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Parameter Calibration of Soil in the Poyang Lake Region Based on Discrete Element Method

[1,2]Baoyu Zhu, [1,2]Jun'an Liu, [1,2]Xiongfei Chen, [1,2]Jiajia Yu, [1,2]Muhua Liu and [3]Qingsong Zhang

[1]*College of Engineering, Jiangxi Agricultural University, Nanchang 330045, China*
[2]*Key Laboratory of Modern Agricultural Equipment Library, Nanchang 330045, China*
[3]*College of Engineering, Huazhong Agricultural University, Wuhan 430070, China*

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Corresponding Author:
Jiajia Yu
College of Engineering, Jiangxi Agricultural University,
Nanchang 330045, China
E-mail: aiyejingling@163.com

Abstract: In order to obtain the soil parameters of Poyang Lake Region before direct seeding, the soil properties of Duchang County, Poyang County and Xinjian District recollected and the discrete element method model is established. The angle of repose of paddy soil is 53.00° tested by the lateral wall collapse method. Eleven parameters are used to establish EDEM simulation model with the Hertz-Mindlin and the Johnson-Kendall-Roberts (JKR) contact model. Based on the Plackett-Burman experiment, the Steepest ascent experiment and Box-Behnken experiment are carried out to study the factors affecting the angle of repose and the regression equation is established. Thus The optimal parameters are obtained with the deviation of 2.23%. Then the furrow width and depth are introduced to verify the soil model and the comprehensive error is 11.60%. Therefore, the soil model before direct seeding can be used to optimize the structure of mechanical direct seeding in Poyang lake region, so as to achieve the purpose of reducing resistance and increasing efficiency.

Keywords: Parameter Calibration, Angle of Repose, Soil, Direct Seeding, Poyang Lake Region, Discrete Element Method

Introduction

Mechanical direct seeding is more and more popular for its great advantages of high efficiency and production in the Poyang Lake Region, the largest freshwater lake in China. However, the interaction effect between the soil and agricultural machine is complex (Makange *et al*., 2020; Tekeste *et al*., 2020) and the soil before direct seeding is studied to design the optimal compartment of direct seeder according to the discrete element method (Mak *et al*., 2012).

Discrete Element Method (DEM) is a numerical method used to analyze the motion of a granular mixture (Liu *et al*., 2020; Tran *et al*., 2020), especially for the microscopic deformation and macroscopic deformation of the granular soil (Sun *et al*., 2018; Solhjou *et al*., 2013). Thus, many researchers have applied this method to study the dryland soil (De Pue and Cornelis, 2019; Shi *et al*., 2019), especially the interaction effect between the soil and the tillage device (Sun *et al*., 2020; Wang *et al*., 2019). Since different soils have different structures and properties and the parameter calibration is the key to analyze the disturbance of soil (Wang *et al*., 2017). Therefore, DEM is used to study a variety of different soil models on dryland (Barr *et al*., 2018; Tamás *et al*., 2013). The DEM models of dryland soil are only suitable for low moisture content (Yang *et al*., 2018; Zeng *et al*., 2017). However, the high moisture content of mechanical direct seeding in paddy fields, the fluidity and thixotropy of soil will change greatly and the DEM model of dryland soil is not suitable for mechanical direct seeding of paddy fields. Furthermore, no prior studies on the evaluation of soil quality indirect seeding field by DEM. With the development of mechanical direct seeding technology (Li *et al*., 2016; Ucgul *et al*., 2014), the interaction between the furrowing device and soil influences the movements of muddy (Ucgul *et al*., 2017). Thus, further study of soil in the direct seeding field is needed.

According to the properties of soil in the Poyang Lake Region before direct seeding, the angle of repose is tested to establish the EDEM model. The Plackett-Burman experiment, the steepest ascent experiment and the Box-Behnken experiment are carried out to obtain the optimal parameters and the fitting equation is built by simulation. Finally, the verification experiment is introduced to compare with the soil simulation model by the comprehensive error. Based on EDEM, the soil model of Poyang Lake Region before direct seeding is established, which can also be used to optimize the structural parameters, reduce resistance and improve efficiency.

Research Methods

Physical Characteristics of the Soil in the Poyang Lake Region

Soil samples of direct seeding filed are randomly selected from the depth of 0-15 cm in three locations around the Poyang Lake Region: Duchang county (116.18'E, 29.27'N), Poyang County (116.67'E, 29.00'N) and Xinjian District (115.82'E, 28.70'N). The soil should be ploughed and soaked in water for 36-48 h and then drained to maintain 50-58% of the moisture content Fig. 1. Thus, the soil in the direct seeding field will be prepared for the construction of large furrow and seed furrow for rice direct seeder.

