Parameter calibration of American ginseng seeds for discrete element simulation

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Abstract: The accurate contact parameters of American ginseng seed particles are the basis for establishing the discrete element simulation model of American ginseng seeds. The parameters of American ginseng seeds were calibrated by combining the physical tests and simulation tests together. The basic physical parameters, contact parameters and repose angle of sprouted American ginseng seeds were determined by physical tests. The simulation parameters were significantly screened by conducting the Plackett-Burman test. Meanwhile, it was determined that the collision recovery coefficient, static friction coefficient and rolling friction coefficient of interspecific contact parameters have significant influences on the repose angle of the simulation test. By the steepest climb test, the optimal interval for the value of the significance parameter was determined. Subsequently, the second-order regression equation between contact parameters and the repose angle was established, the regression equation was optimized and solved, and the best combination of simulation parameters was determined. The collision recovery coefficient between sprouted American ginseng seeds was 0.346, the static friction coefficient was 0.769, and the rolling friction coefficient was 0.490. By the calibrated seed group of American ginseng for discrete element simulation test, the average repose value angle was 38.80°, and the relative error with the measured repose angle was 0.733%. The results revealed that the simulation parameters of American ginseng seeds were reliable, which can provide a basis for the design and performance optimization of American ginseng seed-metering device in the later stage.

Keywords: American ginseng seed, parameter calibration, discrete element, experiments

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1 Introduction

At present, there are some problems in American ginseng sowing, such as seed picking and weak seed filling of the seed-metering device. To solve this problem, the interaction between seed-metering device and seeds needs to be analyzed first, but at this stage, no scholars have been seen to study it, therefore, it is important to establish a simulation model of American ginseng seed to obtain accurate physical characteristics parameters and contact parameters for the preliminary research of the seed-metering device. The particle simulation model of American ginseng seed is constructed by adopting discrete element method[1-3], which can reveal the working mechanism of seed-metering device, provide theoretical support for optimizing the structure of seed-metering device[4-7].

The discrete element method provides a new method for the digital research and development of agricultural equipment[8-11]. Hao et al.[12] used three-dimensional scanning technology to obtain the rapeseed intrinsic parameters, established the rapeseed discrete element model with the help of EDEM, and the calibration results were verified by physical tests and simulations of electromagnetic hopper vibration. Hou et al.[13] established the Agropyron seed discrete element model, the simulation parameters were calibrated by a combination of physical and simulation experiments, with repose angle as the response value, and *t*-test was applied to measure the repose angle and simulate the repose angle, aiming to determine the optimal combination of parameters. Zhang et al.[14] verified the rice seed model by means of gas-solid two-phase flow coupling simulation, study the effect of rice seeds with different filling radii on simulation accuracy, and determined the optimal filling radius of the rice model. Józef et al.[15] studied the effects of particle filling method, seed size and seed length diameter ratio on the vertical pressure distribution at the bottom of silo based on the discrete element method, and verified the model through seed tests of five different shapes. Mehrdad et al.[16] investigated the effects of corn seed particle shape on rotational motion based on EDEM simulation software. In addition, Yuan et al.[17] established the soils and fertilizers discrete element model, study the effect of paddle configuration on the homogeneity of soil and fertilizer mixing, and determined the optimal blade configuration, Hao et al.[18] explored the impacts of particle size on the particle flow characteristics of sandy loam on the basis of EDEM software, and established the discrete element model of yam-sandy loam soil complex, which provides a theoretical basis for constructing the discrete element model of sandy loam soil. In the research on the calibration of discrete element simulation parameters, the calibration objects are mainly large seed, small seed, soil, and fertilizer, and there are few studies and calibration on the discrete element simulation parameters of sprouted American ginseng seeds.

For given above, this research chose the sprouted American ginseng seeds as the main research object, and the repose angle of the stacking test was used as the test index. The discrete element simulation parameters were calibrated by Plackett-Burman test, steepest ascent test and quadratic regression orthogonal rotation combination test. By the comparison and verification of the simulation and the measured repose angle, the reliability of the simulation model parameters was determined, which provides

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references for the exploration of American ginseng seed-metering device.

