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Validation and Calibration of Maize Seed–Soil Inter-Parameters Based on the Discrete Element Method

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Abstract: An appropriate contact mechanics model and parameters are key to achieving accurate results in discrete element analyzis. This is necessary to predict the process of contact collision between the soil and maize seed during deposition. In this paper, the contact process between maize seed and soil is analyzed using the maize seed variety (Liangyu 99) and maize-sowing field soil (with three different moisture contents) as research objects. Based on this, the contact process between maize seeds and soil has been analyzed, on the basis of which a mechanical model suitable for simulating the contact process between maize seeds and soil has been explored, and the selection of parameters between heterogeneous particles (maize seed and soil particles) has been investigated. The results showed that adhesion forces have a significant effect on the collision process between seed and soil particles. While the presence of tangential adhesion force can be replaced by increasing the static and rolling friction coefficients, the normal adhesion force cannot be compensated in this way. The Edinburgh Elasto-Plastic Adhesive (EEPA) model is selected in this paper to describe the contact between seed and soil particles. The significance of the input parameters in the EEPA model is investigated using the Plackett–Burman test. The parameters between soil and seed particles are optimized using the central composite design, and the optimal parameter combinations are obtained. The relative error between the simulation and test result of the slope test for the three soil moisture contents is within 5.4%, validating the accuracy of the calibrated parameters.

Keywords: discrete element method; maize seeds; heterogeneous particles; mechanical modelling; parameter calibration

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1. Introduction

During the process of sowing maize, the three stages of seeding, dropping, and bedding are all interrelated and affect the quality of sowing [1]. The bedding stage, which is the final stage in the seed-sowing process, plays an important role in ensuring that the seeds are placed into the soil in a uniformly and orderly way, ultimately affecting the uniformity of the final seed distribution in the field [2]. However, during the bedding stage, the maize seeds and soil are prone to bouncing and rolling, especially under high-speed operating conditions [2]. This bouncing and rolling seriously affects the quality of sowing and restricts further increases in the yield of maize per unit area. Therefore, there is a need for in-depth and systematic research on the mechanism of maize seed–soil contact and collision bouncing and its influencing factors under high-speed sowing operations. This research will enable improvements in the quality of sowing, which has important theoretical significance and practical application value. Most of the experimental methods used to study the contact collision process between seed particles and soil are time-consuming, labor-intensive, and restricted by time and season. It is also difficult to obtain information on the force between seed particles and soil, particle displacement, and particle velocity, which is essential for the design and optimization of the components of agricultural machinery. One solution to these problems is to use the Discrete Element Method (DEM) [3] to analyze and study the contact collision process between seed particles and soil. DEM has become a common method for analyzing granular materials and is widely used in agricultural engineering [4–6].

One of the keys to discrete element simulation is the selection of the contact mechanics model and its parameters. These are necessary to accurately predict the contact and collision process between maize seeds and soil when seeds are deposited on the soil bed [7,8]. Maize seed particles are non-sticky and dry, so the Hertz–Mindlin (no slip) model can be used to calculate the contact forces between them. However, this model suffers from the problem of multiple contacts when simulating multi-sphere or polyhedral particles [9,10]. In previous work, the author revealed the mechanism affecting multiple contacts and found that the new Hertz–Mindlin restitution model is more suitable for modelling the motion of non-sticky dry particles such as maize seeds [10,11]. The suitable moisture content of field soils for sowing operations is generally around 20%, so soil particles can be considered wet particles and bonding between soil particles needs to be taken into account. Therefore, an in-depth study of which contact mechanics model should be used to calculate the contact forces between seed particles and soil particles is important to make the calculated seed-bouncing and -rolling process consistent with the actual seed-bouncing and -rolling process during precision sowing.

Currently, there are three main methods for determining the parameters of particle mechanics of bulk materials: (1) treating the particle as a solid body and obtaining the mechanical parameters of individual particles through elastic–plastic theoretical analyzes and individual particle tests [12]; (2) obtaining mechanical parameters of the particles through contact mechanics analyzis and trial-and-error methods [13]; (3) using macro-mechanical tests, such as angle of repose, triaxial test, biaxial test, and straight shear test, to obtain the macro-mechanical parameters of the particle population [8,14]. Then, the relationship between the macro-parameters and the micro-particle parameters is established to obtain the mechanical parameters of the particle [15]. However, the above methods may suffer from the problem of there being multiple solutions for the parameters [16], and parameters obtained from a particular test (e.g., angle of repose, straight shear test) may not be applicable to other tests [17]. While scholars have studied the process of seed–soil contact, there has been limited research on the adhesion that occurs between seeds and soil [18,19]. Therefore, an in-depth study of how to solve the problem of multiple solutions and the poor applicability of parameters is necessary. Additionally, for parameter selection between heterogeneous particles, further research is needed to determine whether the existing parameter-selection methods are applicable between heterogeneous particles, such as soil particles and maize seed particles.

Based on the aforementioned issues, this paper focuses on Liangyu 99 maize seeds and maize sowing field soil as the research objects. It analyzes the contact process between maize seeds and soil, explores a mechanical model that can simulate the contact process between maize seeds and soil, and investigates the method of selecting parameters between heterogeneous particles. The model and parameter selection method established by this research are of scientific significance and reference value for analyzing the contact interaction between other heterogeneous particles and studying the working performance of earth-contacting components.

2. Materials and Methods

2.1. Testing of Contact Processes between Soil and Maize Seeds

For the contact between maize seed and soil, further research is needed to determine whether soil adhesion to the seed needs to be taken into account, and whether the presence of adhesion can be mitigated by using methods that increase the static or rolling coefficient of friction.

In this section, the adhesion of soil to maize seeds during vertical contact of maize seed particles with soil is investigated using a texture instrument (TA.XTC-18, BosinTech, shanghai, China), as shown in Figure 1. The adhesion force is then compared to the gravity of the seed particles. The mass of the seed particles used in the test is weighed using a balance with an accuracy of 0.01 g. Three seeds of similar size are selected and their dimensions are 8.22 mm wide, 12.21 mm high and 4.83 mm thick. If the adhesion force is close to or greater than the gravity of the seed particles, it can be concluded that the adhesion force of the soil to the seed particles will significantly affect the contact collision between the seed particles and the soil.

