

Calibration of the simulation parameters of the particulate materials in film mixed materials

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Abstract: In order to obtain accurate contact parameters of a particulate material in residual film mixture collected by cotton field machine in Xinjiang, the angle of repose test and inclined plane test were carried out. In the tests, the angles of repose of the particulate material with the water content of $(6.26 \pm 1.5)\%$ and $(14.1 \pm 2.1)\%$ were measured respectively, as well as the static sliding friction angle between the particulate material and the residual film. At the same time, the EDEM software was used to calibrate the coefficient of restitution, static friction coefficient and dynamic friction coefficient between the material and the film. Then, the second-order response model between contact parameters and the angle of repose and static sliding friction angle was constructed. In addition, the optimal contact parameters between the granular materials and the mulch were obtained by fitting the physical test data. The results indicated that the errors between the physical test results and the numerical simulation results are small. It was proved that the second-order response model could predict the repose angle of granular materials and the static sliding friction angle between granular materials and farmland film. This study could provide theoretical support for the subsequent model construction of the residual film mixture collected by the cotton field machine.

Keywords: cotton field, agricultural film, particulate material, EDEM, contact parameter, response model, calibration

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1 Introduction

Xinjiang is the main cotton producing region of China. With the increase of the cotton planting area in this region, the pollution of residual films in cotton fields becomes very serious. At present, although it is recovered by mechanical means, a large number of soil based granular materials are wrapped in the recovered residual film, which brings certain difficulties and great challenges to the initial cleaning and resource utilization of the residual film. There is no doubt that the use of mechanical equipment for its initial cleaning has become an important means to realize the utilization of residual film. The Particulate Material (PM) is one of the main constituent materials of the residual film mixture collected by the cotton field machine. Its material characteristic parameters have important guiding significance for the construction of the material simulation model and the research of the residual film preliminary cleaning equipment. Particulate material is a complex

gas-solid-liquid multi-phase mixture^[1]. Its physical mechanics and dynamic characteristics are research emphases in the agricultural engineering field and also hotspots difficult for quantitative analysis. In order to ensure the accuracy and reliability of simulation results, boundary conditions such as intrinsic characteristic parameters (density, Poisson's ratio and particle size, etc.), contact parameters (static friction coefficient, dynamic friction coefficient and collision recovery coefficient, etc.) and contact model parameters (surface energy and density energy, etc.) should be set according to the actual situation^[2]. However, some contact parameters and contact model parameters cannot be obtained by means of the test^[3,4], or the parameters of similar granular materials under different conditions are quite different, resulting in a poor agreement between simulation and physical test. Therefore, the simulation software should be used to adjust the parameters of granular materials repeatedly within the range of existing parameters^[5,6], so that the simulation results are consistent with the actual test results of granular materials in specific areas or under specific conditions.

The discrete element method is a numerical simulation analysis method solving the problem of interaction between discontinuous media (particulate materials) and between discontinuous media and boundary or external contact components^[7,8]. Currently, it is widely applied in many fields such as geotechnics, medicine, food and agriculture^[9-11]. In the field of agricultural engineering, discrete element software is mainly used in the study of the flow characteristics of particulate materials^[12,13], contact relations between a particulate material and external contact components, and dynamic response characteristics^[14-16]. In recent years, scholars at home and abroad had used different embedded contact models in the EDEM software to simulate and calibrate soil

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physical materials with different physical characteristics, different operating conditions and different regions. For example, Ucgul et al.^[17,18] used the Hysteretic Spring Contact Model (HSCM) contact model to calibrate the dynamic friction coefficient and collision recovery coefficient between materials under the consideration of whether the beach sand had plastic deformation, and analyzed the beach sand and the external contact parts interaction^[19]. Li et al.^[20-23] calibrated the dynamic friction coefficient, coefficient of restitution for impact, static friction coefficient and surface energy of heavy and sticky black soil in Northeast China and clayey soil in southern China by using Hertz-Mindlin with JKR Cohesion (JKR) contact model and choosing the angle of repose as a response index. Wang et al.^[24] established a model of soil particles dominated by nonstandard balls in an environment of the Edinburgh Elasto-Plastic Cohesion Model (ECM), and calibrated the static friction coefficient and dynamic friction coefficient of sandy loam soil in northern China in combination with the angle of repose and shear tests. Shi et al.^[25] added Liner Cohesion Model (LCM) on the basis of Hysteretic Spring Contact Model (HSCM), chose the angle of repose as a response value, calibrated the static friction coefficient, dynamic friction coefficient and shear strength of the soil in an arid area of northwestern China, and conducted comparison validation by direct shear test and penetration test under the condition of different water contents. Dai et al.^[26] calibrated the coefficient of restitution for impact, static friction coefficient and dynamic friction coefficient of the soil in an arid area of northwestern China by using Hertz-Mindlin (no slip) contact model with the angle of repose as the response value. Zhang et al.^[27] calibrated the coefficient of restitution for impact, static friction coefficient and dynamic friction coefficient of sandy soil by using Hertz-Mindlin (no slip) contact model with the angle of repose as a major response value and compared the calibration results under standard and nonstandard soil particle models.

