CALIBRATION AND EXPERIMENTS OF THE SIMULATION BONDING PARAMETERS FOR PLUG SEEDLING SUBSTRATE BLOCK
/
穴盘苗基质块仿真粘结参数标定与试验

Hongbin BAI[1)], Xuying LI*[1)], Fandi ZENG[1)], Qiang SU[1)], Ji CUI[1)], Junyue WANG[1,2)], Yongzhi ZHANG[1)]

[1)] Inner Mongolia Agricultural University, College of Mechanical and Electrical Engineering, Hohhot/China;

[2)] China Academy of Agricultural Mechanization Science Hohhot Branch Co., Ltd. Hohhot/China

Tel: +86 04714309215; E-mail: bhb81571@163.com

DOI: https://doi.org/10.35633/inmateh-69-59

Keywords: *Simulation; Seedling substrate block; Parameter calibration; Bonding model*

ABSTRACT

To accurately simulate the interactions between the plug seedlings and the planter during the planting process and explore the damage mechanism of the plug seedling substrate block, the bonding parameters of plug seedling substrate block were calibrated by the discrete element method. The physical puncture test showed that the average of maximum force of the cone indenter on substrate block measured by texture analyzer was 4.633 N. A Hertz-Mindlin with the bonding model was established for the substrate block in EDEM software. A virtual calibration experiment was designed with the puncture force of substrate block as the evaluation index. The two-level factorial test and the steepest climbing test were used to screen out the significant parameters and the optimal interval. Then, the Box-Behnken test and the optimization solution were used to obtain the optimal bonding parameter combination of the substrate block particles. Finally, the optimal parameter combination was simulated and verified. The relative error of the maximum puncture force between the simulated value and the measured value was 1.88%, which indicated that the bonding parameters of the substrate block obtained by calibration were accurate and reliable.

摘要

为准确模拟栽植过程中穴盘苗与栽植器间的相互作用，探究穴盘苗基质块的破损机理，采用离散元法校准了穴盘苗基质块的粘结参数。通过物理穿刺试验测得锥形压头对基质块的最大穿刺力平均值为 4.633 N。应用 Hertz-Mindlin with bonding 模型对基质块进行建模，并以最大穿刺力为评价指标，采用二水平析因试验和最陡爬坡试验筛选出显著性参数和最优区间，通过 Box-Behnken 试验和优化求解，得到基质块颗粒的最佳粘结参数组合，针对最优参数组合进行仿真验证，得出仿真值和实测值最大穿刺力相对误差为 1.88%，表明标定所得基质块粘结参数准确可靠。

INTRODUCTION

Transplanting is an agriculture task that involves transferring and planting seedlings grown uniformly in a nursery to a field (*Hwang et al., 2020; Kumar G et al., 2011*). The use of seedling transplanting technology can effectively avoid the impacts of catastrophic weather, create favorable conditions, and increase the survival rates of seedlings (*Kumi F et al., 2016; Zhichao Cui et al., 2022*). The seedlings grow on the substrate block and absorb nutrients from it (*Yongshuang Wen et al., 2021; Luhua Han et al., 2019*). However, during processes of mechanized transplanting, the collision between the plug seedling and the components of machines is unavoidable, which can easily cause mechanical damage to the seedling substrate block, thus seriously affecting the transplanting quality and causing economic losses (*Lvhua Han et al., 2013; Huili Wang et al., 2017*).

The interaction between the plug seedling and components of the transplanting machine is often complicated, and the traditional test and theoretical methods can not accurately analyze the damage mechanism of the seedling substrate block during the collision. In recent years, discrete element method and simulation software EDEM have been widely used in the field of agriculture, providing a new way to study the contact characteristics between agricultural materials and mechanical parts, and promoting the research and development of agricultural equipment and the optimization of related working parameters (*Aikins KA et al., 2023; Obermayr M et al., 2014*).

At present, relevant scholars have conducted a lot of research on agricultural materials based on the discrete element method, and have completed discrete element modeling and simulation research on materials such as potatoes (*Zhongcai Wei et al., 2020*), soil (*Li J. et al., 2022*), seed (*Xuejie Ma et al., 2022; Bhupendra M.G. et al., 2018*), corn straw (*Shuhong Zhao et al., 2021*) and so on. Before the simulation, it is necessary to accurately establish the discrete element model of the material and define the simulation parameters of the model to ensure the reliability of simulation results.

