CALIBRATION OF CONTACT PARAMETERS BETWEEN WHEAT AND KEY COMPONENTS OF GRAIN LEVELING ROBOTS BASED ON DISCRETE ELEMENT METHOD
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基于离散元法的小麦与平粮机器人关键部件接触参数标定

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ABSTRACT

To address the lack of reliable discrete element method (DEM) parameters for wheat leveling using grain leveling robots, Wan Ken Mai 22 wheat grains were selected as the research material. Intrinsic and contact parameters – including static friction, coefficient of restitution, and rolling friction – between wheat grains, steel plates, and rubber surfaces were determined through physical experiments. Using the angle of repose as the response variable, Plackett–Burman, steepest ascent, and Box–Behnken experimental designs were employed to identify significant factors, determine optimal parameter ranges, and obtain optimized parameter combinations. The reliability of the calibrated parameters was verified using a t-test comparing simulation and experimental results. The results indicate that the static friction coefficient, coefficient of restitution, and rolling friction coefficient are 0.5023, 0.4700, and 0.1110 for wheat–steel; 0.622, 0.419, and 0.137 for wheat–rubber; and 0.53, 0.52, and 0.04 for wheat–wheat contacts, respectively. The simulated angles of repose (27.57°, 27.25°, and 26.83°) showed no significant difference from the experimental values (P = 0.5485 > 0.05). The calibrated DEM parameters provide a reliable basis for structural design, parameter optimization, and coupled simulation of tracked grain leveling robots.

摘要

针对平粮机器人在平整小麦过程中缺乏适用离散元仿真参数的问题，以'皖垦麦 22'籽粒为研究对象，采用物理试验测定籽粒本征参数及与钢板、橡胶间的静摩擦系数、碰撞恢复系数和滚动摩擦系数。以堆积角为响应变量依次进行 Plackett-Burman 试验、最陡爬坡试验及 Box-Behnken 响应面试验，筛选出显著性影响参数、确定出最优参数区间并优化参数组合，并对仿真结果与物理试验数据进行 T 检验分析验证可靠性。结果表明：小麦籽粒与钢板的静摩擦系数、碰撞恢复系数、滚动摩擦系数分别为 0.5023、0.4700、0.1110；与橡胶的对应系数分别为 0.622、0.419、0.137；籽粒颗粒间的对应系数分别为 0.53、0.52、0.04。仿真堆积角（27.57°、27.25°、26.83°）与物理试验值无显著差异（P=0.5485>0.05）。本研究标定的离散元仿真参数可为履带式平粮机器人平粮装置的结构设计、工作参数优化及耦合仿真分析提供参考。

INTRODUCTION

As one of China's primary grain crops, wheat requires leveling operations during post-harvest storage and transportation to ensure grain storage safety and minimize losses *(Zhang et al., 2022)*. Tracked grain leveling robots, leveraging their efficient and automated operational advantages, have gradually become the core equipment for large-scale grain storage leveling operations. Their performance directly impacts grain leveling quality and storage efficiency. The Discrete Element Method (DEM), as an efficient numerical technique for simulating bulk material dynamics, has been extensively applied in agricultural machinery design and optimization. It precisely reveals the interaction mechanisms between granular materials and mechanical components, providing scientific support for digital equipment development *(Tian et al., 2023)*.

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Extensive research has been conducted by scholars worldwide on calibrating discrete element parameters for grains. Internationally, Polish researchers have used a two-stiffness Hertz contact model to simulate the compaction and unloading behavior of stored wheat.

Through single-particle compression tests, lateral confinement compression tests, and EDEM simulations, they calibrated contact parameters between wheat particles and between particles and silo walls *(J Horabik et al., 2020)*. In 2012, researchers calibrated the parameters of a discrete-element model for rice using the angle of repose test and validated the results using a grain separator *(Miyamoto et al., 2012)*. *González-Montellano et al., (2012),* found through experiments that there are significant measurement errors in the contact parameters of irregular particles such as corn kernels and olive pits. In domestic studies, researchers have used the angle of repose of wheat piles as the response variable. Through Plackett-Burman and Box-Behnken experiments, they screened and optimized significantly influential contact parameters *(Liu et al., 2016)*. By calibrating the impact recovery coefficient, rolling friction coefficient, and static friction coefficient between the wheat and the conveyor belt, *Sun* and his team resolved the issue of missing discrete element parameters during wheat conveyance on belt conveyors, thereby providing a reference basis for simulating the conveyance of wheat on inclined conveyors *(Sun et al., 2021)*. *Hu* scholars used the response surface method in combination with a hybrid algorithm of particle swarm optimization and backpropagation to calibrate the parameters for the discrete element simulation of wheat straw feed *(Hu., 2025)*. In 2022, researchers focused primarily on calibrating the contact parameters between alfalfa seeds and coating powder, and conducted related discrete element simulation parameter calibration work (*Xue et al., 2022*). *Wang et al., (2021),* proposed a multi-scale particle aggregation modeling approach to address missing material motion parameters in wheat harvesting DM models, calibrating stem-related friction coefficients and coefficients of restitution. *Yang et al., (2025),* addressed the technical requirements for precision seed hole formation and mulch-covered seed placement during dry-seeded rice cultivation in Yunnan. They systematically calibrated contact parameters between rice seeds and between rice seeds and nylon materials, designing a tailored seed placer accordingly. *Chen et al., (2024),* simulated corn-mechanical interactions during production and transport. They calibrated corn-steel plate contact parameters using the inclined plane method and optimized inter-corn parameters through steepest ascent and response surface experiments, providing references for optimizing agricultural equipment design. *Zhang et al., (2025),* constructed a rice seed model and calibrated contact parameters to simulate interactions between non-spherical rice seeds and seeders. Through a series of experimental designs, they optimized and determined key parameters for a multi-sphere rice DEM model.