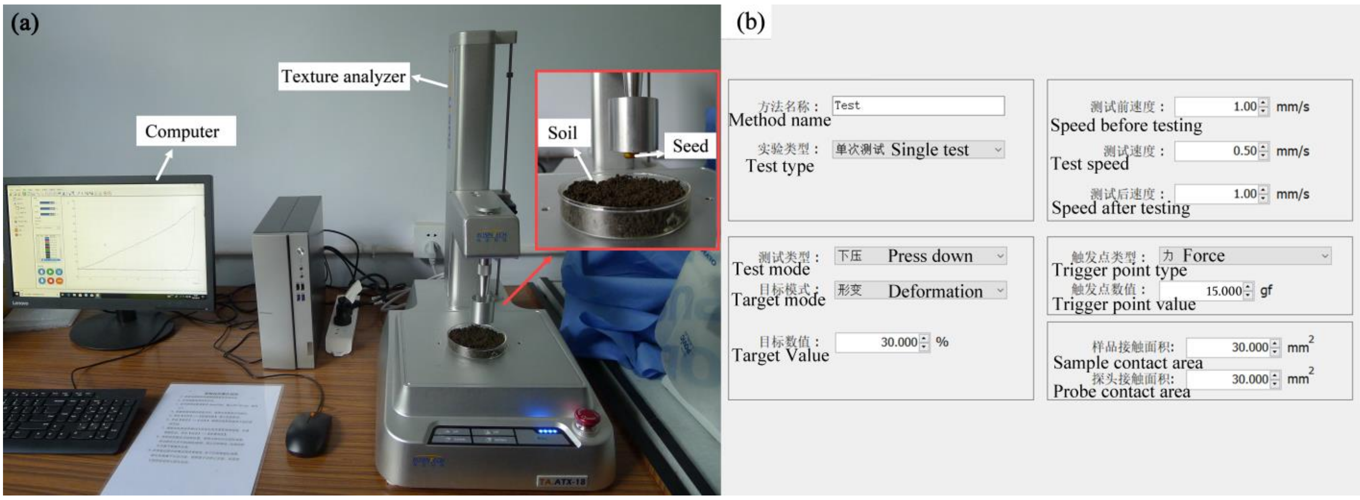

Figure 1. TA.XTC-18 texture instrument and parameter settings: (**a**) sketch of the device, (**b**) parameter settings.

The test procedure is as follows: First, the seeds are fixed onto the probe of the texture instrument so that the flat side of the seeds is in contact with the soil, and the probe of the texture instrument is adjusted to the appropriate height. Then, the probe of the texture instrument is moved downward at a speed of 1 mm/s until the probe compress the soil by 30% of its deformation, and the probe is moved upward. Finally, the curves of force versus displacement and the data are obtained. Three replicate tests are performed for each set of tests.

2.2. Calibration of Parameters between Maize Seed Particles and Soil Particles

The particle model of maize seeds is adopted from the seed model established in previous studies (shown in Figure 2) [10,11]. The mechanical modeling between maize seeds is adopted from the EEPA model, where the constant pull-off force (f_0) is 0, slope exponent is 1.5, tensile exponent is 0, surface energy is 0, contact plasticity ratio is 0, and tangential stiff multiplier is 1. The remaining parameters are adopted from the literature. The soil particle model is used as established in previous studies (shown in Figure 3) [20], and the mechanical modeling between soil particles is based on the EEPA model, with the parameters in the model using data from the literature. In this paper, simulations are performed using EDEM 2018 (4.0.0) software.

In this paper, the parameters between maize seed particles and soil particles are calibrated by means of angle of repose tests. Firstly, a sensitivity study is carried out on the contact parameters to be artificially input into the EEPA model using the Plackett–Burman test. Then, the sensitivity parameters are calibrated and optimized using the Central Composite Design test.

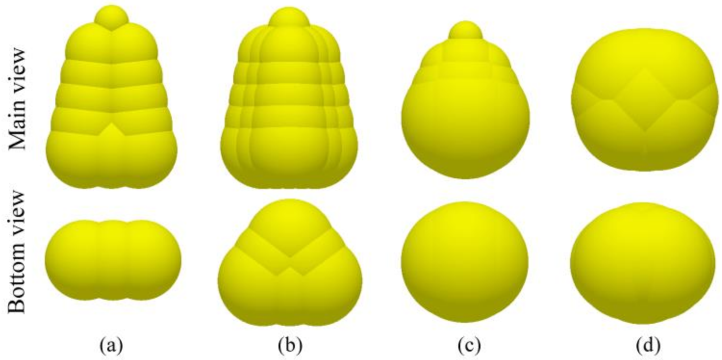

Figure 2. Particle models of maize seeds of (**a**) horse-tooth shape, (**b**) truncated triangular pyramid shape, (**c**) ellipsoid cone shape, (**d**) spheroid shape.

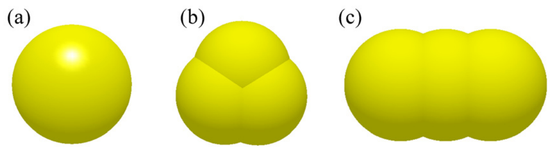

Figure 3. DEM model for different shaped soil particles: (**a**) spheres, (**b**) cylinders and (**c**) triangular pyramid.

2.2.1. EEPA Model

The Edinburgh Elasto-Plastic Adhesive (EEPA) model [21] can capture the shear stresses associated with the stress history and the cohesion of the bulk material. Figure 4 shows a schematic diagram of the EEPA contact spring for the normal direction of f-δ (force-overlap).

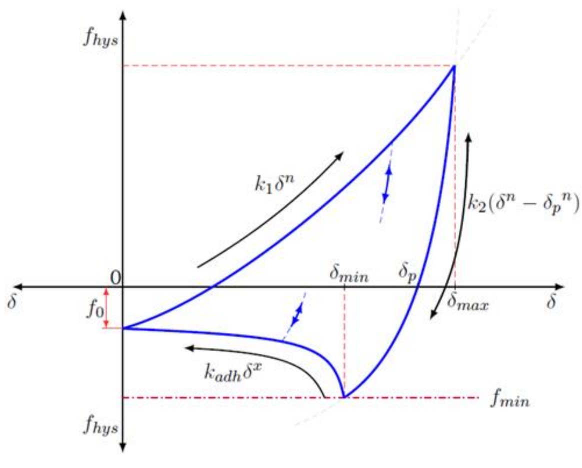

Figure 4. Schematic diagram of the EEPA contact spring for the normal direction.

