# CONSTRUCTION OF A DISCRETE ELEMENT MODEL OF BUCKWHEAT SEEDS AND CALIBRATION OF PARAMETERS

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## *荞麦籽粒离散元模型构建及参数标定*

**Bing Xu, Yanqing Zhang, Qingliang Cui*, Shaobo Ye, Fan Zhao**
College of Agricultural Engineering, Shanxi Agricultural University, Taigu/China
*Tel: +86-0354-6288906; E-mail: glcui@126.com*
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## ABSTRACT

*In view of the lack of seeds contact parameters that can be used as a reference for the design of key mechanical components such as buckwheat planting, harvesting, and processing, this study combines simulation optimization design experiments and physical experiments to calibrate the parameters of simulated discrete element of buckwheat seeds. The non-spherical particle model of buckwheat seeds was established using the automatic filling method, and the simulation accumulating test and physical accumulating test were carried out using the bottomless conical cylinder lifting method; the repose angle of buckwheat seeds was taken as the response value, and the initial parameters were screened for significance based on the Plackett-Burman test; and a second-order regression model of the error value for the repose angle and the significance parameter was established based on the steepest climb test and Box-Behnken test. On this basis, the minimum error value of the repose angle was used as the goal to optimize the significance parameter, the optimal combination of contact parameters was obtained, and parameter validation tests were carried out. The significance screening test showed that the buckwheat-buckwheat static friction coefficient, the buckwheat-stainless steel rolling friction coefficient, and the buckwheat-stainless steel restitution coefficient had significant effects on the repose angle of buckwheat (P<0.05). The optimization test showed that the buckwheat-buckwheat static friction coefficient was 0.510, the buckwheat-stainless steel rolling friction coefficient was 0.053, and the buckwheat-stainless steel restitution coefficient was 0.492. The validation test showed that the repose angle of buckwheat seeds under such parameter was 25.39°, and the error with the repose angle of the physical test was 0.55%, which indicated that the optimal parameter combination was reliable. This study could provide a seed model and simulation contact parameters for the research and development of buckwheat sowing, threshing and hulling machinery.*

## 摘要

*针对可供荞麦种植、收获、加工等机械关键部件设计参考的籽粒接触参数缺乏的现状，本研究结合仿真优化设计试验与物理试验对荞麦籽粒进行离散元仿真参数标定。采用自动填充法建立了荞麦籽粒非球颗粒模型，并采用无底锥筒提升法进行了仿真堆积试验与物理堆积试验；以荞麦籽粒休止角为响应值，基于 Plackett-Burman 试验对初始参数进行了显著性筛选；基于最陡爬坡试验与 Box-Behnken 试验建立了休止角误差值与显著性参数的二阶回归模型，此基础上以休止角误差值最小为目标，对显著性参数进行寻优，得到了接触参数最优组合，并进行参数验证试验。显著性筛选试验表明：荞麦-荞麦静摩擦因数、荞麦-不锈钢滚动摩擦因数、荞麦-不锈钢恢复系数对荞麦休止角影响显著（P<0.05）。优化试验表明：荞麦-荞麦静摩擦因数为 0.510，荞麦-不锈钢滚动摩擦因数为 0.053，荞麦-不锈钢恢复系数为 0.492。验证试验表明：此参数下荞麦籽粒休止角为 25.39°，与物理试验休止角的误差为 0.55%，表明最优参数组合可靠。本研究可为荞麦播种、脱粒、脱壳等机械研发提供籽粒模型及仿真接触参数。*

## INTRODUCTION

Buckwheat is a crop for both food and medicine, and also an important ration variety for improving dietary structure *(Zhang et al., 2017; Zhang et al., 2020)*. In 2018, the buckwheat production in China accounted for 39.1% of the world's total output, which is an important source of income for farmers in China's alpine and hilly areas. As a coarse cereal, buckwheat currently has few dedicated machinery and equipment

*As Lec. Bing Xu, As Lec. Ph.D. Eng. Yanqing Zhang, Prof. Ph.D. Eng. Qingliang Cui*

for production and processing *(Sun et al., 2018; Lu et al., 2020)*. The development of machinery and equipment dedicated to sowing, harvesting, and processing of buckwheat is an important way to promote its industrial development. The collection of the mechanical characteristic parameters of buckwheat seeds in an objective and accurate way is the prerequisite for the development of the machinery and equipment.

