PARAMETERS CALIBRATION FOR DISCRETE ELEMENT MODEL SIMULATION OF WHITE KIDNEY BEAN SEEDS
/
白芸豆种子离散元模型仿真参数标定

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ABSTRACT
This paper addresses the problem of the lack of intrinsic and contact parameters when applying the discrete element method to simulate and analyze the key aspects of white kidney bean seed sowing, harvesting and clearing. The experiment took white kidney bean seeds as the research object, measured the intrinsic parameters of white kidney bean seeds by using the universal testing machine, and measured the collision recovery coefficient of 0.445, static friction coefficient of 0.452 and rolling friction coefficient of 0.091 between white kidney bean seeds and Q235 steel plate by physical test and EDEM discrete element simulation parameter calibration. The stacking experiment was carried out by the cylinder lifting method, numerical processing was performed with MATLAB, and the actual stacking angle of white kidney bean seeds was 31.28°. The steepest climbing test was designed with the interspecific contact parameters as factors and the relative error between the actual and simulated stacking angles as indicators. The optimal combination of the interspecific contact parameters of white kidney bean was determined by response surface optimization analysis, and the interspecific collision recovery coefficient of white kidney bean was obtained as 0.39, static friction coefficient was 0.53, rolling friction coefficient was 0.092. Using the optimal parameters for the simulation test, the relative error between the actual stacking angle of white kidney bean seeds and the simulated stacking angle was 1.63%, indicating that the calibrated simulated contact parameters were reliable and could provide reference for the discrete element simulation of white kidney bean seeds.

摘要
针对应用离散元法对白芸豆播种、收获和清选等关键环节进行仿真分析时，缺乏本征参数和接触参数的问题。该实验以白芸豆种子为研究对象，使用万能试验机测得白芸豆种子本征参数，通过物理试验和EDEM 离散元仿真参数标定，测定白芸豆种子与Q235 钢板之间的碰撞恢复系数为0.445、静摩擦系数为0.452、滚动摩擦系数为0.091。采用圆筒提升法进行堆积试验，用MATLAB 对堆积图像进行数值处理，得到白芸豆种子实际堆积角为31.28°。以种间接触参数为因素，以实际堆积角和仿真堆积角的相对误差为标准，进行最陡爬坡试验，通过响应面优化分析确定白芸豆种间接触参数最优组合，确定白芸豆种间碰撞恢复系数为 0.39，[1]静摩擦系数为0.53，滚动摩擦系数为 0.092。利用最优参数进行仿真验证，结果显示白芸豆种子实际堆积角与仿真堆积角相对误差为1.63%，表明所标定的接触参数具有可靠性，可为白芸豆种子离散元仿真提供参考。

INTRODUCTION
White kidney beans are biologically known as Phaseolus vulgaris, also known as string beans and white beans (*Phaseolus., 2021*), and are native to Mexico, Argentina and other parts of the Americas. China began to introduce cultivation at the end of the 16th century. White kidney beans are one of the most important edible bean crops in China. At present, it is widely planted in various provinces and cities in China, among which Yunnan, Guizhou, Sichuan, Gansu, Inner Mongolia and other provinces have the widest planting area. China is the world's major producer and exporter of kidney beans, and its output ranks third in the world, after India and Brazil. Moreover, white kidney beans are a kind of medicinal and food plant with high nutritional and medicinal value, and have great development potential and economic prospects (*Niu et al., 2020; Zheng et al., 2022; Zi et al., 2015*).

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With the development of discrete element theory and simulation technology, the application of discrete element methods in the field of agricultural engineering is becoming more and more widespread. By applying the discrete element method to simulate the seed sowing and clearing process, it can be visually analyzed the movement of seeds in a complex environment, and then the structural design of seeders can be optimized. (*Dun et al., 2020; Han et al., 2017*). In the simulation using the EDEM-FLUENT gas-solid coupling method, the intrinsic parameters (density, Poisson's ratio and shear modulus) of the discrete element model need to be input to define the contact parameters between the crop and the equipment material and between the crops. The intrinsic parameters can be obtained by physical test measurements, but the interspecies contact parameters are not easy to obtain accurate values by test measurements, so the parameters need to be calibrated to obtain accurate values (*Zhang et al., 2022*).

