RESEARCH ON CONTACT PARAMETER CALIBRATION AND EXPERIMENT OF DISCRETE ELEMENT SIMULATION MODEL FOR RICE STRAW
/
水稻秸秆离散元仿真接触参数标定与试验研究

Guoyang LIU[1,2)], Kaixuan WANG*[1,2)], Xiliang CHEN[1,2)], Jiayuan GONG[1,2)], Zhaowen DENG[1,2)], Bangshuai LI[1,2)]
[1)] School of Intelligent Connected Vehicle, Hubei University of Automotive Technology, Shiyan 442002 / China
[2)] Hubei Engineering Research Center for Intelligent Connected Vehicles and Electronic Control, Shiyan 442002, China
Tel: +86 18707280876; E-mail: 20240104@huat.edu.cn
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ABSTRACT
Considering the current suboptimal calibration of critical contact parameters in the discrete element model (DEM) for rice straw, which consequently limits the applicability of DEM in the design of rice straw processing machinery, this study developed a DEM of rice straw using EDEM software to accurately calibrate the contact parameters. The physical dimensions and the repose angle of rice straw, as well as the friction coefficients between rice straw-rice straw and rice straw-steel plate were determined through physical experiments. Image processing combined with the least squares method was employed to obtain the angle of repose of rice straw. The Plackett-Burman experimental design was selected to screen the contact parameters that significantly influence the repose angle. The results indicated that the coefficient of restitution between rice straw particles, the static friction coefficient between rice straw particles, and the rolling friction coefficient between rice straw particles have a significant effect on the angle of repose of the granular pile. A Box-Behnken design (BBD) was used to establish a second-order response surface model between the contact parameters and the angle of repose. The optimal combination of contact parameters was obtained by performing target optimization using response surface methodology (RSM). A validation experiment for the repose angle was conducted, and the results indicated a relative error of 2.13% between the simulated angle of repose and the physical angle of repose. The result demonstrates that the calibrated parameters can be used for simulating the contact behavior of rice straw and can provide theoretical and data support for the discrete element simulation of the rice straw processing process.

摘要
针对目前水稻秸秆离散元模型的关键接触参数尚未完全优化，限制了离散元模型在水稻秸秆处理设备设计中的应用效果等问题。本研究借助 EDEM 软件构建了水稻秸秆离散元模型开展接触参数标定，通过开展水稻秸秆的物理尺寸，堆积角以及水稻秸秆-水稻秸秆、水稻秸秆-钢板间的摩擦系数测试试验，采用图像处理结合最小二乘法来获得水稻秸秆的堆积角。通过 Plackett —Burman 试验筛选出对堆积角影响显著的接触参数，得出水稻秸秆间碰撞恢复系数、水稻秸秆间静摩擦系数、水稻秸秆间滚动摩擦系数对水稻秸秆颗粒堆休止角影响显著。采用 Box-Behnken 设计（Box-Behnken Design）建立接触参数与休止角之间的二阶响应模型，结合响应曲面法进行目标寻优，获取最优接触参数组合。并进行堆积角验证试验，试验表明仿真堆积角与实际物理堆积角相对误差值为 2.13%。结果证明所标定参数可用于水稻秸秆接触行为的模拟，能够对水稻秸秆处理过程的离散元仿真模拟提供理论和数据支持。

INTRODUCTION
With the acceleration of global agricultural mechanization, the processing and utilization of rice straw as one of the major staple crops, have become increasingly prominent issues (*Zhang et al., 2025*). Rice straw represents not only a significant biomass resource but also plays a crucial role in soil improvement and environmental protection (*Martinez-Guillén et al., 2025*). However, traditional methods for straw treatment, such as burning and stacking, not only result in resource wastage but also contribute to environmental pollution (*Cuong et al., 2025*). Consequently, the exploration of efficient and environmentally friendly straw processing technologies has become a matter of urgent necessity.

Guoyang Liu, Ph.D.; Kaixuan Wang, master degree.; Xiliang Chen, Ph.D.; Jiayuan Gong, Assoc. Prof.; Zhaowen Deng, Prof.; Bangshuai Li, Ph.D.

