PARAMETER CALIBRATION AND VALIDATION OF A STRAW-SOIL DISCRETE ELEMENT MODEL IN HUANG-HUAI-HAI WHEAT STUBBLE FIELDS
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黄淮海麦茬地秸秆土壤离散元模型参数标定与试验

Wenyan YAO[1], Hequan MIAO[1], Meizhou CHEN[2], Peisong DIAO[2], Guangfei XU*[1]
[1]College of Mechanical and Automotive Engineering, Liaocheng University, LIAOCHENG / China
[2]School of Agricultural Engineering and Food Science, Shandong University of Technology, Zibo / China
Tel: +86-15166593390; E-mail: xuguangfei@lcu.edu.cn (correspondent author: Guangfei Xu)
DOI: https://doi.org/10.35633/inmateh-77-28

***Keywords**: Huang-Huai-Hai region, Wheat straw, Soil, EDEM simulation, Parameters calibration, Repose angle*

ABSTRACT
In order to improve the accuracy of discrete element simulation of stubble cleaning soil-engaging parts of corn planter in wheat stubble field, taking the soil straw of Huang-Huai-Hai as the research object, the method of combining physical repose angle with EDEM simulation test was adopted, and the Hertz-Mindlin with bonding contact model was selected to calibrate the simulation contact parameters. Plackett-Burman was used to screen out the main factors that had a significant impact on the test indicators. Design-Expert was used to conduct a central combination test on the screening factors, and regression analysis and significance test were performed on the simulation results to find out the optimal combination of test indicators. The factor screening test showed that the primary and secondary factors affecting the soil repose angle were soil rolling friction factor, soil-device static friction factor, soil static friction factor and soil normal stiffness per unit area. The primary and secondary order of the factors affecting the straw repose angle was the device-straw rolling friction coefficient, the device-straw restitution coefficient, and the straw static friction coefficient. The significant test showed that the soil rolling friction coefficient was 0.574, the soil static friction coefficient was 0.93, the soil-device static friction coefficient was 0.373, the soil normal stiffness per unit area was 9.5×10^9, and the relative error between the optimized parameter simulation test and the actual test was 3.1%. The straw static friction coefficient was 0.598, the device-straw restitution coefficient was 0.754, the device-straw rolling friction coefficient was 0.11, and the relative error between the optimized parameter simulation test and the actual test was 1.45%.

摘要
为提高麦茬地玉米播种机清茬触土部件离散元仿真模拟的准确性，以黄淮海土壤秸秆为研究对象，采用物理堆积角与 EDEM 仿真试验相结合的方法，选用 Hertz-Mindlin with bonding 接触模型对仿真接触参数进行标定。通过 Plackett-Burman 筛选出对试验指标影响显著的主要因子，运用 Design-Expert 对筛选因子进行中心组合试验，对仿真结果进行回归分析与显著性检验，找出试验指标最优的组合。因素筛选试验表明对土壤堆积角影响因素主次顺序为土壤滚动摩擦因数、土壤-装置静摩擦因数、土壤静摩擦因数、土壤单位面积正向刚度；对秸秆堆积角影响因素主次顺序为装置-秸秆滚动摩擦因数、装置-秸秆恢复系数、秸秆静摩擦因数。显著性试验表明土壤滚动摩擦因数为 0.574、土壤静摩擦因数为 0.93、土壤-装置静摩擦因数为 0.373、土壤单位面积正向刚度为 9.5×10^9，优化后的参数仿真试验与实际试验相对误差为 3.1%。秸秆静摩擦因数为 0.598、装置-秸秆恢复系数为 0.754、装置-秸秆滚动摩擦因数为 0.11，优化后的参数仿真试验与实际试验相对误差为 1.45%。

INTRODUCTION
The granular particles in agriculture mainly include soil particles and straw material particles (*Zeng et al., 2021*). In the soil particle parameter calibration and contact model, the soil undergoes dynamic behaviors such as extrusion deformation, crushing, and movement under the action of the machine. Domestic and foreign scholars had carried out a series of calibration studies on the simulation parameters of particles. *Wang et al.*, (*2017*), proposed a general method for the calibration and optimization of soil parameter models based on the surrogate model theory. The Edinburgh Elasto Plastic Cohesion Model was used to obtain the main measurement parameters by simulating soil direct shear and repose angle tests and sensitivity analysis methods.

Shi et al., (*2017*), predicted and verified the soil mechanical parameters by using the Hysteretic Spring Contact Model and Liner Cohesion Model for the soil particles in the arid area of northwest China. *Wu et al., (2017)*, used Hertz Mindlin with Johnson Kendall Roberts contact model to simulate the repose angle of cohesive soil. *Song et al*., *(2022)*, calibrated the discrete element parameters of mulberry garden soil by Hertz Mindlin with Bonding contact model through non-equidistant soil particles. *Song et al.,* (*2021*), used Hertz-Mindlin (no slip) contact model to simulate the repose and sliding process of soil in the process of layered fertilization to calibrate the soil contact parameters of cotton field after tillage. *He et al.,* (*2024*), used Hertz Mindlin with Johnson Kendall Roberts model to calibrate the contact parameters of saline soil particles. The Hysteretic Spring contact model proposed by *Ucgul et al.,* (*2014, 2015*), could comprehensively represent the elastic strain and plastic deformation of the soil, and integrated the cohesive force and linear elastic cohesion through the contact model. *Obermayr et al.,* (*2014*), used a custom linear model to model the constitutive relationship of sand in Pasimodo software, and increased the proportion of positive attraction between particles.