To sum up, many scholars combined with physical test and EDEM discrete element simulation test to calibrate the contact parameters of different particulate materials, which provided a certain reference for subsequent research of the dynamic characteristics of soil in different areas and the characteristics of its interaction with external contact components. However, there are few studies using EDEM to calibrate the simulation contact parameters of the particulate materials in residual film mixture collected by cotton field machines in Xinjiang. Therefore, carrying out the discrete parameter simulation of particulate material contact parameter calibration is not only conducive to the subsequent model construction of the residual film mixture collected by the cotton field machine but also provides conditions for the numerical simulation of the crushing and separation process of the material. At the same time, it provides theoretical support for the research on residual film recycling and preliminary cleaning equipment in cotton fields, and promotes the process of residual film pollution control to a certain extent.

Given this, this research chose the particulate material in the residual film mixture collected by cotton field machine at the northern foot of Tianshan Mountain, Xinjiang as the main research object, and determined the particle size, unit weight and angle of repose of two kinds of particulate material with different water contents, and the static sliding friction angle between the particulate material and the agricultural mulch film. Using the embedded Hysteretic Spring Contact Model (HSCM) delayed elastic contact model in the discrete element software EDEM, the

angle of repose of the granular material and its static sliding friction angle with the farmland mulch film are used as response values. The contact parameters between it and the farmland mulch are calibrated to obtain the optimal second-order response model between the angle of repose and static sliding friction angle and their corresponding contact parameters. This research could provide a reference and basis for the subsequent setting of the contact parameters of the granular model of the bulk material when the discrete element software EDEM is used to study the crushing and separation process of the cotton field machine film-receiving hybrid.

2 Calibration of discrete element contact parameters among particles of PM

Affected by inter-particle static friction, dynamic friction and other factors during the piling of a particulate material, the movements of the particles and the interaction among the particles are extremely complex. In this study, the angle of repose β of the particulate material dominated by the soil in the residual film mixture collected by cotton field machine in Xinjiang was chosen as a response value, the coefficient of restitution for impact e , static friction coefficient μ , dynamic friction coefficient γ and damping coefficient ζ among particles of the particulate material were calibrated by the angle of repose physical test and simulation test.

2.1 Test materials and physical test of angle of repose

The test material was the particulate material in the residual film mixture collected by cotton field machine from Beiwucha Town, Manas County, Xinjiang. This material was dominated by sandy soil from the surface layer of a cotton field at a depth of 0-50 mm, which was hardly removable, as shown in Figure 1.

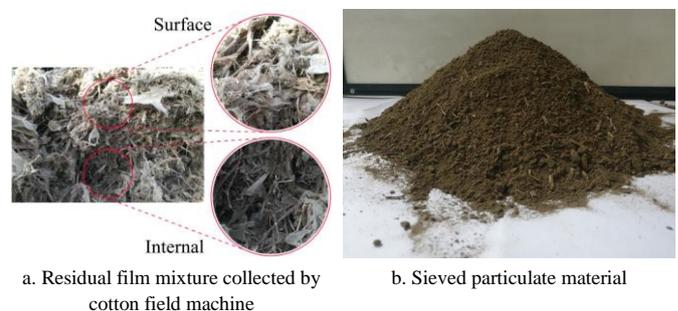


Figure 1 Residual film mixture collected by cotton field machine and sieved particulate material

In the process of collection of test samples, the particulate material in the residual film mixture collected by the cotton field machine was sieved and sorted manually. Firstly, the samples were classified into the surface sample (L) and internal sample (I) for screening according to the locations of the particulate material in the residual film mixture. Then, randomly selected 500 g samples from the two piles of sieved materials through the cross method, as shown in Figure 1. The water content, particle size distribution, volume weight and other physical intrinsic parameters of the two samples were determined three times using a draught drying cabinet, cutting ring (50 mm \times Φ 50 mm), TCS-60 electronic platform scale (the measuring accuracy is 0.2 g) and JMB-5003 electronic balance (the measuring accuracy is 0.001 g), standard soil sieve with a sieve diameter of 0.25-5.0 mm (Zhejiang Shangyu Zhangxing Gauze Screen Factory) and other instruments in accordance with the Standard for Soil Test Method, and the mean values were calculated. The determined values of the basic parameters of the particulate material are shown in Table 1.