Discrete element method is a numerical method for calculating the mechanical behaviour of bulk materials. It is originally used to deal with geotechnical engineering problems abroad *(Wang et al., 2010)*. Repose angle is an important index to measure the friction characteristics of bulk materials. It is the natural slope of the pile when the materials are stacked in the horizontal plane. In recent years, many researchers have focused on the physical stacking of different agricultural bulk materials and simulation stacking based on discrete element method to calibrate the materials parameters through response surface optimization experiments with repose angle as the response value. *Gonzlez-Montellano C. et al.* built a discrete element model for corn kernels *(Gonz lez-montellano C. et al., 2012)*. Researchers used EDEM software to establish a discrete element model of potato, corn kernel, wheat flour, quinoa, and coated cotton-seeds, and performed the parameter calibration *(Liu et al., 2018; Wang et al., 2018; Li et al., 2019; Zhang et al., 2019; Liu et al., 2020; Wang et al., 2021)*. *Guo Xiaojun et al.* used EDEM software to simulate the seed metering effect of sunflower seeding unit under different conditions *(Guo et al., 2019)*. *Li Bing et al.* used EDEM software to simulate the screening process of the tea fresh leaf classifiers, and obtained the drum inclination and rotation speed for a good screening effect of the equipment *(Li et al., 2019)*. *Hou Zhanfeng, Dai Nianzu, et al*, used the discrete element method to simulate the seed and powder mixing uniformity of pelleting coating machine under the action of vibration force field, and obtained the optimal working parameters of pelleting coating machine *(Hou et al., 2020; Dai et al., 2021)*. *Jia Shuanglin et al*, used the Watershed algorithm and EDEM (EM solutions EDEM) algorithm to build a maize granule recognition model for large-scale and intelligent seed metering *(Jia et al., 2021)*. The use of discrete element method to simulate the mechanical behaviour of buckwheat seeds in sowing, threshing, and hulling machinery provides a reference for the development and performance prediction of related components.

In view of the lack of seeds contact parameters that can be used as a reference for the design of key mechanical components such as buckwheat planting, harvesting, and processing, this paper proposed a method to approximate the geometric model of buckwheat seeds with two triangular pyramids with different heights with the bottom planes connected. EDEM can be used for the analysis of particles in different shapes. The particle models that come with the EDEM system appear in only the single-ball, double-ball, three-ball, four-ball square and four-ball straight line models. The particle in other shapes requires manual filling. This paper used an automatic filling method to establish a non-spherical particle model of the buckwheat seeds, and adopted such model to conduct a significant screening test with the repose angle as the response value. A steep-climbing test was conducted for the significance factor, so as to determine the optimal value interval of the significance factor. The relative error of the repose angle was taken as the response value to conduct the Box-Behnken test in order to calibrate the contact parameters, and the parameter validation test was performed with the physical test.

## MATERIALS AND METHODS

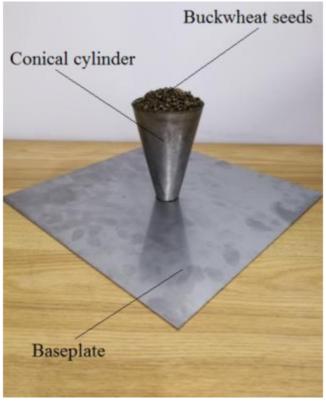
### Test equipment and instruments

The rapid moisture analyser GAC2100AGRI (DICKEY-john Corporation, error ±0.2%) was used to measure the moisture content of the seeds. SU5000 scanning electron microscope was used to observe the morphological structure of seed section. The digital display vernier calliper (with the precision of 0.01 mm) was used to measure the seed size. The repose angle measuring device included a conical cylinder (diameter for a small opening: 30mm, and for a big opening: 80mm, the height is 120mm), and a baseplate (300mm×300mm), made of stainless steel. The digital angle ruler (with an accuracy of 0.05°) was used to measure the repose angle of the physical seeds accumulating test.

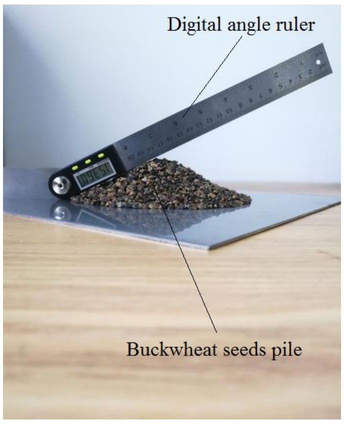
### Test materials and repose angle physical test

This test took buckwheat seeds at harvest as the research subject. The materials for the test were selected from the coarse cereals experimental field of the College of Agricultural Engineering of Shanxi Agricultural University. Before the test, the materials were removed from impurities, shredded seeds and damaged seeds and dried. The moisture content of the seeds was measured to be 12.57%.

The repose angle physical test of buckwheat seeds was carried out in the laboratory using the bottomless conical cylinder lifting method according to the references *(Li et al., 2010)*. During the test, the baseplate was placed on the horizontal test bench, and the conical cylinder was placed on the baseplate with the small opening facing down, and the conical cylinder was filled with buckwheat seeds, as shown in Fig. 1a. The conical cylinder was slowly lifted in the direction perpendicular to the baseplate, and such procedure was repeated for 5 times. After each accumulating test, the digital angle ruler was used to measure the supplementary angle of the two repose angles on the accumulating plane at 180° intervals, as shown in Fig. 1b. The result of each test was the average of two repose angles. The results for the five tests were 25.600°, 25.725°, 24.800°, 24.650° and 25.475°. The final result was the average of the five test results, namely 25.25°, and the standard deviation was 0.49°.