The normal force f_n is equal to the sum of the hysteresis spring force f_{hys} and the normal damping force f_{nd}:

$$f_n = (f_{hys} + f_{nd})u \tag{1}$$

where u is the unit normal vector, directed from the point of contact to the centre of the particle; f_{hys} can be calculated from the following equation:

$$f_{hys} = \begin{cases} f_0 + k_1\delta^n & if \quad k_2(\delta^n - \delta_p{}^n) \geq k_1\delta^n \\ f_0 + k_2(\delta_n - \delta_p{}^n) & if \quad k_1\delta^n > k_2(\delta^n - \delta_p{}^n) > -k_{adh}\delta^x \\ f_0 - k_{adh}\delta^x & if \quad -k_{adh}\delta^x \geq k_2(\delta^n - \delta_p{}^n) \end{cases} \tag{2}$$

The normal damping force f_{nd} is calculated by the following equation:

$$f_{nd} = \beta_n v_n \quad (3)$$

where v_n is the normal relative velocity; β_n is the normal damping factor, which can be calculated from the following equation:

$$\beta_n = \sqrt{\frac{4m * k_1}{1 + (\frac{\pi}{\ln \quad e})^2}} \quad (4)$$

where $m*$ is the equivalent mass, m^* = ($mimj/mi$ + mj), where mi and mj are the masses of the individual particles; e is the coefficient of restitution.

The tangential force f_t is the sum of the tangential elastic force f_{ts} and the tangential damping force f_{td}.

$$f_t = (f_{ts} + f_{td}) \quad (5)$$

The tangential elasticity fts can be expressed in incremental terms as:

$$f_{ts} = f_{ts(n-1)} + \Delta f_{ts} \quad (6)$$

where $f_{ts(n-1)}$ is the tangential elastic force at the previous step; Δf_{ts} is the increment in the tangential elastic force, calculated from the following equation.

$$\Delta f_{ts} = -k_t \delta_t \quad (7)$$

where k_t is the tangential stiffness coefficient, the ratio of the tangential stiffness coefficient to the normal stiffness coefficient is 1 in EDEM, i.e., the two values are equal; in the luding model, the ratio is 0.2; in LAMMPS and PFC, this value is 2/7; however, the ratio of the tangential stiffness to the normal stiffness of a real elastic material is between 2/3 and 1, subject to the Poisson's ratio; δ_t is the tangential displacement increment.

The tangential damping force ftd is equal to the product of the tangential damping factor β_t and the tangential relative velocity vt, calculated by the following formula.

$$f_{td} = -\beta_t v_t \quad (8)$$

The tangential damping factor β_t is calculated by the following formula.

$$\beta_t = \sqrt{\frac{4m * k_t}{1 + (\frac{\pi}{\ln \quad e})^2}} \quad (9)$$

The ultimate tangential friction is calculated using the Coulomb friction criterion with the normal force modified by the adhesion force:

$$f_{ct} \leq \mu(\left| f_{hys} + k_{adh}\delta^n - f_o \right|) \quad (10)$$

where f_{ct} is the ultimate tangential friction force and μ is the coefficient of friction.

In this paper, the EDEM default rolling friction model is used and the total applied torque τ_i is calculated by the following equation.

$$\tau_i = -\mu_r \left| f_{hys} \right| R_i w_i \quad (11)$$

where μ_r is the coefficient of rolling friction; R_i is the distance from the point of contact to the centre of mass of the particle and w_i is the unit angular velocity at the point of contact.

2.2.2. Experimental Setup for Angle of Repose Tests

The angle of repose test for maize seed particles and soil particles was conducted using an electronic universal testing machine. The plexiglass cylinder was lifted upward at a certain speed to complete the accumulation process. To ensure full contact between the seed particles and soil particles and calibrate the contact parameters, maize seed particles were homogeneously mixed with soil particles at a ratio of 4:3. The angle of repose tests were conducted as shown in Figure 5.

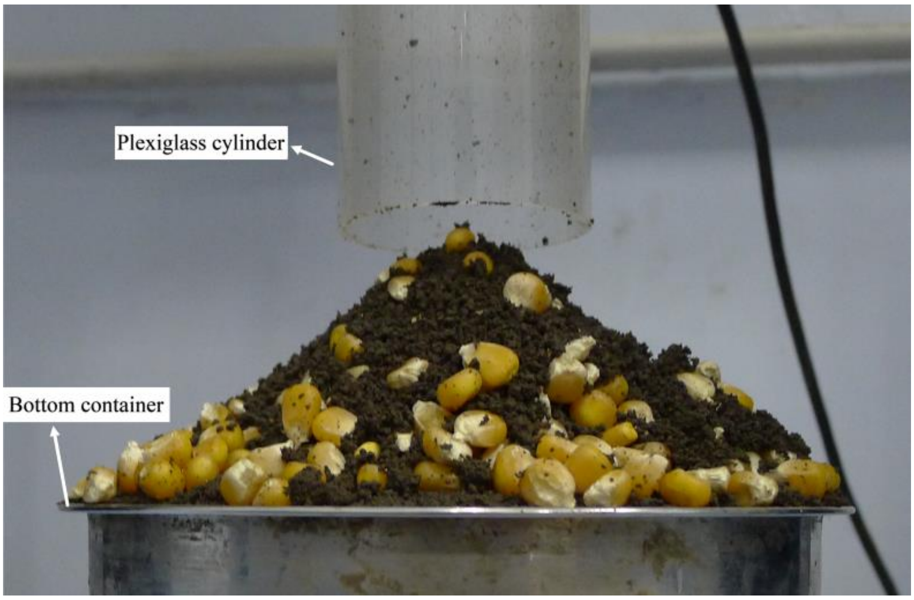

Figure 5. Schematic diagram of the angle of repose test between maize seed particles and soil particles.

The test procedure is as follows: First, fill the bottom container with soil of a certain water content and make the surface flat. Next, mix 0.2 kg of soil and 0.15 kg of maize seeds with the same water content in the plexiglass cylinder. Put the cylinder on the soil in the bottom container, and connect the cylinder and the electronic universal testing machine to the fixed position. Then, the electronic universal testing machine lifts the cylinder upwards at a speed of 300 mm/min, and the mixed seed particles and soil flow out of the cylinder, eventually piling up on the subsoil to form an angle of repose. Finally, use image recognition to obtain the size of the angle of repose. Three replicate trials are performed for each set of trials.

2.2.3. Simulation Setup for Angle of Repose Tests

In the simulation of the angle of repose test, the cylinder size and diameter of the bottom cylinder are the same as in the actual test. The simulation steps are as follows: first, soil particles are generated in the bottom container and the soil surface is leveled. After the bottom soil particles stabilize, a certain mass of soil particles and maize seed particles are generated in the cylinder, which are stabilized in the cylinder with the support of the bottom soil particles (see Figure 6a). Then, the cylinder moves upwards at a speed of 300 mm/min, and soil particles and maize seed particles flow out of the cylinder and accumulate on the underlying soil particles, forming an angle of repose (see Figure 6b). Finally, the angle of repose is measured using an image recognition method. Each set of trials is repeated three times.

