SIMULATION AND EXPERIMENT OF POTATO EXCAVATOR
/
马铃薯挖掘机仿真与试验

Boxuan CHEN[1], Xuhong CHU*[1], Bingshen HUANG[1], Xiangdong LIU[1], Yiyuan GE[1]
[1] College of Mechanical Engineering, Jiamusi University, Jiamus 154007, China
Tel: +86-15046495399; E-mail: chuxuhongemail@163.com

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ABSTRACT

In this study, the potato excavator with loosening shovel was designed in order to solve the problems of serious soil obstruction and high excavation resistance during the potato harvest. Using EDEM discrete element simulation software, potato excavation simulation experiments were carried out on soil broken effects and excavation resistance. Through the comparative analysis with loosening shovel and without, the results showed that the increase of soil broken effects was close to 52%, and the excavation resistance decreased by 16.57%. Through the two-factor and three-level field orthogonal experiment with excavation depth and loosening depth as influencing factors, the optimal operating parameters was determined for potato excavators: the excavation depth was 23 cm and the loosening depth was 20 cm. At this time, the excavation potato rate was 98.21%, and the rate of damaged potato was 1.31%. The traction resistance was 1826 N, which met the requirements of relevant industry standards. Through comparative analysis of simulation experiments and field experiment, it was found that when the excavation depth was 23 cm and the loosening depth was 20 cm, the error value of traction resistance was 11.3% between simulation experiments and field experiments. The discrete element simulation analysis can provide a preliminary reference for potato excavation design.

摘要

设计带松土铲的马铃薯挖掘机以解决小规模种植马铃薯收获时挖掘铲壅土严重、挖掘阻力大等问题。利用 EDEM 离散元仿真软件，进行马铃薯挖掘仿真试验，发现增加松土铲对土壤的破碎效果增幅接近 52%，挖掘阻力降低 16.57%。进行以挖掘深度、松土深度为影响因素的两因素三水平的田间正交试验，确定马铃薯挖掘机的最优作业参数：挖掘深度 23cm，松土深度 20cm。此时明薯率为 98.21%，伤薯率为 1.31%，挖掘效果最好，牵引阻力 1826N，符合相关行业标准的要求。通过仿真试验与田间试验对比分析，当挖掘深度增加至 23cm 时，仿真试验与田间试验牵引阻力的误差值低至 11.3%。离散元仿真分析为马铃薯挖掘机设计提供了前期参考。

INTRODUCTION

Potatoes are an important food crop that can be used as raw materials in various fields such as food processing, petrochemicals, and healthcare, in addition to being consumed directly *(Luo et al., 2020; An et al., 2022; Devaux et al., 2021)*.

Extensive research has been conducted in the field of designing or simulating potato excavator. Aiming at the potato cropping pattern in the hilly area of southwest China, a small digging device for potato harvester was designed by *Fu et al. (2023)*. The simulation experiment was carried out by the discrete element (DEM) software. The simulation results showed that the excavation potato rate was 87.3%. A small vibrating shovel excavator was designed by *Joel et al. (2023)*, which was superior to the ordinary excavator in terms of soil crushing and drag reduction. A potato digging shovel with a non-smooth surface structure was designed based on bionics theory by *Zhao et al. (2023)*. Through the simulation comparison test results showed that the soil adhered to the mechanical surface can be effectively reduced by 93.3%. A self-propelled crawler and potato harvester was designed by *Zhou et al. (2021)*. The harvester could complete the tasks of digging potatoes, separating potatoes from the soil, transporting potatoes, and collecting potatoes in a single operation. Aiming at the problems of traditional potato excavation shovel, such as high resistance, easy to wear, high fuel consumption, high cost and so on, *Bao Jianlun (2021)* of Jilin University designed a bionic self-sharpening excavation shovel, which mimics the incisors of rabbits.