Domestic and foreign scholars had carried out a series of studies on the mechanical properties and simulation parameters of flexible crop stalks. *Wang et al.,* (*2020, 2021*), constructed a discrete element model of wheat plants based on Hertz Mindlin with Bonding model and calibrated the discrete element parameters of wheat plants at harvest time. Based on Hertz-Mindlin with Bonding model, *Liu et al.,* (*2018*), established a flexible straw model to simulate the bending behavior of wheat straw. Through three-point bending test, single factor sensitivity analysis and calibration of bonding parameters were carried out. *Schramm et al.,* (*2019, 2022*), developed a calibration method for simulating the shear of wheat straw flexible fibers in the discrete element method for discrete element simulation, using cantilever beam test, three-point bending test, uniaxial compression test and direct shear test for calibration. *Bart et al.,* (*2014*), established a flexible straw particle model in EDEM, and its physical properties have been calibrated using real straw properties, simulating grain-straw separation in discrete element modeling. *Tom et al.,* (*2016*), developed a contact model based on crop stem data. These models combine realistic deformation behavior with a minimal number of model parameters. Furthermore, the effect of plastic deformation and damage was incorporated in the model.

Due to the regional differences, there were some differences in the physical and mechanical properties of soil structure, which was difficult to be universal. The physical properties of wheat straw after harvest had changed, and the existing research basis was difficult to apply. In order to further improved the accuracy of discrete element simulation of stubble cleaning soil-engaging parts of corn planter in wheat stubble field, the soil straw of Huang-Huai-Hai was taken as the research object, and the method of combining physical stacking angle with EDEM simulation test was adopted. The Hertz-Mindlin with Bonding contact model was used to calibrate the simulation contact parameters. In order to provide reference for the calibration of discrete element simulation parameters of farmland soil straw in Huang-Huai-Hai region.

MATERIALS AND METHODS

Test Materials

The soil occurrence types in the Huang-Huai-Hai region are mainly alluvial soil and cinnamon soil, and the soil texture is mostly sandy loam and there are many wheat varieties. The research object of this paper was the soil and straw of wheat stubble field in wheat-corn rotation area. The material came from the sandy loam in the northwest plain of Shandong Province, and the wheat variety was Jimai 22. The test equipment mainly included universal testing machine (measurement range 0.1-5000N, relative error of beam displacement indication ±1%, acquisition rate 200 times/s, test speed 5-500 mm/min, test stroke 1200 mm), custom fixture, steel cylinder (height 200 mm, diameter 100 mm), steel plate (length 330 mm, width 330 mm), electric drying oven (101-0BS), electronic analytical balance (FA2204, range 0-220g, accuracy 0.1 mg), vernier caliper (range 100mm, accuracy 0.01 mm), high-speed camera (OSG030-815UM), etc.

Electric drying oven

Electronic analytical balance

Universal testing machine

Circular soil cutter

Fig.1 - Test equipment

Soil Parameters

Due to the complex and uneven soil structure, the size and shape of soil solid matter are different. In order to simplify the simulation test, the soil was regarded as a sphere. The soil characteristic parameters were sampled according to the national standard 'GB/T50123-1999 geotechnical test method standard' (*Yi, 2008*), and the soil depth was selected as 0-60 mm. Through the soil screening test, 72.1% of the particle size was 0.075-5 mm, and 17.8% of the particle size was less than 0.075 mm. The dry base moisture content of soil was 12.1% by drying method. The average soil density was 1400.25 kg/m^3 by cutting ring method. Soil Poisson 's ratio v and shear modulus G were obtained by literature and soil direct shear test (*Wang, 2021; Zhao, 2021; Guo, 2017; Fang,2016*).

Straw Parameters

The average wheat plant height of the test sample was 720 mm, the ratio of thick and thin stems was 0.5, and the stubble height was 250-300 mm. The straw in the field after harvest was shown in Figure 2. The amount of crushed straw on the seedling belt was 1.02 kg/m^2 (Fig.2a), and the wall thickness of the crushed straw was 1-2 mm. The proportion of different straw lengths was obtained by analysis. When the length was 0-100 mm, the proportion of the number was 21.95%. When the length was 100-150 mm, the proportion was 21.95%. When the length was 150-200mm, the proportion was 19.51%. When the length was 200-250 mm, the proportion was 21.95%. When the length was 250-300 mm, the proportion was 14.63%, and the rest of the short straw and miscellaneous were not counted. The wet base moisture content of defoliated stem was 10.57% and that of non-defoliated stem was 11.26 % by drying method. The average density of straw obtained by measuring the weight and volume was 523.16 kg/m^3.

