DESIGN AND SIMULATION TEST OF DIGGING DEVICE FOR SMALL POTATO HARVESTER

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小型马铃薯收获机挖掘装置的设计与仿真试验

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ABSTRACT

Aiming at the potato cropping pattern in the hilly area of southwest China, a small digging device for potato harvester was designed. First, the overall structure of the harvester was determined according to the soil physical characteristic and cropping pattern of the test site. Then, the digging shovel, the key components of harvester were designed and was analyzed the relationship between the inclination of the digging shovel and the power loss under the conditions of different digging speed, digging depth and soil bulk density by MATLAB software, and the mathematical models were established. Finally, the three-dimensional model of the whole machine was established by SolidWorks, and the simulation experiment was carried out with the model of soil particles, potato particles and potato ridges created by the discrete element (DEM) software. The simulation results show that when the working speed of the harvester is 1 m/s, the digging depth is 170 mm, and the potato expose rate is 87.3%. Under normal working conditions of the digging device, appropriately reducing the digging depth can reduce the resistance and wear of the digging shovels.

摘要

针对西南丘陵地区马铃薯种植模式，设计了一款小型马铃薯收获机挖掘装置。首先根据试验场地的土壤物理特性和种植模式，确定了收割机的整体结构；然后设计了关键部件挖掘铲，并利用 MATLAB 软件分析了在不同挖掘速度、挖掘深度和土壤容重条件下挖掘铲的倾角与消耗功率之间的关系，建立了数学模型；最后使用 SolidWorks 建立整机三维模型，结合 DEM 软件建立的土壤颗粒、马铃薯颗粒和马铃薯种植垄的模型，进行了仿真试验。仿真结果表明：当收割机的工作速度为1m/s 时，开挖深度为170mm，马铃薯的明薯率为87.3%，在挖掘装置正常工作条件下，适当减小其挖掘深度，可以减小挖掘铲的阻力和磨损情况。

INTRODUCTION

Potatoes, typical root crops, are widely planted and used for food and vegetables, but also has a certain energy value (Nobuhisa K et al.,2013; Kang Wenqin et al., 2014; Yang Bingnan et al.,2015). As the world's largest potato producer, China produces about a quarter of the world's potato production where Sichuan Province is one of the main potato planting areas. However, because of the complexity of terrain, potato scale, standardization and mechanization production are still relatively weak. Mechanized potato harvesting is the key link to realize the whole process of potato mechanized production, which can improve its working efficiency and ensure the increase of production and income (*Lv Jinqing et al., 2015; Lv Jinqing and Tian Zhongen et al., 2015; Liu Chonglin et al., 2019; Wang Gongpu et al., 2014*). Potato harvesters in many developed countries have been at the world's leading level, can complete one-time digging, potato and soil separation, automatic sorting of potato size, automatic loading, small damage to potato (*Chuai Deming, 2017*). These potato harvesters have the characteristics of high efficiency, high technical level, high stability. However, potato harvesters in developed countries are mostly used on large areas of cultivated land, which are not suitable for small and medium-sized plots in the main potato producing areas in southwest China, and this type of machine is more expensive. (*Wei Hongan et al., 2013; Kempenaar C. and Struik P.C., 2008; Li Zihui et al., 2019*).

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The research of potato harvester in China started late, the technical reserve is insufficient and the development speed is slow (*Ke Jianhong et al., 2017*). At present, the potato harvester produced by our country is mainly a small and medium potato harvester, which mainly takes the method of multi-stage harvest. To deal with the phenomenon that the soil block area is small and the surface is uneven in the hilly area of the south, the small and medium potato harvester can realize the digging and the separation of potato and soil in the early stage, and the later stage needs for potatoes to be picked up manually.

In view of the above problems, this paper designs a small potato harvester, using SolidWorks to create a three-dimensional model of the harvester, using EDEM to carry out discrete element simulation experiments, creating soil particles and potato particles, establishing a potato ridge simulation model, simulating the harvester to dig potatoes, analyzing the position and velocity changes of potato particles, soil particle position and potential energy changes and the wear of the harvester.

