Parameter calibration of discrete element model for alfalfa seeds based on EDEM simulation experiments

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Abstract: In order to establish an accurate discrete element model of alfalfa seeds, real physical experiments were combined with simulation experiments, and the contact parameters of alfalfa seeds were calibrated using the repose angle of alfalfa seeds as the response value. Some intrinsic parameters (thousand grain weight, triaxial size, density) and contact parameters (static friction coefficient, rolling friction coefficient) of alfalfa seeds were obtained through physical experiments, and a spherical particle model was established. Through the Plackett Burman experiment, the static friction coefficient between alfalfa seeds, the rolling friction coefficient between alfalfa seeds, and the static friction coefficient between alfalfa seeds and ABS plastic were determined to have a significant impact on the experiment. The steepest climb test is used to narrow down the selection range of the optimal parameters, and the box Behnken test is used to obtain the quadratic regression equation of the repose angle. The optimal parameter combination was obtained with the objective of minimizing the repose angle error: the static friction coefficient between alfalfa seeds and alfalfa seeds was 0.418, the rolling friction coefficient between alfalfa seeds and alfalfa seeds was 0.086, and the static friction coefficient between alfalfa seeds and ABS plastic was 0.471. The repose angle and mass flow rate experiments show that the model is effective and reliable.

Keywords: alfalfa seeds, discrete element, parameter calibration, EDEM
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1 Introduction

Alfalfa is an important high-quality forage resource in China, with a planting area of approximately 1.33 million hm^2, accounting for 78.5% of the national artificial planting area[1,2]. It is known as the “Grass Queen”[3]. Due to its small size, light weight, and low sowing rate (about 15.0-22.5 kg/hm^2), alfalfa seeds are often sown in strips, making it difficult to achieve mechanized precision sowing. In order to improve seeding accuracy, a precise simulation model of seed particles was established using virtual simulation technology. The motion characteristics of the seeds were studied, and the interaction mechanism between the seeds and the seeder was revealed. The key structural design of the seeder was completed, which is of great significance for achieving mechanized and precise seeding of alfalfa seeds[4].

The discrete element method is a numerical simulation method for solving the problem of medium discontinuity, which can be used for simulating and modeling seed stress and motion trajectory during the sowing process. In recent years, it has been widely used in agricultural machinery[5,6]. Domestic and foreign personnel have completed the establishment of discrete element models and calibration of related parameters for agricultural inputs such as soil[7,8], wheat[9], rice[10], peanuts[11], and maize[12-14], providing data support for the improvement of sowing technology and the optimization of sowing machine structure[15-17]. In order to obtain an accurate particle simulation model, this paper uses a combination of physical and simulation experiments to calibrate and verify the contact parameters between alfalfa seeds and ABS plastic sheets, and finally obtains a reasonable discrete element model of alfalfa seeds.

2 Materials and methods

2.1 Parameter calibration test

In order to construct a spherical particle model of alfalfa seeds in EDEM software, some intrinsic parameters (thousand grain weight, triaxial size, density) and contact parameters (static friction coefficient, rolling friction coefficient) of lucerne seeds were determined[18-20].

2.1.1 Intrinsic parameter measurement

Randomly select 1000 alfalfa seeds and measure their mass using an electronic scale with an accuracy of 0.01 g. Then randomly select alfalfa seeds and use a vernier caliper with a measurement accuracy of 0.01 mm to measure the three-axis external dimensions of alfalfa seeds, the results are listed in Table 1. Statistical analysis is conducted on the three-axis dimensions and thousand grain weight of alfalfa seeds, and the statistical results show a normal distribution curve.

Table 1 3D dimension and 1000-seed weight of alfalfa seeds

Test index	Length/mm	Width/mm	Height /mm	1000-seed weight/g
Maximum	2.82	1.75	1.12	1.93
Minimum	2.21	1.50	0.89	1.89
Average	2.61	1.60	1.01	1.91
Standard-deviation	0.24	0.09	0.07	0.01
CV/%	9.2	5.6	6.9	0.5

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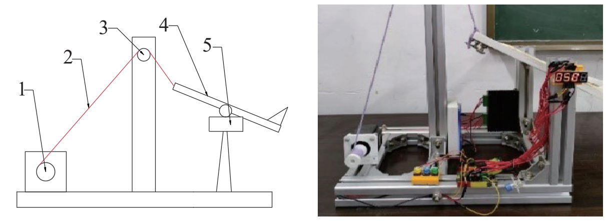
The seed density was determined to be 1154 kg/m^3 using the drainage method, and a measuring cylinder with a measurement accuracy of 1 mL was used. After multiple measurements, the average value was taken.