(a) Stubble situation (b) Cutting height (c) Pulverized straw (d) Stubble straw

Fig. 2 - Field straw situation

Test Method

The discrete element model parameters of straw and soil were calibrated by the combination of physical test of repose angle and EDEM simulation test. The cylinder lifting method was used to test the repose angle of straw and soil, and the actual value of the repose angle of straw and soil was measured by high-speed camera technology and Kinovea2023. Based on EDEM 2.7, the repose angle simulation test of the material was carried out, and the Plackett-Burman screening test design was carried out by Design-Expert software to screen out the parameters that had a significant impact on straw and soil. According to the Central Composite test, the regression model of straw and soil repose angle and significant parameters was established, and the parameters were optimized to obtain the optimal parameter combination. The simulation test was carried out by using the optimal parameter combination, and the difference between the simulated repose angle and the actual repose angle was compared and analyzed to verify the accuracy of the calibration model parameters.

Repose Angle Physical Test

The soil was placed in an aluminum box (80mm × 60mm) by a cutting ring (70mm × 52mm). Before the test, the test sample was filled with a steel cylinder. The bottom of the cylinder was placed on the platform steel plate of the universal testing machine, and the top of the cylinder was connected to the universal testing machine. The cylinder was raised at a constant speed (500 mm/min), and the soil formed a pile on the steel plate. The soil repose angle image was recorded by a high-speed camera. The experiment was repeated five times. The average repose angle was 35.22°, and the coefficient of variation was 6.49 % (Fig.3).

In the straw repose angle test, the straw was treated with leaf removal (when the leaves were not removed, the stem fluidity was poor, and the repose angle was almost unchanged at a right angle). The collected wheat straw was randomly cut into particle mixtures of different lengths, and the straw length range was 20-80 mm. The test process was the same as the soil repose angle test. The average repose angle of straw was 31.28°(Fig.4), and the coefficient of variation was 7.32 %.

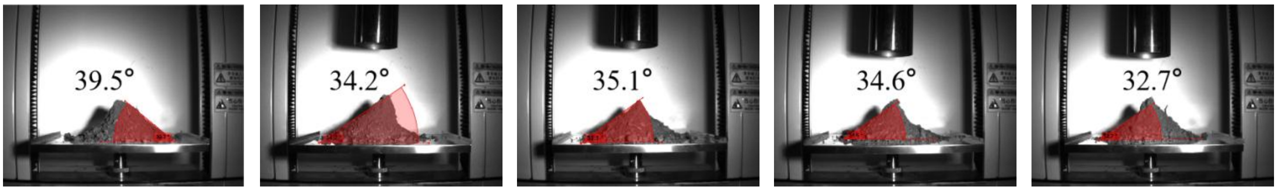


Fig. 3 Soil repose angle measurement

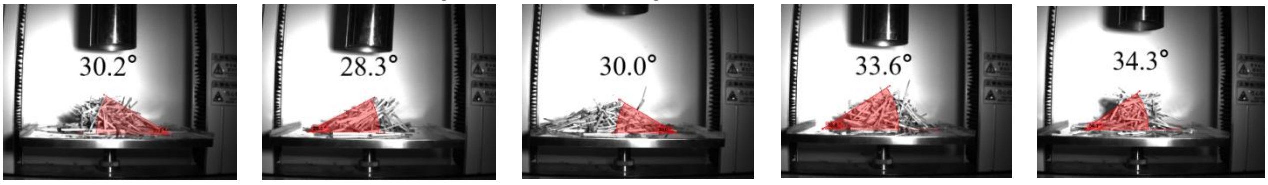


Fig. 4 - Measurement of straw repose angle

EDEM SIMULATION TEST

Simulation Model Establishment

In order to better verify the interaction between the various materials, Hertz-Mindlin with Bonding model was used between the materials, and Hertz-Mindlin (no slip) model was used between the device and the material. Based on the physical properties of the soil, the soil model was established by using EDEM. In this paper, a sphere with a radius of 2.5 mm was used as the soil matrix, and the sphere diameter ratio was 0.5-1.5. The simulation model was shown in Figure 5. The soil density was 1400.25 kg·m^{-3}, the soil Poisson's ratio was 0.38, and the soil shear modulus was 10^6 Pa. The density of the device was 7865 kg·m^{-3}, the Poisson's ratio of the device was 0.3, and the shear modulus of the device was 7.9×10^{10} Pa. The wheat straw particles were hollow cylinders, and the cross section was approximately elliptical (*Li, 2013*). In order to simplify the model, the straw was composed of sphere particles bonded. The particle diameter was 3.5 mm, and the straw lengths were 20 mm, 30 mm, 40 mm, and 50 mm (Fig. 6a). The straw density was 523.16 kg·m^{-3}, the straw Poisson's ratio was 0.4, and the straw shear modulus was 10^6 Pa (Fig.6).

