Engenharia Agrícola

ISSN: 1809-4430 (on-line)

www.engenhariaagricola.org.br

Technical Paper
Doi: http://dx.doi.org/10.1590/1809-4430-Eng.Agric.v44e20230085/2024

CALIBRATION AND OPTIMIZATION OF DISCRETE ELEMENT PARAMETERS FOR COATED COTTON SEEDS

Zenglu Shi[1*], Meijing Wang[1], Xuejun Zhang[1], Jinpeng Cheng[1], Dengming Lu[2]

[1*] Corresponding author. College of Mechanical and Electrical Engineering, Xinjiang Agricultural University/Urumqi, China.
E-mail: shizlfd@163.com | ORCID ID: http://orcid.org/0000-0003-4579-0037

KEYWORDS

discrete element, simulation, cotton seed, parameter calibration, optimization.

ABSTRACT

The geometric characteristics, physical parameters and contact parameters of coated cotton seeds were obtained through theoretical analysis and experimental measurements. A discrete element model reflecting the intrinsic parameters of cotton seeds was established, the contact parameters of coated cotton seeds were calibrated using Discrete Element Method (DEM), and the significant factors affecting the stacking angle were screened using the Plackett-Burman method. The optimal ranges of the parameters were determined by the steepest ascent method, and a second-order regression model of the stacking angle and significant parameters was established by a central composite design. The following optimal values were obtained for cotton seeds: collision recovery (0.38), static friction (0.57) and rolling friction (0.19) coefficients. The average value of the stacking angle obtained by simulations with the best combination of parameters was 30.52°, the result of the simulation test was 30.91°, and the relative error was 1.278%. It is shown that the discrete element particle model and calibration parameters of cotton seed are closer to the actual situation, which can provide theoretical reference for analyzing the precise seeding of cotton seed and optimizing the structural parameters of seed disperser.

INTRODUCTION

Cotton, as an important cash crop, plays a pivotal role in the national economy of China (Xin et al., 2021; Yang et al., 2013; Liu et al., 2022). China is the second largest cotton producer in the world, and according to statistics, the annual production of cotton in China reached 5.13 million tons in recent years. Xinjiang, the largest cotton-producing region in China, accounts for more than 89.5% of its production in the country and approximately 20% of the world's cotton production (Shen, 2022; Zhang et al., 2023 a). With the increasing mechanization of agriculture, a variety of cotton production machinery has been developed (Wang et al., 2022; Song et al., 2021). Precision sowing is a key aspect of cotton production, and the superiority of sowing performance directly affects the cost and efficiency of cotton production (Zhao & Chen, 2023). Precision sowing technology has received much attention and research from scholars at home and abroad (Zhao et al., 2020; Zhao & Na, 2014).

The Discrete Element Method (DEM), initially proposed by Cundall, regards a discrete body as a combination of a finite number of discrete units. Nowadays, advanced modeling techniques can be used to quickly and accurately model various types of solid bulk materials, such as coal briquettes, ores, soils, tablets, and so on, for the simulation and analysis of the production process of particle handling and its manufacturing equipment in industrial production (Zhang & Jin, 2023). Discrete element method is now widely used in the field of agriculture, Zhang et al. (2023 b) based on discrete element method to simulate the potato sorting process, the sorting device operating parameters to optimize, reduce the rate of injury to the potato, improve the qualification rate of commercial potato; Xu et al. (2023) with the help of discrete element software to establish buckwheat grains of the multi-spherical particles model of the vibrating screen in the different vibration frequency under the sieve process of numerical simulation, get the vibrating screen operating effect of

[1] College of Mechanical and Electrical Engineering, Xinjiang Agricultural University/Urumqi, China.
[2] Xinjiang Jintiancheng Machinery & Equipment Company Limited/Aksu, China.

Area Editor: Gizele Ingrid Gadotti
Received in: 5-30-2023
Accepted in: 11-15-2023

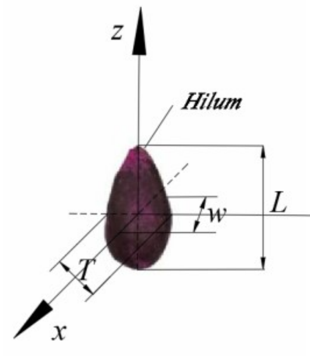
the vibrating frequency of the case of a better job. Discrete meta-analysis method through the simulation of the working process of mechanical equipment, to obtain some of the physical test is difficult to get the information, for example, cotton seeds in the seed discharge device due to the more complex stress situation of the cotton seeds and the seed discharge device inside the space is narrow, direct observation and analysis of the greater difficulty (Zhang et al., 2023 c; Zhang et al., 2021). However, with the help of discrete element technology, the movement of cotton seeds in the seed displacer can be simulated by setting relevant parameters, which provides a new research method for improving the seed displacing structure and seeding precision. Therefore, it is necessary to apply discrete element technology to seeding machinery (Xu et al., 2020; Li et al., 2022).