In order to analyze the three physical properties of soil, i.e., granular composition, internal friction angle and cohesion, the samples are tested by vibrating sieve (Shangyu Zone Daoxuyuezhou Geotechnical Instrument of Shaoxing City) Fig. 2 and ZJ Strain Direct Shear Testing Apparatus (Nanjing Soil Instrument) Fig. 3. The results are shown in Figs. 4 and 5.

The results show that the soil particle composition in three locations had no difference and 95% of granular soil is less than 2 mm of diameters Fig. 4. While the internal friction angle and cohesion of soil from the three locations have no significant difference, only the soil of Duchang County has a great internal friction and less cohesion, while the soil in Poyang County and Xinjian Dsitrict has the same properties (Fig. 5). The soil of direct seeding field in the Poyang Lake Region has the same structural composition and a general soil could be used for studying the interaction effect between the soil and the furrowing device.

EDEM Simulation Model

Granular Model and Contact Model of Soil

DEM is applied for mechanical direct seeding of rice so as to study the interaction between soil and furrow. Considering the simulation accuracy and calculation time, the semi-diameter of soil ball is set to 2.5 mm. Hertz-Mindlin and Johnson-Kendall-Roberts (JKR) contact model are used for simulation (Chen and Elliott, 2020).

In order to obtain the influencing parameters of soil in direct seeding filed, the cohesive force between wet soil particles is considered and the cohesive and aggregate particles are simulated assoil and crop (Style *et al*., 2013), thus the surface energy could indicate the cohesion energy (Fig. 6).

Fig. 1: Soil of direct seeding field

Fig. 2: Vibrating sieve

Fig. 3: ZJ strain-controlled direct shear apparatus

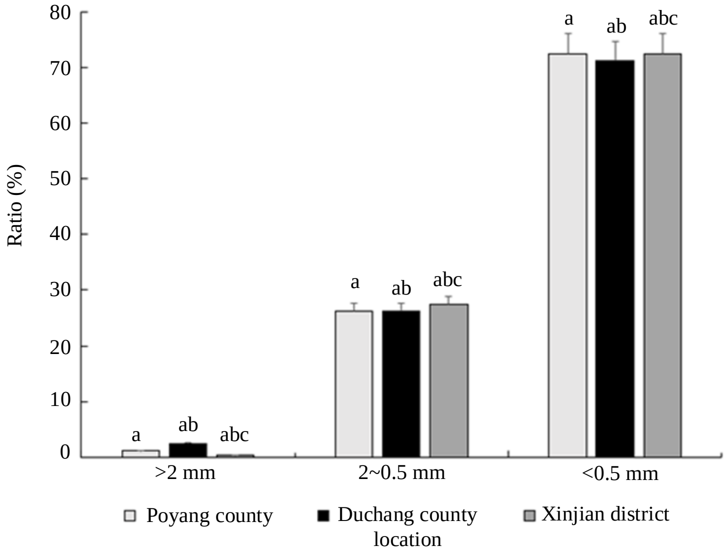
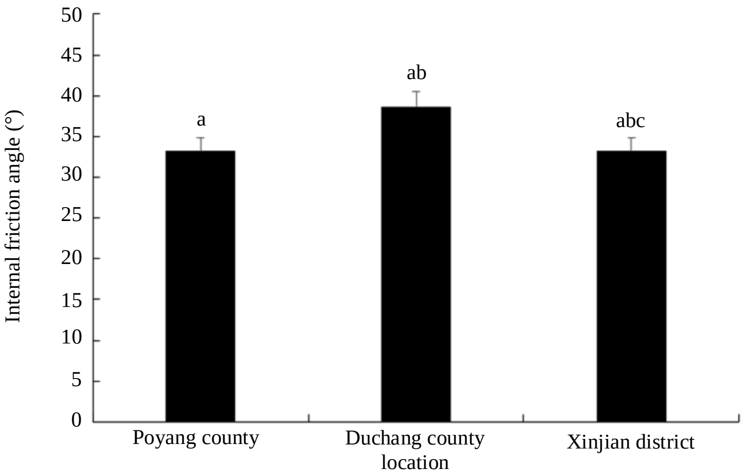
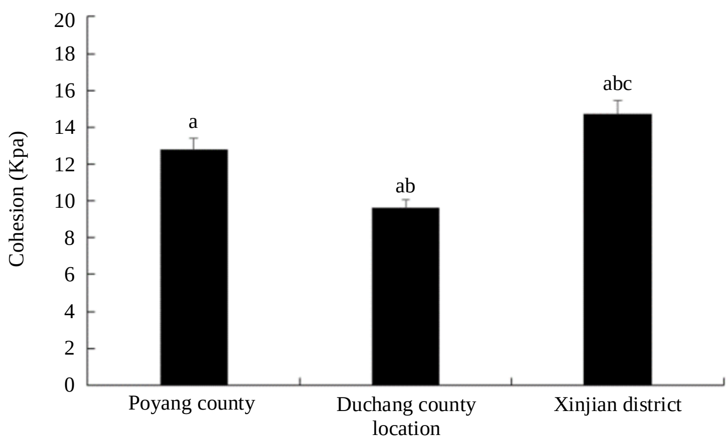


