PARAMETER CALIBRATION AND DISCRETE ELEMENT MODEL OF HIGHLAND BARLEY STEM BASED ON EDEM
/
基于 EDEM 的青稞茎秆离散元参数标定

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ABSTRACT
In view of the lack of accurate contact parameters and the difficulty of measuring contact parameters in the discrete element simulation of mechanized harvesting of highland barley, this study took the wax-ripening highland barley as the object, carried out the discrete element simulation of highland barley stem based on EDEM, and calibrated the discrete element simulation parameters of highland barley stem by response surface optimization. In this paper, Plackett-Burman test was used to screen 8 initial parameters. It was found that the static friction coefficient between highland barley stems, the rolling friction coefficient between highland barley stems, and the rolling friction coefficient between highland barley stems and steel plates have significant effects on the particle angle of repose. Based on the optimal value range of significant factors determined by the steepest ascent test, a second-order regression model of the angle of repose and significant parameters was established and optimized based on the results of Box-Behnken test. The optimal parameter combination of significant parameters was obtained as follows: static friction coefficient between highland barley stems is 0.27, rolling friction coefficient between highland barley stems is 0.07, and rolling friction coefficient between highland barley stems and steel is 0.26. Finally, the simulation results under the optimal parameter combination are compared with the actual test angle of repose. The relative error is 0.52 %. That indicates that the parameters of the simulation calibration are credible, which can provide a reference for the future research on the cleaning device in the mechanized harvesting of highland barley.

摘要
针对目前青稞机械化收获离散元仿真缺乏准确的接触参数、接触参数测量难度大的问题，本研究以蜡熟期的青稞为对象，基于EDEM 开展青稞茎秆离散元仿真，通过响应面优化标定了青稞茎秆离散元仿真参数。研究应用Plackett-Burman 试验对8 个初始参数进行筛选，发现青稞茎秆间静摩擦系数、青稞茎秆间滚动摩擦系数与青稞茎秆-钢板滚动摩擦系数对颗粒堆积角有显著影响。以最陡爬坡试验确定的显著性因素最优取值区间为基础，基于Box-Behnken 试验结果建立堆积角与显著性参数的二阶回归模型并对其进行优化，得到显著性参数的最佳参数组合为青稞茎秆间静摩擦系数 0.27、青稞茎秆间滚动摩擦系数 0.07、青稞茎秆-钢板滚动摩擦系数 0.26。最后将最佳参数组合下的仿真结果与真实试验堆积角对比，二者相对误差为 0.52%，误差很小表明仿真标定的参数是可信的，可以为以后的青稞机械化收获中清选装置的研究提供参考。

INTRODUCTION
As the largest food crop in the Qinghai-Tibet Plateau, highland barley is also an agricultural characteristic industry in the plateau area, which can provide an important driving force for local agricultural development (*Xu et al., 2020*). At present, an important problem is that the mechanized harvesting level of highland barley is not high, which restricts the good development of highland barley related industries to a certain extent (*Bian et al., 2015; Zhang et al., 2022*). Due to the similarity with rice and wheat plants, the mechanized harvesting of highland barley is mainly carried out by improving the grain combine harvester, but a large amount of grain is often lost in the cleaning process and the impurity content is high. In order to solve the problem of cleaning loss and high impurity content during the harvesting process, it is crucial to establish a more accurate stem model and contact parameters (*Wang et al., 2017; Wang et al., 2021*).

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As a numerical simulation method to solve the problem of discontinuous media, discrete element method has been widely used in the field of agricultural engineering (*Wang et al., 2018*). Parametric simulation of the operation process of agricultural machinery is carried out. Parameter calibration is one of the key problems in discrete element simulation (*Su et al., 2020*). Among them, Hertz Mindlin (no slip) contact model and Hertz Mindlin with Bonding bond contact model in EDEM are widely used in material modeling, and a series of important progress has been made in parameter calibration of rice, wheat, corn and other crops (*Liao et al., 2020; Hou et al., 2022; Chen et al., 2023*). Many scholars have provided effective research methods for the calibration of discrete element parameters of stems (*Zeng et al., 2021*), but there are few studies on the parameter calibration of highland barley stems. In this study, the highland barley stems are short stems after threshing, so the multi-sphere aggregation model is used to establish the stem geometric model (*Zhang et al., 2020*).

