seed-seed SFC (X_5), seed-acrylic SFC (X_6), and seed-seed RFC (X_7) were selected as high (+1), medium (0), and low (-1), the three levels of No. 5, No. 4, and No. 3 for the design of the experiment, respectively, as shown in Table 5 (*Hou et al., 2020*). The values of the non-significant parameters were kept the same as in the SA test.

Table 5

Test factor codes for the BBD test

No.	X_5	X_6	X_7	Repose angle θ / °	Relative error / %
1	0.20	0.30	0	0	100
2	0.35	0.40	0.03	19.53	37.28
3	0.50	0.50	0.06	26.23	15.77
4	0.65	0.60	0.09	29.67	4.72
5	0.80	0.70	0.12	33.15	6.45

Table 6

Design and results of BBD test

No.	Factor			Relative error / %
	X_5	X_6	X_7	
1	-1	-1	0	15.45
2	1	-1	0	3.82
3	-1	1	0	5.20
4	1	1	0	0.9
5	-1	0	-1	16.21
6	1	0	-1	11.43
7	-1	0	1	3.28
8	1	0	1	4.78
9	0	-1	-1	14.10
10	0	1	-1	9.22
11	0	-1	1	1.64
12	0	1	1	4.14
13	0	0	0	2.76
14	0	0	0	4.27
15	0	0	0	5.39

Following the design and results of BBD test (Table 6), a second-order regression equation for the simulated repose angle was derived through multivariate regression fitting using Design-Expert 13.0.

$$\theta=29.85+1.12X_5+0.93X_6+2.14X_7-0.57X_5X_6+0.26X_5X_7+0.07X_6X_7-0.55X_5^2-0.14X_6^2-0.19X_7^2 \quad (3)$$

According to the variance analysis of the model (Table 7), X_5, X_6, and X_7 had extremely significant effects on the repose angle of the particles, while the X_5X_6, X_5^2 showed significant effects. The P-value of the repose angle regression model is 0.003 ($P<0.01$), indicating that the model is highly significant. The lack-of-fit term has a P-value of 0.6564 ($P>0.05$), suggesting a good fit between the model and the actual data. The coefficient of determination (R^2) is 0.9884, with an adjusted R^2 of 0.9675, a coefficient of variation (CV) of 1.25%, and an accuracy of 22.2219, all of which demonstrate that the test results are highly reliable and precise.

Table 7

Variance analysis of the results of the BBD test

Parameters	Sum of Squares	df	Mean Square	F-value	p-Value	Significance
Modal	56.17	9	6.24	46.94	0.003	**
X_5	9.97	1	9.97	74.98	0.003	**
X_6	6.88	1	6.88	51.77	0.008	**
X_7	36.51	1	36.51	274.63	<0.001	**
X_5X_6	1.30	1	1.30	9.78	0.0261	*
X_5X_7	0.2756	1	0.2756	2.07	0.2094	
X_6X_7	0.0196	1	0.0196	0.1474	0.7168	
X_5^2	1.10	1	1.10	8.29	0.0346	*
X_6^2	0.0711	1	0.0711	0.5347	0.4974	
X_7^2	0.1351	1	0.1351	1.02	0.3597	
Residual	0.6647	5	0.1329			
Lack of Fit	0.3261	3	0.1087	0.6420	0.6564	
Pure Error	0.3386	2	0.1693			
Cor Total	56.83	14				

*Note: * indicates a significant impact (0.01<P<0.05) ; ** indicates that the effect is extremely significant (P≤0.01).*

Based on the results of the ANOVA, the interaction between seed-seed SFC and seed- acrylic SFC (X_5X_6) has a significant effect on the repose angle of the particles ($P<0.05$). The response surface plot for X_5X_6, generated using Design-Expert 13, visually illustrates the interaction effects between these parameters, as shown in Figure 9. As the values of these two parameters increase, the repose angle of the particles also shows an upward trend.

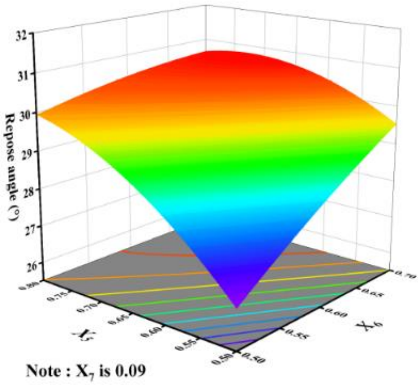


Fig. 9 - Response surface of the interaction between factors on the repose angle

Determine the optimal parameter combination

To identify the optimal simulation parameters and achieve the best possible fit to the actual repose angle, the relative error η was used as the optimization criterion. In Design-Expert 13.0, the response values were optimized, with the objective function and constraints set accordingly.