The simulation parameters are usually obtained by direct measurement and parameter calibration. *Ghodki et al.,* (*2019*), calibrated the discrete element simulation parameters of soybean pellets. *Wu et al*., (*2017*), designed the rest-angle simulation test based on the Box-Behnken principle and realized the contact parameter calibration of the discrete element model of cohesive soil. *Zhang et al.,* (*2022*), measured the maximum shear force of water chestnuts by shear test, and used it as a reference to conduct simulation parameter calibration of water chestnut bonding parameters by a screening test, response surface variance analysis, and regression equation optimization method. *Feng et al.,* (*2016*) and *Wu et al.,* (*2021*), respectively measured the simulation parameters of the substrate block of Antrata and strawberry plug seedlings by direct measurement method. *Yuan et al.,* (*2020*) and *Sheng et al.,* (*2021*), used the Hertz-Mindlin with bonding model to calibrate the simulation parameters of the soil model with the actual soil firmness as the target value.

In order to accurately establish the discrete element model of the plug seedling substrate block and ensure the reliability of the subsequent discrete element simulation results for the transplanting process, the physical test and simulation test were combined to calibrate the bonding parameters of the substrate block. The maximum puncture force of the cone indenter on the substrate block was obtained through a physical puncture test. Based on this, the two-level factorial test, steepest climb test and Box-Behnken test were carried out successively to calibrate the discrete element simulation bonding parameters of the substrate block.

MATERIALS AND METHODS

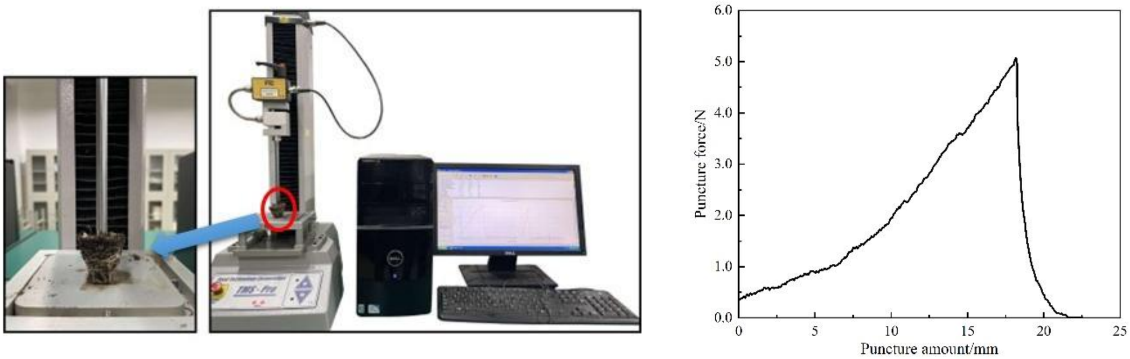
Test material

A typical variety of oil sunflower seedlings, Tonghui 562, was selected as the test subject, as shown in Figure 1. The seedlings were cultivated at the Hohhot Modern Agriculture Development Base. The age of seedlings was 30 d. The moisture content of the substrate block was about 60%. The seedling substrate was a mixture of charcoal, perlite, and vermiculite. The volume ratio was as follows: 3:1:1 of charcoal, perlite, and vermiculite, respectively.

Fig. 1 - Oil sunflower plug seedlings at the planting stage

Physical puncture test of the seedling substrate block

The TMS-Pro texture analyzer was used to perform the puncture test on the seedling substrate block to obtain the actual reference value reflecting the bonding parameters, as shown in Figure 2a. During the test, the forward speed of puncture was set to 30 mm/s, the return speed was 45 mm/s, the puncture height ratio was 60%, the trigger force was 0.34 N, and a data point was collected every 0.1 seconds. The experiment was repeated 10 times, and the average value of the maximum puncture force of the cone indenter on the substrate block was 4.633 N, which was used as the physical reference value of the bonding parameters for the virtual calibration test. Figure 2b shows the change curve of puncture force and puncture amount after the puncture test.



a. Puncture test of seedling substrate block b. Puncture force-amount curve

Fig. 2 - Puncture test process and result curve

Substrate block discrete element model construction

The Hertz-Mindlin with bonding model is often used in the case of material breakage and fracture. The model is bonded by multiple particles, and the bonding bonds are formed between the particles. When the model is subjected to external force, the bonding bonds between the particles will change, and the formed particle clusters will produce fracture and crushing effects. Therefore, the Hertz-Mindlin with the bonding model is more suitable for the study of the contact mechanism between materials and mechanical components (*Shijie Feng, 2020*).