Fig. 4: Mass fraction of soil particle composition in direct seeding



(a)



(b)

Fig. 5: Internal friction angle and cohesion of soil (a) Internal friction angle of soil; (b) Cohesion of soil

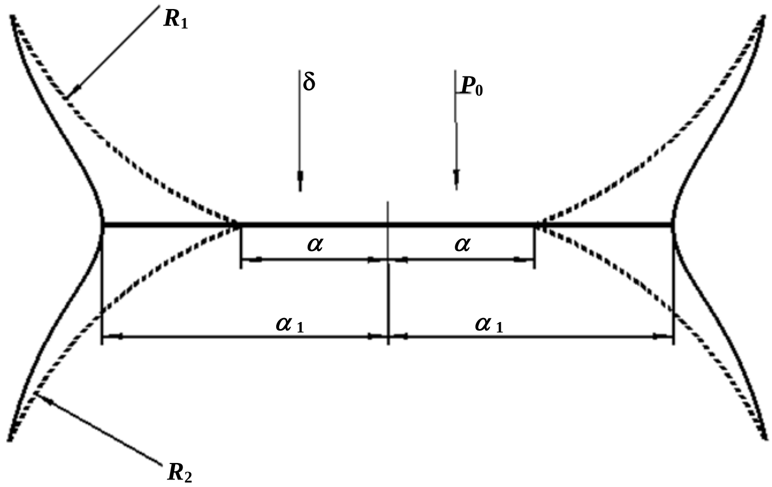


Fig. 6: The Johnson-Kendall-Roberts contact model

The normal contact force F_{JKR} between soil particles is calculated, as shown in Equation (1):

$$F_{JKR} = -4\sqrt{\pi\gamma E^*}\alpha^{3/2} + \frac{4E^*}{3R^*}\alpha^3 \tag{1}$$

F_{JKR} = The JKR normal contact force
α = The tangential overlap
γ = The surface tension of particle
R^* = The equivalent diameter
E^* = The equivalent elastic modulus

The tangential overlap δ is calculated:

$$\delta = \frac{\alpha^2}{R^*}\sqrt{4\pi\gamma\alpha / E^*} \tag{2}$$

The equivalent diameter R^* and elastic modulus E^* are:

$$\frac{1}{E^*} = \frac{(1\text{-}v_1)}{2G_1} + \frac{(1\text{-}v_2)}{2G_2} \tag{3}$$

$$\frac{1}{R^*} = \frac{1}{R_1} + \frac{1}{R_2} \tag{4}$$

When the surface energy is 0, F_{Hertz} is described as shown in Equation (5):

$$F_{Hertz} = \frac{4}{3}E^*\sqrt{R^*}\delta^{\frac{3}{2}} \tag{5}$$

When the tangential overlap δ is 0, $F_{pullout}$ is shown in Equation (6):

$$F_{pullout} = \frac{8}{3}\pi\gamma R^* \tag{6}$$

Soil Angle of Repose of Direct Seeding Field

The soil angle of repose indirect seeding filed is tested by the lateral wall collapse method (Qi *et al*., 2019; Tekeste *et al*., 2020). Apolymethyl methacrylate (PMMA) cuboid with 130×100×100 mm is selected (Fig. 7) and the moisture content of the soil is 50%. When the lateral wall is removed, the wet soil collapsed and flowed with a new inclined surface. The angle of repose is 53.00°.

The simulation parameters are set according to the generic EDEM material model database shown in Table 1. The soil particles fill with 8000 balls in the cuboid granular factory (100×95 mm) to establish the model and the Rayleigh gradually reaches 20%. When the ball velocity is 0r/min, the angle of repose is measured by removing the lateral wall, shown in Fig. 8.

