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Establishment and Parameter Calibration of a Simulation Model of Coated Cotton Seeds and Soil

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Abstract: Precision seeding technology is an important component of agricultural mechanization production. The precise regulation of seed movement behavior is the core of precision sowing technology and the key to improving the quality of single seed precision sowing. To accurately obtain the interaction law between seeds and soil after touching the soil, it is necessary to conduct comprehensive physical experiments to determine the simulation parameters of the seed and soil. This article takes coated cotton seeds as the research object, and the basic physical parameters of coated cotton seeds are measured through biological experiments. Based on the Hertz–Mindlin with bonding V2 contact model, a simulation model of compression between coated cotton seeds and soil is established. Using peak compression force as the response value, a combination of physical experiments and simulation simulations was used to calibrate the simulation parameters of the simulation mode of coated cotton seeds and soil. Through PB testing, it was found that four factors have a significant impact on the peak compressive force, and the parameter range was obtained. The Poisson's ratio of coated cotton seeds was 0.14–0.26. The static friction coefficient between coated cotton seeds and steel plate was 0.38–0.58. The static friction coefficient between soil and soil was 0.3–1.2. The rolling friction coefficient between soil and soil was 0.1–0.6. Through response surface experiments with four factors and three levels, regression models were established between various factors and response values, and the optimal combination of simulation parameters was determined: the Poisson's ratio of coated cotton seeds was 0.21; the static friction coefficient between coated cotton seed and steel plate was 0.47; the static friction coefficient between soil and soil was 0.34; and the rolling friction coefficient between soil and soil was 0.59. Based on the optimal parameter combination, the simulation of compression between coated cotton seeds and soil was continued, and the variation law of soil particle bonding bonds at different positions of coated cotton seeds during the compression process was obtained. This study provides a basis for exploring the interaction mechanism between the trencher seed soil of precision seeders and optimizing the design of critical components of cotton precision seeders.

Keywords: coated cotton seeds; Hertz–Mindlin with bonding V2; peak compression force; discrete element method; response surface experiment; simulation parameters

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1. Introduction

As a high-quality raw material in the textile industry, cotton has high economic benefits. It not only plays an irreplaceable role in the development of China's agriculture and the promotion of national economic development but also dramatically helps to adjust the agricultural industry structure and improve the economic income of farmers [1,2]. Cotton sowing is a crucial process as it directly affects the yield and quality of cotton [3,4]. In the process of field sowing, the environment is complex, and there are many parameters of the

sowing device, which also has many objective functions that meet the work requirements. The functional relationship between parameters and various objectives is also complex, and the interaction is vital. The optimization of critical components of a single sowing mechanism makes it difficult to meet the requirements of sowing quality. There is still a certain distance between the accuracy control in the actual sowing process, and the theoretical one, and one important reason is the particle spacing error caused by the bouncing and rolling of the seeds in the ditch after leaving the seeder and falling into the seed ditch [5,6].

Currently, improving the performance of seeders, profiling mechanisms, trenchers, and soil covering and compaction mechanisms, as well as reducing the seeding height and zero speed seeding, are the goals pursued in designing precision seeding machinery. Multiple achievements have been made in research in this area domestically and internationally. Molin et al. [7], Yazgi et al. [8], Ahmad et al. [9], and other researchers studied soybean and corn seeds and analyzed the influence of working parameters of suction seeding devices on seeding performance; Zhao et al. [10] designed an air absorption sunflower seed seeding device based on structure assisted stable suction posture to improve the stability of seed adsorption. Li et al. [11] designed a wheeled variable seeding device with an inverted fin-shaped model hole structure based on the principle of variable seeding mechanism. Numerical simulation analysis was conducted on four standard model holes to verify the structural reliability of various model holes and main components of the seeding device. Based on the theory of fluid mechanics, the force model of each stage in the seed discharge process was constructed, and the key factors affecting the motion state of cotton seeds in the seed discharge process were obtained [12]. Hu et al. [13] proposed a magnetic suction plate precision seeding technology. They analyzed its performance using particle discrete element EDEM to determine the main factors and parameter range that affect seeding performance. Zhao et al. [14] designed a V-shaped groove puller-type seed guide component, established a discrete element model between the seed guide component and corn grains, and analyzed the influence of various parameters on the seed guide performance; Ma et al. [15] studied the bouncing process of seeds after falling into seed trenches, as well as the grain spacing of seeds in the field and the field plant spacing after emergence. Based on the discrete element method, the precision planter furrow opener was investigated on the displacement of seeds after touching the soil, and the effects of stiffness coefficients and damping coefficients, which are important parameters for computer simulation, on the displacement of soybean seeds after touching the soil were obtained [16]. Xia et al. [17] designed a horizontal rotating precision seeding device, conducted a kinematic analysis of the seeding process, determined the main influencing factors of seeding performance evaluation indicators, and conducted bench tests to verify. The bouncing and rolling of seeds after touching the soil are the main reasons that affect the spatial position of seeds after sowing. Due to the bouncing and rolling of seeds after touching the soil, even if the seeder discharges a very uniform seed flow during sowing, the depth of the furrow can be accurately controlled, and the seeds can be delivered to the bottom of the furrow [18,19]. However, the ideal plant spacing and sowing depth cannot be achieved. Only by effectively controlling the bouncing and rolling of seeds after touching the soil can the perfect plant spacing and sowing depth be achieved; only by fully utilizing the excellent performance of various components of precision sowing machinery can the seeds achieve the ideal plant spacing. There is relatively little research on the interaction laws between seeds and soil.