Boxuan CHEN, Master Degree; Xuhong CHU, Tutor; Bingshen HUANG, Professor; Xiangdong LIU, Professor; Yiyuan GE, Professor.*

Through experimental research and analysis, it was found that it was better than ordinary excavation shovel in self-sharpening and drag reduction. Li's bionic excavation shovel designed according to pangolin scales and Fan Yu's bionic excavation shovel designed by observing the arch mouth of wild boar were both effective in drag reduction *(Li et al., 2020; Fan et al., 2022)*. An experimental sample of digging working parts for potato harvesting machines was developed and manufactured by *Hrushetsky et al.* (*2019)*, whose verification in operation confirmed their work ability and efficiency. *Wei Mengyang (2018)* designed a drum potato harvester and simulated the key components. The excavator shovel was in the shape of an arrow, but it had high power consumption and serious damage to the potato. *Lv Jinqing et al. (2018)* designed a lifting chain potato excavator, its two excavation shovels correspond to a ridge, and the oblique angle of the blade on both sides of each excavation shovel was different, and the shovel pieces adjacent to the two excavation shovels bend downward to a certain angle, reducing the oblique angle of the shovel edge adjacent to the excavation shovel, but the groove shape of the whole excavation shovel was still approximately flat, which not only increases the slip cutting but also ensures the smooth shape of the ditch. The 4U2A double-row potato harvester was also designed, which was characterized by the design of an anti-blocking system, which solved the problems of high resistance and anti-entanglement of weeds *(Lv et al., 2015)*.

At present, there are many studies on reducing resistance for potato excavation. In this study, a kind of potato excavator with loosening shovel was designed by our group, aiming at the problems such as lack of small potato digging machinery, poor digging effect and serious soil choking phenomenon.

The tractor was connected to the whole machine through three-point suspension. The soil loosening shovel first loosened the soil, the excavation shovel excavated the potato and the soil and transported it to the vibrating screen, which separated the potato soil and laid the potato on the ground. The tractor transmission shaft was connected with the gearbox through the universal joint, and the gearbox adjusted the transmission ratio, input the power into the chain drive through the transmission shaft, drove the vibrating screen to work, and shook up and down the vibrating screen to achieve the purpose of separating the potato soil, as shown in Fig.1 *(Chen et al., 2023)*.

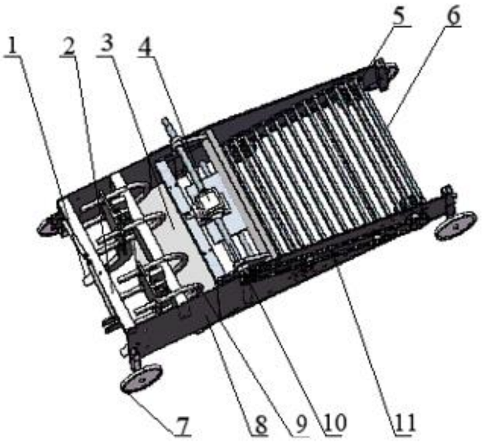


Fig. 1 - General assembly diagram of potato excavator

1. loosening shovel; 2. three-point suspension; 3. excavation shovel; 4. gearbox; 5. driving wheel; 6. vibration sieve; 7. ground wheel; 8. frame; 9. U bolts; 10. transmission shaft; 11. chain drive

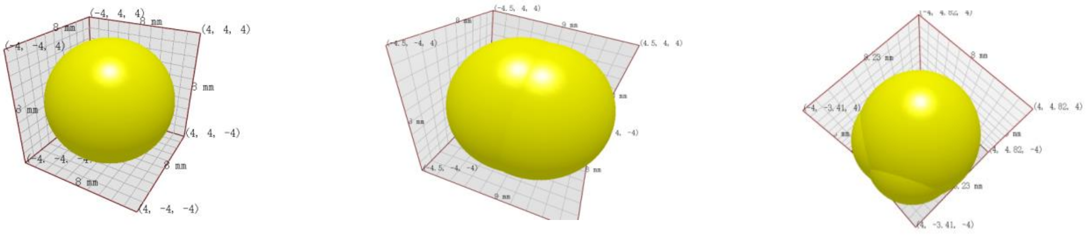
MATERIALS AND METHODS

Discrete element simulation analysis of potato excavating process

The soil trough and potato models for excavation simulation experiments were generated by using the discrete element software EDEM. The soil trough and potato were both composed of particles in EDEM simulation.

Generation of soil trough model

The actual shape and size vary between different soil particles, so it is not possible to replace all soil with a spherical particle simply. In this study, the soil particle models were generated after simplification, including single sphere particles, double sphere particles, and three sphere particles, all with a particle radius of 4 mm as shown in Fig. 2. The contact radius between soil particles was 4 mm, and the soil particles were connected by Bond key. Through the particle factory, the soil trough model was generated with a length of 2000 mm, a width of 700 mm, and a height of 260 mm, as shown in Fig. 3.