Experimental Design

To study the influencing parameters of soil in the direct seeding field based on EDEM, a Plackett-Burman experiment, a Steepest ascent experiment and a Box-Behnken experiment are carried out.

Plackett-Burman Experiment

Using Plackett Burman test, 11 parameters of the soil simulation model are set in the design experts, including six real parameters and five virtual parameters. A high level and low level are selected for each parameter to calculate the distribution of each parameter, as shown in Table 2. Thus, the significant parameters are found from 13 treatments and the angle of repose is used as the evaluation index.

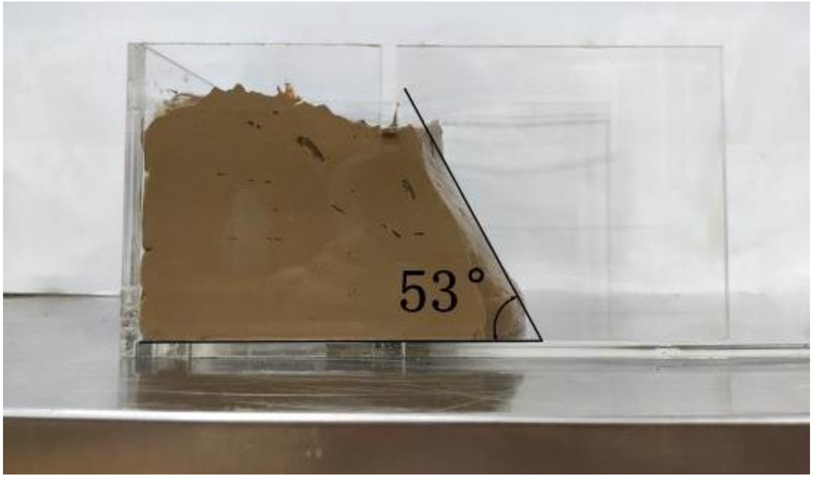


Fig. 7: Test the angle of repose of the soil

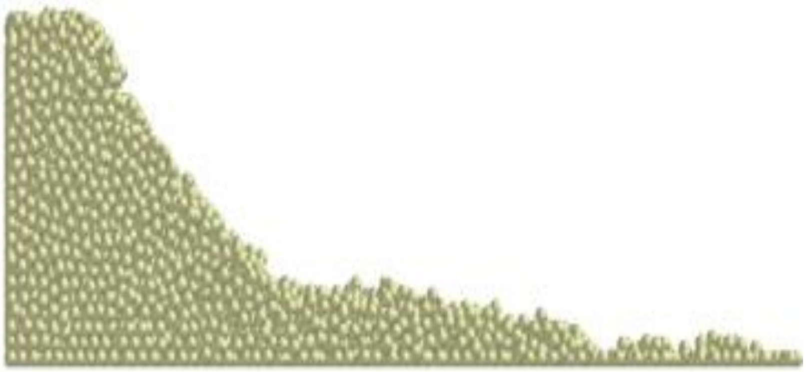


Fig. 8: Angle of repose of soil in EDEM

Table 1: Simulation parameters of soil

Parameters	Date
Soil density (g/cm^3)	1.661
PMMA density (g/cm^3)	1.18
Poisson ratio of soil	0.1-0.3 q
Poisson ratio of PMMA	0.3
Shear modulus of soil (MPa)	50-100 q
Shear modulus of PMMA (MPa)	2
Static friction coefficient between soil and soil	0.1-0.5 q
Dynamic friction coefficient between soil and soil	0.1-0.5 q
Coefficient of restitution between soil and soil	0.05-0.4 q
Surface energy between soil and soil (J/m^2)	0.5-4 q

Note: q indicates that this item is a test variable

Table 2: Plackett-Burman experimental parameters

No.	Parameters	Low level	High level
A	Shear modulus of soil (MPa)	1.00	50.0
B	Coefficient of restitution between soil and soil	0.05	0.4
C	Dynamic friction coefficient between soil and soil	0.10	0.5
D	Surface energy between soil and soil (J/m^2)	0.50	4.0
E	Poisson ratio of soil	0.10	0.3
F	Static friction coefficient between soil and soil	0.10	0.5
G, H, I, J, K	Virtual parameter	-1.00	1.0

Steepest Ascent Experiment

In order to obtain the optimal range of parameters, the steepest climb experiment is carried out by selecting the significant parameters of Plackett Burman test results and the object value is the angle of repose. The Rayleigh gradually increased and the relative error is the evaluation index. Therefore, the parameters of minimum relative error are selected to carry out the Box-Behnken experiment.