Cotton seeds are wrapped with a layer of non-seed materials containing fungicides, insecticides, micro-fertilizers and other materials on the surface of the seeds through mechanical equipment before sowing, and the coated-treated cotton seeds can achieve the purpose of preventing and controlling seedling pests and diseases, promoting growth and development, and improving crop yield. The contact parameters of the cotton seeds after the coating treatment are changed, and it is necessary to carry out calibration tests on the material properties of the used materials under working conditions to obtain relevant data from them before simulation using discrete element software (DEM) (Zeng et al., 2021). Through the computer simulation of the physical experimental process, and according to the simulation results in the DEM simulation program to adjust the corresponding parameters, so that the simulation results are consistent with the experimental data. The main purpose of this study is to determine the contact parameters related to cotton seeds through physical tests. In order to check the reliability of the measured parameters, the parameters are calibrated and optimized by establishing a stacking angle simulation test, and the results obtained can provide data references for the subsequent precision sowing simulation test.

MATERIAL AND METHODS

Determination of basic physical parameters

The cotton seeds used in this study were Tron Cotton No. 508. First, the basic physical parameters of the cotton seeds were determined. Five hundred randomly selected cotton seeds were divided into 5 groups, weighed separately and averaged using an electronic balance with an accuracy of 0.01 g. Their thousand-grain weight was measured to be 84.42 g. The moisture content of the seeds was 10% as measured by a constant temperature drying oven. The seed density was 869.10 kg m^{-3}, as measured by the specific gravity bottle method (Liu et al., 2020). To establish a three-dimensional physical model of cotton seeds, 100 randomly selected cotton seeds were measured by electronic Vernier calipers for their characteristic dimensions (length L × width W × thickness T) in this study (Wu et al., 2020), as shown in Figure 1. Taking the average of the measurement results gave a profile size of 8.64 mm × 4.70 mm × 4.12 mm.



Note: The long axis of the seed is along the z - axis, along the umbilical direction is along the y - axis, and the transverse direction is along the x - axis; L, W, and T are the length, width and thickness of peanut seed particles, mm.

FIGURE 1. Schematic diagram of cotton characteristic size.

Poisson's ratio is one of the important mechanical characteristic parameters of cotton seed, due to the small size of cotton seed, conventional test methods to determine its Poisson's ratio is more difficult, so the use of the definition of the method combined with experimental determination of Poisson's ratio (Li et al., 2023; Shu et al., 2022). In this paper, the compression deformation test of cotton seed was carried out using a universal pressure testing machine, and Poisson's ratio was calculated by measuring the deformation in the length and thickness directions before and after loading of the cotton seed, as shown in Figure 2.

FIGURE 2. Compression test of a cotton seed.

The test used a square platen as the loading device. The lengths and thicknesses of the seeds were measured before the test, and the cotton seeds were fixed on the lower platen of the test bench during the test. The upper platen was lowered by remote control until the cotton seeds were in false contact with the lower platen. Then, the upper platen was loaded at a speed of 0.5 mm s^{-1} with a loading time of 3 s by clicking the start command on the control computer. When the upper platen touched the seeds, the computer started to record data through the sensor, and the state of the cotton seeds and the image of the compressor were observed on the computer. The machine was stopped after 3 s of loading in the seed length direction, and the deformation of the seed in the thickness direction was measured by using electronic Vernier calipers. The test was repeated 6 times, and the average value was taken. Poisson's ratio of cotton seeds was calculated by [eq. (1)] as 0.21.

$$\delta = \left|\frac{\lambda_1}{\lambda_2}\right| = \frac{\Delta L / L}{\Delta T / T} \quad (1)$$

in which:

δ - Poisson's ratio, dimensionless;

λ_1 - the strain in the direction of the length of the seed;

λ_2 - the strain in the direction of seed thickness;

ΔL - the absolute deformation in the direction of the length of the seed, mm;

L - the original length of the seed, mm;

ΔT - the absolute deformation in the direction of the seed thickness, mm,

T - the original length in the direction of the thickness of the seed, mm.

The cotton seed elastic modulus was determined by a universal pressure tester for the seed compression test. The test was placed horizontally on the test bench, with a loading speed of 0.25 mm s^{-1} and a loading time of 6 s, using the side length of a 6 cm pressure plate, along the thickness of the direction of the load for 6 s and then stopped. The compression force-displacement curves during the seed compression test were obtained using the computer software post-processing module, as shown in Figure 3.

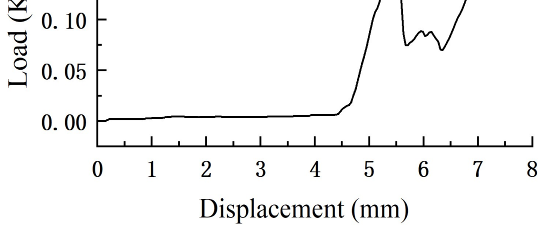


FIGURE 3. Load-displacement curve.

The test was repeated six times, the average value was calculated, and the modulus of elasticity of the cotton seeds was calculated from [eq. (2)] as $E = 2.73 \times 10^6$ Pa.

$$E = \left(\frac{\sigma}{A}\right) \Big/ \upsilon \quad (2)$$

in which:

E - the modulus of elasticity of cotton seeds, Pa;

σ - the maximum compressive stress, KN;

A - the contact area of the upper platen with the cotton seed is 0.112 mm^2,

υ - line strain.

$$G = \frac{E}{2(1+\delta)} \quad (3)$$

in which:

G - the cotton seed shear modulus, Pa;

E - the shear modulus of cotton seeds, Pa,

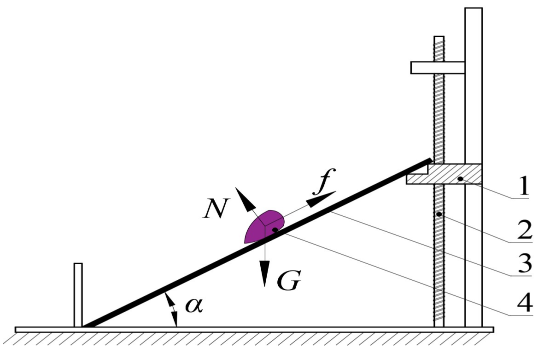
δ - Poisson's ratio of cotton seeds, dimensionless.