In this context, discrete element simulation technology, as an advanced numerical simulation method, provides new research insights for the processing of rice straw (*Li et al., 2024*). Through discrete element simulation, the interactions between straw and agricultural machinery, soil, and other media can be precisely modelled, offering scientific basis for the design and optimization of straw processing machinery (*Zou et al., 2024*). Among these, the repose angle, as an important parameter for measuring material flow characteristics, plays a crucial role in the calibration of discrete element contact model parameters (*Chen et al., 2025; Tan et al., 2021*). Numerous studies have been conducted by scholars worldwide on the calibration of discrete element contact model parameters, focusing primarily on the interaction between agricultural machinery and straw, the influence of environmental factors, multi-scale simulation, and simulation of comprehensive straw utilization (*Mohammadi et al., 2025; Zhang et al., 2025*). He et al investigated the impact of different rotary tillage operation parameters on the spatial distribution quality of straw using discrete element simulation and field experiments. They found that the blade roller speed and forward speed significantly affect the uniformity of straw distribution. The simulation results were in good agreement with the experimental data, providing theoretical support for the optimization of rotary tillage machine parameters and the prediction of straw returning quality (*He et al., 2022*). Liu et al addressed the issue of insufficient parameter accuracy for flexible rice straw in discrete element simulations by calibrating the discrete element parameters for both the flexible straw and the soil. Considering the cohesive forces between soil particles, they used the soil repose angle as an experimental index to calibrate the model parameters and established a discrete element model for straw-covered soil (*Liu et al., 2023*). A comprehensive and in-depth exploration of the mechanical properties of straw and an analysis of its interactions with machine components constitute the essential theoretical foundation for the design and parameter optimization of straw utilization equipment (*Xie et al., 2024*). Xia et al addressed the issue of lacking an accurate straw discrete element model for analyzing the interaction between straw and cutting tools during the design optimization process of straw returning machinery. Using rice straw as the research object, they adopted a particle replacement method to construct a flexible discrete element model for rice straw and conducted calibration of the discrete element contact model parameters along with multi-working-condition experimental validation (*Xia et al., 2024*). Furthermore, other researchers have combined indoor soil bin tests and field experiments to thoroughly investigate the interaction mechanisms among rice straw, rotary blades, and soil, providing crucial references for the optimized design of rotary tillage machinery. Li et al developed a discrete element model based on the Hertz-Mindlin bond V2 contact model to reproduce the realistic process of straw deformation. They calibrated the bonding parameters using compression, shear, and three-point bending tests. Orthogonal experiments were conducted to determine the optimal parameter combination. The results indicated that the proposed straw model accurately simulated the cracking, breaking, and flow characteristics (*Li et al., 2024*).

In summary, although significant progress has been made in the study of the interaction between agricultural machinery and straw, the influence of environmental factors, and multi-scale simulation, both domestically and internationally, the simulation results often deviate from reality due to the imprecision of contact parameters. The angle of repose is the minimum angle formed between a pile of loose granular material and the horizontal surface when it rests. It is an important parameter that describes the flow characteristics of granular materials and has wide applications in engineering design, materials science, and granulometry. The angle of repose is influenced by various factors, including particle shape, size, surface roughness, density, moisture content, and interparticle friction and adhesion forces. By measuring the angle of repose, one can evaluate the flowability of granular materials and predict their behavior during storage, transportation, and processing, providing a basis for the design and operation of related equipment. Taking rice straw fragments as the research object, actual and simulated experiments of roller lifting were conducted. The relative errors of the angle of repose and the angle of repose were used as experimental indicators. Through Plackett-Burman experiments, the contact parameters that significantly affect the indicators were screened out. Response surface methodology (RSM) was employed to establish a second-order mathematical model between the significant parameters and each indicator. Using optimization methods, a more convergent and diverse set of optimal solutions was obtained, and validation experiments of the angle of repose were conducted. This study aims to provide a reference for the parameter calibration of the discrete element model of rice straw and to offer more substantial and specific theoretical support for the efficient utilization of rice straw and the development of agricultural mechanization.