Box-Behnken Experiment

A Box-Behnken experiment is used to calculate the optimal parameters and three levels, including a high, low and medium level are selected as the upper (+1), lower (-1) and average level (0) in the significant parameters. The average value of other parameters is taken as the steepest ascent experiment and "three center points method" is used to achieve the angle of repose. The fitting equation is built by 29 times of simulation.

Experimental Results

Plackett-Burman Experimental Results

The results show the restitution coefficient, shear modulus, rolling friction coefficient and surface energy have great influence on the angle of repose, as shown in Tables 3 and 4. However, the Poisson ratio of soil and static friction coefficient between soils had a low contribution and four parameters with shear modulus (A), of restitution coefficient (B), rolling friction Coefficient (C) and surface energy (D) a reconsidered.

Steepest Ascent Experimental Results

The results show that different levels of shear Modulus (A), restitution coefficient (B), rolling friction Coefficient (C) and surface energy (D) could form different angles of repose shown as Table 5. The angles of Repose (R1) will increase with the increase of restitution coefficient, shear modulus and energy. The relative errors firstly decrease and then increase and the middle level, i.e., No. 3, has a minimum relative error. Thus No. 3 is taken as the center point and No. 2 and No. 4 are taken as the low and high levels in the Box-Behnken experiment respectively.

Box-Behnken Experimental Results

According to the results in Table 5, shear modulus (A), restitution coefficient (B), rolling friction Coefficient (C) and surface energy (D) with three levels (No. 2, 3 and 4) are selected to design Box-Behnken experiment. 29 Angles of Repose (R1) of soil are obtained by simulation shown as Table 6. The results show that four parameters with three different levels would influence the different angles of repose. The variance analysis is carried out to find the significant difference of parameters as shown in Table 7.

Table 3: Plackett-Burman experimental results

No.	A	B	C	D	E	F	G	H	I	J	K	R_1(°)
1	1	-1	1	-1	-1	1	-1	1	-1	1	1	17.49
2	-1	-1	1	1	1	1	1	1	-1	-1	-1	0.00
3	-1	1	1	-1	1	1	-1	-1	1	-1	1	6.27
4	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	2.37
5	-1	1	-1	1	-1	1	-1	1	1	1	-1	90.00
6	1	1	1	-1	-1	-1	1	1	1	-1	-1	18.35
7	-1	1	-1	-1	1	-1	1	1	-1	1	1	13.53
8	1	1	-1	1	-1	1	1	-1	-1	-1	1	90.00
9	-1	-1	1	1	-1	-1	1	-1	1	1	1	0.38
10	1	-1	-1	-1	1	1	1	-1	1	1	-1	19.79
11	1	-1	-1	1	1	-1	-1	1	1	-1	1	90.00
12	1	1	-1	1	1	-1	-1	-1	-1	1	-1	90.00
13	0	0	0	0	0	0	0	0	0	0	0	90.00

Note: R_1 is the angle of repose

Table 4: Plackett-Burman parameters variance analysis

Parameters	Standardized effect	Sum of squares	Contribution	Sequence
A	35.58	3797.13	18.67	2
B	29.75	2655.51	13.06	3
C	-28.93	2510.63	12.35	4
D	47.03	6636.54	32.64	1
E	0.23	0.16	7.861×10^{-4}	6
F	1.55	7.21	0.035	5

Table 5: Steepest ascent experimental results

No.	A (MPa)	B	C	D (J/m^2)	R1 (°)	Relative error%
1	0.4	0.1	0.0	0.5	00.7	98.67
2	0.8	0.2	0.1	1.0	10.8	79.62
3	1.2	0.3	0.2	1.5	24.1	54.51
4	1.6	0.4	0.3	2.0	90.0	69.81
5	2.0	0.5	0.4	2.5	90.0	69.81