Table 1 Determined values of the basic parameters of the particulate material under the condition of different water contents

Sample	Water content/%	Particle size distribution/%						Average volume weight/kg m ⁻³
		<0.25	[0.25,0.5)	[0.5,1)	[1,2)	[2,5)	≥5	
L	6.26±1.5	16.66	11.37	20.36	14.36	24.52	12.73	1687.85
I	14.1±2.1	38.58	7.9	19.94	8.47	18.75	6.36	

The angle of repose of the particulate material was measured by the injection method, and the instrument used is a particulate material angle of repose gauge. During the test, 500 g was sampled from each of the two kinds of particulate material with different water contents. In order to improve measurement accuracy and reduce the measurement error of the angle of repose, the two samples were subjected to a physical test for 20 times. During the experiment, the camera was used to take photos of the bulk materials, and Matlab image processing software was used to extract and analyze the edge image information of the angle of repose. Fitting the boundary points of the angle of repose of the bulk material by the least square method (Figure 2), so as to calculate the angles of repose β_1 and β_2 of the two particulate material samples with a water content of (6.26±1.5)% and (14.1±2.1)% respectively were obtained. They were (31.07±2.1)° and (39.88±2.2)° respectively.

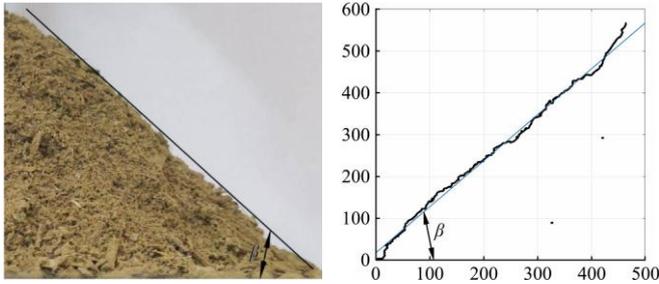


Figure 2 Edge image information of the angle of repose and extraction and fitting results

2.2 Selection of discrete element simulation contact models and determination of simulation parameters

By referring to references^[17,18,25], and considering the types, features and physicochemical properties of the cotton field soil in Xinjiang, during calibration of discrete element simulation parameters of the particulate material dominated by the soil in the residual film mixture collected by cotton field machine, Hysteretic Spring Contact Model (HSCM) in discrete element software EDEM was used to establish the basic units and analog simulation of the particles of the particulate material. The schematic diagram for force-displacement relation and the structural schematic diagram^[28] are shown in Figure 3.

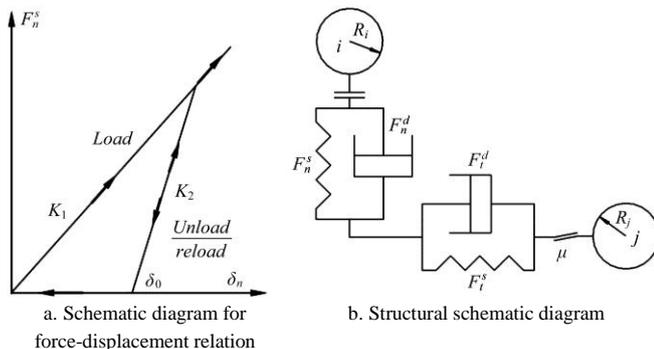


Figure 3 Schematic diagram for force-displacement relation and structural schematic diagram of HSCM

In this contact model, the normal contact force F_n^s among stressed particles could be expressed as:

$$F_n^s = \begin{cases} K_1 \delta_n; & (K_1 \delta_n < K_2 (\delta_n - \delta_0)) \\ K_2 (\delta_n - \delta_0); & (\delta_n > \delta_0) \\ 0; & (\delta_n \leq \delta_0) \end{cases} \quad (1)$$

where, K_1 and K_2 are loading stiffness and unloading stiffness, N/m; δ_n is normal overlap, m; δ_0 is residual overlap, m.

The loading stiffness K_1 in Equation (2) is associated with the yield strengths σ_i and σ_j of two contact particles i and j . The specific relations are shown below:

$$\begin{cases} K_1 = 5R^* \min(\sigma_i, \sigma_j) \\ R^* = \frac{R_i + R_j}{R_i R_j} \end{cases} \quad (2)$$

where, R^* is the equivalent radius of contact particles i and j , m; σ_i and σ_j are the yield strengths of the contact particles i and j , MPa; R_i and R_j are the radii of the contact particles i and j , m.

The calculation equation of the coefficient of restitution for impact e , damping coefficient ζ and stiffness coefficient ζ between the two contact particles are shown below:

$$\begin{cases} e = \sqrt{\frac{K_1}{K_2}} \\ \zeta = -\frac{F_n^d}{2v_n \ln e} \sqrt{\frac{\ln^2 e + \pi^2}{m^* K}} \\ \zeta = \frac{(F_t^d)^2 (\ln^2 e + \pi^2)}{4v_t^2 m^* K \ln^2 e} \\ m^* = \frac{m_i m_j}{m_i + m_j} \end{cases} \quad (3)$$

where, F_n^d and F_t^d are linear normal and tangential damping forces, N; v_n and v_t are normal and tangential moving speeds of the particle, m s⁻¹; m^* , m_i and m_j are equivalent mass, mass of particle i and mass of particle j , kg; K is K_1 or K_2 .

