RESEARCH ON CONTACT PARAMETERS CALIBRATION OF SOYBEAN SEEDS BASED ON DISCRETE ELEMENT SIMULATION
/
基于离散元的大豆种子仿真接触参数标定研究

Yuejiang TENG[1,2], Chengqian JIN[*3], Fuxiang XIE[1,2], Jian SONG[1,2], Yanjun LI[1,2]
[1] College of Machinery and Automation, Weifang University, Weifang / China;
[2] Shandong Key Laboratory of Intelligent Manufacturing Technology for Advanced Power Equipment, Weifang / China;
[3] Nanjing Institute of Agricultural Mechanization, Ministry of Agriculture and Rural Affairs, Nanjing / China
Tel: +86-19525369138; E-mail: tyj2021to2026@163.com
Correspondent author: Chengqian JIN
DOI: https://doi.org/10.35633/inmateh-78-96

Keywords: *discrete element simulation, soybean, contact parameters, calibration test*

ABSTRACT
To promote the application of the discrete element method (DEM) in the research and development of soybean production equipment, reduce development costs, and improve testing efficiency, the contact parameters of soybean seeds in a discrete element environment were calibrated. A discrete element model of soybean seeds was established in EDEM software using a multi-sphere aggregation approach. The coefficient of restitution between soybean seeds and a Q235 steel plate was calibrated to 0.54 using a collision rebound test. The static friction coefficient between soybean seeds and the Q235 steel plate was calibrated to 0.34 through an inclined-plane sliding test, whereas the rolling friction coefficient was calibrated to 0.01 using an inclined-plane rolling test. The angle of repose of soybean seeds was determined to be 31 ° using the steel-box extraction method. Based on a quadratic regression orthogonal rotational combination design, a regression model describing the relationship between the soybean angle of repose and inter-particle contact parameters was established. The model was optimized through analysis of variance, and the optimal combination of inter-particle contact parameters was determined as follows: coefficient of restitution between seeds of 0.65, static friction coefficient between seeds of 0.55, and rolling friction coefficient between seeds of 0.04. Under these parameter conditions, the relative error of the angle of repose between the simulation and bench tests was 0.32%, demonstrating the accuracy of the calibrated contact parameters and the feasibility of the simulation method. The obtained results can provide a reference for selecting soybean seed contact parameters in discrete element simulations.

摘要
为了促进离散元法在大豆农业生产装备研发中的应用，降低研发成本，提高试验效率，对离散元环境下大豆的接触参数进行了标定。基于多球聚合模型，在 EDEM 软件中建立了大豆种子的离散元模型。通过碰撞弹跳试验、斜面滑移试验和斜面滚动试验，分别标定了大豆种子与 Q235 钢板间的碰撞恢复系数为 0.54、静摩擦因数为 0.34 和滚动摩擦因数为 0.01。通过堆积试验获得了大豆种子堆积角为 31°。基于二次回归正交旋转组合试验，建立了大豆堆积角与种间接触参数的二阶回归模型。通过优化求解，得到种间接触参数的最佳组合为：种间碰撞恢复系数为 0.65，种间静摩擦因数为 0.55，种间滚动摩擦因数为 0.04。该条件下仿真试验堆积角与台架试验堆积角的相对误差为 0.32%，证明了试验测得的接触参数的准确性和仿真试验的可行性。试验结果可为大豆种子离散元仿真参数的选取提供参考。

INTRODUCTION
Soybean is an important source of high-quality protein in the human diet and also represents a major raw material for the production of meat, eggs, and milk. During soybean planting, harvesting, and post-harvest processing, the interactions among soybean seeds and between soybean seeds and agricultural machinery are highly complex, making them difficult to analyze using conventional analytical methods. In recent years, with the rapid development of computer technology, the discrete element method has been increasingly applied in the research and development of agricultural equipment (*Aikins et al., 2021; Cui et al., 2025*).

Yuejiang Teng, Lecturer, Ph.D.; Chengqian Jin, Prof., Ph.D.; Fuxiang Xie, Prof., Ph.D.; Jian Song, Prof., Ph.D.; Yanjun Li, A.P., Ph.D.

Studying simulation parameters of soybean in the discrete element analysis not only helps to promote the application of the discrete element method in the research of soybean production equipment, but also helps to reduce test costs, improve test efficiency and accelerate the improvement of and agricultural equipment for soybean production (*Chen et al.*, *2025; Zeng et al., 2021*).

Scholars at home and abroad have conducted a lot of research on agricultural materials based on the discrete element method. *Liu et al.* (*2016*) proposed a three-dimensional discrete element modeling method for irregular granular materials such as rice based on three-dimensional laser scanning, and established a discrete element model for rice seeds based on particle aggregation theory. The natural angle of repose of the rice seed discrete element model was simulated and measured, and compared with the actual experimental results to demonstrate the effectiveness and feasibility of this modeling method. *Hou et al.* (*2020*) calibrated the simulation parameters of ice grass seeds through a combination of physical and simulation experiments. The experimental results indicated that the static friction coefficient, rolling friction coefficient, and coefficient of restitution between ice grass seeds had a significant impact on the simulated angle of repose. The optimal combination of simulation parameters for ice grass seeds was obtained through multi-objective optimization. In order to study the influence of rice seed models with different filling ball radii on the dynamic response characteristics between particles, *Zhang et al*. (*2020*) used three-dimensional scanning and inverse fitting methods to obtain the outline of rice seeds, and filled them with ball particles of different radii to form a gas-solid coupled rice particle bonding polymerization model. The inter-particle static and rolling friction coefficients of seed models with different sphere radii were calibrated through comparative experiments. The results indicated that as the radius of the filled sphere decreases, the simulation results become closer to the true values. To improve the accuracy of discrete element simulation experiments for precision sowing of mung beans, *Zhang et al. (2022)* calibrated the contact parameters between mung bean seeds and contact materials using the free-fall rebound method, inclined-plane sliding method, and inclined-plane rolling method. The optimal combination of inter-particle contact parameters for mung beans was determined through a rotational combination experimental design. A seeding verification test was subsequently conducted using the calibrated parameters. The results showed that the relative error between the simulation and bench-test results was very small, thereby confirming the reliability of the calibrated parameters. In order to better apply the discrete element method to study the mixed sowing process of oat and arrow pea seeds and improve the accuracy of the seed discrete element model, *Liao et al.* (*2022*) used collision tests, inclined sliding tests, and inclined rolling tests to calibrate the coefficient of restitution, static friction coefficient, and rolling friction coefficient between oat seeds and arrow pea seeds and ABS plastic plates, respectively. The calibration results were validated using a spiral seeding device, confirming the reliabilit*y of the simulation experiment. To accurately determine the contact parameters of apples, Zhang et al.* (*2024*) conducted contact parameter calibration tests on simulation models of three types of apple particles using the discrete element method. The coefficients of restitution, static friction coefficients, and rolling friction coefficients between the three types of apples and acrylic sheets, as well as between apples of the same type, were obtained. The research results can provide theoretical basis and model support for the study of apple physical characteristics and low loss harvesting technology.