Table 6: Box-Behnken experimental results

No.	A (MPa)	B	C	D (J/m^2)	R_1(°)
1	1.2	0.3	0.2	1.5	26.55
2	1.6	0.3	0.3	1.5	87.09
3	1.2	0.2	0.3	1.5	8.46
4	1.2	0.3	0.2	1.5	26.87
5	1.6	0.4	0.2	1.5	90.00
6	1.2	0.3	0.3	1.0	6.82
7	1.6	0.3	0.2	1.0	90.00
8	1.2	0.3	0.2	1.5	27.00
9	0.8	0.3	0.1	1.5	23.70
10	1.2	0.4	0.1	1.5	90.00
11	1.6	0.3	0.1	1.5	90.00
12	1.2	0.2	0.1	1.5	13.04
13	1.6	0.2	0.2	1.5	13.66
14	1.2	0.4	0.2	2.0	90.00
15	1.2	0.3	0.1	2.0	90.00
16	1.2	0.3	0.1	1.0	90.00
17	1.6	0.3	0.2	2.0	90.00
18	1.2	0.3	0.3	2.0	21.24
19	1.2	0.2	0.2	2.0	15.73
20	1.2	0.4	0.3	1.5	90.00
21	0.8	0.3	0.3	1.5	12.28
22	0.8	0.4	0.2	1.5	90.00
23	0.8	0.3	0.2	2.0	16.98
24	1.2	0.2	0.2	1.0	7.70
25	0.8	0.3	0.2	1.0	8.78
26	0.8	0.2	0.2	1.5	13.70
27	1.2	0.3	0.2	1.5	28.72
28	1.2	0.4	0.2	1.0	90.00
29	1.2	0.3	0.2	1.5	30.16

Table 7: Variance analysis of box-behnken experimental results

Source of variation	Sum of squares	df	Mean square	F-value	P-value
Model	24828.63	14	1773.47	26.28	<0.0001*
A	1485.47	1	1485.47	22.01	0.0003*
B	565.11	1	565.11	8.37	0.0118*
C	1585.28	1	1585.28	23.49	0.0003*
D	738.32	1	738.32	10.94	0.0052*
AB	2531.96	1	2531.96	37.52	<0.0001*
AC	2501.00	1	2501.00	37.06	<0.0001*
BC	1493.71	1	1493.71	22.13	0.0003*
B^2	287.76	1	287.76	4.26	0.0580
C^2	1867.98	1	1867.98	27.68	0.0001*
D^2	857.99	1	857.99	12.71	0.0031*
A^2B	854.04	1	854.04	12.65	0.0032*
A^2C	2693.94	1	2693.94	39.92	<0.0001*
AB^2	1686.06	1	1686.06	24.98	0.0002*
B^2C	1646.37	1	1646.37	24.39	0.0002*
Residual	944.84	14	67.49	0.95	0.5701
Lack of Fit	665.62	10	66.56		
Pure Error	279.22	4	69.81		
Cor Total	25773.47	28			

R^2 = 0.96; R^2_{adj} = 0.93; CV = 14.45%; Adeq precision = 13.03

Parameters of A, B, C, D, AB, AC, BC, C^2, D^2, A^2B, A^2C, AB^2 and B^2C have significant influence on the angle of repose (P<0.01), while B^2 does not (P>0.05). In addition, the coefficient of variation of the optimal soil model is 14.45% and the coefficient of determination R^2 reaches 0.96. The optimal soil model could be established according to Table 7, which has a good fit for the soil of direct seeding filed in the Poyang Lake region.

Equation (7) is calculated as follows:

$$\begin{aligned} R_1 &= 524.16 - 5.41\times10^{-4}A - 3230.58B + \\ &3747.75C - 128.62D + 5.48\times10^{-3}AB \\ &-4.28\times10^{-3}AC - 1.58\times10^{-4}BC + \\ &3919.14B^2 + 1696.15C^2 + 45.98D^2 \\ &-6.98\times10^{-10}A^2B + 1.83\times10^{-9}A^2C - \\ &6.29\times10^{-3}AB^2 + 2.74\times10^{-4}B^2C \end{aligned} \tag{7}$$

In order to study the relationship between the angle of repose and four parameters of shear modulus (A), restitution coefficient (B), rolling friction Coefficient (C) and surface energy (D), the angle of repose is used as the dependent variable. A, B, C and D are taken as the independent variables and the cubic polynomial fitting mathematical model is established according to the results in Equation 7.

While the real angle of repose is tested as 53.00° and the optimal parameters are obtained according to Equation 7: The Poisson ratio of soil is 0.20, the shear modulus is 1.20 MPa and the static and dynamic friction coefficients are 0.30 and 0.20 respectively. The restitution coefficient between soils is 0.30 and their surface energy is 1.50 J/m^2.

Verification Experiment

In order to verify the optimal parameters of the soil in the direct seeding field, the furrowing test bench is established and an EDEM simulation model is established to calculate the relative errors. The relative errors of furrow depth and width are the evaluation index (Ucgul and Saunders, 2020).