Domestic and foreign scholars have calibrated the discrete element simulation parameters of Agropyron, Mung-been, Fresh lotus seed, Peanut, Soybean, Panax notoginseng, and broad bean seeds (*Hou et al., 2020; Zhang et al., 2017; Zhang et al., 2023; Wu et al., 2020; Yu et al., 2020; Wang et al., 2023*), and the results showed that the contact parameters varied among different crops, but little has been reported about the parameter calibration of white kidney bean seeds. The experiment takes white kidney bean seeds as the research object and establishes the discrete element model of white kidney bean seeds based on their three-dimensional size with the basic unit ball combination method in EDEM, and conducts simulation tests to calibrate the contact parameters between white kidney bean seeds and Q235 steel plates, and determines the optimal combination of contact parameters between white kidney bean seeds through stacking tests, steepest climbing tests, quadratic orthogonal rotation combination tests and response surface optimization analysis, in order to provide reference for the structural optimization of white kidney bean seed dischargers and the simulation design of clearing devices.

MATERIALS AND METHODS

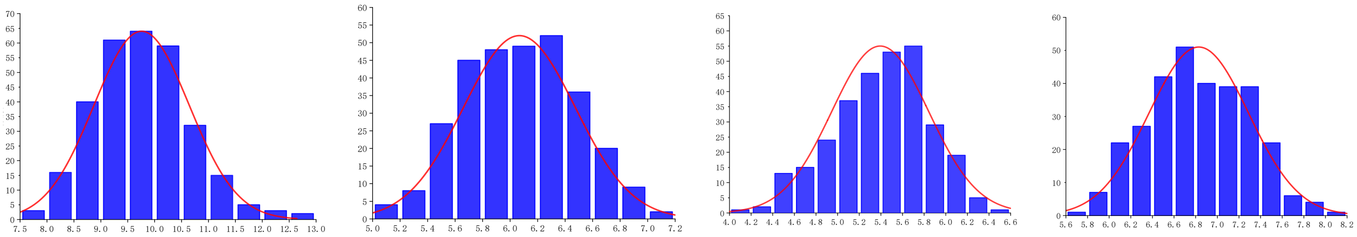
Determination of intrinsic parameters and discrete element model of white kidney beans

Three-dimensional size

To accurately establish the three-dimensional model and discrete element model of white kidney bean seeds, 300 white kidney bean seeds without damage and mildew were randomly selected, and the three-dimensional size (length L, width W, thickness T) of white kidney bean seeds were measured by electronic vernier caliper (accuracy 0.01 mm). The average length L of white kidney bean seeds was 9.76 mm, the average width W was 6.07 mm, and the average thickness T was 5.39 mm. The length, width, thickness and equivalent diameter of white kidney bean seeds are approximately subject to normal distribution (Fig. 1). The length range is 7.5 ~ 13.0 mm, the width range is 5.0 ~ 7.2 mm, and the thickness range is 4.0 ~ 6.6 mm. According to the formula (1,2), the equivalent diameter (D_p) is 6.83 mm and the sphericity (φ) is 70.19%.

$$D_p = \sqrt[3]{L \cdot W \cdot T} \tag{1}$$

$$\varphi = \frac{\sqrt[3]{L \cdot W \cdot T}}{L} \tag{2}$$



(a) length (b) width (c) thickness (d) equivalent diameter

Fig. 1 - Probability density distribution of triaxial dimensions

Thousand seed weight, density and moisture content

Randomly select 1000 white kidney bean seeds, using an electronic balance (accuracy 0.01g) to measure their weight m_1; in order to measure the results accurately, measure five times to obtain the average value, measured the amount of white kidney bean seeds thousand seed weight is 249.20g.

Using the drainage method to measure the density of white kidney bean seeds, weigh 30 g of white kidney bean seeds with an electronic balance, put the white kidney bean seeds into a measuring cylinder with a certain volume of water, record the volume V_1 before putting in the seeds and the volume V_2 after putting in the seeds, make multiple measurements, and measure the density as being 1363.60 kg/m3.

The water content of white kidney bean seeds was measured with a constant temperature drying oven, weighing the mass of m_1 seed samples, placing the seed samples into the drying oven, setting the temperature at 105°C, weighing every 2h until the sample mass no longer changes, and recording the mass of the sample at this time, m_2, then the water content of the white kidney bean seeds is $(m_1\text{-}m_2)/m_1 \times 100\%$.

Poisson ratio

Poisson ratio of white kidney bean seeds was measured by compression test using the universal material testing machine. 10 white kidney bean seeds were randomly selected, the length (axial) and width (transverse) of the original size were recorded. A universal testing machine was used at a speed of 5 mm/min on the white kidney bean seeds for compression, and the measurement of compression after the axial and transverse deformation of the white kidney bean seeds was performed. Poisson's ratio was calculated from formula (3) and the results were averaged.

$$\mu = \frac{w/W}{l/L} = \frac{(H_1 - H_2)/W}{(A_1 - A_2)/L} \tag{3}$$

where:

μ is Poisson ratio; w is transverse deformation, mm; l is axial deformation, mm; W is the width of white kidney bean seeds, mm; L is the length of white kidney bean seeds, mm; H_1 is the width of white kidney bean seeds after rupture, mm; H_2 is the original width of white kidney bean seeds, mm; A_1 is the original length of white kidney bean seeds, mm; A_2 is the length of white kidney bean seeds after rupture, mm.