MATERIALS AND METHODS

Overall Scheme Design and Working Principle

The design of the potato harvester is based on the project of the research group to carry out research, and the design and experiment are carried out in accordance with the agronomic requirements of the experimental demonstration base in Pengzhou City, Sichuan Province. The overall structure of the potato harvester is shown in Fig.1. The main work components include the digging shovel mechanism, the vibration shovel mechanism, the lifting chain mechanism, the buffer regulating mechanism and the frame. The whole machine is towed by a tractor. After the digging shovels dig up the potato-soil mixture, the vibrating shovel shakes and separates the potato soil mixture. Then the potato soil mixture is lifted and sieved by the elevator chain, and finally the potatoes are fall on the soil ridge. The digging shovel mechanism is composed of multiple digging shovels. Vibration shovel mechanism is forced vibration, which is the vibration transfer of eccentric wheel under the rotation of drive shaft. The lifting chain mechanism rotates under the action of both sides of the chain drive to separate the potato soil mixture from the potato soil. The convey chain conveys potatoes to reduce the collision damage caused by parabolic motion. The adjusting mechanism is composed of screw and nut, and the back end of the digging device is raised and lowered by spiral drive, which realizes the adjustment of the digging inclination angle of the digging device.

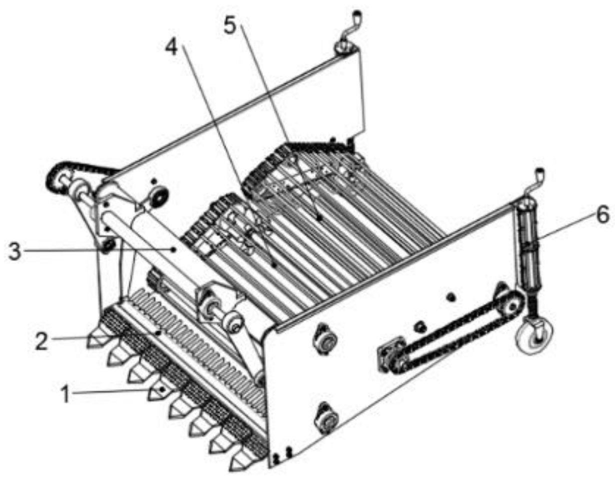


Fig. 1 - Overall structure of potato harvester

1-digging shovel mechanism; 2-Vibration shovel structure; 3-Frame;
4-Lifting chain mechanism; 5-Conveying chain mechanism; 6-Adjusting mechanism

Key component design

According to the agronomic requirements of potato planting and the experimental data obtained from the test, the digging shovel shape is designed as a triangular curved surface structure, as shown in Fig.2.

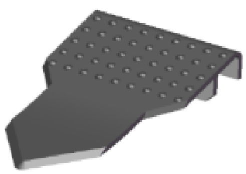


Fig. 2 - Triangular Surface Digging

Statics Analysis of digging Potato-soil Mixture

To smoothly shovel the potato-soil mixture during the working process of the digging device, it is necessary to overcome the reaction force of the traction resistance of the digging device; Analyze the force of the digging shovel, and establish the traction resistance model of the shovel using the concept of the virtual dip angle of the plane shovel (*Li Jinchuan et al., 2017; Li Baoling et al., 2016*).

$$W = G\tan(\alpha+\varphi) = SL\rho g(\alpha+\varphi) \tag{1}$$

$$Q = W + K_s + K_W G \tag{2}$$

where: L is the length of digging shovel, m; S is the cross-sectional area for cropping ridges, m^2; K is the soil specific resistance in furrow, N/m^2, (Medium solid soil, K=24000~30000 N/m^2); ρ is the soil density, kg/m^3; φ is the inner friction angle of soil, º; α is the angle of the digging shovel, º; K_W is the resistance coefficient of the machine driving along the ridge, (Medium solid soil, K_W =0.14~0.17); G is the machines and soil gravity on shovels, N; Q is the tractor traction force, N; K_S is the force needed to dig up the soil, N; K_wG_1 is the resistance the machine needs to overcome as it moves along the ridge, N.