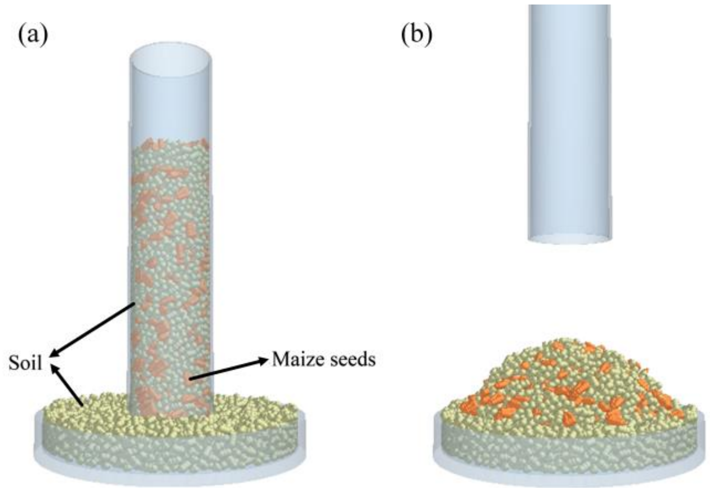

Figure 6. Simulation setup for the angle of repose test between maize seed particles and soil particles: (**a**) cylinder erected on soil, (**b**) angle of repose formation.

2.3. Verification Tests

In this section, the parameters between the calibrated soil and seed are validated by the inclined slide test, which is a good basis for the following simulation test of maize seed bouncing by touching the soil.

2.3.1. Inclined Slide Test Setup

A sketch of the setup for the inclined slide test of soil and seed particles is presented in Figure 7. The test setup consists of a high-speed video camera, a computer, an inclinometer, and an angle meter. The steps of the inclined slide test are as follows: first, fill the square slot of the inclinometer with soil of a certain water content and make the surface soil level. Then, place the maize seed particles statically on the surface of the soil and place the inclinometer horizontally, as shown in Figure 7. Next, slowly lift the inclinometer until the maize seed grain slides off the soil surface. Finally, use a high-speed camera to obtain an indication φ of the angle meter at the time when the sliding of the maize seed particles on the inclined plane first occurs. Repeat each experiment three times.

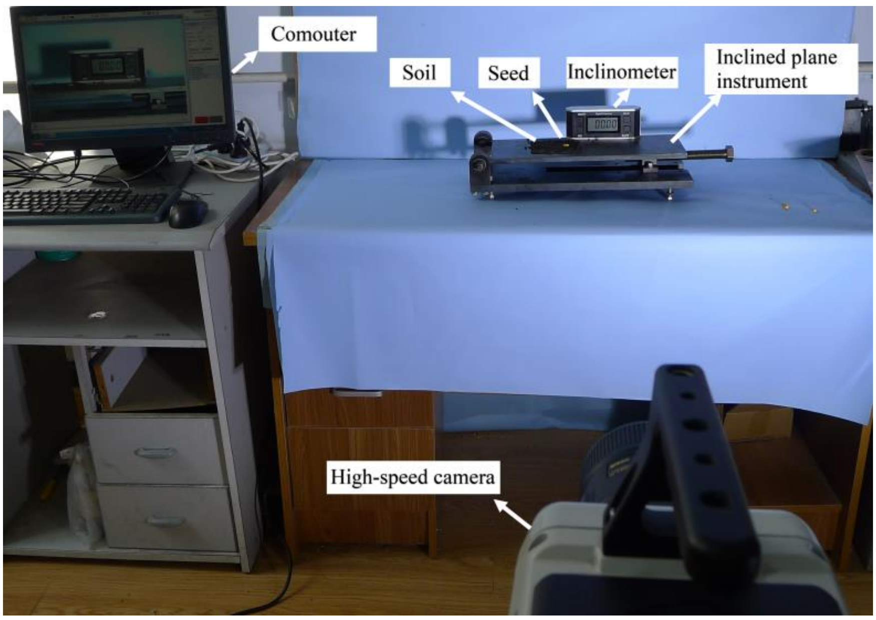

Figure 7. Sketch of the test set-up for the inclined slide test of soil and seed particles.

2.3.2. Simulation Setup for Inclined Slide Test

The simulation of inclined sliding uses the calibrated parameters, while the other parameters remain consistent with those used in the actual test. The simulation setup for inclined sliding is shown in Figure 8. The simulation steps are as follows: first, a seed particle is generated on the soil surface with a frontal downward attitude; then, the soil layer is rotated anticlockwise at 10 deg/s until the seed particle slip off the soil. Finally, the angle of inclination of the seed particles as they slip off the soil is calculated. Each set of simulations is repeated three times.

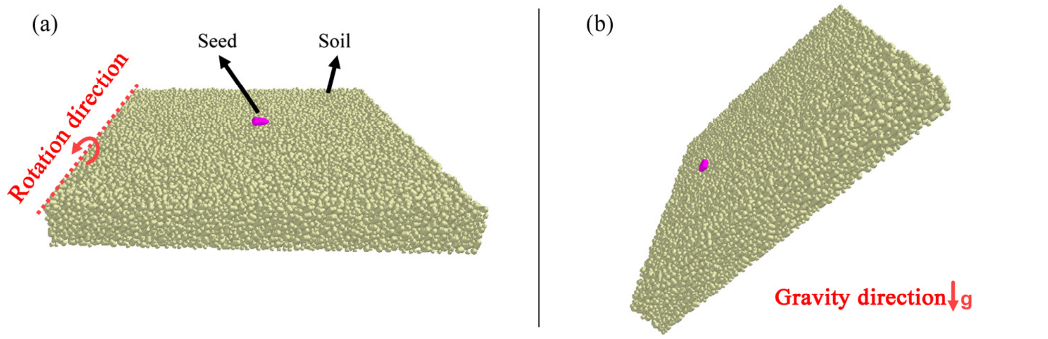

Figure 8. Simulation setup for the inclined slip test of soil and seed particles: (**a**) seed resting on the soil, (**b**) seed slipping off the soil.

3. Results and Discussion

3.1. Analyzsis of Contact Modelling between Soil and Maize Seeds

The force-versus-displacement curves for three moisture contents of soil in normal contact with seeds are shown in Figure 9 (where gf is the unit of force equal to the magnitude of the force of gravity on an object with a mass of 1 g). It should be noted that the horizontal axis of the graph represents the change in probe displacement, while the vertical axis represents the magnitude of the contact force between the maize seed and the soil. The maximum negative force in the graph represents the maximum adhesion of the soil to the seed.