Elastic modulus and shear modulus

The elastic modulus is a scale used to measure the resistance of the material to elastic deformation. 10 white kidney bean seeds were randomly selected and placed on the circular platform of the universal testing machine, and the load was applied to the white kidney bean seeds using a circular indenter with a loading speed of 5 mm/min, and the load F and deformation (ΔL) were recorded. 10 white kidney bean seeds were repeated in turn, and the above test was calculated from equation (4,5,6). The average value of elastic modulus E was 128.30 MPa and the average value of shear modulus G was 343.84 MPa.

$$E = \left(\frac{F}{A}\right) \Big/ \varepsilon \tag{4}$$

$$\varepsilon = \frac{\lim}{L_1 \to 0}\left(\frac{\Delta L}{L_1}\right) \tag{5}$$

$$G = \frac{E}{2(1+\mu)} \tag{6}$$

where: E is the elastic modulus, MPa; F is the axial load on the white kidney bean seeds, N; A is the contact area, mm^2; ε is the strain; ΔL is the deformation of white kidney bean seeds after compression, mm; G is the shear modulus, MPa; μ is the Poisson ratio of white kidney bean seeds.

Discrete element model of white kidney bean seed

According to the three-dimensional size and shape of white kidney bean seeds, the three-dimensional model of white kidney bean seeds was established in SOLIDWORKS, the built three-dimensional model was imported into EDEM software, and the basic spherical unit combination method was used to establish the discrete element simulation model of white kidney bean seeds, using 12 different radii of spherical particles filled until close to the real thing, white kidney bean seed particles and discrete element model (Fig. 2).

In physical experiments, the surface of white kidney bean seeds and steel plates are smooth and almost free of adhesion, so the Hertz-Mindlin no-slip contact model is selected in EDEM simulation. The intrinsic parameters of white kidney bean seeds and Q235 steel in EDEM simulation tests are obtained through experiments and literature review, as shown in Table 1.

(a) White kidney bean seed (b) Three-dimensional model (c) Discrete element model

Fig. 2 - White kidney bean seed particle and discrete element model

Table 1

White kidney bean seed, Q235 steel intrinsic parameters

Materials	Poisson ratio (μ)	Shear modulus (G / MPa)	Elastic modulus (E / MPa)	Density ($\rho/kg.m^3$)
White kidney bean seed	0.34	128.30	343.84	1363.60
Q235 steel	0.30	700.00	1820.00	7800.00

Calibration of contact parameters between white kidney bean seeds and Q235 steel plates

Collision recovery factor

The experiment used the free fall method to measure the collision recovery coefficient from white kidney bean seeds to Q235 steel, the experiment used Q235 steel plate as the bottom plate of the test bench, the white kidney bean seeds were free falling from the height H_1 (360 mm) to Q235 steel plate. The process was recorded using a video camera, and the video was processed to mark the maximum height H_2 that the white kidney bean seeds popped up after falling after the test. The test was repeated 10 times, its average value was calculated, white kidney bean seeds and Q235 collision was measured after popping up the maximum height of the average H_2=71mm. It was calculated by the formula (7) to get white kidney bean seeds collision recovery coefficient e which is 0.429.

$$x_1 = \frac{v_2}{v_1} = \frac{\sqrt{2gH_2}}{\sqrt{2gH_1}} \tag{7}$$

The static and rolling friction coefficients between white kidney bean seeds and Q235 steel plates and the contact parameters between white kidney bean seeds have no effect on the height of pop-up after collision of white kidney bean seeds. In the EDEM simulation test, set the parameters other than the collision recovery coefficient between white kidney bean seeds and Q235 steel to 0. After the pre-simulation test, set the range of collision recovery coefficient between white kidney bean seeds and Q235 steel plate to 0.3~0.6, design 7 groups of simulation tests, repeat each group of tests 10 times, and take the average value of simulation results. The curve fitting of the experimental results is shown in Fig. 5.