*a) Measuring device of repose angle*




*b) Measurement of repose angle*

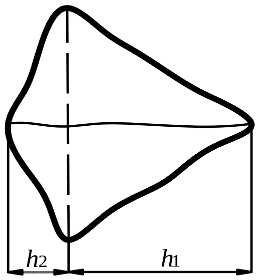
**Fig. 1 - Physical accumulating test**

## Simulation Test

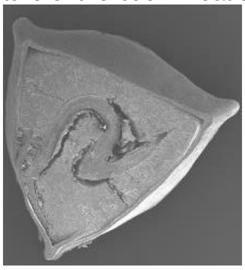
### Construction of discrete model of buckwheat seeds

A geometric model of buckwheat seeds should be established ahead of the discrete element model of buckwheat seeds. Observation of the buckwheat seeds found that the bottom of the buckwheat seeds was not a plane in the strict sense, as shown in Fig. 2a. In this paper, the geometric model of buckwheat seeds is approximated by two triangular pyramids with different heights and connected bottom planes. The preliminary research by the research group determined the shape characteristics of buckwheat seeds *(Sun et al., 2018)*. The outline of buckwheat seeds was shown in Fig. 2b, where $h_1$ is the height of the upper triangular pyramid and $h_2$ is the height of the lower triangular pyramid.

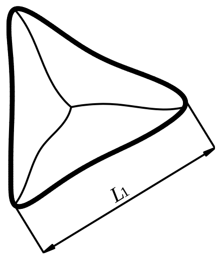
*a) Picture of the buckwheat seeds*




*b) Outline of the whole buckwheat seeds*



*c) Scanning electron microscopy of the buckwheat seeds section*

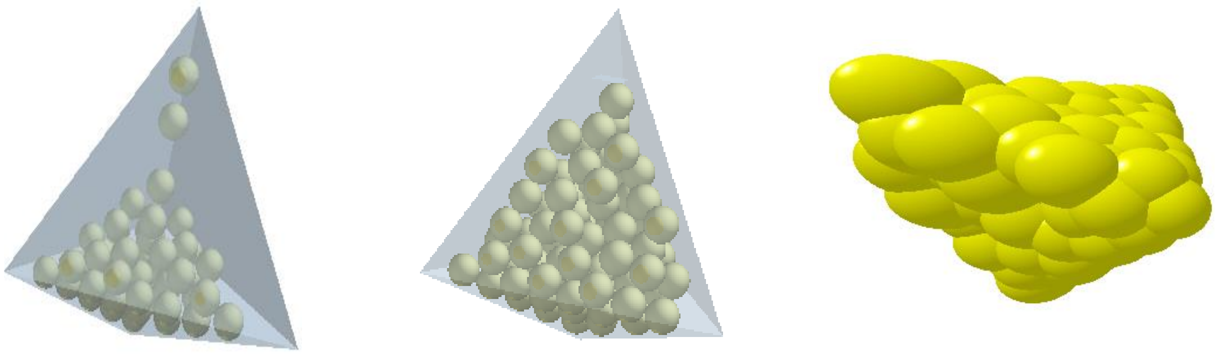



*d) Outline of the buckwheat seeds section*

**Fig. 2 - Shape and section of buckwheat seeds**

The cross section of the connected surface of buckwheat seeds observed under the electron microscope was shown in Fig. 2c. It could be seen that the connected surface was approximately an equilateral triangle. The cross-sectional schematic diagram of buckwheat seeds was shown in Fig. 2d, where $L_1$ is the side length of the connected surface. Based on this approximate method, the characteristic size of buckwheat seeds was measured. The specific measurement method was as follows: 10 firm seeds without visible damages were selected from the harvested seeds as samples. The digital display vernier calliper was used to measure the characteristic size of the samples, and the average value was calculated. The average value of $h_1$ was 4.22mm and 1.31mm for $h_2$, and the average value of $L_1$ was 5.50mm. A three-dimensional model was established in the Inventor according to the characteristic size of buckwheat seeds.

The buckwheat seeds shape is not spherical or ellipsoid like ordinary rice grains. It has sharp edges and corners, which is not easy for manual filling. In this paper, EDEM particle factory was used for automatic filling, and the three-dimensional Inventor model of buckwheat seeds established was converted into STL format and imported into EDEM as the filled model. According to the characteristic size of buckwheat seeds, it was determined that the particle factory would use the single-sphere particles with a radius of 0.3mm. The filling process was shown in Fig. 3a, and the filling result was shown in Fig. 3b. After the dynamic filling in the particle factory was completed, the sphere centre coordinates and radius data of each spherical particle were generated. In order to eliminate the gap between the small balls after filling, the radius of the spherical particle would be doubled when the sphere centre coordinates remained unchanged. The data processed were imported into EDEM to generate a buckwheat seeds bonding model, as shown in Fig. 3c. Such model was saved as a buckwheat seeds template.