Therefore, this article takes coated cotton seeds as the research object and uses biological experiments to measure its basic parameters. We establish a discrete element model of coated cotton seeds and soil based on the Hertz–Mindlin with bonding V2 contact model. Using peak compression force as the response value, a combination of physical experiments and simulation simulations was used to calibrate and calibrate the simulation parameters of coated cotton seeds. Based on the optimal parameter combination, this study explores the changes in soil particle bonding bonds of coated cotton seeds at different positions

during the compression process to provide a reference for further studying the interaction mechanism between the trencher seed soil and precision seeders.

2. Materials and Methods

2.1. Determination of Intrinsic Parameters of Coated Cotton Seeds

2.1.1. Determination of Basic Parameters

Taking coated cotton seeds is the research object. The variety is Shikang 126. Measure its three-axis dimensions with a vernier caliper (accuracy of 0.02 mm). The weight of a thousand grains was measured using an electronic balance. Measure the volume of one hundred coated cotton seeds using the drainage method. Measure its moisture content using the drying method. Each experiment is repeated 50 times, and the average value is taken as the final value. The experimental results are shown in Table 1.

Table 1. Basic parameter determination of coated cotton seeds.

Physical Parameters	Value
Three axis dimensions (length L × Wide B × Thickness W)/mm	8.85 × 4.90 × 4.22
Mass/g	93.9
Density/(kg/m^3)	8.69 × 10^2
Moisture content/%	10.8

2.1.2. Determination of Friction Coefficient

Measure the friction coefficient between coated cotton seeds and coated cotton seeds (soil) using a CNY-1 inclined plane instrument (Chenchi Instrument Company Ltd., Jinan, China) [20,21]. When measuring the static friction coefficient between coated and coated cotton seeds, the coated cotton seeds are bonded to form a coated cotton seeds board (Figure 1a) and connected to the test plane. The inclined plane meter is rotated until the coated cotton seeds are observed to slide, and the angle on the digital inclinometer is recorded (Figure 1b). The static friction coefficient between the coated cotton seeds is calculated using Formula 1. When the coated cotton seeds begins to roll, stop rotating and record the angle on the digital inclinometer. Use Formula (2) to calculate the rolling friction coefficient between the coated cotton seeds. Each experiment is repeated 10 times, and the average value is taken as the final value. According to Equation (1), the static friction coefficient between coated cotton seeds is 0.66, and the static friction coefficient between coated cotton seeds and soil is 0.77. According to Formula (2), the rolling friction coefficient between coated cotton seeds is 0.33, and the rolling friction coefficient between coated cotton seeds and soil is 0.32.

$$\mu_1 = \tan \alpha_1 \quad (1)$$

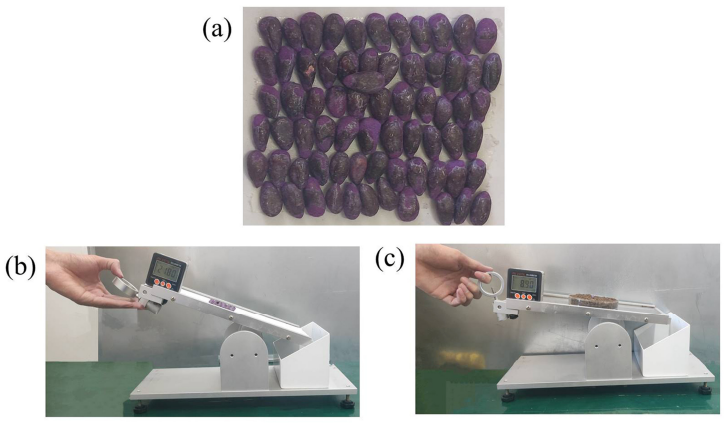


Figure 1. Test for measuring the friction coefficient of coated cotton seeds. (**a**) Coated cotton seed board; (**b**) the static friction coefficient between coated cotton seeds; (**c**) the static friction coefficient between coated cotton seeds and soil.

In the formula, μ_1 is the static friction coefficient; α_1 is the critical angle for the static friction coefficient, °.

$$\mu_2 = \tan \alpha_2 \tag{2}$$

In the formula: μ_2 is the static friction coefficient; α_2 is the critical angle for the static friction coefficient, °.