In order to shorten the operation time of the simulation software^[29], the simulation model and the angle of repose test platform model of the particles of the particulate material were simplified by referring to references^[17,28]. When HSCM of discrete element software EDEM was used to model the particle units of the particulate material, the spherical sensitivity theory was applied and the standard ball basic particle units with a particle radius of 4 mm and 5 mm respectively were used as basic particles. These two standard ball basic particle units were overlaid in a staggered manner to form a nonstandard ball basic particle unit, as shown in Figure 4a. In order to reduce the error between the analog simulation results of the angle of repose of the particulate material and the physical test, the particle sizes of the particulate material particle models generated during simulation were all randomly distributed in a range of 0.5-1.5 times of the particle size of the nonstandard ball basic particle unit. Further, with the increase of the particle size of the basic particle model of the particulate material, the structural parameters of the angle of repose test platform increased, too, so the structural parameters of the test platform model were also

four times the actual structural parameters. The angle of the repose test platform model established in a simplified way as shown in Figure 4b.

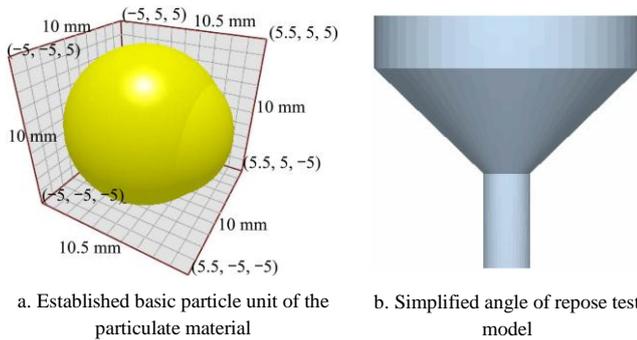


Figure 4 Basic particle unit and angle of the repose test model of the particulate material

As the particulate material in the residual film mixture collected by cotton field machine mainly contains soil, the intrinsic characteristic parameters and contact model parameters of the particulate material were all set with reference to the relevant parameters of soil. As shown in Table 2, the value ranges of the contact parameters between the particles of the particulate material were also preliminarily determined according to the ranges of relevant parameters of soil.

Table 2 Values of simulation parameters of the particle of the particulate material

Parameter	Value	Source
** Poisson ratio of particles ν	0.46	[20]
** Volume weight of particles $\rho/\text{kg m}^3$	1687.85	Measurement
** Shear modulus of particles G/Pa	1×10^6	[24,25]
* Inter-particle coefficient of restitution for impact e	0.5-0.7	[16,21,24]
* Inter-particle static friction coefficient μ	0.3-0.5	[25,26]
* Inter-particle dynamic friction coefficient γ	0.1-0.3	[25,30]
* Damping coefficient ζ	0-0.2	[19,25]
** Stiffness coefficient ξ	0.95	[19,25]

Note: * is a simulated parameter to be calibrated, and ** is a simulated parameter set by default

The setting of the factors influencing the angle of repose β simulation test of the particulate material and their level values were shown in Table 3.

Table 3 Test factors and levels

Level	-1	0	1
Coefficient of restitution for impact e (A)	0.5	0.6	0.7
Static friction coefficient μ (B)	0.3	0.4	0.5
Dynamic friction coefficient γ (C)	0.1	0.2	0.3
Damping coefficient ζ (D)	0.0	0.1	0.2

2.3 Simulation test and test verification

According to the description of response indexes and calibration parameters in 1.2, a response curve test was designed using Box-Behnken in a data processing software Design expert. The simulation test program was shown in Table 4.

According to the testing program, the data results of β obtained from the simulation test after combinations of various parameters in an environment of discrete element software EDEM were shown in Table 4. Design expert data processing software was used to conduct regression variance analysis of the simulation test results in Table 4, and the analysis results were shown in Table 5.

Table 4 Testing program and results

Test No.	Code				Response value
	A	B	C	D	Y
1	-1	-1	0	0	37.51
2	1	-1	0	0	34.76
3	-1	1	0	0	42.92
4	1	1	0	0	39.74
5	0	0	-1	-1	33.75
6	0	0	1	-1	41.96
7	0	0	-1	1	30.58
8	0	0	1	1	45.15
9	-1	0	0	-1	39.99
10	1	0	0	-1	42.91
11	-1	0	0	1	41.54
12	1	0	0	1	37.45
13	0	-1	-1	0	31.14
14	0	1	-1	0	34.49
15	0	-1	1	0	38.33
16	0	1	1	0	49.20
17	-1	0	-1	0	32.73
18	1	0	-1	0	30.65
19	-1	0	1	0	44.46
20	1	0	1	0	46.79
21	0	-1	0	-1	34.91
22	0	1	0	-1	42.52
23	0	-1	0	1	38.87
24	0	1	0	1	41.85
25	0	0	0	0	39.33
26	0	0	0	0	39.54
27	0	0	0	0	41.05
28	0	0	0	0	40.12
29	0	0	0	0	40.09