Attest bench included a soil bin (2000×600×400 mm), motor, guide, frame and the furrowing opener (Fig. 9). The upper base of the opener is 100 mm, the lower base is 20 mm and the height is 120 mm, the moisture content is 50% and the furrow depth is 90 mm. When the motor run with the forward speed of 1.00 m/s, the values of furrow depth and width are tested every 0.5 m with three times (Fig. 10). Meanwhile, the furrowing opener is carried out to establish the EDEM model and the parameters of soil are the optimal value. The granular number is 4.50×10^5.

The opener could open a V-shape furrow in EDEM and the bench is shown in Fig. 11 and 12. The furrow width and depth are tested as shown in Fig. 13. The results show that the optimal parameters of soil in the direct seeding filed is the same as the real value. The simulation model of soil can be established to study the direct seeding in the Poyang Lake Region.

Fig. 9: Test bench

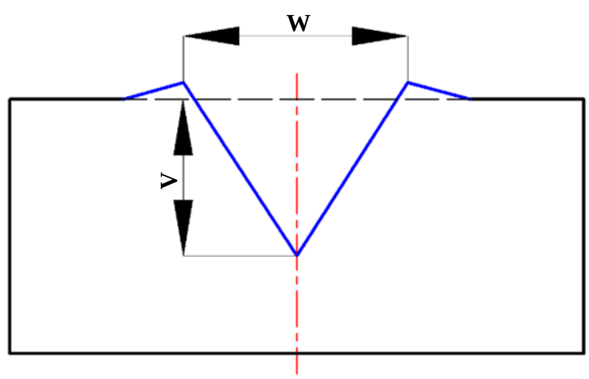


Fig. 10: Diagram of the furrow width and depth

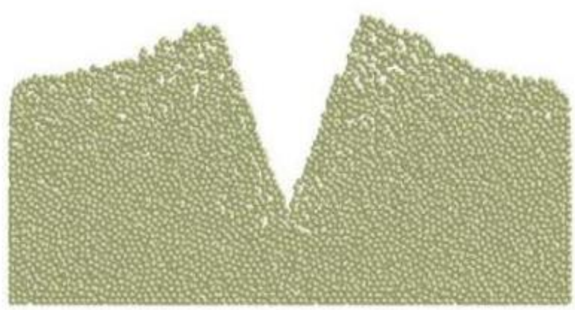


Fig. 11: Simulation of furrow in EDEM

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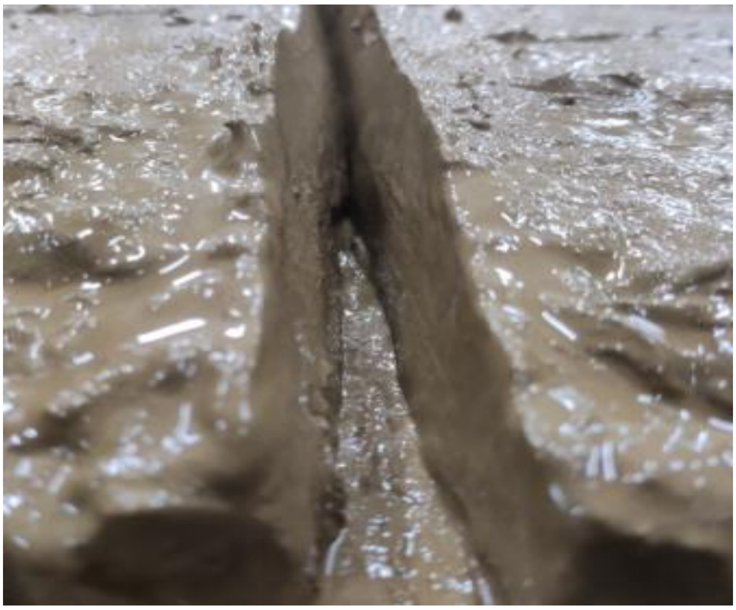

