

Calibration and test of the contact parameters for chopped cotton stems based on discrete element method

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Abstract: In view of the fact that the existing cotton stem simulation models are simplified and have a large discrepancy from the actual appearance and the contact parameters have not been calibrated. In this study, the simulation model and numerical simulation were established using the discrete element software EDEM. Then a second-order response model between contact parameters and repose angle had been constructed. The test result showed that the static friction coefficient, rolling friction coefficient, and coefficient of restitution between cotton stems were crucial factors affecting the repose angle. The determination coefficient corrected determination coefficient and p -value of the second-order response model were $R^2=0.959$, $R^2_{adj}=0.921$, and $p<0.0001$ respectively. The error values of the comparison between the simulation test results and the corresponding physical test values were all less than 10%, which showed that the model was reliable and had high interpretation and predictability, this study can provide a certain theoretical basis and data support for the setting of contact parameters in the data simulation of cotton stem harvesting and processing, mechanically-harvested film residue crushing and film stem separation, etc.

Keywords: discrete element method, cotton stem, repose angle, contact parameters, calibration

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1 Introduction

The farmland film mulching technology is one of the key factors promoting China to become an important cotton producer in the world^[1] and has also promoted the gradual migration of China's cotton growing areas from the Yangtze and Yellow River basins to the inland areas in Northwest China. Promoted by farmland film mulching technology, Xinjiang has gradually become the main cotton-producing area in China. The total cotton plantation area of Xinjiang was 254.1×10^4 hm² in 2019, accounting for about 76.1% of China's total cotton plantation area^[2]. Although many years of continuous film mulching have promoted the increase of cotton output and income in Xinjiang, it has also caused serious pollution of residual film in farmland^[3,4]. In recent years, the residual film has been recovered by mechanization in most parts of Xinjiang. This method has alleviated the problem of residual film pollution to a certain extent, but the recovered residual films contain impurities such as a lot of cotton stems, granular materials dominated by soil particles, etc., so as to form mechanically-

harvested film residues in cotton fields, which are characterized by disordered film-stem-soil distribution, complex film-stem entwining, strong film-soil adhesion, etc. It is difficult to preliminarily clean up and recycle the film residues, so they are randomly dumped, buried, and incinerated, which causes secondary environmental pollution and wasting of resources extremely easily. The cotton stem is one of the main components of mechanically-harvested film residues in cotton fields, and its material characteristic parameters are the key factors for the selection of the crushing method of film residues and the design of the crushing device. In addition, the reasonable setting of the contact parameters (static friction coefficient, rolling friction coefficient, coefficient of restitution, etc.) of the cotton stem simulation model is an important basis for accurate simulation model construction and numerical simulation analysis of the crushing process of cotton stems or film residues using simulation software^[5]. Material contact parameters can be obtained through physical tests. However, due to the influences of multiple factors such as test condition, environment, equipment and personnel operation level, etc., some material contact parameters cannot or are difficult to measure or the measurement results are inaccurate^[6,7], thereby affecting the accuracy of cotton stem simulation model construction and numerical simulation. With the improvement of computer level and the diversification of simulation software, the use of simulation software for material simulation model construction, contact parameter calibration, and numerical simulation of the process has become one of the main methods for studying material characteristic parameters.

Discrete Element Method (DEM), as a discontinuous numerical simulation method^[8], has become one of the most widely used numerical simulation software in the field of agricultural

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engineering. DEM is not only widely used for model construction, contact parameter calibration, and simulation analysis of bulk materials such as soil, seeds, and fertilizers^[9,10], but also in the study of stem material characteristics and model construction. Kattenstroth et al.^[11] built a stem model using a multi-sphere bonding in EDEM to conduct a simulation analysis on the cutting process. Li et al.^[12] constructed a stem model in EDEM, and numerically simulated the process of separation of grains from stems using the CFD-DEM coupling method. Nguyen et al.^[13] built a flexible member simulation model using the standard spherical particles to bond in PFC3D, and verified the reliability of the model through a cantilever beam deflection, vibration test, and fixed hinged beam deflection test. Lenaerts et al.^[14] calibrated the simulation contact parameters of the wheat stem model, which was constructed with bendable deformation characteristics in the DEMeter++, and the feasibility and accuracy of the model and calibrated contact parameters were verified by comparing the physical test results with the simulation test results. Ramírez-Gómez et al.^[15] constructed the simulation models of maize stems, rice husks, and rape stems in EDEM, and calibrated the density, Young's modulus, and model contact parameters of the blocky biomass fuel made by mixing and compressing such materials. Ma et al.^[16] measured the contact parameters between alfalfa and its external contact materials in order to improve the accuracy of alfalfa compression numerical simulation, and calibrated the contact parameters of alfalfa stems using discrete element software on this basis. Feng et al.^[17] built a stem model in EDEM combined with the Linear Cohesion contact model and Hertz-Mindlin (No Slip) contact model, calibrated the contact parameters between stem particles, and analyzed the movement characteristics of stem particles in a rotating drum during mixing. Ma et al.^[18] used the basic particle sphere unit model of rice stems based on the Hertz-Mindlin contact model in the simulation of the process of separating rice from sundries during the operation process of combine harvesters. Leblicq et al.^[19,20] constructed a wheat stem model using EDEM considering the influences of plastic deformation and damage based on the existing wheat stem contact parameters, and verified the feasibility of the model by means of compression and bending simulation tests. Zhang et al.^[21] constructed a maize stem model using the Hertz-Mindlin with Bonding contact model in EDEM, and calibrated the contact parameters between maize stems as well maize stems and rubbing device hammer sheets. Zeng et al.^[22] built a wheat stem model by bonding continuous basic particle spheres with discrete element software on the premise of not considering plastic deformation and bending of wheat stems, and used the model for stubble no-tillage simulation tests after giving the existing contact parameters. Li et al.^[23] and Guo et al.^[24] built a tomato stem simulation model based on basic particle sphere units with equal stem diameter bonding in EDEM and gave it basic contact parameters for simulation tests on the mixing process. Liao et al.^[25] calibrated the contact parameters of the harvested stems of forage rape in EDEM, and obtained the simulation parameters of rape stems.