2.2. Compression Test between Coated Cotton Seeds and Soil

This article uses the TMS-PRO texture analyzer (Food Technology Corporation Ltd., Sterling, VA, USA) to conduct compression tests on coated cotton seeds and soil [22], as shown in Figure 2. It obtains the maximum pressure of the cylindrical probe on coated cotton seeds. The experimental soil is sourced from Xujiazhuang Village, Beijiao Town, Zibo City, Shandong Province. Using a ring knife to sample soil at a 0–100 mm depth, the density was obtained as 1.38×10^3 kg/m^3 through 10 measurements. The moisture content measured is 12.47% using the drying method. Firstly, place the coated cotton seeds horizontally on the soil surface and set the loading speed and deformation of the cylindrical probe to 20 mm/min and 10%, respectively, with a triggering force of 1 N. The experiment was repeated 10 times, and the average value was taken as the final value, resulting in a peak compressive force (P_{max}) of 65.46 N between cotton seeds and soil.

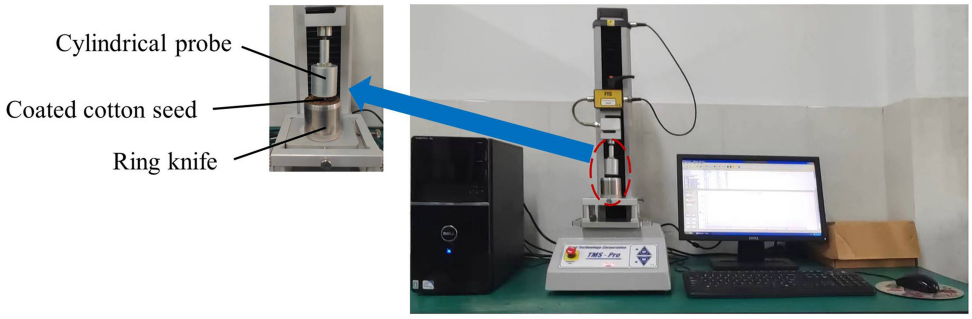


Figure 2. Compression test of coated cotton seeds and soil.

2.3. Determination of Contact Model

The Hertz–Mindlin with Bonding V2 contact model is an improved version of the original bonding model by EDEM, and combined with the function of elemental particles, it can rapidly create composite particles with different particle sizes. The spherical units of field soil are constructed using Bond bonds to bond with each other, and the bonding points can withstand tangential and normal displacements from the outside. The bonding fracture must meet the maximum regular and tangential shear stresses, and the calculation process is compatible with the GPU acceleration function. It has excellent development potential in agricultural material research [23,24]. When using this model to create particles, the interaction between particles is calculated using the Hertz–Mindlin (no slip) contact model before the specified bonding time. After reaching the specified bonding time, the particles will be bonded together through parallel bonding bonds, and the interparticle forces and moments are set to 0 and gradually updated:

$$\begin{cases} \delta F_n = -v_n k_n A \delta_t \\ \delta F_t = -v_t k_t A \delta_t \\ \delta M_n = -\omega_n k_t J \delta_t \\ \delta M_t = -\omega_t k_n \frac{I}{2} \delta_t \end{cases} \tag{3}$$

Among them,

$$\begin{cases} A = \pi R^2 \\ J = \frac{1}{2} \pi R^4 \\ R = rs \end{cases} \tag{4}$$

In the formula, A is the cross-sectional area of the bonding bond, mm^2; F_t is the normal bonding force, N; M_n is the tangential bonding force, N; M_t is the normal bonding moment, N·m; k_n is the tangential bonding stiffness, N·m; k_t is the normal bonding stiffness, N/m^3; v_n is the tangential bonding stiffness, N/m^3; v_t is the normal relative velocity of particles, m/s; ω_n is the tangential relative velocity, m/s; ω_t is the normal relative velocity of particles, rad/s; δ_t is the tangential relative velocity of particles, rad/s; J is the time step size, s; R is the polar moment of inertia of the bonding key cross-section, mm^4; Cross section radius of bonding key, mm; r is the smallest particle radius in the bonding pair, mm; s is the bonding radius ratio.

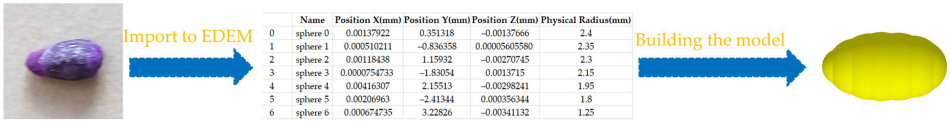
When the maximum normal stress between particles,

$$\begin{cases} \sigma_{\text{critical}} \leq \sigma_{\max} = \frac{-F_n}{A} + \frac{2M_t}{J}R \\ \tau_{\text{critical}} \leq \tau_{\max} = \frac{-F_t}{A} + \frac{M_n}{J}R \end{cases} \quad (5)$$

2.4. Establishment of a Compression Model between Coated Cotton Seeds and Soil

2.4.1. Establishment of the Discrete Element Model

Establish a geometric model of coated cotton seeds particles using 3D modeling software, then convert the seed model into * step format and import it into discrete element simulation software. In the simulation process, the higher the degree of particle reduction, the more basic spherical particle units are required for modeling and the lower the efficiency. However, the number of filled balls is too small during modeling. In that case, it will increase the model's error, resulting in a significant error in the setting of inter-species contact parameters during simulation analysis. Therefore, this article uses multiple overlapping spheres to establish a discrete element simulation model for coated cotton seeds, with six single spherical particles filled, as shown in Figure 3.