In this study, a discrete element model of soybean seeds was established using the multi-sphere method based on three-dimensional measurements of soybean seed geometry (*Awuah et al., 2023*). By combining bench experiments with simulation tests, the contact parameters between soybean seeds and a Q235 steel plate were calibrated using rebound, inclined-plane sliding, and inclined-plane rolling tests. The angle of repose of soybean particles was determined using the steel-box extraction method. The optimal combination of discrete element contact parameters between soybean seeds was obtained through the steepest ascent test and the Box–Behnken experimental design. Under these parameter conditions, the relative error between the angle of repose obtained from the simulation and that measured in the bench test was 0.32%, confirming the accuracy of the calibrated contact parameters and the feasibility of the simulation method.

MATERIALS AND METHODS

Test materials

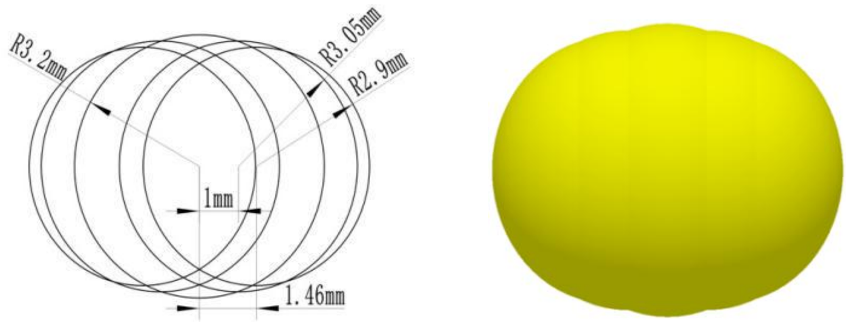
The moisture content of the soybean was 12.5% and the density was 1250 kg/m^3. The Poisson's ratio was 0.4 and the shear modulus was 3.23×10^2 MPa (*Ding et al*., *2023*).

The shape of soybean seeds was approximately ellipsoid. 100 soybean seeds were selected randomly and the length, width and thickness of soybean seeds were measured by vernier calipers.

The length of soybean seeds was distributed in the range from 7.60 mm to 10 mm with an average value of 8.72 mm. The width was distributed in the range from 5.30 mm to 7.70 mm with an average value of 6.84 mm. The thickness was distributed in the range from 4.60 mm to 7.00 mm with an average value of 5.98 mm.

Construction of discrete element model of soybean seed

For soybean seeds, its shape is approximately ellipsoidal and it can′t be directly simulated with a single spherical discrete element model. In order to truly simulate the characteristics, the multi-sphere aggregation model can be used. The multi-sphere aggregation model is formed by the overlapping of several spherical particles with different diameters which is closer to the actual situation (*Dong et al., 2023*). According to the measurement results, the radius and relative position of each spherical element were given, as shown in Fig.1a. Using the EDEM software, the 5-ball combination method was used to construct a discrete element model of soybean seeds as shown in Fig.1b.



a. Two-dimensional graph of multi-particle model of soybean *b. EDEM model of soybean particle*

Fig. 1 - Particle model of soybean seed

Selection of materials for soybean seed contact model

In the process of soybean planting, harvesting and post-harvest processing, soybean seeds will be in contact with other materials in addition to the contact between the seeds. The contact material used in the experiment in this paper was the Q235 steel which was commonly used in agricultural equipment. Its density is 7850 kg/m^3, the Poisson's ratio is 0.28 and the shear modulus is 8.20×10^4 MPa (*Weston et al., 2025*).

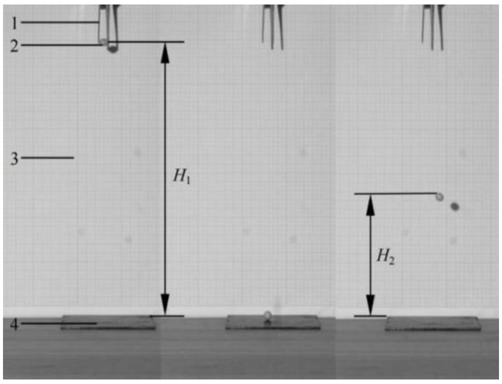
Test methods

The soybean contact parameters mainly include the coefficient of restitution x_1, static friction coefficient x_2 and rolling friction coefficient x_3 between soybean seeds and Q235 steel plate, as well as the coefficient of restitution X_1, static friction coefficient X_2 and rolling friction coefficient X_3 between soybean seeds. In this study, a combination of bench experiments and simulation tests was used to determine and calibrate the contact parameters of soybean seeds. Inclined-plane rebound, inclined-plane sliding, inclined-plane rolling, and angle-of-repose tests were commonly used methods for calibrating contact parameters (*Zhou et al., 2023*).

The coefficient of restitution was measured using a Phantom VE0410L-72G high-speed camera (Vision Research, USA). The camera was equipped with a Nikon 24-85 mm F2.8D zoom lens (Nikon, Japan). The measurements were performed at a frame rate of 5200 fps with a full resolution of 1280 × 800 pixels. The camera’s optical axis was aligned perpendicular to the collision plane to ensure clear recording of the impact process.