MATERIALS AND METHODS

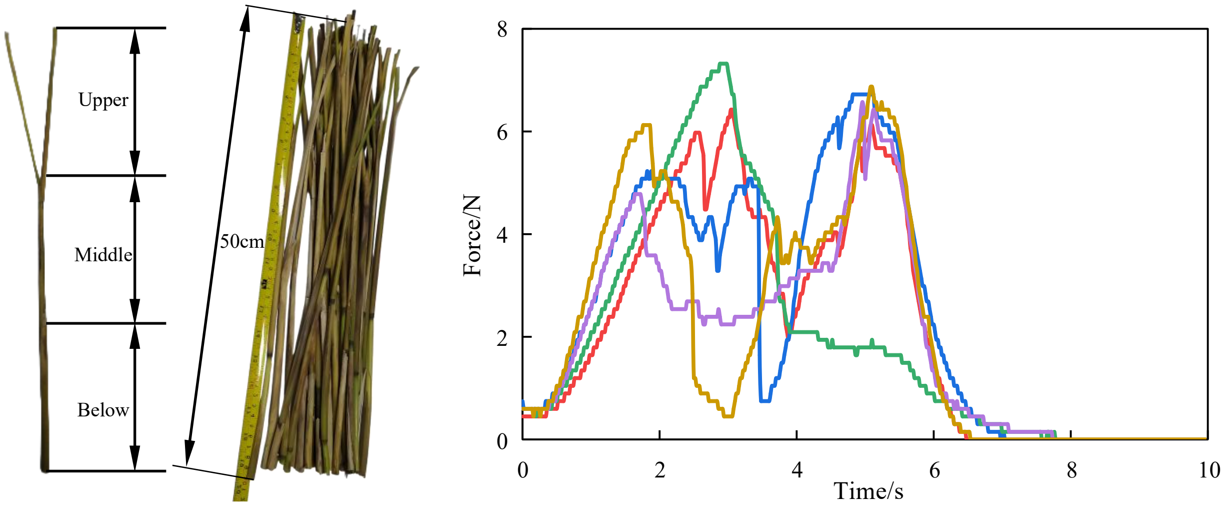
Experimental materials

In this study, rice straw samples were collected from the modern agricultural science and technology experimental base of Huazhong Agricultural University. After being harvested by a rice combine harvester, the average stubble height of the straw was between 45 and 65 cm. One hundred undamaged straws were randomly selected, and 50 cm sections were cut from the base of each straw to create experimental samples. The outer dimensions of these samples were measured using a Vernier caliper, the measured data being presented in Table 1. Additionally, cylindrical specimens with a diameter of approximately 6 mm and a length of 50 mm were prepared from the middle sections of the rice straw stems. These specimens were subjected to a flat-plate uniaxial compression test using a TMS-Pro Texture Analyzer (FTC Company, USA). The compression test was conducted at a speed of 20 mm/min with a loading displacement of 5 mm, and the test was repeated 10 times. As shown in Figure 1, by analyzing the changes in height and diameter before and after the uniaxial compression test, the shear modulus, elastic modulus, and Poisson's ratio of the rice straw were calculated to be 1.2×10^6 Pa, 3.4×10^6 Pa, and 0.4, respectively.

Table 1

Statistics of rice straw size parameters

Measurement parameters	Diameter			Wall thickness		
Stem position	Upper	Middle	Below	Upper	Middle	Below
Maximum value/mm	5.37	6.55	8.57	1.05	1.34	1.55
Minimum value/mm	3.83	5.08	5.97	0.41	0.45	0.70
Average value/mm	4.78	5.70	7.01	0.72	0.96	1.01
Standard deviation	0.57	0.44	0.79	0.22	0.26	0.27
Coefficient of variation	0.12	0.08	0.11	0.30	0.27	0.27



(a) Measurement of various parts of rice straw (b) Mechanical properties testing of rice straw

Fig. 1 - Measurement of rice straw parameters

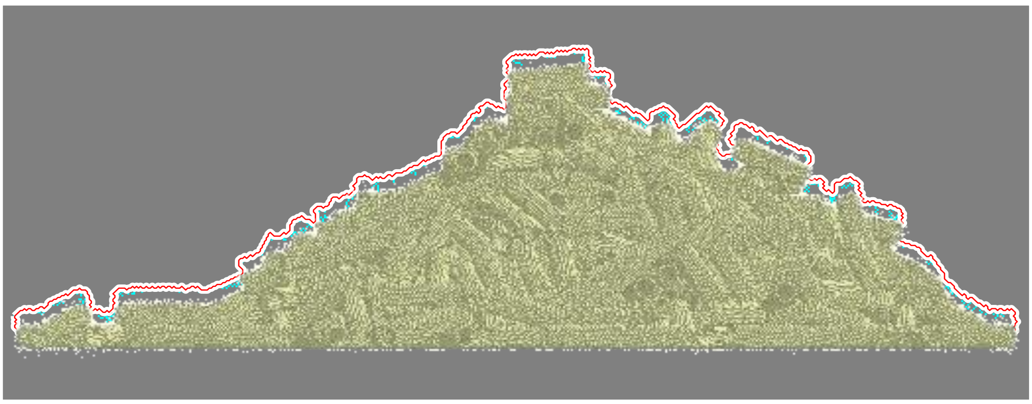
Experimental method

Based on previous research, the cylindrical lift method was employed to measure the angle of repose of rice straw, providing experimental data for the calibration of discrete element simulation contact parameters (*Chen et al., 2025; Guo et al., 2025*). Using EDEM software, the Hertz-Mindlin model was applied to conduct simulation experiments on the response angle of rice straw. This model, in essence, decomposes the movement and force interactions between rice straw particles into three components: normal movement, tangential movement, and rolling movement between the particles (*Zeng et al., 2021*). As shown in Figure 2, the rice straw was cut into five different lengths of 20, 30, 40, 50, and 60 mm as prefabricated samples and mixed in equal mass proportions. These were then filled into a steel cylinder with an inner diameter of 80 mm and a height of 150 mm. A universal material testing machine was used to lift the cylinder at a constant speed of 0.05 m/s, forming a pile of rice straw, and the angle of repose was measured. With the development of digital image processing technology, image-based methods for measuring the angle of repose have gradually emerged.

The fundamental principle of this method is to capture an image of the piled material and then use image processing algorithms to automatically identify the boundary of the material, fit its contour, and subsequently calculate the angle of repose. Compared to traditional methods, image-based measurement of the angle of repose offers advantages such as improved accuracy and repeatability. After five repeated trials, the average angle of repose was statistically determined to be 31.07°, with a standard deviation of 0.73 and a coefficient of variation of 2.35%. To ensure accuracy, the average value was taken from multiple measurements.

(a) Rice straw response angle test

(b) Extraction of rice straw response angle boundary



(c) Discrete element simulation and boundary extraction of rice straw response angle

Fig. 2 - Image processing measurement of rice straw response angle

The results of the boundary extraction and contour fitting can be seen in Figure 3. This demonstrates that the contour information of the pile can be extracted using image processing techniques. Subsequently, a mathematical model is employed to fit the contour and calculate the angle of repose. This approach is feasible. The results indicate a high fitting accuracy, with the coefficient of determination (R^2) exceeding 0.9, suggesting that the fitting model effectively describes the actual contour of the pile. The measurement results exhibit high reliability and accuracy.