However, existing research has primarily focused on calibrating grain parameters during seeding and harvesting/conveying operations. Specialized parameters tailored for tracked grain-leveling robots remain scarce, and significant morphological and physical variations exist among wheat varieties. Applying generic parameters to *Wan Ken Mai 22* wheat often leads to simulation errors *(Cui et al., 2024)*. Therefore, this study uses *Wan Ken Mai 22* wheat seeds as the research material. By determining key contact parameters through physical experiments and combining discrete element method (DEM) simulation with response surface methodology, a parameter system suitable for tracked grain-leveling robots is established. This work provides a theoretical and technical basis for the structural design of tracked grain-leveling devices, optimization of operating parameters, and coupled simulation analysis.

MATERIALS AND METHODS

Test Materials

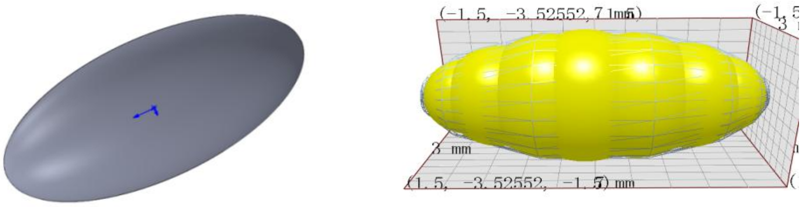
The experimental wheat seeds were *Wan Ken Mai 22*, provided by the Anhui Academy of Agricultural Sciences. The bulk density of the wheat was measured by the displacement method as 870 kg/m³, and the seed moisture content was determined by the drying method as 11% *(Bai et al., 2023)*. Using a digital vernier caliper (accuracy 0.02 mm), the three-axis dimensions (length, width, and thickness) of the seeds were found to follow a normal distribution *(Ma et al., 2025)*. The mean length was 7.02 mm (standard deviation 0.15 mm); the mean width was 3.50 mm (standard deviation 0.12 mm); and the mean thickness was 3.12 mm (standard deviation 0.10 mm). Three parallel samples (1000 intact seeds per sample) were selected and weighed using an electronic balance (accuracy 0.01 g) to determine the 1000-seed weight, which averaged 39.8 g. All physical tests in this study were conducted in a climate-controlled laboratory under the following environmental conditions: temperature 25±1°C and relative humidity 60±5%, to prevent fluctuations in temperature and humidity from interfering with the physical properties of the wheat grains and the test results.

Test Methods

This study determined the static friction coefficient, coefficient of restitution, and rolling friction coefficient for seed-seed, seed-steel plate, and seed-rubber interactions through inclined plane slip tests, free-fall collision tests, and inclined plane rolling tests, respectively. Based on the parameters obtained from the physical experiments, combined with the discrete element simulation method, Plackett-Burman experiments, steepest ascent experiments, and Box-Behnken experiments were sequentially conducted with the angle of repose as the response variable to calibrate and validate the discrete element simulation model of wheat seeds. T-tests were performed using SPSS on both simulation results and experimental data to validate the reliability of the simulation experiments and determine the optimal combination of simulation parameters.

Discrete Element Simulation Model for Wheat Grain Particles

Based on the triaxial dimensions of *Wan ken Mai 22* seeds measured in this study, a three-dimensional solid model of the seed was created using SOLIDWORKS software. This 3D model was then imported into EDEM software in STL format. The Hertz-Mindlin discrete element contact model was selected, employing spherical particles for filling. Considering the significant impact of particle count on simulation time—excessive particles drastically increase simulation duration while insufficient particles lead to substantial model-reality discrepancies *(Ma et al., 2025)*—a balanced approach was adopted. Seven spherical particles with radii ranging from 0.9 to 1.4 mm were used for filling. The seed's 3D model and discrete element model are shown in Figure 1.



(a) 3D Model (b) Discrete element model

Fig. 1 – 3D-model of wheat seeds and discrete element model

To visually demonstrate the application platform for parameter calibration in this study and clarify the contact scenarios between wheat grains and key components of the grain leveling robot, Figure 2 presents the physical structure of the tracked grain leveling robot along with annotations of its core contact parts. The numbered components—specifically the steel grain leveling shovel, grain leveling comb, and rubber tracks—directly interact with the grains. Subsequent contact parameter calibrations will focus on the materials corresponding to these components.