The seedling substrate block is an inverted square quadrangle with a relatively regular shape, so a conventional modeling approach was used to create a simulation model of the substrate block and cone indenter, with all dimensions consistent with the physical tests. The discrete element model of the substrate block was established by referring to the reference *Zhang et al.,* (*2022*), and the simulation model of the substrate block composed of particles was obtained. As shown in Figure 3, the radius of the particles is set to 1 mm, the number of particles in the mantle is 3882, and a total of 11151 bonds are generated. Table 1 shows the parameters of mechanical properties (density, Poisson's ratio, modulus of elasticity), and the basic contact parameters (coefficient of collision recovery, coefficient of static friction, and coefficient of dynamic friction) between a substrate block and stainless steel (*Ying Wang et al., 2014; Feng T, 2016; Shijie Feng, 2020*).

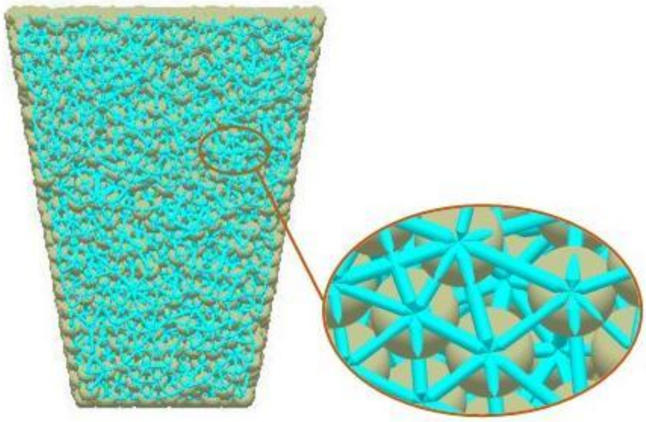


Fig. 3 - Discrete element simulation model of the seedling substrate block

Table 1

Mechanical properties and basic contact parameters

Mechanical properties parameters		Basic contact parameters	
Parameters	**Values**	**Parameters**	**Values**
Substrate block density/[kg/m^3]	395	Block-block collision recovery coefficient	0.20
Substrate block Poisson's ratio	0.43	Block-block static friction coefficient	0.65
Substrate block elasticity modulus/[Pa]	1.25×10^6	Block-block dynamic friction coefficient	0.43
stainless steel density/[kg/m^3]	7850	Steel-block collision recovery coefficient	0.21
stainless steel Poisson's ratio	0.35	Steel-block static friction coefficient	0.44
stainless steel elasticity modulus/[Pa]	7.0×10^{10}	Steel-block dynamic friction coefficient	0.13

TEST METHODS

Two-level factorial test

The two-level factorial test can quickly screen out the significant influence on the test index under the condition of many influencing factors. It greatly reduces the number of tests. According to the Hertz-Mindlin with bonding model, the breakage of the bond between particles is related to the particle contact radius X_1, the normal stiffness per unit area X_2, the tangential stiffness per unit area X_3, the critical normal stress X_4, the critical tangential stress X_5 and the bonding radius X_6. The initial range of bonding parameters was determined by reviewing the relevant literature (*Ying Wang et al., 2014; Feng T, 2016; Shijie Feng, 2020*) and extensive pre-tests, and are summarized in Table 2. Based on the determined range of bond parameters, a total of 16 sets of two-level factorial tests were designed, as shown in Table 3.