*a) Filling process* *b) Completion of filling* *c) Bonding model of buckwheat seeds*

**Fig. 3 - Construction of discrete element model for buckwheat seeds**

### Simulation parameters

EDEM 2018 software was used for simulated accumulating. Plackett-Burman test was designed to perform the significance screening of the simulation contact parameters by taking the repose angle of buckwheat seeds on the stainless steel plate as the response value. References to the literature *(Li et al.,2019)* determined that the discrete element simulation parameters of stainless steel were as follows: stainless steel Poisson's ratio was 0.29, the shear modulus was 70,000 MPa, and the density was 8,000 Kg/m$^3$.

The main contact parameters of buckwheat seeds and stainless steel were used as the test factors, and three Virtual variables were introduced to estimate the error *(Xu et al., 2010)*. According to relevant research literature on buckwheat, buckwheat seeds, and rice grains at home and abroad *(Li et al., 2019; Zhang et al., 2019)*, the levels of these test factors were determined, as shown in Table 1.

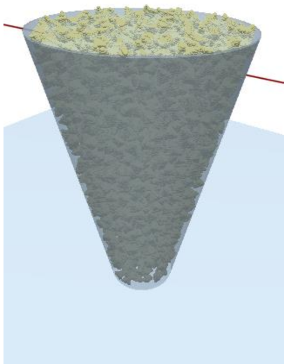
**Table 1**

**The parameters of Plackett Burman test**

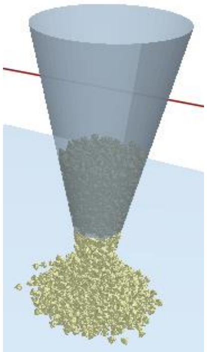
| Parameters | low-level | high-level |
|---|---|---|
| Poisson's ratio of buckwheat *A* | 0.3 | 0.45 |
| Shear modulus of buckwheat *B* | 300 | 450 |
| Buckwheat-buckwheat restitution coefficient *C* | 0.48 | 0.72 |
| Buckwheat-buckwheat static friction coefficient *D* | 0.24 | 0.36 |
| Buckwheat-buckwheat rolling friction coefficient *E* | 0.008 | 0.012 |
| Buckwheat-stainless steel restitution coefficient *F* | 0.4 | 0.6 |
| Buckwheat-stainless steel static friction coefficient *G* | 0.448 | 0.672 |
| Buckwheat-stainless steel rolling friction coefficient *H* | 0.016 | 0.024 |
| Virtual variable *J* | -1 | 1 |
| Virtual variable *K* | -1 | 1 |
| Virtual variable *L* | -1 | 1 |

**Simulation model of the repose angle**

The particles for the simulated accumulating test were the buckwheat seeds template established above. The conical cylinder and baseplate models of the same material and size as those in the laboratory accumulating process were established in EDEM. The small opening end of the conical cylinder was placed on the baseplate, and the conical cylinder was statically filled with buckwheat seeds, as shown in Fig. 4a. After filling, the conical cylinder was moved upwards perpendicular to the baseplate. The lifting speed of the conical cylinder was 0.02m/s, as shown in Fig. 4b.



a) Static particles filling

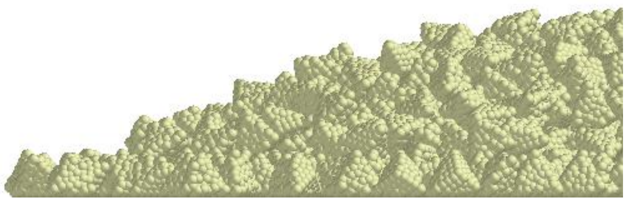


b) The accumulating process of particles

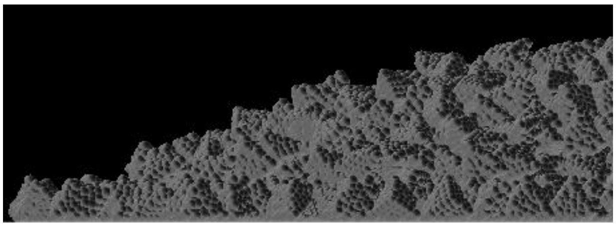
**Fig. 4 - Simulation test of accumulating process**

**Measurement of repose angle of simulation test**

After the simulation of the accumulating process, the left half of the seeds pile image in the accumulating test was subjected to processing in order to obtain the repose angle of the accumulating test *(Cai et al., 2019)*, as shown in Fig. 5a. First, Fig. 5a was subjected to gray processing to obtain Fig. 5b, and then the binarization processing of Fig. 5b brought Fig. 5c. Fig. 5d was obtained by edge detection of Fig. 5c. The edge curve was simulated by a straight line, as shown in Fig. 5e. The angle of the fitted straight line was exported. The repose angle on the right half of the seeds pile was obtained with the same method. The repose angle of each simulated accumulating process was the average value of the repose angles on the left and right sides.