Calibration method for the coefficient of restitution between soybean seeds and a steel plate

A rebound test was conducted to calibrate the coefficient of restitution between soybean seeds and a steel plate, as shown in Fig. 2. During the experiment, the steel plate was positioned horizontally, and soybean seeds were allowed to fall freely from a height of 310 mm onto the steel plate. After impact, the seeds rebounded to their maximum height.



a. Initial state b. Collision c. Rebound

Fig. 2 - Method for determining the coefficient of restitution between soybean seeds and a steel plate

1- Clamping; device; 2-Soybean; 3-Graph paper; 4-Steel plate; H_1 is the initial falling height of the soybean seed before impact, mm; H_2 is maximum rebound height after collision between the soybean seed and the steel plate, mm.

The calculation method for the coefficient of restitution between soybean seeds and a Q235 steel plate is given in Eq. (1).

$$x_1 = \sqrt{\frac{H_2}{H_1}} \tag{1}$$

where: x_1 is the coefficient of restitution between soybean seeds and the steel plate; H_1 is the initial falling height of the soybean seed before impact, mm; H_2 is the maximum rebound height after the soybean seed collides with the steel plate, mm.

The test process was recorded by a high-speed camera and the highest rebound height of seed was obtained through later analysis. The bench test was repeated for 12 times. A maximum value and a minimum value in the test results were removed. From the remaining 10 test results, the range of the measured value of the coefficient of restitution between soybean and steel plate and the average value of the highest rebound height could be obtained by equation (1). With reference to the value range of the coefficient of restitution between the soybean and the steel plate measured by the bench test, the EDEM software was used to simulate the rebound height of the soybean after collision with the steel plate. Since the static friction coefficient x_2, rolling friction coefficient x_3 between soybean seed and steel plate and the coefficient of restitution X_1 between soybean seeds, static friction coefficient X_2 and rolling friction coefficient X_3 had no effect on the rebound height of soybean seed after collision with the steel plate, the values of the above parameters were set to 0 when conducting simulation experiments in order to avoid interference. By fitting the simulation test data, the fitting curve about the rebound height y_1 and the coefficient of restitution x_1 between soybean and steel plate in the simulation environment could be obtained. The average value of the highest rebound height measured by the bench test was brought into the fitting curve to obtain the coefficient of restitution between the soybean and the steel plate in the simulated environment.

Calibration method for the static friction coefficient between soybean seeds and a steel plate

In this study, the static friction coefficient x_2 between soybean seeds and a steel plate was calibrated using the inclined-plane sliding test method, as shown in Fig. 3.

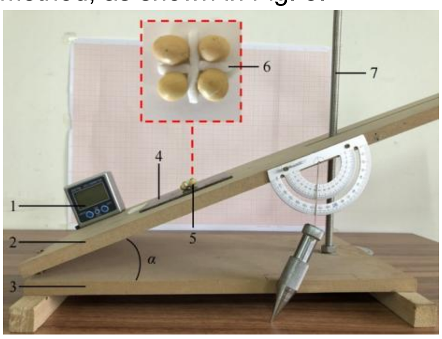


Fig. 3 - Method for determining the static friction coefficient between soybean seeds and a steel plate

1-Goniometer; 2-Adjustable board; 3- Base; 4-Steel plate; 5-Soybean seeds; 6-Adhesive tape; 7-Support stand

During the test, the steel plate and the protractor were fixed to the adjustable board of the test device, and the soybean seeds were placed on the steel plate. The angle between the adjustable board and the base was gradually increased until the soybean seeds began to slide on the steel plate. This angle was measured using the goniometer (*Zhao et al., 2022*). To prevent the soybean seeds from rolling during the measurement of the static friction coefficient, four soybean seeds were fixed together using adhesive tape and tested as a group. The calculation method for the static friction coefficient between soybean seeds and the steel plate is given in Eq. (2):

$$x_2 = \tan\alpha \tag{2}$$

where: x_2 is the static friction coefficient between soybean seeds and the steel plate; α is the angle between the adjustable board and the base, °.

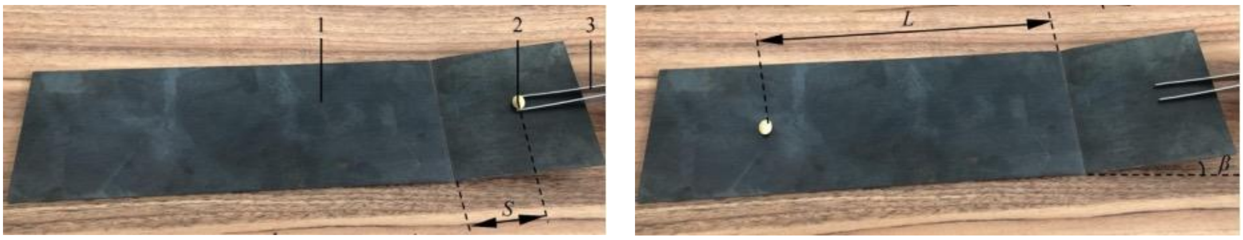
By combining bench experiments with simulation tests, the static friction coefficient between soybean seeds and the steel plate was determined according to Eq. (2). During the simulation experiments, the rolling friction coefficient was set to zero.

Calibration method for the rolling friction coefficient between soybean seeds and a steel plate

An inclined-plane rolling test was used to calibrate the rolling friction coefficient between soybean seeds and a steel plate, as shown in Fig. 4. During the test, a soybean seed was placed on the inclined steel plate and released from rest to roll down the inclined surface. The rolling distance of the soybean seed along the inclined steel plate was denoted as S, after which the seed continued to roll along the horizontal steel plate surface. Owing to rolling friction, the soybean seed eventually stopped after travelling a certain distance on the horizontal steel plate. The rolling distance on the horizontal surface was denoted as L and was experimentally measured (*Ma et al., 2025*). According to the law of conservation of energy, Eq. (3) can be obtained:

$$mgS\sin\beta = x_3 mg(S\cos\beta + L) \tag{3}$$

where: x_3 is the rolling friction coefficient between soybean seeds and the steel plate; m is the mass of the soybean seed, g; *g* is the gravitational acceleration, taken as 10 m/s in this study; S is the rolling distance of the soybean seed along the inclined plane, taken as 10 mm; L is the rolling distance of the soybean seed on the horizontal plane, mm. β is the angle between the inclined plane and the horizontal plane, which was set to 15° in this experiment.



a. Initial state *b. The state at the end*

Fig. 4 - Method for determining the rolling friction coefficient between soybean seeds and a steel plate

1- Stell plate; 2-Soybean seed; 3-Clamping device; S rolling distance of the soybean seed along the inclined plane, mm; L rolling distance of the soybean seed on the horizontal plane, mm. β is the angle between the inclined plane and the horizontal plane, °

The rolling friction coefficient x_3 between soybean seeds and the steel plate was determined using Eq. (3). Based on the measured rolling distance of soybean seeds on the horizontal steel plate, the range and average values of the rolling friction coefficient were obtained. Subsequently, using the above-mentioned method in combination with bench experiments and simulation tests, the rolling friction coefficient between soybean seeds and the steel plate was calibrated. During the simulation experiments, the coefficient of restitution and the static friction coefficient between soybean seeds and the steel plate were determined using the methods described previously.