When EDEM is used to simulate the grain cleaning process, the parameter setting of the stem directly affects the accuracy of the simulation results (*Wang et al., 2020*). The model parameters mainly include material intrinsic parameters and basic contact parameters. The intrinsic parameters such as material density, geometric size, shear modulus and Poisson's ratio are obtained by physical measurement (*Wang et al., 2017*). The static friction factor, rolling friction factor and collision recovery coefficient between the material and the contact material are obtained by physical test (*Wang et al., 2022; Liu et al., 2016*). In this paper, the highland barley stem harvested at wax ripening stage was used as the test object, and the basic parameter test was carried out. Based on the EDEM and Hertz Minding (no slip) contact model, the discrete element simulation parameters were calibrated by Plackett-Burman, steepest ascent and Box-Behnken tests, and the results of the short stem angle of repose real test and the simulation test were compared and verified, in order to provide basic parameters for the simulation study of the highland barley harvesting process.

MATERIALS AND METHODS

Intrinsic characteristics of the material

The stem of highland barley Zangqing-2000 used in the experiment was selected from the experimental field of Gannan Institute of Agricultural Sciences. The collected highland barley was in the state of wax ripening, no pests and diseases, no mechanical damage, and the spikes and leaves were removed. The moisture content of 50 g treated highland barley stems was 22.45 %, and the true density of the test stems was 757 kg/m^3. The outer diameter and wall thickness of 20 highland barley stems were measured by vernier caliper. The average outer diameter was 5.1 mm and the wall thickness was 0.52 mm.

Physical parameter measurements

The physical parameters required for the calibration of discrete element parameters of highland barley stalk include Poisson's ratio, shear modulus, static friction coefficient, rolling friction coefficient and collision recovery coefficient, etc. The test equipment required for the test includes material characteristics test bench and SUNS universal mechanical testing machine.

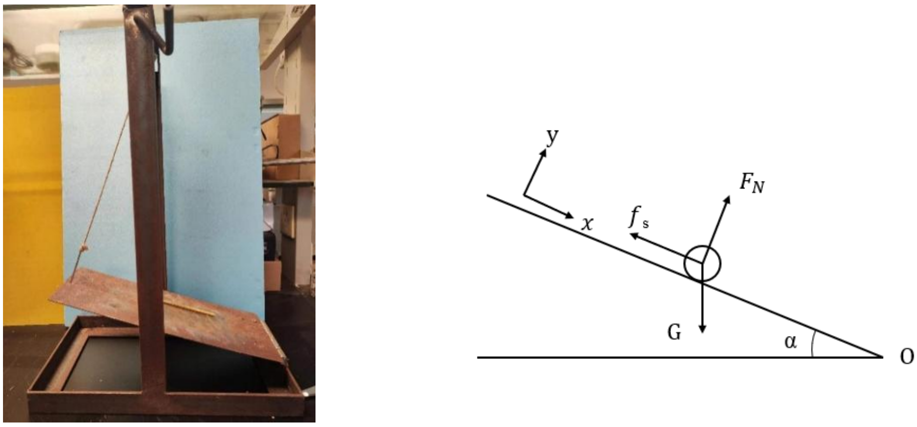
Coefficient of static friction

The static friction coefficient is the ratio of the maximum static friction force to the normal pressure on the object (*Wang et al., 2020*). During the measurement, the highland barley stem to be measured is placed axially on the horizontal steel plate, and the angle meter is placed in a suitable position. The handle is rotated to make the steel plate rise slowly. When the highland barley stem slides on the surface of the steel plate, it stops, and the angle α of the angle meter is recorded at this time. The static friction coefficient is calculated according to Equation (1). The measurement process and force analysis are shown in Fig. 1.

$$f_s = tan\ \alpha \tag{1}$$

where: f_s is the coefficient of static friction and α is the critical angle of static friction (°).

When measuring the static friction coefficient of highland barley stem-highland barley stem, the uniform arrangement of highland barley stem plate can replace the steel plate. Repeat the test for 20 times, the range of static friction coefficient between highland barley stems is 0.2 ~ 0.6, and the range of static friction coefficient between highland barley stems and steel plate is 0.3 ~ 0.6.