Fig. 12: Diagram of furrow

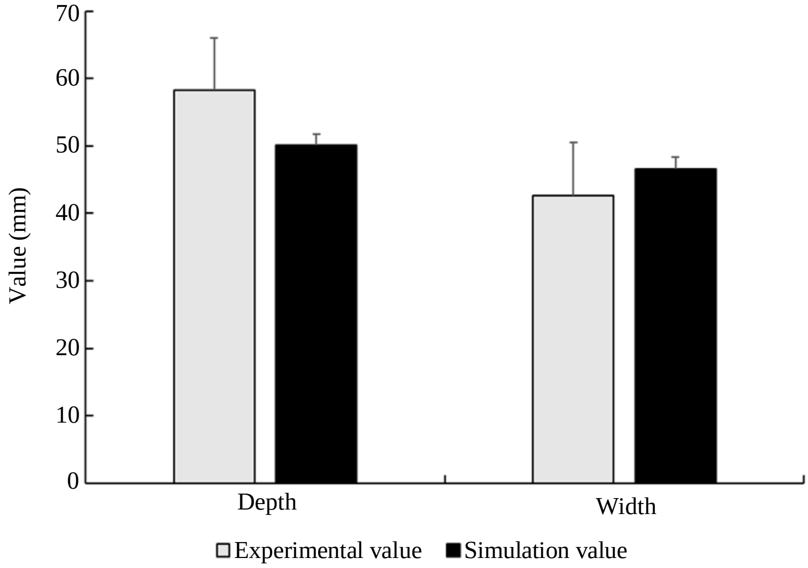

Fig. 13: Results of furrowing width and depth

The relative errors of furrow width and depth are 14.02 and 9.18% respectively. The comprehensive error is taken as the index to evaluate the difference (Barr *et al*., 2020). Equation 8 is as follows:

$$RE = \frac{1}{2}\left(\frac{|W_P - W_S|}{W_P} + \frac{|V_P - V_S|}{V_P}\right) \times 100\% \tag{8}$$

Where:
RE = The comprehensive error (%)
W_P = The real furrow width (mm)
W_S = The furrow width in the simulation model (mm)
V_P = The real furrow depth (mm)
V_S = The furrow depth in the simulation model (mm)

The comprehensive error is calculated as 11.60% and the simulation model of furrow had no significant difference with the real furrow. Four optimal parameters of the indirect seeding field is considered as same as the reality. The study could be used for studying the interaction between the soil of direct seeding filed and mechanical direct seeder in the Poyang Lake Region.

Conclusion

(1) The soil samples before direct seeding from Duchang County, Poyang County and Xinjian District in the Poyang Lake Region are collected to test the mass component, internal friction and cohesion. The percentages of mass fraction less than 2 mm are 98.90, 97.59 and 99.70% and the internal friction angles are 33.22, 38.61 and 33.23° respectively. The cohesions of soil in the three locations are 12.76 N, 9.57 N and 14.70N° respectively. The results show there is no difference in three locations and a general soil model could be used for study

(2) The angle of repose before direct seeding with 50% moisture content tested is 53° by lateral collapse method and the Hertz-Mindlin and the Johnson-Kendall-Roberts (JKR) contact model are used for simulating the soil in the paddy field. Eleven parameters are tested to build the soil simulation model in EDEM

(3) The Plackett-Burman experiment is designed to calculate the contribution of parameters for the angle of repose. The result shows that the restitution coefficient (A), shear modulus (B), dynamic friction Coefficient (C) and surface energy (D) are obtained. The Steepest ascent experiment is used to seek the optimal range of four parameters and then the low, media and high level are determined according to the results

(4) The polynomial fitting equation of soil is established with an R^2 of 0.96 by using Box-Behnken experiments. The optimal parameters are obtained as follows: The Poisson ratio of soil is 0.2, the shear modulus is 1.2×10^6 Pa and the static and dynamic friction coefficients are 0.30 and 0.20 respectively. The coefficient of restitution between soils is 0.30 and its surface energy is 1.50 J/m^2. The angle of repose is calculated as 51.82° with the deviation of 2.23%

(5) The verification experiment is carried out to open the furrow of soil bench and EDEM. The furrow width and depth are the evaluation indexes. The results show that the soil model of furrow simulation and the real furrow have the same V-shape. The relative errors are 14.02 and 9.18% respectively and the comprehensive error is 11.60%

(6) The optimal parameters of soil model are only applied for direct seeding filed in the Poyang Lake Region and the range of application should be enlarge. Furthermore, the soil model can be used to study the interaction effect between direct seeding machines, which is conducive to optimize the structure of the direct seeding machine, reduce the resistance and improve the efficiency

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Author Contributions

Baoyu Zhu and Jiajia Yu: Designed and performed the experiments, analyzed the data and prepared the paper.

Jun'an Liu and Xiongfei Chen: Designed the experiments and simulated on EDEM.

Muhua Liu and Qingsong Zhang: Participated to collect the materials related to the experiment and revised the manuscript.

Conflict of Interest

The authors declare that they have no competing interests. The corresponding author affirms that all of the authors have read and approved the manuscript.

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