PARAMETER CALIBRATION OF DISCRETE ELEMENT SIMULATION MODEL OF WHEAT STRAW-SOIL MIXTURE IN HUANG HUAI HAI PRODUCTION AREA
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黄淮海产区小麦秸秆-土壤混合物的离散元仿真模型参数标定

Zenghui GAO[1], Shuqi SHANG[1,2], Nan XU[3], Dongwei WANG [2*]

[1] Xinjiang Agricultural University, College of Mechanical and Electronic Engineering, Xinjiang, China
[2] Qingdao Agricultural University, College of Mechanical and Electronic Engineering, Shandong, China
[3] Shandong Agricultural University, College of Mechanical and Electronic Engineering, Shandong, China
*Tel: 13869881615; *) Corresponding author E-mail: w88030661@163.com*

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ABSTRACT

At present, there is a lack of accurate discrete element simulation model and parameters in the equipment in Huang Huai Hai double cropping production area, which hinders the optimization and improvement of equipment operation effect. In this paper, the discrete element method is used to study the interaction between soil-touching components and wheat straw-soil mixture to improve the performance of equipment. Firstly, the Hertz-Mindlin with JKR Cohesion contact model is selected for the wheat straw-soil mixture to calibrate the parameters. Then, the method of combining physical test and simulation test is used to calibrate the parameters, the cylinder lifting method is used to determine the buildup angle of wheat straw soil mixture, and the Plackett-Burman screening method and the steepest climbing test are used to determine the optimal combination range of soil-straw static friction coefficient, soil-straw dynamic friction coefficient and soil-soil dynamic friction coefficient contact model parameters. Using Box-Behnken optimization research and development of key components such as soil contact of seedbed preparation test, the regression equation of the stacking angle of wheat straw soil mixture was obtained, and the variance and interaction effect of the regression model were analysed. The regression model was used to find the optimal solution in Design-Expert software with an angle of repose of 41.23°, which yielded a soil-straw static friction factor of 0.072, a soil-straw dynamic friction factor of 0.78, and a soil-soil dynamic friction factor of 0.068, with an angle of repose error of 1.43%, indicating that the contact model parameters are reliable, and the parameters can provide a reference and theoretical basis for the study of the key components of the seedbed preparation equipment such as touching soil in the Yellow and Huaihai Sea two-maturity zone.

摘要

当前我国黄淮海两熟制产区种床制备装备触土等关键部件优化研发过程中缺乏精确的离散元仿真模型与参数，阻碍了装备作业效果的优化提升。本文采用离散元法对触土部件与小麦秸秆-土壤混合物进行互作研究，首先针对小麦秸秆-土壤混合物，选用Hertz-Mindlin with JKR Cohesion接触模型，进行参数标定；然后使用圆筒提升法对小麦秸秆-土壤混合物堆积角进行测定，使用Plackett-Burman筛选法与最陡爬坡试验，确定了各参数最优组合范围，使用Box-Behnken试验，得到了小麦秸秆-土壤混合物堆积角的回归方程，并进行了回归模型方差与交互效应分析；在Design-Expert软件中以堆积角为41.23°为目标，通过回归模型寻找到了最优解，得出土壤-秸秆静摩擦因数0.072、土壤-秸秆动摩擦因数0.78、土壤-土壤动摩擦因数0.068，堆积角误差为1.43%，说明接触模型参数较为可靠，参数可以为研究黄淮海两熟制产区种床制备装备触土等关键部件提供参考与理论依据。

INTRODUCTION

The main planting mode in Huang Huai Hai double cropping area is peanut direct seeding in summer after wheat. Wheat straw burying and returning to the field is an important way to deal with straw, which plays an important role in improving soil fertility, storing water and moisture, and realizing high yield of crops in the following season.

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[1] *Zenghui Gao, Ph.D. Stud. ; Shuqi Shang, Prof. ; Nan Xu, Ph.D. Stud. ; Dongwei Wang, Prof.*

At present, most of the Huang Huai marine production areas use land preparation equipment such as dynamic rake to treat wheat straw, so as to realize the deep burial of straw and the preparation of high-quality summer peanut seedbed. Due to the complex characteristics of wheat straw soil mixture, it is impossible to study the interaction relationship through traditional methods such as field experiment. Therefore, it is of great significance to calibrate the contact parameters of wheat straw soil mixture by discrete element method.