The above references indicate that domestic and foreign scholars have done a lot of research on the simulation model construction of different crop stems, the calibration of contact parameters, and the calibration of bonding parameters, but few on cotton stems. The current cotton stem simulation model is mainly constructed by continuous stacking of multiple basic particle sphere units with equal stem diameter, and fixed-value contact parameters obtained from physical tests or literature review are assigned for

numerical simulation^[26]. The modeling method is simple, the simulation calculation speed is fast, and the cycle is short, but the contact parameters of the cotton stem simulation model are not calibrated. In addition, the constructed cotton stem simulation model is quite different from the actual appearance, easily leading to a low degree of coincidence or distortion between the simulation and physical test result.

For this reason, the dwarf-dense-early cotton variety stems in the cotton planting area in Northern Tianshan Mountains, Xinjiang was taken as the research objects, the repose angle of the chopped whole cotton stems after removing lateral branches with different moisture content was measured by physical experiment. According to the biological characteristics of cotton stems and subsequent research needs, the basic model of cotton stem simulation was established by using non-equal-size basic particle ball units. The cotton stem simulation model was used to carry out a numerical simulation test of the repose angle, and the contact parameters between cotton stems were calibrated. The second-order response model between contact parameters and repose angle was constructed. The influences of static friction coefficient, rolling friction coefficient, and coefficient of restitution on the repose angle were obtained. The reliability of the model was verified by the validation test. This research can provide accurate and reliable cotton stem simulation models and contact parameters for studies on the simulation of the mechanical properties of cotton stems, the crushing process of film residues, and the cotton stem-machine interaction characteristics, as well as to ensure that the simulation analysis results are in good agreement with the physical test values.

2 Test materials and methods

The test time was November 2019, and the test site was the Key Laboratory of Northwest Agricultural Equipment of the Ministry of Agriculture and Rural Affairs, Shihezi University. The test materials were sampled from the test field of Shihezi University. The cotton variety was Xinluzao series No.45. Whole cotton stems free of defects, cracks, damage, and disease and insect pests were selected to the greatest extent possible during sampling. The instruments and equipment required during the test mainly included an electric heating blast drying oven, TCS-60 electronic platform scale (measurement accuracy: 2 g, manufacturer: China Shanghai Yousheng Weighing Apparatus Co., Ltd.), JMB5003 electronic balance (measurement accuracy: 0.001 g, manufacturer: Yuyao Jiming Weighing and Calibration Equipment Co., Ltd., Zhejiang Province, China), Sartorius MA100 electronic rapid moisture test apparatus (mass accuracy: 0.001 g, moisture content accuracy: 0.01%, Manufacturer: Beijing Sartorius Instrument System Co., Ltd.), Vernier calipers (measurement accuracy: 0.02 mm), trimmers, repose angle test devices by discharge method, etc.

2.1 Physical test on the repose angle of cotton stems

The diameter of the main stem of a cotton stem is different, there are many branches and bud bulges, and the stem is curved when the span is large, so it is impossible to directly use a long cotton stem to conduct the physical test on the repose angle. In order to ensure the test effect of the repose angle of cotton stems and improve the accuracy of the contact parameters to be calibrated (Figure 1a), referring to the method of measuring the repose angle of chopped stems in literatures [27,28], a whole cotton stem after removing lateral branches was chopped as per a certain length (the length of the chopped cotton stem is 10-20 mm), and the chopped

stem at stem bud bulges and lateral branches was removed, and then the repose angle test was performed by the discharge method^[29]. A total of 20 physical tests were carried out to reduce the measurement error of the repose angle α . During the test process, a camera was used to take pictures of the cotton stem pile (Figure 1b), and MATLAB was used to extract and processed the two-sided boundary information of it. Moreover, the Origin software was used to fit the extracted boundaries (Figure 1c), and the arithmetic mean of the cotton stem repose angle was calculated.

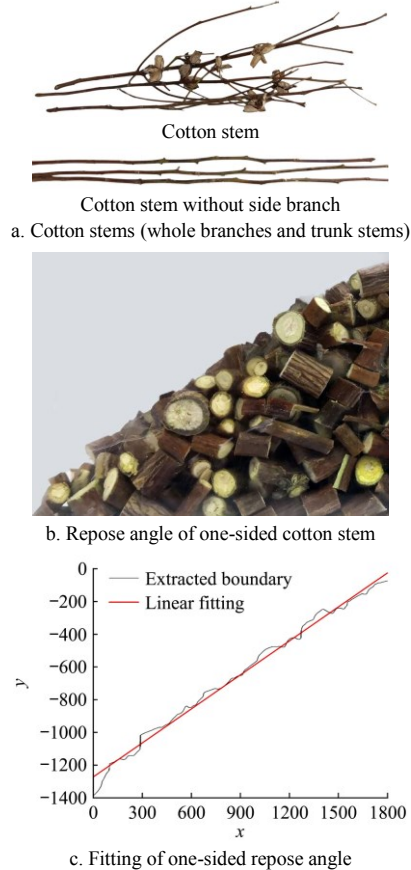


Figure 1 Repose angle of one-sided cotton stem and fitting of repose angle α

During the test process, the total mass of the chopped cotton stem used was 1.5 kg, and the stem diameter ranged from 5 mm to 15 mm. The average moisture content of the randomly sampled cotton stem measured by the Sartorius MA100 electronic moisture test apparatus was 66.16%. In addition, the moisture content of the whole chopped cotton stem sample was adjusted according to the methods and steps in GB/T 1928-2009, GB/T 1931-2009, and literature [30]. The chopped cotton stem was laid flat in the electrothermal blast drying oven as a whole. After drying for 8 h at a temperature of $(103\pm 2)^\circ\text{C}$, it was weighed with a TCS-60 electronic platform scale. It was placed in the electrothermal blast drying oven to continue drying for 2 h. It was weighed again. The mass values obtained by weighing the sample twice were compared. If the relative error was less than 0.5%, the sample was considered completely dry. After full soaking of the absolutely dry sample with clean water, the moisture content of the test sample was adjusted to 10%, 30%, and 50% respectively using the electrothermal blast drying oven at $(45\pm 2)^\circ\text{C}$. After the moisture content of the cotton stem was well adjusted, the chopped cotton stem with a moisture content of 10%, 30%, and 50% respectively was subjected to a stacking test using the repose angle test device by the discharge method, and the repose angle was

extracted and fitted. The test result showed that the repose angle α of the chopped cotton stem with a moisture content of 66.16% was $(33.08\pm 3.84)^\circ$, and the angles of repose α_{10} , α_{30} , and α_{50} of the chopped cotton stem with a moisture content of 10%, 30%, and 50% were $(33.49\pm 2.87)^\circ$, $(34.98\pm 3.53)^\circ$ and $(31.38\pm 2.02)^\circ$ respectively.