To facilitate the creation of the model, the influence of impurities is ignored in the Digging process. The mixture of rising potato and soil, ignoring the phenomenon that the distribution of potato in soil is not continuous and uniform. The resistance that the shovel needs to overcome when shoveling up the potato soil mixture was analyzed, as shown in Fig. 3. In the process of rising, the potato soil mixture mainly undergoes three processes of cutting, squeezing and raising. Squeezed section of the potato-soil mixture is shown in Fig.4.

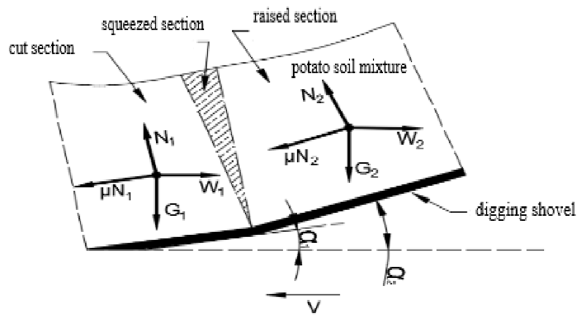


Fig. 3 - Force analyze of the mixture of potato and soil on the digging shovel

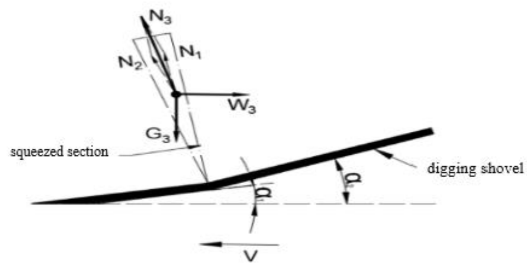


Fig. 4 - Squeezed potato-soil mixture

The potato-soil mixture in the squeeze section is subjected to the positive pressure of the cut section and the rising section. Because of the small inclination angle of the shovel surface on the cut section and the large inclination angle of the raised section, the soil will squeeze each other at the intersection.

The digging shovel surface force diagram is shown in Fig. 5. In the process of rising up, the digging device keeps the speed as far as possible, and the potato soil mixture is conveyed backward in an orderly manner. In order to simplify the force model and ignore the cohesion between soil particles and between soil and potato, the movement of the soil mixture is set to be in equilibrium.

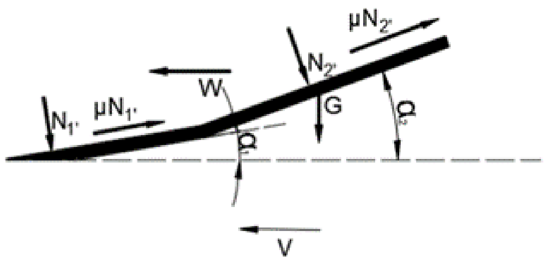


Fig. 5 - Force analysis of the digging shovel

$$W_1\cos\alpha_1 + W_2\cos\alpha_2 - G_1\sin\alpha_1 - G_2\sin\alpha_2 - \mu N_1 - \mu N_2 = 0 \tag{3}$$

$$N_1 + N_2 - G_1\cos\alpha_1 - G_2\cos\alpha_2 - W_1\sin\alpha_1 - W_2\sin\alpha_2 = 0 \tag{4}$$

$$W = W_1 + W_2 + W_3 \tag{5}$$

$$N_3 = N_1\cos\beta_2 + N_2\cos\beta_1 \tag{6}$$

$$\beta_1 + \beta_2 = \alpha_2 - \alpha_1 \tag{7}$$

where: β_1 is the angle between the positive pressure of the rising section and the upward force of the squeeze section along the shovel surface, N; β_2 is the angle between the positive pressure of cut section and the upward squeeze pressure along the shovel surface, N;

The digging resistance coefficient Z_1 and Z^2:

$$Z_1 = \cos\alpha_1 - \mu\sin\alpha_1 \tag{8}$$

$$Z_2 = cos\alpha_2 - \mu sin_{\alpha_2} \tag{9}$$

Bring in the above equations:

$$Z_1W_1 + Z_2W_2 = G_1\sin\alpha_1 + G_2\sin\alpha_2 + \mu G_1\cos\alpha_1 + \mu G_2\cos\alpha_2 \tag{10}$$