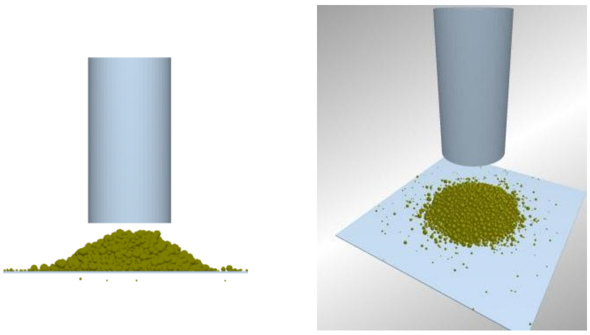
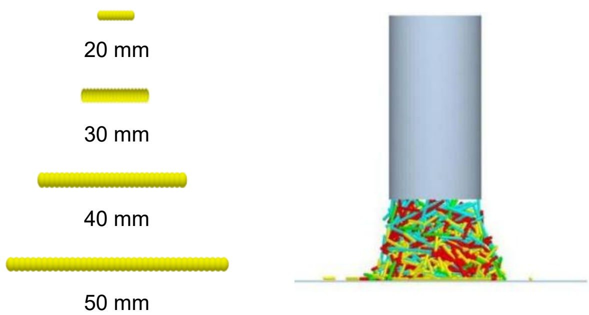


Fig. 5 - Simulation test of soil repose angle



(a) Straw lengths (b) Repose angle test
Fig. 6 - Simulation test of straw repose angle test

EDEM Software Simulation Settings

The steel plate and cylinder were generated in SolidWorks 2018 software and imported into the EDEM software. During the simulation process, the soil particles were statically generated, and the soil particles fill the entire virtual factory. The particle size position was randomly generated, and the data storage interval was 0.2 s. In the process of straw simulation, two kinds of virtual straw particle factories were first established, each factory fixed to generate two lengths of straw, and then the whole virtual particle factory was statically filled with the same time. The position of straw particles was randomly generated, and the data storage interval was 0.2 s. In the soil repose angle test, the cylinder lifting start time was 10 s, the end time was 15 s, the cylinder upward speed was 0.05 m/s, and the whole simulation time was 20 s. In the straw repose angle test, the cylinder lifting start time was 15 s, the end time was 20 s, the cylinder upward speed was 0.05 m/s, and the whole simulation time was 30 s. During the test, the particles slowly flowed out from the bottom of the cylinder, and the particle pile gradually stabilized on the bottom plate to form a stable repose angle. The repose angle value was extracted by Kinovea 2023 software.

Through literature and experiments, the simulation parameters and levels of soil and straw in the discrete element simulation process were shown in Table 1.

Table 1

Parameters and level required in DEM simulation

Simulation parameter	Level -1	Level 1	Simulation parameter	Level -1	Level 1
Soil restitution coefficient x_1	0.2	0.8	Device-straw restitution coefficient X_1	0.2	0.8
Soil-device restitution coefficient x_2	0.1	0.6	Straw restitution coefficient X_2	0.2	0.3
Soil static friction coefficient x_3	0.2	1	Device-straw static friction coefficient X_3	0.3	0.8
Soil-device static friction coefficient x_4	0.3	0.8	Straw static friction coefficient X_4	0.3	0.8
Soil rolling friction coefficient x_5	0.05	0.7	Device-straw rolling friction coefficient X_5	0.01	0.3
Soil-device rolling friction coefficient x_6	0.02	0.05	Straw rolling friction coefficient X_6	0.01	0.3
Soil normal stiffness per unit area x_7	10^6	10^{10}	Straw normal stiffness per unit area X_7	10^6	10^{10}
Soil shear stiffness per unit area x_8	10^6	10^{10}	Straw shear stiffness per unit area X_8	10^6	10^{10}
Soil bonded disk radius x_9	1	10	Straw bonded disk radius X_9	1	10

RESULTS AND ANALYSIS

Analysis of Soil Simulation Test Results

Soil Factor Significance Screening Test

Table2

Soil screening test design and results

Test No.	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	R
1	1	1	-1	1	1	1	-1	-1	-1	23.7°
2	-1	1	1	-1	1	1	1	-1	-1	19.3°
3	1	-1	1	1	-1	1	1	1	-1	17.7°
4	-1	1	-1	1	1	-1	1	1	1	17.6°
5	-1	-1	1	-1	1	1	-1	1	1	24°
6	-1	-1	-1	1	-1	1	1	-1	1	13.3°
7	1	-1	-1	-1	1	-1	1	1	-1	7.5°
8	1	1	-1	-1	-1	1	-1	1	1	8.7°
9	1	1	1	-1	-1	-1	1	-1	1	9.5°
10	-1	1	1	1	-1	-1	-1	1	-1	18.7°
11	1	-1	1	1	1	-1	-1	-1	1	27°
12	-1	-1	-1	-1	-1	-1	-1	-1	-1	11°

Table 3

Analysis of variance of performance index

Parameter	Variation Source	Sum of Squares	Degree of freedom	Mean Square	F value	P value
Angle of repose	Model	456.49	9	50.72	11.92	0.0798
	x_1	8.00	1	8.00	1.88	0.3039
	x_2	0.75	1	0.75	0.18	0.7155
	x_3	98.61	1	98.61	23.17	0.0406**
	x_4	120.33	1	120.33	28.27	0.0336**
	x_5	134.67	1	134.67	31.64	0.0302**
	x_6	19.76	1	19.76	4.64	0.1640
	x_7	66.27	1	66.27	15.57	0.0586*
	x_8	7.68	1	7.68	1.80	0.3113
	x_9	0.40	1	0.40	0.095	0.7873
	Residual	8.51	2	4.26		
	Cor Total	465	11			

Note: ***means extremely significant (P<0.01), **means significant (0.01≤P<0.05), *means more significant (0.05≤P<0.1)

The design and results of soil screening test were shown in Table 2. According to the significance P value of variance analysis (Table 3), the significance of factors to test indexes was determined.