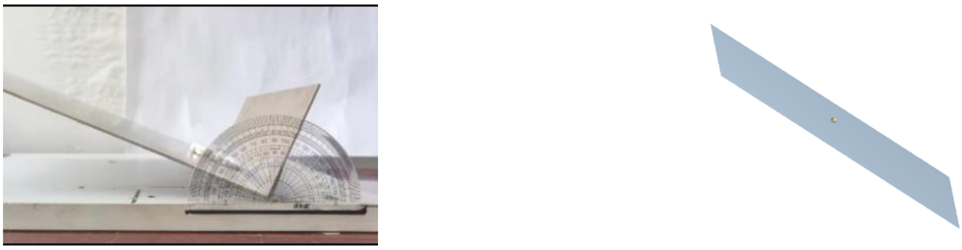
The fitted equation is shown in equation (8).

$$h = 332.952x_1^2 + 14.9x_1 - 1.827 \quad (R^2 = 0.9986) \tag{8}$$

The physical test white kidney bean seeds and Q235 steel plate maximum pop-up height average value of 71 mm was substituted into the formula (8), to obtain x_1 = 0.445. The simulation was verified in EDEM software, and the average value was calculated by repeating 10 tests. The relative error between the maximum height of pop-up after the simulation test and the maximum height of pop-up in the actual test was 3.5%, indicating that the difference between the simulation test and the actual test result was not significant, so the collision recovery coefficient between white kidney bean seeds and Q235 steel plate x_1=0.445 was determined in the EDEM simulation test.

Static friction coefficient

The size of the coefficient of friction is generally affected by the roughness of the object's surface, material, temperature, load, etc. The coefficient of static friction is the ratio of the maximum static friction force on the object in the friction pair to the normal pressure on it. In this test, the static friction coefficient between white kidney bean seeds and Q235 steel is measured by the slanting method (Fig.3).The white kidney bean seed adhesion plate is placed on the surface of the Q235 steel measuring plate, the other end of the measuring plate is slowly pulled up by an asynchronous motor, the measuring plate is tilted from the horizontal state and the state of white kidney beans on the measuring plate is carefully observed. When the white kidney bean adhesion plate is found to start sliding downward, the stop button is immediately pressed, the angle α is recorded, and the test results are repeated 10 times to take the average value. The static friction coefficient between the white kidney bean seeds and the Q235 steel plate was calculated from f=tanα as 0.58.



(a) Physical test (b) Simulation experiment

Fig. 3 - Static friction coefficient calibration

The rolling friction coefficient between the white kidney bean seeds and the Q235 steel plate, as well as the static friction coefficient, rolling friction coefficient and collision recovery coefficient between the white kidney bean seeds had no effect on the tilt angle of the Q235 steel measuring plate. The collision recovery coefficient between white kidney bean seeds and Q235 steel plate was set to the already calibrated parameter 0.445 during the EDEM simulation test. After a large number of pre-simulation tests, the static friction coefficient between white kidney bean seeds and Q235 steel plate was determined to be 0.30~0.60. 7 groups of simulation tests were designed, and each group of tests was conducted ten times, and the results were taken as the average value. The curve fitting of the experimental results is shown in Fig.5.

The fitted equation is shown in equation (9).

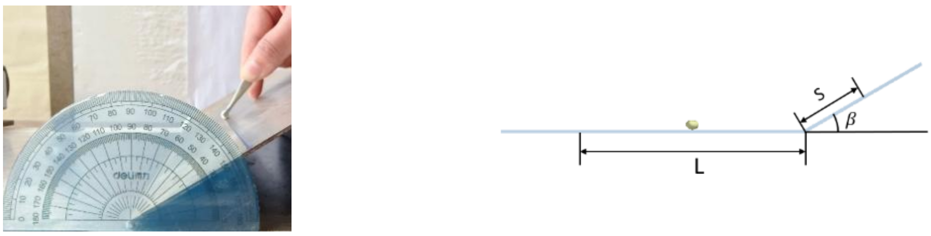
$$y = 4.2381x_2^2 + 44.5643x_2 - 21.0174 \quad \left(R^2 = 0.9988\right) \tag{9}$$

Substituting the inclination angle of 24.15° of the bench test, the coefficient of static friction x_2=0.452 was obtained. Simulation tests were carried out in EDEM, and the average value was repeated 10 times, and the simulated inclination angle was measured as 25.31°, and the relative error with the actual inclination angle obtained from the bench test was 4.8%, and the results were basically the same so that it can be determined that the coefficient of static friction between the seeds of the white kidney bean and the Q235 steel plate is x_2=0.452.