(a) single sphere particle (b) double sphere particle (c) three sphere particle

Fig. 2 - Model of Soil particle

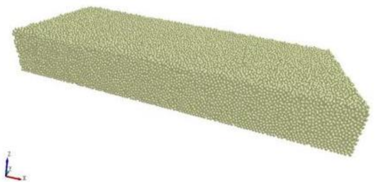


Fig. 3 - Soil trough model

Generation of potato model

In order to improve the calculation speed and facilitate analysis, this article used potatoes with the same size for simulation. The potato model was created by using SolidWorks, and imported into EDEM software. The potato model was filled with spherical particles in EDEM, as shown in Fig. 4. Three boxes were added to the soil trough, all of which were set as virtual structures. The spacing between the three boxes was set to 60 mm, and all with dimensions of 500 mm in length, 300 mm in width, and 200 mm in height. Three particle factories were set directly above the three boxes, as shown in Fig. 5. When generating particles, first the bottom soil particles were generated with a depth of 60 mm, and then potatoes and soil particles were simultaneously generated above them. The number of potatoes generated in each box was 22.

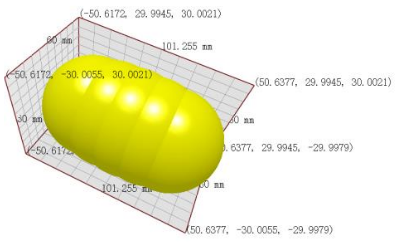
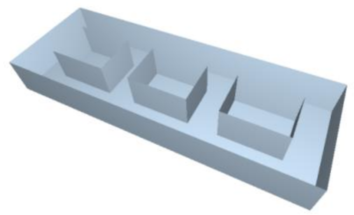
	

Fig. 4 - Potato model	**Fig. 5 - Soil trough particle factory and three boxes particle factories**

The Hertz-Mindlin (no slip) contact model was set up between potatoes and soil particles. In order to prevent the potato bouncing, the descent speed of potato particles was reduced during the potato model formation.

By consulting the relevant materials *(Xin et al., 2020; Fan et al., 2022)* and EDEM material library, the parameter values were shown in Table 1 and Table 2, which were used in discrete element analysis.

Table 1

Basic parameters of discrete element method simulation

Material parameters	**Value**
Soil moisture content, %	13.33
Soil particle density, g/cm^3	1.57
Poisson's ratio of soil	0.3
Soil shear modulus, Pa	1.01×10^6
Potato density, g/cm^3	1.05
Potato moisture content, %	80.3
Potato shear modulus, Pa	25.01×10^6
Poisson's ratio of potato	0.45
Excavation shovel shear modulus, Pa	7.01×10^7
Excavation shovel density, g/cm^3	7.85
Poisson's ratio of excavation shovel	0.5

Table 2

Contact parameters between particles

	Restitution coefficient	**Static friction coefficient**	**Dynamic friction coefficient**
Potato - Excavation shovel	0.72	0.56	0.16
Potato-Potato	0.31	0.39	0.04

To avoid excessively long computation time, the simulation experiment time step was set to 20%, and the grid size was set to 8 mm. The save time was set to 0.5 s.

Using the EDEM software to simulate the potato excavating process. The excavation shovel model (which was generated by SolidWorks software) was imported into EDEM software, then the position of the excavation shovel was set, the simulation process was started.

Field experiment

The orthogonal experiment was selected, and the two-factor three-level orthogonal experiment with excavation depth A and loosening depth B as influencing factors were selected. The level of experiment factors was shown in Table 3.

Table 3

The levels of experiment factors

Level	**Experiment factors**	
	Excavation depth x_1/（cm）	**Loosening depth** x_2/（cm）
1	13	10
2	18	15
3	23	20

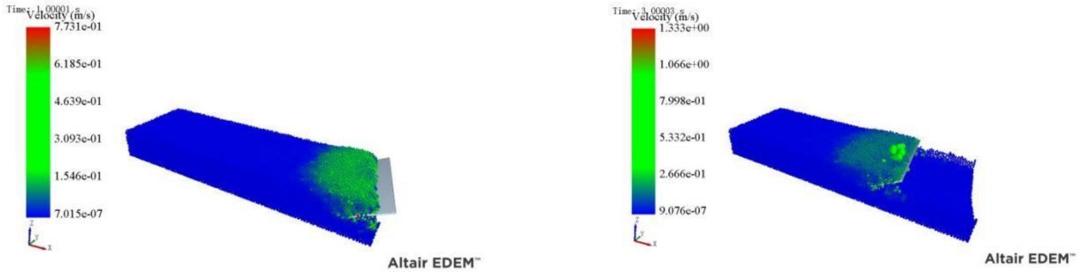
Because the interaction between the two factors should be considered, the orthogonal table L9 (3^4) was selected to arrange the experiment. According to the requirements of the Agricultural Industry Standard of the People's Republic of China NY/T1130-2006, the assessment indicators were selected including the traction resistance, the rate of excavation potato and the rate of damaged potato.