The shear modulus of the cotton seeds was calculated from [eq. (3)] as 1.13×10^6 Pa.

Test determination of exposure parameters

Coefficient of static friction

As shown in Figure 4, determination the static friction factor was determined by the slope method (Hao et al., 2021). First, a measuring board was fixed to the test device, and a cotton seed was placed on the measuring board. The angle of the inclined plane was increased at a constant speed by means of a screw at the right end. When the seed started to slide downward, the angle of the inclined plane α was recorded.



1. Filament sliders 2. Adjusting screws 3. Measuring board 4. Cotton seeds.

FIGURE 4. Static friction factor measurement test schematic

The test was repeated 5 times for each group of seeds, and the data were averaged. The formula was:

$$\mu_f = \frac{mg\sin\alpha}{mg\cos\alpha} = \tan\alpha \quad (4)$$

in which:

μ_f - the coefficient of static friction between the seed and the material, dimensionless;

m - the mass of the cotton seed, g;

α - the bevel angle, (°),

g - the gravitational acceleration, m s^{-2}.

Record the angle of inclination of the measuring plate during the static friction test between the seed and the seed, the seed and the seed picker disc (made of nylon), and the seed and the steel plate, respectively. The static friction coefficients of the cotton seed and the cotton seed, the toothed disk, and the steel plate were calculated to be 0.54, 0.50, and 044, respectively, according to [eq. (4)].

Coefficient of rolling friction

The rolling friction coefficient was measured by the bevel rolling method, as shown in Figure 5. Seeds were initially at rest on an inclined plane at a fixed angle. The seeds were released, and they rolled down the inclined plane. Due to rolling friction, the seeds eventually came to rest on a horizontal surface.

FIGURE 5. Schematic diagram of the method used to measure the rolling friction of a cotton seed.

Assuming that a seed was an ideal sphere and only affected by rolling friction while rolling, then by the law of conservation of energy, we obtained:

$$\mu_d = \frac{mgL\sin\beta}{mg(S + L\cos\beta)} = \frac{L\sin\beta}{S + L\cos\beta} \quad (5)$$

in which:

μ_d - the coefficient of rolling friction between the seed and the material, dimensionless;

m - the mass of the cotton seed, g;

g - the gravitational acceleration, m s^{-2};

L - the bevel rolling distance, mm;

β - the inclination of the bevel, (°),

S - the flat rolling distance, mm.

Because cotton seeds are not ideal spheres, when the inclination angle and the inclined rolling distance are large, the seeds bounced during the rolling process, which affected the accuracy of the test results. Otherwise, conditions were not conducive to test measurements. Therefore, after extensive pre-testing, the inclination of the bevel β was set to 20° and the bevel rolling distance L was 30 mm. As shown in Figure 8, to reduce experimental error, the test was repeated 10 times, and the data were averaged. The coefficients of rolling friction of the cotton seeds on steel and nylon plates were 0.15 and 0.07, respectively, and the coefficient of rolling friction between cotton seeds was 0.18.

Restitution coefficient

As shown in Figure 6, the free fall collision method was used to calibrate the collision recovery coefficients between the seed and the materials (Zhou et al., 2021). Graph paper was placed at 90° on a horizontal table to simulate a two-dimensional coordinate system before the test. To reduce test errors caused by air resistance, the seeds were released at a height of 120 mm from the plate of material H to be tested, the seeds hit the material plate and bounced. The maximum bounce height h was measured by a high-speed camera system, and the test was repeated six times. The collision recovery factor is calculated as:

$$e = \frac{v_n}{v_0} = \frac{\sqrt{2gh}}{\sqrt{2gH}} = \sqrt{\frac{h}{H}} \quad (6)$$

in which:

e - the collision response factor, dimensionless;

v_n - 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.

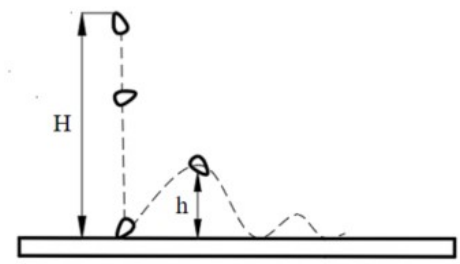


FIGURE 6. Schematic diagram of the test used to measure the collision recovery coefficient.

To reduce the experimental error, the position of the initial release of the cotton seed was recorded as (x_0, y_0) from the initial position the cotton seed and the material. The coordinates of the center of mass of the cotton seed at this time were defined as (x_1, y_1), and the value could be obtained from the graph paper. Similarly, the coordinates (x_2, y_2) at the moment when the cotton seeds bounced back from the collision to the highest point could be found, where (y_1-y_0) and (y_2-y_1) were the measured heights H and h. The recovery coefficients of the collision between the cotton seeds and the cotton, steel and nylon plates were 0.33, 0.42 and 0.37, respectively, as calculated by [eq. (6)].