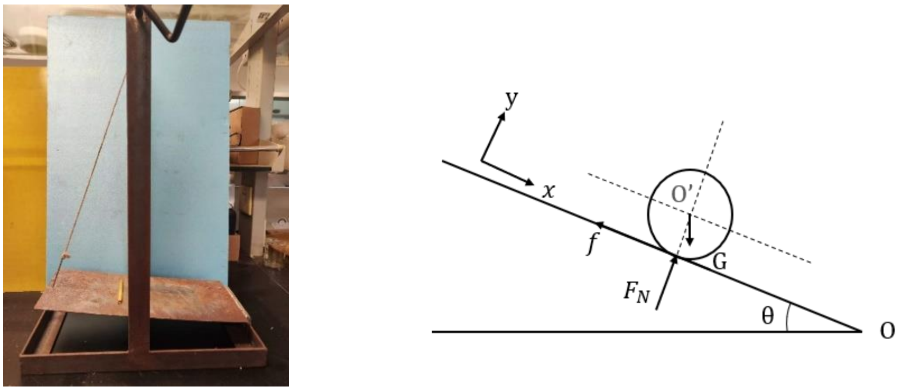
a) b)

Fig. 1 – Barley stem static friction coefficient measurement device and force analysis diagram

a) Measurement device; b) Force analysis diagram

Rolling friction coefficient

Rolling friction refers to the blocking effect of the deformation of the object on the contact surface on rolling when an object rolls without sliding or has a rolling trend on the surface of another object (*Chen et al., 2023*). Similar to the static friction coefficient measurement method, the stem was placed horizontally on the horizontal steel plate, and the handle was shaken to slowly raise the steel plate. When it was observed that the highland barley stems had just rolled purely on the steel plate, stop shaking the handle. The tilt angle θ of the plane at this time was measured by the angle meter. The measuring device and force analysis are shown in Fig. 2.



a) b)

Fig. 2 – Barley stem rolling friction coefficient measurement device and force analysis diagram

a) Measurement device; b) Force analysis diagram

During the rolling process of highland barley, the rolling friction moment M is proportional to the positive pressure F_N of the support surface. As the inclination angle of the slope increases, the highland barley stem rolls. From the force analysis:

$$M = fF_N \tag{2}$$

$$F_N - Gcos\theta = 0 \tag{3}$$

$$Grsin\theta - M = 0 \tag{4}$$

$$f = \frac{M}{F_N} = rtan\theta \tag{5}$$

Where:

M - rolling friction moment, [N•m];

f - coefficient of rolling friction;

F_N - the support force of the bevel to the stem, [N];

G - gravity of barley stems, [N];

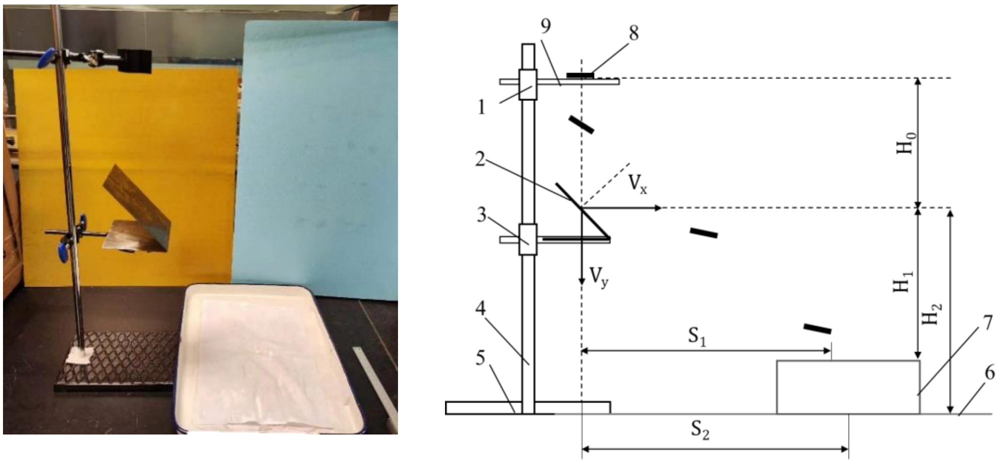
θ - critical angle of rolling friction of barley stems, [°];

r - radius of barley stems, [mm].