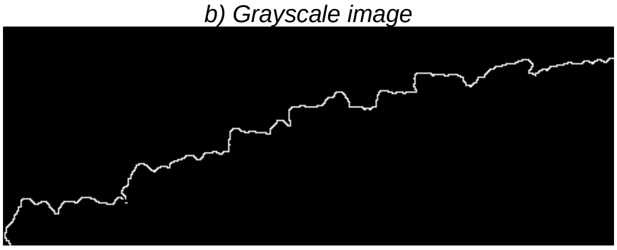


*a) The left half image of the seeds pile*

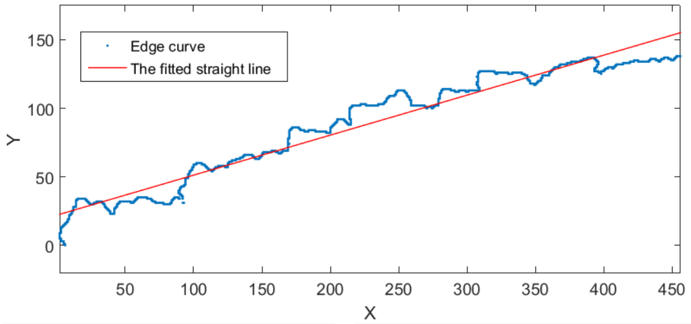


*b) Grayscale image*

*c) Binary image*



*d) Edge detection image*




*e) Linear fitting*

**Fig. 5 - Image processing of buckwheat seeds pile**

## RESULTS

### Plackett-Burman test

Plackett-Burman test design was carried out using Design expert 10.0.4 software. The test plan and results were shown in Table 2.

**Table 2**

**The design and results of Plackett Burman test**

| Number | *A* | *B* | *C* | *D* | *E* | *F* | *G* | *H* | *J* | *K* | *L* | Repose angle / (°) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | -1 | 1 | 1 | -1 | 1 | 1 | 1 | -1 | -1 | -1 | 1 | 18.49 |
| 2 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | 18.87 |
| 3 | 1 | 1 | -1 | -1 | -1 | 1 | -1 | 1 | 1 | -1 | 1 | 19.27 |
| 4 | 1 | 1 | 1 | -1 | -1 | -1 | 1 | -1 | 1 | 1 | -1 | 19.32 |
| 5 | -1 | -1 | 1 | -1 | 1 | 1 | -1 | 1 | 1 | 1 | -1 | 19.53 |
| 6 | 1 | -1 | -1 | -1 | 1 | -1 | 1 | 1 | -1 | 1 | 1 | 21.33 |
| 7 | -1 | -1 | -1 | 1 | -1 | 1 | 1 | -1 | 1 | 1 | 1 | 22.24 |
| 8 | 1 | 1 | -1 | 1 | 1 | 1 | -1 | -1 | -1 | 1 | -1 | 22.38 |
| 9 | 1 | -1 | 1 | 1 | 1 | -1 | -1 | -1 | 1 | -1 | 1 | 22.82 |
| 10 | 1 | -1 | 1 | 1 | -1 | 1 | 1 | 1 | -1 | -1 | -1 | 23.50 |
| 11 | -1 | 1 | 1 | 1 | -1 | -1 | -1 | 1 | -1 | 1 | 1 | 23.81 |
| 12 | -1 | 1 | -1 | 1 | 1 | -1 | 1 | 1 | 1 | -1 | -1 | 24.31 |

The Design expert 10.0.4 software was used to analyse the variance of the test data, and the results were shown in Table 3.

**Table 3**

**Analysis of variance**

| Source | Effect | Sum of squares | Contribution % | *F* | *P* |
|---|---|---|---|---|---|
| Model | / | 49.31 | / | 84.79 | 0.0019 |
| *A* | 0.23 | 0.16 | 0.32 | 2.15 | 0.2387 |
| *B* | -0.12 | 0.042 | 0.085 | 0.58 | 0.5024 |
| *C* | -0.15 | 0.072 | 0.15 | 0.99 | 0.3928 |
| *D* | 3.71 | 41.26 | 83.29 | 567.49 | 0.0002 |
| *E* | 0.31 | 0.29 | 0.58 | 3.92 | 0.1420 |
| *F* | -0.84 | 2.13 | 4.29 | 29.23 | 0.0124 |
| *G* | 0.42 | 0.53 | 1.06 | 7.22 | 0.0746 |
| *H* | 1.27 | 4.85 | 9.79 | 66.73 | 0.0038 |

It could be seen from Table 3 that the model was significant. The buckwheat-buckwheat static friction coefficient *D*, buckwheat-stainless steel rolling friction coefficient *H* and buckwheat-stainless steel restitution coefficient *F* had significant effects on the repose angle ($P<0.05$), while other factors were not significant ($P>0.05$).