Table 5 Regression variance analysis of test results

Source	Mean squares	F value	P-value	Significant
Mold	43.59	23.38	<0.0001	**
A	3.91	2.1	0.1696	—
B	103.25	55.38	<0.0001	**
C	438.63	235.25	<0.0001	**
D	0.03	0.016	0.9009	—
AB	0.046	0.025	0.8771	—
AC	4.86	2.61	0.1286	—
AD	12.29	6.59	0.0224	*
BC	14.14	7.58	0.0155	*
BD	5.36	2.87	0.1121	—
CD	10.11	5.42	0.0354	*
A ²	2.96E-04	1.59E-04	0.9901	—
B ²	2.81	1.51	0.2399	—
C ²	15.27	8.19	0.0126	*
D ²	5.84E-05	3.13E-05	0.9956	—
Lack of Fit	2.43	5.46	0.0581	

$R^2 = 0.959$; $R^2_{adj} = 0.918$; $CV = 3.49\%$; $Pred R^2 = 0.7755$.

Notes: ** highly significant ($p \leq 0.01$), * significant ($0.01 < p \leq 0.05$), — insignificant ($p > 0.05$).

As shown in Table 5, single factor items B and C are factors with a highly significant influence on β , and interaction items AD, BC, CD and C² are all factors with significant influence on β . As

value P of other factor items is >0.05 , so they are all factors with insignificant influence on β , and the sequence of the factors with highly significant influence on β and the factors with significant influence on β was: $B > C > C^2 > BC > AD > CD$. Besides, the model coefficient P obtained from regression variance analysis is <0.0001 , and determination coefficient $R^2=0.959$; adjusted determination coefficient $R^2_{adj}=0.918$, and coefficient of variation $CV=3.49\%$. All these could explain that the influencing factors A, B, C and D have a high degree of interpretation to β , a second-order response model with a high fitting response degree could be obtained in Equation (4):

$$\hat{Y} = 40.03 - 0.57A + 2.93B + 6.05C - 0.05D - 0.11AB + 1.1AC - 1.75AD + 1.88BC - 1.16BD + 1.59CD - 6.75e^{-3}A^2 - 0.66B^2 - 1.53C^2 - 3e^{-3}D^2 \quad (4)$$

In Figure 5, *I* is a curved surface of the influence of the interaction term BC on β . It could be seen from this figure that as μ (B) and γ (C) gradually raise from the low level (-1) to the high level (1), β increases continuously. Compared with ζ (D), γ (C) has a more significant effect on β . Under the interaction of single factor item B and single factor item C , with the increase of the level of the two factors, β increases significantly. *II* is a curved surface of the effect of interaction term CD on β . When γ (C) raises from low level (-1) to high level (1), the increasing trend of β is more obvious, while with ζ (D) rising from low level (-1) to high level (1), β presents a downward trend due to the dynamic friction system. Because γ (C) has a great influence on β , β still increased with the increase in the level of the two factors. *III* is the influence curved surface of interaction term AD on β . According to the results of regression analysis of variance in Table 5, single factor A and single factor D are the nonsignificant factors affecting β , while when the two factors interact, the influence of two factors on β is relatively weak; according to response curved surface *III*, a single factor is relatively weak. When factor A and factor D are increased from low level (-1) to high level (1), β increases, but the growth trend is relatively slow, while under the influence of the two factors, β increases first and then decreases.

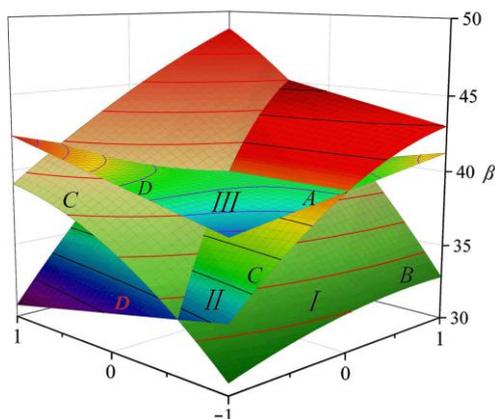


Figure 5 Surface chart of influence of interaction items on the angle of repose

As shown in Figure 6 which showed the predicted response and actual scatters of the angle of repose, x -axis stands for the actual value of β , and y -axis stands for the predicted value of β , and the scatters in the figure stand for the distribution pattern of predicted β . In this figure, the predicted scatters are close to the straight line and distribute on the two sides of the straight line, also proving the reliability of the second-order response model of β .