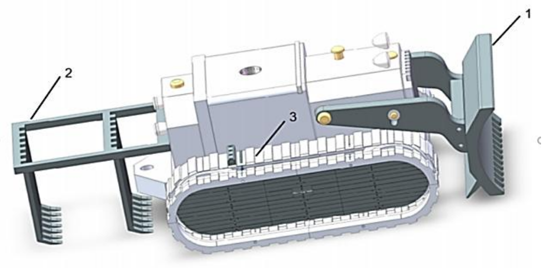


Fig. 2 – Physical Structure of Tracked Grain Leveling Robot and Annotation of Core Contact Components

WHEAT GRAIN CONTACT PARAMETER CALIBRATION AND OPTIMIZATION

Contact parameters primarily include static friction coefficient, rolling friction coefficient, coefficient of restitution, and angle of repose *(Hou et al., 2020)*. Based on engineering practice and the manufacturing materials of grain leveling robots *(Xing et al., 2020)*, components in the grain leveling device that directly contact wheat seeds include: front and rear leveling blades made of steel plates, leveling combs, and rubber tracks. Therefore, the contact parameters between wheat seeds and steel plates, between wheat seeds and rubber tracks, and between wheat seeds themselves are critical references for structural design and operational parameter optimization of the grain leveling device. The fundamental parameters for wheat seed discrete element simulation are listed in Table 1. This study employs EDEM software for simulation experiments.

Table 1

Basic parameters for discrete element method simulation of winter wheat seeds

Simulation parameters	Unit	Numeric	Literature sources
Poisson's ratio of wheat	—	0.29	*(Wang. et al., 2024)*
Shear modulus of wheat	[Pa]	$5.01\text{x}10^8$	*(Wang. et al., 2024)*
Density of wheat	[kg/m^3]	870	This research
Poisson's ratio of steel plate	—	0.3	*(Zhang. et al., 2018)*
Shear modulus of steel plate	[Pa]	$7.9\text{x}10^{10}$	*(Zhang. et al., 2018)*
Density of steel plate	[kg/m^3]	7865	*(Zhang. et al., 2018)*
Poisson's ratio of rubber	—	0.48	*(Jin. et al., 2022)*
Shear modulus of rubber	[Pa]	$1\text{x}10^9$	*(Jin. et al., 2022)*
Density of rubber	[kg/m^3]	1380	*(Jin. et al., 2022)*

Basic Determination Test for Contact Parameters

Determination of Static Friction Coefficient Test

This experiment employed the inclined plane slip test method to determine the static friction coefficients between wheat grains of different varieties, as well as between wheat grains and the two materials: steel plate and rubber *(Zhang. et al., 2022)*. The tests were conducted using a homemade static friction coefficient tester. Materials used included: several undamaged wheat grains from the same batch, from which 50 grains were randomly selected as test specimens. The remaining grains were used to prepare test specimens: wheat grain plates, steel plates, and rubber plates (each with dimensions L×W×H=200mm×200mm×4mm, as shown in Figures 3(a), 3(b), and 3(c), respectively). The apparatus comprised a self-made tester, an angle measuring instrument, and double-sided adhesive tape as auxiliary material.

Fig. 3(a) – To-be-tested Wheat Seed Plate

Fig. 3(b) – To-be-tested Steel Plate

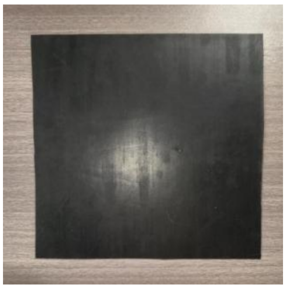


Fig. 3(c) – To-be-tested Rubber Plate

The test panel was mounted horizontally on the experimental apparatus, and corresponding platforms were prepared for different contact surfaces (Fig. 4(a): seed–seed interface; Fig. 4(b): seed–steel interface; Fig. 4(c): seed–rubber interface). Five intact wheat seeds from the same batch were evenly placed on the panel. The inclination angle of the panel was increased slowly and uniformly until at least 3 seeds began to slide. At this point, the test was stopped immediately, and the sliding friction angle θ was recorded using a goniometer. Ten sample groups were prepared, with ten repeated measurements conducted for each group. The static friction coefficient was calculated based on the average sliding friction angle. The standard deviations of the static friction coefficient for each contact surface (seed–seed: 0.012; seed–steel: 0.009; seed–rubber: 0.015) were used to evaluate data dispersion and measurement uncertainty. The static friction coefficient between wheat seeds and each contact material was determined as $tan\theta$. The results are presented in Table 2.