When measuring the rolling friction coefficient between highland barley stems, the steel plate can be replaced by the evenly arranged highland barley stem plate. The range of rolling friction coefficient between highland barley stem was 0.05 ~ 0.15, and the range of rolling friction coefficient between highland barley stem and steel plate was 0.2 ~ 0.4.

Collision restitution coefficient

The collision recovery coefficient is the ratio of the normal velocity of the center of mass at the end of the collision to the normal velocity of the center of mass before the collision. It is a parameter to measure the recovery ability of the object after deformation (*Xiao et al., 2019*). The test device and principle are shown in Fig. 3.



a) *b)*

Fig. 3 - Measurement device and motion analysis of barley stem collision restitution coefficient

a) Measurement device; b) Motion analysis of barley stem collision restitution coefficient

During the experiment, the short stem of highland barley fell freely from a certain height H without initial velocity, and collided with the inclined plate (steel plate and stem inclined plane) placed at 45° directly below, and the stem made a flat parabolic motion, and finally fell on the receiving plate. The relative height of the receiving plate and the collision point O is H_1, and the horizontal displacement of the stem is S_1. Changing the relative height H_2 between the blanking plate and the collision point obtains the horizontal displacement of the stem as S_2, and the collision recovery coefficient e between the stem and the inclined plate can be calculated by kinematic Equation (6). The test was repeated for 20 times, and the collision recovery coefficient between barley stem and barley stem was 0.1~0.6, and the collision recovery coefficient between barley stem and steel plate was 0.4~0.8.

$$e = \frac{\sqrt{\left({v_x}^2 + {v_y}^2\right)} \cdot cos\left[45° + arctan\left(\frac{v_x}{v_y}\right)\right]}{v_0 \cdot sin45°} \tag{6}$$

Among them, v_0 is the vertical velocity component before stem collision, which can be calculated by falling height, [mm/s]. The horizontal velocity component v_x and the vertical velocity component v_y after stem collision can be obtained by Equation (7):

$$\begin{cases} v_x = \sqrt{\dfrac{gS_1S_1(S_1 - S_2)}{2(H_1S_2 - H_2S_1)}} \\ v_y = \dfrac{H_1 v_x}{S_1} - \dfrac{gS_1}{2v_x} \end{cases} \tag{7}$$

Physical experiment on the angle of repose of highland barley stem

This research adopts a steel plate (Q235) cylinder, according to the length of the highland barley stem particles, the inner diameter and height were determined to be 100 and 180 mm respectively. During the measurement, the cylinder is placed on the plane of the steel plate and filled with the test sample, and then the universal testing machine is used to raise it at a constant speed of 0.05 m/s to form a stable stack of test sample and measure the angle of repose, as shown in Fig. 4. The test was repeated 10 times, and the average angle of repose was 30.82°.

Fig. 4 - Physical test of the angle of repose by cylinder lifting method

Model of simulation test and parameters

Discrete element model of highland barley

The short stem model of highland barley was established by software EDEM2021 as shown in Fig. 5. Since the stem wall was very thin, the calculation amount of the real value was too large, so the stem wall thickness was enlarged in the simulation. According to the test in Reference (Liu., 2018), it was proved that the enlarged wall thickness had no significant effect on the test results during the simulation. Therefore, the stem wall thickness of the simulation model was set to 1 mm, the outer diameter was 5.20 mm, and the length was 25 mm.

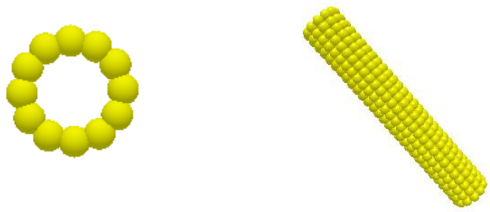


Fig. 5 - Particle model of highland barley stem

Simulation parameters

In order to improve the accuracy of calibration parameters, the multi-sphere aggregation model in EDEM2021 was used in the simulation test of highland barley stem particle accumulation (*Ding et al., 2021*). In order to be the same as the actual accumulation test stem particle length, the stem particle length is 25 mm. Combined with the previous physical experiment of stem intrinsic parameters and the related literatures (*Shu et al., 2022; Wang et al., 2012*) of discrete element simulation of agricultural materials, the numerical range of each simulation parameter in this study is shown in Table 1.