2 Materials and methods

2.1 Determination of physical parameters of sprouted American ginseng seeds

2.1.1 3D dimension measurement and geometric model establishment

The sprouted American ginseng seeds were taken as the research object. According to the national standard GB/T3543.1-3543.7–1995 (Code for Inspection of Crop Seeds). The density of their seed particles was 878 kg/m^3, and the bulk density was 513 kg/m^3, and the average water content was 45.45%. A total of 100 American ginseng seeds were randomly selected, and their 3D dimension (length L, width W and thickness T) were measured by digital vernier caliper (accuracy 0.01 mm). The 1000-seed weight of American ginseng seeds was determined by electronic balance (accuracy 0.1 mg). The specific results of 3D dimension and 1000-seed weight of American ginseng seeds are displayed in Table 1. The 3D dimension of American ginseng seeds was statistically analyzed, and the seed size was normally distributed (is shown in Figure 1).

Table 1 3D dimension and 1000-seed weight of sprouted American ginseng seeds

Test index	Length/mm	Width/mm	Thickness /mm	1000-seed weight/g
Maximum	6.88	5.53	4.02	54.00
Minimum	4.86	3.86	2.48	51.00
Average	5.90	4.69	3.26	52.50
Standard deviation	0.54	0.41	0.45	1.02
CV/%	9	9	14	2

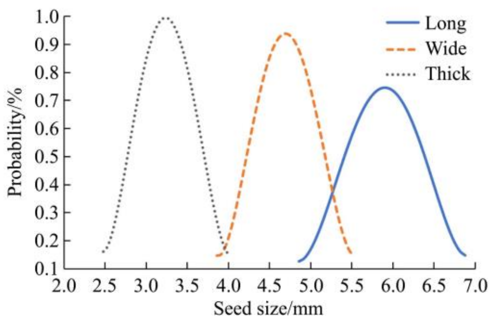
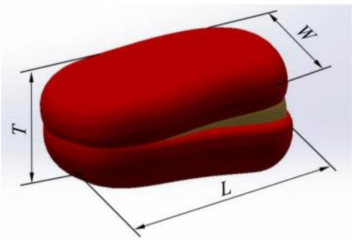


Figure 1 3D dimension probability distribution diagram

It can be seen from Table 1 and Figure 1 that the 1000-seed weight of sprouted American ginseng seeds was (52.5±1.02) g, the length L was (5.90±0.54) mm, the width W was (4.69±0.41) mm, and the thickness T was (3.26±0.45) mm. The geometric model of American ginseng seed was an elliptical cylinder. The 3D dimension geometric model of American ginseng seed was established by SolidWorks software (as shown in Figure 2).



Note: *L*, *W*, and *T* are the length, width and thickness of American ginseng seeds, respectively, mm.

Figure 2 Geometric model of sprouted American ginseng seed

2.1.2 Poisson's ratio

The sprouted American ginseng seeds were selected, and the width and thickness of American ginseng seeds were measured with digital vernier caliper. The microcomputer-controlled electronic universal testing machine (Model: CHS2000; Sensor range: 0-2 kN, Shanghai Hongge Co., Ltd) was used to carry out the seed compression deformation test. The load along the thickness direction of the seed at the speed of 5 mm/min was applied, the deformations of American ginseng seed in the thickness direction (axial direction) and width direction (transverse direction) were recorded with a digital vernier caliper[19,20]. The test was repeated 15 times, Poisson's ratio was calculated according to Equation (1), and then the average value was taken. The calculation results are listed in Table 2.

$$\mu = \left|\frac{\varepsilon'}{\varepsilon}\right| = \left|\frac{\Delta d / d}{\Delta l / l}\right| = \left|\frac{(d_1 - d)/d}{(l_1 - l)/l}\right| \quad (1)$$

where, μ is Poisson's ratio; ε' refers to the strain in the direction perpendicular to the load; ε marks the strain in the load direction; Δd means the deformation in the width (transverse) direction, mm; d stands for the width (transverse) dimension of American ginseng seeds before loading, mm; Δl represents the deformation in thickness (axial) direction, mm; l is the thickness (axial) dimension of American ginseng seeds before loading, mm; d_1 denotes the width (transverse) dimension of American ginseng seeds after loading, mm; l_1 is the thickness (axial) dimension of American ginseng seeds after loading, mm.