Through experiments, the weight of a thousand seeds of alfalfa is (1.91±0.01) g, the length is (2.61±0.24) mm, the width is (1.60±0.09) mm, and the height is (1.01±0.07) mm.

2.1.2 Friction coefficient measurement

The relevant friction coefficient of alfalfa seeds was measured using a tilt test bench, which is shown in Figure 1.



a. Structural diagram of tilt test bench b. Tilt test bench

1. PTO 2. Rope 3. Pulley 4. Discharge plate 5. Digital tube

Figure 1 Tilt test bench

The experimental data are listed in Table 2. According to the experimental data in Table 2, the static friction coefficient between alfalfa seeds and alfalfa seeds is (0.30±0.15). The rolling friction coefficient between alfalfa seeds and alfalfa seeds is (0.075±0.05). The static friction coefficient of alfalfa seed ABS plastic board is (0.45±0.1); The rolling friction coefficient of alfalfa seed ABS plastic board is (0.3±0.2).

Table 2 Frictional coefficient of alfalfa seeds

Test index	Max	Min	Ave	Standard deviation
Static friction coefficient of alfalfa seeds-alfalfa seeds	0.46	0.29	0.30	0.15
Rolling friction coefficient of alfalfa seeds-alfalfa seeds	0.125	0.025	0.075	0.050
Static friction coefficient of alfalfa seeds-ABS plastic plate	0.53	0.36	0.45	0.10
Rolling friction coefficient of alfalfa seeds-ABS plastic plate	0.48	0.11	0.30	0.20

2.1.3 Repose angle test

The repose angle of alfalfa was measured using the hollow cylinder unloading method[21-23]. The ABS plastic cylinder and plastic bottom plate were placed on an electronic universal testing machine controlled by GHS200 microcomputer, which is shown in Figure 2.

Figure 2 Physical stacking test

Set the uniform lifting speed of the experimental equipment fixture to 300 mm/min to allow the purple clover seeds to form a pile. Using a camera to take photos, using MATLAB software to denoise, grayscale process, and binarize the image, extracting contour curves through hole filling and expansion processing, fitting a straight line using the least squares method, and calculating the repose angle based on the slope of the obtained straight line.

The original image is shown in Figure 3a, the binarized image is shown in Figure 3b, and the fitted straight line image is shown in Figure 4. Repeat the experiment 10 times and take the average value. After the experiment, the average repose angle of alfalfa seeds was determined to be 31.464°.

a. Seed unilateral stacking image

b. Image binarization

Figure 3 Edge contour extraction process of repose angle

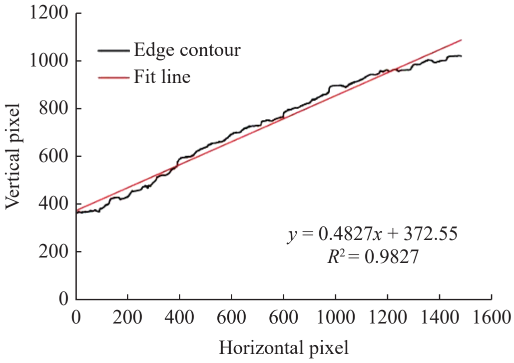


Figure 4 Single side edge contour fitting

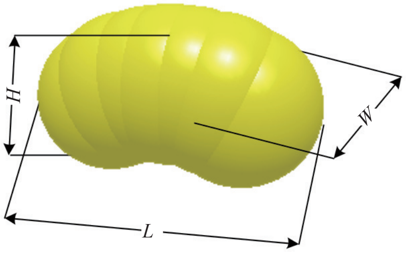
2.2 Discrete element modeling and calibration of simulation parameters

2.2.1 Establishment of discrete element simulation model

A three-dimensional model of alfalfa seeds was established based on their triaxial dimensions. Save the 3D model in stl format and import it into EDEM software to generate a spherical particle model of alfalfa seeds composed of seven spheres, as shown in Figure 5.

2.2.2 Plackett-Burman test

The Plackett-Burman test can screen for factors that have a significant impact on the experiment among many other factors. Use Design Expert software to conduct Plackett Burman experimental design and identify the factors that have a significant impact on the repose angle of alfalfa seeds. The testing coefficients and levels are listed in Table 3. *A*-*G* is the real factor, *H*-*K* is the virtual factor, and the factor level is determined based on the above prediction results and literatures[24,25]. The method for determining the repose angle in simulation experiments is the same as the method for determining the actual repose angle. The testing plan and results are listed in Table 4. The analysis of experimental factors is listed in Table 5. The experimental process is shown in Figure 6.