Fig. 4(a) – Seed-seed interface test platform

Fig. 4(b) – Seed-plate interface test bench

Fig. 4(c) – Seed-rubber sheet interface test bench

Table 2

Coefficient of static friction between wheat seed particles and different materials

Materials	Slope angle / [°]	Coefficient of static friction	Standard deviation
Wheat seeds	27.9	0.53	0.012
Steel plate	26.3	0.494	0.009
Rubber	31.9	0.622	0.015

Determination Test for Coefficient of restitution

During leveling, mutual compression and collision occur between wheat seeds, between wheat and leveling components, and between wheat and the track *(Hou et al., 2020)*. The coefficient of restitution is a parameter measuring an object's ability to return to its original shape after collision. It is defined as the ratio of the relative velocity of two objects after separation to their relative approach velocity before collision. The calculation formula for the coefficient of restitution e of wheat grains is shown in Equation (1) *(Ma et al., 2025)*. The test employed the free-fall impact method to determine the coefficient of restitution between wheat grains and three test materials; the testing principle is illustrated in Figure 5. The distance between the test bench funnel and the test material sample was set to 200 mm, and the background plate was calibrated to 10 mm increments. High-speed imaging was performed using a digital camera, and the recorded videos were played back at 10× slow motion to observe and measure the rebound height of the grains after impact with the test material. Each test group was repeated ten times, and the average rebound height was used to calculate the coefficient of restitution. The standard deviations of the impact recovery coefficients measured at each interface were as follows: 0.010 for wheat grains against each other, 0.008 for grains against steel plate, and 0.011 for grains against rubber. These standard deviations comprehensively reflect the overall measurement fluctuations caused by factors such as deviations in the falling position of the grains and errors in high-speed photography measurements during the test. The results of the impact recovery coefficient measurements are shown in Table 3.

$$e = \frac{|v_2 - v_1|}{|V_2 - V_1|} = \frac{|v_2|}{|V_2|} = \sqrt{\frac{h}{H}} \tag{1}$$

where: V_1 is the initial velocity of wheat during free fall, i.e. $V_1 = 0\, m/s$; V_2 is the initial velocity of wheat before colliding with the test material, [m/s]; v_1 is the velocity of wheat at its highest rebound point after colliding with the test material, [m/s]; v_2 is the velocity of wheat after colliding with the test material, i.e. v_2=0 m/s; h is the height of wheat before free fall, [mm]; H is the maximum rebound height of the wheat kernel after impact, [mm].

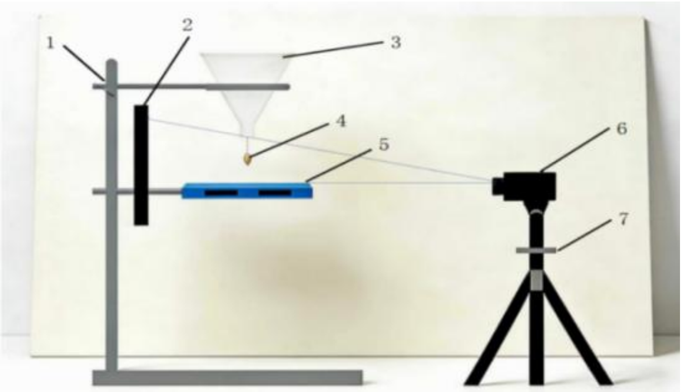


Fig. 5 – Schematic diagram of the free-fall test for wheat seeds

1. Bracket; 2. Grid plate with graduations; 3. Funnel; 4. Wheat seeds; 5. Test material;
6. High-speed camera; 7. Tripod

Table 3

Coefficient of coefficient of restitution between wheat seed particles and different materials

Materials	Drop height /[mm]	Coefficient of restitution	Standard deviation
Wheat seeds	200	0.52	0.010
Steel plate	200	0.472	0.008
Rubber	200	0.419	0.011

Determination of Rolling Friction Coefficient Test

The rolling friction coefficient between wheat seeds and test materials (wheat seed plates, steel plates, and rubber plates) was calibrated using the inclined plane rolling test method, with the experimental principle illustrated in Figure 6. During testing, the angle θ between the material plate and the horizontal plane was first adjusted to an appropriate value. Seeds were then placed at the top of the inclined plane, ensuring a consistent rolling distance S (set to 20 mm) for each trial. Due to frictional forces, the seeds ultimately came to rest on the horizontal material plate *(Ma et al., 2025)*. Each test was repeated 10 times. The grain rolling distance L was recorded, and the average value was used to calculate the rolling friction coefficient. The standard deviations of the rolling friction coefficient for each contact surface were as follows: wheat–wheat: 0.007; wheat–steel: 0.006; wheat–rubber: 0.009. Measurement errors mainly arose from small deviations in initial grain placement and manual reading errors of rolling distances. According to Equation (2), the rolling friction coefficient μ_0 between the wheat seed and the material plate under test can be obtained. The measurement results are shown in Table 4.

$$mg\sin\theta \times S = \mu_0 mg\cos\theta \times S + \mu_0 mgL \tag{2}$$

where:

m is the mass of the wheat seed, [Kg]; θ is the inclination angle of the test plate, [°]; S is the rolling distance of the wheat seed on the inclined test plate, [mm]; μ_0 is the coefficient of rolling friction between the wheat seed and the test plate; L is the rolling distance of the wheat seed on the horizontal test plate, [mm].