Calibration method for contact parameters between soybean seeds

A response surface optimization method based on a quadratic orthogonal rotational regression design was used to calibrate the contact parameters between soybean seeds through angle-of-repose tests, combined with bench and simulation experiments (*Bai et al., 2024*).

The angle of repose of soybean seeds was determined using the box extraction method. The measuring device was manufactured from Q235 steel and consisted of a box (105 mm long, 105 mm wide, and 200 mm high), a sliding plate (100 mm long and 200 mm high), and a bottom plate (200 mm long and 200 mm wide), as shown in Fig. 5.

Fig. 5 - Device for measuring the angle of repose of soybean seeds
1-Sliding plate; 2-Soybean seeds; 3-Bottom plate; 4-Steel box

During the test, soybean seeds were filled into the steel box and allowed to collapse naturally after the sliding plate was slowly lifted. After the seed pile became stable, the angle formed between the slope surface of the soybean pile and the horizontal plane was defined as the angle of repose θ. Before conducting the quadratic orthogonal rotational regression test, the zero-level values and the optimal ranges of each contact parameter were determined using the steepest ascent test. The value range of each parameter was established based on preliminary experiments, and six equally spaced parameter levels within each range were selected. In the simulation environment, the angle of repose corresponding to each parameter combination was determined and comparatively analyzed. The evaluation index was the relative error between the angle of repose obtained from the simulation test and that measured in the bench test. The calculation method is given by:

$$\tau = \frac{|\theta_2 - \theta_1|}{\theta_1} \tag{4}$$

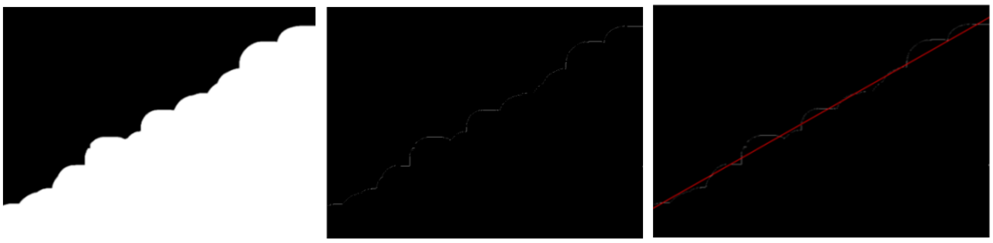
where: τ is the relative error between the angle of repose obtained from the simulation and bench tests; θ_1 is the experimentally measured angle of repose, °; θ_2 is the simulated angle of repose, °.

The zero-level values and the optimal ranges of the contact parameters were determined through comparative experiments. Based on the steepest ascent test, the parameter combination corresponding to the minimum relative error of the angle of repose was selected as the zero-level condition for each influencing factor in the quadratic orthogonal rotational regression test.

Method for measuring the angle of repose of soybean seeds

The angle of repose of soybean seeds was determined through angle-of-repose tests. To avoid experimental errors associated with manual measurement, MATLAB software was used for image processing and analysis. As shown in Fig. 6, the acquired images were sequentially subjected to denoising, grayscale conversion, and binarization processing, after which the boundary points were extracted. The curve formed by the extracted boundary points represented the profile boundary of the soybean seed pile. The least-squares method was then used to fit the boundary points with a straight line. The angle formed between the fitted straight line and the horizontal plane was defined as the angle of repose (*Zheng et al., 2024*).

a. The original image *b. Grayscale processing* *c. Binarization*



d. Hole filling *e. Extract boundary curve* *f. Straight line fitting*

Fig. 6 - Image processing

RESULTS AND DISCUSSION

Test of the coefficient of restitution between soybean seeds and a steel plate

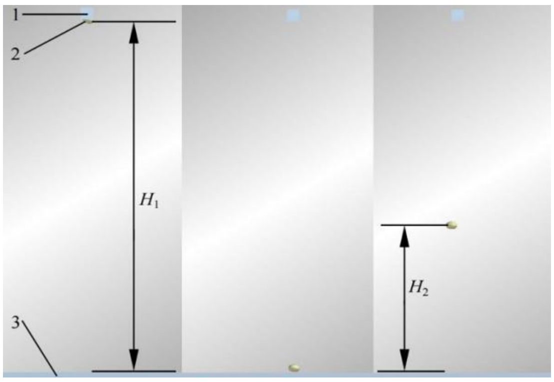
The maximum rebound height data obtained from the bench test for determining the coefficient of restitution between soybean seeds and a steel plate are presented in Table 1.

Table 1

Bench-test results of the maximum rebound height of soybean seeds

Serial number	1	2	3	4	5	6	7	8	9	10
Rebound height (mm)	96	100	102	97	70	94	90	93	88	120

The average maximum rebound height of the soybean seeds was determined to be 95 mm. According to Eq. (1), the coefficient of restitution between soybean seeds and the steel plate ranged from 0.47 to 0.62. The collision process between soybean seeds and the steel plate was simulated, as shown in Fig. 7. During the simulation experiments, the coefficient of restitution between soybean seeds and the steel plate was varied within the range of 0.45–0.65. The simulation results are presented in Table 2.



a. Initial state *b. Collision* *c. Rebound*

Fig. 7 - Simulation of the coefficient of restitution between soybean seeds and a steel plate

1-Particle generator; 2- Soybean seed; 3-Steel plate

Table 2

Simulation results for the coefficient of restitution between soybean seeds and a steel plate

Serial number	x_1	y_1 **(mm) ±Standard deviation (mm)**
1	0.45	70±3
2	0.49	82±5
3	0.53	91±6
5	0.57	104±5
5	0.61	117±6
6	0.65	129±4

Note: x_1 is the coefficient of restitution between soybean seeds and the steel plate; y1y_1y1 is the maximum rebound height of the soybean seeds.