Table 2 Poisson's ratio of sprouted American ginseng seeds

Test No.	d_1/mm	d/mm	ε'	l_1/mm	l/mm	ε	Poisson ratio μ
1	4.74	4.65	0.019	3.14	3.40	0.076	0.25
2	3.84	3.79	0.013	2.88	3.05	0.056	0.23
3	5.07	4.96	0.022	3.18	3.36	0.054	0.41
4	5.54	5.42	0.022	2.91	3.12	0.067	0.33
5	6.12	5.77	0.061	2.71	3.27	0.170	0.36
6	4.75	4.58	0.037	2.51	2.72	0.077	0.48
7	5.26	5.12	0.027	2.82	3.26	0.135	0.20
8	5.21	5.06	0.030	2.75	3.23	0.150	0.20
9	4.59	4.45	0.031	2.74	3.06	0.105	0.30
10	5.25	5.12	0.025	3.26	3.64	0.104	0.24
11	5.46	5.30	0.030	2.51	2.95	0.150	0.20
12	4.85	4.65	0.043	2.93	3.65	0.197	0.22
13	4.88	4.52	0.080	2.54	3.06	0.170	0.47
14	5.19	4.96	0.046	2.92	3.21	0.090	0.51
15	5.30	5.18	0.023	3.44	3.73	0.077	0.30
Average							0.31
Standard deviation							0.11

According to the test data in Table 2, the Poisson's ratio of sprouted American ginseng seeds was (0.31±0.11), and the standard deviation was 0.11.

2.1.3 Elastic modulus and Shear modulus

The 3D dimension of seeds with digital vernier caliper was measured, and microcomputer-controlled electronic universal testing machine was used to load along the direction of seed thickness at the speed of 10 mm/ min, and stop loading after the seed shell makes a cracking sound[21,22]. The test data and *F* (test force) - Δ*l* (displacement) curve can be obtained by the universal testing machine (as shown in Figure 3). The test was repeated 40 times. According to the *F*-Δ*l* curve, coordinate points *C* and *D* in the *OA* section of the seed elastic range were selected, the elastic modulus was calculated according to Equation (2), and then the average value was taken. The calculation results are demonstrated in Table 3, and the shear modulus was calculated according to Equation (3).

$$E=\frac{\sigma_D-\sigma_C}{\varepsilon_D-\varepsilon_C}=\frac{(F_D-F_C)/A}{(\Delta l_D-\Delta l_C)/l} \tag{2}$$

$$G=\frac{E}{2(1+\mu)} \tag{3}$$

where, E is the elastic modulus, MPa; σ_D means the normal stress at point D, MPa; σ_C marks the normal stress at point C, MPa; ε_D refers to the strain in the load direction of point D; ε_C stands for the strain in the load direction of point C; F_D represents the test force on point D, N; F_C refers to the test force on point C, N; A denotes American ginseng seed cross sectional area of instrument contact, mm^2; Δl_D is the thickness direction (axial) deformation of American ginseng seed at point D, mm; Δl_C marks the thickness direction (axial) deformation of American ginseng seed at point C, mm; l is the thickness (axial) dimension of American ginseng seeds before loading, mm; G represents shear modulus, MPa; μ is the Poisson's ratio of sprouted American ginseng seeds.

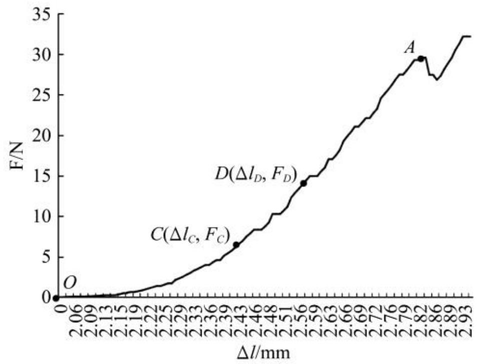


Figure 3 F-Δl curve graph of American ginseng seeds

Table 3 Elastic modulus of sprouted American ginseng seeds

Test index	Maximum /MPa	Minimum /MPa	Average /MPa	Standard deviation/MPa	CV/%
Modulus of elasticity E	5.54	3.22	4.36	0.60	13.6

According to the test data in Table 3 and Equation (3), the elastic modulus of sprouted American ginseng seeds was (4.36±1.24) MPa, the standard deviation was 0.60 MPa, the coefficient of variation was 13.6%, and the shear modulus was (1.66±0.34) MPa.