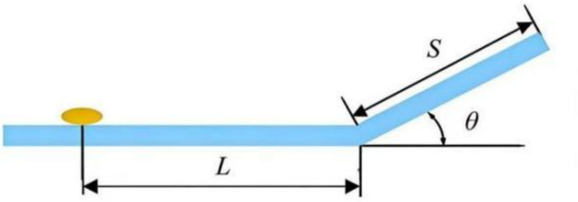


Fig. 6 – Schematic diagram of wheat seed rolling test on inclined plane

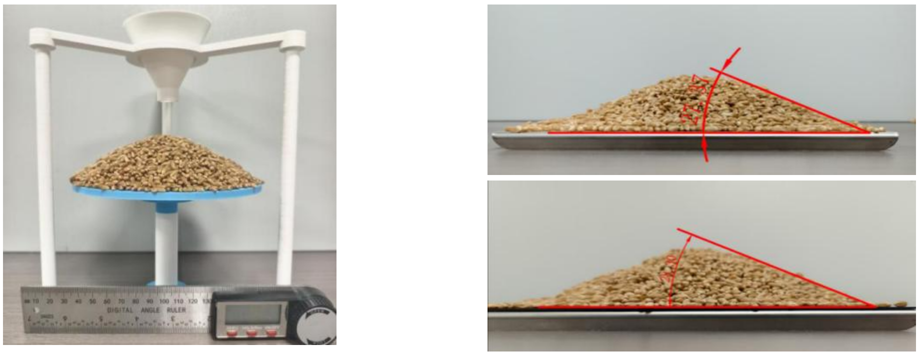
Table 4

Coefficient of rolling friction between wheat seed particles and different materials

Materials	Rolling length of slope / [mm]	Coefficient of rolling friction	Standard deviation
Wheat seeds	20	0.08	0.007
Steel plate	20	0.113	0.006
Rubber	20	0.137	0.009

Determination of the angle of repose

The angle of repose is a macroscopic parameter reflecting the flow ability and friction characteristics of granular materials, and seed accumulation also occurs during grain leveling *(Liu et al., 2016; Yang et al., 2023)*. To further validate the accuracy of the calibrated parameters, the angle of repose was selected as the test indicator. This experiment employed the funnel method to measure the angle of repose, as illustrated in Figure 7(a). Wheat seeds were placed into the funnel. As the seeds fell, they formed a roughly conical pile on the designated test platform. A camera was centered and positioned at the same height as the platform. Images of the wheat pile were captured, and the angle of repose was measured using boundary extraction in image processing software, as shown in Figure 7(b). After repeating the test 10 times, the average angle of repose of 28.30° was taken as the reference value for the actual physical test. The standard deviation of the measurement was 0.25°, with measurement errors primarily attributable to boundary extraction errors in the image processing software and random pile-up deviations caused by the falling grains *(Al-Hashemi B.M.H. et al., 2018)*.



(a) Bench-scale test setup (b) Pile formation and angle measurement

Fig. 7 – Angle of repose test for wheat

Optimization and Simulation Calibration of Contact Parameters

Determination of Significant Influence Factors for Contact Parameters

In this study, Design-Expert software was used to conduct Plackett-Burman experimental design and data analysis. Experimental parameters were determined based on the results of the aforementioned physical experiments. Using the angle of repose of wheat grains as the response variable, the Plackett-Burman test was employed to identify parameters that have a significant effect on the response variable. Due to differences in the material properties of rubber and steel plates, the interaction mechanisms between the grains and the contact materials are entirely different, thereby altering the relative influence of each factor on the angle of repose. Therefore, separate Plackett-Burman experiments were required. Nine experimental parameters were selected, with each parameter set at three levels (low, medium, and high), represented by codes −1, 0, and +1, as shown in Tables 5 and 7. In this study, all Plackett-Burman simulation experiments were repeated three times, and the average of the simulated angle of repose results was taken as the experimental result. The standard deviations of the simulated angles of repose for the grain-steel plate and grain-rubber plate groups were 0.32° and 0.28°, respectively, ensuring the reliability of the simulation results. The Plackett-Burman test plan and results are shown in Tables 6 and 8.

Table 5

Plackett-Burman Test Parameter Range Table

Test parameters	Low level(-1)	Middle level(0)	High level(+1)
Coefficient of restitution (seed–steel), x1	0.372	0.472	0.572
Static friction coefficient (seed–steel), x2	0.394	0.494	0.594
Rolling friction coefficient (seed–steel), x3	0.063	0.113	0.163
Coefficient of restitution (seed–seed), x4	0.420	0.520	0.620
Static friction coefficient (seed–seed), x5	0.480	0.530	0.580
Rolling friction coefficient (seed–seed), x6	0.060	0.080	0.100

Table 6

Plackett–Burman Experimental Design and Results

Run	Test parameters						Angle of repose /[°]
	X1	X2	X3	X4	X5	X6	
1	1	1	-1	1	1	1	31.26
2	-1	1	1	-1	1	1	33.21
3	1	-1	1	1	-1	1	31,72
4	-1	1	-1	1	1	-1	27.54
5	-1	-1	1	-1	1	1	27.75
6	-1	-1	-1	1	-1	1	23.00
7	1	-1	-1	-1	1	-1	26.51
8	1	1	-1	-1	-1	1	33.24
9	1	1	1	-1	-1	-1	33.06
10	-1	1	1	1	-1	-1	33.59
11	1	-1	1	1	1	-1	28.36
12	-1	-1	-1	-1	-1	-1	25.11