Analysis of angle range of digging shovel

According to the force analysis of the digging shovel during the digging process, the inclination angle of the digging shovel is related to the working speed, the digging depth and the soil type. Ignoring the local force of the shovel, the equation can be obtained:

$$\alpha = \text{arctge}\frac{W - \mu G}{G = \mu W} \tag{11}$$

$$W = \frac{P}{V} \tag{12}$$

Where: P is the digging consumption power; V is the digging shovel forward speed;

Bring in the equation:

$$\alpha = arctg\frac{P - \mu GV}{GV + \mu P} \tag{13}$$

$$P = \frac{\tan\alpha GV + \mu GV}{1 - \tan\mu} \tag{14}$$

According to the physical characteristics of the soil, the soil can be divided into sandy soil, clay soil and loam soil, and the bulk density between the soils is different, which determines the different digging inclination angle needed for digging shovels between different types of soils. Ignoring the partially raised soil, the cross section of the ridge mixture can be simplified to elliptical (*Cheng Huidong et al., 2007*). Establish soil bulk density model. The cross section of potato planting ridges is shown in Fig. 6:

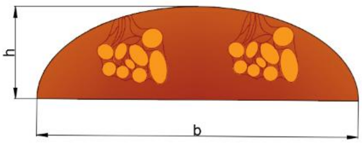


Fig. 6 - Cross section of potato planting ridge

The coordinate system is established along the center of potato ridge bottom. The ridge height direction is X axis, the ridge bottom width direction is Y axis, and the ridge bottom length direction is Z axis. The mathematical model of potato ridge section is established. The surface equation of potato ridge is as follows:

$$\frac{y^2}{h^2} + \frac{z^2}{(b/2)^2} = 1 \tag{15}$$

$$y = h\sqrt{1 - \frac{z^2}{(b/2)^2}y} \tag{16}$$

$$S = \iint_{\Sigma} dS = \iint_D \sqrt{1 + \frac{4h^2z^2}{b^2\left((b/2)^2 - z^2\right)}}dzdx \tag{17}$$

Volume equation of potato ridge:

$$V = Sl \tag{18}$$

$$S = \frac{\pi hb}{4} \tag{19}$$

$$M = \rho v \tag{20}$$

$$G = Mg \tag{21}$$

where: ρ is the soil bulk density, kg/m^3; l is the digging shovel length, mm; h is the maximum digging depth, mm; b is the maximum depth ridge width, mm;

The above joint equations can be obtained:

$$G = \frac{\pi \rho g l h b}{4} \tag{22}$$

The relationship between the loss power needed to dig the potato soil mixture and the working speed, digging depth, and soil type is shown in equation (23).

$$P = \frac{\pi \rho g l h b}{4} \cdot \frac{V(\tan\alpha + \mu)}{1 - \tan\alpha\mu} \tag{23}$$

Relationship between digging loss power and digging dip angle per unit time at different operating speeds, digging depth and soil bulk density

In the actual digging process, different digging speed corresponds to different digging dip angle, and the setting of digging dip angle is the key factor to reduce the digging power loss.

Operating speeds, digging depth and soil bulk density are the main parameters in this experiment. When one parameter is a variable, the other two parameters are set as constants. For example, when the operating speed is determined as a variable, the digging depth and soil bulk density are determined as constants. The experimental parameters are determined as shown in Table 1.