	Name	Position X(mm)	Position Y(mm)	Position Z(mm)	Physical Radius(mm)
0	sphere 0	0.00137922	0.351318	−0.00137666	2.4
1	sphere 1	0.000510211	−0.836358	0.00005605580	2.35
2	sphere 2	0.00118438	1.15932	−0.00270745	2.3
3	sphere 3	0.0000754733	−1.83054	0.0013715	2.15
4	sphere 4	0.00416307	2.15513	−0.00298241	1.95
5	sphere 5	0.00206963	−2.41344	0.000356344	1.8
6	sphere 6	0.000674735	3.22826	−0.00341132	1.25

Geometrical the model Particle coordinates Simulation the model

Figure 3. Establishment of simulation model for coated cotton seeds.

2.4.2. Establishment of Soil Particle Simulation Model

Currently, many scholars have conducted discrete element simulation research on cultivation, and the soil particle size is generally more significant than the actual size of the soil. Considering the simulation's accuracy and the computer's computational power, this article adopts a bimodal distribution with particle size following a normal distribution. Large particles occupy the central spatial position, while small particles are tightly arranged around the large particles. The particles have a high coordination number, which improves the filling density of the particle group and reduces the porosity. This can make the overall mechanical properties of the particle group close to the actual soil mechanical properties [25,26]. Figure 4 shows the discrete element model of soil particles with added bonding bonds. The model is 50 mm high, with a bottom diameter of 50 mm, and consists of 16,000 particles of non-uniform size. A single spherical particle cannot be destroyed in a computer simulation, and external forces can separate particles.

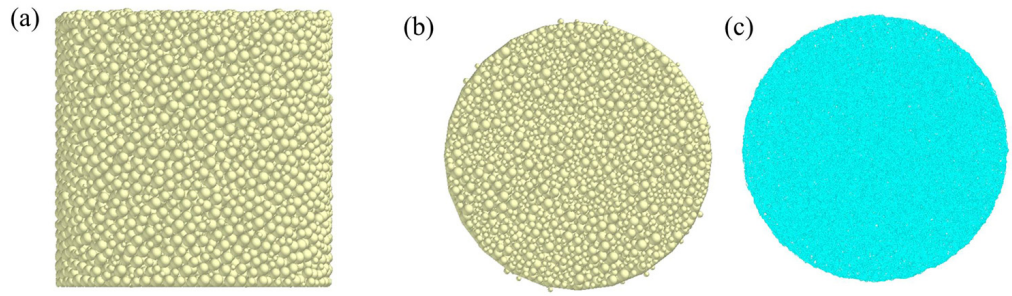


Figure 4. Soil simulation model. (**a**) Main view; (**b**) top view; (**c**) bonding bond.

The contact model between soil particles in this article adopts Hertz–Mindlin with bonding V2, which is determined by five parameters: unit area standard stiffness, unit area tangential stiffness, critical everyday stress, critical tangential stress, and bonding radius ratio to determine the final strength of the bonding bond. To simplify simulation operations, it is assumed that the standard stiffness per unit area of soil particles equals the tangential stiffness per unit area, the critical everyday stress equals the acute tangential stress, and the bonding radius ratio is 1.2–2 times. The initial range was obtained by simulating a large number of coated cotton seeds and soil, laying the foundation for subsequent simulation experiments.

2.4.3. Establishment of a Compression Model for Coated Cotton Seeds and Soil

In the discrete element simulation experiment, Hertz–Mindlin (no slip) was selected as the contact model between coated cotton seeds, steel plates, and soil, while Hertz–Mindlin with bonding V2 was used as the contact model between soil particles. The compression simulation model between coated cotton seeds and soil is shown in Figure 5. Firstly, a cylinder virtual particle plane was added to the ring cutter, and the particles are generated dynamically at a rate of 20,000/s for developing soil particle models. Then, a polygon virtual particle plane was established above the cylindrical probe and the ring cutter to generate a coated cotton seeds particle. When the coated cotton seeds particle was placed horizontally on the surface of the soil particle, the cylindrical probe was set to move vertically downwards at a loading speed of 20 mm/min. the Rayleigh time step was set to 25%. The grid size was set to 3R min, and the data storage interval was 0.01 s. After each set of simulation experiments is completed, the peak compression force between coated cotton seeds and soil was obtained in the post-processing software of the discrete element.