Physical stacking angle determination test

The stacking angle was determined by the draw plate method (Yu et al., 2021). To reduce the variation in results due to different bottom materials, a 130 mm diameter, 20 mm high Petri dish was placed under the funnel, which was first filled with cotton seeds and scraped flat, and a funnel was set 100 mm from the top of the Petri dish, as shown in Figure 7. The inlet and outlet of the funnel have internal diameters of 140 mm and 35 mm, respectively. The lower face of the funnel is blocked by a baffle plate, and the funnel is filled with an appropriate number of seeds, which are quickly withdrawn from the baffle plate to allow them to fall freely and form a stacking angle at the top end of the Petri dish. A front view image of the seed pile was taken with a high-definition camera, and the seed pile image was grayed out and binarized. Image boundary pixel points were extracted, and boundary pixel points were fitted by MATLAB to obtain the unilateral pile angle of the cotton seeds, as shown in Figure 8. The average physical test stacking angle for cottonseed was 30.52° and obtained by 10 replicate tests.

FIGURE 7. Stacking angle measurement.

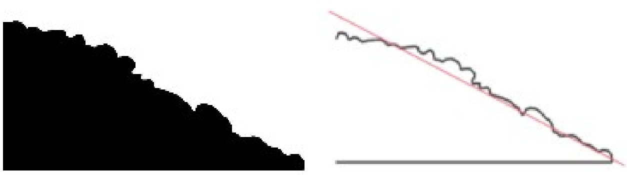


FIGURE 8. Unilateral stacking angle edge contours and fitted straight lines.

Discrete element modeling and simulation

3D modeling was performed in Solidworks according to the actual size of the cotton seeds, and then the seed model was transferred to IGS format and imported into Discrete Element Method simulation software (DEM) for particle filling to generate a simulation model that matched the actual sizes of the features (Liu et al., 2021; Zhang et al., 2020). A photograph, physical model and discrete element model of a cotton seed are shown in Figure 9.

(a) Cotton seed (b) Physical model (c) Discrete element model

FIGURE 9. Cotton seed and discrete element model.

Cotton seed is a bulk material, and the seeds underwent bulk motion in the simulated device. The Hertz-Mindlin model was used to simulate the interparticle and particle-device interactions when using discrete element simulation software for analysis. The materials of the device in contact with the cotton seeds included stainless steel and nylon, and their relevant parameters are shown in Table 1 (Li et al., 2019; Zhang et al., 2023 d).

TABLE 1. Simulation parameters of materials in contact with seeds.

Materials	Characteristic	Numerical value
Stainless Steel	Poisson's ratio	0.3
	Shear modulus/Pa	8×10^{10}
	Density/ (kg m^{-3})	7810
Nylon	Poisson's ratio	0.42
	Shear modulus/Pa	9.5×10^{8}
	Density/ (kg m^{-3})	1150

In the simulations of the cotton seed pile-up angle experiments, the required models were drawn to the actual dimensions of the tool. A polygon virtual particle plane was created above the funnel to generate the cotton seed particles, and with the effect of gravity, they begin to fall freely and form a pile-up angle on the bottom disc, as shown in Figure 10.

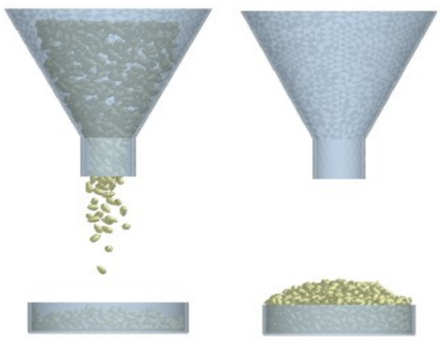


FIGURE 10. Model of the simulation of the test of the repose angle.

Parameter optimization for discrete element simulation

The basic physical parameters and contact parameters of the cotton seeds have been determined by physical tests. Due to the large number of measured parameters, directly substituting the physical parameters into the discrete element simulation software requires a large number of simulated stacking angle experiments in order to obtain simulation results that are closer to those of the physical stacking angle tests. Therefore, before the simulation test, the Plackett-Burman test is used to screen the relevant parameters that have a significant effect on the stacking angle, and then the steepest climbing test is used to approach the optimal solution step by step by continuously adjusting the values of the parameters.

Determination of significant impact parameters

The Plackett-Burman experimental design was performed using Design-Expert 13.0 software, and the test parameters were selected according to the physical test measurements using the cotton seed accumulation angle as the response value. The parameters that had a significant effect on the response value were screened by the Plackett-Burman method (Yuan et al., 2022; Liu et al., 2016). According to the literature, the size and shape of the physical model had little influence on the simulation results, while the interactions between seeds and between and seeds and contact materials could not be neglected. Therefore, the maximum and minimum values of the 11 test parameters in Table 2 were coded as levels +1 and -1, respectively, and 12 sets of tests were conducted separately. The scheme and results are shown in Table 3. After each group of simulation tests, the stacking angle of cotton seeds was measured using the same method used for the physical tests to determine the stacking angle.

TABLE 2. Plackett-Burman test measurement range table.