Table 7

Plackett-Burman Test Parameter Range Table

Test parameters	Low level(-1)	Middle level(0)	High level(+1)
Coefficient of restitution (seed–seed), x4	0.420	0.520	0.620
Static friction coefficient (seed–seed), x5	0.480	0.530	0.580
Rolling friction coefficient (seed–seed), x6	0.060	0.080	0.100
Coefficient of restitution (seed–rubber), x7	0.319	0.419	0.519
Static friction coefficient (seed–rubber), x8	0.522	0.622	0.722
Rolling friction coefficient (seed–rubber), x9	0.087	0.137	0.187

Table 8

Plackett-Burman Test Protocol and Results

Run	Test parameters						Angle of repose / [°]
	x4	x5	x6	x7	X8	X9	
1	1	1	1	1	1	-1	28.56
2	-1	1	1	-1	1	1	29.20
3	1	-1	1	1	-1	1	27.10
4	1	1	-1	-1	1	-1	24.98
5	-1	1	1	-1	-1	1	28.09
6	1	-1	1	-1	-1	-1	26.49
7	-1	1	-1	1	-1	-1	25.73
8	-1	-1	1	1	1	-1	28.79
9	-1	-1	-1	1	1	1	22.73
10	1	-1	-1	-1	1	1	23.74
11	1	1	-1	1	-1	1	23.14
12	-1	-1	-1	-1	-1	-1	23.12

Analysis of variance (ANOVA) was performed on the results of the B-P screening test to determine the influence of each parameter, as shown in Tables 9 and 10. The analysis revealed that in the angle of repose test conducted between steel plates and seeds, the seed-steel plate coefficient of restitution (X1), the seed-steel plate static friction coefficient (X2), and the seed-steel plate rolling friction coefficient (X3) significantly affected the angle of repose, while the influence of other parameters was relatively minor. In the angle of repose tests conducted between rubber and seeds, only the seed-seed rolling friction coefficient (X6) significantly influenced the angle of repose, while the effects of other parameters were minor. Therefore, only the significantly influential factors listed above were considered in the subsequent steepest ascent test and Box-Behnken test.

Table 9

Significance analysis of Plackett-Burman test parameters

parameters	Sum of Squares	Degree of freedom	Mean Square	F	Significance
X1	16.2169	1	16.2169	6.5700	Significant
X2	72.2752	1	72.2752	29.2600	Highly significant
X3	36.8551	1	36.8551	14.9200	Significant
X4	0.9690	1	0.9690	0.3900	Not significant
X5	2.1590	1	2.1590	0.8700	Not significant
X6	3.0100	1	3.0100	1.2200	Not significant

Table 10

Significance analysis of Plackett-Burman test parameters

parameters	Sum of Squares	degree of freedom	Mean Square	F	Significance
X4	1.1102	1	1.1102	1.4700	Not significant
X5	4.9794	1	4.9794	6.6000	Not significant
X6	51.2120	1	51.2120	67.8700	Highly significant
X7	0.0154	1	0.0154	0.0200	Not significant
X8	1.5624	1	1.5624	2.0700	Not significant
X9	1.1224	1	1.1224	1.4900	Not significant

Steepest Climb Test Design

Based on the Plackett-Burman test results, the three significant parameters identified in the seed-steel plate tests (seed-steel plate coefficient of restitution, seed-steel plate static friction coefficient, seed-steel plate rolling friction coefficient) and the one significant parameter identified in the seed-rubber tests (seed-seed rolling friction coefficient) were each subjected to steepest climb tests. The relative error between the simulated angle of repose and the actual angle of repose was used as the evaluation metric. The difference from the target value was employed to determine the optimal range for the three test parameters and the optimal value for the single experimental parameter. The design and results of the steepest slope test are shown in Tables 11 and 12 *(Liu et al., 2016)*. During simulation, non-significant parameters adopted the intermediate levels from the Plackett-Burman test, while significant parameters were incrementally increased according to the selected step size *(Liu et al., 2016)*.

Table 11

Steepest ascent test results for seed–steel interactions

Run	X1	X2	X3	Angle of repose/[°]	Relative error/[%]
1	0.468	0.490	0.109	29.53	7.89
2	0.470	0.492	0.111	31.07	13.52
3	0.472	0.494	0.113	28.88	5.52
4	0.474	0.496	0.115	32.38	18.30
5	0.476	0.498	0.117	31.32	14.43

Table 12

Single-factor steepest ascent test results for seed–rubber interactions

Run	X6	Angle of repose [°]	Angle of repose [°]	Angle of repose [°]	Mean value [°]	Standard deviation	Deviation from target
1	0.030	25.97	26.73	27.62	26.77	0.83	1.53
2	0.040	32.01	26.69	29.03	29.24	2.67	0.94
3	0.050	24.63	27.59	25.78	26.00	1.51	2.30
4	0.060	28.83	33.18	32.42	31.48	2.32	3.18
5	0.070	29.53	32.36	34.53	32.14	2.51	3.84
6	0.080	32.67	33.34	29.27	31.76	2.12	3.46
7	0.090	30.30	30.31	31.26	30.62	0.56	2.32
8	0.100	31.22	31.58	30.61	31.14	0.49	2.84