### Steep climbing test

A steep-climbing test was carried out to determine the best range of buckwheat-buckwheat static friction coefficient *D*, buckwheat-stainless steel rolling friction coefficient *H* and buckwheat-stainless steel restitution coefficient *F*. The level of significant factors in the test fell in the range of the low and high levels given in Table 1. The values were taken according to the arithmetic sequence, and the levels of other insignificant factors were taken as the middle value of the high and low levels in Table 1. The design plan and results of the steep climbing test were shown in Table 4.

**Table 4**

**Experimental parameters and results of steep slope climbing**

| Number | *D* | *H* | *F* | Repose angle (°) | Relative error *φ* % |
|---|---|---|---|---|---|
| 1 | 0.24 | 0.016 | 0.40 | 20.49 | 18.85 |
| 2 | 0.36 | 0.032 | 0.45 | 22.01 | 12.83 |
| 3 | 0.48 | 0.048 | 0.50 | 25.40 | 0.59 |
| 4 | 0.60 | 0.064 | 0.55 | 26.52 | 5.00 |

It could be seen from Table 4 that the optimal interval of buckwheat-buckwheat static friction coefficient *D* was 0.36-0.60, 0.032-0.064 for the buckwheat-stainless steel rolling friction coefficient *H* and 0.45-0.55 for the buckwheat-stainless steel recovery coefficient *F*.

## Box-Behnken test

### Test design and results

In order to obtain the optimal combination of buckwheat-buckwheat static friction coefficient *D*, buckwheat-stainless steel rolling friction coefficient *H* and buckwheat-stainless steel restitution coefficient *F*, the Box-Behnken response surface test was performed with the relative error value of the repose angle as the response value, and the factor levels of the steep-climbing tests 2, 3 and 4 were taken as the low, medium and high levels of the corresponding factors in the Box-Behnken response surface test, respectively. The Box-Behnken test design and results were shown in Table 5.

**Table5**

**The design and results of Box-Behnken test**

| Number | *D* | *H* | *F* | Repose angle (°) | Relative error *φ* % |
|---|---|---|---|---|---|
| 1 | 0.48 | 0.032 | 0.55 | 24.49 | 3.01 |
| 2 | 0.6 | 0.048 | 0.45 | 25.11 | 0.55 |
| 3 | 0.48 | 0.064 | 0.45 | 24.25 | 3.96 |
| 4 | 0.48 | 0.048 | 0.5 | 24.95 | 1.19 |
| 5 | 0.36 | 0.048 | 0.55 | 23.28 | 7.80 |
| 6 | 0.48 | 0.032 | 0.45 | 24.04 | 4.79 |
| 7 | 0.48 | 0.048 | 0.5 | 25.07 | 0.71 |
| 8 | 0.36 | 0.064 | 0.5 | 23.65 | 6.34 |
| 9 | 0.36 | 0.048 | 0.45 | 23.46 | 7.09 |
| 10 | 0.48 | 0.048 | 0.5 | 25.35 | 0.40 |
| 11 | 0.6 | 0.032 | 0.5 | 24.67 | 2.30 |
| 12 | 0.6 | 0.064 | 0.5 | 25.38 | 0.51 |
| 13 | 0.36 | 0.032 | 0.5 | 23.10 | 8.51 |
| 14 | 0.6 | 0.048 | 0.55 | 25.19 | 0.24 |
| 15 | 0.48 | 0.064 | 0.55 | 24.74 | 2.02 |

### Analysis and optimization of model variance

The Box-Behnken test results were analysed and the second-order regression model of the repose angle error value and the buckwheat-buckwheat static friction coefficient *D*, the buckwheat-stainless steel rolling friction coefficient *H* and the buckwheat-stainless steel restitution coefficient *F* were established.

The regression equation is:

$$\varphi = 302.95 - 218.92D - 902.19H - 886.67F + 62.50DH + 102.50DF + 1162.50HF + 143.17D^2 + 2799.48H^2 + 784.67F^2 \quad (1)$$

The analysis of the model variance was shown in Table 6.

**Table 6**

**Variance analysis of regression equation of Box-Behnken test**

| Source | Sum of square | Mean square | *F* | *P-value* |
|---|---|---|---|---|
| Model | 120.09 | 13.34 | 117.10 | < 0.0001 |
| *D* | 85.41 | 85.41 | 749.60 | < 0.0001 |
| *H* | 1.01 | 1.01 | 8.85 | 0.0310 |
| *F* | 0.18 | 0.18 | 1.58 | 0.2643 |
| *DH* | 0.058 | 0.058 | 0.51 | 0.5089 |
| *DF* | 1.51 | 1.51 | 13.28 | 0.0148 |
| *HF* | 3.46 | 3.46 | 30.36 | 0.0027 |
| $D^2$ | 15.69 | 15.69 | 137.74 | < 0.0001 |