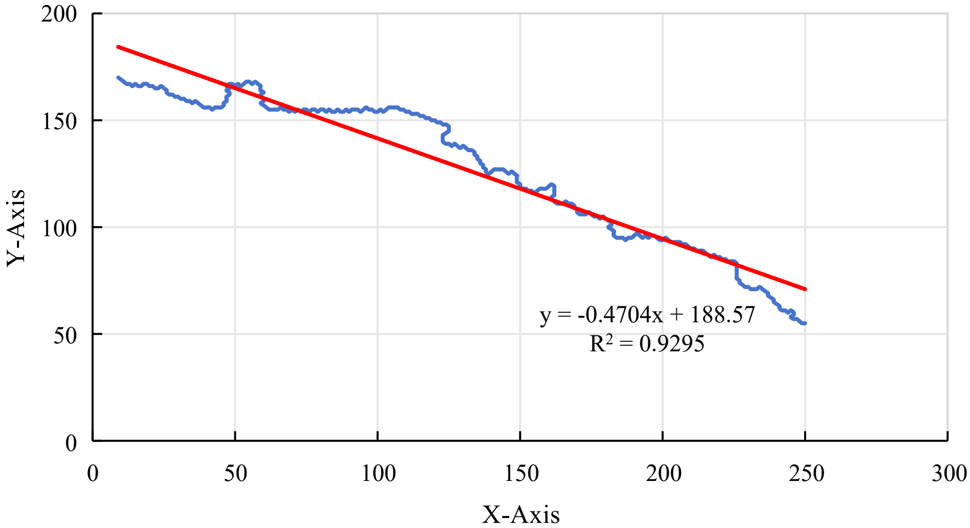


Fig. 3 - Fitting of extracted boundary curves

Contact parameter calibration

In this study, Design-Expert 10.6 software was used to design experiments, combined with EDEM software for discrete element simulation analysis of rice straw particles using the cylindrical lift method. The Plackett-Burman design was employed to screen parameters that significantly affect the angle of repose. The steepest ascent method was used to determine the range of parameter values. Subsequently, a Box-Behnken Design (BBD) orthogonal experiment was conducted, followed by variance analysis based on the experimental results. The response surface methodology was applied to establish a regression model. Optimization was performed to minimize the relative error between the simulated and measured angles of repose, ultimately calibrating the accurate contact parameters for rice straw particles. The Hertz-Mindlin model in EDEM software was used for simulating the accumulation behavior of rice straw particles, and different lengths of particle models were constructed using a combination of circular particles (as shown in Figure 4). Based on the determination of particle intrinsic parameters, as well as referencing relevant studies on contact parameters for agricultural materials and vine-like materials interacting with different materials (*Xia et al., 2024; Guo et al., 2024; Wang et al., 2020; Liao et al., 2020*), and friction tests (as shown in Figure 5), the range of variation for each simulation parameter in this study was determined, as shown in Table 2.

Table 2

Range of calibration parameters for rice straw

Parameter	Values
Rice straw density/kg·m^{-3}	228
Shear modulus of rice straw/Pa	1.2×10^{6}
Poisson's ratio of rice straw	0.4
Steel plate density/kg·m^{-3}	7865
Shear modulus of steel plate/Pa	7.9×10^{10}
Poisson's ratio of steel plate	0.3
Coefficient of restitution between rice straw (A)	0.15-0.75
Static friction coefficient between rice straw (B)	0.20-1.16
Rolling friction coefficient between rice straw €	0-0.2
Coefficient of restitution between rice straw and steel (D)	0.1-0.8
Static friction coefficient between rice straw and steel €	0.2-0.9
Rolling friction coefficient between rice straw and steel (F)	0-0.2

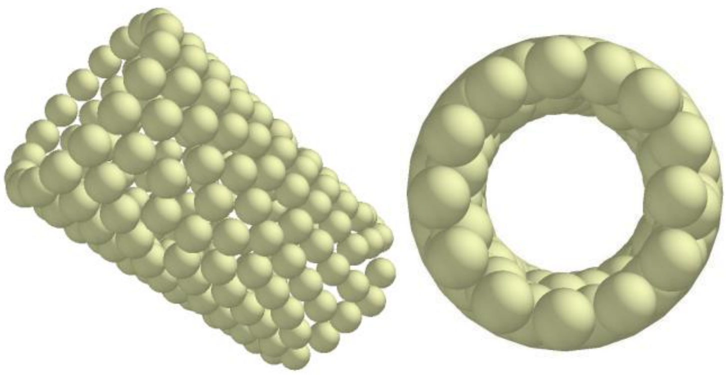
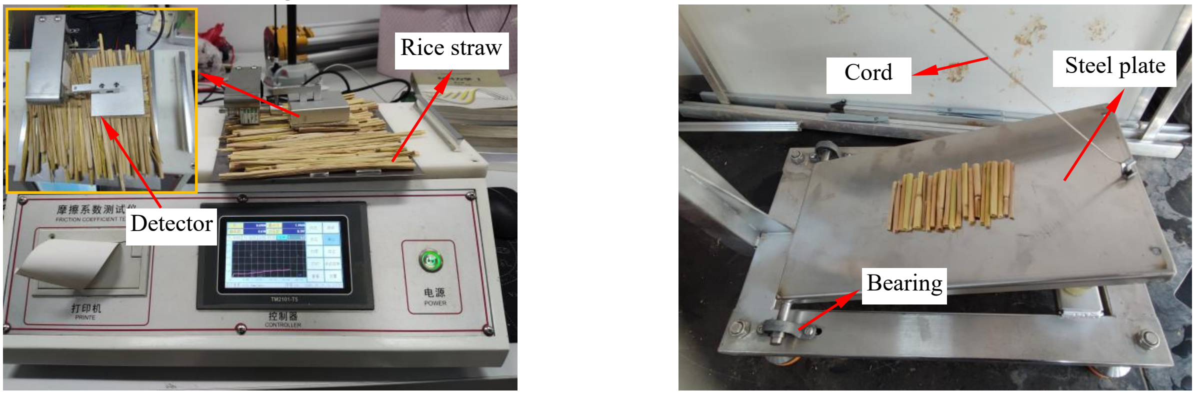