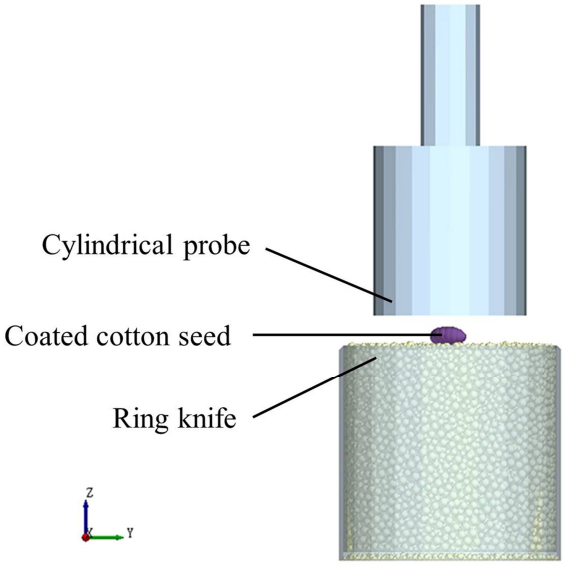


Figure 5. Establishment of a compression simulation model for coated cotton seeds and soil.

2.5. Calibration of Simulation Parameters for the Interaction Model between Coated Cotton Seeds and Soil

For the calibration of discrete element simulation parameters for the interaction model between coated cotton seeds and soil, a Plackett–Burman experiment was used to screen the significance of the simulation parameters. Using the peak compressive force (P_{max}) of coated cotton seeds and soil as the response value in simulation experiments, a quadratic regression model was established between the significant parameters obtained from Box–Behnken Design experiments and the response values. Response surface analysis was performed on the experimental results to determine the optimal parameter combination.

2.5.1. Plackett–Burman Test

The friction coefficients between coated cotton seeds and coated cotton seeds and between coated cotton seeds and soil were measured using a slope meter. Other simulation parameters were consulted in the relevant literature [27–34]. The peak compressive force (P_{max}) between coated cotton seeds and soil obtained from physical experiments was used as the response value, and the parameters significantly impacting the response value were selected through the Plackett–Burman experiment. Encode the minimum and maximum values of the experimental parameters in Table 2 as −1 and +1, respectively. The encoded value of −1 represents the low level of the parameter, and +1 represents the high level of the parameter. Each experiment was repeated 3 times, and the average value is taken as the final value.

Table 2. Plackett–Burman parameter table.

No.	Test Parameters	Code		
		Low (−1)	**Middle (0)**	**Hight (+1)**
X_1	Poisson's ratio of coated cotton seeds	0.14	0.2	0.26
X_2	The shear modulus of coated cotton seeds/MPa	4	9	14
X_3	Recovery coefficient between coated cotton seeds	0.18	0.27	0.36
X_4	Recovery coefficient of coated cotton seeds and soil	0.2	0.3	0.4
X_5	Recovery coefficient of coated cotton seeds and steel plate	0.38	0.45	0.52
X_6	Recovery coefficient of steel plate and soil	0.4	0.5	0.6
X_7	Soil and soil recovery coefficient	0.2	0.4	0.6
X_8	Static friction coefficient between coated cotton seeds and steel plate	0.38	0.48	0.58
X_9	Static friction coefficient between steel plate and soil	0.4	0.8	1.2
X_{10}	Static friction coefficient between soil and soil	0.3	0.75	1.2
X_{11}	Rolling friction coefficient between coated cotton seeds and steel plate	0.08	0.1	0.12
X_{12}	Rolling friction coefficient between steel plate and soil	0.1	0.2	0.3
X_{13}	Rolling friction coefficient between soil and soil	0.1	0.35	0.6
X_{14}	Normal stiffness per unit area/(N/m^3)	4×10^7	7×10^7	10×10^7
X_{15}	Tangential stiffness per unit area/(N/m^3)	4×10^7	7×10^7	10×10^7
X_{16}	Critical normal stress/KPa	1×10^5	5×10^5	9×10^5
X_{17}	Critical tangential stress/KPa	1×10^5	5×10^5	9×10^5
X_{18}	Bond radius ratio	1.2	1.6	2

2.5.2. Box–Behnken Design Experiment

A Box–Behnken Design experiment was conducted to determine the simulation parameters for the interaction between coated cotton seeds and soil, with the range of significant influence parameters as the level and the peak compressive force (P_{max}) of the simulated coated cotton seeds and soil as the response value. The horizontal coding of coated cotton seeds is shown in Table 3. Each experiment was repeated 3 times, and the average value is taken as the final value.

Table 3. Parameter level coding table.

Levels	Parameters			
	X_1	X_8	X_{10}	X_{13}
−1	0.14	0.38	0.3	0.1
0	0.2	0.48	0.75	0.35
+1	0.26	0.58	1.2	0.6

2.5.3. Simulation Experiment on Compression between Coated Cotton Seeds and Soil

Based on the optimal parameter combination, establish an interaction model between coated cotton seeds and soil, simulate the compression of coated cotton seeds and soil, and explore the changes in soil particle bonding bonds of coated cotton seeds at different positions during the compression process.