To address the problem of complex straw-soil mixing characteristics, in recent years, experts and scholars in related fields at home and abroad have proposed the use of the discrete element method to calibrate the parameters of simulation models for granular materials such as soil, straw, fertilizer and seeds (*Wang et al., 2019; Zhou et al., 2014*). Joash Bryan Adajar and others studied the macro and micro shear characteristics of five different crop straws (rape, corn, flax, oats and wheat) and their interaction with soil, so as to improve the reliability of the discrete element model simulating the interaction between soil and crop residues in the process of tillage (*Joash et al., 2021*). Zeng Fandi et al. verified the correctness of the duckbill planter-soil discrete element simulation model by using the Hertz-Mindlin with Bonding model to calibrate the parameters of the field soil in the transplanting environment in Inner Mongolia (*Zeng et al., 2021*). In view of the lack of accurate and reliable discrete element simulation parameters in the research on the interaction mechanism between soil and rotary tillage components on the Loess Plateau, Sun Jingbin and others selected the Hertz-Mindlin with JKR coordination contact model in EDEM to calibrate the relevant simulation parameters, and verified the accuracy of the calibration results of discrete element simulation parameters through the field test and simulation test of rotary tillage on the slope (*Sun et al., 2022*). Liu F. et al. used Hertz-Mindlin with JKR Bonding in EDEM to calibrate the parameters of quinoa stacking angle and set up a comparative test for validation using quinoa (*Liu F. et al., 2020*). Aiming at the lack of accurate discrete element simulation model parameters in the design and optimization of key agricultural machinery components in conservation tillage in black soil area, Tian Xinliang and others used the method of combining physical test and EDEM simulation test, and selected Hertz-Mindlin with JKR contact model to calibrate the discrete element simulation contact parameters (*Tian et al., 2021*). In order to improve the accuracy of the parameters required by the discrete element simulation in the process of dense forming of corn straw powder, Wang Weiwei and others took corn straw powder as the research object, and used the Hertz-Mindlin with JKR Bonding contact model in EDEM software to calibrate the parameters of the discrete element simulation model of dense forming of corn straw powder (*Wang et al., 2021*). Jia S.L. et al. calibrated the parameters related to the mid-term of maize dispersal under different conditions by constructing a maize seed disperser model and performing simulation analysis based on EDEM (*Jia S.L. et al., 2021*). In order to obtain the discrete element simulation parameters that can be used for the interaction between viscous black soil and soil contacting parts in Northeast China, Li Junwei and others calibrated the relevant parameters of viscous black soil in Northeast China with different moisture content by using the Hertz- Mindlin with JKR Cohesion contact model in EDEM (*Li et al., 2019*).

From the above information, it can be seen that the current studies by experts and scholars at home and abroad are all aimed at different operating conditions in different regions, and most of them revolve around the types of soils such as north-eastern clay and north-western loam, combined with locally grown crops. There is a lack of research on the calibration of discrete element simulation parameters for wheat straw-soil mixtures in loamy soils of the Yellow Huaihai Sea. Accurate completion of parameter calibration lays a theoretical foundation for further research on the interaction relationship between soil-touching components and is of great importance for improving the quality of seedbed preparation.

In this paper, the Hertz-Mindlin with JKR fusion contact model in EDEM is selected, and the parameters of the discrete element simulation model of wheat straw-soil mixture are calibrated by the combination of physical test and virtual simulation test. Then, the angle of repose simulation test is carried out and compared with the angle of repose results of physical test to verify the accuracy of the calibration results of discrete element simulation parameters (*Liu et al., 2016; Qi et al., 2019*).

MATERIALS AND METHODS

Test material

This paper studies the wheat straw-soil mixture. The selected wheat straw-soil mixture materials are from the experimental base in Taishan District, Tai'an City (36°16′ N, 117°16′ E). The soil of the experimental base is clay loam with pH value of about 7.5, base saturation of 82% and annual precipitation of about 700 mm. Its soil organic matter and nutrient status are suitable for planting wheat, peanut and other crops.

The soil and straw of the selected plot have been subject to the disc harrow operation. After the disc harrow operation, the wheat straw is basically mixed into the soil surface to the depth of 20 cm, so the mixture at the depth of 0-20 cm is selected.