By fitting the test data in Table 2, the fitting curve for y_1 and x_1 could be obtained, as shown in equation (5). The determination coefficient R^2 of the fitted curve was 0.9987, indicating that the reliability of the curve fitting was high. The average rebound height of soybean seeds obtained from the bench test was taken into equation (5) and the coefficient of restitution between soybean seeds and steel plate was 0.54.

$$y_1 = 178.6x_1^2 + 98.57x_1 - 10.23 \tag{5}$$

A simulation verification test was conducted by inputting the calibrated coefficient of restitution between soybean seeds and the steel plate into EDEM software. The verification test was repeated 10 times, and the average maximum rebound height of the soybean seeds in the simulation environment was 94 mm. The relative error between the average maximum rebound heights obtained from the simulation and bench tests was 1%, thereby confirming the accuracy of the calibrated coefficient of restitution.

Test of the static friction coefficient between soybean seeds and a steel plate

The bench-test results for the static friction coefficient between soybean seeds and the steel plate are presented in Table 3. The average sliding angle was determined to be 19.5°. According to Eq. (2), the static friction coefficient between soybean seeds and the steel plate ranged from 0.33 to 0.38.

Table 3

Bench-test results for the static friction coefficient between soybean seeds and a steel plate

Serial number	1	2	3	4	5	6	7	8	9	10
Sliding angle (°)	18.9	20.7	19.6	19.9	18.8	19.5	20.4	19.6	19.2	18.4

The sliding process of soybean seeds on the steel plate surface was simulated in EDEM, as shown in Fig. 8. During the simulation experiments, the coefficient of restitution between soybean seeds and the steel plate was set to 0.54. The parameter settings for the static friction coefficient and the corresponding simulation results are presented in Table 4.

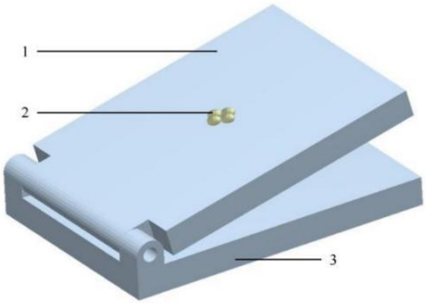


Fig. 8 - Simulation of the static friction coefficient between soybean seeds and a steel plate

1-Adjustable steel plate; 2-Soybean seeds; 3-Base

Table 4

Simulation plan and results for the static friction coefficient between soybean seeds and a steel plate

Serial number	x_2	y_2 (°)
1	0.25	15
2	0.29	17
3	0.33	19
5	0.37	21
5	0.41	23
6	0.45	25

Note: x_2 is the static friction coefficient between soybean seeds and the steel plate. y_2 is the sliding angle of soybean seeds on the steel plate surface.

By fitting the experimental data presented in Table 4, the relationship between y_2 and x_2 was obtained, as expressed in Eq. (6). The coefficient of determination R^2 of the fitted curve was equal to 1, indicating a high degree of fitting reliability. By substituting the average sliding angle obtained from the bench test into Eq. (6), the static friction coefficient between soybean seeds and the steel plate was determined to be 0.34.

$$y_2 = 50x_2 + 2.5 \tag{6}$$

A simulation verification test was subsequently conducted by inputting the calibrated static friction coefficient between soybean seeds and the steel plate into EDEM software. The verification test was repeated 10 times, and the average sliding angle obtained in the simulation environment was 19.5°. No relative error was observed between the sliding angles obtained from the simulation and bench tests, thereby confirming the accuracy of the calibrated static friction coefficient.

Test of the rolling friction coefficient between soybean seeds and a steel plate

The bench-test results for the rolling friction coefficient between soybean seeds and the steel plate are presented in Table 5. The average rolling distance was determined to be 214 mm.

Table 5

Bench-test results for the rolling friction coefficient between soybean seeds and a steel plate

Serial number	1	2	3	4	5	6	7	8	9	10
Rolling distance (mm)	215	200	220	200	230	210	210	225	215	215

In EDEM, the rolling process of soybean seeds on the steel plate surface was simulated, as shown in Fig. 9. During the rolling simulation tests, the coefficient of restitution between soybean seeds and the steel plate was set to 0.54, while the static friction coefficient was set to 0.34.

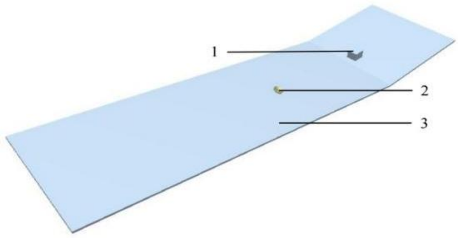


Fig. 9 - Simulation of the rolling friction coefficient between soybean seeds and a steel plate

1-Particle generator; 2- Soybean seed; 3-Steel plate

The parameter settings for the rolling friction coefficient and the corresponding simulation results are presented in Table 6. By fitting the experimental data in Table 6, the relationship between y_3 and x_3 was obtained, as expressed in Eq. (7). The coefficient of determination R^2 of the fitted curve was 0.9874, indicating a high degree of fitting reliability. By substituting the average rolling distance of soybean seeds on the horizontal steel plate obtained from the bench test into Eq. (7), the rolling friction coefficient between soybean seeds and the steel plate was determined to be 0.01.

Table 6

Simulation plan and results for the rolling friction coefficient between soybean seeds and a steel plate

Serial number	x_3	y_3 (mm)±Standard deviation (mm)
1	0.01	216±4
2	0.02	125±3
3	0.03	93±5
4	0.04	48±6
5	0.05	36±7
6	0.06	27±6

Note: x_3 is the rolling friction coefficient between soybean seeds and the steel plate; y_3 is the rolling distance of soybean seeds on the horizontal steel plate.