Based on the relative error results in the table, when the seed-steel plate coefficient of restitution is 0.472 and the seed-steel plate rolling friction coefficient is 0.113, the relative error between the simulated angle of repose and the actual angle of repose is small. This confirms that the static friction coefficient between seeds and steel plates is 0 a static friction coefficient of 0.494 between seed and steel plate, and a rolling friction coefficient of 0.113 between seed and steel plate, the relative error between the simulated angle of repose and the actual angle of repose is relatively small. This confirms that the optimal range is centered around factor 3. Therefore, subsequent Box-Behnken response surface experiments will use factor 3 as the central point, with factors 2 and 4 representing low and high levels, respectively *(*Hou *et al., 2020)*. Based on the deviation values from the target in the table, when the seed-seed rolling friction coefficient is 0.040, the deviation from the target value is 0.940. The simulated angle of repose is closest to the measured value of 28.30. Therefore, X6 (seed-seed rolling friction coefficient) is set to 0.040. Both the seed–steel and seed–rubber steepest ascent tests were simulated three times for each parameter combination. The mean standard deviations were 0.23° and 0.19°, respectively, with an overall average standard deviation of 0.21° for both tests.

Box-Behnken Experimental Design

This study employed Design-Expert 13.0 software to conduct a Box-Behnken experimental design. Using Design 3 as the central point, Designs 2 and 4 were set at low (-1) and high (+1) levels, respectively, to perform a Box-Behnken test for significant parameters. The parameter ranges for the experiments are shown in Table 13. All other parameters in the simulation experiments were configured according to those used in the steepest climb test. The experimental plan and results are presented in Table 14. All Box-Behnken simulation results in Table 14 represent the average angle of repose from three replicate simulations, with the maximum standard deviation for any single simulation not exceeding 0.30°.

Table 13

Factor levels for the Box–Behnken design

Level value	X1	X2	X3
-1	0.470	0.492	0.111
0	0.472	0.494	0.113
+1	0.474	0.496	0.115

Table 14

Box-Behnken Experimental Design and Results

Run	X1	X2	X3	Angle of repose [°]
1	-1	-1	0	32.02
2	1	-1	0	30.84
3	-1	1	0	29.34
4	1	1	0	32,39
5	-1	0	-1	28,14
6	1	0	-1	32,51
7	-1	0	1	32,20
8	1	0	1	29.68
9	0	-1	-1	31.41
10	0	1	-1	30.85
11	0	-1	1	32.14
12	0	1	1	30.15
13	0	0	0	31,93
14	0	0	0	33.91
15	0	0	0	32,30

Using Design-Expert 13.0 software to analyze the experimental results and perform multiple regression fitting, the second-order regression equation for the angle of repose β in the wheat seed simulation test is obtained as follows:

$$\begin{gathered}\beta = 32.7133 + 0.4650A - 0.4600B + 0.1575C + 1.0575AB - 0.3575AC \\ -1.7225BC - 1.0354\,A^2 - 0.5304\,B^2 - 1.0454\,C^2\end{gathered} \tag{3}$$

Considering the significance of the factors, the second-order regression model for the angle of repose in the simplified model can be expressed as follows:

$$\beta = 32.7133 + 1.0575AB - 1.7225BC - 1.0354\,A^2 - 1.0454\,C^2 \tag{4}$$

The results of the Box-Behnken test analysis of variance are shown in Table 15. Analysis of the table reveals that A(X1), B(X2), C(X3), BC, and B2 have no significant effect on the angle of repose. AB, A2, and C2 have a significant effect on the angle of repose, while AC has a highly significant effect. The fitted model's p-value is 0.0317 (P < 0.05), indicating a significant relationship between the dependent and independent variables in this model. The coefficient of determination R² = 0.9148 indicates that the model explains 91.48% of the variation in the angle of repose, demonstrating a high degree of fit.

Table 15

Analysis of variance (ANOVA) for the second-order regression model (Box–Behnken design)

Item	Coefficient	Standard error	T-value	P-value	Significance
Intercept	32.7133	0.4202	77.851	0.0000	
A (x1)	0.4650	0.2573	1.807	0.1306	Not significant
B (x2)	-0.4600	0.2573	-1.788	0.1339	Not significant
C (x3)	0.1575	0.2573	0.612	0.5672	Not significant
AB	1.0575	0.3639	2.906	0.0336	significant
AC	-1.7225	0.3639	-4.733	0.0052	highly significant
BC	-0.3575	0.3639	-0.982	0.3710	Not significant
A^2	-1.0354	0.3788	-2.734	0.0411	significant
B^2	-0.5304	0.3788	-1.400	0.2203	Not significant
C^2	-1.0454	0.3788	-2.760	0.0398	significant
Source	**df**	**Sum of Squares**	**Mean Square**	**F-value**	**p-value**
Regression Model	9	28.4405	3.1601	5.9656	0.0317
Residual	5	2.6486	0.1526	—	—
Total	14	31.0891	—	—	—
$R^2 = 0.9775; Adjusted\ R^2 = 0.7615$					—

Simulation Parameter Calibration and Experimental Validation

In the EDEM simulation experiments, the contact and material parameters obtained from physical tests and optimization were input into the simulation model. The angle of repose measurement model was constructed strictly according to the dimensions of the actual experimental apparatus, as shown in Fig. 8. A particle factory was defined at the large-diameter opening above the hopper to generate wheat particles dynamically. The particle size was kept constant, with a generation rate of 1000 particles/s, resulting in a total of 600 particles. To ensure both computational efficiency and simulation accuracy, the mesh size was set to three times the minimum particle radius. The simulation process was as follows: during the initial stage, particles were generated from the particle factory and fell freely under gravity. Particle generation was completed at 0.6 s, and the simulation was terminated at 2.0 s. The particles accumulated naturally on the base plate to form a granular pile. The boundary of the pile was extracted using the post-processing module of EDEM, and the angle of repose was subsequently calculated.