Table 2

Simulation test parameters range

Simulation parameters	Low level	High level
Particle contact radius X_1 [mm]	1.2	2.0
Normal stiffness per unit area X_2 [N/m^3]	1.0×10^6	8.0×10^6
Tangential stiffness per unit area X_3 [N/m^3]	1.0×10^6	8.0×10^6
Critical normal stress X_4 [Pa]	2200	3000
Critical tangential stress X_5 [Pa]	2200	3000
Bonding radius X_6 [mm]	1.2	2.0

Steepest climbing test

To quickly determine the range of the optimal values, based on the two-level factorial test, the steepest climbing test was carried out on the screened significant factors. During the experiment, the relative error between the maximum simulated puncture force and the physical reference value was used as the evaluation index. The non-significant bonding parameter takes the intermediate level value in the two-level factorial test, and the significant parameter gradually increases within the value range according to the set step size.

The relative error calculation formula is shown in Eq. (1).

$$e=\frac{\left|F_P-F_S\right|}{F_P}\times100\% \tag{1}$$

Where: e is the relative error, %; F_P is the physical reference value of puncture force, N; F_S is the maximum simulated puncture force, N.

Box-Behnken test

Based on the results of the two-level factorial test and the steepest climbing test, the Box-Behnken test was designed using Design-Expert 13 software to obtain the best combination of bonding parameters for the simulation. Test parameter No. 5 in the steepest climbing test was taken as the intermediate level, and test parameters No. 6 and No. 4 were taken as high and low levels respectively for the Box-Behnken test, and the maximum puncture force of the simulation test was taken as the evaluation index.

Calibration result verification

To check whether the calibrated parameters can be used in subsequent discrete element simulation studies, so that the simulated puncture force value is closest to the physical reference value, it is necessary to optimize and solve the regression equation in the optimization module of the Design-Expert 13 software, and compare with the physical reference value to verify the accuracy and reliability of the parameter calibration.

RESULTS AND DISCUSSION

Two-level factorial test and significance analysis

The two-level factorial test scheme and results are shown in Table 3. Minitab 19 software was used to conduct variance analysis on the test results, and the significant results of each simulation parameter were obtained, as shown in Table 4. As can be seen from Table 4, the normal stiffness per unit area (X_2) and bonding radius (X_6) have an extremely significant effect on the maximum puncture force; the tangential stiffness per unit area (X_3) has a significant effect on the maximum puncture force; the influence of other parameters on the maximum puncture force is not significant.

Table 3

Two-level factorial test scheme and results

No.	X_1 [mm]	X_2 [$\times 10^6$N/m^3]	X_3 [$\times 10^6$N/m^3]	X_4 [Pa]	X_5 [Pa]	X_6 [mm]	Maximum puncture force [N]
1	2.0	1.0	8.0	3000	2200	1.2	1.993
2	1.2	1.0	1.0	2200	2200	1.2	0.765
3	1.2	1.0	8.0	2200	3000	2.0	3.050
4	1.2	8.0	1.0	3000	3000	1.2	2.320
5	2.0	1.0	1.0	2200	3000	1.2	0.798
6	2.0	8.0	8.0	3000	3000	2.0	5.980
7	1.2	1.0	8.0	3000	3000	1.2	2.232
8	1.2	8.0	8.0	2200	2200	1.2	2.080
9	1.2	8.0	1.0	2200	3000	2.0	5.010
10	2.0	1.0	1.0	3000	3000	2.0	2.290
11	2.0	1.0	8.0	2200	2200	2.0	2.230
12	1.2	8.0	8.0	3000	2200	2.0	4.990
13	2.0	8.0	1.0	3000	2200	1.2	2.400
14	1.2	1.0	1.0	3000	2200	2.0	1.930
15	2.0	8.0	8.0	2200	3000	1.2	4.230
16	2.0	8.0	1.0	2200	2200	2.0	4.830

Table 4

Variance analysis of two-level factorial test

Parameter	Degree of freedom	Sum of squares	Mean square	F-value	P-value
Model	6	32.904	5.484	11.89	0.001
X_1	1	0.352	0.352	0.76	0.405
X_2	1	17.123	17.123	37.11	<0.0001**
X_3	1	2.594	2.594	5.62	0.042*
X_4	1	0.082	0.082	0.18	0.684
X_5	1	1.376	1.376	2.98	0.118
X_6	1	11.377	11.377	24.66	0.001**
Residual	9	4.152	0.461		