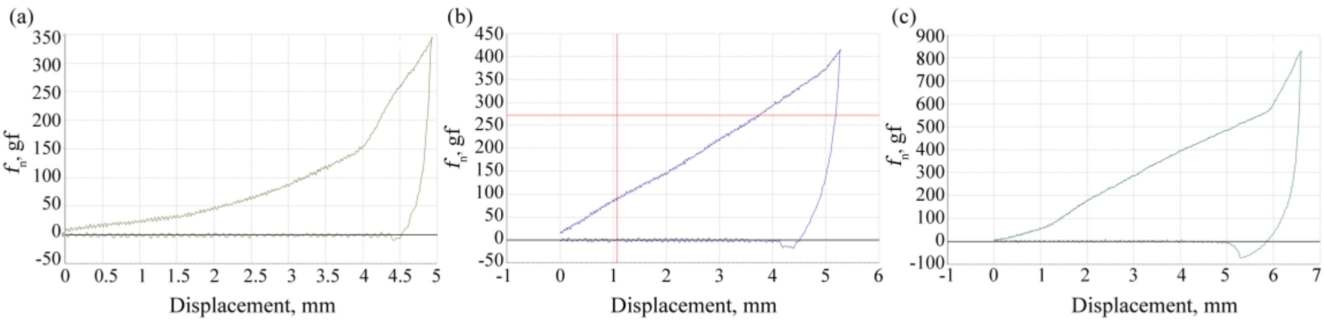

Figure 9. Curves of normal contact force versus displacement of seed particles with soils of varying moisture contents: (**a**) 15% moisture content, (**b**) 20% moisture content, and (**c**) 25% moisture content.

The experimental data are tallied, and the mass of the seed particles used in the test is weighed using a balance with an accuracy of 0.01 g, as shown in Figure 10. The mass of the seed particles is 0.31 g, and the weight of the seed particles is calculated to be 0.0031 N.

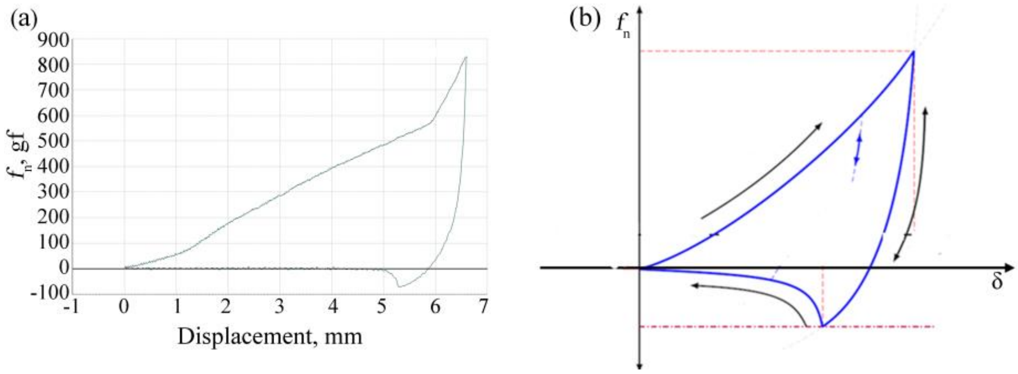

Figure 10. (**a**) Force versus displacement curves for seed particles in normal contact with soil; (**b**) curves for the non-linear model of normal contact for the EEPA model (f_0 = 0).

The maximum adhesion force of the soil in normal contact with the seed at three moisture contents is statistically analyzed, as shown in Table 1 below. From the table, it can be concluded that the maximum adhesion of soil to maize seed particles is 0.099993 N when the soil moisture content is 15%. This can be compared to the gravitational force of seed particles, which is 32.26 times the gravitational force of the seed particles. When the soil moisture content is 20%, the maximum adhesion of soil to maize seed particles is 0.158897 N, which is compared to the gravity of seed particles, and the adhesion force is 51.26 times the gravity of seed particles. When the soil moisture content is 25%, the maximum adhesion of soil to maize seed particles is 0.56029 N, which is compared to the gravity of seed particles, and the adhesion force is 180.76 times the gravity of seed particles. Therefore, it is necessary to consider the presence of adhesion forces for the contact of seed particles with soil, which can significantly affect the process of seed–soil contact collisions. In addition, the presence of tangential adhesion can be replaced by increasing the coefficient of static friction and the coefficient of rolling friction, but the adhesion in the normal direction cannot be compensated in this way.

Table 1. Maximum adhesion of maize seed particles in normal contact with soil versus seed mass.

Moisture Content, %	Mean Value, gf	Standard Deviation	Mean Value, N	Seed Weight, N	Adhesion to Seed Weight Ratio
15	−9.9993	0.2489	−0.099993	0.0031	32.26
20	−15.8897	2.6890	−0.158897	0.0031	51.26
25	−56.029	16.2674	−0.56029	0.0031	180.74

In addition, for example, the curve of the normal contact force and displacement between the soil and seed with 25% water content, as well as the loading process, unloading process, and adhesion process of the force of this curve, are similar to the curve in the nonlinear model of normal contact of the EEPA model (f_0 = 0), as shown in Figure 10.

In summary, the EEPA model was chosen as the contact model between seed particles and soil particles in this paper.

3.2. Calibration of Parameters between Maize Seed Particles and Soil Particles

The results of the angle of repose test between maize seed particles and soil particles are shown in Table 2. From the data in the table, it is worth noting that the angle of repose does not increase with increasing soil moisture content. For example, the angle of repose of soil mixed with seed particles at 25% moisture content is less than the angle of repose of soil mixed with seed particles at 20% moisture content. This is due to the fact that the soil with 25% moisture content mixed with the seed particles has a higher adhesion between the soil and the seed particles. This adhesion prevents the seed particles from scattering on the subsoil at the beginning stage of the ascent of the cylinder; instead, consolidation occurs, as shown in Figure 11. As the cylinder continues to rise, the mixed soil and seed particles collapse, resulting in the formation of a smaller angle of repose.

Table 2. Results of angle of repose tests.

Moisture Content, %	Sequences	Test Results, deg	Averages, deg	Standard Deviation
15	1	31.8486	33.6973	2.0156
		37.3436		
	2	34.2392		
		32.4808		
	3	33.9090		
		32.3624		
20	1	33.4208	36.0503	1.9474
		37.3364		
	2	35.7765		
		37.7040		
	3	35.6216		
		36.4422		
25	1	31.8279	34.0365	2.6678
		33.0440		
	2	37.9150		
		33.3689		
	3	34.5824		
		33.4807		

Figure 11. Consolidation between seeds and soil with 25% water content.