Fig. 4 – Discrete element model of broken hollow rice straw



(a) Friction coefficient measuring instrument for rice straw (b) Experiment on inclined surface of rice straw

Fig. 5 – Friction experiment of rice straw

RESULTS AND ANALYSIS

The contact parameters between rice straw and rice straw, and between rice straw and steel, as listed in Table 2, were selected as experimental factors to conduct simulation studies on the angle of repose of rice straw particles. The key factors influencing the angle of repose were investigated. A two-level fractional factorial design method was adopted, and the simulation results are summarized in Table 3, presenting the simulated angle of repose values for rice straw particles under different parameter combinations. To further determine the significant effects of each factor on the angle of repose, an in-depth significance analysis was conducted, and the results are shown in Table 4.

Table 3

Simulation values of the angle of repose of rice straw particles under different parameter combinations (Plackett-Burman)

Number	A	B	C	D	E	F	R
1	0.15	0.20	0	0.8	0.20	0.20	24.37
2	0.15	1.16	0.20	0.8	0.20	0	46.3
3	0.15	1.16	0	0.8	0.90	0	26.57
4	0.15	0.20	0.20	0.1	0.90	0.20	39.73
5	0.75	0.20	0	0.1	0.90	0	21.9
6	0.75	0.20	0.20	0.8	0.90	0	34.63
7	0.15	1.16	0.20	0.1	0.90	0.20	48.91
8	0.75	0.20	0.20	0.8	0.20	0.20	31.58
9	0.15	0.20	0	0.1	0.20	0	23.19
10	0.75	1.16	0	0.8	0.90	0.20	26.99
11	0.75	1.16	0.20	0.1	0.20	0	43.01
12	0.75	1.16	0	0.1	0.20	0.20	23.99

Based on the three significant parameters obtained from the Plackett-Burman experiment, a steepest ascent experiment was conducted to rapidly approach the optimal parameter region (Coefficient of restitution between rice straw (A), Static friction coefficient between rice straw (B), Rolling friction coefficient between rice straw (C)).

Each significant parameter was incrementally increased within its specified range according to predetermined step sizes, and simulations of the angle of repose were performed. The coefficient of restitution between rice straw and steel (D), the static friction coefficient between rice straw and steel (E), and the rolling friction coefficient between rice straw and steel (F) were set at 0.45, 0.55, and 0.10, respectively. The results are presented in Table 5.

Table 4

Analysis of variance of Plackett Burman experiment results

Parameters	Sum of squares	F-value	P-value	Significance	Significant ranking
A	60.62	8.48	0.0333	*	3
B	135.81	18.99	0.0073	**	2
C	786.51	110.00	0.0001	**	1
D	8.82	1.23	0.3172		4
E	3.30	0.46	0.5273		5
F	7.500E-005	1.049E-005	0.9975		6

*Note: * indicates significant differences in factors ($P<0.05$), ** indicates extremely significant differences in factors ($P<0.01$). The same below.*

Table 5

The steepest climbing test design scheme and result

Number	Coefficient of restitution between rice straw (A)	Static friction coefficient between rice straw (B)	Rolling friction coefficient between rice straw (C)	Repose angle	Relative error
1	0.15	0.20	0	28.97	6.76%
2	0.30	0.44	0.05	32.34	4.09%
3	0.45	0.68	0.10	35.02	12.71%
4	0.60	0.92	0.15	44.75	44.03%
5	0.75	1.16	0.20	50.09	61.22%

The data in the table indicate that as these three parameters were progressively increased, the angle of repose exhibited a significant upward trend. Specifically, when the coefficient of restitution increased from 0.15 to 0.75, the static friction coefficient from 0.20 to 1.16, and the rolling friction coefficient from 0 to 0.20, the angle of repose increased from 28.97° to 50.09°, demonstrating a significant positive effect of each parameter on the angle of repose. Among these, the rolling friction coefficient had the most pronounced influence on the angle of repose, followed by the static friction coefficient, while the impact of the coefficient of restitution was relatively smaller. However, as the angle of repose increased, the relative error also grew, rising from 6.76% to 61.22%. This suggests that under conditions of high angles of repose, the discrepancies between the simulation model and actual conditions become more pronounced, indicating a need for further model optimization to enhance accuracy. When parameters A, B, and C were set at 0.30, 0.44, and 0.05, respectively, the relative error of the simulated angle of repose was minimized. Therefore, these factor levels were adopted as the center points for the response surface experiment. Concurrently, the values of parameters from trials 1 and 3 were designated as the low and high levels for the response surface experiment, respectively.