2.2 Determination of seed contact parameters of sprouted American ginseng seeds

2.2.1 Static friction coefficient

The static friction angles between sprouted American ginseng seeds and aluminum plate were measured by inclinometer[23,24], (as shown in Figure 4). The static friction coefficient between the American ginseng seed and aluminum plate was calculated according to Equation (4). The test was repeated 20 times and the average value was taken. The test results are listed in Table 4.

$$\gamma=\tan\alpha \tag{4}$$

where, γ is the static friction coefficient; α represents the measured included angle, (°).

According to the test data in Table 4, the static friction coefficient between sprouted American ginseng seed and aluminum plate was (0.55±0.04); The static friction coefficient between sprouted American ginseng seeds and aluminum plate was (0.75±0.05).

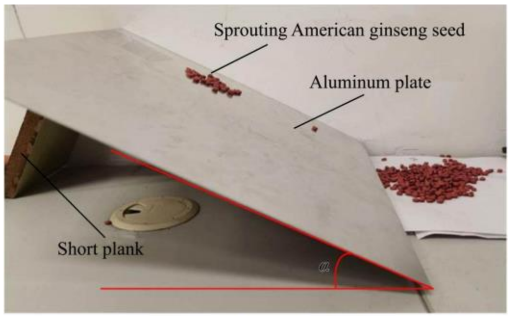


Figure 4 Measurement test of friction coefficient

Table 4 Static friction coefficient of sprouted American ginseng seeds

Test index	Static friction coefficient between sprouted American ginseng seed and aluminum plate	Static friction coefficient between sprouted American ginseng seeds
Maximum	0.62	0.84
Minimum	0.47	0.60
Average	0.55	0.75
Standard deviation	0.04	0.05
CV/%	7	7

2.2.2 Rolling friction coefficient

By using the inclinometer, in the process of pushing the short board at a uniform speed, when the sprouted American ginseng seeds roll, the researcher need to stop pushing, record the angle between the instrument and the horizontal plane, then calculate the rolling friction coefficient. This test was repeated 20 times and the average value was taken. The test results are displayed in Table 5.

Table 5 Rolling friction coefficient of sprouted American ginseng seeds

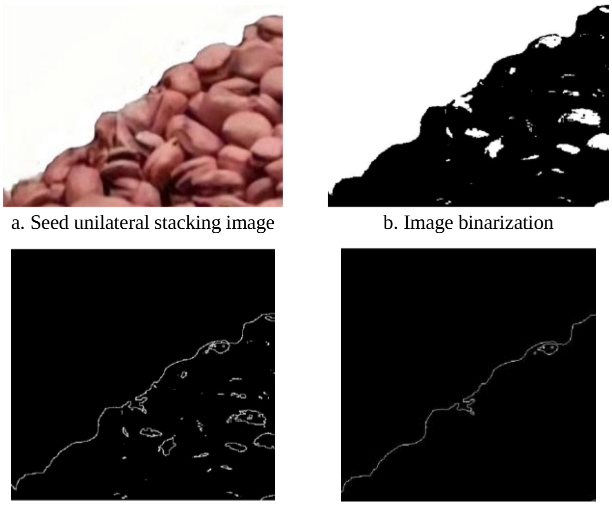
Test index	Rolling friction coefficient between sprouted American ginseng seed and aluminum plate	Rolling friction coefficient between sprouted American ginseng seeds
Maximum	0.49	0.58
Minimum	0.34	0.40
Average	0.41	0.51
Standard deviation	0.10	0.05
CV/%	24	10

According to the test data in Table 5, the rolling friction coefficient between sprouted American ginseng seed and aluminum plate was (0.41±0.1); the rolling friction coefficient between sprouted American ginseng seeds and aluminum plate was (0.51±0.05).