Rolling friction coefficient

The rolling friction coefficient between white kidney bean seeds and Q235 steel plate was measured using the slant method, as shown in Fig.4. The white kidney bean seeds were placed on a steel plate with an inclination angle of β. After several preliminary experiments, the inclination angle β = 30° was initially determined. Release the white kidney bean seeds from S=50 mm with an initial velocity of 0, and record the rolling distance in the horizontal plane when the seeds completely stop rolling L. Assuming that the seeds are only affected by rolling friction in the rolling process, the rolling friction coefficient is calculated by the formula (10). The test was repeated 10 times, and the average value of rolling distance of white kidney bean seeds in the horizontal plane was measured to be 251.7 mm, and the rolling friction coefficient was 0.09.

$$mg\,S \cdot \sin\beta = mg\left(S \cdot \cos\beta + L\right)X \tag{10}$$



(a) Physical test (b) Simulation experiment

Fig. 4- Static friction coefficient calibration

In the simulation test, the parameters that have been calibrated are used to set the collision recovery coefficient x_1=0.445 and the static friction coefficient x_2=0.452 between the white kidney bean seeds and the Q235 steel plate. Other parameters have no effect on the horizontal rolling distance, and they are all set to 0 to avoid interference. After the previous pre-simulation work, the range of the rolling friction coefficient x_3

between the white kidney bean seeds and the Q235 steel plate is taken as 0.06~0.12. Seven groups of tests are designed, each group of tests is carried out 10 times, and the results are averaged. The curve fitting of the experimental results is shown in Fig.5. The fitted equation is shown in equation (11).

$$L = 28350x_3^2 - 8441.86x_3 + 770.72 \quad \left(R^2 = 0.9976\right) \tag{11}$$

The horizontal rolling distance L=237.2 mm of the white kidney bean seed of the bench test is substituted into equation (11) to obtain x_3=0.091. Simulation is carried out to verify that the horizontal rolling distance of the simulation test is 226.28 mm, and the relative error with the actual measured distance is 4.6%, which indicates that the simulation result after calibration is basically the same as that of the bench test. Therefore, the rolling friction coefficient between the white kidney bean seeds and the Q235 steel plate was determined as x_3=0.091.

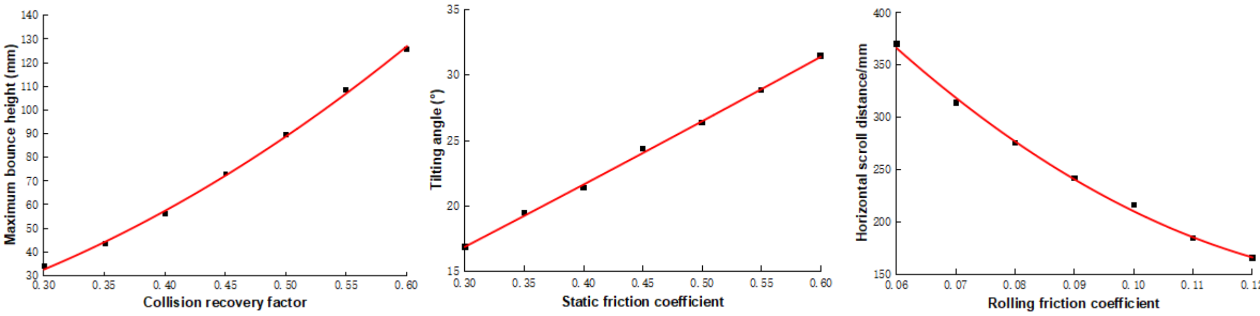


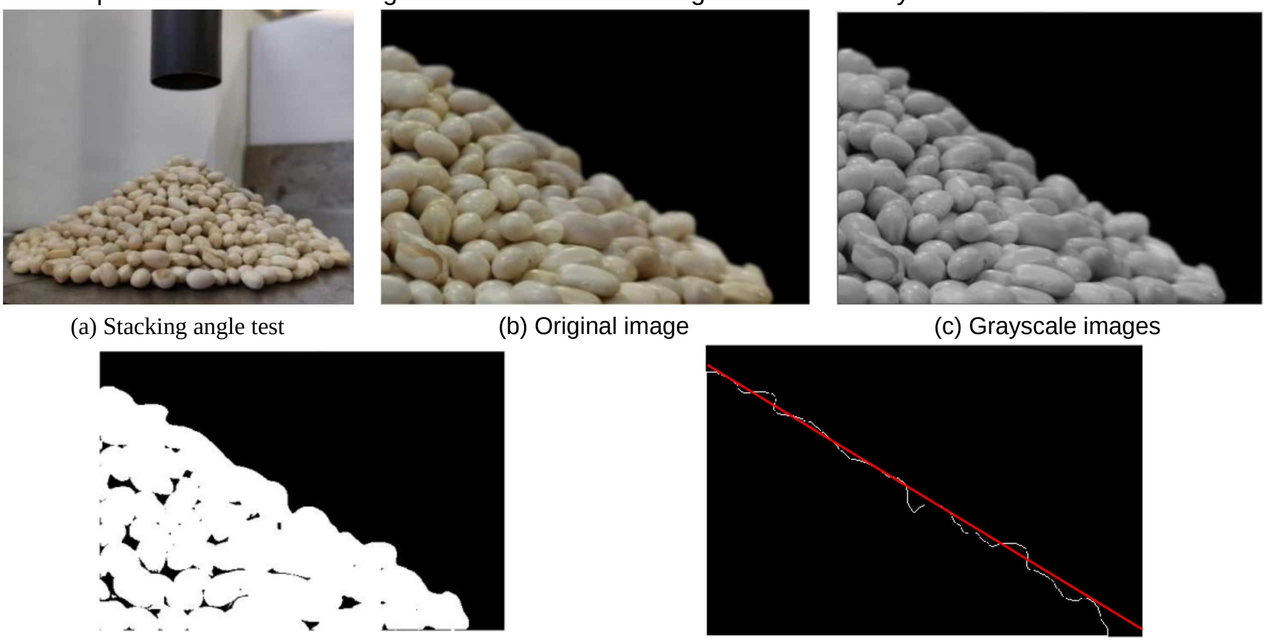
Fig. 5 - Calibration of contact parameters of white kidney bean seeds with Q235 steel plates