**Table 6 (continuation)**

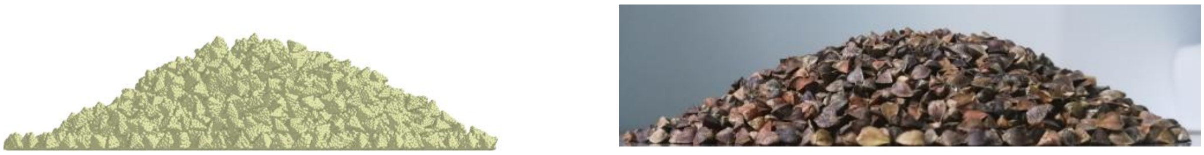
**Variance analysis of regression equation of Box-Behnken test**

| Source | Sum of square | Mean square | *F* | *P-value* |
|---|---|---|---|---|
| $H^2$ | 1.90 | 1.90 | 16.64 | 0.0095 |
| $F^2$ | 14.21 | 14.21 | 124.70 | 0.0001 |
| Residual | 0.57 | 0.11 | / | / |
| Lack of Fit | 0.25 | 0.084 | 0.53 | 0.7043 |
| Pure Error | 0.32 | 0.16 | / | / |
| Cor Total | 120.66 | / | / | / |
| $R^2$=0.9953, $Adj$-$R^2$=0.9868 | | | | |

It could be seen from Table 6 that the fitting model had $P$<0.0001, the determination coefficient $R^2$=0.9953, and the correction determination coefficient $Adj$-$R^2$=0.9868, which were all close to 1, indicating that the regression model of the repose angle error value was extremely significant. The coefficients *D*, *HF*, $D^2$, $H^2$, and $F^2$ had extremely significant effects on the repose angle error, and the coefficients *H*, and *DF* had significant effects on the repose angle error, and other coefficients were not significant. Taking the minimum relative error value as the optimal goal, the established regression model was used to get the optimal solution: buckwheat-buckwheat static friction coefficient *D* was 0.510, and buckwheat-stainless steel rolling friction coefficient *H* was 0.053, and buckwheat-stainless steel rolling friction coefficient *F* was 0.492.

**Simulated validation**

Three simulation accumulating tests were performed with the calibrated parameters, and the repose angle was measured. The results were 24.97°, 25.67°, and 25.53°, respectively, and the average value was 25.39°. The error with the repose angle measured in the physical test was 0.55%. The test comparison map was shown in Fig. 6. The validation results showed that the methods to establish the discrete element and calibrate the parameters of buckwheat seeds were feasible.



a) Simulation test b) Physical test

**Fig. 6 - Comparison of simulation and Physical test**

## CONCLUSIONS

(1) According to the characteristic size of buckwheat seeds, a three-dimensional Inventor model of the buckwheat seeds is established, and a discrete element model of non-spherical particles of buckwheat seeds is established by the particle filling method in EDEM.

(2) The discrete element model of buckwheat seeds is used for simulated accumulating process. The repose angle is used as the response value for the significant screening test. The results show that the buckwheat-buckwheat static friction coefficient, buckwheat-stainless steel rolling friction coefficient, and buckwheat-stainless steel restitution coefficient have significant effects on the repose angle of buckwheat ($P$<0.05).

(3) The results of steep climbing test showed that the buckwheat-buckwheat static friction coefficient is 0.36-0.60, the buckwheat-stainless steel rolling friction coefficient is 0.032-0.064, and the buckwheat-stainless steel restitution coefficient is 0.45-0.55.

(4) A second-order regression model of the repose angle error and the significance parameter is established with the Box-Behnken test. The minimum relative error value of the repose angle is taken as the goal, and the significance parameters are optimized, in order to obtain the optimal combination: the buckwheat-buckwheat static friction coefficient is 0.510, the buckwheat-stainless steel rolling friction coefficient is 0.053, and the buckwheat-stainless steel restitution coefficient is 0.492. The calibrated parameters are used in the simulation test, and the average repose angle is 25.39°, with an error of 0.55% compared with the repose angle in the physical test.

(5) This research can provide a seed model and the simulation contact parameters for the research and development of buckwheat sowing, threshing and hulling machinery.

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## REFERENCES

[1] Cai L.M., (2019), *Digital image processing Using MATLAB* (数字图像处理——使用 MATLAB 分析与实现), ISBN 9787302515043, Tsinghua University Press, Beijing/P.R.C.

[2] Dai H.Z., (2021), Numerical simulation and experiment of vibration pelletizer based on EDEM (基于 EDEM 振动丸化包衣机的数值模拟与试验). *INMATEH Agricultural Engineering*, Vol.63, Issue 1, pp. 469-478, Bucharest/Romania;

[3] Gonzalez-Montellano C., (2012), Determination of the mechanical properties of maize grains and olives required for use in DEM simulations. *Journal of Food Engineering*, Vol. 111, Issue 4，pp.553-562, Netherlands;

[4] Guo X.J., (2019), Simulation research on spoon-type seed metering device of sun flower seed based on EDEM (基于 EDEM 的勺轮式葵花排种器离散元仿真研究). *Journal of Chinese Agricultural Mechanization*, Vol.40, Issue 2, pp.19-24, Nanjing/P.R.C.;