*Note: ** indicates an extremely significant effect (p<0.01),* indicates a significant effect (p<0.05). Same as below*

Analysis of the steepest climbing test

The three significant parameters obtained from the two-level factorial test were subjected to the steepest climbing test. The test design and results are shown in Table 5. With the gradual increase of the value of each significant parameter, the maximum puncture force of the cone indenter on the seedling substrate block gradually increases, and the relative error between the simulated puncture force and the physical reference value decreases first and then increases. Among them, under the parameter combination corresponding to the No.5 test, the relative error is the smallest, and the optimal range can be determined near the No.5 test.

Table 5

Schemes and results of steepest climbing test

No.	X_2 [$\times 10^6$N/m^3]	X_3 [$\times 10^6$N/m^3]	X_6 [mm]	Maximum puncture force [N]	Relative Error [%]
1	0.9	0.9	1.1	0.600	87.04
2	2.5	2.5	1.3	1.766	61.86
3	4.1	4.1	1.5	2.970	35.85
4	5.7	5.7	1.7	4.150	10.37
5	7.3	7.3	1.9	4.980	7.56
6	8.9	8.9	2.1	5.910	27.65

Box-Behnken test results and analysis

Based on the steepest climbing test results, the Box-Behnken response surface test was carried out on the three parameters of normal stiffness per unit area (X_2), tangential stiffness per unit area (X_3), and bonding radius (X_6). The test parameter levels is shown in Table 6. The Box-Behnken test schemes and results are shown in Table 7, and the Box-Behnken test analysis of variance is shown in table 8.

Table 6

Parameter levels code table

Level	Test parameters		
	X_2 [×10^6N/m^3]	X_3 [×10^6N/m^3]	X_6 [mm]
-1	5.7	5.7	1.7
0	7.3	7.3	1.9
1	8.9	8.9	2.1

Table 7

Box-Behnken test schemes and results

No.	X_2 [×10^6N/m^3]	X_3 [×10^6N/m^3]	X_6 [mm]	Maximum puncture force [N]
1	-1	1	0	4.22
2	0	1	-1	4.34
3	0	0	0	4.98
4	0	0	0	4.98
5	0	-1	-1	4.52
6	-1	-1	0	4.20
7	0	0	0	4.89
8	-1	0	1	4.57
9	1	1	0	4.35
10	1	0	-1	4.61
11	0	1	1	4.51
12	1	0	1	4.55
13	1	-1	0	4.88
14	0	0	0	4.73
15	0	0	0	4.73
16	-1	0	-1	3.72
17	0	-1	1	4.84

Table 8

Analysis of variance for Box-Behnken test results

Source of variance	Mean square	Degree of freedom	Sum of squares	F-value	P-value
Model	0.186	9	1.670	17.32	0.0005**
X_2	0.353	1	0.353	32.85	0.0007**
X_3	0.130	1	0.130	12.11	0.0103*
X_6	0.205	1	0.205	19.07	0.0033**
$X_2 X_3$	0.076	1	0.076	7.04	0.0328*
$X_2 X_6$	0.207	1	0.207	19.28	0.0032**
$X_3 X_6$	0.006	1	0.006	0.52	0.4927
$X_2^{\ 2}$	0.431	1	0.431	40.08	0.0004**
$X_3^{\ 2}$	0.071	1	0.071	6.60	0.0371*
$X_6^{\ 2}$	0.136	1	0.136	12.67	0.0092**
Residual	0.011	7	0.075		
Lack of Fit	0.004	3	0.012		

Design-Expert 13 software was used to perform multiple regression fitting on the test results in Table 7, and the regression equation with the cone indenter's puncture force on the seedling substrate block as the target value and X_2, X_3, X_6 as the variables was obtained:

$$\begin{aligned} F &= -134.43+13.27X_2+4.72X_3+87.84X_6-0.22X_2X_3-2.84X_2X_6 \\ &-0.47X_3X_6-0.50X_2^2-0.21X_3^2-17.98X_6^2 \end{aligned} \tag{2}$$