Symbols	Test parameters	Low level (-1)	Hight level (+1)
X_1	Poisson's ratio of cotton seeds	0.18	0.26
X_2	Cotton seed shear modulus/Pa	1.1×10^6	1.7×10^6
X_3	Cotton seed-cotton seed collision recovery factor	0.32	0.47
X_4	Cotton seed-cotton seed coefficient of static friction	0.41	0.6
X_5	Cotton seed-cotton seed rolling friction coefficient	0.12	0.28
X_6	Cotton seed-steel plate collision recovery factor	0.23	0.55
X_7	Cotton seed-steel plate static friction coefficient	0.35	0.52
X_8	Cotton seed-steel plate rolling friction coefficient	0.08	0.22
X_9	Cotton seed-nylon sheet crash recovery factor	0.4	0.6
X_{10}	Cotton seed-nylon sheet coefficient of static friction	0.48	0.78
X_{11}	Cotton seed-nylon sheet rolling friction coefficient	0.05	0.2

TABLE 3. Plackett-Burman test protocol and results.

No.	X_1	X_2	X_3	X_4	X_5	X_6/X_9	X_7/X_{10}	X_8/X_{11}	Stacking angle
1	-1	-1	1	-1	1	1	-1	1	41.07/42.25
2	1	1	-1	-1	-1	1	-1	1	36.01/37.67
3	-1	1	1	1	-1	-1	-1	1	37.71/38.95
4	1	-1	1	1	1	-1	-1	-1	41.04/42.13
5	-1	-1	-1	1	-1	1	1	-1	36.89/38.33
6	-1	1	-1	1	1	-1	1	1	38.18/39.62
7	1	-1	1	1	-1	1	1	1	37.95/39.06
8	-1	-1	-1	-1	-1	-1	-1	-1	37.84/39.27
9	1	1	-1	1	1	1	-1	-1	37.57/38.79
10	-1	1	1	-1	1	1	1	-1	41.36/42.66
11	1	-1	-1	-1	1	-1	1	1	41.61/43.03
12	1	1	1	-1	-1	-1	1	-1	40.59/41.78

Analysis of variance (ANOVA) was performed on the test results using Design-Expert 13.0 software to obtain significance results for each simulation parameter, as shown in Table 4. In Table 4, $P<0.01$ for the cotton seed-cotton seed collision recovery coefficient and cotton seed-cotton seed rolling friction coefficient indicated extremely significant effects on the stacking angle of the simulation test. $P<0.05$ for the cotton seed-cotton seed collision recovery coefficient indicated a significant effect on the stacking angle of the simulation test. The other simulation test parameters with $P>0.05$ had minimal effectd on the simulation test stacking angle.

TABLE 4. Significance analysis of Plackett-Burman test parameters.

Parameters	Degree of freedom	Sum of squares	F value	P value
X_1	1	0.2465/0.1587	0.7753/0.5012	0.4434/0.5300
X_2	1	2.07/1.76	6.50/5.57	0.0840/0.0994
X_3	1	11.25/8.53	35.38/26.95	0.0095/0.0139
X_4	1	6.96/7.97	21.89/25.17	0.0184/0.0152
X_5	1	15.96/15.01	50.20/47.40	0.0058/0.0063
X_6/X_9	1	3.12/3.02	9.82/9.54	0.0519/0.0538
X_7/X_{10}	1	2.38/2.45	7.47/7.73	0.0717/0.0690
X_8/X_{11}	1	0.6348/0.4720	2.00/1.49	0.2526/0.3093

Note: **Indicates that the impact was extremely significant (P<0.01), and * indicates that the impact was significant (P<0.05). The same below.

Steepest ascent design

On the basis of the Plackett-Burman test, the steepest ascent test was conducted on three significant parameters (cottonseed-cottonseed static friction coefficient, cottonseed-cottonseed rolling friction coefficient, and interspecies collision recovery coefficient) (Ding et al., 2023), and the relative error between the simulated stacking angle and the actual stacking angle was used as an evaluation η index to determine the optimal range of each simulated test parameter. η was calculated as:

$$\eta = \left| \frac{\varphi - \varphi_v}{\varphi_v} \right| \tag{7}$$

in which:

η - the relative error between the simulated stacking angle and the actual stacking angle;

φ - the actual measured value of the stacking angle, (°),

φ_v - the simulated value of the stacking angle, (°).

To quickly and accurately approximate the optimal parameter range, the steepest ascent test design scheme and results are shown in Table 5. In the simulation test, other insignificant parameters were used to determine its average value by physical test. The results showed that the relative error was minimum at No. 3, and the optimal interval range was determined to be around No. 3; thus, No. 3 is taken as the central point, and No. 2 and No. 4 were taken as low and high levels for subsequent central composite design response surface tests, respectively.

TABLE 5. The steepest ascent test design scheme and results.

No.	Cottonseed-cottonseed collision recovery coefficient	Cottonseed-Cottonseed static friction coefficient	Cottonseed-Cottonseed rolling friction coefficient	Relative Error
1	0.30	0.40	0.10	18.79
2	0.35	0.45	0.15	6.69
3	0.40	0.50	0.20	2.98
4	0.45	0.55	0.25	10.06
5	0.50	0.60	0.30	16.62

Center composite experimental design

In Design-Expert 13.0 software, No. 3 in the steepest climb test was taken as the central point (0), No. 2 and No. 4 were taken as the low (-1) and high (+1) levels, respectively, and the coefficient of recovery from collisions between cotton seeds, the coefficient of static friction and the coefficient of rolling friction were used as test factors. The relative error between the physical test stacking angle and the simulated test stacking angle was used as the test index for a three-factor, five-level central response surface test, with the simulated test factors coded as shown in Table 6 (Huang et al., 2023; Gao et al., 2023). Perform 20 sets of simulation tests.

TABLE 6. Simulation test factor coding.