The results showed that the significance of the influence on the repose angle was from large to small was soil rolling friction coefficient x_5 (P=0.030), soil-device static friction coefficient x_4 (P=0.034), soil static friction coefficient x_3 (P=0.041), soil normal stiffness per unit area x_7 (P=0.05). The simulation screening test of soil repose angle was shown in figure 7a.

Regression Model and Response Surface Analysis

In order to find the optimal parameter combination of x_5, x_4, x_3 and x_7 in the simulation test, a four-factor and five-level test design was carried out according to the central rotation combination test, and a total of 30 tests were carried out. The test plan was shown in Table 4. Other parameters were x_1=0.8, x_2=0.6, x_6=0.05, $x_8=10^6 N \cdot m^{-2}$ and x_9=1mm. The simulation regression test of soil repose angle was shown in figure 7b.

Table 4

Test design scheme and response value

Test No.	Factor				Value
	x_5	x_4	x_3	x_7	Angle of repose
1	0.2125	0.3	0.4	2.50075×10^9	29.7
2	0.5375	0.3	0.4	2.00755×10^9	32.1
3	0.2125	0.5	0.4	2.50075×10^9	25.6
4	0.5375	0.5	0.4	2.50075×10^9	33.5
5	0.2125	0.3	0.8	2.50075×10^9	26.6
6	0.5375	0.3	0.8	2.50075×10^9	26.6
7	0.2125	0.5	0.8	2.50075×10^9	26.6
8	0.5375	0.5	0.8	2.50075×10^9	30.4
9	0.2125	0.3	0.4	7.50025×10^9	26
10	0.5375	0.3	0.4	7.50025×10^9	26
11	0.2125	0.5	0.4	7.50025×10^9	26.6
12	0.5375	0.5	0.4	7.50025×10^9	29.3
13	0.2125	0.3	0.8	7.50025×10^9	26.5
14	0.5375	0.3	0.8	7.50025×10^9	31.7
15	0.2125	0.5	0.8	7.50025×10^9	31.3
16	0.5375	0.5	0.8	7.00255×10^9	33
17	0.05	0.4	0.6	5.0005×10^9	17.7
18	0.7	0.4	0.6	5.0005×10^9	37.1
19	0.375	0.2	0.6	5.0005×10^9	26.3
20	0.375	0.6	0.6	5.0005×10^9	35.4
21	0.375	0.4	0.2	5.0005×10^9	25.2
22	0.375	0.4	1	5.0005×10^9	27.5
23	0.375	0.4	0.6	10^6	32.5
24	0.375	0.4	0.6	10^{10}	31.3
25	0.375	0.4	0.6	5.0005×10^9	31.8
26	0.375	0.4	0.6	5.0005×10^9	35.2
27	0.375	0.4	0.6	5.0005×10^9	28.2
28	0.375	0.4	0.6	5.0005×10^9	30.1
29	0.375	0.4	0.6	5.0005×10^9	30.1
30	0.375	0.4	0.6	5.0005×10^9	28.7

The variance of soil repose angle results was as shown in table 5, and the overall test results were significant ($0.01 \le P < 0.05$). The soil rolling friction coefficient x_5 was extremely significant, the soil-device static friction coefficient x_4 was more significant, and the interaction between soil normal stiffness per unit area x_7 and soil static friction coefficient x_3 was significant. The quadratic term of soil static friction coefficient x_3 was significant, and the other terms were not significant to the response value. The primary and secondary order of the influence of each factor on the response value was x_5, x_4, x_3 and x_7. The insignificant variance source term was incorporated into the residual term, and then the variance analysis was carried out. After eliminating the insignificant factors, the regression equation of the influence of each factor level on the soil repose angle was obtained as follows:

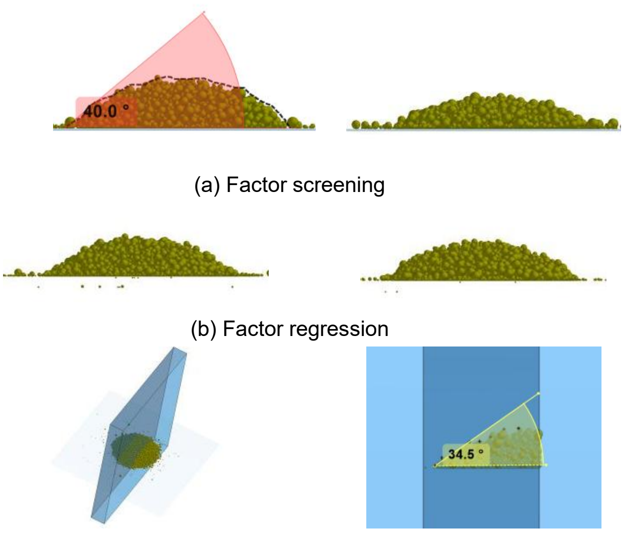
$$R = +18.37220 + 16.02564x_5 + 12.20833x_4 + 17.80934x_3 - 1.94936 \times 10^9 x_7 + 3.16282 \times 10^9 x_3 x_7 - 26.54514x_3^2 \quad (1)$$

The variance was tested for lack of fit P=0.47, which was not significant (P > 0.1), indicating that the test analysis results were reasonable and the regression equation had a high degree of fitting. The determination coefficient R^2 of the model was 0.62 and 0.7119 before and after eliminating insignificant factors, respectively, indicating that the model could fit more than 62% of the results and could be used for test prediction.