Response surface experiment

Based on the aforementioned experimental results, the fundamental contact parameters, including the coefficient of restitution between rice straw particles, the static friction coefficient between rice straw particles, and the rolling friction coefficient between rice straw particles, were selected for a three-factor, three-level response surface methodology (RSM) experimental design. A total of 17 groups of parameter combinations were subjected to simulation experiments for the angle of repose, with five replicates conducted at the central level. The experimental design and simulation results are presented in Table 6 and Figure 6.

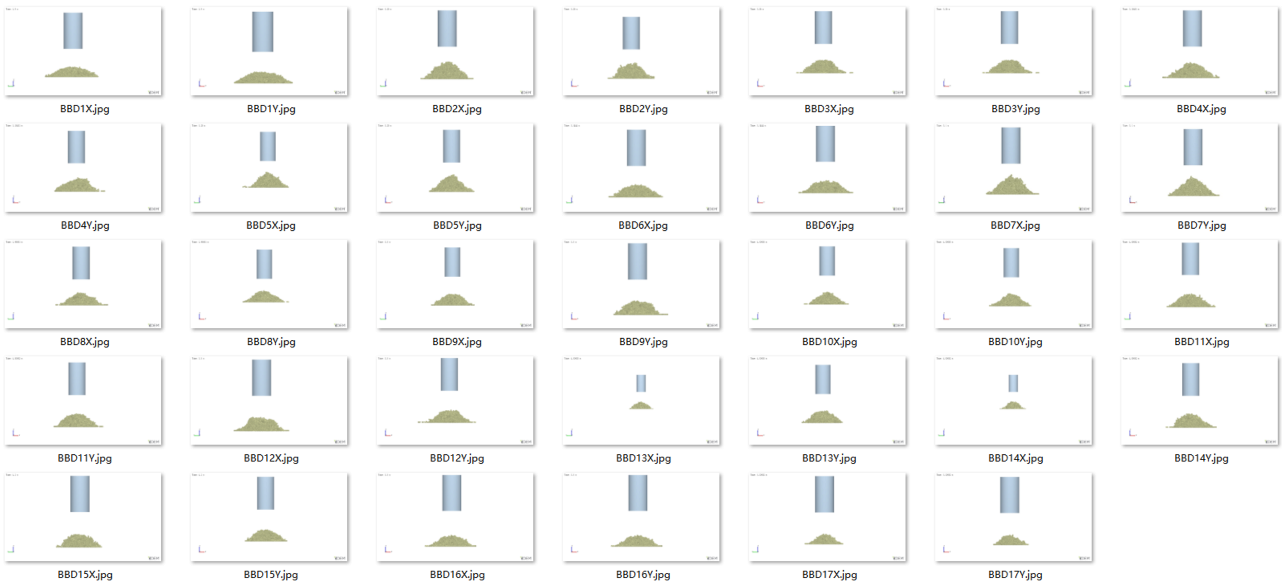


Fig. 6 - BBD experiment EDEM simulation experiment result chart

Table 6

Box Behnken experimental design

Level	Coefficient of restitution between rice straw (A)	Static friction coefficient between rice straw (B)	Rolling friction coefficient between rice straw (C)
-1	0.15	0.20	0
0	0.30	0.44	0.05
+1	0.45	0.68	0.10

Table 7

Box Behnken experimental results

Number	Coefficient of restitution between rice straw (A)	Static friction coefficient between rice straw (B)	Rolling friction coefficient between rice straw (C)	Repose angle
1	**0**	**-1**	**-1**	29.81
2	0	1	1	42.66
3	1	1	0	46.44
4	0	0	0	39.83
5	-1	0	1	37.78
6	-1	0	-1	32.94
7	1	0	1	41.15
8	1	-1	0	34.56
9	0	0	0	38.96
10	0	-1	1	33.28
11	0	0	0	39.18
12	0	1	-1	35.61
13	0	0	0	38.30
14	0	0	0	37.74
15	-1	1	0	39.98
16	1	0	-1	31.73
17	-1	-1	0	40.30