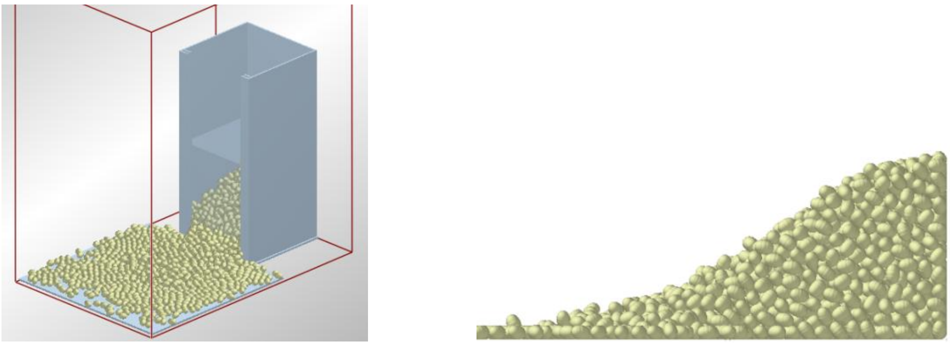
$$y_3 = 8.75e+04x_3^2 - 9.716e+03x_3 + 298.2 \tag{7}$$

A simulation verification test was conducted by inputting the calibrated rolling friction coefficient between soybean seeds and the steel plate into EDEM software. The verification test was repeated 10 times, and the average rolling distance of soybean seeds on the horizontal steel plate in the simulation environment was 216 mm. The relative error between the rolling distances obtained from the simulation and bench tests was 0.93%, thereby confirming the accuracy of the calibrated rolling friction coefficient.

Calibration test of contact parameters between soybean seeds

Steepest Ascent Test

Through the angle-of-repose test (Fig. 5), an image of the soybean seed pile was obtained. By processing the image (Fig. 6), the angle of repose θ_1 of the soybean seeds was determined to be 31°. The simulation experiment for soybean seed piling is shown in Fig. 10. According to the preliminary experiments, during the steepest ascent simulation test, the coefficient of restitution between soybean seeds ranged from 0.45 to 0.70, the static friction coefficient between soybean seeds ranged from 0.20 to 0.70, and the rolling friction coefficient between soybean seeds ranged from 0.01 to 0.06. The experimental design and results of the steepest ascent simulation test are presented in Table 7.



a. Simulation of soybean seed piling *b. Simulated soybean seed pile*

Fig. 10 - Steepest ascent simulation test

Table 7

Experimental design and results of the steepest ascent simulation test

Serial number	Test factors			Test indexes	
	X_1	X_2	X_3	θ_2 (°)	τ (%)
1	0.45	0.20	0.01	24	22.58
2	0.50	0.30	0.02	26.2	15.48
3	0.55	0.40	0.03	28.1	9.35
4	0.60	0.50	0.04	30	3.23
5	0.65	0.60	0.05	31.9	2.90
6	0.70	0.70	0.06	33.8	9.03

Note: X_1 is the coefficient of restitution between soybean seeds. X_2 is the static friction coefficient between soybean seeds. X_3 is the rolling friction coefficient between soybean seeds.

It can be seen from Table 7 that the relative error of the angle of repose in the steepest ascent simulation test first decreased and then increased. The minimum relative error was obtained for Group 5. Therefore, the optimal interval of the contact parameters was located near the parameter combination of Group 5. Accordingly, during the quadratic orthogonal rotational regression test, the parameter values corresponding to Groups 4, 5, and 6 were selected as the -1, 0 and +1 levels, respectively.

Results of the quadratic orthogonal rotational regression test

To determine the optimal combination of the coefficient of restitution, static friction coefficient, and rolling friction coefficient between soybean seeds in the EDEM simulation, a three-factor, three-level quadratic orthogonal rotational regression test was conducted using the Box-Behnken design method. The coded factor levels used in the simulation experiments are presented in Table 8.

Table 8

Coded factor levels used in the simulation experiments

Coded value	Test factors		
	X_1	X_2	X_3
-1	0.55	0.40	0.03
0	0.60	0.50	0.04
1	0.65	0.60	0.05

The experimental design and results of the simulation tests are presented in Table 9. In Table 9, A, B and C represent the coded values of the coefficient of restitution, static friction coefficient, and rolling friction coefficient between soybean seeds, respectively.

Table 9

Experimental design and results of the simulation tests

Serial number	Test factors			Test indexes
	A	*B*	*C*	θ_2 (°)
1	0	0	0	30.3
2	0	0	0	29.8
3	-1	1	0	29.8
4	-1	0	1	29.9
5	1	0	-1	29.4
6	0	0	0	30.3

Serial number	Test factors			Test indexes
	A	*B*	*C*	θ_2 (°)
7	0	1	1	31.5
8	0	-1	-1	28.2
9	1	1	0	31.1
10	1	-1	0	29.5
11	-1	0	-1	28.4
12	-1	-1	0	28.5
13	0	-1	1	28.9
14	0	1	-1	29.4
15	1	0	1	31.3
16	0	0	0	29.7
17	0	0	0	30.1

The experimental data presented in Table 9 were subjected to multiple regression analysis using Design-Expert 10 software. A ternary quadratic polynomial regression model describing the relationship between the simulated angle of repose and the coefficient of restitution, static friction coefficient, and rolling friction coefficient between soybean seeds was established, as expressed in Eq. (8):

$$\theta_2=30.04+0.59A+0.84B+0.78C+0.075AB+0.1AC+0.35BC-0.033A^2-0.28B^2-0.26C^2 \quad (8)$$

The analysis of variance (ANOVA) for the regression equation is presented in Table 10. It can be seen that the P-value of the regression model for the angle of repose was less than 0.01 (P<0.01), indicating that the model was highly significant. The P-value of the lack-of-fit term was 0.63 (P>0.05), indicating that the lack of fit was not significant and that the regression model could therefore be used to analyze and predict the experimental results. The P-values of the coefficient of restitution between soybean seeds (A), static friction coefficient between soybean seeds (B), rolling friction coefficient between soybean seeds (C), and the interaction term between the static and rolling friction coefficients (BC) were all less than 0.01, indicating that these factors had highly significant effects on the angle of repose. The P-values of the remaining terms were greater than 0.05, indicating that they did not significantly affect the angle of repose.