2.3 Determination of repose angle in seed stacking test of sprouted American ginseng seeds

Since American ginseng seeds were sprouted seeds with poor seed fluidity, according to the national standard GB11986-89 (Measurement of repose angle of surfactants, powders and particles), the stacking test of sprouted American ginseng seeds was carried out by lifting method[25-28]. The cylinder height and inner diameter were 98 mm and 33 mm, respectively[29]. The microcomputer-controlled electronic universal testing machine (Model: CHS2000; Sensor range: 0-2 kN) was used to lift the cylinder at a uniform speed of 50 mm/s[30]. After the seeds were completely stationary, the main view of the particle pile was recorded by the photographing equipment, (as shown in Figure 5). To ensure the accuracy of the test data acquisition, the unilateral images were intercepted and processed by Matlab software[31-34]. The graythresh, im2bw, imfill and bwperim functions were respectively used to extract the edge contour of the image (as shown in Figure 6), then the pixel points of the extracted contour were scanned, the fitting straight line was obtained by the least square method, and the fitting equation was obtained. The tangent of the repose angle was the slope of the fitting equation, (as shown in Figure 7). The test was repeated 8 times, and the average value of repose angle of seed stacking test of sprouted American ginseng seeds was 38.52°.

Figure 5 Physical accumulation test of sprouted American ginseng seeds



a. Seed unilateral stacking image b. Image binarization

c. Contour extraction before hole filling d. Edge contour extraction

Figure 6 Edge contour extraction process of repose angle

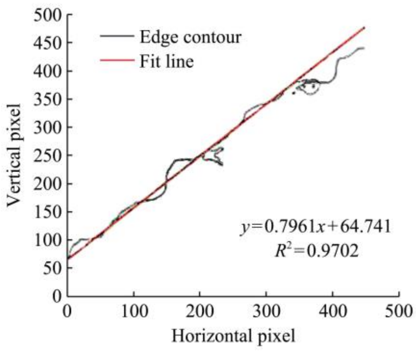


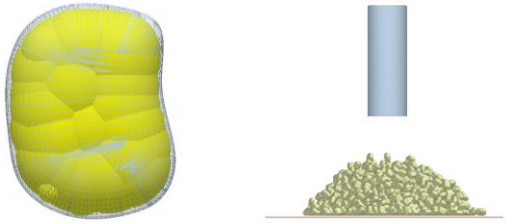
Figure 7 Single side edge contour fitting

2.4 Establishment of discrete element simulation model

The setting range of simulation parameters was determined by combining the results of physical test measurements[35-37], as shown in Table 6. The discrete element model of sprouted American ginseng seeds was established[38-40], (as shown in Figure 8a). The particle factory was set up above the cylinder, the particle production mode was dynamic generation, the production rate was 5000 particles/s, 1400 particles were generated, and the particle generation ended after 0.28 s. After the particles were stabilized, the cylinder was lifted at a uniform speed of 50 mm/s. At this time, the seeds fall freely, and the seed pile was formed after the simulation was over, (as shown in Figure 8b).

Table 6 Parameters required for discrete element simulation

Parameters	Value
Density of American ginseng seed/kg m^{-3}	878
Density of aluminum/kg m^{-3}	2700
Poisson’s ratio of American ginseng seed	0.20-0.42
Poisson's ratio of aluminum	0.25
Shear modulus of American ginseng seeds/MPa	1.32-2.00
Shear modulus of aluminum/MPa	27 000
American ginseng seed-American ginseng seed collision recovery coefficient	0.1-0.6
American ginseng seed-aluminum collision recovery coefficient	0.1-0.3
American ginseng seed-American ginseng seed static friction coefficient	0.7-0.8
American ginseng seed-aluminum static friction coefficient	0.51-0.59
American ginseng seed-American ginseng seed rolling friction coefficient	0.46-0.56
American ginseng seed-aluminum rolling friction coefficient	0.31-0.51



a. Seed simulation model b. Simulation model of stacking test

Figure 8 Measurement model of repose angle in simulation test

3 Results and discussion

3.1 Analysis of significance parameters

The Plackett-Burman test was designed based on the Design-Expert12 software. By taking the sprouted American ginseng seeds repose angle as the response value, the significant parameters that affect the repose angle were screened. The test parameters were represented by *A*-*H*, three virtual parameters, namely *J*, *K* and *L*, were set, and the maximum and minimum values of the test parameters were coded, as shown in Table 7. After the completion of each group of simulation tests, the images of simulation test results were collected, the repose angles of the left and right sides of the images were measured with the help of Matlab software, and then the average values were taken. The Plackett-Burman test scheme and results are listed in Table 8.