2.2 Simulation contacts model selection and model construction

When constructing the simulation model of the repose angle of the cotton stem, the basic particle sphere unit built by the embedded model Hertz-Mindlin (No Slip) in EDEM was selected as a basis to establish the cotton stem simulation model. In order to simplify the model, the constructed cotton stem simulation model was regarded as an isotropic material, and the bonding parameters between particles were not in consideration.

The Hertz-Mindlin (No Slip) contact model (Figure 2) is the basic model in EDEM. The normal force and tangential force of the two basic particle models bonded to each other have damp components. The tangential friction force complies Coulomb's friction law and the rolling friction force can be achieved by contact with the independent directional constant torque model.

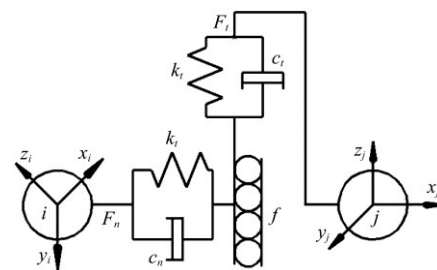


Figure 2 Schematic diagram of Hertz-Mindlin (No Slip) contact model

While the particle tangential force F_t was limited by the static friction force μ_s and the normal force F_n , the normal force F_n and the tangential force F_t also had a certain functional relationship with the overlap quantities δ_n and δ_t in their respective directions. The relational equation could be expressed as,

$$\begin{cases} F_n = \frac{4}{3} \delta_n^{\frac{3}{2}} \left[\frac{E_i + E_j}{E_i(1-\nu_i^2) + E_j(1-\nu_j^2)} \right] \sqrt{\frac{r_i r_j}{r_i + r_j}} \\ F_t = -8\delta_t \frac{G_i G_j}{G_j(2-\nu_i) + G_i(2-\nu_j)} \sqrt{\frac{r_i r_j}{r_i + r_j}} \delta_n \end{cases} \quad (1)$$

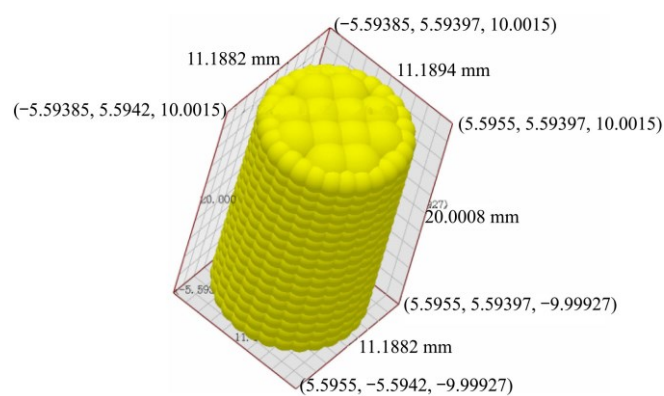
where, F_n , F_t are the normal force and tangential force, respectively, N; k_n , k_t are the normal stiffness coefficient and the tangential stiffness coefficient, respectively, N/m; δ_n , δ_t are the normal overlap quantity and tangential overlap quantity, respectively, m; ν_i , ν_j are the Poisson's ratio of particles i and j respectively; E_i , E_j are the elastic modulus of particles i and j respectively, Pa; r_i , r_j are the radius of particles i and j respectively, mm; G_i , G_j are the shearing modulus of particles i and j respectively, Pa.

In this case, the tangential resistance and normal resistance of the particles can be expressed as,

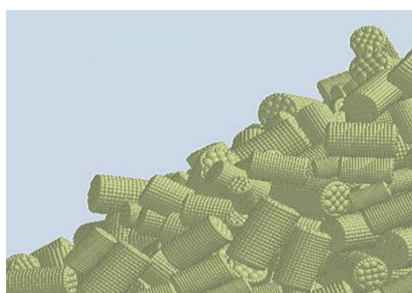
$$\begin{cases} F_n^d = -\nu_n \ln e \sqrt{\frac{10k_n m_i m_j}{3(m_i + m_j)(\ln^2 e + \pi^2)}} \\ F_t^d = -\nu_t \ln e \sqrt{\frac{10k_t m_i m_j}{3(m_i + m_j)(\ln^2 e + \pi^2)}} \end{cases} \quad (2)$$

where, F_n^d , F_t^d are the normal resistance and tangential resistance, respectively, N; m_i , m_j are the mass of the particle spheres i and j , kg; ν_n , ν_t are the normal and tangential components of the relative velocity of the particles, respectively, m/s; e is the particle recovery coefficient.

When constructing the basic model of the cotton stem used for repose angle simulation, the particle factory API was used to generate basic particle units for binding at regular positions, and the epidermis and internal tissues (xylem and medullary core) were respectively filled (Figure 3a). The constructed cotton stem simulation model was 20mm in height and 10mm in diameter, and consists of 612 basic particle units. The average radius of the basic particle units used for the cotton stem skin was 1mm, and for internal tissues was 2 mm. It was composed of 494 particle units and 108 particle units respectively. A total of 3000 cotton stem models were generated for numerical simulation of the repose angle, the diameter and the height of the cotton stem model were randomly generated at 0.5-1.5 times and 0.5-1.0 times the size of the basic model of the cotton stem.



a. Basic model of cotton stem repose angle simulation



b. Repose angle simulation test

Figure 3 Cotton stem simulation model and repose angle simulation test

The experimental device model was simplified on the scale of 1:1 in SolidWorks. The simplified model was imported into the EDEM, and the hertz-Mindlin (No Slip) contact model simulation environment was used for the simulation test of the repose angle of the chopped cotton stem, as shown in Figure 3b. After the simulation test, the boundaries of the repose angle of two-sided of the cotton stem pile were still determined using the boundary extraction and fitting method in the physical test in Section 2.1.