RESULTS

Calibration of interspecific contact parameters for white kidney bean

Stacking test

The collision recovery coefficient, static friction coefficient and rolling friction coefficient between seeds have an effect on the stacking angle of white kidney bean seeds during the stacking and molding process. In this test, the bottomless cylinder lifting method was used to measure the actual stacking angle of white kidney bean seeds. During the test, a Q235 steel cylinder (inner diameter of 36 mm, height of 350 mm) was placed vertically on the horizontal steel surface of the test bench, 1,000 white kidney bean seeds were put into the cylinder, and the operating speed of the stepping motor was set so that the cylinder was lifted at a uniform speed of 20 mm/s, and the stacking slope and horizontal angle formed by natural stacking under gravity were the angle of stacking between white kidney bean seeds and the horizontal clamping angle. The natural accumulation of white kidney bean seeds in the cylinder under the action of gravity formed by the accumulation of the slope and the horizontal angle is the accumulation angle of white kidney bean seeds.



(a) Stacking angle test (b) Original image (c) Grayscale images

(d) Binarized image (e) Straight Line Fitting Images

Fig. 6 - Stacking angle image processing

A high-definition camera was used to capture the image of white kidney bean seed stacking, and MATLAB was used to process the stacking image in grayscale, binarization, hole filling, and extraction of contour curves (Fig.6), and finally, a straight line was fitted to the extracted contour curves using the least-squares method, and the mean value of the stacking angle of the white kidney bean seed θ = 31.28° was obtained from the slope of the fitted straight line.

Steepest Climb Test

In order to determine the values of the interspecies collision recovery coefficient, static friction coefficient and rolling friction coefficient of white kidney bean, the steepest climb experiment was designed by taking the actual stacking angle measured by bench test as the control, the interspecies collision recovery coefficient, static friction coefficient and rolling friction coefficient of white kidney bean as the test factors, and the relative error δ between the actual stacking angle and the simulated stacking angle as the criterion. The steepest climb design scheme and results are shown in Table 2.

The relative error δ between the simulated stacking angle and the actual stacking angle is calculated as (12).

$$\delta = \left|\frac{\theta' - \theta}{\theta}\right| \times 100\% \tag{12}$$

Table 2

Steepest climb test program and results

Test number	Test factors			Test results	
	Collision recovery coefficient X_1	Static friction coefficient X_2	Rolling friction coefficient X_3	Simulation stacking angle	Relative error δ /%
1	0.34	0.30	0.065	27.22	12.97
2	0.37	0.35	0.075	28.93	7.51
3	0.40	0.40	0.085	29.54	5.56
4	0.43	0.45	0.095	30.83	1.44
5	0.46	0.50	0.105	33.54	7.23
6	0.49	0.55	0.115	34.23	9.43
7	0.52	0.60	0.125	35.63	13.91

As can be seen from Table 2, the stacking angles obtained from the simulation of different parameter combinations are different, and the relative errors show a tendency of decreasing and then increasing, and the relative error between the simulated stacking angle and the actual stacking angle of the 4th group is the smallest. Therefore, the 4th group of test factors is selected as the 0-level test factors of the quadratic orthogonal rotational combination design test, and the 3rd and 5th groups are selected as the -1 and 1-level test factors, respectively.