Code	Factors		
	Crash recovery coefficient X_3	Static friction coefficient X_4	Rolling friction coefficient X_5
-1.682	0.32	0.42	0.12
-1	0.35	0.45	0.15
0	0.40	0.50	0.20
1	0.45	0.55	0.25
1.682	0.47	0.58	0.28

RESULTS AND DISCUSSION

Analysis of simulation results

The simulation results of the center composite test are shown in Table 7, where the other non-significant parameters are set as used in the steepest ascent test.

TABLE 7. Center composite test simulation results.

No.	Experimental factors			Relative Error
	X_3	X_4	X_5	
1	-1	-1	-1	2.65
2	1	-1	-1	2.43
3	-1	1	-1	10.53
4	1	1	-1	1.55
5	-1	-1	1	11.6
6	1	-1	1	12.05
7	-1	1	1	29.13
8	1	1	1	12.93
9	-1.682	0	0	25.78
10	1.682	0	0	17.03
11	0	-1.682	0	13.38
12	0	1.682	0	3.48
13	0	0	-1.682	1.75
14	0	0	1.682	17.78
15	0	0	0	4.15
16	0	0	0	3.5
17	0	0	0	0.05
18	0	0	0	0.25
19	0	0	0	4.68
20	0	0	0	3.85

Multiple regression fitting of the experimental results by Design-Expert 13.0 was performed to obtain the second-order regression equation for the stacking angle of the simulation test:

$$R_1=41.77+1.1X_3-1.64X_4-2.64X_5+1.69X_3X_4+0.4375X_3X_5-0.46X_4X_5-2.67X_3^2+1.06X_4^2-1.02X_5^2 \quad (8)$$

The results of the central composite test ANOVA are shown in Table 8. According to the analysis of the table, the effects of X_3, X_4, X_5, X_3X_4, X_3^2, X_4^2 and X_5^2 on the stacking angle were extremely significant. The effects of X_3X_5 and X_4X_5 on the stacking angle were not significant. The results for the stacking angle fitted regression model ($P<0.0001$) and the misfit term ($P=0.4479>0.05$) indicated that the model fit well and that no misfitting occurred. The regression equation had a coefficient of determination R^2 = 0.9739, a corrected coefficient of determination adjusted R^2 = 0.9504, and a coefficient of variation CV = 2.25%. In summary, this regression model was extremely significant, provided a reliable and realistic response to the true situation and can be used for further prediction and analysis of target stacking angles.

TABLE 8. Analysis of central composite test results.

Parameters	Degree of freedom	Sum of squares	F value	P value
Modal	9	300.93	41.41	<0.0001
X_3	1	16.45	20.37	0.0011
X_4	1	36.66	45.40	<0.0001
X_5	1	82.47	102.14	<0.0001
X_3X_4	1	22.85	28.30	0.0003
X_3X_5	1	1.53	1.90	0.1985
X_4X_5	1	1.69	2.10	0.1783
X_3^2	1	102.49	126.93	<0.0001
X_4^2	1	16.18	20.04	0.0012
X_5^2	1	15.02	18.61	0.0015
Residual	10	8.07		
Lack of Fit	5	4.29	1.13	0.4479
Pure Error	5	3.79		
Cor Total	19	309.00		

Note: ** indicates that the impact is extremely significant (P<0.01), and * indicates that the impact is significant (P<0.05). The same below.

To visually analyze the relationship between the factors and the test index, the response surfaces were plotted using Design-Expert 13; the response surfaces between the collision recovery factor and the static friction factor and the stacking angle are shown in Figure 11. As shown in Figure 11, with a constant static friction factor, the stacking angle increased and then decreased as the collision recovery factor increased. When the collision recovery factor was constant, the stacking angle increased rapidly and then tended to level off as the static friction factor increased.

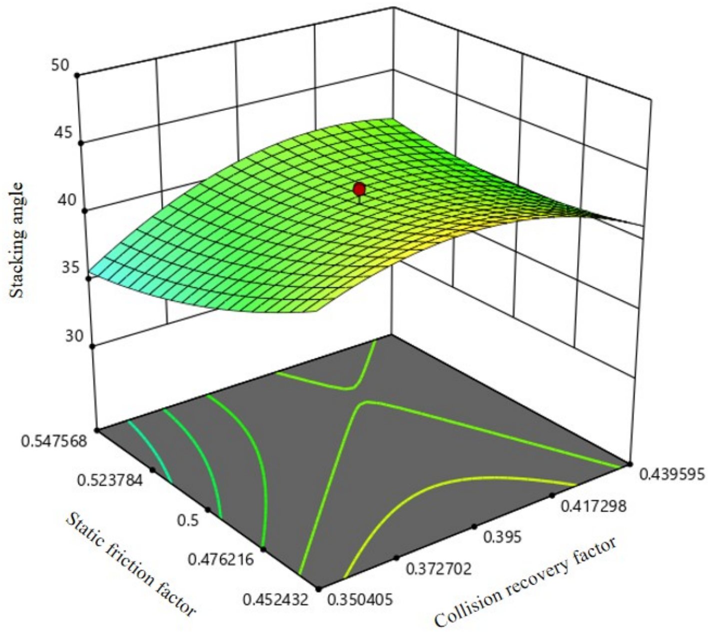


FIGURE 11. Effect of the collision recovery coefficient and static friction factor on the stacking angle.