3.2.1. Plackett–Burman Test

In the EEPA model, the contact parameters to be determined between maize seed particles and soil particles include restitution coefficient, coefficient of static friction, coefficient of rolling friction, constant pull-off force, surface energy, contact plasticity ratio, tensile exp, slope exp and tangential stiff multiplier. The constant pull-off force is taken as 0, the slope exp is taken as 1.5, and the ranges of the other seven parameters are shown in Table 3.

Table 3. Parameter-level settings for the Plackett–Burman test.

Symbolic	Parameter	Low Level (−1)	High Level (+1)
X_1	Restitution coefficient	0.2	0.7
X_2	Coefficient of static friction	0.05	0.2
X_3	Coefficient of rolling friction	0.01	0.1
X_4	Surface energy	1	5
X_5	Contact plasticity ratio	0.4	0.7
X_6	Tensile exp	1	4
X_7	Tangential stiff multiplier	0.5	0.9
X_8–X_{11}	Virtual parameters	—	—

The design scheme of the Plackett–Burman test and the results of the test are shown in Table 4.

Table 4. Plackett–Burman test results for angle of repose tests.

Sequences	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	Angle of Repose, deg
1	1	1	−1	1	1	1	−1	−1	−1	1	−1	35.078
2	−1	1	1	−1	1	1	1	−1	−1	−1	1	27.013
3	1	−1	1	1	−1	1	1	1	−1	−1	−1	25.500
4	−1	1	−1	1	1	−1	1	1	1	−1	−1	36.182
5	−1	−1	1	−1	1	1	−1	1	1	1	−1	24.046
6	−1	−1	−1	1	−1	1	1	−1	1	1	1	26.196
7	1	−1	−1	−1	1	−1	1	1	−1	1	1	24.238
8	1	1	−1	−1	−1	1	−1	1	1	−1	1	29.434
9	1	1	1	−1	−1	−1	1	−1	1	1	−1	28.520
10	−1	1	1	1	−1	−1	−1	1	−1	1	1	31.467
11	1	−1	1	1	1	−1	−1	−1	1	−1	1	29.366
12	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	23.727
13	0	0	0	0	0	0	0	0	0	0	0	28.937

The test results are then analyzsed by ANOVA to determine the degree of influence of each parameter on the angle of repose, as shown in Table 5.

Table 5. ANOVA for the Plackett–Burman test.

Targets	Sources of Variance	Equation of Squares	Degrees of Freedom	Mean Square	F	*p*
Angle of repose	Model	183.43	7.00	26.20	19.49	0.0024 **
	X_1	1.02	1.00	1.02	0.76	0.4228
	X_2	99.88	1.00	99.88	74.30	0.0003 **
	X_3	6.67	1.00	6.67	4.96	0.0765
	X_4	59.90	1.00	59.90	44.55	0.0011 **
	X_5	10.23	1.00	10.23	7.61	0.0399 *
	X_6	3.24	1.00	3.24	2.41	0.1815
	X_7	2.49	1.00	2.49	1.85	0.2315
	Residuals	6.72	5.00	1.34		
	Synthesis	190.15	12.00			

Note: ** indicates that the item is highly significant ($p < 0.01$) and * indicates that the item is significant ($p < 0.05$).

From the results of the Plackett–Burman test, it can be seen that the coefficient of static friction and surface energy ($p < 0.01$) between soil and seed particles has a highly significant effect on the angle of repose, while the contact plasticity ratio between soil and seed particles has a significant effect on the angle of repose ($p < 0.05$). For the other parameters, the restitution coefficient is assumed to be 0.7, the coefficient of rolling friction to be 0.05, the tensile exp to be 3, and the tangential stiff multiplier to be 0.67.

3.2.2. Central Composite Design

The sensitive parameters (coefficient of static friction, surface energy, and contact plasticity ratio) are calibrated and optimized based on Plackett–Burman tests. The high and low levels of the coefficients of static friction between soil and seed particles are 0.05 and 0.2, respectively. The high and low levels of surface energy between soil and seed particles are 1 and 5, respectively. The high and low levels of contact plasticity ratio between soil and seed particles are 0.4 and 0.7, respectively. Table 6 shows a coded table of factor levels for the Central Composite Design trial.

Table 6. Factor-level design table for the Central Composite Design trial.

Level	Coefficient of Static Friction (X_2)	Surface Energy (X_4), J/m^2	Contact Plasticity Ratio (X_5)
γ	0.1696	4.1892	0.6392
1	0.2	5	0.7
0	0.13	3	0.55
−1	0.05	1	0.4
$-\gamma$	0.0804	1.8108	0.4608

The design solutions and simulation results of Central Composite Design test are shown in Table 7.

Table 7. The design solutions and simulation results of Central Composite Design test.

Sequences	X_2	X_4, J/m^2	X_5	Angle of Repose (Y)
1	−1	−1	−1	32.6869
2	1	−1	−1	36.3865
3	−1	1	−1	35.6033
4	1	1	−1	40.1298
5	−1	−1	1	33.7951
6	1	−1	1	34.022
7	−1	1	1	37.6747
8	1	1	1	42.2059
9	−1.682	0	0	30.0701
10	1.682	0	0	39.5794
11	0	−1.682	0	29.6997
12	0	1.682	0	41.0097
13	0	0	−1.682	34.4625
14	0	0	1.682	38.6959
15	0	0	0	38.1124
16	0	0	0	40.5867
17	0	0	0	40.421
18	0	0	0	36.2433
19	0	0	0	38.8288
20	0	0	0	37.8508

From the experimental results obtained in the table, the following binary multiple regression equations are derived using the coefficient of static friction (X_2), surface energy (X_4), and contact plasticity ratio (X_5) as independent variables, and the angle of repose (Y) as the response value:

$$\begin{aligned} Y = 38.64 + 2.12X_2 + 2.76X_4 + 0.73X_5 + 0.64X_2X_4 - 0.43X_2X_5 \\ +0.68X_4X_5 - 1.12X_2{}^2 - 0.93X_4{}^2 - 0.49X_5{}^2 \end{aligned} \quad (12)$$

The results of the tests in the table are also analyzed by ANOVA, and the results are shown in Table 8.

Table 8. ANOVA results for the Central Composite Design trial.

Source	Equation of Squares	Degrees of Freedom	Mean Square	F	*p*	
Model	210.64	9	23.4	7.7	0.0019	significant
X_2	61.48	1	61.48	20.22	0.0011 **	
X_4	104.32	1	104.32	34.3	0.0002 **	
X_5	7.34	1	7.34	2.41	0.1514	
$X_2 X_4$	3.29	1	3.29	1.08	0.3227	
$X_2 X_5$	1.5	1	1.5	0.49	0.498	
$X_4 X_5$	3.65	1	3.65	1.2	0.2989	
X_2^2	17.92	1	17.92	5.89	0.0356 *	
X_4^2	12.41	1	12.41	4.08	0.071	
X_5^2	3.53	1	3.53	1.16	0.3066	
Residual	30.41	10	3.04			
Misfit term	16.77	5	3.35	1.23	0.4129	insignificant
Error term	13.64	5	2.73			
Total deviation	241.04	19				

Note: ** indicates that the item is highly significant ($p < 0.01$) and * indicates that the item is significant ($p < 0.05$).