Quadratic orthogonal rotating combination test

In order to determine the optimal combination of white kidney bean interspecific contact parameters (collision recovery coefficient x_1, static friction coefficient x_2, and rolling friction coefficient x_3) in the EDEM simulation test, a three-factor, five-level quadratic orthogonal rotational combination test was conducted, and the factor codes for the simulation test are shown in Table 3, and the experimental scheme and results are shown in Table 4, with the test factor codes A, B, and C representing the collision recovery coefficient x_1, the static friction coefficient x_2, and the rolling friction coefficient x_3 of the white kidney bean interspecific contact, respectively.

Table 3

Simulation test factor codes

Code	Test factors		
	Collision recovery coefficient X_1	Static friction coefficient X_2	Rolling friction coefficient X_3
-1.682	0.37	0.35	0.075
-1	0.40	0.40	0.085
0	0.43	0.45	0.095
1	0.46	0.50	0.105
1.682	0.49	0.55	0.115

Multiple regression was fitted to the test data (Table 4) using Design-Expert 8.0.6, and the fitted equation for the relative error in stacking angle was obtained as equation (13).

$$\delta = 897.17 - 2211.69A - 1064.91B - 3974.84C + 1600.14AB$$
$$+2459.99AC + 459.99BC + 1484.22A^2 + 372.32B^2 + 14902.63C^2 \qquad (13)$$

The ANOVA results of the regression equation are shown in Table 5, with a quadratic regression model (P<0.0001), a loss of fit term (P=0.8557>0.05), and a coefficient of determination R^2=0.9887, which indicates that the regression model is well fitted and no loss of fit occurs, suggesting that the model is significant, accurate, and predictive. A, C, AB, AC, A^2, B^2, and C^2 have highly significant effects on the relative error δ, and B and BC have non-significant effects on δ, indicating that the effects of the relevant test factors on the response values are not simple linear relationships, and there is a quadratic relationship.

Table 4

Experiment scheme and results

Number	Test factors			$\delta/\%$	Number	Test factors			$\delta/\%$
	A	B	C			A	B	C	
1	0.40	0.40	0.085	8.76	**13**	0.43	0.45	0.075	6.88
2	0.46	0.40	0.085	3.40	**14**	0.43	0.45	0.115	11.68
3	0.40	0.50	0.085	3.51	**15**	0.43	0.45	0.095	3.58
4	0.46	0.50	0.075	10.03	**16**	0.43	0.45	0.095	2.86
5	0.40	0.40	0.105	9.27	**17**	0.43	0.45	0.095	3.05
6	0.46	0.40	0.105	6.75	**18**	0.43	0.45	0.095	2.66
7	0.40	0.50	0.105	4.82	**29**	0.43	0.45	0.095	2.49
8	0.46	0.50	0.105	11.93	**20**	0.43	0.45	0.095	3.67
9	0.37	0.45	0.095	7.24	**21**	0.43	0.45	0.095	3.45
10	0.49	0.45	0.095	9.96	**22**	0.43	0.45	0.095	3.71
11	0.43	0.35	0.095	6.62	**23**	0.43	0.45	0.095	3.74
12	0.43	0.55	0.095	7.34					

Table 5

Variance analysis of regression equation

Source of variation	Sum of Squares	Degree of Freedom	Mean Square	F Value	P Value
Model	204.90	9	22.77	126.86	<0.0001**
A	4.84	1	4.84	26.96	0.0002**
B	0.095	1	0.095	0.53	0.4808
C	24.74	1	24.74	137.84	<0.0001**
AB	44.39	1	44.39	247.37	<0.0001**
AC	5.11	1	5.11	28.50	0.0001**
BC	0.49	1	0.49	2.72	0.1230
A^2	50.44	1	50.44	281.09	<0.0001**
B^2	24.49	1	24.49	136.48	<0.0001**
C^2	70.15	1	70.15	390.92	<0.0001**
Residual	2.33	13	0.18		
Lack of fit	0.44	5	0.088	0.37	0.8557
Pure error	1.89	8	0.24		
Sum	207.23	22			