Test Method

The parameters of the wheat straw-soil mixture were calibrated using a combination of the physical test method of cylinder lifting and the EDEM discrete element simulation test method. The parameters with significant effects on the angle of repose of wheat straw-soil were selected using the Plackett-Burman section of the Design-Expert software, and the optimal interval of each parameter was determined by the steepest climbing method, and the optimal combination of parameters was finally determined using the Design-Expert software. The differences between the angles of repose derived from physical tests and those from simulation experiments were compared to verify the accuracy of the parameter calibration (*Zhang et al., 2018*).

Physical experiment on the angle of repose of wheat straw-soil mixture

The cylinder lifting method is applied to build the physical test device for the angle of repose of wheat straw-soil mixture, as shown in the Figure 1, which is mainly composed of Sans cmt4503 universal tester, cylindrical steel pipe and steel plate (*Feng et al., 2015*). The length of steel pipe is 200 mm and the diameter is 50 mm. The initial state is that the steel pipe is erected on the steel plate, the wheat straw-soil mixture is in the steel pipe, the universal tester is used to lift the steel pipe upward at a uniform speed of 0.05 m/s, and the mixture falls on the steel plate until the mixture pile tends to be relatively stable. After that, the high-definition camera is used to take photos vertically with the steel plate to obtain the main view of the mixture pile, and then the gray-scale processing is carried out by MATLAB software, The contour of the mixture pile is linearly fitted, and the angle of repose is obtained. After repeating the test for 10 times, the average value of the results is obtained, and the angle of repose of wheat straw-soil mixture is 41.23°.

Fig. 1 – Physical test of angle of repose by cylinder lifting method

SIMULATION EXPERIMENT ON ANGLE OF REPOSE OF WHEAT STRAW-SOIL MIXTURE

Contact model selection

The selected soil is one of the typical soil types in the Yellow Huaihai region, and it is mostly clay loam, and after research and literature search, it is known that the soil moisture content in this region is generally between 15-20%. Since the main research objective is to investigate the interaction mechanism of wheat straw-soil mixture in the Yellow and Huaihai Sea region, and since there is a certain adhesion phenomenon between the particles of clay loam, the contact model should be chosen to represent the type of adhesion and agglomeration between the particles.

EDEM mainly has three more suitable contact models between soil and straw, namely Hertz-Mindlin, Hertz-Mindlin with bonding and Hertz-Mindlin with JKR Cohesion. Hertz-Mindlin cannot show the influence of the bonding force between granular materials, and cannot accurately simulate the movement and fragmentation of soil after dynamic target operation; Hertz-Mindlin with bonding is suitable for simulating hard objects such as seeds; Hertz-Mindlin with JKR Cohesion is a cohesive contact model based on Hertz-Mindlin and JKR theory. It mainly considers the influence of the bonding force between water particles on the movement and fragmentation of material particles.

It is suitable for studying materials such as soil due to water bonding and agglomeration. Because the moisture content of the selected soil and straw mixture is high, the Hertz-Mindlin with JKR Cohesion model is selected to simulate the wheat straw-soil mixture in the Huang Huai Hai area, and the parameters required by the model are calibrated.

Simulation model building

The virtual three-dimensional model of the physical test device is drawn and established with SolidWorks software, and the size is completely consistent, as shown in Figure 2.

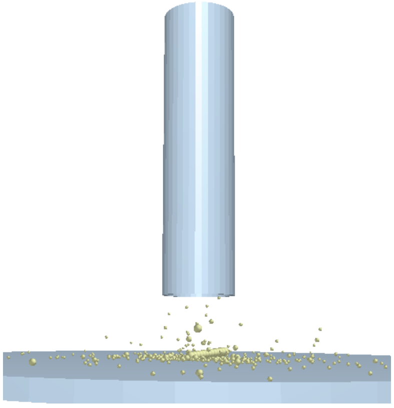

Fig. 2– Simulation test of angle of repose of cylinder lifting method

The ring blade method is used to measure the wet density of soil. The ring knife with a volume of 200 cm^3 is mainly used to sample soil, and the electronic balance with a measuring range of 510 g and an accuracy of 0.001 g is used to carry out 10 repeated tests, and the average value of 1280 kg/m^3 is obtained. Referring to the literature, the wet density of wheat straw is 241 kg/m^3. The Poisson's ratio and shear modulus of soil and straw samples were measured by SMS texture analyser (as shown in Figure 3).