3. Results and Analysis

3.1. Analysis of Plackett–Burman Test Results

Due to the multiple influencing factors in the compression test between coated cotton seeds and soil, a Plackett–Burman test was needed to determine the significance of each factor on the stacking angle test. Using the peak compression force between coated cotton seeds and soil as the response value, the contact parameters between coated cotton seeds and soil were screened. Each parameter was set at three levels of high (1) and low (−1), with 12 experiments. Each experiment was repeated three times, and the average value was taken. The experimental plan and results are shown in Table 4. The significance analysis of Plackett–Burman test results is shown in Table 5. Through significance screening, it was found that four factors, X_1, X_8, X_{10}, and X_{13}, significantly impact the peak compression force of cotton seeds and soil. Therefore, further analysis is needed to investigate the impact of X_1, X_8, X_{10}, and X_{13} on the peak compression force.

Table 4. Plackett–Burman trial protocol and results.

No.	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}	X_{16}	X_{17}	X_{18}	P_{max}/N
1	−1	1	−1	1	−1	−1	−1	−1	1	1	−1	1	1	−1	−1	1	1	1	180.9
2	1	1	−1	1	−1	1	−1	−1	−1	−1	1	1	−1	1	1	−1	−1	1	86.27
3	−1	−1	1	1	−1	1	1	−1	−1	1	1	1	1	−1	1	−1	1	−1	142.3
4	1	−1	1	1	−1	−1	1	1	1	1	−1	1	−1	1	−1	−1	−1	−1	124.8
5	−1	1	1	1	1	−1	1	−1	1	−1	−1	−1	−1	1	1	−1	1	1	61.7
6	−1	−1	−1	1	1	−1	1	1	−1	−1	1	1	1	1	−1	1	−1	1	72.2
7	1	−1	−1	−1	−1	1	1	−1	1	1	−1	−1	1	1	1	1	−1	1	177.7
8	−1	1	1	−1	−1	1	1	1	1	−1	1	−1	1	−1	−1	−1	−1	1	81.6
9	−1	−1	1	1	1	1	−1	1	−1	1	−1	−1	−1	−1	1	1	−1	1	106.6
10	1	1	−1	1	1	−1	−1	1	1	1	1	−1	1	−1	1	−1	−1	−1	161
11	1	1	1	−1	1	−1	1	−1	−1	−1	−1	1	1	−1	1	1	−1	−1	88.5
12	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	76.35
13	−1	−1	−1	−1	1	1	−1	1	1	−1	−1	1	1	1	1	−1	1	−1	68.3
14	1	1	1	1	−1	1	−1	1	−1	−1	−1	−1	1	1	−1	1	1	−1	78.66
15	1	1	−1	−1	1	1	1	1	−1	1	−1	1	−1	−1	−1	−1	1	1	102.5
16	−1	1	−1	−1	−1	−1	1	1	−1	1	1	−1	−1	1	1	1	1	−1	82
17	1	−1	−1	1	1	1	1	−1	1	−1	1	−1	−1	−1	−1	1	1	−1	82.5
18	1	−1	1	−1	1	−1	−1	−1	−1	1	1	−1	1	1	−1	−1	1	1	161.2
19	−1	1	1	−1	1	1	−1	−1	1	1	1	1	−1	1	−1	1	−1	−1	106.6
20	1	−1	1	−1	−1	−1	−1	1	1	−1	1	1	−1	−1	1	1	1	1	69.7

Table 5. Significance analysis of Plackett–Burman test parameters.

Parameters	Effect	Mean Square Sum	Influence Ratio
X_1	15.43	1190.12	4.19
X_2	−5.19	134.78	0.47
X_3	−6.81	231.61	0.82
X_4	8.25	340.15	1.20
X_5	−8.92	397.65	1.40
X_6	−4.53	102.70	0.36
X_7	−7.98	318.24	1.12
X_8	−21.67	2347.08	8.27
X_9	11.82	698.80	2.46
X_{10}	57.98	16,809.56	59.20
X_{11}	−2.06	21.30	0.08
X_{12}	−2.72	37.10	0.13
X_{13}	31.33	4909.10	17.29
X_{14}	−7.25	262.96	0.93
X_{15}	−2.32	27.00	0.10
X_{16}	−2.07	21.34	0.08
X_{17}	−5.19	134.47	0.47
X_{18}	8.94	399.26	1.41

3.2. Analysis of Box–Behnken Test Results

3.2.1. Establishment and Variance Analysis of Peak Compression Force Simulation Parameter Regression Model

A four-factor three-level orthogonal experiment was conducted with X_1, X_8, X_{10}, and X_{13} as experimental factors and peak compression force as response values. The number of experiments was 29. Each experiment was repeated multiple times, and the average value is taken as the final value. As shown in Table 6, multiple regression fitting analysis was performed on the peak compression force, and a quadratic polynomial regression model was established for X_1, X_8, X_{10}, and X_{13} concerning the peak compression force, as shown in Formula (6):

$$P_{max} = 128.94 + 3.92X_1 + 6.89X_8 + 62.51X_{10} + 3.5X_{13} - 6.6X_1X_8 - 2.1X_1X_{10} - 11.35X_1X_{13} + 2.4X_8X_{10} - 13.57X_8X_{13} - 1.03X_{10}X_{13} - 4.25X_1^2 - 6.44X_8^2 + 3.06X_{10}^2 - 13.08X_{13}^2 \quad (6)$$

Table 6. Design scheme and results of peak compression force test.