Table 8

Analysis of variance of Box-Behnken experimental results

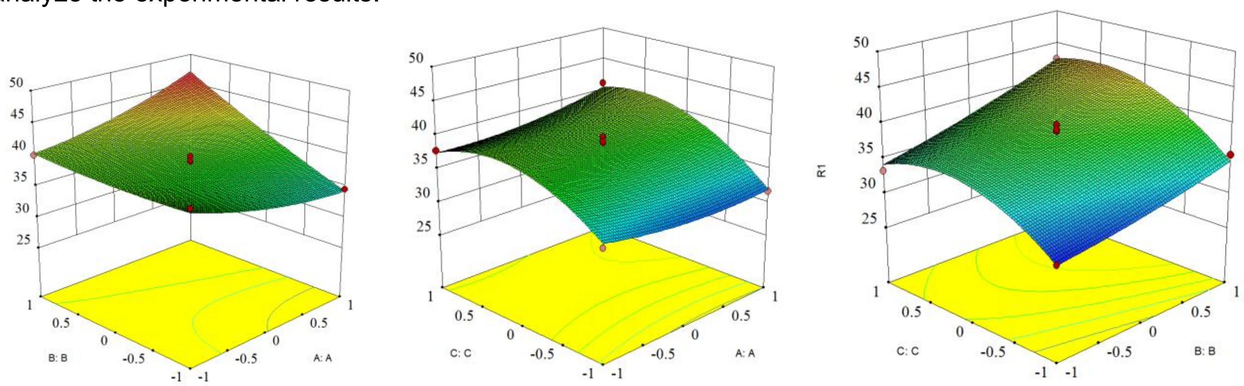
Source	Sum of Squares	Mean Square	F Value	P-Value	Significance
Model	281.57	31.29	35.04	< 0.0001	**
A-A	1.04	1.04	1.16	0.3169	
B-B	89.38	89.38	100.1	< 0.0001	**
C-C	76.76	76.76	85.96	< 0.0001	**
AB	37.21	37.21	41.67	0.0003	**
AC	5.24	5.24	5.87	0.0459	*
BC	3.2	3.2	3.59	0.1	
A2	4.55	4.55	5.09	0.0587	
B2	0.97	0.97	1.08	0.3328	
C2	65.4	65.4	73.24	< 0.0001	**
Residual	6.25	0.89			
Lack of Fit	3.65	1.22	1.87	0.2761	
Pure Error	2.6	0.65			
Cor Total	287.82				

Analysis of variance (ANOVA) was performed on the experimental results using Design-Expert 10.6 software, yielding the significance of each simulation parameter, as presented in Table 8. Table 8 indicates that the P-values for the static friction coefficient between rice straw (B) and the rolling friction coefficient between rice straw (C) were both less than 0.01, demonstrating an extremely significant effect on the simulation test angle of repose. In contrast, the P-value for the coefficient of restitution between rice straw (A) was greater than 0.05. This outcome is not uncommon and aligns with the inherent characteristics of the experimental design methodology employed. The Plackett-Burman (PB) design, utilized as an efficient screening method, primarily aims to rapidly identify factors with potential significant effects on the response variable within a limited number of experimental runs, focusing on estimating main effects. However, the estimation of effects by PB designs may lack precision, and the relatively small number of runs increases the probability of Type I errors, where factors that are actually non-significant might be preliminarily identified as significant. When these three factors were selected based on the PB results for subsequent investigation using a Box-Behnken Design (BBD), the BBD was implemented to provide a more precise estimation of the main effects and interaction effects of these selected factors, and to fit a quadratic model for response optimization. The ANOVA associated with the BBD typically offers a more rigorous and accurate analysis. Consequently, observing P-values below 0.05 for two factors and above 0.05 for one factor in the BBD ANOVA suggests that, under the more precise BBD design and analysis, one factor initially flagged as potentially significant by the PB screening did not exhibit a main effect or individual contribution that reached the predetermined significance threshold. This precisely underscores the necessity of transitioning from a screening design (PB) to an optimization design (BBD), which serves to validate and refine the preliminary screening results, thereby ensuring the accuracy and reliability of the final analysis. From the perspective of factor interactions, the interaction between the coefficient of restitution (A) and the static friction coefficient (B) was found to be extremely significant ($P < 0.01$), the interaction between the coefficient of restitution (A) and the rolling friction coefficient (C) was significant ($P < 0.05$), whereas the interaction between the static friction coefficient (B) and the rolling friction coefficient (C) was not significant.

The response surfaces depicting the effects of the interaction between various factors on the angle of repose are shown in Figure 7. Multivariate regression analysis was performed on the experimental results listed in the table using Design-Expert software, yielding a second-order regression model for the simulated angle of repose of rice straw in relation to the three significant parameters. The equation for this model is:

$$\begin{aligned}\theta=&45.80-70.22A-22.54B+140.97C+84.72AB+152.67AC\\&+74.58BC+46.18A^2+8.32B^2-1576.40C^2\end{aligned} \tag{1}$$

As shown in Figure 7a, with the rolling friction coefficient (C) between the rice straw held constant, the angle of repose gradually increased with the coefficient of restitution (A), and the rate of this increase progressively accelerated. Conversely, as the static friction coefficient (B) between the rice straw increased, the angle of repose decreased slightly, with a minor change in magnitude. Figure 7b illustrated that when the static friction coefficient (B) was held constant, the angle of repose gradually decreased with an increase in the coefficient of restitution (A), and the rate of decrease slowed slightly. Furthermore, as the rolling friction coefficient (C) increased, the angle of repose exhibited a trend of first decreasing and then increasing. Figure 7c indicated that with the coefficient of restitution (A) held constant, the angle of repose gradually increased with the static friction coefficient (B), but the rate of increase progressively diminished. Additionally, as the rolling friction coefficient (C) increased, the angle of repose decreased and eventually stabilized. As shown in Table 8, the ANOVA results for the angle of repose revealed a highly significant quadratic regression model, with $F = 35.04$ and $P < 0.0001$. The coefficient of determination (R^2) was 0.9783, the adjusted coefficient of determination (R^2adj) was 0.9504, and the lack-of-fit term was not significant ($P > 0.05$). These results indicate a good fit of the regression equation, suggesting that this equation can be effectively used to analyze the experimental results.