Table 7 Plackett-Burman test parameter range table

Symbol	Test parameters	Low level (–1)	High level (+1)
A	Poisson’s ratio of American ginseng seed	0.20	0.42
B	Shear modulus of American ginseng seeds/MPa	1.32	2.00
C	American ginseng seed-American ginseng seed collision recovery coefficient	0.1	0.6
D	American ginseng seed-aluminum collision recovery coefficient	0.1	0.3
E	American ginseng seed-American ginseng seed static friction coefficient	0.7	0.8
F	American ginseng seed-aluminum collision recovery coefficient	0.51	0.59
G	American ginseng seed-American ginseng seed rolling friction coefficient	0.46	0.56
H	American ginseng seed-aluminum rolling friction coefficient	0.31	0.51
J, *K*, *L*	Virtual parameters	—	—

Table 8 Plackett-Burman test protocol and results

No.	Test parameters											Repose angle θ/(°)
	A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*J*	*K*	*L*	
1	0	0	0	0	0	0	0	0	0	0	0	38.36
2	–1	–1	–1	1	–1	1	1	–1	1	1	1	36.56
3	–1	1	1	1	–1	–1	–1	1	–1	1	1	38.89
4	1	1	1	–1	–1	–1	1	–1	1	1	–1	39.97
5	1	–1	1	1	1	–1	–1	–1	1	–1	1	39.90
6	1	1	–1	1	1	1	–1	–1	–1	1	–1	36.46
7	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	35.09
8	–1	1	1	–1	1	1	1	–1	–1	–1	1	43.31
9	1	1	–1	–1	–1	1	–1	1	1	–1	1	33.55
10	–1	–1	1	–1	1	1	–1	1	1	1	–1	38.20
11	1	–1	–1	–1	1	–1	1	1	–1	1	1	39.83
12	1	–1	1	1	–1	1	1	1	–1	–1	–1	36.47
13	–1	1	–1	1	1	–1	1	1	1	–1	–1	40.12

Through the analysis of variance, it was found that the static friction coefficient between American ginseng seeds (E), the collision recovery coefficient between American ginseng seeds (C) and the rolling friction coefficient between American ginseng seeds (G) have significant effects on the repose angle. The significance results of each test parameter are displayed in Table 9.

Table 9 Significance analysis of Plackett-Burman test parameters

Parameters	Sum of squares	Degree of freedom	Effect	Significance
A	2.99	1	–1.00	6
B	3.26	1	1.04	5
C	19.08	1	2.52	2
D	0.20	1	–0.26	8
E	24.91	1	2.88	1
F	7.13	1	–1.54	4
G	16.73	1	2.36	3
H	1.49	1	–0.71	7

3.2 Analysis of the optimal range of significance parameters

The significance analysis of the parameters of the Plackett-Burman test indicated that the three significant parameters had positive effects on the repose angle, and the fixed step size should be increased gradually. The relative error of repose angle was used as the evaluation index to narrow down the setting range of the optimal parameters, and the test results are exhibited in Table 10 to determine the optimal interval. The coefficient recovery of collision between American ginseng seeds was [0.225, 0.475], the coefficient of static friction of American ginseng seeds was [0.725, 0.775], and the coefficient of rolling friction of American ginseng seeds was [0.485, 0.535].

Table 10 The steepest ascent test design scheme and results

No.	Recovery coefficient of collision between seeds *C*	Static friction coefficient between seeds *E*	Rolling friction coefficient between seeds *G*	Repose angle θ/(°)	Relative error/%
1	0.100	0.700	0.460	32.97	14.41
2	0.225	0.725	0.485	35.62	7.54
3	0.350	0.750	0.510	37.67	2.21
4	0.475	0.775	0.535	40.77	5.84
5	0.600	0.800	0.560	43.92	14.02

3.3 Analysis of optimal values of significance parameters

The three significant parameters of collision recovery coefficient between American ginseng seeds, static friction coefficient between American ginseng seeds and rolling friction coefficient between American ginseng seeds were used as the simulation test factors, the repose angle was the response value, and a three-factor quadratic orthogonal rotational combination test was conducted. The simulation test factors were coded, as shown in Table 11, and the test design and results are listed in Table 12.