Table 5

Analysis of variance of performance index

Parameter	Variation Source	Sum of Squares	Degree of freedom	Mean Square	F value	P value
	Model	315.08	14	22.51	2.65	0.0357**
	x_5	162.76	1	162.76	19.15	0.0005***
	x_4	35.77	1	35.77	4.21	0.0581*
	x_3	3.01	1	3.01	0.35	0.5606
	x_7	0.40	1	0.40	0.047	0.8311
	x_5x_4	4.52	1	4.52	0.53	0.4773
	x_5x_3	0.33	1	0.33	0.039	0.8463
	x_5x_7	1.27	1	1.27	0.15	0.7050
	x_4x_3	4.73	1	4.73	0.56	0.4672
Angle of repose	x_4x_7	4.95	1	4.95	0.58	0.4572
	x_3x_7	40.01	1	40.01	4.71	0.0465**
	x_5^2	20.65	1	20.65	2.43	0.1399
	x_4^2	7.44×10^4	1	7.44×10^4	8.754×10^5	0.9927
	x_3^2	35.04	1	35.04	4.12	0.0605*
	x_7^2	1.82	1	1.82	0.21	0.6506
	Residual	127.50	15	8.50		
	Lack of fit	95.07	10	9.51	1.47	0.3526
	Pure error	32.43	5	6.49		
	Cor total	442.57	29			



(a) Factor screening

(b) Factor regression

(c) Factor verification

Fig. 7 - Soil repose angle test

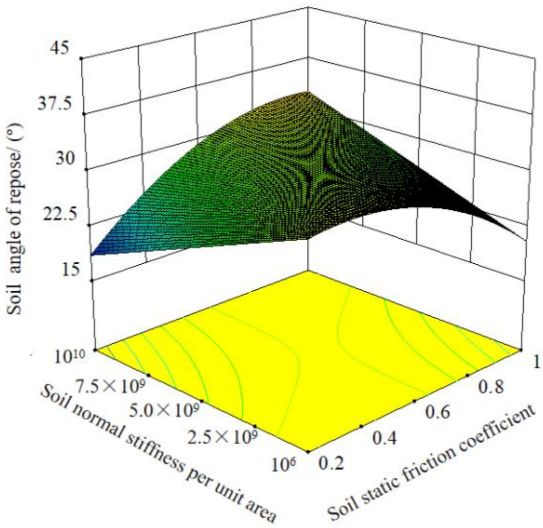


Fig. 8 - Response surface of interaction factors to indexes

The Design Expert software was used to analyze the significance of the interaction factors of the test results. When the soil rolling friction coefficient x_5 was 0.375 and the soil-device static friction coefficient x_4 was 0.4, the response surface of the interaction between the soil static friction coefficient x_3 and the soil normal stiffness per unit area x_7 to the repose angle was shown in Figure 8.

The influence of soil static friction coefficient and soil normal stiffness per unit area on the interaction was not much different. When the value of x_7 was constant, with the increase of x_3, the repose angle first increases and then decreases. When the value of x_3 was constant, the repose angle decreases steadily with the increase of the soil normal stiffness per unit area.

In order to obtain better working performance parameters, the regression model was optimized and solved within the factor level range. The model was solved with the target value R=35.22°, and the soil rolling friction factor was 0.574, the soil static friction factor was 0.930, the soil-device static friction factor was 0.373, and the soil normal stiffness per unit area was 9.5×10^9. Using the optimized parameters, three repeated simulation tests were carried out. The average value of the simulated repose angle was 34.12°, and the relative error with the actual physical repose angle was 3.1 %. The simulation verification test of soil repose angle was shown in figure 7c.

Straw Simulation Test and Result Analysis

Factor Significance Screening Test

The design and results of straw screening test were shown in table 6. According to the significance P value of variance analysis variables, the influence on the test indexes was determined. The significance of the influence on the repose angle from large to small was straw static friction coefficient X_4 (P=0.004), device-straw restitution coefficient X_1 (P=0.011), device-straw rolling friction coefficient X_5 (P=0.066). The simulation screening test of straw repose angle was shown in Figure 9a.