Note: L, W, and H are the length, width and Height of alfalfa seeds, respectively

Figure 5 Discrete element model of alfalfa seed

Table 3 Plackett-Burman test parameter range table

Symbol	Test parameters	Low level (–1)	High level (+1)
A	Poisson's ratio of Alfalfal seed	0.2	0.5
B	Alfalfa seeds-Alfalfa seeds collision recovery factor	0.1	0.63
C	Alfalfa seeds-Alfalfa seeds static friction factor	0.15	0.45
D	Alfalfa seeds-Alfalfa seeds rolling friction factor	0.025	0.125
E	Alfalfa seed-ABS collision recovery factor	0.1	0.9
F	Alfalfa seeds-ABS static friction factor	0.35	0.55
G	Alfalfa seeds-ABS rolling friction factor	0.1	0.5
H,I,J,K	Virtual parameters	--	--

Table 4 Plackett-Burman test protocol and results

No.	Test parameters											Repose angle θ/(°)
	A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*	*K*	
1	1	1	–1	1	1	1	–1	–1	–1	1	–1	19.84
2	–1	1	1	–1	1	1	1	–1	–1	–1	1	25.64
3	1	–1	1	1	–1	1	1	1	–1	–1	–1	31.15
4	–1	1	–1	1	1	–1	1	–1	1	–1	–1	19.42
5	–1	–1	1	–1	1	1	–1	1	1	1	–1	25.24
6	–1	–1	–1	1	–1	1	1	–1	1	1	1	21.39
7	1	–1	–1	–1	1	–1	1	1	–1	1	1	19.56
8	1	1	–1	–1	–1	1	–1	1	1	–1	1	18.21
9	1	1	1	–1	–1	–1	1	–1	1	1	–1	28.76
10	–1	1	1	1	–1	–1	–1	1	–1	1	1	31.06
11	1	–1	1	1	1	–1	–1	–1	1	–1	1	33.09
12	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	21.44

Table 5 Significance analysis of Plackett-Burman test parameters

Parameters	Sum of squares	Impact rate/%	*p*-value	Effect	Significance
A	3.43	1.097	0.1623	1.07	6
B	6.66	2.126	0.0758	–1.49	5
C	252.8	80.716	0.0001	9.18	1
D	24.37	7.779	0.0104	2.85	2
E	7.08	2.262	0.0700	–1.54	4
F	11.72	3.742	0.0342	–1.98	3
G	0.73	0.233	0.4744	–0.49	7

2.2.3 Design of steepest climb test

The conclusion drawn from the Plackett Burman test is that factors C, D, and F have a significant impact on the test results[26]. In order to narrow the range of factor levels and further find the optimal combination of parameters, the steepest climb test was conducted, The experimental results are listed in Table 6. Choose an appropriate step size based on the high and low levels of significance factors, with significance factors of unequal increments as the intermediate level (Poisson's ratio of 0.35, collision recovery coefficient between alfalfa seeds and alfalfa seeds is 0.365, collision recovery coefficient between alfalfa seeds and ABS plastic is 0.5, and rolling friction coefficient between alfalfa seeds and ABS plastic is 0.3). Using the relative error of the repose angle as the response value for finding the optimal value, the relative error of the repose angle is shown in Equation (1)[27].

$$Y = \frac{\beta - \theta}{\theta} \times 100\% \tag{1}$$

where, Y is the relative error of repose angle; β is the simulation test of repose angle, (°); θ is the actual test repose angle, (°).

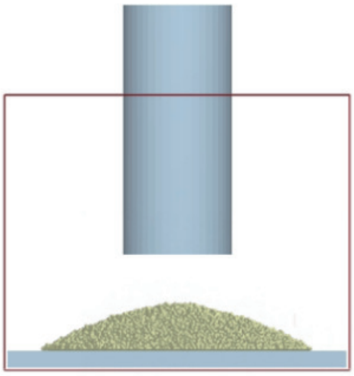


Figure 6 Simulation stacking test

Table 6 Steepest ascent test design scheme and results

No.	Alfalfa seeds - Alfalfa seeds static friction factor *C*	Alfalfa seeds - Alfalfa seeds rolling friction factor *D*	Alfalfa seeds - ABS static friction factor *F*	Repose angle *β*/(°)	Relative error/%
1	0.15	0.025	0.35	20.551	34.68
2	0.21	0.045	0.39	22.802	27.53
3	0.27	0.065	0.43	26.197	16.74
4	0.33	0.085	0.47	30.019	4.59
5	0.39	0.105	0.51	32.141	2.15
6	0.45	0.125	0.55	35.310	12.22

2.2.4 Design of Box-Behnken test

The test results of the steepest climbing test are listed in Table 7[28]. As the seed contact parameter values increase, the repose angle error shows a trend of first decreasing and then increasing. At level 5, the error reached its minimum value. Therefore, the optimal combination should be close to level 5, with level 5 as the center point, and levels 4 and 6 as the high and low levels of Box Behnken test, respectively. The test code table is listed in Table 7, and the test plan and results are listed in Table 8[29].