2.3 Simulation parameter setting and test scheme determination

When setting the material property boundary conditions of the cotton stem model, the value ranges of the coefficient of restitution $e(a)$, static friction coefficient $\mu(b)$, and rolling friction coefficient $\gamma(c)$ between cotton stems were determined referring to literature [26]. Since the parameters of cotton stems such as density, Poisson's ratio, and shearing modulus have little effect on the repose angle, they were set to fixed values. The set basic parameters of the simulation model are listed in Table 1.

The test influencing factors such as a , b and c have been coded using the CCD (Central Composite Design) module in the Design expert 8.0.6 software. The settings of the code and the level value

of the influencing factors of the simulation test on the cotton stem repose angle are listed in Table 2.

Table 1 Setting of contact parameters of the simulation model of the cotton stem repose angle

Parameters	Values
Stem density $\rho/\text{kg}\cdot\text{m}^{-3}$	110
Shear modulus of stem G/MPa	10
Poisson's ratio of stem ν	0.35
*Stem-stem coefficient of restitution e	0.15-0.45
*Stem-stem static friction coefficient μ	0.3-0.6
*Stem-stem rolling friction coefficient γ	0.02-0.06

Note: * is the parameter to be calibrated.

Table 2 Test factors and level values

Level	Coefficient of restitution $e(a)$	Static friction coefficient $\mu(b)$	Rolling friction coefficient $\gamma(c)$
-1.682	0.048	0.198	0.006
-1	0.15	0.30	0.02
0	0.30	0.45	0.04
1	0.45	0.60	0.06
1.682	0.552	0.702	0.074

According to the influencing factors and their level values set in Table 2, a three-factor five-level central composite test has been designed taking the repose angle $\alpha(\gamma)$ as the response index and using the CCD module in the Design Expert 8.0.6 software. The test had 20 groups, and the test scheme is listed in Table 3.

Table 3 Testing program and results

Test No.	Code			Response value
	a	b	c	γ
1	-1	-1	-1	32.55±1.21
2	1	-1	-1	30.40±5.27
3	-1	1	-1	32.25±3.76
4	1	1	-1	32.70±3.39
5	-1	-1	1	34.65±3.00
6	1	-1	1	36.31±2.65
7	-1	1	1	32.68±2.82
8	1	1	1	40.79±5.30
9	-1.682	0	0	32.59±2.76
10	1.682	0	0	36.29±3.32
11	0	-1.682	0	33.47±1.39
12	0	1.682	0	35.34±2.26
13	0	0	-1.682	30.67±4.21
14	0	0	1.682	38.50±2.83
15	0	0	0	32.47±1.23
16	0	0	0	31.98±1.23
17	0	0	0	32.21±0.92
18	0	0	0	32.52±2.06
19	0	0	0	33.48±2.49
20	0	0	0	31.46±1.18

3 Analysis, discussion and verification of the repose angle test result

3.1 Test result analysis

According to the test scheme, the cotton stem repose angle α after different parameter combinations were subjected to a simulation test using EDEM. The simulation test results are listed in Table 3. The simulation test result in Table 3 was processed using the analysis module in the Design Expert 8.0.6, and a regression variance analysis was performed on the single factor terms and interaction terms that affect the cotton stem repose angle α . The analysis results are listed in Table 4.

According to the regression variance analysis of the test result in Table 4, the p values of the single factor items a and c and the interaction items ab , ac , a^2 and c^2 were all <0.01 , which were extremely significant influencing factors of the response value y . The p values of the single factor item b and the interaction item b^2 were 0.0181 and 0.0106 and were both within the range of 0.01-0.05, which were significant influencing factors of y . Since the p -value of the interaction term bc was 0.811, which was more than 0.05, it was an insignificant influencing factor of y . Ignoring the insignificant influencing factor, the descending order of extremely significant and significant influencing factors that affect the response value y was c , ac , a , ab , c^2 , a^2 , b^2 , b .

Table 4 Regression variance analysis of the test results

Source	Sum of squares	Mean square	F-value	p-value
Model	124.97	13.89	25.75	<0.0001**
a	14.96	14.96	27.74	0.0004**
b	4.29	4.29	7.96	0.0181*
c	64.58	64.58	119.76	<0.0001**
ab	10.24	10.24	18.98	0.0014**
ac	16.45	16.45	30.49	0.0003**
bc	0.03	0.033	0.06	0.811
a^2	5.52	5.52	10.23	0.0095**
b^2	5.30	5.30	9.82	0.0106*
c^2	6.47	6.47	11.99	0.0061**
Residual	5.39	0.54		
Lack of fit	3.12	0.62	1.38	0.367
Pure error	2.27	0.45		
Cor total	130.37			

$$R^2=0.959; R^2_{adj}=0.921; CV=2.18\%; R_{pred}=0.771$$

Note: ** means extremely significant factor ($p \leq 0.01$); * means significant factor ($0.01 < p \leq 0.05$); $p > 0.05$ means non-significant factor. CV: Coefficient of vibration.