Note: P<0.05(significant,); P<0.01(highly significant,**)*

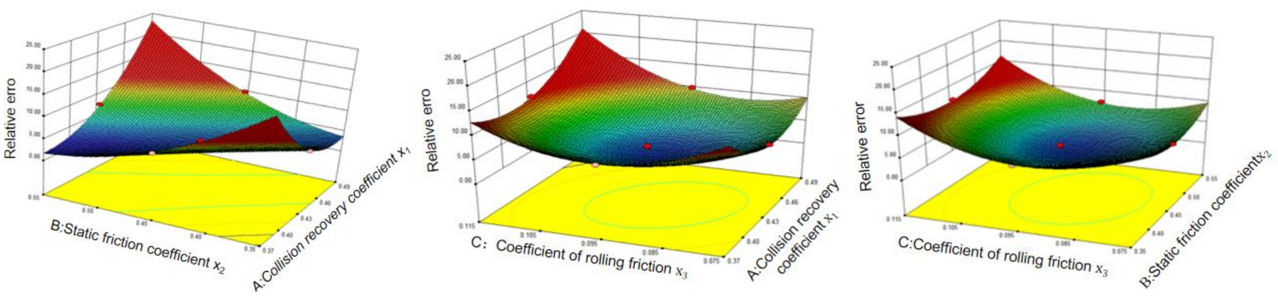


Fig. 7- Response surface of relative error and test factor

Response surface analysis using Design-Expert 8.0.6 software can visually analyze the effects of interactions among factors on the test indexes, and the effects of interactions among factors on the relative error δ of the stacking angle of white kidney beans are shown in Figure 7. With the increase of A (collision recovery coefficient x_1), B (static friction coefficient x_2) and C (rolling friction coefficient x_3), the relative error δ of the stacking angle of white kidney beans all decreased firstly and then increased.

Optimal parameter combination determination and validation

Through Design-Expert 8.0.6, with the objective of minimizing the relative error between the simulated stacking angle and the actual stacking angle, the regression equations are optimally solved, the response surface is analyzed, and the optimal solution is sought for the model. The system of objective and constraint equations is shown in equation (14)

$$\begin{cases} \min Y(X_1, X_2, X_3) \\ s.t \begin{cases} 0.37 \leqslant X_1 \leqslant 0.49 \\ 0.35 \leqslant X_2 \leqslant 0.55 \\ 0.075 \leqslant X_3 \leqslant 0.115 \end{cases} \end{cases} \tag{14}$$

The finalized coefficient of recovery of white kidney bean interspecific collision x_1 was 0.39, static friction coefficient x_2 was 0.53 and rolling friction coefficient x_3 was 0.092. The white kidney bean seed stacking angle test was carried out with optimal parameter combinations and replications were performed 10 times. The simulation test stacking angle is shown in Fig. 8. The stacking angle obtained from the simulation test is 31.79°, and the actual measured stacking angle of the bench test is 31.28°. The relative error between the actual measured stacking angle and the simulation stacking angle is 1.63%, which indicates that the contact parameters calibrated by this discrete element model are accurate and reliable, and can be used in the subsequent EDEM simulation test.

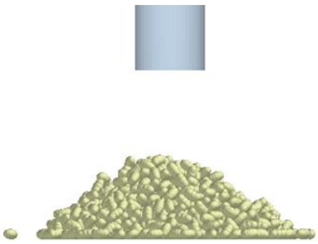


Fig. 8 - Simulation of accumulation angle experiment of white kidney bean

CONCLUSIONS

In this paper, white kidney bean seeds were used as the research object to measure the physical characteristics of white kidney bean seeds. The mean values of the triaxial dimensions of white kidney bean seeds were 9.76 mm, 6.07 mm and 5.39 mm for length, width and thickness respectively, and the triaxial dimensions conformed to normal distribution. Through experimental measurements, the Poisson's ratio of white kidney bean seeds is 0.34, the elastic modulus is 128.30 MPa, and the shear modulus is 348.34 MPa. In EDEM, the Hertz-Mindlin contact model was selected to build a discrete elemental model of the white kidney bean seeds, and the contact parameters of the white kidney bean seeds and Q235 steel were calibrated. The collision recovery coefficient between the white kidney bean seeds and Q235 steel was measured to be 0.429, the static friction coefficient was 0.452, and the rolling friction coefficient was 0.091.

The white kidney bean seed stacking angle test was carried out, and MATLAB was used to process the stacking angle pictures, extract the boundary contours, and perform curve fitting to obtain the actual stacking angle of 31.28°. With the objective of minimizing the relative error δ between the actual stacking angle and the simulated stacking angle, the steepest-climbing test and the quadratic orthogonal rotational combination test were designed for optimization solving, and the optimal combination of the contact parameters between the white kidney bean species was determined: the coefficient of recovery of the collision between the species of the white kidney bean was 0.39, the coefficient of static friction was 0.53, and the coefficient of rolling friction was 0.092, respectively. The simulated stacking angle test is carried out with the optimal parameter combination, and the simulated stacking angle is measured to be 31.79°, and the relative error with the actual stacking angle is 1.63%, which indicates that the discrete element model and the calibrated contact parameters are accurate and reliable.

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