Table 6

Straw screening test design and results

Test No.	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	R
1	1	1	-1	1	1	1	-1	-1	-1	33°
2	-1	1	1	-1	1	1	1	-1	-1	11°
3	1	-1	1	1	-1	1	1	1	-1	35.8°
4	-1	1	-1	1	1	-1	1	1	1	20°
5	-1	-1	1	-1	1	1	-1	1	1	12°
6	-1	-1	-1	1	-1	1	1	-1	1	25.3°
7	1	-1	-1	-1	1	-1	1	1	-1	20°
8	1	1	-1	-1	-1	1	-1	1	1	19.2°
9	1	1	1	-1	-1	-1	1	-1	1	20°
10	-1	1	1	1	-1	-1	-1	1	-1	26.9°
11	1	-1	1	1	1	-1	-1	-1	1	30°
12	-1	-1	-1	-1	-1	-1	-1	-1	-1	16.6°

Table 7

Analysis of variance of performance index

Parameter	Variation Source	Sum of Squares	Degree of freedom	Mean Square	F value	P value
Angle of repose	**Model**	673.69	9	74.85	38.92	0.0253**
	X_1	177.87	1	177.87	92.48	0.0106**
	X_2	7.68	1	7.68	3.99	0.1837
	X_3	0.21	1	0.21	0.11	0.7708
	X_4	434.40	1	434.40	225.86	0.0044***
	X_5	26.40	1	26.40	13.73	0.0657*
	X_6	0.65	1	0.65	0.34	0.6190
	X_7	2.61	1	2.61	1.36	0.3640
	X_8	0.33	1	0.33	0.17	0.7176
	X_9	23.52	1	23.52	12.23	
	Residual	3.85	2	1.92		
	Cor Total	677.54	11			

Regression Model and Response Surface Analysis

In order to find the optimal parameter combination of X_4, X_1 and X_5 in the simulation test, a three-factor and five-level test design was carried out according to the central rotary combination test, and a total of 20 tests were carried out. The test scheme was shown in table 8. Other parameters were X_2=0.3, X_3=0.3, X_6=0.0825, X_7=10^{10}, X_8=10^6 and X_9=1. The simulation regression test of straw accumulation angle was shown in figure 9b.

Table 8

Test design scheme and response value

Test No.	Factor			Value
	X_4	X_1	X_5	Angle of repose R/°
1	0.425	0.35	0.0825	30.6
2	0.675	0.35	0.0825	24.3
3	0.425	0.65	0.0825	28.2
4	0.675	0.65	0.0825	30.4
5	0.425	0.35	0.2275	25.9
6	0.675	0.35	0.2275	23.6
7	0.425	0.65	0.2275	26.7
8	0.675	0.65	0.2275	25
9	0.3	0.5	0.155	25.4
10	0.8	0.5	0.155	26
11	0.55	0.2	0.155	25.2
12	0.55	0.8	0.155	32.8
13	0.55	0.5	0.01	26.8
14	0.55	0.5	0.3	20.6
15	0.55	0.5	0.155	27.2
16	0.55	0.5	0.155	27.4
17	0.55	0.5	0.155	30
18	0.55	0.5	0.155	28.3
19	0.55	0.5	0.155	30.4
20	0.55	0.5	0.155	26.8

The variance of the repose angle results was shown in table 9, and the overall test results were significant (0.01≤P<0.05). The effect of the device-straw restitution coefficient X_1 on the repose angle was significant, and the effect of the device-straw rolling friction coefficient X_5 on the repose angle was extremely significant. The interaction between the straw static friction coefficient X_4 and the device-straw restitution coefficient X_1 had a significant effect on the repose angle. The quadratic term of the device-straw restitution coefficient X_1 had a significant effect on the repose angle. The quadratic term of the device-straw rolling friction coefficient X_5 had a very significant effect on the repose angle, and the other terms had no significant effect on the response value. The order of influence of each factor on the response value was X_5, X_1, X_4. The non-significant variance source term was incorporated into the residual term, and then the variance analysis was carried out. After eliminating the non-significant factors, the regression equation of the influence of each factor level on the straw repose angle was obtained as follows:

$$\begin{aligned} R = &+27.34760+14.55381X_4-24.57500X_1+48.68991X_5 \\ &+60.66667X_4X_5-43.94286X_4^2-225.75166X_5^2 \end{aligned} \tag{2}$$

The variance was tested for lack of fit P= 0.49, which was not significant (P>0.1), indicating that the test analysis results were reasonable and the regression equation had a high degree of fitting. The coefficient of determination R^2 of the model before and after eliminating insignificant factors were 0.8033 and 0.7964, respectively, indicating that the model could fit more than 79% of the results and could be used for test prediction.

The test results were analyzed and processed by Design Expert software. When the device-straw rolling friction coefficient X_5 was 0.155, the response surface of the interaction between the straw static friction coefficient X_4 and the device-straw restitution coefficient X_1 on the repose angle was shown in Figure 10.

The straw static friction coefficient had a great influence on the interaction. When the straw static friction coefficient was constant, with the increase of the device-straw restitution coefficient, the straw repose angle increased. When the value of the device-straw restitution coefficient was constant, with the increase of the static friction coefficient of the straw, the repose angle of the straw increased first and then decreased.