In addition, according to the regression variance analysis result, the p -value of the model coefficient was <0.0001 , which was extremely significant, while the p -value of the lack of fit term was 0.367 far greater than 0.05, which was extremely insignificant, and the coefficient of variation $CV=2.18\%$, which is low. This showed that the second-order response model between the stem-stem contact parameters and the repose angle obtained from the regression variance analysis was reliable, and the predicted value of the model had a high degree of fitting with the physical test value. The determination coefficient R^2 and corrected determination coefficient R^2_{adj} of the second-order response model were 0.959 and 0.921 respectively. The predicted determination coefficient $R_{pred}=0.771$, and the SNR (Adeq precision) was 20.41%. This showed that the regression model was extremely significant and the influencing factors a , b , and c had a high degree of interpretation for the response value y , and that the second-order response model could better predict and optimize the repose angle of chopped cotton stems under different conditions. According to the regression variance analysis result and code factors, the second-order response model between the stem-stem contact parameters and the repose angle had been obtained, as shown in Equation (3):

$$y=32.37+1.05a+0.56b+2.17c+1.13a \times b+1.43a \times c+0.064b \times c+0.62a^2+0.61b^2+0.67c^2 \quad (3)$$

In addition, the p -value of the interaction term $b \times c$ was far greater than 0.05, and was an insignificant influencing factor of the test response value y ; therefore, if the insignificant influencing factor in the second-order response model was eliminated, Equation (3) could be changed to:

$$\hat{y}=32.37+1.05a+0.56b+2.17c+1.13a \times b+1.43a \times c+0.62a^2+0.61b^2+0.67c^2 \quad (4)$$

3.2 Analysis of the law of influence of a single factor term on the repose angle

In order to better observe the influence trend of the test influencing factors a , b and c respectively on the test response value y , when analyzing the influence of a single factor on the response value y , the other two single factors were fixed at the central level value 0, and then the influence law of factors terms a , b and c on the response value y are obtained respectively, as shown in Figure 4.

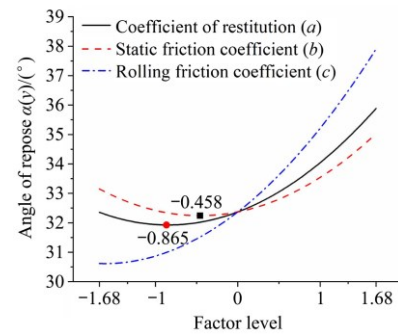


Figure 4 Relation charts of a single factor term vs. repose angle α

As can be seen in Figure 4, when the level value of a increases from -1.682 to -0.865 , y gradually decreases, and when the level value of a was -0.865 , y was at least 31.93° . When the level value of a increased from -0.865 to 1.682 , y gradually increased. That was, as the coefficient of restitution gradually increased in the range of 0.048-0.552, the cotton stem repose angle first decreased and then increased. The coefficient of restitution was the ratio of the relative velocities before and after two particles collide with each other. A larger coefficient of restitution means that the relative velocity after the collision of two particles was also larger and the dispersion effect of particles was better, resulting in a decrease in the repose angle. Peng et al.^[31] also obtained the same conclusion when studying the repose angle of feed particles. Cotton stems were non-standard sphere particles with poor fluidity; therefore, when the coefficient of restitution continues to increase, the particles falling at the center and moving out after collision will be stabilized at the repose angle boundary, thereby forming a large repose angle. This may be the reason why the repose angle first decreases and then increased with the increasing coefficient of restitution.

In Figure 4, similar to the variation trend of the influence of a on y , the influence of b on y also first decreased and then increases. When the level value of b increased from -1.682 to -0.458 , y gradually decreased, and when the level value of b was -0.458 , the test response value y was at least 32.24° . When the level value of b increased from -0.458 to 1.682 , y gradually increased. That is, as the static friction coefficient gradually increased in the range of 0.198-0.702, the cotton stem repose angle first decreased and then increased. With the increasing static friction coefficient between particles, the Coulomb friction force and tangential force between particles also gradually increased, the fluidity of particles became worse, and particles at the contact surface were relatively static, thus forming a stable accumulation body, and leading to an obvious trend of increase in the repose angle. When studying the changing law of influence of contact parameters on the repose angle of granular fertilizers, Liu et al.^[32] also explained the changing law of influence of static friction coefficient on the repose angle. Due to the influence of cotton stem shape and the coefficient of restitution

and rolling friction coefficient between particles, the formed repose angle boundary had randomness and irregularity^[33]. This may be the main reason why the repose angle first decreased and then increased with the increasing static friction coefficient between particles.

In Figure 4, unlike the law of influence of the above two test influencing factors on the test response value y , the test response value y tends to gradually increase as the level value of the test influencing factor c increases. That was, as the rolling friction coefficient gradually increased in the range of 0.006-0.074, the cotton stem repose angle gradually increased. In addition, when the level value of c increased in the range of -1.682 to 0 , y increased slowly. When the level value of c increased in the range of 0 - 1.682 , y increased sharply. In the process of particle accumulation, the interaction between particles is intense and complicated. When the rolling friction coefficient was small, the rotational kinetic energy of boundary particles was large and the inhibiting effect of the moment of inertia was small. Moreover, when squeezed by central particles, boundary particles easily lose stability, causing the outer boundary of accumulation to continuously extend and spread, and forming a small repose angle. With the increasing rolling friction coefficient between particles, the external diffusivity of boundary particles becomes worse, which thus made it easier to form more stable particle accumulation, and results in an increase in the repose angle. Peng et al.^[31,32,34] have also explained the changing law of influence of the rolling friction coefficient on the repose angle.

The response model between test influencing factors a , b , and c and test response value y is shown in Equation (5).

$$\begin{cases} y_a = 32.37 + 1.05a + 0.62a^2 \\ y_b = 32.37 + 0.56b + 0.61b^2 \\ y_c = 32.37 + 2.17c + 0.67c^2 \end{cases} \quad (5)$$

3.3 Analysis of the law of influence of interaction terms on the repose angle

According to the analysis of the simulation result of the repose angle of the chopped cotton stem, the interaction terms ab and ac had extremely significant influences on the test response value y , while the influence of the interaction term bc on the test response value y was extremely insignificant. Therefore, only the change law of ab and ac on the test response value y was analyzed, as shown in Figures 5 and 6.

3.3.1 Influence of the interaction term ab on the repose angle

In Figure 5, when the level value of a was -1.682 and the level value of b was increased from -1.682 to 1.682 , the test response value y tends to first decrease and then increase. When the level value of b was 1.1 , the minimum value of y was 31.62° , which was the same as the changing trend of the influence of single factor b on the repose angle. As the level value of a increases gradually, the cotton stem repose angle's trend of decreasing at first and then increasing significantly changed. When the level value of the test influencing factor a was 1.682 and the level value of the test influencing factor b was increased from -1.682 to 1.682 , the test response value y tends to increase. The changing trend was different from that of the influence of the single factor term b on the repose angle.