Table 7 Simulation test factors and codes

Code	Alfalfa seeds - Alfalfa seeds static friction factor *C*	Alfalfa seeds - Alfalfa seeds rolling friction factor *D*	Alfalfa seeds - ABS static friction factor *F*
–1	0.33	0.085	0.47
0	0.39	0.105	0.51
1	0.45	0.125	0.55

Use Design Expert software to perform multiple regression fitting analysis on experimental data, and finally obtain the second-order regression equation for the relative error of repose angle Y, as shown in Equation (2)[30].

$$Y = 6.386 + 0.735C + 1.886\,25D + 1.573\,75F + 2.56CD + 2.19CF + 0.557\,5DF + 0.795\,75C^2 - 0.346\,75D^2 - 2.576\,75F^2 \tag{2}$$

From Table 9, it can be seen that the regression terms C, DF, C^2, and D^2 have no significant effect on the relative error Y of the repose angle ($p \geq 0.05$), while D, F, CD, CF, and F^2 have a significant effect on the relative error of the repose angle ($p<0.05$). The degree of influence on the descending order of the results is D, F^2, CD, F, and CF. The fitted regression model has a $p<0.001$, indicating that the model has a high level of significance; The fitting failure term $p=0.0773$ is not significant, indicating that the model fits well and there are no other main factors affecting the test indicators; The determination coefficient of the regression equation $R^2=0.9523$ indicates that the regression equation fits well[31].

Table 8 Experimental design and results of Box-Behnken

No.	Alfalfa seeds - Alfalfa seeds static friction factor C	Alfalfa seeds - Alfalfa seeds rolling friction factor D	Alfalfa seeds - ABS static friction factor F	Error rate Y/%
1	–1	–1	–1	7.62
2	1	–1	–1	2.37
3	–1	1	–1	6.18
4	1	1	–1	11.17
5	–1	–1	1	3.68
6	1	–1	1	2.37
7	–1	1	1	2.46
8	1	1	1	9.91
9	–1.682	0	0	0.52
10	1.682	0	0	3.27
11	0	–1.682	0	2.54
12	0	1.682	0	7.52
13	0	0	–1.682	6.45
14	0	0	1.682	6.78
15	0	0	0	5.37
16	0	0	0	6.55
17	0	0	0	6.78

Table 9 Box-Behnken test regression model analysis of variance

Sorуce of variation	Mean square	Degree of freedom	Sum of square	F-value	p-value
Model	129.88	9	14.43	15.51	0.0008**
C	4.32	1	4.32	4.65	0.0681
D	28.46	1	28.46	30.60	0.0009**
F	19.81	1	19.81	21.30	0.0024**
CD	26.21	1	26.21	28.18	0.0011**
CF	19.18	1	19.18	20.62	0.0027**
DF	1.24	1	1.24	1.34	0.2856
C^2	2.67	1	2.67	2.87	0.1343
D^2	0.5063	1	0.5063	0.54	0.4847
F^2	27.96	1	27.96	30.06	0.0009**
Residual	6.51	7	0.9302		
Lack of fit	5.14	3	1.71	4.99	0.0773
Pure error	1.37	4	0.3434		
Sum	136.39	16			

Note: ** indicates a highly significant effect ($p<0.01$), * indicates a significant effect ($p<0.05$).

In order to seek the optimal combination of simulation parameters, Design Expert software is used to solve with the minimum repose angle error as the optimization objective, and the objective function is shown in Equation (3).

$$\begin{cases} \min Y(C,D,F) \\ \text{s.t.} \begin{cases} 0.330 \leq C \leq 0.450 \\ 0.085 \leq D \leq 0.125 \\ 0.470 \leq F \leq 0.550 \end{cases} \end{cases} \tag{3}$$

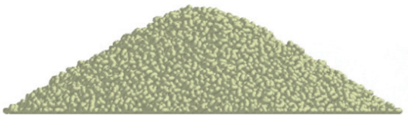
The optimal parameter combination obtained is: static friction coefficient between alfalfa seeds and alfalfa seeds: 0.418, rolling friction coefficient between alfalfa seeds and alfalfa seeds: 0.086, plastic static friction coefficient between alfalfa seeds and ABS: 0.471, and predicted repose angle error value of 0.747%.