Table 1

Parameters required in DEM simulation

Parameter	Value
The Poisson's ratio of barley stem	0.2~0.5
The Poisson's ratio of the steel plate	0.3
Shear modulus of barley stem / MPa	50~90
Shear modulus of steel plate / MPa	7.9×10^4
Density of barley stem / ($kg\cdot m^{-3}$)	758
Density of steel / ($kg\cdot m^{-3}$)	7800
Restitution coefficient between barley stems	0.1~0.6
Static friction coefficient between barley stem and barley stem	0.2~0.6
Rolling friction coefficient between barley stem and barley stem	0.05~0.15
Restitution coefficient between barley stem and steel	0.4~0.8
Static friction coefficient between barley stem and steel	0.3~0.6
Rolling friction coefficient between barley stem and steel	0.2~0.4

Cylinder lifting experiment

The inner diameter and height of the cylinder in the simulation are the same as those in the experiment. The dynamic particle generation method was used to freely fall in the particle factory and fill the cylinder. The generation rate was 5000/s, the generation time was 1s, and a total of 500 particles were generated. After the particle state was stable, the cylinder was lifted vertically at a speed of 0.05 m/s. The stem particles slowly flowed out from the bottom of the cylinder, and finally formed a stable particle pile on the bottom plate. Combined with the mechanical characteristics of highland barley stem and the calculation accuracy of the model, the Hertz-Mindlin (no slip) contact model built in EDEM software was adopted. All simulation time steps select 20 % Rayleigh time step. In the simulation, the mesh size is 2.5 times of the spherical unit size, and the simulation time is 6 s.

RESULTS

Plackett-Burman test and result

R4.2.3 was used for experimental design and data analysis. In order to screen out the parameters that have a significant effect on the angle of repose of highland barley stem particles, 8 real parameters and 3 virtual parameters were selected for the Plackett-Burman test with a design level of 2. The factor levels are expressed in the form of -1 and +1, as shown in Table 2.

There is only one central point in this experiment. A total of 13 experiments were conducted. The experimental design and results are shown in Table 3.

Table 2

Parameters of Plackett-Burman test

Symbol	Parameters	Low level (-1)	High level (+1)
X_1	The Poisson's ratio of barley stem	0.2	0.5
X_2	Shear modulus of barley stem /MPa	50	90
X_3	Barley stem-barley stem restitution coefficient	0.1	0.6
X_4	Barley stem-barley stem static friction coefficient	0.2	0.6
X_5	Barley stem-barley stem rolling friction coefficient	0.05	0.15
X_6	Barley stem -steel restitution coefficient	0.4	0.8
X_7	Barley stem -steel static friction coefficient	0.3	0.6
X_8	Barley stem -steel rolling friction coefficient	0.2	0.4
X_9、X_{10}、X_{11}	Virtual parameters	-	-

Table 3

Design and results of Plackett-Burman test

No.	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	Angle of repose/ [°]
1	-1	1	1	-1	1	1	1	-1	-1	-1	1	30.65
2	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	28.9
3	-1	1	-1	1	1	-1	1	1	1	-1	-1	38.71
4	1	1	-1	-1	-1	1	-1	1	1	-1	1	32.38
5	-1	1	1	1	-1	-1	-1	1	-1	1	1	37.54
6	1	1	1	-1	-1	-1	1	-1	1	1	-1	30.96
7	1	-1	-1	-1	1	-1	1	1	-1	1	1	34.15
8	-1	-1	-1	1	-1	1	1	-1	1	1	1	31.44
9	1	-1	1	1	-1	1	1	1	-1	-1	-1	33.63
10	1	1	-1	1	1	1	-1	-1	-1	1	-1	38.44
11	1	-1	1	1	1	-1	-1	-1	1	-1	1	36.36
12	-1	-1	1	-1	1	1	-1	1	1	1	-1	33.69
13	0	0	0	0	0	0	0	0	0	0	0	38.29

R4.2.3 was used to analyze the variance of the Plackett-Burman test results, and the influence of each parameter was shown in Table 4 below. From the variance results, the P values of the static friction coefficient between barley stems (X_4), the rolling friction coefficient between barley stems (X_5) and the rolling friction coefficient between barley stems and steel plate (X_8) were all less than 0.05, indicating that the impact on the angle of repose was significant, and other factors had no significant effect on the experimental results. Therefore, these three factors can be used directly as test factors for the steepest ascent test and the Box-Behnken test.