Table 10

Analysis of variance for the regression equation of the angle of repose

Sources	Sum of squares	Degrees of freedom	Mean square	*F*-value	Significant level *P*
Model	14.40	9	1.60	24.37	<0.01
A	2.76	1	2.76	42.06	<0.01
B	5.61	1	5.61	85.48	<0.01
C	4.81	1	4.81	73.20	<0.01
AB	0.02	1	0.02	0.34	0.58
AC	0.04	1	0.04	0.61	0.46
BC	0.49	1	0.49	7.46	0.03
A^2	4.45E-003	1	4.45E-003	0.07	0.80
B^2	0.34	1	0.34	5.12	0.06
C^2	0.28	1	0.28	4.25	0.08
Residual	0.46	1	0.07		
Lack of fit	0.15	3	0.05	0.63	0.63
Pure error	0.31	4	0.08		
Total sum	14.86	16			

Note: P<0.01 (highly significant); 0.01≤P<0.05 (significant); P≥0.05 (not significant).

The response surface describing the interaction effect (BC) between the static friction coefficient and the rolling friction coefficient on the angle of repose was generated using Design-Expert 10 software, as shown in Fig. 11. It can be seen from Fig. 11 that the angle of repose increased with increasing static and rolling friction coefficients between soybean seeds. This behavior can be explained by the fact that higher static and rolling friction coefficients increase the frictional resistance during seed movement, thereby reducing seed flowability and consequently increasing the angle of repose.

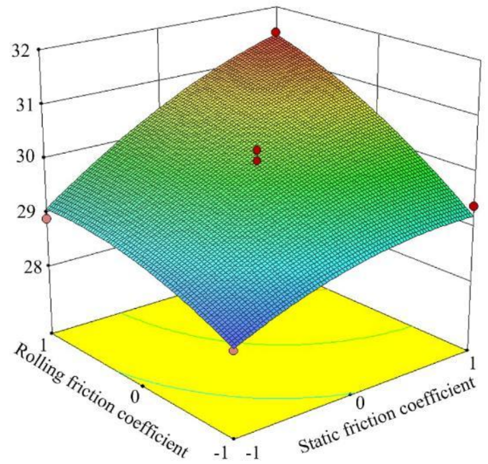


Fig. 11 - Effect of the interaction between the static friction coefficient and the rolling friction coefficient on the angle of repose

The contribution value K reflects the degree of influence of an individual factor on the regression model. A larger K value indicates a greater influence of the corresponding factor on the model. The calculation methods for the contribution value are given in Eqs. (9) and (10). According to the data presented in Table 10, and based on Eqs. (9) and (10), the contribution values of the coefficient of restitution, static friction coefficient, and rolling friction coefficient between soybean seeds to the regression model of the angle of repose were determined to be 0.976, 1.854, and 1.852, respectively. Therefore, the order of significance of the influencing factors on the regression model of the angle of repose was as follows: static friction coefficient between seeds > rolling friction coefficient between seeds > coefficient of restitution between seeds.

$$\delta=\begin{cases}0 & F\leqslant 1\\ 1-\dfrac{1}{F} & F>1\end{cases} \tag{9}$$

$$K_{X_i}=\delta_{X_i}+\frac{1}{2}\sum\delta_{X_iX_j}+\delta_{X_i^2} \tag{10}$$

where: F is the F value obtained from the analysis of variance. δ is the evaluation value. Here i, j=1,2,3, and $i \neq j$.

Parameter optimization

The optimization analysis was conducted using the minimum relative error of the angle of repose as the optimization objective. The constraint conditions are given in Eq. (11):

$$\begin{cases}-1\le A\le 1\\ -1\le B\le 1\\ -1\le C\le 1\\ \min\left(\theta_2\left(A,B,C\right)-31\right)\end{cases} \tag{11}$$

Based on Eq. (11), the multi-objective optimization problem was solved using the optimization module of Design-Expert software. The optimal combination of inter-particle contact parameters for soybean seeds was determined as follows: coefficient of restitution between soybean seeds of 0.65, static friction coefficient between soybean seeds of 0.55, and rolling friction coefficient between soybean seeds of 0.04. Under these parameter conditions, the predicted angle of repose obtained from the simulation was 31°, while the experimentally simulated value was 30.9°. The relative error of the angle of repose was only 0.32%, confirming the accuracy of the optimized combination of contact parameters.

CONCLUSIONS

1) Based on a combination of bench experiments and simulation tests, the coefficient of restitution between soybean seeds and a Q235 steel plate was calibrated to 0.54 using a rebound test. The relative error of the maximum rebound height between the simulation and bench tests was 1%.

The static friction coefficient between soybean seeds and the Q235 steel plate was calibrated to 0.34 using an inclined-plane sliding test. The rolling friction coefficient between soybean seeds and the Q235 steel plate was calibrated to 0.01 using an inclined-plane rolling test, and the relative error of the rolling distance on the horizontal plane between the simulation and bench tests was 0.93%.

2) The angle of repose of soybean seeds was determined to be 31° using the steel-box extraction method. Through the steepest ascent simulation test, the optimal parameter interval for the contact parameters between soybean seeds was identified. Based on the quadratic orthogonal rotational regression test, a regression model describing the relationship between the soybean angle of repose and the inter-particle contact parameters was established. The model was optimized through analysis of variance. The results showed that the coefficient of restitution, static friction coefficient, and rolling friction coefficient between soybean seeds had significant effects on the angle of repose.

3) The optimal combination of contact parameters was determined as follows: coefficient of restitution between soybean seeds of 0.65, static friction coefficient between soybean seeds of 0.55, and rolling friction coefficient between soybean seeds of 0.04. Under these parameter conditions, the relative error of the angle of repose between the simulation and bench tests was 0.32%, confirming the accuracy of the calibrated contact parameters between soybean seeds.

ACKNOWLEDGEMENT

This work was supported by Weifang City Science and Technology Development Plan Project (grant numbers 2025GX010) and the doctoral research start-up fee (grant numbers 44122025).

REFERENCES

[1] Aikins K.A., Ucgul M., Barr J.B., Jensen T.A., Antille D.L., Desbiolles J.M.A., (2021). Determination of discrete element model parameters for a cohesive soil and validation through narrow point opener performance analysis. *Soil and Tillage Research*, Vol. 213, Netherlands.