The results of the Box-Behnken test ANOVA (analysis of variance) are shown in Table 8. Perform the ANOVA on the test results, where X_2, X_6, X_2X_6, $X_2{}^2$, and $X_6{}^2$ all have extremely significant effects on the maximum puncture force; X_3, X_2X_3, and $X_3{}^2$ has a significant effect on the maximum puncture force; the remaining parameters have no marked effect on the maximum puncture force. The p-value of the quadratic regression models is less than 0.001, where the regression model coefficient of determination R^2=0.957 and Adjusted R^2=0.902 are both close to 1 and with a coefficient of variation C.V.=2.27%. The results showed that the regression model reliably reflects the real situation. According to the above regression equation, the response surfaces of the interaction of each significance parameter to the maximum puncture force were obtained respectively, as shown in Figure 4.

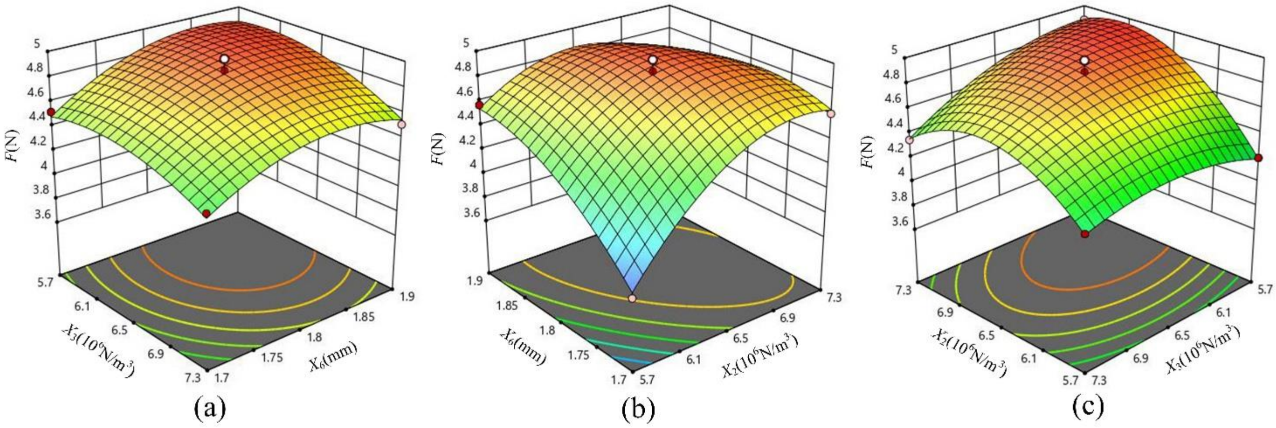


Fig. 4 – Box-Behnken test results response surface

Note: (a) Effect of tangential stiffness per unit area and bonding radius on maximum puncture force;
(b) Effect of bonding radius and normal stiffness per unit area on maximum puncture force;
(c) Effect of normal stiffness per unit area and tangential stiffness per unit area on maximum puncture force.

Seedling substrate block simulation test validation

Optimization of the regression equation is made to obtain the optimal combination of bonding parameters for substrate seedling block, using the physical reference value 4.633 N as the target value by Design-Expert 13.0 software: the normal stiffness per unit area (X_2) is 7.3×10^6 N/m^3, the tangential stiffness per unit area (X_3) is 6.775×10^6 N/m^3, and the bonding radius (X_6) is 1.813 mm. The other bonding parameters were taken as the intermediate level values in the two-level factorial test.

In order to verify the accuracy and reliability of the simulation calibration, the above parameters are used as the EDEM simulation parameters to simulate the puncture test of the seedling substrate block. The simulation validation test was repeated 3 times. The average of maximum puncture force of substrate block is 4.72 N, with a relative error of 1.88% compared with the physical reference value of 4.633 N. T test was performed on the sample using SPSS software, and P=0.799>0.05 was obtained, indicating that there was no significant difference between the simulated puncture force and the physical reference value. The test comparison is shown in Figure 5. In the simulated puncture test, the interaction between the cone indenter and the seedling substrate block is represented using the substrate block bonding bond.