Table 11 Simulation test factors and codes

Code	Recovery coefficient of collision between American ginseng seeds *C*	Static friction coefficient between American ginseng seeds *E*	Rolling friction coefficient between American ginseng seeds *G*
–1.682	0.140	0.708	0.468
–1	0.225	0.725	0.485
0	0.350	0.750	0.510
1	0.475	0.775	0.535
1.682	0.560	0.792	0.552

Table 12 Experimental design and results

No.	Recovery coefficient of collision between American ginseng seeds *C*	Static friction coefficient between American ginseng seeds *E*	Rolling friction coefficient between American ginseng seeds *G*	Repose angle θ/(°)
1	–1	–1	–1	36.14
2	1	–1	–1	37.11
3	–1	1	–1	37.35
4	1	1	–1	38.23
5	–1	–1	1	37.56
6	1	–1	1	38.77
7	–1	1	1	41.14
8	1	1	1	44.56
9	–1.682	0	0	35.26
10	1.682	0	0	37.69
11	0	–1.682	0	38.17
12	0	1.682	0	42.41
13	0	0	–1.682	37.83
14	0	0	1.682	41.07
15	0	0	0	37.69
16	0	0	0	38.32
17	0	0	0	38.49
18	0	0	0	38.51
19	0	0	0	38.76
20	0	0	0	39.49
21	0	0	0	38.21
22	0	0	0	38.53
23	0	0	0	38.61

The second-order regression equation for the repose angle was obtained by Design-Expert 12 software as:

$$\theta = 38.51 + 0.7737C + 1.38E + 1.37G + 0.265CE + 0.3475CG + 0.88EG - 0.6984C^2 + 0.6504E^2 + 0.3534G^2 \quad (5)$$

The analysis of variance proved that the effects of interspecific collision recovery coefficient *C*, interspecific static friction coefficient E, interspecific rolling friction coefficient *G*, interaction item *EG* of interspecific static friction coefficient and interspecific rolling friction coefficient, squared item C^2 of interspecific collision recovery coefficient, squared item E^2 of interspecific static friction coefficient on repose angle were extremely significant. The squared item G^2 of interspecific rolling friction coefficient on repose angle was significant, while other items were not significant. The results are listed in Table 13. The model coefficient p<0.0001, the model was significant, and the p value of the lack of fit item was not significant, which suggests that the quadratic relationship between the dependent variable (repose angle) and the independent variable (significance parameters) was significant. The coefficient of variation CV = 1.48%, the coefficient of determination R^2 = 0.9518, the corrected coefficient of determination R^2_{adj} = 0.9184, and the value is close to 1, which confirms that the reliability of the fitting equation is high, and the predicted value fits well with the actual value; Precision = 22.7853 indicated that the model has high accuracy and can predict the repose angle of sprouted American ginseng seeds.

Table 13 Variance analysis of regression equation

Source of variation	Mean square	Degree of freedom	Sum of square	*F*-value	*p*-value
Model	83.89	9	9.32	28.5	<0.0001
C	8.18	1	8.18	25	0.0002
E	25.96	1	25.96	79.38	<0.0001
G	25.47	1	25.47	77.85	<0.0001
CE	0.5618	1	0.5618	1.72	0.2127
CG	0.9661	1	0.9661	2.95	0.1094
EG	6.2	1	6.2	18.94	0.0008
C^2	7.75	1	7.75	23.69	0.0003
E^2	6.72	1	6.72	20.55	0.0006
G^2	1.98	1	1.98	6.07	0.0285
Residual	4.25	13	0.3271		
Lack of Fit	2.42	5	0.484		0.1657
Pure Error	1.83	8	0.229		
Sum	88.14	22			

R^2=0.9518; R^2_{adj}=0.9184; *CV*=1.48%; Adeq Precision=22.7853

Note: p<0.01 indicates extremely significant; 0.01≤ p<0.05 indicates significant; p≥0.05 means not significant.