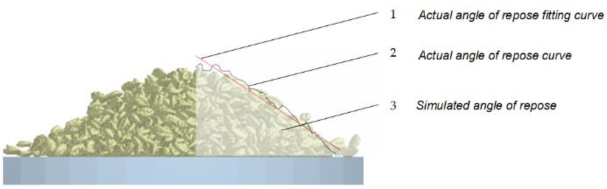
$$\begin{cases} \min \eta(A,B,C) \\ s.t.\begin{cases} 0.5 \le A \le 0.8 \\ 0.5 \le B \le 0.7 \\ 0.06 \le C \le 0.12 \end{cases} \end{cases} \quad (4)$$

The optimal simulation parameters for seed-seed SFC, seed-acrylic SFC, and seed-seed RFC were solved to be 0.62, 0.69, and 0.1, respectively.

Static verification test

To verify the reliability and accuracy of the calibrated discrete element simulation parameters for coated wheat seeds, these optimal parameters were input into EDEM for three simulation trials. As shown in Figure 10, the repose angles of the coated wheat seeds were found to be 30.27°, 29.78°, and 32.15°, respectively. The relative error between the average repose angle from physical tests (31.14°) and the average repose angle from simulation tests (30.73°) was 1.31%. This indicates that the calibrated parameters can serve as a valuable reference for future simulation studies of coated wheat seeds.

a) Real test schematic



b) Comparison chart

Fig. 10 - Comparison of simulated angle of repose and actual angle of repose fitting plots

Dynamic verification test

To validate the consistency between the DEM and the actual physical model, a precision seed-metering test bench for wheat was established, as shown in Figure 11.

The coated wheat seeds of the "Xindong 20" variety were selected for the bench test. The seed-metering wheel had a diameter of 52 mm, with 12 teeth per row, arranged in a staggered pattern across two rows.

Fig. 11 - Coated wheat seed metering test device

Fig. 12 - Simulation test of coated wheat seed rowing

The seeder model was simplified, and the DEM of the coated wheat seeds, along with the optimal contact parameters obtained from calibration, was imported into EDEM for simulation, as shown in Figure 12.

In accordance with the GB/T 9478-2005 "Test Methods for Grain Drills," the variation coefficients for seeding consistency (determined by counting the number of seeds discharged by the seed-metering wheel after three revolutions, with three groups of 10 measurements each, and then calculating the coefficient of variation) and seeding uniformity (by dividing the conveyor belt into ten 100×50 mm grids, counting the number of seeds in each grid, repeating three times, averaging the results, and calculating the coefficient of variation) were used as key parameters.

The formulas are shown in 5, 6. The relative error between the variation coefficients from the simulation and the bench tests at different speeds was used as a reference indicator.

$$S = \sqrt{\frac{1}{n-1}\sum (X-\bar{x})^2} \tag{5}$$

$$a = \frac{100S}{\bar{x}} \tag{6}$$

where: S - the standard deviation, dimensionless; n - the number of zones, dimensionless; X - the number of seeds per zone, pcs; $\bar{x}$ - the mean number of seeds per zone, pcs; a- the coefficient of variation, dimensionless.

The experimental results (Table 8) show that the average relative error in the variation coefficients for seeding consistency and uniformity was less than 5%, indicating that the optimal parameter combination obtained from calibration can provide theoretical support for precision wheat seeding and the structural optimization of the seed-metering device.

Table 8

Coefficient of variation of discharge consistency and seeding uniformity at different speeds

Velocity km/h-1	Coefficient of variation of displacement consistency C_1 / %			Coefficient of variation of seeding uniformity C_2 / %		
	Simulation text	Bench text	Relative error	Simulation text	Bench text	Relative error
5	2.42	2.38	1.68	8.77	8.47	3.54
6	1.97	2.02	2.48	5.14	4.93	4.26
7	2.19	2.14	2.34	7.33	7.55	2.91

CONCLUSIONS

Through physical experiments, the "Xindong 20" wheat seeds were found to have a Poisson's ratio of 0.3, a shear modulus of 4.93×10^8 Pa, and a natural angle of repose of 31.14°. The SFC between seed-seed and seed-acrylic were determined to be 0.60 and 0.51, respectively; the RFC were 0.05 and 0.01, respectively; and the CRC were 0.48 and 0.54.

The PB test identified seed-seed and seed-acrylic SFC, along with seed-seed RFC, as the significant influencing parameters. Subsequent SA test further refined these parameter ranges to 0.5-0.8, 0.5-0.7, and 0.06-0.12.

Using a BBD response surface test, a quadratic regression model was established to describe the relationship between the significant influencing parameters and the angle of repose. Analysis of the interaction between seed-seed SFC and seed-acrylic SFC showed that the angle of repose increased as the values of these two parameters rose. By optimizing the relative error of the angle of repose, the optimal simulation parameters were determined to be 0.62 for seed-seed SFC, 0.69 for seed-acrylic SFC, and 0.1 for seed-seed RFC. Validation experiments using these optimal parameters showed a relative error of 1.31% in the simulated angle of repose, indicating no significant difference.

Under different speed conditions, the average relative error between the variation coefficients of seeding consistency and uniformity in both bench and simulation tests was less than 5%. These results demonstrate that the DEM and the simulation parameters can effectively support the optimization of seed-metering device structures in precision wheat seeding.

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