(a) Cutting Ring *(b) SMS Texture Analyzer*

Fig. 3 – Parameter calibration physical test instrument

Soil and straw are homogeneous isotropic materials, and the relationship between shear modulus, Young's modulus and Poisson's ratio is as follows:

$$G=\frac{E}{2(1+v)} \tag{1}$$

According to the material model established by L.H. Han and others for the powder, through the fixed transverse deformation space, it is known that the stress-strain during rebound is related to the Young's modulus and Poisson's ratio of the sample *(L.H. Han* et al., *2008)*, and the relation is as follows:

$$S=\frac{E(1-v)}{(1+v)(1-2v)} \tag{2}$$

where: v - Poisson's ratio;

G - shear modulus, MPa;

E - Young's modulus, GPa;

S - Stress strain ratio during rebound.

The ratio of the modulus of resilience to the strain of the soil is calculated by the Young's modulus of resilience and the ratio of the shear modulus to the mass of the soil as shown in the Table 1.

Table 1

Basic properties of test samples

Material	Poisson's ratio	Shear modulus [Pa]	Density [kg/m^3]	Source
Soil	0.38	1×10^6	1280	Determination
Straw	0.40	1×10^6	241	Literature *(Guo, 2017)*

According to many field tests, in the range of soil depth 0-20 cm, the length of straw after crushing and returning to the field generally does not exceed 50 mm, and the quality of soil and straw is about 98:2. Other motion and physical parameters are the same as those in physical test.

Using the generic EDEM material model database (GEMM), according to the measured density and angle of repose of soil and straw, combined with the parameter selection range of references, the contact model parameters to be calibrated are obtained, as shown in the Table 2.

Table 2

Contact model parameters

Parameter	Numerical value
Soil-soil recovery coefficient	0.15-0.75
Soil-soil static friction coefficient	0.32-1.16
Soil-soil dynamic friction coefficient	0.05-0.1
Soil-straw recovery coefficient	0.15-0.75
Soil-straw static friction coefficient	0.60-1.00
Soil-straw dynamic friction coefficient	0.05-0.1
Straw-straw recovery coefficient	0.35-0.75
Straw-straw static friction coefficient	0.20-1.16
Straw-straw dynamic friction coefficient	0.15-0.20
Soil JKR surface energy / (J·m^{-2})	4-16
Soil-straw JKR surface energy / (J·m^{-2})	4-14

Significance screening test of contact model parameters

Because there are many parameters in the contact model, the parameters that have a significant impact on the angle of repose should be selected first. The Plackett-Burman section of design expert software is used for screening test design. Taking the angle of repose of soil-wheat straw mixture as the index, the soil-soil recovery coefficient (A), soil-soil static friction coefficient (B), soil-soil dynamic friction coefficient (C), soil-straw recovery coefficient (D), soil-straw static friction coefficient (E), soil-straw dynamic friction coefficient (F), straw-straw recovery coefficient (G) straw-straw static friction coefficient (H), straw-straw dynamic friction coefficient (I), soil JKR surface energy (J) and soil-straw JKR surface energy (K) are the factors. The level is shown in Table 3.

Table 3

Factors and levels

Level	A	B	C	D	E	F	G	H	I	J	K
-1	0.15	0.32	0.05	0.15	0.60	0.05	0.35	0.20	0.15	4	4
0	0.45	0.74	0.075	0.45	0.80	0.075	0.55	0.68	0.175	10	9
1	0.75	1.16	0.10	0.75	1.00	0.10	0.75	1.16	0.20	16	14

RESULTS AND ANALYSIS

Plackett-Burman screening test and significance analysis

The software generates Plackett-Burman test design, and applies EDEM to complete 12 tests to obtain the angle of repose. The test design and results are shown in Table 4. Then, the design expert software is used to analyse and obtain the contribution degree and ranking of various factors, that is, the significance relationship. From Table 5, it can be seen that: soil-straw static friction factor, soil-straw dynamic friction factor and soil-soil dynamic friction factor have the most significant effect on the angle of repose, while the contribution of the remaining factors does not exceed 5%.