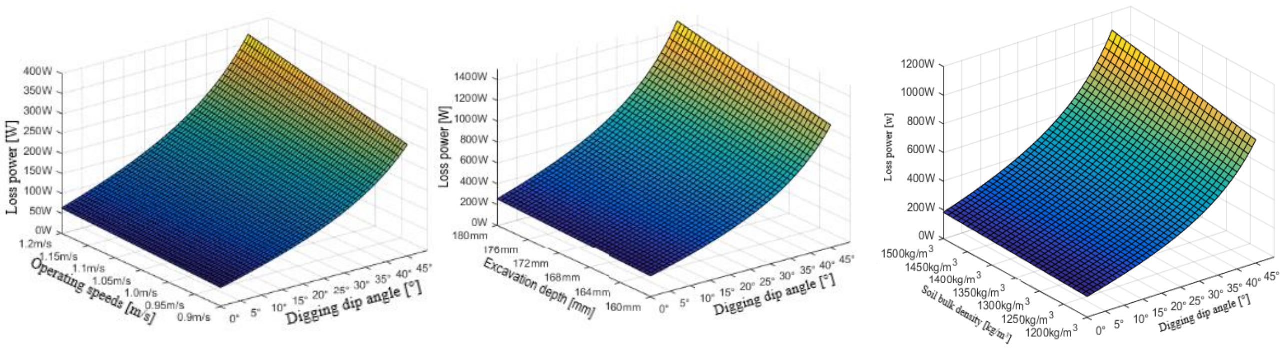
Table 1

Parameters		**Operating speeds**	**Digging depth h**	**Length of shovel surface l**	**Soil bulk density ρ**		**Friction angle of soil**	**Rest angle of soil**
					sandy soil	**clay soil**		
		[m/s]	**[mm]**	**[mm]**	**[g/cm3]**		**[°]**	**[°]**
Ranges		0.9~1.2	160~180	350-400	1.2~1.8	1.0~1.5	18~20	30~40
Value	(a)	0.9~1.2	170	350	1.3		20	35
	(b)	1	160~180		1.3			
	(c)	1	170		1.2~1.5			

The width of ridge section is related to the rest angle of soil, and the maximum ridge width is obtained:

$$b = \frac{h}{\tan\alpha} \tag{16}$$

Based on the balance equation and experimental parameters of potato soil mixture, the relationship between digging loss power and digging dip angle per unit time is determined at different operating speeds, digging depth and soil bulk density are shown in Fig. 7.



(a) (b) (c)

Fig. 7 - Relationship between digging loss power and digging dip angle per unit time at different operating speeds, digging depth and soil bulk density

From Fig. 7, the following analysis can be made: (a) The loss power per unit time increases with the increase of soil bulk density and digging dip angle when the digging dip angle is constant. The ratio of the loss power per unit time to the change of working speed tends to be stable during the period of 15º~30º, which is beneficial to the digging shovel under the specified working speed. (b) The loss power increases with the increase rate of digging speed change in unit time when the digging dip angle is constant.

When the dip angle is less than 10º, the loss power per unit time tends to be stable under the change of digging depth, which is beneficial to the shear effect of the shovel blade on the soil and ridge bottom. The dip angle of digging shovel increases gradually, the digging shovel is between 10º~30º, and the ratio of loss power to digging depth is stable in unit time, which is beneficial to the rise of potato soil mixture at the end of digging shovel. If the digging dip angle is more than 30º, the loss power per unit time has a sharp upward trend from both the digging dip angle and the digging depth, which is not conducive to the digging shovel under the condition of the change of the digging dip angle and the digging depth. (c) The loss power per unit time increases with the increase of soil bulk density and digging dip angle. When the digging dip angle is less than 8º, the loss power per unit time increases with the increase of soil bulk density, but the increment is small, which is suitable for the design of the digging shovel front dip angle. The digging dip angle is in the range of 8º~30º. With the increase of soil bulk density and digging dip angle, the loss power per unit time increases slowly and the increment is stable. If the digging dip angle is more than 30º, the loss power per unit time increases sharply with the increase of digging dip angle and soil bulk density, and the increment is large, and the loss power per unit time changes greatly and is unstable.

According to the relationship between soil loss power and digging dip angle under different digging conditions, the digging shovel force model is established. The relationship between working speed, digging depth and soil bulk density are analyzed as shown in Fig. 8.

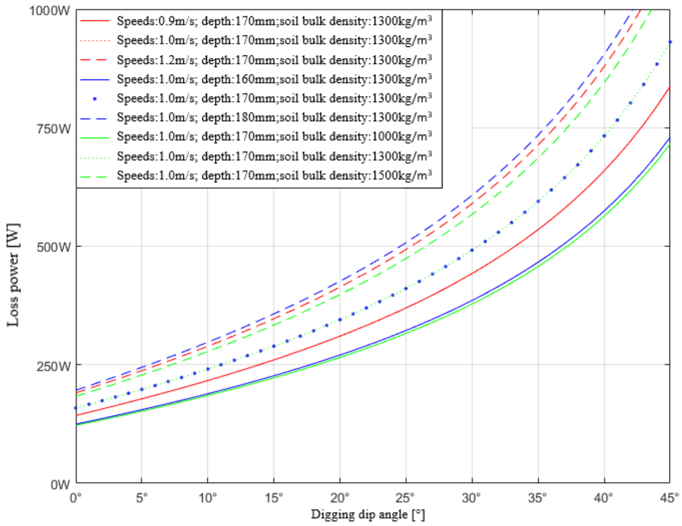


Fig. 8 - Relationship between digging loss power and digging dip angle per unit time under different digging conditions