RESULTS

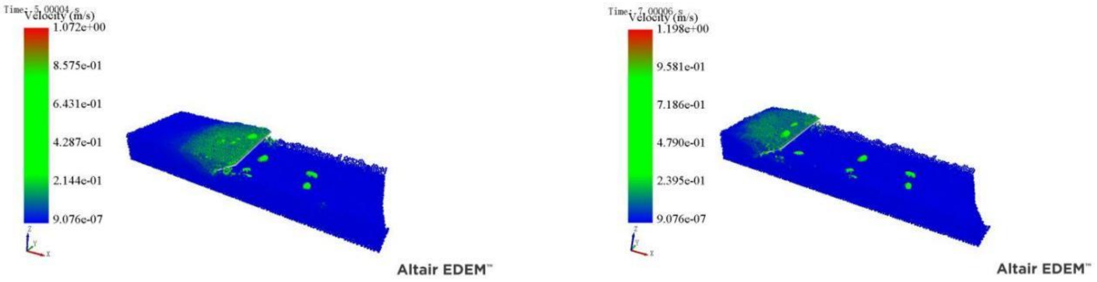
Discrete element simulation analysis results

Simulation analysis of excavation without loosening shovel

In order to study the disturbance of soil particles when digging and shoveling into the soil and the movement state of soil particles, the schematic diagram of the velocity of soil particles at different times during excavation was intercepted, as shown in Fig. 6.



(a) soil particle velocity map at the 1st second (b) soil particle velocity map at the 3rd second



(c) soil particle velocity map at the 5th second (d) soil particle velocity map at the 7th second

Fig. 6 - Motion velocity map of soil particles at different times

In Fig. 6, it indicated an increasing speed from blue to red, with large bright green tubers representing potato tubers. As can be seen from Fig. 6, after the potato excavation shovel digging at 1st second, the soil particles in the front and middle end of the shovel blade increased obviously, showing a light green color. With the increase of time, from 3rd second to 5th second, the speed of soil particles further increased, showing a bright green. When the time reached 7th second, when the soil particles slip from the excavation shovel, several red particles appeared, indicating that when the soil particles moved backward on the excavation shovel, they did parabola movement without the support of the excavation shovel. The speed of soil particles were further accelerated under the action of excavation shovel and gravity. From Fig. 6 (b), it can be found that most of the soil particles in the middle part of the excavation shovel had a higher speed, while the soil particles in the two sides of the excavation shovel were slower than those in the middle part, and the soil disturbance was more concentrated in the middle part.

Simulation analysis of excavation with loosening shovel

As shown in Fig. 7, after adding the loosening shovel, it was found that the soil showed a large area of red particles, the velocity of soil particles increased, and the disturbance of soil particles were greater. The loosening shovel could increase the disturbance to the soil and increased the disturbance range, and there was an obvious change in the soil particle velocity on both sides of the excavation shovel. The soil movement area increased obviously, and the soil height above the excavation shovel also increased obviously.

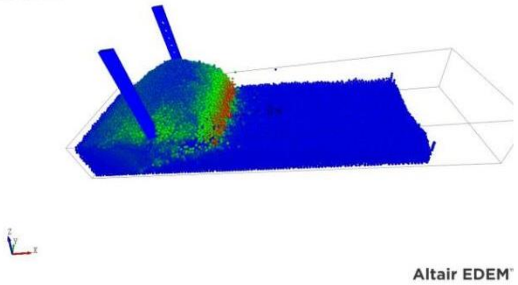


Fig. 7 - Excavation process of potato with loosening shovel

Comparative analysis with loosening shovel and without loosening shovel

When digging potatoes, soil blocks can easily cause soil blockage at the entrance of the excavator. Therefore, the crushing effect on soil was also an indicator for testing the performance of excavation devices. In EDEM, the soil crushing effect was replaced by the breaking of the connection bond. As shown in Fig. 8, the solid line represented the soil particle breaking effect of the excavation shovel with loosening shovel, and the dotted line represents the soil particle crushing effect of the excavation shovel without loosening shovel. It can be found from Fig. 8 that the crushing effect of soil was improved close to 52% by adding loosening shovel. Both the tip and handle of loosening shovel had a certain influence on the crushing effect.