Experimental verification

Based on the Central Composite results and the quadratic regression equation, with the objective of minimizing the relative error η of the stacking angle obtained from the test, the optimal solution analysis of the test factors X_3, X_4, and X_5 is carried out in the optimization module of the Design-Expert 13.0 software, and the objective function and constraints are set as follows:

$$\begin{cases} \min \eta(X_3, X_4, X_5) \\ s.t. \begin{cases} 0.32 \le X_3 \le 0.47 \\ 0.42 \le X_4 \le 0.58 \\ 0.12 \le X_5 \le 0.28 \end{cases} \end{cases} \tag{9}$$

When the optimization solution obtained the collision recovery coefficient, static friction coefficient and rolling friction coefficient of cotton seed-cotton seed are 0.38, 0.57 and 0.19, respectively, the stacking angle of the simulation test is the closest to the stacking angle of the physical test, which means that this parameter combination is the best parameter combination, and can be used in the simulation test.

To verify the reliability and realism of the discrete element simulation parameters after cotton seed calibration, the parameters determined above were substituted into EDEM as simulation parameters, and three simulation tests were conducted to obtain cotton seed stacking angles of 31.61°, 29.78° and 31.34°. The relative error between the average value of the physical test stacking angle (30.52°) and the average value of the simulated test stacking angle (30.91°) was 1.278%, which further verified the reliability and realism of the simulated test.

Compared with existing studies, this paper improves the accuracy of the model by reducing the relative error of 2% to 1.278% through a combination of physical and simulation tests. The obtained test parameters can be directly applied to the simulation test of seeding implements such as cotton seeder to provide reliable discrete element parameter models.

CONCLUSIONS

In this study, the basic physical parameters (particle size, thousand kernel weight, density, moisture content, modulus of elasticity, shear modulus, and Poisson's ratio) as well as the coefficients of recovery from collision, static friction, and rolling friction between the cotton seed and the contact materials were determined by physical tests on cotton seed No. 508.

The physical parameters determined by physical tests were used as the basis for the selection of simulation test parameters, and the optimal range interval of parameters with significant influence on the stacking angle was screened by the Plackett-Burman screening test and the steepest climb test; the optimal simulation parameters were obtained by optimizing the solution with the minimum value of relative error η of the stacking angle through the central composite response surface test.

In this paper, through the discrete element calibration test on the coated cotton seed, the relevant parameters obtained can be used for the subsequent design of the structure and parameter optimization of the cotton seed rower, and through the simulation test to simulate the working process of the seed rower, it can be evaluated and predicted that the qualification rate of the seed rower and the crushing rate of the seed rower can be evaluated under different factors, so as to optimize the structure of the seed rower, reduce the number of physical pre-tests, and avoid the problem that the sowing test can not be carried out for the reason of season, reduces production costs and improves research efficiency.

ACKNOWLEDGMENTS

This work was supported by the regional Collaborative Innovation Special Project (Science and Technology Assistance Program) in the Autonomous Region, China (No. 2021E02055), Proyek R & D Mesin Pertanian Xinjiang, Manufaktur, Promosi dan Integrasi Aplikasi (YTHSD2022-02) and Major Science and Technology Special Projects in Xinjiang Uygur Autonomous Region (2022A02003-3). Funding was provided by the Ministry of Science and Technology of China.

REFERENCES

Ding XT, Li K, Hao W, Yang QC, Yan FX, Cui YJ (2023) Calibration of Simulation Parameters of Camellia oleifera Seeds Based on RSM and GA-BP-GA Optimization. Transactions of the Chinese Society of Agricultural Machinery 54(02):139-150.

Gao JY, Wang C, Si ZJ (2023) Optimization of Pleurotus eryngii fortune cookies formula by response surface methodology. Food Engineering 166(01):52-55.

Hao JJ, Wei WB, Huang PC, Qin JH, Zhao JG (2021) Calibration and experimental verification of discrete element parameters of oil sunflower seeds. Transactions of the Chinese Society of Agricultural Engineering 37(12):36-44.

Huang DL, Zhou XY, Dai R, Li J, Wang JH (2023) Process optimization of green tea cookies with camellia oil based on response surface design. Food Engineering 166(01):28-33.

Li HC, Wang S, Chen Y, Hu B, Wan XZ, Liu QQ (2022) Simulation study on performance of double-chamber cotton precision seed metering device based on EDEM. Xinjiang Agricultural Mechanization 211(01):10-14.

Li YX, Li FX, Xu XM, Shen CP, Meng KP, Chen J, Chang DT (2019) Parameter calibration of wheat flour for discrete element method simulation based on particle scaling. Transactions of the Chinese Society of Agricultural Engineering 35(16):320-327.

Li ZP, Liu FY, Wei ZQ, Deng CZ, Wang SW, Xie SY (2023) Parameter calibration of discrete element model of stem mustard seeds. Journal of Chinese Agricultural Mechanization 44(22):83-90.

Liu FY, Zhang J, Li B, Chen J (2016) Calibration of parameters of wheat required in discrete element method simulation based on repose angle of particle heap. Transactions of the Chinese Society of Agricultural Engineering 32(12):247-253.

Liu R, Li YJ, Liu ZJ, Liu LJ, Lü HT (2021) Analysis and Calibration of Discrete Element Parameters of Coated Maize Seed. Transactions of the Chinese Society of Agricultural Machinery 52(S1):1-8+18.