(a) C=0 (b) B=0 (c) A=0

Fig. 7 - Response surface of interaction between factors

Within the range of the experimental factor levels set, the optimization module of Design-Expert software was utilized to optimize the regression model for the angle of repose, targeting the measured physical angle of repose of 31.07°. As shown in Table 9, several sets of solutions were obtained. Subsequently, simulation verification of the angle of repose was conducted for these solutions. One optimal set of solutions was identified, which yielded a simulated shape closely resembling the physical experimental results. The optimization results were utilized to calibrate and determine the optimal combination of simulation parameters for rice straw. After rounding, the final values were set as follows: the restitution coefficient, static friction coefficient, and rolling friction coefficient for rice straw-rice straw were 0.29, 0.22, and 0.01, respectively. Other less significant simulation parameter values were retained at the previously determined values mentioned above.

Tabel 9

Multiple sets of optimization solution results

Number	Coefficient of restitution between rice straw (A)	Static friction coefficient between rice straw (B)	Rolling friction coefficient between rice straw (C)	Repose angle	Relative error
1	0.422	0.239	0.015	30.19	2.83%
2	0.266	0.269	0.000	34.61	11.39%
3	0.444	0.202	0.021	26.65	14.23%
4	0.291	0.224	0.005	31.13	0.19%
5	0.404	0.362	0.003	38.18	22.88%
6	0.290	0.347	0.000	31.42	1.13%
7	0.424	0.397	0.000	31.84	2.48%
8	0.401	0.291	0.009	28.51	8.24%
9	0.350	0.268	0.008	33.29	7.15%

Number	Coefficient of restitution between rice straw (A)	Static friction coefficient between rice straw (B)	Rolling friction coefficient between rice straw (C)	Repose angle	Relative error
10	0.313	0.381	0.000	29.81	4.06%
11	0.341	0.307	0.005	26.12	15.93%
12	0.372	0.396	0.001	32.38	4.22%
13	0.389	0.200	0.017	34.47	10.94%
14	0.281	0.307	0.001	31.45	1.22%

To further validate the reliability of the discrete element model for rice straw and the optimized simulation parameters, targeted experiments were designed and conducted. A comparison and analysis were performed between the simulation results and the experimental data. The simulation experiments were replicated five times, yielding measured angles of repose of 32.37°, 31.48°, 32.46°, 31.03°, and 31.32°. The average simulated angle of repose was 31.73°, with a coefficient of variation of 2.03% and an average relative error of 2.13%. The results indicate that the optimized parameter combination can significantly improve straw processing efficiency and reduce energy consumption, showing good agreement with the simulation results. This confirms the effectiveness of the model and the optimization methodology.

CONCLUSIONS

(1) Through experiments, the diameters of the upper, middle, and lower sections of the rice straw were measured to be 4.78, 5.70, and 7.01 mm, respectively. The shear modulus, Young's modulus, and Poisson's ratio were determined to be 1.2×10^{6} Pa, 3.4×10^{10} Pa, and 0.4, respectively. The average angle of repose for the rice straw was measured to be 31.07°. The ranges for the contact parameters were established as follows: restitution coefficient between rice straw 0.15-0.75, static friction coefficient between rice straw 0.20–1.16, rolling friction coefficient between rice straw 0–0.2, restitution coefficient between rice straw and steel 0.1–0.8, static friction coefficient between rice straw and steel 0.2–0.9, and rolling friction coefficient between rice straw and steel 0–0.2.

(2) A discrete element model for rice straw was established, and the contact parameters were calibrated. The angle of repose for rice straw was obtained through image processing combined with the least squares method. Using the Plackett-Burman experimental design, the contact parameters significantly influencing the angle of repose were screened. The results indicated that the restitution coefficient, static friction coefficient, and rolling friction coefficient between rice straw particles significantly affected the angle of repose of the particle pile.

(3) A second-order response model relating the contact parameters to the angle of repose was constructed using the Box-Behnken Design (BBD). Analysis of variance (ANOVA) results revealed the order of significance of the factors as follows: rolling friction coefficient between rice straw (C), static friction coefficient between rice straw (B), coefficient of restitution between rice straw (A).

(4) Target optimization methods were employed to obtain the optimal combination of contact parameters: inter-straw restitution coefficient of 0.29, inter-straw static friction coefficient of 0.22, and inter-straw rolling friction coefficient of 0.01. Subsequently, validation experiments for the angle of repose were conducted. Compared to the actual value of 31.07°, the experimental results showed that the simulated angle of repose was 31.73°, with a coefficient of variation of 2.03% and an average relative error of 2.13%.

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