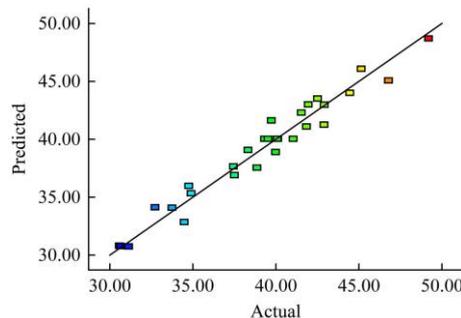


Figure 6 Chart for predicted responses and actual scatters of the angle of repose

The angles of repose β_1 (31.07 ± 2.1)° and β_2 (39.88 ± 2.2)° with a water content of (6.26 ± 1.5)% and (14.1 ± 2.1)% respectively were chosen as fitting targets. The optimized second-order response model of the angle of response was solved using Design expert. The obtained response values under two water contents, including the contact parameters between the particles of the particulate material, are shown in Table 6. The fitting results indicate that the inter-particle contact parameters of the particular material vary with water content. With the increase of water content, contact parameters increase to some extent, too.

Table 6 Calibration results of contact parameters among particles of the PM under different water contents

Water content/%	6.26±1.5	14.1±2.1
Coefficient of restitution for impact e	0.58	0.69
Static friction coefficient μ	0.30	0.38
Dynamic friction coefficient γ	0.10	0.23
Damping coefficient ζ	0.12	0.19

In order to verify the reliability of the fitting results from the optimized second-order response model of β , discrete element software EDEM was used to conduct simulation analysis of the optimized and fit inter-particle contact parameters of the particulate material. The angle of repose for the particular material obtained from the simulation in each group was measured three times to get a mean value. The verification results of the simulation test indicate: as shown in Figure 7a, when the set contact parameters e, μ, γ and ζ among particles of the particulate material with a water content of (6.26 ± 1.5)% are 0.58, 0.30, 0.10 and 0.12, its angle of repose is 29.66°, and the error from the measured value 31.07° is 1.36%; as shown in Figure 7b, when the set contact parameters e, μ, γ and ζ with a water content of (14.1 ± 2.1)% are 0.69, 0.38, 0.23 and 0.19, its angle of repose is 40.99°, and the error from the measured value 39.88° is only 2.78%. Therefore, the verification results of the simulation test in the two groups are relatively consistent with the measured values.

3 Calibration of discrete element contact parameters between PM and agricultural mulch film

3.1 Test material and physical test

In order to study the contact characteristics and adhesion characteristics between granular materials and farmland mulch film, the static sliding friction angle $\theta(y)$ between granular materials and farmland mulch film was measured by slope method in accordance with the standard Determination of external friction coefficient of granular materials for continuous conveying equipment. Taking this parameter as the response value, the contact parameters such as the recovery coefficient $e'(E)$, the static friction coefficient $\mu'(f)$ and the dynamic friction coefficient $\gamma'(g)$ between the granular material

and the mulch film were calibrated by using the discrete element software EDEM. The test instruments and tools used in the physical test mainly include inclined plane tester, bottomless container, agricultural mulch film with the undamaged surface, scissors and steel ruler. During the test, a single layer of agricultural mulch film covered the upper surface of the cantboard on the inclined plane tester. Be sure the agricultural mulch film was in good contact with the upper surface of the cantboard, there were no bubbles, folds and humps between the two materials, and human errors are avoided as far as possible. The structural schematic diagram of this test was shown in Figure 8a.

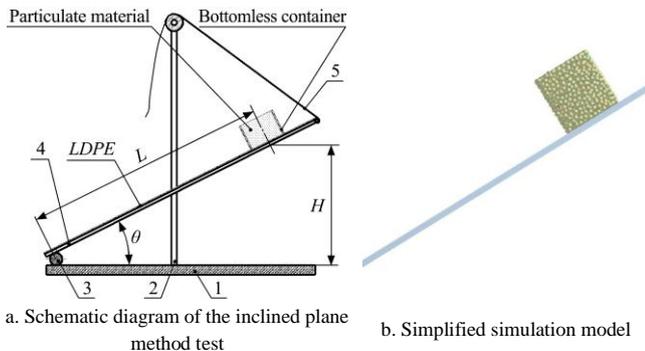


a. Comparison of angle of repose physical test and simulation test of the particulate material with a water content of (6.26±1.5)%



b. Comparison of angle of repose physical test and simulation test of particulate material with water content of (14.2±2.1)%

Figure 7 Comparison of the angle of repose physical test and simulation test of the PM with different water contents



1. Base 2. Support frame 3. Spindle 4. Cantboard 5. Tow rope
Figure 8 Particulate material - agricultural mulch film friction test and simulation