As can be seen from the data in the table, the regression model has a p value of <0.0001, indicating that the difference reaches a highly significant level. Additionally, the level of the misfit term is not significant ($p > 0.05$), indicating a good fit of the equation. These findings suggest that it is feasible to apply a modified mathematical model to characterize the extent of influence of the factors on the response values.

In addition, as shown in the table, X_2 (coefficient of static friction) and X_4 (surface energy) have a highly significant effect ($p < 0.01$) on the angle of repose, while X_5 (contact plasticity ratio) has no significant effect ($p > 0.05$) on the angle of repose. Among the secondary terms, X_2^2 has a significant effect ($p < 0.05$) on the angle of repose. None of the interaction terms have a significant interaction effect ($p > 0.05$).

The response surface plots among the factors are obtained based on the quadratic regression equation, which reveals the interaction between the factors and the optimal parameter combinations. From Figure 12, it can be observed that the optimal parameters exist within the designed range of factor levels.

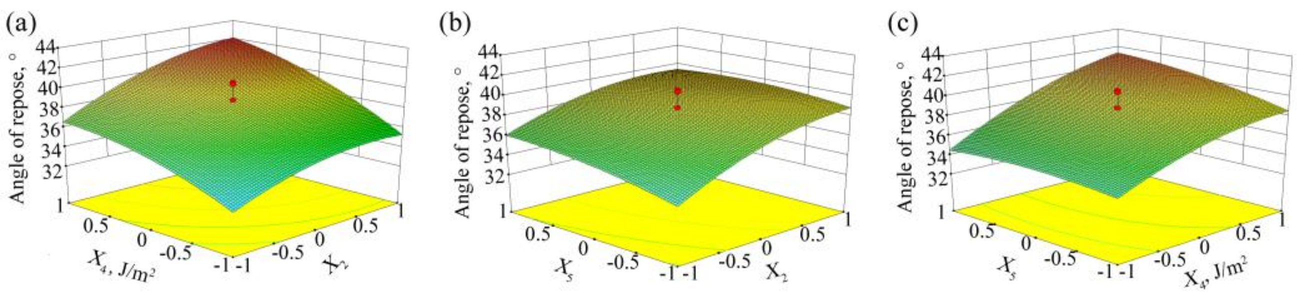

Figure 12. Response surface plots of the interaction of factors on the effect of angle of repose: (**a**) X_4 and X_2, (**b**) X_5 and X_2, (**c**) X_5 and X_4.

Optimization of the established mathematical model by means of statistical analyzis software resulted in a set of optimal parameters for soil with a moisture content of 15%. These parameters include a static coefficient of friction between soil and seed particles of 0.17, a surface energy of 0.97, and a contact plasticity ratio of 0.48; the optimal parameters for a soil with 20% moisture content are: a static friction coefficient of 0.19 between soil and seed particles, a surface energy of 1.12, and a contact plasticity ratio of 0.63; for a soil with 25% moisture content, the optimal parameters are: a static friction coefficient of 0.1 between soil and seed particles, a surface energy of 2.7, and a contact plasticity ratio of 0.41.

3.3. Results of the Validation Test

A comparison of the test and simulation results for the inclined slip test is shown in Figure 13. For soils with 15%, 20%, and 25% moisture content, the relative error between the simulation results and the actual test results of the slope test are 4.3%, 0.8%, and 5.4%, respectively. This proves the accuracy of the parameters obtained from the calibration.

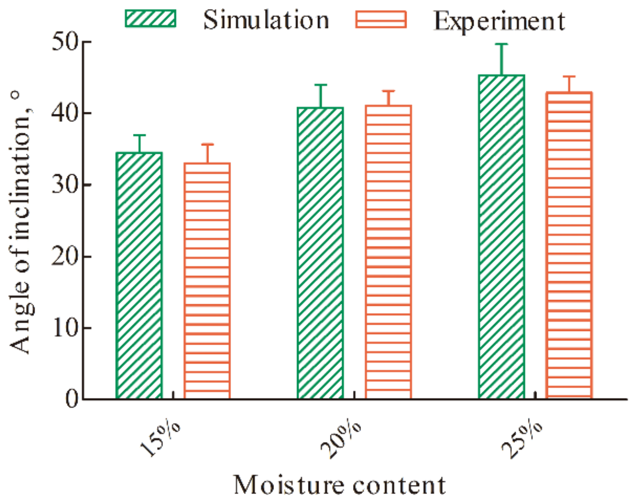

Figure 13. A comparison of the test and simulation results for the inclined slip test.

4. Conclusions

This paper analyzes the contact process between maize seeds and soil. Based on this analysis, it explores a mechanical model that is suitable for simulating the contact process between maize seeds and soil. Additionally, it investigates the selection method of parameters between heterogeneous particles. The following conclusions are drawn:

(1) In this paper, a contact mechanics model suitable for modeling the contact between heterogeneous particles (maize seeds and soil particles) is investigated. This is achieved by studying the magnitude of the adhesion force of the soil on the maize seeds when the maize seed particles are in vertical contact with the soil. The adhesion force is then compared with the gravity force of the seed particles. The result is as follows: when the moisture content of soil particles is between 15 and 25%, the vertical adhesion between the seed and soil is 32–180 times the weight of the seed. Therefore, when considering the contact between seed particles and soil, it is necessary to take into account the presence of adhesion, which can significantly affect the collision process between the seed and soil. In addition, the presence of tangential adhesion can be reduced by increasing the coefficients of static and rolling friction, but the adhesion in the normal direction cannot be compensated for in this way. Moreover, the loading process, unloading process, and adhesion process of the normal contact force and displacement curves between the soil and seed are similar to the curves of the non-linear model of normal contact ($f_0 = 0$) of the EEPA model. In summary, the EEPA model was chosen as the contact model between seed particles and soil particles in this paper.

(2) For the test on the angle of repose between maize seed particles and soil particles, it is found that the angle of repose does not increase with an increase in soil moisture content, but instead increases and then decreases. For example, the angle of repose of soil mixed with seed particles with 25% moisture content is smaller than the angle of repose of soil mixed with seed particles with 20% moisture content. This is due to the fact that the soil with 25% moisture content mixed with seed particles has a higher adhesion between the soil and the seed particles. During the ascent of the cylinder, it does not scatter on the subsoil at the beginning stage but instead is cemented

together. As the cylinder continues to rise, the mixed soil and the seed particles collapse, resulting in the formation of a smaller angle of repose.