When the level value of b was -1.682 and the level value of a increased from -1.682 to 1.628 , the test response value y showed a trend of decreasing first and then increasing, and when the level value of a was 0.7 , the test response value y had a minimum of 32.86° . The changing trend was the same as that of influence of the

single factor term a on the repose angle. As the level value of b increased gradually, the cotton stem repose angle's trend of decreasing at first and then increasing changed gradually to a rising trend. When the level value of the test influencing factor b was 1.682 and the level value of the test influencing factor a was increased from -1.682 to 1.682 , the test response value y increased sharply with the increasing level value of the test influencing factor a . In addition, under the combined effects of test influencing factors a and b , when the level values of the two factors both rise from -1.682 to 1.682 , the test response value y showed a trend of firstly decreasing and then increasing, and the increasing trend was far greater than the decreasing trend. The second-order response model composed of test influencing factors a , b , and interaction term ab was:

$$y_{ab} = 32.37 + 1.05a + 0.56b + 1.13a \times b + 0.62a^2 + 0.61b^2 \quad (6)$$

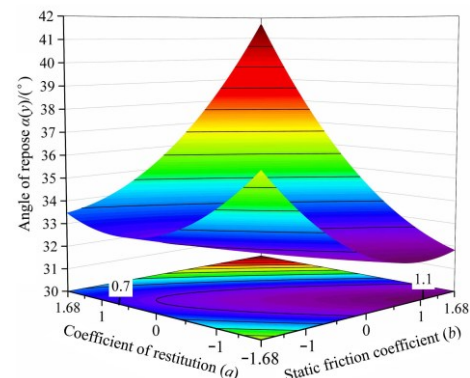


Figure 5 Relation of interaction term ab vs. repose angle α

3.3.2 Influence of the interaction term ac on the repose angle

In Figure 6, when the level value of the test influencing factor a was -1.682 and the level value of the test influencing factor c was increased from -1.682 to 1.682 , the test response value y tends to first decreased and then increased. When the level value of c was 0.19 , the minimum value of y was 32.34° . The changing trend was somewhat different from that of the influence of the single factor term c on the repose angle. As the level value of the test influencing factor a increased gradually, the cotton stem repose angle's trend of decreasing at first and then increasing significantly changed. When the level value of the test influencing factor a was 1.682 and the level value of the test influencing factor c was increased from -1.682 to 1.682 , the test response value y tends to increase. The changing trend was the same as that of influence of the single factor term c on the repose angle.

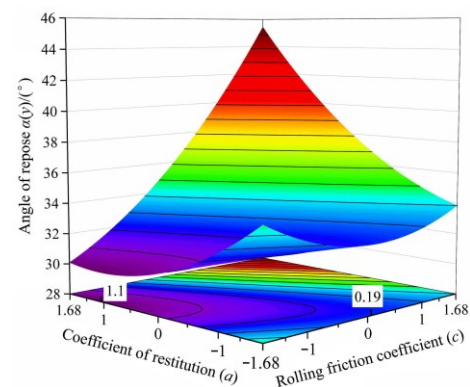


Figure 6 Relation of interaction term ac vs. repose angle α

When the level value of the test influencing factor c was -1.682 and the level value of test influencing factor a increased from -1.682 to 1.682 , the test response value y showed a trend of decreasing first and then increasing, and when the level value of a

was 1.1, the test response value y had a minimum of 29.88° . The changing trend was the same as that of the influence of the single factor term a on the repose angle. As the level value of the test influencing factor c increased gradually, the cotton stem repose angle's trend of decreasing at first and then increasing had changed gradually to a rising trend. When the level value of the test influencing factor c was 1.682 and the level value of the test influencing factor a was increased from -1.682 to 1.682 , the test response value y tends to increase sharply. The changing trend was somewhat different from that of the influence of the single factor term a on the repose angle. In addition, under the combined effects of test influencing factors a and c , when the level values of the two factors both rise from -1.682 to 1.682 . The test response value y showed a trend of first decreasing and then increasing, and the increasing trend was far greater than the decreasing trend. The second-order response model composed of test influencing factors a , c , and interaction term ac was

$$y_{ac} = 32.37 + 1.05a + 2.17c + 1.43ac + 0.62a^2 + 0.67c^2 \quad (7)$$

3.4 Numerical fitting and test verification

In order to verify the accuracy and reliability of the constructed second-order response model between the cotton stem contact parameters and the repose angle, the repose angle of the chopped cotton stem obtained by physical tests under different moisture content conditions was used as the target value. The target value was fitted by the Optimization module in the Design-expert software, the regression equation was solved as well as the response surface was analyzed, and the contact parameter value between cotton stems under the condition of different cotton stem repose angles at different moisture contents was determined. Objective and conditional constraint equations were

$$\begin{cases} y(a, b, c) = \alpha(33.49^\circ, 34.98^\circ, 31.38^\circ, 33.08^\circ) \\ 0.15 \leq a \leq 0.45 \\ 0.3 \leq b \leq 0.6 \\ 0.02 \leq c \leq 0.06 \end{cases} \quad (8)$$

According to Equation (8), the contact parameters such as the coefficient of restitution, static friction coefficient, and rolling friction coefficient corresponding to each repose angle were obtained. Then taking the obtained contact parameters as boundary conditions for simulation in EDEM, the corresponding cotton stem repose angles from numerical simulation under different moisture content conditions were obtained. Each group of tests was carried out 3 times and the arithmetic mean was calculated. The contact parameters between chopped cotton stems and their corresponding numerical simulation repose angles in four moisture contents obtained from fitting solution are listed in Table 5.