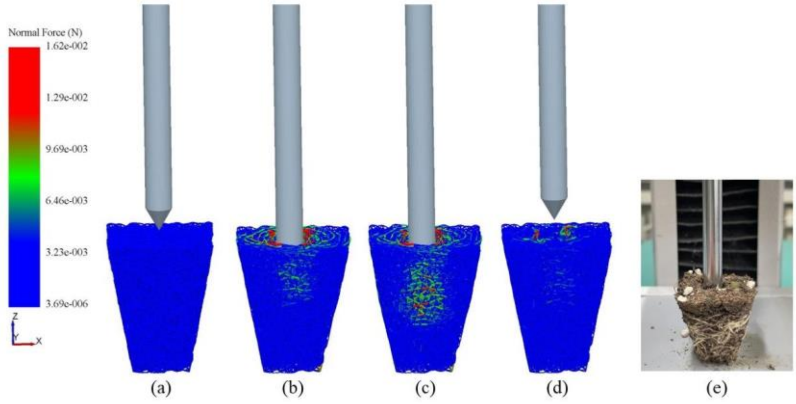


Fig. 5- Experiment comparison on puncturing of seedling substrate block

Note: (a) Cone indenter Puncture preparation stage; (b) Cone indenter puncture stage; (c) Cone indenter punctured to lowest point; (d) Return of the cone indenter to the initial stage of the puncture; (e) Physical puncture test.

CONCLUSIONS

Based on Hertz-Mindlin with bonding model, combined with physical test and virtual calibration test, the discrete element simulation parameters of plug seedling substrate block were calibrated, and the optimal parameter combination of the substrate block bonding model was obtained and verified. The calibration results can improve the precision of simulated transplanting experiment and optimize the parameters of field transplanting operation. The main conclusions are as follows:

(1) Two-level factorial test and steepest climbing test were used to screen out the parameters which had significant influence on the puncture force of the plug seedling substrate block.

(2) A Box-Behnken response surface test was performed to establish a second-order regression model of the puncture force on the significance parameters. The model was optimally solved for the physical reference value (4.633 N), and the best combination of parameters was obtained as follows: the normal stiffness per unit area (X_2) is 7.3×10^6 N/m^3, the tangential stiffness per unit area (X_3) is 6.775 $\times10^6$ N/m^3, and the bonding radius (X_6) is 1.813 mm.

(3) The T-test showed that P=0.799>0.05, indicating that there was no significant difference between the maximum puncture force of the physical test and that of the simulated test, and the relative error is 1.88%, which further verifies the authenticity and reliability of the simulation parameters.

ACKNOWLEDGEMENTS

We acknowledge that this work was supported by the National Natural Science Foundation of China (No. 32160423) and the Natural Science Foundation of Inner Mongolia Autonomous Region of China (No. 2021MS05048).

REFERENCES

[1] Hwang S.J., Park J.H, Lee J.Y. et al. (2020). Optimization of main link lengths of transplanting device of semi-automatic vegetable transplanter. *Agronomy*, 10(12), 1938.

[2] Kumar G., Raheman H. (2011). Development of a walk-behind type hand tractor powered vegetable transplanter for paper pot seedlings. *Biosystems Engineering*, 110(2), 189-197.

[3] Kumi F., Mao H., Li Q. et al. (2016). Assessment of Tomato Seedling Substrate-Root Quality Using X-Ray Computed Tomography and Scanning Electron Microscopy. *Applied Engineering in Agriculture*, 32(4), 1-11.

[4] Zhichao Cui, Chunsong Guan, Tao Xu et al. (2022). Development status of technology and equipment of substrate block seedling cultivation and transplanting (基质块育苗移栽技术与装备发展现状). *Journal of Chinese Agricultural Mechanization*, 43(05), 29-34.

[5] Yongshaung Wen, Leian Zhang, Xuemei Huang et al. (2021). Design of and Experiment with Seedling Selection System for Automatic Transplanter for Vegetable Plug Seedlings. *Agronomy*, 11(10), 2031.

[6] Luhua Han, Kumi F, Hanping Mao et al. (2019). Design and tests of a multi-pin flexible seedling pick-up gripper for automatic transplanting. *Applied engineering in agriculture*, 35(6), 949-957.