Liu WJ, Fan YS, Dong YQ, Qu T, Zhu K, Liu YC, Wei F (2022) Analysis of the current situation of cotton production in China and suggestions. China Seed Ind 322(01):21-25.

Liu ZF, Yuan QH, Luo WJ (2020) Consideration and Improvement of Seed Gravity Test Method. Seed 39(03):165-166.

Shen L (2022) Present Situation and Application of Cotton Precision Sowing Technology. Agriculture Technology and Equipment 388(04):84-86.

Shu CX, Yang J, Wan XY, Yuan JC, Liao YT, Liao QX (2022) Calibration and experiment of the discrete element simulation parameters of rape threshing mixture in combine harvester. Transactions of the Chinese Society of Agricultural Engineering 38(09):34-43.

Song DP, Wang C, Sun DX, Liu KK, Zhang AM (2021) Design and test of intelligent cotton planter based on Beidou navigation.Journal of Intelligent Agricultural Mechanization (In Chinese and English) 2(01):44-50+63.

Wang G, Chen B, Wang XW, Chen B, Ma XM (2022) The whole-process mechanization technology by integrating agricultural machinery with agronomy in Xinjiang cotton. China cotton 49(3):24-26.

Wu MC, Cong JL, Yan Q, Zhu T, Peng XY, Wang YS (2020) Calibration and experiments for discrete element simulation parameters of peanut seed particles. Transactions of the Chinese Society of Agricultural Engineering 36(23):30-38.

Xin MH, Wang ZB, Han YC, Fan ZY, F L,Yang BF, Li XF, Wang GP, Lei YP, Xing FF, Xiong SW, Li YB (2021) Review,Status and Measures of Xinjiang Machine-picked Cotton.Journal of Agricultural Science and Technology 23(7):11-20.

Xu B, Zheng DC, Cui QL (2023) Modeling of buckwheat grains based on EDEM and numerical simulation of vibratory screening. Journal of Chinese Agricultural Mechanization 44(05):121-126.

Xu ZY, Zhou Y, Hu MJ, Ke HB, Zhang MY, Lu Wc (2020) Seeding simulation test of inside-filling cotton seed-metering device based on EDEM. J. Gansu Agricultural University 55(04):175-183.

Yang ZN, Tang JJ, Yu XL (2013) Study on the impact of cotton industry in Xinjiang on national economy and countermeasures. Agricultural Modernization Research 34(03):298-302.

Yu CC, Duan HB, Cai XK, Xu T, Yao FH, Chen ZH, Yan FY (2021) Discrete element simulation parameters-based measurement of materials for potato minituber. Journal of Huazhong Agricultural University 40(01):210-217.

Yuan JT, Zhang HR, Yang C, Song QH, Zhang J (2022) Calibration of discrete element parameters of grass carp feed based on repose angle test. Manufacturing Automation 44(12):61-67.

Zeng ZW, Ma X, Cao XL, Li ZH, Wang XC (2021) Critical review of policátions of discrete element method in agricultural engineering. Transactions of the Chinese Society of Agricultural Machinery 52(04):1-20.

Zhang F, Jin YJ (2023) Analysis of Discrete Element in Coal Mine Machinery Research Status and Prospects. Mechanical Management and Development 38(08):57-59.

Zhang QX, Liu FY, Yang ZY, Li JW, Han MJ, Li XQ (2023 b) Operation parameter optimization and experiment of potato sorting device based on discrete element. Journal of Chinese Agricultural Mechanization 44(04):96-103.

Zhang RF, Jiao W, Zhou JL, Qi B, Liu H, Xia QQ (2020) Parameter Calibration and Experiment of Rice Seeds Discrete Element Model with Different Filling Particle Radius. Transactions of the Chinese Society of Agricultural Machinery 51(S1):227-235.

Zhang RW, Chen YL, Zhao DJ (2023 a) Development Status of Cotton Industry in Xinjiang and the Suggestions. Journal of Smart Agriculture 3(06):1-5.

Zhang XJ, Chen Y, Shi ZL, Jin W, Zhang HT, Fu H, Wang DJ (2021) Design and experiment of double-storage turntable cotton vertical disc hole seeding and metering device. Transactions of the Chinese Society of Agricultural Engineering 37(19):27-36.

Zhang XJ, Cheng JP, Shi ZL, Wang MJ, Fu H, Wu HF (2023 c) Simulation and experiment of seed taking performance of swing clamp type maize precision seed-metering device. Transactions of the Chinese Society of Agricultural Machinery 54 (04):38-50.

Zhang XR, Wen ZT, Zhang ZF, Sun ZJ, Zhang H, Liu JX (2023 d) Design and Test Automatic Rubber-tapping Device with Spiral Movement.Transactions of the Chinese Society of Agricultural Machinery 54 (03):169-179.

Zhao LP, Na XY (2014) Present situation of research and development of precision seed metering device. Agricultural Technology and Equipment 240(06):30-31.

Zhao PF, Cao Y, Wang L, Wang XF, Guo WS, Hu C, He XW (2020) Design and experiment of precision hill planter performance detection device based on image technology and sensor fusion. Journal of Tarim University 32(04):59-67.

Zhao Y, Chen XG (2023) Problems and prospects of high quality cotton production in China. Journal of Tarim University 35(01):1-8.

Zhou L, Yu JQ, Liang LS, Wang Y, Yu YJ, Yan DX, Sun K, Liang P (2021) DEM parameter calibration of maize seeds and the effect of rolling friction. Processes 9(6).