Table 5 Contact parameters between cotton stems under different moisture content conditions and simulation test result

Moisture content/%	10.00	30.00	50.00	66.16
Coefficient of restitution e	0.332	0.347	0.251	0.326
Static friction coefficient μ	0.462	0.453	0.392	0.449
Rolling friction coefficient γ	0.046	0.054	0.029	0.044
Simulated repose angle $\alpha'/(^\circ)$	36.59 ± 1.43	38.02 ± 2.91	34.43 ± 1.34	35.98 ± 1.60
Error value compared with the physical test value/%	9.26	8.69	9.72	8.77

According to the verification result of the simulation test of the cotton stem repose angle, the calibrated cotton stem contact parameters were used as the boundary conditions, and the discrete element software EDEM was used to perform the numerical simulation of the repose angle; moreover, the repose angle α' value at the chopped cotton stem moisture content of 10%, 30%, 50%,

and 66.16% respectively was $(36.59 \pm 1.43)^\circ$, $(38.02 \pm 2.91)^\circ$, $(34.43 \pm 1.34)^\circ$ and $(35.98 \pm 1.60)^\circ$, and the error values compared with the corresponding physical test values are all $<10\%$. This showed that the simulation test value of the repose angle was in good agreement with its physical test value. In addition, when the cotton stem moisture content was 50%, the maximum error between the simulated value of the repose angle and its physical test value was 9.72%. When the cotton stem moisture content was 30%, the minimum error between the simulated value of the repose angle and its physical test value was 8.69%. The average error between the simulated value of the repose angle and its physical test value was $(9.11 \pm 0.41)\%$ at 4 moisture contents, indicating that the simulated value of the repose angle was in good agreement with its physical test value. This further showed that the constructed second-order response model between the coefficient of restitution, static friction coefficient, rolling friction coefficient, and the repose angle can be used to calibrate the contact parameters of cotton stems with different moisture contents.

4 Conclusions

The dwarf-dense-early cotton variety stem in the cotton planting area of the Northern Tianshan Mountains in Xinjiang was taken as research objects. The discharge method was used to obtain the repose angle of chopped cotton stems under different moisture content conditions. In addition, the cotton stem simulation model had been constructed using discrete element simulation software. Moreover, the repose angle simulation test was carried out. By regression analysis, the second-order response model of the stem-stem contact parameters and the repose angle had been constructed, and the response law of the cotton stem repose angle and contact parameters had been obtained. The specific conclusions were as follows:

1) The repose angle of chopped cotton stems under different moisture content conditions had been measured using the discharge method, and the repose angle boundary had been extracted, denoised, and fitted using Matlab image processing software and Origin software. The test result showed that the repose angle α of the chopped cotton stem with a moisture content of 10%, 30%, 50%, and 66.16% was $(33.49 \pm 2.87)^\circ$, $(34.98 \pm 3.53)^\circ$, $(31.38 \pm 2.02)^\circ$ and $(33.08 \pm 3.84)^\circ$ respectively.

2) The chopped cotton stem simulation model had been constructed and numerically simulated, According to the test result, the determination coefficient of the model was $R^2=0.959$, the corrected determination coefficient was $R^2_{adj}=0.921$, the predicted determination coefficient was $R_{Pred}=0.771$, the variation coefficient was $CV=2.18\%$, and the SNR (Adeq precision) was 20.41%; in addition, the p -value of the model coefficient was <0.0001 , while the p -value of the lack-of-fit term was 0.367. This showed that the second-order response model between the stem-stem contact parameters and the repose angle was reliable;

3) As the coefficient of restitution and static friction coefficient gradually increase in the ranges of 0.048-0.552 and 0.198-0.702 respectively, the cotton stem repose angle tends to first decrease and then increase. As the rolling friction coefficient gradually increased in the range of 0.006-0.074, the cotton stem repose angle gradually increases. Under the influence of the interaction between the coefficient of restitution and the static friction coefficient and that between the coefficient of restitution and the rolling friction coefficient, as the value of each contact parameter increased from a low level to a high level, the repose angle firstly decreased and then increased, and the increasing trend was more obvious;

4) The physical test values of cotton stem repose Angle under different moisture content were taken as the fitting objective, the contact parameters between cotton stems under different conditions were obtained and numerical simulation was carried out. According to the simulation test verification result, the error between the simulation test verification result of the repose angle and the corresponding physical test value was less than 10%. This showed that the simulated value of the repose angle was in good agreement with its physical test value, and the constructed second-order response model had high predictability;

5) The simulation model established in this paper can only be used for the calibration of contact model parameters, but not for the numerical simulation of the destruction process. On the basis of this model, a cotton stem simulation model representing failure characteristics will be constructed by particle replacement method, and the bonding characteristic parameters will be calibrated.

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[References]