Table 4

Analysis of significance of parameters in Plackett-Burman test

Source of variation	Quadratic sum	Freedom	Mean square	F	P value
Model	112.91	8	14.11	14.7	0.0246*
X1	2.08	1	2.08	2.16	0.238
X2	9.21	1	9.21	9.58	0.0535
X3	0.12	1	0.12	0.12	0.7491
X4	53.72	1	53.72	55.93	0.0050**
X5	24.51	1	24.51	25.52	0.0150*
X6	3.4	1	3.4	3.54	0.1564
X7	5.03	1	5.03	5.24	0.1061
X8	14.85	1	14.85	15.46	0.0293*
Residual	112.91	3	14.11		

*Note: * shows the term is significant (P<0.05), ** shows the term is significant (P<0.01).*

Steepest ascent test and result

In order to quickly approach the optimal value, the steepest ascent test was carried out based on the significant influencing factors screened by Plackett-Burman test. The static friction coefficient between highland barley stems, the rolling friction coefficient between highland barley stems, and the rolling friction coefficient between highland barley stems and steel plates gradually increase according to the fixed steps. The non-significant factors take the intermediate level of the Plackett-Burman test. The relative error of the angle of repose between the simulation results and the actual test is the test index. The design and results of test is shown in Table 5.

Table 5

Design and results of steepest ascent test

No.	Barley stem- barley stem static friction coefficient A	Barley stem- barley stem rolling friction coefficient B	Barley stem-steel rolling friction coefficient C	Angle of repose [°]	Relative error [%]
1	0.2	0.05	0.2	29.16	5.39
2	0.28	0.07	0.24	31.66	2.73
3	0.36	0.09	0.28	34.95	13.40
4	0.44	0.11	0.32	36.15	17.29
5	0.52	0.13	0.36	41.63	35.07
6	0.6	0.15	0.4	52.27	69.60

It can be seen from the table that the angle of repose increases with the increase of the test factor value, and the relative error can show a trend of decreasing first and then increasing. When the values of A, B and C are 0.28, 0.07 and 0.24 respectively, the relative error of the angle of repose is the smallest. Therefore, the optimal value interval is near the level 2. The level 2 is set as the center point of the response surface test, and the levels 1 and 3 are taken as the low level and high level of the response surface test.

Box-Behnken test and regression model

According to the screening results, the three contact parameters of the static friction coefficient A between highland barley stems, the rolling friction coefficient B between highland barley stems, and the rolling friction coefficient C between highland barley stems and steel plates were taken as test factors, and the design of Box-Behnken test with three-factor and three-level was carried out. The number of repetitions of the center point was 4, and a total of 16 sets of simulation tests were carried out. The experimental design and results are shown in Table 6.

Table 6

Design and results of Box-Behnken test

No.	Barley stem- barley stem static friction coefficient A	Barley stem- barley stem rolling friction coefficient B	Barley stem-steel rolling friction coefficient C	Angle of repose [°]
1	-1 (0.2)	-1 (0.05)	0 (0.24)	26.79
2	1 (0.36)	-1	0	31.89
3	-1	1 (0.09)	0	32.8
4	1	1	0	33.3
5	-1	0 (0.07)	-1 (0.2)	28.02
6	1	0	-1	33.82
7	-1	0	1 (0.28)	32.55
8	1	0	1	32.32
9	0 (0.28)	-1	-1	27.8
10	0	1	-1	33.88
11	0	-1	1	30.28
12	0	1	1	32.89
13	0	0	0	32.02
14	0	0	0	32.12
15	0	0	0	32.61
16	0	0	0	32.25

The regression model was established based on the response surface regression test results. The quadratic regression model between the angle of repose θ and static friction coefficient A between barley stem, rolling friction coefficient B between barley stem and rolling friction coefficient C between barley stem - steel was obtained as follows:

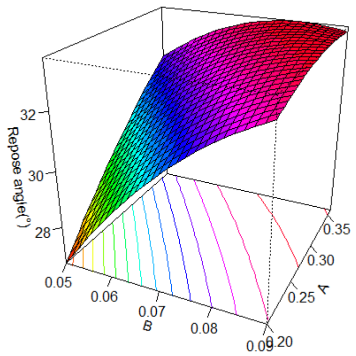
$$\theta = -72.145 + 209.92A + 841.31B + 316.43C - 718.75AB - 471.1AC - 1084.4BC - 51.95A^2 - 1993.75B^2 - 196.88C^2 \tag{8}$$

According to the variance analysis results of the model, the static friction coefficient A between the highland barley stems, the rolling friction coefficient B between the highland barley stems, and the rolling friction coefficient C between the highland barley stems and the steel plate have extremely significant effects on the accumulation angle. The interaction terms AB, BC, AC and quadratic term B^2 also have extremely significant effects on the angle of repose. The response surface of the interaction between the factors on the angle of repose is shown in Fig. 6.

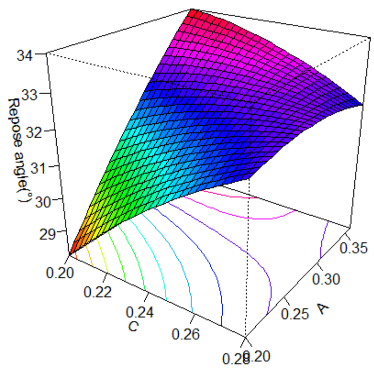
The P value ($P<0.0001$) of the fitting regression model shows that the regression relationship reaches extremely significant, and the regression model can describe the quantitative relationship of most experimental data. The P value of the lack of fit is 0.49230, and there is no lack of fit, indicating that the regression equation fits well. The determination coefficient R^2 is equal to 0.9868, adjusted R^2_{adj} is equal to 0.9669, both are close to 1, indicating that the fitting equation has high reliability. The variance test results are shown in Table 7 below.

In the case of ensuring that the model is significant and the lack of fit is not significant, the items with insignificant effects are eliminated, and the quadratic regression model is optimized to obtain a new regression Equation (9):

$$\theta = -58.649 + 180.83A + 866.31B + 226.94C - 718.75AB - 471.1AC - 1146.88BC - 2056.25B^2 \tag{9}$$



a)



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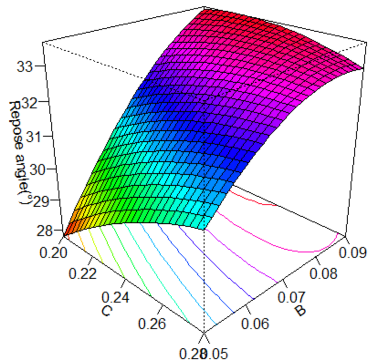

c)

Fig. 6 - Response surfaces for angle of repose

Table 7

ANOVA of quadratic polynomial model of Box-Behnken test

Source of variation	Quadratic sum	Freedom	Mean square	F	P value
Model	71.365	9	7.929	49.73	<.0001***
A	15.596	1	15.596	95.7233	<.0001***
B	33.252	1	33.252	204.0888	<.0001***
C	2.785	1	2.785	17.0921	0.0061**
AB	5.29	1	5.29	32.4681	0.0013**
AC	9.09	1	9.09	55.7925	0.0003 ***
BC	3.367	1	3.367	20.6668	0.0039**
A2	0.378	1	0.378	2.3214	0.1784
B2	2.706	1	2.706	16.6086	0.0065 **
C2	0.462	1	0.462	2.838	0.143
Residual	0.978	6	0.1629		
Lack of fit	0.495	3	1649	1.0244	0.4923
Pure error	0.483	3	0.161		
Sum	72.343	15			

*Note: * shows the term is significant (P<0.05), ** shows the term is significant (P<0.01), *** shows the term is significant (P<0.001)*

The variance analysis of the optimized regression model is shown in Table 8. The coefficient of determination R^2 of the model is equal to 0.9754, and the adjusted R^2_{adj} is equal to 0.9539, both of which are close to 1, indicating that the fitting reliability of the optimized equation is still high. The standard error of the residual is 0.4767, and a smaller value indicates that the higher the prediction accuracy of the model, the better the fit of the model. It is explained that the optimization model can be used to predict the accumulation angle of the particle pile.