Table 4

Test design and results

Serial number	Factor											Angle of repose / (°)
	A	B	C	D	E	F	G	H	I	J	K	
1	1	1	-1	1	1	1	-1	-1	-1	1	-1	42.63
2	1	-1	-1	-1	1	-1	1	1	-1	1	1	40.89
3	1	-1	1	1	1	-1	-1	-1	1	-1	1	41.05
4	1	-1	1	1	-1	1	1	1	-1	-1	-1	41.16
5	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	38.52
6	-1	1	1	1	-1	-1	-1	1	-1	1	1	39.48
7	1	1	-1	-1	-1	1	-1	1	1	-1	1	41.54
8	-1	-1	-1	1	-1	1	1	-1	1	1	1	40.96
9	-1	1	-1	1	1	-1	1	1	1	-1	-1	39.26
10	1	1	1	-1	-1	-1	1	-1	1	1	-1	40.08
11	-1	1	1	-1	1	1	1	-1	-1	-1	1	43.08
12	-1	-1	1	-1	1	1	-1	1	1	1	-1	43.86

Table 5

Test results analysis

Factors	A	B	C	D	E	F	G	H	I	J	K
Contribution degree /%	1.44	0.041	7.22	3.53	24.43	58.31	0.82	0.005	0.29	3.24	0.67
Sort	6	10	3	4	2	1	7	11	9	5	8

Analysis of the steepest climbing test

Soil-straw static friction coefficient, soil-straw dynamic friction coefficient and soil-soil dynamic friction coefficient have great influence on the size of angle of repose. Therefore, based on the screening test, in order to determine the optimal range of contact model parameters required in the simulation, the steepest climbing test analysis is carried out. For the parameters with insignificant influence, the level 0 values in Table 3 are selected, namely soil-soil recovery coefficient 0.45, soil-soil static friction coefficient 0.74, soil-straw recovery coefficient 0.45, straw-straw recovery coefficient 0.55, straw-straw static friction coefficient 0.68, straw-straw dynamic friction coefficient 0.175, soil JKR surface energy 10 and soil-straw JKR surface energy 9. The steepest climbing test design and result analysis are shown in Table 6.

Table 6

Experimental design and result analysis

Serial number	C	E	F	Angle of repose / (°)	Error / %
1	0.05	0.60	0.05	35.76	13.26
2	0.0625	0.70	0.0625	38.32	7.05
3	0.075	0.80	0.075	42.58	3.27
4	0.0875	0.90	0.0875	44.91	8.92
5	0.10	1.00	0.10	46.19	12.03

It can be seen from the table that the angle of repose error of test 3 is relatively small, so the optimal combination of contact model parameters is near test 3.

Box-Behnken test analysis

In order to reduce the error of each contact model parameter and improve the accuracy of simulation, it is necessary to carry out the optimal parameter combination test for soil-straw static friction coefficient, soil-straw dynamic friction coefficient and soil-soil dynamic friction coefficient. According to the steepest climbing test, it is known that the optimal combination of contact model parameters is near test 3, so the box Behnken test is carried out at the level of test 2, 3 and 4, and the three factor and three-level test is carried out with the angle of repose as the test index. The test design and results are shown in Table 7.

Table7

Experimental design and results

Serial number	Factors			Angle of repose R (°)
	C	E	F	
1	-1	0	-1	42.03
2	-1	-1	0	42.24
3	-1	0	1	43.92
4	-1	1	0	42.32
5	0	-1	1	43.81
6	0	0	0	42.58
7	1	-1	0	42.40
8	1	0	1	44.06
9	0	1	1	44.38
10	0	0	0	42.58
11	0	-1	-1	41.86
12	0	0	0	42.58
13	1	0	-1	42.10
14	0	0	0	42.58
15	0	1	-1	42.25
16	0	0	0	42.58
17	1	1	0	42.79

It can be seen intuitively from the above table that the three factors of soil-straw static friction coefficient, soil-straw dynamic friction coefficient and soil-soil dynamic friction coefficient are taken as the research objects to explore the relevant conclusions affecting the size of angle of repose. The angle of repose is generally within 41.86 ~ 44.38%.