(3) A significance study of the input parameters in the EEPA model using the Plackett–Burman test shows that the coefficient of static friction and surface energy between the maize seed and the soil particles has a highly significant effect on the angle of repose test. Additionally, the contact plasticity ratio has a significant effect on the angle of repose test. The parameters between soil particles and seed particles are optimized using Central Composite Design, and the optimum combination of parameters is obtained. For a soil with 15% moisture content, the optimal parameters are as follows: a static coefficient of friction between soil and seed particles of 0.17, a surface energy of 0.97, and a contact plasticity ratio of 0.48. The optimal parameters for a soil with 20% moisture content are: a static friction coefficient of 0.19 between soil and seed particles, a surface energy of 1.12, and a contact plasticity ratio of 0.63. For a soil with 25% moisture content, the optimal parameters are: a static friction coefficient of 0.1 between soil and seed particles, a surface energy of 2.7, and a contact plasticity ratio of 0.41.

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References

1. Yuan, Y.; Bai, H.; Fang, X.; Wang, D.; Zhou, L.; Niu, K. Research Progress on Maize Seeding and Its Measurement and Control Technology. *Trans. Chin. Soc. Agric. Mach.* **2018**, *49*, 1–18.
2. Yitao, L.; Chengliang, L.; Qingxi, L.; Lei, W.A. Research Progress of Seed Guiding Technology and Device of Planter. *Trans. Chin. Soc. Agric. Mach.* **2020**, *51*, 1–14.
3. Cundall, P.A.; Strack, O.D.L. A discrete numerical model for granular assemblies. *Geotechnique* **1979**, *29*, 47–65. [CrossRef]
4. Walunj, A.; Chen, Y.; Tian, Y.; Zeng, Z. Modeling Soil–Plant–Machine Dynamics Using Discrete Element Method: A Review. *Agronomy* **2023**, *13*, 1260. [CrossRef]
5. Wang, F.; Dai, F.; Zhang, F.; Song, X.; Shi, R.; Zhao, W.; Ma, H. Simulation Analysis and Test on the Effect of Picking Up the Residual Film of Typical Film Lifting Parts. *Agronomy* **2023**, *13*, 488. [CrossRef]
6. Yuan, F.; Yu, H.; Wang, L.; Shi, Y.; Wang, X.; Liu, H. Parameter Calibration and Systematic Test of a Discrete Element Model (DEM) for Compound Fertilizer Particles in a Mechanized Variable-Rate Application. *Agronomy* **2023**, *13*, 706. [CrossRef]
7. Yan, D.; Yu, J.; Wang, Y.; Zhou, L.; Tian, Y.; Zhang, N. Soil Particle Modeling and Parameter Calibration Based on Discrete Element Method. *Agriculture* **2022**, *12*, 1421. [CrossRef]
8. Mudarisov, S.; Farkhutdinov, I.; Khamaletdinov, R.; Khasanov, E.; Mukhametdinov, A. Evaluation of the significance of the contact model particle parameters in the modelling of wet soils by the discrete element method. *Soil Tillage Res.* **2022**, *215*, 105228. [CrossRef]
9. Höhner, D.; Wirtz, S.; Kruggel-Emden, H.; Scherer, V. Comparison of the multi-sphere and polyhedral approach to simulate non-spherical particles within the discrete element method: Influence on temporal force evolution for multiple contacts. *Powder Technol.* **2011**, *208*, 643–656. [CrossRef]
10. Zhou, L.; Yu, J.; Liang, L.; Yu, Y.; Yan, D.; Sun, K.; Wang, Y. Study on key issues in the modelling of maize seeds based on the multi-sphere method. *Powder Technol.* **2021**, *394*, 791–812. [CrossRef]
11. Zhou, L.; Yu, J.; Wang, Y.; Yan, D.; Yu, Y. A study on the modelling method of maize-seed particles based on the discrete element method. *Powder Technol.* **2020**, *374*, 353–376. [CrossRef]
12. Wang, S.; Yu, Z.; Zhang, W. Study on the modeling method of sunflower seed particles based on the discrete element method. *Comput. Electron. Agric.* **2022**, *198*, 107012. [CrossRef]

13. Landry, H.; Thirion, F.; Lague, C.; Roberge, M. Numerical modeling of the flow of organic fertilizers in land application equipment. *Comput. Electron. Agric.* **2006**, *51*, 35–53. [CrossRef]
14. Li, X.; Du, Y.; Liu, L.; Zhang, Y.; Guo, D. Parameter calibration of corncob based on DEM. *Adv. Powder Technol.* **2022**, *33*, 103699. [CrossRef]
15. Tang, Z.; Gong, H.; Wu, S.; Zeng, Z.; Wang, Z.; Zhou, Y.; Fu, D.; Liu, C.; Cai, Y.; Qi, L. Modelling of paddy soil using the CFD-DEM coupling method. *Soil Tillage Res.* **2023**, *226*, 105591. [CrossRef]
16. Zhou, L.; Yu, J.; Liang, L.; Wang, Y.; Yu, Y.; Yan, D.; Sun, K.; Liang, P. DEM parameters calibration of maize seed and effect of rolling friction. *Processes* **2021**, *9*, 914. [CrossRef]
17. Wang, X.; Zhang, S.; Pan, H.; Zheng, Z.; Huang, Y.; Zhu, R. Effect of soil particle size on soil-subsoiler interactions using the discrete element method simulations. *Biosyst. Eng.* **2019**, *182*, 138–150. [CrossRef]
18. Zhou, H.; Chen, Y.; Sadek, M.A. Modelling of soil–seed contact using the Discrete Element Method (DEM). *Biosyst. Eng.* **2014**, *121*, 56–66. [CrossRef]
19. Gong, H.; Zeng, Z.; Qi, L. A discrete element model of seed-soil dynamics in soybean emergence. *Plant Soil* **2019**, *437*, 439–454. [CrossRef]
20. Zhou, L.; Lan, Y.; Yu, J.; Wang, Y.; Yan, D.; Sun, K.; Wang, W.; Chen, Y. Validation and calibration of soil parameters based on EEPA contact model. *Comput. Part. Mech.* **2023**, *10*, 1295–1307. [CrossRef]
21. Morrissey, J.P. *Discrete Element Modelling of Iron Ore Pellets to Include the Effects of Moisture and Fines*; The University of Edinburgh: Edinburgh, UK, 2013.