Table 8

ANOVA of modified model of Box-Behnken test

Source of variation	Quadratic sum	Freedom	Mean square	F	P value
Model	72.081	7	10.297	45.31	<0.0001***
A	15.596	1	15.596	68.622	<0.0001***
B	33.252	1	33.252	146.307	0.008**
C	2.78	1	2.78	12.253	0.008**
AB	2.706	1	2.706	11.906	0.001**
AC	5.29	1	5.29	23.276	<0.0001***

Source of variation	Quadratic sum	Freedom	Mean square	F	P value
BC	9.09	1	9.09	39.997	0.005**
B2	3.367	1	3.367	14.816	0.008**
Residual	1.81	8	0.228		
Sum	73.891	15			

Optimal parameter combination and simulation verification

The ridge analysis of software R was used to obtain the parameter combination closest to the true value in the regression model. The static friction coefficient between barley stem was 0.27, the rolling friction coefficient between barley stem was 0.07, and the rolling friction coefficient between barley stem and steel should be 0.26. The other non-significant parameters take the intermediate level (the Poisson's ratio of highland barley stem is 0.35, the shear modulus of highland barley stem is 70 MPa, restitution coefficient between barley stem is 0.35, restitution coefficient between barley stem and steel is 0.6, and the static friction coefficient between barley stem and steel is 0.45). The numerical simulation of the above parameters is used to verify the accuracy of the optimal parameter combination. The particle accumulation morphology is simulated by using the above parameter values as shown in Fig. 7. The angles of repose of highland barley stem particles obtained by repeated three experiments were 30.26 °, 31.04 ° and 30.68 °, respectively, with an average value of 30.66 °. The relative error between the simulated and experimental values was 0.52 %. The small relative error indicates that there is no significant difference between the simulation results and the actual test results, indicating that the calibrated parameters are credible. It can be used for discrete element simulation of highland barley and provide reference for subsequent research on highland barley screening.

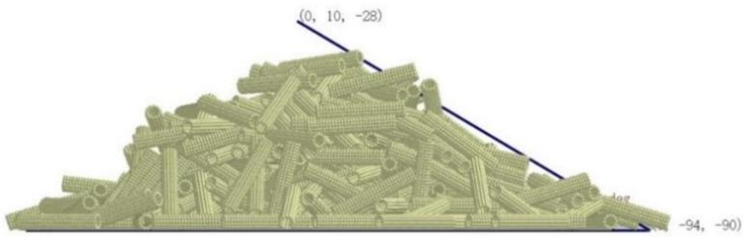

Fig. 7 - Simulation model of highland barley stem angle of repose

CONCLUSIONS

1) Through the Plackett-Burman test results, three factors that had significant effects on the accumulation angle of highland barley stem particles were screened out: static friction coefficient between barley stems, rolling friction coefficient between barley stems and rolling friction coefficient between barley stem and steel; the Poisson's ratio, shear modulus and collision recovery coefficient of highland barley stem had no significant effect on the stacking angle.

2) According to the results of the Box-Behnken experiment, a quadratic regression model between the significance parameters and the accumulation angle was established and optimized, and the primary terms of the three significance parameters (static friction coefficient between barley stems, rolling friction coefficient between barley stems, rolling friction coefficient between barley stems and steel) and the quadratic terms of the rolling friction coefficients between barley stems had significant effects on the calibration of barley parameters, and a quadratic regression model between the angle of repose θ and the three significance parameters was established.

3) By solving the optimized regression model, it is found that when the static friction coefficient between barley stems is 0.27, the rolling friction coefficient between barley stems is 0.07, the rolling friction coefficient between barley stems and steel should be 0.26, and the other non-significant parameters are at the intermediate level (the Poisson's ratio of highland barley stems is 0.35, the shear modulus of highland barley stems is 70 MPa, restitution coefficient between barley stems is 0.35, restitution coefficient between barley stems and steel is 0.6, and the static friction coefficient between barley stems and steel is 0.45), the relative error between the simulation and the actual test is 0.52 %. It shows that the calibrated contact parameters are effective and feasible.

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