Through the above test results, the regression coefficient and significance of the angle of repose are analysed. According to the feedback information in the above table, the regression equation of the angle of repose is:

$$\begin{gathered} R = 42.58 + 0.11C + 0.18E + 0.99F + 0.077CE + 0.018CF \\ +0.045EF - 0.095C^2 - 0.048E^2 + 0.54F^2 \end{gathered} \tag{3}$$

According to the regression equation, the influence of the three influencing factors on the angle of repose is that the soil-soil dynamic friction coefficient is the largest, the soil-straw dynamic friction coefficient is slightly smaller, and the soil-straw static friction coefficient is the smallest.

Table 8

Analysis of variance of regression model

Source	Sum of squares	Freedom Degrees	Mean Square	F Value	P-value Prob＞F
Model	9.50	9	1.06	125.90	< 0.0001
C	0.088	1	0.088	10.52	0.0142
E	0.26	1	0.26	30.49	0.0009
F	7.86	1	7.86	937.78	< 0.0001
CE	0.024	1	0.024	2.87	0.1343
CF	1.225E-003	1	1.225E-003	0.15	0.7136
EF	8.100E-003	1	8.100E-003	0.97	0.3583
C^2	0.038	1	0.038	4.53	0.0708
E^2	9.500E-003	1	9.500E-003	1.13	0.3224
F^2	1.24	1	1.24	147.84	< 0.0001
Residual	0.059	7	8.382E-003	_	_
Lack of Fit	0.059	3	0.020	_	_
Pure Error	0.000	4	0.000	_	_
Cor Total	9.56	16	_	_	_