[7] Lvhua Han, Hanping Mao, Jianping Hu et al. (2019). Experiment on mechanical property of seedling pot for automatic transplanter (穴盘苗自动移栽钵体力学特性试验). *Transactions of the Chinese Society of Agricultural Engineering*, 29(02), 24-29.

[8] Huili Wang, Yong Zhou, Peitong Wang et al. (2017). Mechanical properties of cotton bowl seedling and cotton bowl (棉花钵苗和钵体的力学特性试验). *Journal of Huazhong Agricultural University*, 36(02), 117-122.

[9] Aikins K.A., Ucgul M., Barr J.B. et al. (2023). Review of Discrete Element Method Simulations of Soil Tillage and Furrow Opening. *Agriculture*, 13(3), 541.

[10] Obermayr M., Vrettos C., Eberhard P. et al. (2014). A discrete element model and its experimental validation for the prediction of draft forces in cohesive soil. *Journal of Terramechanics*, 53, 93–104.

[11] Zhongcai Wei, Guosu Liang, Xueqiang Li et al. (2020). Parameter Optimization and Test of Potato Harvester Wavy Sieve Based on EDEM (基于离散元的马铃薯收获机波浪形筛面参数优化与试验). *Transactions of the Chinese Society for Agricultural Machinery*, 51(10), 109-122.

[12] Li J., Xie S., Liu F. et al. (2022). Calibration and testing of discrete element simulation parameters for sandy soils in potato growing areas. *Applied Sciences*, 12(19), 10125.

[13] Xuejie Ma, Zhanfeng Hou, Min Liu. (2022) Calibration of simulation parameters of coated particles and analysis of experimental results. *INMATEH-Agricultural Engineering*, 67(2), 233-242.
[14] Bhupendra M Ghodki, K. Charith Kumar, T.K. Goswami. (2018). Modeling breakage and motion of black pepper seeds in cryogenic mill. *Advanced Powder Technology*, 29(5), 1055-1071.
[15] Shuhong Zhao, Lianlong Gao, Yiwen Yuan et al. (2022). Maize straw motion law in subsoiling operation using discrete element method (基于离散元法的深松作业玉米秸秆运动规律). *Transactions of the Chinese Society of Agricultural Engineering*, 37(20), 53-62.
[16] Ghodki, Bhupendra M. Patel, ManishNamdeo, RohitCarpenter et al. (2019). Calibration of discrete element model parameters: soybeans. *Computational particle mechanics*, 6(1), 3-10.
[17] Wu T., Huang W., Chen X. et al. (2017). Calibration of discrete element model parameters for cohesive soil considering the cohesion between particles (考虑颗粒间黏结力的黏性土壤离散元模型参数标定). *Journal of South China Agricultural University*, 38(03), 93-98.
[18] Zhang G., Chen L., Liu H. et al. (2022). Calibration and experiments of the discrete element simulation parameters for water chestnut (荸荠离散元仿真参数标定与试验). *Transactions of the Chinese Society of Agricultural Engineering*, 38(11), 41-50.
[19] Feng T. (2016). *Optimization design and test research of plug seedlings end-effector in greenhouse* [Master's thesis], Beijing University of Technology.
[20] Wu D. (2021). *Design and experiment of small electric strawberry directional transplanter machine* [Master's thesis], Jiangsu University.
[21] Yuan J., Li J., Zou L. et al. (2020). Optimal Design of Spinach Root-cutting Shovel Based on Discrete Element Method (基于离散元的菠菜收获机根切铲优化设计与试验). *Transactions of the Chinese Society for Agricultural Machiner*y, 51(S2), 85-98.
[22] Sheng Y. (2021). *Improved Design and Experimental Research of Straw Forage Harvester Based on Discrete Element Method* [Master's thesis], Inner Mongolia Agricultural University.
[23] Shijie Feng. (2020). *Study on Pick-up System and Pot Body Damage Mechanism of Rape Pot Seedling Based on Movable Tray* [Doctor's thesis], Hunan Agricultural University.
[24] Ying Wang, Jianneng Chen, Jiawei Wu et al. (2014). Mechanics property experiment of broccoli seedling oriented to mechanized planting (用于机械化栽植的西兰花钵苗力学特性试验). *Transactions of the Chinese Society of Agricultural Engineering*, 30(24), 1-10.