[2] Awuah E., Aikins K.A., Antille D.L., Zhou J., Gbenontin B.V., Mecha P., Liang Z., (2023). Discrete Element Method Simulation and Field Evaluation of a Vibrating Root-Tuber Shovel in Cohesive and Frictional Soils. *Agriculture*, Vol. 13, no. 8: 1525, Switzerland.

[3] Bai, H., Wu, Y., Ma, Y., Xuan, D., Du, W., Liu, F., & Zhao, X., (2024). Discrete Element Model Construction and Dehulling Simulation Verification Based on Harvested Quinoa Grains. *Journal of Food Science*, Vol. 89, pp. 9336-9353.

[4] Chen, Z., Che, G., Wan, L., Wang, H., & Zhang, K., (2025). Calibration and Experimental Validation of Discrete Element Parameters for Long-Grain Rice with Different Moisture Contents Based on Repose Angle. *Agriculture*, Vol. 15, pp. 1058-1058.

[5] Cui Y., Ye S., Feng S., Zhang D., (2025). Calibration of Discrete Element Simulation Parameters for Buckwheat Seeds (荞麦种子离散元仿真参数标定). *INMATEH-Agricultural Engineering*, Vol. 75, no.1, pp. 110-120, Bucharest/Romania.

[6] Ding X., Wang B., He Z., Shi Y., Li K., Cui Y., & Yang Q., (2023). Fast and precise DEM parameter calibration for Cucurbita ficifolia seeds. *Biosystems Engineering*, Vol. 236, pp. 258-276, England.

[7] Dong, W., Li, N., Liu, F., Zhao, X., Wang, L., Xuan, D., Zhong, W., Hu, H., Kong, X., Meng, X., Li, M., & Duan, Z., (2023). Study on vibration adsorption characteristics of small particle size seeds based on DEM. *INMATEH-Agricultural Engineering*, 71(3).

[8] Hou, Z., Dai, N., Chen, Z., Chou, Y., & Zhang, X., (2020). Determination of Physical Parameters of Agropyron Cristatum Seeds and Calibration of Discrete Element Simulation Parameters (冰草种子物性参数测定与离散元仿真参数标定) [J]. *Transactions of the Chinese Society of Agricultural Engineering*, Vol.36, No.24, pp. 46-54. Beijing/China.

[9] Liang W., Meng W., Zhang B., Zhang H., Jin Y., & Zhang J., (2025). Calibration method and experimental verification of corn discrete element parameters. *Measurement Science and Technology*, Vol. 36, issue 5, pp. 055003, England.

[10] Liao, Y., You, Y., Wang, D., Zhang, X., Zhang, H., & Ma, W., (2022). Parameter calibration and experiment of discrete element model for mixed seeds of oat and arrow pea. *Transactions of the Chinese Society for Agricultural Machinery*, Vol.53, No.08, 14-22.

[11] Liu, C., Wang, Y., Song, J., Li, Y., & Ma, T., (2016). Study on Discrete Element Modeling and Experiment of Rice Seeds Based on 3D Laser Scanning (基于三维激光扫描的水稻种子离散元建模及试验). *Transactions of the Chinese Society of Agricultural Engineering*, Vol. 32, pp. 294-300.

[12] Ma Q., Li T., Xu D., & Wang Q., (2025). Determination of Physical Parameters of Pelleted Rice Seeds and Calibration of Discrete Element Simulation Parameters (丸粒化水稻种子物性参数测定与离散元仿真参数标定). *INMATEH Agricultural Engineering*, Vol. 75, no. 1, pp. 490-500, Bucharest/Romania.

[13] Weston, D., Cabiscol, R., Yule, W., & Gobby, D., (2025). Discrete Element Method Contact Force Parameter Impact for Particle-Level Interactions in Agitated Mills. *Powder Technology*, Vol. 469, pp. 121728-121728.

[14] Zeng, Z., Ma, X., Cao, X., Li, Z., & Wang X., (2021), Critical Review of Applications of Discrete Element Method in Agricultural Engineering (离散元法在农业工程研究中的应用现状和展望). *Transactions of the Chinese Society for Agricultural Machinery*, Guangzhou/China, vol.52, no.4, pp.1-20, ISSN.1000-1298.2021.04.001.

[15] Zhang, H., Han, X., Yang, H., Chen, X., Zhao, G., Sun, J., Sun, L., & Wang J., (2024). Calibration of Contact Parameters and Simulation Experiment for Discrete Element Model of Apple Particles (苹果颗粒离散元接触参数标定与仿真试验) [J]. *Transactions of the Chinese Society of Agricultural Engineering*, Vol.40, No.12, pp. 66-76. Beijing/China.

[16] Zhang, R., Jiao, W., Zhou, J., Qi, B., Liu, H., & Xia, Q., (2020). Parameter calibration and experiment of rice seeds discrete element model with different filling particle radius (不同填充颗粒半径水稻种子离散元模型参数标定). *Transactions of the Chinese Society for Agricultural Machinery*, Vol. 51, No. s1, pp. 227-235, China.

[17] Zhang, S., Zhang, R., Chen, T., Fu, J., & Yuan, H., (2022). Calibration of Discrete Element Simulation Parameters and Seeding Experiment for Mung Bean Seeds (绿豆种子离散元仿真参数标定与排种试验) [J]. *Transactions of the Chinese Society for Agricultural Machinery*, Vol.53, No.03, pp. 71-79. Beijing/China.

[18] Zhao, L., Zhou, H., Xu, L., Song, S., Zhang, C., & Yu, Q., (2022). Parameter calibration of coconut bran substrate simulation model based on discrete element and response surface methodology. *Powder Technology*, 395, 183-194.

[19] Zheng X., He X., Shang S., Wang W., Li, C., Shi, Y., Zhao, Z., & Lu, Y., (2024). Journal of Agricultural Mechanization Research (油莎豆种子籽粒离散元仿真参数标定与试验). *Journal of Agricultural Mechanization Research*, Vol. 46, issue 2, pp. 172-8, Harbin/China.

[20] Zhou, H., Chen, H., Geng, D., Chen, M., & Zhang, Y., (2023). Discrete element modeling and parameter calibration of typical soil in maize field tillage layer. *Transactions of the Chinese Society for Agricultural Machinery*, Vol.54, No.11, 49-60+113.