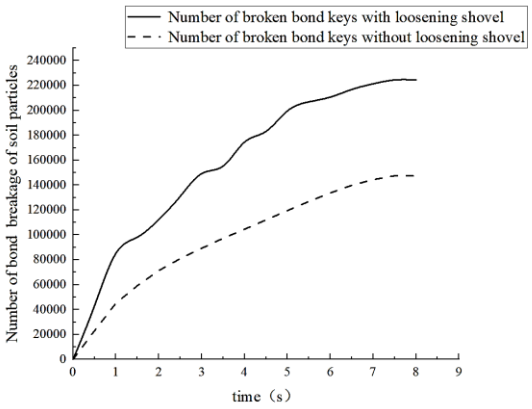


Fig. 8 - Comparison of broken number of soil particle bonds with and without loosening shovel

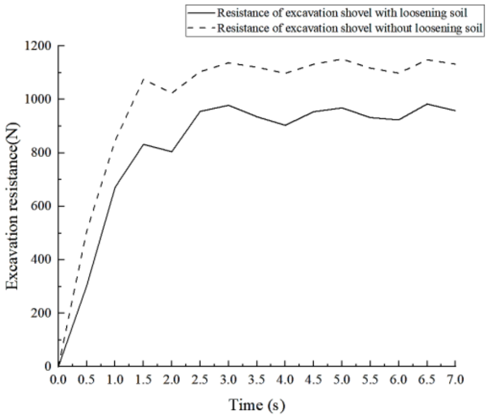


Fig. 9 - Comparison of excavation resistance with and without loosening shovel

It can be seen from Fig. 9 that the resistance of the excavation shovel with loosening shovel was obviously lower than without loosening shovel. The average excavation resistance was calculated in a stable area after 1.4 seconds.

The excavation resistance of the excavation shovel without loosening shovel was 1111.60 N, while that of the excavation shovel with loosening shovel was 927.39 N. The resistance of the excavation shovel with loosening shovel was 16.57% lower than that of the excavating shovel without loosening shovel.

Effect of excavation depth on traction resistance with loosening shovel

Excavation depth was one of the important influencing factors of traction resistance. When the excavation depth was too shallow, although the traction resistance was low, it may increase the rate of damaged potatoes and reduce the rate of excavation potatoes; when the excavation depth was too deep, it increased the traction resistance and excavated too much soil which may lead to the occurrence of soil blockage and increase the energy consumption and wear of working equipment. The discrete element simulation was used to analyze the influence of different excavation depth on the traction resistance when the machine speed was 1.1 m/s and the loosening depth was 20 cm, as shown in Table 4.

Table 4

The traction resistance on different excavation depth

Excavation depth / cm	Traction resistance / N
13	1205.58
18	1403.92
23	1619.43

Field experiment results

The experiment results were shown in Table 5.

Table 5

The experiment results with loosening shovel

Experiment number	Experiment factors				Assessment indicators		
	Excavation depth A /（Level）	Loosening depth B /（Level）	A×B	Empty column	Traction resistance/（N）	Excavation potato rate /（%）	Damaged potato rate/（%）
1	1	1	1	1	1372	87.31	4.51
2	1	2	2	2	1445	88.5	3.22
3	1	3	3	3	1562	89.77	2.92
4	2	1	2	3	1507	96.42	3.11
5	2	2	3	1	1610	96.55	2.73
6	2	3	1	2	1724	96.79	1.42
7	3	1	3	2	1672	98.15	2.87
8	3	2	1	3	1730	98.17	2.49
9	3	3	2	1	1826	98.21	1.31
Traction resistance	K_1	4379	4551	4826	Optimal solution: A_1B_1		
	K_2	4841	4785	4778			
	K_3	5228	5112	4844			
	R	849	561	66			
Excavation potato rate	K_1	262.58	281.88	282.27	Optimal solution: A_3B_3		
	K_2	289.76	282.22	282.13			
	K_3	294.53	282.77	282.47			
	R	31.95	0.89	0.2			
Damaged potato rate	K_1	10.65	10.49	8.42	Optimal solution: A_3B_3		
	K_2	7.26	8.44	7.64			
	K_3	6.67	5.65	8.52			
	R	3.98	4.84	0.88			