- [1] Dai J R, Dong H Z. Intensive cotton farming technologies in China: Achievements, challenges and countermeasures. *Field Crops Research*, 2014; 155: 99–110.
- [2] Bureau Statistics. A slight decline in national cotton output in 2019 - An explanation from Huang Bingxin, senior statistician at the NBS' Rural Affairs Department. Available: http://www.stats.gov.cn/tjsj/sjjd/201912/t20191217_1718008.html. Accessed on [2021-1-12].
- [3] Liu E K, He W Q, Yan C R. 'White revolution' to 'white pollution'—agricultural plastic film mulch in China. *Environmental Research Letters*, 2014; 9(9): 091001. doi: 10.1088/1748-9326/9/9/091001.
- [4] Wu Q, Wang Z H, Zheng X R, Zhang J Z, Li W H. Effects of biodegradation film mulching on soil temperature, moisture and yield of cotton under drip irrigation in typical oasis area. *Transactions of the CSAE*, 2014; 33(16): 135–143. (in Chinese)
- [5] Quist J, Evertsson C M. Cone crusher modelling and simulation using DEM. *Minerals Engineering*, 2016; 85: 92–105.
- [6] Gonzalezmontellano C, Fuentes J, Ayugatellez E, Ayuga F. Determination of the mechanical properties of maize grains and olives required for use in DEM simulations. *Journal of Food Engineering*, 2012; 111(4): 553–562.
- [7] Rackl M, Hanley K J. A methodical calibration procedure for discrete element models. *Powder Technology*, 2016; 307: 73–83.
- [8] Cil M B, Alshibli K A. Modeling the influence of particle morphology on the fracture behavior of silica sand using a 3D discrete element method. *Comptes Rendus - Mécanique*, 2015; 343(2): 133–142.
- [9] Radvilaitis U, Ramirezgomez A, Kacianauskas R. Determining the shape of agricultural materials using spherical harmonics. *Computers and Electronics in Agriculture*, 2016; 128: 160–171.
- [10] Cunha R N, Santos K G, Lima R N, Duarte C R, Barrozo M. Repose angle of monoparticles and binary mixture: An experimental and simulation study. *Powder Technology*, 2016; pp.203–211.
- [11] Kattenstroth R, Harms H H, Lang T. Systematic alignment of straw to optimise the cutting process in a combine's straw chopper. In: *Proceedings of Land. Technik AgEng 2011, Hannover, Germany*, 2011; 11: 11–12.
- [12] Li H C, Li Y M, Gao F, Zhao Z, Xu L Z. CFD–DEM simulation of material motion in air-and-screen cleaning device. *Computers and Electronics in Agriculture*, 2012; 88: 111–119.
- [13] Nguyen D H, Kang N, Park J. Validation of partially flexible rod model based on discrete element method using beam deflection and vibration. *Powder Technology*, 2013; 237: 147–152.
- [14] Lenaerts B, De Ketelaere B, Tijskens E, Herman R, Baerdemaeker J D, Aertsen T, Saeys W. Simulation of grain–straw separation by Discrete Element Modeling with bendable straw particles. *Computers and Electronics in Agriculture*, 2014; 101: 24–33.
- [15] Ramírez-Gómez E, Gallego J M, Fuentes C, González-Montellano F, Ayuga. Values for particle-scale properties of biomass briquettes made from agroforestry residues. *Particology*, 2014; 12(1): 100–106.
- [16] Ma Y H, Song C D, Xuan C Z, Wang H Y, Yang S, Wu P. Parameters calibration of discrete element model for alfalfa straw compression simulation. *Transactions of the CSAE*, 2020; 36(11): 22–30. (in Chinese)
- [17] Feng J X, Lin J, Li S Z, Zhou J Z, Zhou Z X. Calibration of discrete element parameters of particle in rotary solid state fermenters. *Transactions of the Chinese Society of Agricultural Machinery*, 2015; 46(3): 208–213. (in Chinese)
- [18] Ma Z, Li Y, Xu L. Discrete-element method simulation of agricultural particles' motion in variable-amplitude screen box. *Computers and Electronics in Agriculture*, 2015; 118: 92–99.
- [19] Leblicq T, Smeets B, Ramon H, Saeys W. A discrete element approach for modelling the compression of crop stems. *Computers and Electronics in Agriculture*, 2016; 123(C): 80–88.
- [20] Leblicq T, Smeets B, Vanmaercke S, Ramon H, Saeys W. A discrete element approach for modelling bendable crop stems. *Computers and Electronics in Agriculture*, 2016; 124: 141–149.
- [21] Zhang T, Liu F, Zhao M Q, Ma Q, Wang W, Fan Q, Yan P. Determination of corn stalk contact parameters and calibration of discrete element method simulation. *Journal of China Agricultural University*, 2018; 23(4): 120–127. (in Chinese)
- [22] Zeng Z, Chen Y. Simulation of straw movement by discrete element modelling of straw-sweep-soil interaction. *Biosystems Engineering*, 2019; 180: 25–35.
- [23] Li P P, Wu S, Zhang X L, Wang J Z, Xu Y F. Parameter optimization of vertical screw mixing for tomato straw and fermentation strains. *Transactions of the CSAM*, 2016; 47(11): 114–120. (in Chinese)
- [24] Guo Q, Zhang X L, Xu Y F, Li P P, Chen C, Xie H. Simulation and experimental study on cutting performance of tomato cane straw based on EDEM. *Journal of Drainage and Irrigation Machinery Engineering*, 2018; 36(10): 1017–1022.
- [25] Liao Y T, Liao Q X, Zhou Y, Wang Z T, Jiang Y J, Liang F. Parameters calibration of discrete element model of fodder rape crop harvest in bolting stage. *Transactions of the CSAM*, 2020; 51(6): 73–82. (in Chinese)
- [26] Jiang D L, Chen X G, Yan L M, Mo Y S, Yang S M. Design and experiment on spiral impurity cleaning device for profile modeling residual plastic film collector. *Transactions of the CSAM*, 2019; 50(4): 137–145. (in Chinese)
- [27] Huo L L, Meng H B, Tian Y S, Zhao L X, Hou S L. Experimental study on physical property of smashed crop straw. *Transactions of the CSAE*, 2012; 28(11): 189–195. (in Chinese)
- [28] Tian Y S, Yao Z L, Ouyang S P, Zhao L X, Meng H B, Hou S L. Physical and chemical characterization of biomass crushed straw. *Transactions of the CSAM*, 2011; 42(9): 124–128, 145. (in Chinese)
- [29] Lu F Y, Ma X, Tan S Y, Chen L T, Zeng L C, An P. Simulative calibration and experiment on main contact parameters of discrete elements for rice bud seeds. *Transactions of the CSAM*, 2018; 49(2): 93–99. (in Chinese)
- [30] Hirai Y, Inoue E, Mori K, Hashiguchi K. Investigation of mechanical interaction between a combine harvester reel and crop stalks. *Biosystems Engineering*, 2002; 83(3): 307–317.
- [31] Peng F, Wang H Y, Fang F, Liu Y D. Calibration of discrete element model parameters for pellet feed based on injected section method. *Transactions of the CSAM*, 2018; 49(4): 140–147. (in Chinese)
- [32] Liu C L, Wei D, Song J N, Li Y N, Du X, Zhang F Y. Systematic study on boundary parameters of discrete element simulation of granular fertilizer. *Transactions of the CSAM*, 2018; 49(9): 82–89. (in Chinese)
- [33] Han Y L, Jia F G, Tang Y R, Yang L, Qiang Z. Influence of granular coefficient of rolling friction on accumulation characteristics. *Acta Physica Sinica*, 2014; 63(17): 533–538.
- [34] Shi L R, Zhao W Y, Sun B G, Sun W. Determination of the coefficient of rolling friction of irregularly shaped maize particles by using discrete element method. *Int J Agric & Biol Eng*, 2020; 13(2): 15–25.