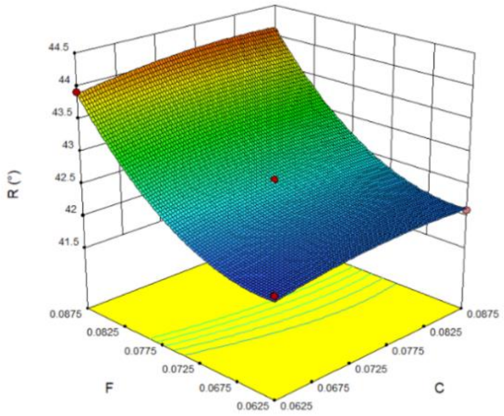

Fig. 4 – Effect of C and F on angle of repose (R) response surface

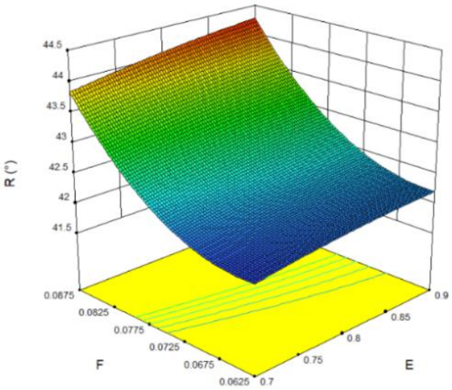

Fig. 5 – Effect of E and F on angle of repose (R) response surface

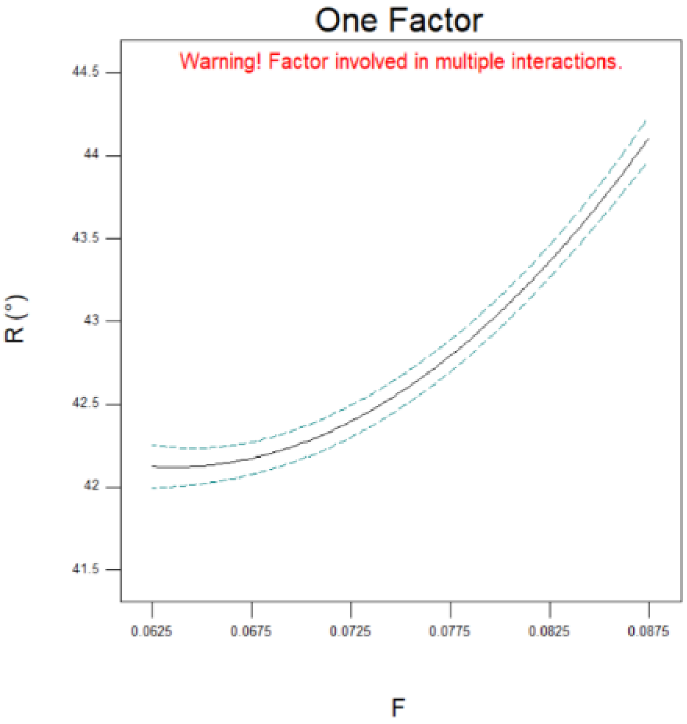

Fig. 6 – Effect of F on angle of repose (R) response curve

It can be seen from Table 8 and figures 4, 5 and 6 that E, F and F^2 have a significant impact on the angle of repose, C has a significant impact on the angle of repose, and CE, CF, EF, C^2 and E^2 have no significant impact on the angle of repose.

Using the parameter optimization module in the design expert software, the optimal solution is found through the regression model with the angle of repose of 41.23°. After several groups of simulation verification, the optimal solutions are soil-straw static friction coefficient 0.072, soil-straw dynamic friction coefficient 0.78 and soil-soil dynamic friction coefficient 0.068. The simulation angle of repose under the optimal solution is 41.82 and the error is 1.43%. The results of physical test and simulation test are shown in Figure 7.

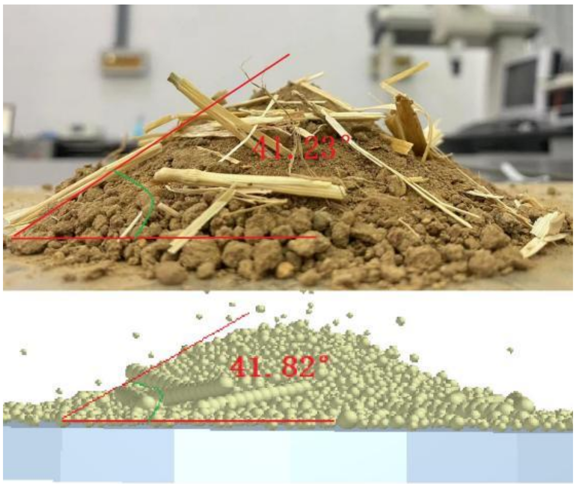

Fig. 7 – Comparison of angle of repose between physical and simulation tests

DISCUSSION

The calibration of discrete element model parameters for straw-soil mixtures had important effects on straw return, seedbed preparation, and optimization of structure and motion parameters of soil-touching components, which is the same as the findings of *Wang et al., (2021), Guo, (2017*). *Tian et al., (2021)*, when analysing the factors affecting the angle of repose, concluded that the influence of each factor on the angle of repose was caused by as soil-soil dynamic friction factor, soil-straw dynamic friction factor, and soil-straw static friction factor, which is consistent with the results of this study. The results in research done by *Sun et al., (2021), Li et al. (2019)* showed that the errors of 1.7% and 1.52% for the angle of repose simulation experiments and physical tests, respectively, were higher than the 1.43% results obtained in this study, which proved that the contact model used in this study is more reliable.

CONCLUSIONS

1) The discrete element method was used to conduct a study on the interaction between soil-touching components and wheat straw-soil mixtures. For wheat straw-soil mixtures, the EDEM software was applied and the Hertz-Mindlin with JKR Cohesion contact model was selected for parameter calibration to lay the foundation for conducting research on seedbed preparation equipment in the Yellow and Huaihai regions.

2) The parameter calibration adopts the method of combining physical test and simulation test. The cylinder lifting method was used to measure the angle of repose of wheat straw-soil mixture. Using Plackett-Burman screening method and steepest climbing test, the optimal combination range of soil-straw static friction coefficient, soil-straw dynamic friction coefficient and soil-soil dynamic friction coefficient contact model parameters was determined. Using box Behnken test, the regression equation of angle of repose of wheat straw-soil mixture was obtained, and the variance and interaction effect of the regression model were analysed.

3) Using the parameter optimization module in design expert software, aiming at the accumulation angle of 41.23°, the optimal solution is found through the regression model. The soil-straw static friction coefficient is 0.072, the soil-straw dynamic friction coefficient is 0.78, the soil-soil dynamic friction coefficient is 0.068, and the accumulation angle error is 1.43%, indicating that the parameters of the contact model are relatively reliable.

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