Because there were relatively many experiment indexes, the comprehensive balance method was used to determine the optimal solution in this experimental analysis. For factor A (excavation depth), the range of traction resistance and excavation potato rate were the largest, A1 and A3 were selected respectively. The range of damaged potato rate was relatively small, so the A3 was selected. The A3 was the best factor after comprehensive analysis. For factor B (loosening depth), the range of damaged potato rate was the largest, so the B3 was selected. The traction resistance and excavation potato rate had less influence on B1 and B3 respectively, so the B3 was the best after comprehensive analysis.

The depth of loosening soil should be deeper than the actual growth depth of potato. According to the field experiment, it was found that although the loosening shovel was set on the side of the ridge, it still caused some damage to potato. With the increase of the loosening depth, the damaged potato rate decreased gradually.

As shown in Fig. 10, the solid line represents the excavation potato rate, and the dotted line represents the damaged potato rate. When the excavation depth was smaller than the actual growth depth of potato, the loosening shovel had a certain influence on the excavation rate. With the depth of loosening increased, the excavation potato rate gradually increased. The reason was that during the operation of the loosening shovel, the soil and potatoes moved upwards. Therefore, it can reduce the actual excavation depth to a certain extent with the loosening shovel.

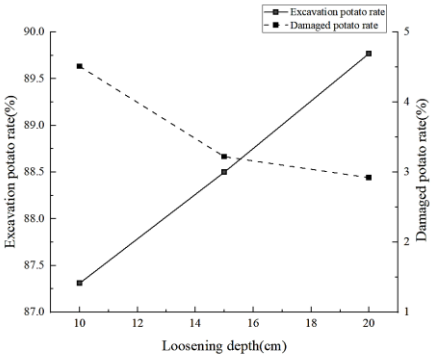


Fig. 10 - The effect of loosening depth on excavation potato rate and damaged potato rate

The significant factor affecting the excavation potato rate was the excavation depth of the shovel. When the excavation depth was 23 cm, the excavation potato rate was the highest. Loosening shovel also had a certain effect on the excavation potato rate, and the excavation potato rate was the highest when the depth of loosening was 20 cm. From the perspective of considering the excavation potato rate, the excavation potato rate was the highest when the depth of loosening was 20 cm and the depth of excavation was 23 cm.

The significant factor affecting the damaged potato rate was the excavation depth. When the excavation depth was 13 cm, the damaged potato rate was the highest. When the excavation depth was 23 cm, the damaged potato rate was the lowest. Therefore, under the condition of only considering reducing the rate of damaged potato, the excavation depth was 23 cm and the depth of loosening was 20 cm.

Through the above analysis, the optimal operating parameters of the potato excavation were determined: the excavation depth was 23 cm, the loosening depth 20 cm. At this time, the excavation effect was the best, including the traction resistance was 1826 N, the rate of excavation potato was 98.21%, the rate of damaged potato was 1.31%.

Comparative analysis with loosening shovel and without loosening shovel

The field experiment measured the traction resistance, excavation potato rate and damaged potato rate without loosening shovel when the excavation depth was 13 cm, 18 cm, 23 cm, as shown in Table 6. The comparative analysis was shown in Fig. 11. The dotted line represented the traction resistance of the excavation device without loosening shovel at different excavation depth, and the solid line represented the traction resistance of the excavation device with loosening shovel at different excavation depth. It can be found that with the increase of excavation depth, the traction resistance with loosening shovel was similar to that without loosening shovel. It showed that with the increase of excavation depth, the effect of loosening shovel to reduce excavation resistance was more obvious. The comparison of excavation potato rate and damaged potato rate with loosening shovel and without loosening shovel was shown in Fig. 12. It can be found from the picture that when the excavation depth was insufficient, the loosening shovel can improve the excavation potato rate to a certain extent, but when the loosening depth was insufficient, the damaged potato rate was higher, and the excavation potato rate decreased with the increase of the loosening depth. When the depth of loosening soil was 18 cm, the damaged potato rate with loosening shovel was similar to that without loosening shovel, indicating that when the depth of loosening was greater than 18 cm, increasing loosening shovel had little effect on the damaged potato rate.