The static sliding friction angles θ between particulate material samples with a water content of (6.26±1.5)% and (14.1±2.1)% respectively and agricultural mulch film were determined by the inclined plane method. During the test, the inclined plane was raised at a uniform speed until the bottomless container and the particulate material began to slide. The distance H from the center point of the bottomless container at the initial location to the upper surface of the base was measured. From the ratio between the above measured distance and the distance L ($L=300$ mm) from the center point of the bottomless container at the initial location to the center of the spindle, the static sliding friction angle θ between particulate material and agricultural mulch film was calculated by Equation (5). In order to reduce measurement error, ten groups of

tests were set in this physical test. Each group of tests was repeated three times and the mean values were calculated. From the inclined plane physical test, it was determined that the static sliding friction angles θ_1 and θ_2 between the particulate material samples with a water content of (6.26±1.5)% and (14.1±2.1)% respectively and agricultural mulch film were (25.42±2.6)° and (30.46±3.2)°.

$$\theta = \arcsin \frac{H}{L} \tag{5}$$

3.2 Simulation test and test verification

When discrete element simulation software was used to calibrate the contact parameters $e'(E)$, $\mu'(F)$ and $\gamma'(G)$ between particulate material and agricultural mulch film, the establishment of particle models, the setting of boundary conditions and the setting of simulation time are all same as the parameter setting in the angle of repose simulation test in 1.2. The test platform model for the determination of a static sliding friction angle between particulate material and agricultural mulch film established in a simplified way in this simulation process, as shown in Figure 8b. The setting of the level values of the factors influencing this simulation test was shown in Table 7.

Table 7 Test factors and levels

Level	-1	0	1
Coefficient of restitution for impact $e'(E)$	0.5	0.6	0.7
Static friction coefficient $\mu'(F)$	0.4	0.5	0.6
Dynamic friction coefficient $\gamma'(G)$	0.05	0.15	0.25

The response curve analysis method was applied, and the testing program designed by Box-Behnken in the data processing software Design expert was shown in Table 8.

Table 8 Testing program and results

Test No.	Code			Response value
	E	F	G	y
1	-1	-1	0	25.05
2	1	-1	0	26.09
3	-1	1	0	35.1
4	1	1	0	35.84
5	-1	0	-1	30.01
6	1	0	-1	30.87
7	-1	0	1	31.19
8	1	0	1	31.77
9	0	-1	-1	26.15
10	0	1	-1	35.76
11	0	-1	1	26.72
12	0	1	1	36.11
13	0	0	0	31.14
14	0	0	0	31.49
15	0	0	0	31.36
16	0	0	0	31.56
17	0	0	0	31.63

According to the testing program, a simulation test was done using EDEM. The test results were shown in Table 8. The test data were analyzed using Design expert data processing software by the regression variance analysis method. The analysis results are shown in Table 9.

Table 9 Regression variance analysis of test results

Source	Mean squares	F value	p-value	Significant
Mold	21.4	363.67	<0.0001	**
<i>E</i>	1.3	22.02	0.0022	**
<i>F</i>	188.18	3197.47	<0.0001	**
<i>G</i>	1.13	19.12	0.0033	**
<i>EF</i>	0.023	0.38	0.5559	—
<i>EG</i>	0.02	0.33	0.582	—
<i>FG</i>	0.012	0.21	0.664	—
<i>E</i> ²	1.37	23.29	0.0019	**
<i>F</i> ²	0.5	8.54	0.0223	*
<i>G</i> ²	0.038	0.64	0.4504	—
Lack of Fit	0.088	2.35	0.2142	

$$R^2=0.998; R^2_{adj}=0.995; CV=0.78\%; \text{Pred } R^2=0.9770.$$

Notes: ** highly significant ($p \leq 0.01$), * significant ($0.01 < p \leq 0.05$), — insignificant ($p > 0.05$).

The results of the simulation test and regression variance analysis indicate: factor items *E*, *F*, *G* and *E*² are factors with a highly significant influence on θ , factor item *F*² is a factor with a significant influence on θ , while other factor items do not have a significant influence on it. The sequence of influences of the factor items is $F > E^2 > E > G > F^2$. Further, among the results of regression variance analysis in this test, model coefficient $p < 0.0001$, determination coefficient $R^2 = 0.998$, adjusted determination coefficient $R^2_{adj} = 0.995$, and coefficient of variation $CV = 0.78\%$, suggesting that the influencing factors *E*, *F* and *G* have a high degree of interpretation to response index y , and the obtained second-order response model is highly reliable. Therefore, the optimum regression equation of θ fit from the regression coefficients of the highly significant and significant influencing factors above is:

$$\hat{y} = 31.44 + 0.4E + 4.85F + 0.38G - 0.075EF - 0.07EG - 0.055FG - 0.57E^2 - 0.35F^2 + 0.095G^2 \quad (6)$$

As shown in Figure 9, under the influence of factor item *E*, when it changed from low level -1 to central level 0, the rising trend of θ is slow as the factor level raise, while in the range of level 0-1, θ shows a slow downward trend, that is when $e'(E)$ raise from 0.5 to 0.6, θ also raise slowly, and when $e'(E)$ increases from 0.6 to 0.7, θ decreases slowly. When factor item *F* raise from low level (-1) to high level (1), the increasing trend of θ is extremely significant, that is, when $\mu'(F)$ changes from 0.4 to 0.6, the increasing trend of θ is obvious, which is consistent with the results of regression analysis of variance. In addition, with the factor item *G* rising from low level (-1) to high level (1), θ also raise, but the rising speed is relatively slow, that is when $\gamma'(G)$ changes from 0.05 to 0.25, θ increases, but the increasing trend is relatively slow, which also shows that $\gamma'(G)$ have limited influence on θ in a certain range.