No.	Factors				P_{max}/N
	X_1	X_8	X_{10}	X_{13}	
1	1	1	0	0	133.9
2	0	1	−1	0	64.1
3	1	−1	0	0	125
4	0	1	0	−1	121.1
5	0	−1	1	0	179.3
6	0	0	0	0	132.2
7	1	0	0	1	102.5
8	0	1	1	0	192.9
9	−1	0	0	1	136.1
10	0	0	−1	1	54
11	−1	−1	0	0	92.3
12	0	−1	−1	0	60.1
13	0	0	0	0	116.9
14	0	−1	0	−1	83.5
15	0	0	0	0	124.6
16	−1	0	1	0	186.3
17	0	0	−1	−1	63.5
18	0	1	0	1	108.2
19	1	0	−1	0	73.4

Table 6. *Cont.*

No.	Factors				P_{max}/N
	X_1	X_8	X_{10}	X_{13}	
20	−1	0	0	−1	95.1
21	0	0	1	1	175.2
22	0	−1	0	1	124.9
23	1	0	0	−1	106.9
24	0	0	0	0	140.4
25	1	0	1	0	197
26	0	0	0	0	130.6
27	0	0	1	−1	188.8
28	−1	1	0	0	127.6
29	−1	0	−1	0	54.3

In the formula: P_{max} is the peak compression force, N; X_1, X_8, X_{10}, X_{13} are the Poisson's ratio of cotton, static friction coefficient between coated cotton seeds and steel plate, static friction coefficient between soil and soil, and rolling friction coefficient between soil and soil.

Variance analysis was performed on the regression model of peak compression force, and the experimental results are shown in Table 7. The $p < 0.001$ of this regression model indicates that the relationship between various factors and response values is highly significant. The table shows that X_8, X_1X_{13}, and X_8X_{13} have a considerable impact, while X_{10} and X_{13}^2 are highly substantial. The loss of fit term $p = 0.3517$ indicates a good fit of the equation. The coefficient of determination $R^2 = 0.9709$ suggests that 97.09% of the experimental differences can be explained by this model, which has a high degree of fit with the actual data. The correction determination coefficient Adj-$R^2 = 0.9418$ for this equation is very close to R^2 and 1, indicating that the regression equation has high reliability and can be used for further analysis.

Table 7. Analysis of variance of peak compression force.

Source	Sum of Squares	Freedom	Mean Square	*F*	*p*
Model	50,765.62	14	3626.12	33.38	<0.0001 **
X_1	184.08	1	184.08	1.69	0.214
X_8	569.94	1	569.94	5.25	0.038 *
X_{10}	46,887.5	1	46,887.5	431.63	<0.0001 **
X_{13}	147	1	147	1.35	0.2642
X_1X_8	174.24	1	174.24	1.6	0.226
X_1X_{10}	17.64	1	17.64	0.16	0.6931
X_1X_{13}	515.29	1	515.29	4.74	0.047 *
X_8X_{10}	23.04	1	23.04	0.21	0.6522
X_8X_{13}	737.12	1	737.12	6.79	0.0208 *
$X_{10}X_{13}$	4.2	1	4.2	0.039	0.8469
X_1^2	117.35	1	117.35	1.08	0.3163
X_8^2	269.09	1	269.09	2.48	0.1378
X_{10}^2	60.7	1	60.7	0.56	0.4671
X_{13}^2	1109.47	1	1109.47	10.21	0.0065 **
Residual	1520.8	14	108.63		
Misfit term	1212.29	10	121.23	1.57	0.3517
Error	308.51	4	77.13		
Sum	52,286.42	28			

Note: * indicates significant ($p < 0.05$), ** indicates extremely significant ($p < 0.01$).

3.2.2. Parameter Optimization and Validation

Within the given experimental factor level range, the regression model of peak compression force (P_{max}) between coated cotton seeds and soil measured by physical exper-

iments is optimized with the goal of 65.46 N. Through software calculation, it can be obtained that the Poisson's ratio of coated cotton seeds is 0.21; the static friction coefficient between coated cotton seeds and steel plate is 0.47; the static friction coefficient between soil and soil is 0.34; and the rolling friction coefficient between soil and soil is 0.59. Continuing the compression test between coated cotton seeds and soil using EDEM software, the peak compression force was measured to be 67.6 N, with a relative error of 3.27%. The experimental error is within the actual range.

3.3. Simulation Experiment on Compression between Coated Cotton Seeds and Soil

Establish an interaction model between coated cotton seeds and soil based on the optimal parameter combination, and conduct simulation experiments on the compression between coated cotton seeds and soil. The distribution of bonding bonds and their force distribution during the compression process are shown in Figure 6, with colors of blue, green, and red, indicating a sequential increase in bonding bond strength. Figure 6a shows the bonding bonds in the initial state, where the bonding bonds between particles are subjected to relatively small forces and uniformly distributed throughout. Figure 6b shows the vertical downward movement of the cylindrical probe, where the coated cotton seeds come into contact with the soil, and the bonding bonds at the contact interface are subjected to greater force. As the coated cotton seeds gradually immerse themselves in the soil, the bonding forces at the contact interface also gradually increase, as shown in Figure 6c.