Table 6

The experiment results without loosening shovel

Experiment number	Experiment factors		Inspection indexes		
	Excavation depth A / (cm)	Loosening depth B / (cm)	Traction resistance / (N)	Excavation potato rate / (%)	Damaged potato rate / (%)
1	13	0	1027	87.42	2.03
2	18	0	1189	96.53	1.41
3	23	0	1332	98.15	1.25

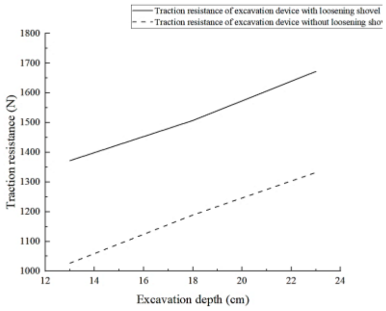


Fig. 11 - Comparative analysis of traction resistance with and without loosening shovel

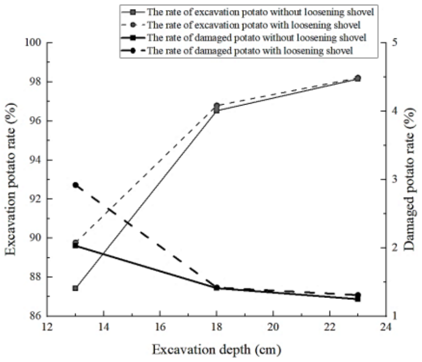


Fig. 12 - Comparative analysis of excavation potato rate and damaged potato rate with and without loosening shovel

Comparative analysis of discrete element simulation and field experiment

When loosening depth was 20 cm, the comparison of traction resistance between field experiment and simulation experiment with different excavation depth was shown in Fig. 13. It can be found that the maximum difference of traction resistance between field experiment and simulation experiment appeared when the excavation depth was small. With the increase of excavation depth, the difference of traction resistance between field experiment and simulation experiment decreased gradually. When the excavation depth was 23 cm, the error value of traction resistance was 11.3% between simulation experiments and field experiments.

It can be seen from Fig. 13 that the traction resistance of discrete element simulation was relatively small compared with field experiments. The main reason was that the working environment was relatively bad in the field experiment, and the simulation experiment only considered the force of soil and potato on the excavation shovel in the ideal state, but the influence of other factors was not considered. In addition, there were some differences in physical and mechanical properties between the soil particle model in the discrete element analysis and the actual soil particles in the field, which was also one of the reasons why the traction resistance of the discrete element simulation was relatively small compared with the field experiment.

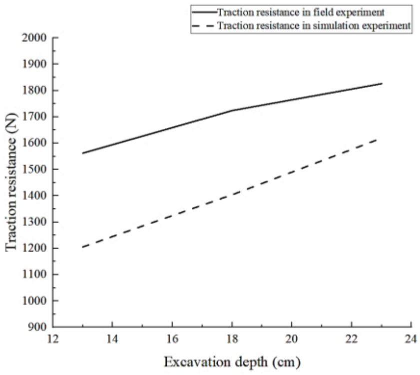


Fig. 13 - Comparative analysis of discrete element simulation and field experiment

CONCLUSIONS

(1) Based on the discrete element simulation analysis of the potato excavation process, it was found that including the loosening shovel increased the disturbance to the soil, and the crushing effect of the loosening shovel on the soil was improved close to 52%. The excavation resistance with loosening shovel was 16.57% lower than that of the excavating shovel without loosening shovel. Under the same working conditions, the service life of the excavation shovel with loosening shovel was longer.

(2) Based on the field experiment with excavation depth and loosening depth as influencing factors, the two-factor and three-level orthogonal experiment was carried out to obtain the optimal operation parameters of the excavation device. When the excavation depth was 23 cm and the loosening depth was 20 cm, the operation effect was the best at this time, while the traction resistance was 1826 N. The excavation potato rate was 98.21%, and the damaged potato rate was 1.31%, which met the requirements of relevant industry standards.

(3) Through comparative analysis of discrete element simulation and field experiments, it was found that the traction resistance value obtained from discrete element simulation was lower than that obtained from field experiments. The main reason was that the simulation experiment only considered the forces exerted by soil and potatoes on the excavation shovel under ideal conditions, without taking into account the influence of other factors. When the excavation depth was 23 cm and the loosening depth was 20 cm, the error value of traction resistance was 11.3% between simulation experiments and field experiments. The discrete element simulation analysis can provide a preliminary reference for potato excavation design.

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