The static sliding friction angles θ_1 (25.42 ± 2.6)° and θ_2 (30.46 ± 3.2)° between a particulate material with a water content of (6.26±1.5)% and (14.1±2.1)% respectively and the agricultural mulch film determined in the physical test were chosen as fitting targets. The optimal second-order response model of θ was solved using Design expert. Through calibration, the contact parameters between particulate material with two different water contents and agricultural mulch film were obtained, as shown in Table 10. The fitting results indicate that the contact parameters between particulate material and agricultural mulch film vary with water content. With the increase of water content, contact parameters increase to some extent, too.

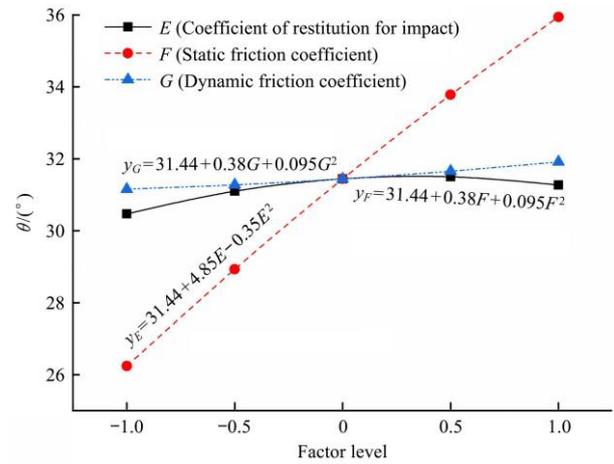


Figure 9 Relationship between factor term and static sliding friction angle θ

Table 10 Calibration results of contact parameters between PM and agricultural mulch film under different water contents

Water content/%	6.26±1.5	14.1±2.1
Coefficient of restitution for impact e'	0.51	0.53
Static friction coefficient μ'	0.4	0.48
Dynamic friction coefficient γ'	0.12	0.22

In order to verify the reliability of simulation analysis and model fitting, discrete element software EDEM was used to conduct the simulation analysis of the optimized and fit contact parameters. The static sliding friction angle obtained from the simulation in each group was measured three times to get a mean value. The verification results of the simulation test indicate: when the set contact parameters e , μ and γ between particulate material with a water content of (6.26±1.5)% and agricultural mulch film are 0.51, 0.4 and 0.12, its static sliding friction angle is 25.64°, and the error from the measured value 25.42° is 0.87%; when the contact parameters e , μ and γ between particulate material with a water content of (14.1±2.1)% and agricultural mulch film are 0.53, 0.48 and 0.22, its static sliding friction angle is 30.69°, and the error from the measured value 30.46° is only 0.76%. Therefore, the verification results of the simulation test in the two groups are relatively consistent with the measured values and all fall in the error range of measured values of the physical test.

4 Conclusions

(1) The Hysteretic Spring Contact Model (HSCM) of discrete element software EDEM was applied. The basic simulation unit of nonstandard spherical particle was established in a simplified way, and angle of repose and inclined plane simulation tests were conducted on this basis. The test results indicate that HSCM and the established nonstandard ball particle unit can effectively calibrate the contact parameters of the particulate material;

(2) By using Box-Behnken function module in Design Expert, a response curve test for simulating the angle of repose (β) of particulate material and the static sliding friction angle (θ) between particulate material and agricultural mulch film were designed respectively. The test results were subjected to regression variance analysis, the second-order response model for β and θ were optimized, and the influence rules of single factor items and interaction items in the optimized second-order response model on β and θ were analyzed.

(3) The physical test values of the angle of repose (β_1 , β_2) and the static sliding friction angle (θ_1, θ_2) under different water

content were chosen as fitting targets. The optimized second-order response model was solved, and the contact parameters were obtained under this condition. The optimized and fit contact parameters among particles of the particulate material were set and subjected to a simulation test in EDEM. The test results indicate that under the two conditions of water content, the errors between the simulation and the physical test value of repose angle β are 1.36% and 2.78%, and of the static sliding fraction angle θ are 0.87% and 0.76%;

(4) Based on the calibration of contact parameters of granular materials, the construction of the hybrid material model of the cotton field machine will be continued in the future, which provides conditions for the numerical simulation of the crushing and separation process of the material.

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