3.4 Discrete element parameter calibration and experimental verification

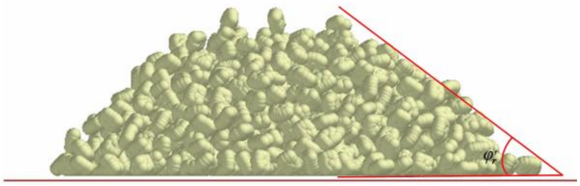
The repose angle (38.52°) was measured by the stacking test, with American ginseng seeds as the objective. The optimal results were as follows: the collision recovery coefficient between American ginseng seeds, the static friction coefficient between American ginseng seeds, and the rolling friction coefficient between American ginseng seeds were 0.346, 0.769 and 0.490, respectively.

The discrete element simulation test was performed with the calibrated parameters, and the parameters were set, as shown in Table 14. The simulation test was repeated 4 times, and the values were 40.01°, 38.39°, 38.17°, and 38.64°, respectively. With an average value of 38.80°, the relative error was 0.733%, and with an average value of 38.52°, the relative error was measured by the physical test. The test comparison graph is displayed in Figure 9.

Table 14 Discrete element simulation parameter table

Symbol	Test parameters	Value
A	Poisson's ratio of American ginseng seed	0.31
B	Shear modulus of American ginseng seeds/MPa	1.66
C	American ginseng seed-American ginseng seed collision recovery coefficient	0.346
D	American ginseng seed-aluminum collision recovery coefficient	0.2
E	American ginseng seed-American ginseng seed static friction coefficient	0.769
F	American ginseng seed-aluminum collision recovery coefficient	0.55
G	American ginseng seed-American ginseng seed rolling friction coefficient	0.49
H	American ginseng seed-aluminum rolling friction coefficient	0.41

a. Physical test



b. Simulation test

Note: φ_r and φ'_r were measured repose angle and simulated repose angle, respectively

Figure 9 Comparison between physical test and simulation test

4 Conclusions

(1) The physical parameters of sprouted American ginseng seeds were determined by performing physical test. The average values of the length, width and thickness of sprouted American ginseng seeds were (5.90±0.54) mm, (4.69±0.41) mm and (3.26±0.45) mm, respectively, and the 1000-seed weight was (52.5±1.02) g; the Poisson's ratio of seeds was (0.31±0.11), the modulus of elasticity was (4.36±1.24) MPa, and the Shear modulus was (1.66±0.34) MPa; the static friction coefficient between sprouted American ginseng seeds and aluminum plate was (0.55±0.04) and rolling friction coefficient was (0.41±0.1); the static friction coefficient between sprouted American ginseng seeds was (0.75±0.05) and rolling friction coefficient was (0.51±0.05). Through the stacking test of sprouted American ginseng seeds, the repose angle of sprouted American ginseng seeds was 38.52°.

(2) Based on Design-Expert 12 software, by Plackett-Burman test, the parameters that have significant impacts on the repose angle were selected, and they were interspecific static friction coefficient of American ginseng, interspecific collision recovery coefficient of American ginseng and interspecies rolling friction coefficient of American ginseng. The steepest ascent test was used to determine the range of significant parameters: Interspecific collision recovery coefficient of American ginseng was 0.225-0.475, the static friction coefficient of American ginseng seeds was 0.725-0.775, and the rolling friction coefficient of American ginseng seeds was 0.485-0.535.

(3) The second-order regression equation between the test dependent variable (repose angle) and the test independent variable (significance parameter) was established by an orthogonal rotational combination test. Moreover, the measured repose angle (38.52°) was used as the target value to optimize the solution of the regression equation. The results proved that the best combinations of simulation parameters are as follows: The collision recovery coefficient between sprouted American ginseng seeds was 0.346, the static friction coefficient was 0.769, and the rolling friction coefficient was 0.490. The repose angle was experimentally verified by the determined parameters with a relative error of 0.733%, which proved that the calibrated discrete element model is reliable. Most importantly, the results of the study can provide a basis for the design and performance optimization of the seed-metering device for American ginseng at a later stage.

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