3 Results and discussion

3.1 Experimental verification of repose angle

The static friction coefficient of alfalfa seeds, the rolling friction coefficient between alfalfa seeds and alfalfa seeds, and the plastic static friction coefficient of alfalfa seeds ABS obtained by seeking the optimal parameters are used as the intermediate values for the other factor levels. The average repose angle measured by 5 EDEM simulations is 31.23°, and compared with the values measured by physical tests, the relative error is only 0.74%. The results indicate that the EDEM discrete element model of alfalfa seeds has certain basis. The experimental verification comparison chart is shown in Figure 7.

a. Real test results



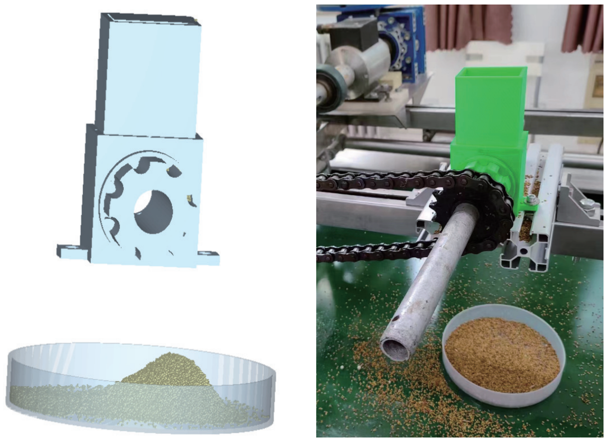
b. Simulation test results

Figure 7 Test verification of repose angle

3.2 Seeding test effect verification

Due to the weight of a thousand seeds of alfalfa being only 1.93 g, using a 3D small external groove wheel seeder for sowing can improve the accuracy of test data. Using mass flow rate as the response value, compare the relative error between the experimental and simulated values of the seeding table, and verify the reliability of the model parameters. The bench test verification is shown in Figure 8, and the comparison curve of the experimental results is shown in Figure 9.

Set the speed of the seed remover to 30 r/min and test for 10 s. Measure the mass flow rate of alfalfa seeds at slotted wheel lengths of 5 mm, 10 mm, 15 mm, and 20 mm, respectively. The maximum error between the actual mass flow rate of alfalfa seed rowers and the simulated mass flow rate is less than 5.42%, indicating that the discrete element model of alfalfa seeds is effective and reliable.



a. Real test b. Simulation test

Figure 8 Test verification of mass flow rate

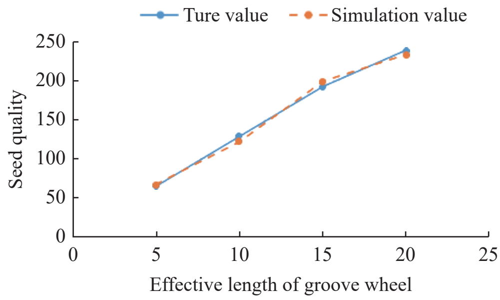


Figure 9 Comparison curve of the experimental results

4 Conclusions

1) The thousand grain weight of alfalfa seeds was measured to be 1.93 g, and the triaxial size was 2.606 mm×1.598 mm× 1.014 mm, density 1154 kg/m^3, static friction coefficient between seeds 0.15-0.45, rolling friction coefficient between seeds 0.025-0.125, discrete element model of seed ABS rolling alfalfa seeds composed of 7 spherical particles, friction coefficient 0.1-0.5.

2) Through the Plackett Burman experiment, factors that significantly affect the repose angle were selected from several factors, including the static friction coefficient between alfalfa seeds, the rolling friction coefficient between alfalfa seeds, and the plastic static friction coefficient between alfalfa seeds and ABS.

3) Reduce the significance parameter range through the steepest climb test and determine the optimal combination interval between level 4 and level 6. A second-order regression equation for the relative error of repose angle was established using Box Behnken test. The optimal combination of contact parameters for alfalfa repose angle was determined as follows: the static friction coefficient between alfalfa seeds and alfalfa seeds was 0.418, the rolling friction coefficient between alfalfa seeds and alfalfa seeds was 0.086, and the plastic static friction coefficient between alfalfa seeds and ABS was 0.471.

4) The EDEM simulation test verifies that the repose angle is 31.23°, and the repose angle error is 0.74%. By comparing the external groove wheel and simulation model in seed discharge experiments, it was verified that the relative error of mass flow rate is less than 5.42%, further verifying the reliability of the discrete element simulation model.

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