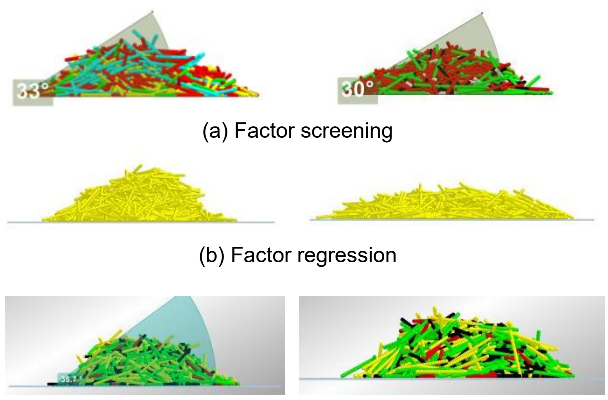
Table 9

Analysis of variance of performance index

Parameter	Variation Source	Sum of Squares	Degree of freedom	Mean Square	F value	P value
Angle of repose	**Model**	123.65	9	13.74	4.54	0.0135**
	X_4	2.98	1	2.98	0.98	0.3448
	X_1	27.83	1	27.83	9.19	0.0126**
	X_5	38.13	1	38.13	12.60	0.0053***
	X_4X_1	10.35	1	10.35	3.42	0.0941*
	X_4X_5	1.25×10^{-3}	1	1.25×10^{-3}	4.13×10^{-4}	0.9842
	X_1X_5	0.28	1	0.28	0.093	0.7667
	X_4^2	10.59	1	10.59	3.50	0.0910*
	X_1^2	0.78	1	0.78	0.26	0.6227
	X_5^2	33.19	1	33.19	10.96	0.0079***
	Residual	30.27	10	3.03		
	Lack of fit	18.71	5	3.74	1.62	0.3049
	Pure error	11.56	5	2.31		
	Cor total	153.91	19			

In order to obtain better working performance parameters, the regression model was optimized and solved within the factor level range. The model was solved with the target value R=31.28°, and the straw static friction coefficient X_4 was 0.598, the device-straw restitution coefficient X_1 was 0.754, and the device-straw rolling friction coefficient X_5 was 0.11. The optimized parameters were used to carry out three repeated simulation tests.

Using the optimized parameters, three repeated simulation tests were carried out. The average value of the simulated repose angle was 31.73°, and the relative error with the actual physical repose angle was 1.45 %. The simulation verification test of straw repose angle was shown in figure 9c.



(a) Factor screening

(b) Factor regression

(c) Factor verification

Fig. 9 - Straw repose angle test

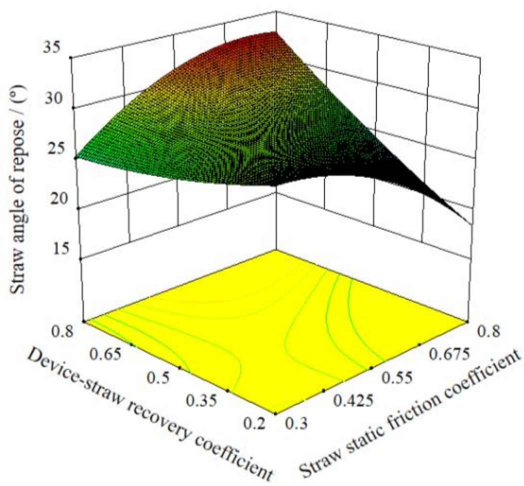


Fig. 10 - Response surface of interaction factors to indexes

CONCLUSIONS

Based on the discrete element simulation software EDEM, the Hertz–Mindlin with Bonding contact model was used to simulate wheat straw and soil in the Huang-Huai-Hai region, and the relevant parameters were calibrated. In the discrete element model, the soil particle diameters ranged from 2.5 to 7.5 mm, and four straw lengths (20 mm, 30 mm, 40 mm, and 50 mm) were selected. The repose angle was measured using Kinovea 2023.

A combination of physical experiments and simulation tests was used. The factors that had significant effects on the repose angles of straw and soil were identified through a Plackett-Burman screening test.

The factor screening test showed that the primary and secondary factors influencing the soil repose angle were the soil rolling friction coefficient, the soil-device static friction coefficient, the soil static friction coefficient, and the soil normal stiffness per unit area. For the straw repose angle, the main influencing factors were the device-straw rolling friction coefficient, the device-straw restitution coefficient, and the straw static friction coefficient. Based on the Central Composite Design test, regression models for the soil and straw repose angles and their significant parameters were established. Variance analysis and interaction effect analysis of the regression models were then performed.

Taking the measured physical repose angle as the optimization target, the parameters influencing the accumulation angle were optimized and solved. The optimized soil parameters were: rolling friction coefficient of 0.574, static friction coefficient of 0.93, soil-device static friction coefficient of 0.373, and soil normal stiffness per unit area of 9.5×10^{9}. The relative error between the simulation with optimized parameters and the physical experiment was 3.1%. The optimized straw parameters were: static friction coefficient of 0.598, device-straw restitution coefficient of 0.754, and device-straw rolling friction coefficient of 0.11. The relative error between the simulation and the experiment under these parameters was 1.45%, confirming the reliability of the proposed simulation parameter calibration. These results provide a reference for calibrating discrete element simulation parameters of farmland soil and straw in the Huang-Huai-Hai region.

ACKNOWLEDGEMENT

The author was supported by the doctoral research start-up fee (318052520).

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