Fig. 8 – Wheat Grain Angle of Repose Measurement Model

In MATLAB software, the aforementioned second-order regression equation was optimized and solved. The average of 1000 optimal combinations was taken, yielding the following values: seed-steel plate coefficient of restitution of 0.4700, seed-steel plate static friction coefficient of 0.5023, a seed-steel plate rolling friction coefficient of 0.1110, and a seed-seed rolling friction coefficient of 0.040. The remaining non-significant parameters were set to the physical test averages. To verify the accuracy of the optimal parameter combination, simulation tests were conducted using EDEM. The test procedure is shown in Figure 9. The results of three repetitions yielded angle of repose values of 27.57°, 27.25°, and 26.83°, with a standard deviation of 0.37°. A t-test analysis was performed using SPSS 23 software to compare simulation results with experimental values, yielding $P=0.5485>0.05$. In statistics, when P-values exceed 0.05, it is generally concluded that no significant difference exists between two data sets. This result indicates that simulation outcomes highly correlate with actual physical test values, fully validating the accuracy and reliability of the optimal parameter combination.

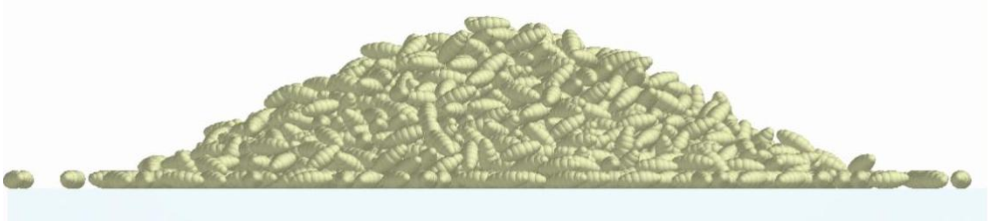


Fig. 9 – Verification of Discrete Element Simulation for Wheat Grain Angle of Repose

RESULTS

This study addresses the lack of reliable discrete element method parameters for the wheat leveling process in tracked grain leveling robots. Using *Wan Ken Mai 22* wheat seeds as the research material, a combination of physical experiments and simulation tests was employed to calibrate the contact parameters of wheat seeds. The main results are summarized as follows:

(1) The triaxial dimensions of *Wan Ken Mai 22* wheat grains follow a normal distribution. The average length, width, and thickness are 7.02 mm, 3.50 mm, and 3.12 mm, respectively. The thousand-grain weight is 39.8 g, and the bulk density is 870 kg/m³.

(2) Physical experiments were conducted to determine the static friction coefficient, coefficient of restitution, and rolling friction coefficient for three contact pairs: wheat–wheat, wheat–steel, and wheat–rubber. The corresponding values are 0.53, 0.52, and 0.08; 0.494, 0.472, and 0.113; and 0.622, 0.419, and 0.137, respectively.

(3) The results of the Plackett–Burman test indicate that, for wheat–steel interactions, the static friction coefficient, rolling friction coefficient, and coefficient of restitution are significant factors affecting the angle of repose. For wheat–rubber interactions, only the rolling friction coefficient between wheat particles is identified as a highly significant factor.

(4) The optimal DEM parameter combination obtained through the steepest ascent test and Box–Behnken design is as follows: static friction coefficient (wheat–steel) = 0.5023; coefficient of restitution (wheat–steel) = 0.4700; rolling friction coefficient (wheat–steel) = 0.1110; and rolling friction coefficient (wheat–wheat) = 0.040.

(5) The angles of repose obtained from three repeated simulation tests were 27.57°, 27.25°, and 26.83°, respectively. A t-test comparing the simulated and experimental values yielded $P = 0.5485 > 0.05$, indicating no significant difference between the two.

CONCLUSIONS

The calibrated DEM contact parameters established in this study provide essential foundational data for high-precision simulation and design of tracked grain leveling robots. These parameters can be directly applied to:

(1) Optimize the structural design of key working components, including steel leveling shovels, leveling combs, and rubber tracks.

(2) Improve operational performance, such as leveling uniformity, material flow stability, and working efficiency.

(3) Support the optimization of operating parameters, including working speed, shovel angle, and track coordination, thereby reducing grain damage and energy consumption.

(4) Shorten the research and development cycle and reduce the cost of physical prototype testing for grain leveling equipment.

This study fills the gap in DEM parameter calibration for wheat leveling processes and provides important engineering support for structural design, performance enhancement, and the digital development of intelligent grain storage machinery.

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