[5] Hou Z.F., (2020), Numerical simulation and experimental study on pelleting motion law of agropyron seeds under vibration force field(振动力场作用下冰草种子丸化运动规律数值模拟与试验研究). *INMATEH Agricultural Engineering*, Vol.62, Issue 3, pp. 299-308, Bucharest/Romania;

[6] Jia S.L., (2021), Simulation analysis and construction of maize seeder model based on EDEM (em solutions EDEM) (基于 EDEM 的玉米排种器模型构建与仿真分析). *INMATEH - Agricultural Engineering*, Vol.63, Issue 1, pp. 365-374, Bucharest/Romania;

[7] Li Y.X., (2019), Parameter calibration of wheat flour for discrete element method Simulation based on particle scaling (基于颗粒缩放的小麦粉离散元参数标定). *Transactions of the Chinese Society of Agricultural Engineering*, Vol.35, Issue 8, pp.320-327, Beijing/P.R.C.;

[8] Li B., (2019), Research on Screening Rate of Fresh Tea Leaves Classifier Based on EDEM (基于 EDEM 的茶鲜叶分级机的筛分率的研究). *Journal of Tea Science*, Vol.39, Issue 4, pp.484-494, Hangzhou/P.R.C.;

[9] Li M.S., (2019), Design and Test of a Seed Metering Device for Buckwheat Seeder Based on the Discrete Element Method(基于离散单元法的荞麦播种机排种器设计与试验). *Journal of Southwest Agricultural University*, Issue 4, pp.78-85, Chongqing/P.R.C.;

[10] Liu W.Z., (2018), Calibration of Simulation Parameters for Potato Minituber Based on EDEM (基于离散元的微型马铃薯仿真参数标定). *Transactions of The Chinese Society of Agricultural Machinery*, Vol.49, Issue 5, pp. 125- 135+142, Beijing/P.R.C.;

[11] Liu F., (2020), Analysis and calibration of quinoa grain parameters used in a discrete element method based on the repose angle of the particle heap (基于堆积试验的藜麦离散元参数分析及标定). *INMATEH - Agricultural Engineering*, Vol.61, Issue 2, pp.77-86, Bucharest/Romania;

[12] Lu Q., (2020), Problems and Thoughts on Mechanized Harvesting Technology of Buckwheat in China (我国荞麦机械化收获技术问题与思考). *Agricultural engineering*, Vol.10, Issue 01, pp.6-9, Beijing/P.R.C.;

[13] Qinliang Li, (2010), The research of granular piling and bulk material transfer process using DEM Simulation (颗粒堆积性质和散状物料转载过程的 DEM 仿真研究). Northeastern University, Shenyang/P.R.C.;

[14] Sun J.X., (2018), Experimental study on biomechanical properties of buckwheat grain and viscoelastic properties of buckwheat powder (荞麦籽粒生物力学性质及内芯黏弹性试验研究). *Transactions of the Chinese Society of Agricultural Engineering*, Vol.34, Issue 12, pp.287-298, Beijing/P.R.C.;

[15] Wang L., (2021), A general modelling approach for coated cotton-seeds based on the discrete element method (基于多目标优化的包衣棉种离散元接触参数标定). *INMATEH - Agricultural Engineering*, Vol.63, Issue 1, pp. 221-230, Bucharest/Romania;
[16] Xu X.H., (2010), *Experimental design and application of design expert and SPSS* (试验设计与 Design-Expert、SPSS 应用), ISBN 9787030278678, Science Press, Beijing/P.R.C.;
[17] Zhang J., (2020), Establishment of Rapid Detection Model of Buckwheat Nutritional Components Based on Near Infrared Spectroscopy (基于近红外建立荞麦营养成分快速检测模型). *Journal of the Chinese Cereals and Oils Association*, Vol.35, Issue 6, pp.151-158, Beijing/P.R.C.;
[18] Zhang Y.W., (2017), Principal component analysis and comprehensive evaluation of protein and amino acid in different varieties of buckwheat and buckwheat sprout (不同种荞麦发芽前后蛋白质及氨基酸变化主成分分析与综合评价). *Food and Fermentation Industries*, Vol.43, Issue 7, pp.214-221, Beijing/P.R.C.;
[19] Wang G.Q., (2010), *Discrete element method and its application in EDEM* (离散单元法及其在 EDEM 上的实践), ISBN 9787561227978, Northwestern Polytechnic University Press, Xi'an/P.R.C.;
[20] Wang M.M., (2018), Research of discrete element modeling method of maize kernel based on EDEM (基于 EDEM 的玉米子粒建模方法的研究). *Journal of Henan Agricultural University*, Vol.52, Issue 1, pp.80-84+103, Zhengzhou/P.R.C.;
[21] Zhang C., (2019), The Measurement of Contact Parameters of Buckwheat Rice Screening Material and Discrete Element Simulation Calibration (荞麦米筛分物料接触参数测量与离散元仿真标定). *Journal of Agricultural Mechanization Research*, Vol.41, Issue 1, pp.46-51, Haerbin/P.R.C.;