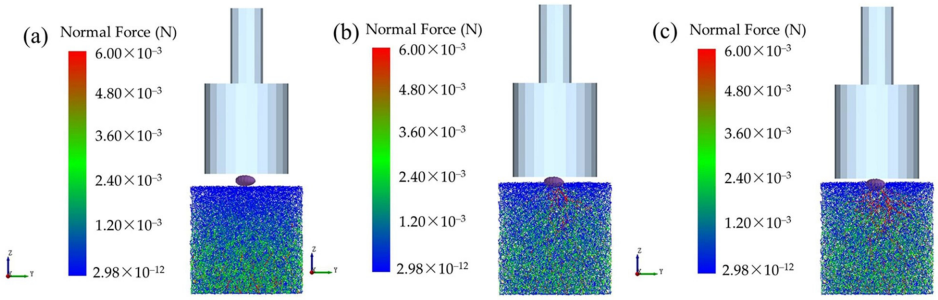


Figure 6. The bonding bond and its stress cloud map during the compression process. (**a**) Initial state bonding bond; (**b**) bond key at the beginning of compression; (**c**) bond after soil penetration.

4. Discussion

The bouncing and rolling of seeds after touching the soil are the main reasons that affect the spatial position of seeds after sowing. Due to the bouncing and rolling of seeds after touching the soil, even if the seeder discharges a very uniform seed flow during sowing, the depth of the furrow can be accurately controlled, and the seeds can be delivered to the bottom of the furrow. However, the ideal plant spacing and sowing depth cannot be achieved. Only by effectively controlling the bouncing and rolling of seeds after touching the soil can the perfect plant spacing and sowing depth be achieved; only by fully utilizing the excellent performance of various components of precision sowing machinery can the seeds achieve the ideal plant spacing. There is relatively little research on the interaction laws between seeds and soil. To accurately obtain the interaction law between seeds and soil after touching the soil, it is necessary to conduct comprehensive physical experiments to determine the simulation parameters of coated cottonseed and soil and calibrate the simulation parameters of coated cottonseed and soil based on the physical experiment measurement parameters. Some scholars have conducted the stacking angle test on a mixture of the mazie seed and soil, established a simulation model between the mazie seed and soil, and calibrated its simulation parameters [35].

In the actual sowing process, the seeds collide with the soil, and the soil is squeezed, which causes the seed bouncing and rolling. In this paper, using peak compression force as the response value, a combination of physical experiments and simulation simulations was used to calibrate the simulation parameters of the simulation mode of coated cotton seeds and soil. Through PB testing, it was found that four factors have a significant impact on

the peak compressive force, and the parameter range was obtained. The Poisson's ratio of coated cotton seeds was 0.14–0.26. The static friction coefficient between coated cotton seeds and steel plate was 0.38–0.58. The static friction coefficient between soil and soil was 0.3–1.2. The rolling friction coefficient between soil and soil was 0.1–0.6. Through response surface experiments with four factors and three levels, regression models were established between various factors and response values, and the optimal combination of simulation parameters was determined: the Poisson's ratio of coated cotton seeds was 0.21; the static friction coefficient between coated cotton seed and steel plate was 0.47; the static friction coefficient between soil and soil was 0.34; and the rolling friction coefficient between soil and soil was 0.59. Based on the optimal parameter combination, the simulation of compression between coated cotton seeds and soil was continued, and the variation law of soil particle bonding bonds at different positions of coated cotton seeds during the compression process was obtained.

Next, this simulation parameter will be used to further study the displacement changes of cotton seeds in the X, Y, and Z directions after touching the soil. This study provides a basis for optimizing the design of key components of cotton precision seeders.

5. Conclusions

(1) The basic physical parameters of coated cottonseed were measured through biological experiments, and a simulation model of compression between coated cotton seeds and soil was established based on the Hertz–Mindlin with bonding V2 contact model.

(2) Through PB testing, it was found that four factors have a significant impact on the peak compressive force, and the parameter range was obtained. The Poisson's ratio of coated cotton seeds was 0.14–0.26. The static friction coefficient between coated cotton seeds and steel plate was 0.38–0.58. The static friction coefficient between soil and soil was 0.3–1.2. The rolling friction coefficient between soil and soil was 0.1–0.6.

(3) Using peak compression force as the response value, a regression model was established between each factor and the response value through a four factor and three level response surface experiment, and the optimal combination of simulation parameters was determined: the Poisson's ratio of coated cotton seeds was 0.21; the static friction coefficient between coated cotton seeds and steel plate was 0.47; the static friction coefficient between soil and soil was 0.34; and the rolling friction coefficient between soil and soil was 0.59. Based on the optimal parameter combination, the simulation of compression between coated cotton seeds and soil was continued, and the variation law of soil particle bonding bonds at different positions of coated cotton seeds during the compression process was obtained.

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