The analysis shows that the loss power per unit time increases with the increase of digging dip angle under the condition of certain operating speed, digging depth and soil bulk density. From the analysis of the change of digging dip angle, the change of digging depth unit increment has the greatest influence on the loss power, followed by soil bulk density, and the change of operating speed unit increment has little effect on the change of loss power. When the dip angle is less than 25º, the loss power per unit time is less than 500 W, which is an ideal traction state for walking tractor. If the digging dip angle is less than 15º, the increment of the loss power is smaller and the loss power is lower, so it is suitable for the design of the front end of digging shovel dip angle.

Parameter Design of Digging Shovel

According to the potato planting scale and the power required by the digging device, the traction power of the digging device is to choose a small tractor. In potato digging process, the forward speed of the digging shovel generally needs to be maintained between 0.9 ~ 1.2 m/s. Therefore, the forward speed of the digging shovel is taken as 1 m/s; theoretically, the digging depth of the digging shovel needs to be greater than the maximum potato Bury depth to avoid damage to potatoes during the digging process. After field measurement, the general burial depth of potatoes is about 150 mm. Therefore, in order to ensure the quality of potato harvest, the digging depth of the shovel is 170 mm.

Width Design of Digging Shovel

The width of the digging shovel mainly depends on the distribution width of the potato underground and the uniformity between its row spacing. The gap between the shovels should be less than the average triaxial size of the potato. During the digging process, the connection between the digging shovel and the frame is subject to greater stress and the stress is concentrated, which is likely to cause damage to the digging shovel. In order to ensure that the digging shovel has good soil penetration and rigidity, the selection of the width of the shovel surface is very important. The shape of the shovel adopts a canard-type design, which can ensure that the front section of the digging shovel has a good soil penetration capacity. The larger width of the digging shovel is to improve the stability of the digging shovel; the blades on both sides of the digging shovel play the role of cutting grass roots and potato roots, avoiding the clogging of the potato soil mixture due to the accumulation of grass roots and roots.

On the basis of the measured data, the average row spacing of potato planting ridges is 170 mm, the average width of potato block distribution of double row potato is 501.6 mm, and the working width of potato harvesting device is 500 mm, and the working width is small. The running deviation of the machine can be controlled. In this paper it is set as 40 mm.

The comprehensive standard deviation can be calculated from the following formula:

$$\sigma = \sqrt{\sigma_M^2 + \sigma_b^2} \tag{24}$$

where: σ_m is the standard deviation of line spacing, mm; σ_b is the standard deviation of distribution width of potato, mm;

The comprehensive standard deviation is 8.83 mm, the integral is 10 mm, and the working width of the digging device is B=780 mm.

The digging shovel assembly diagram is shown in Fig. 9:

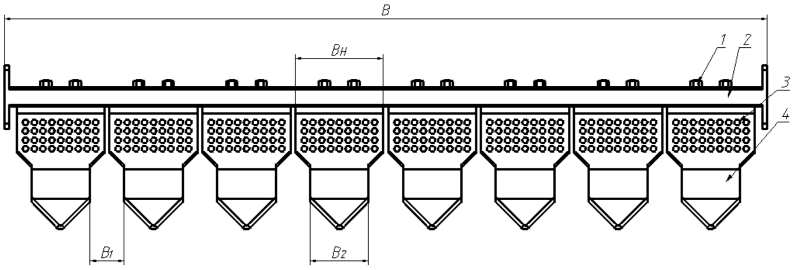


Fig. 9 - Digging shovel assembly

1–bolts; 2 - installing-frame; 3-bulge; 4-digging shovel

Digging shovel width and clearance satisfied:

$$\lambda B_2 + (\lambda - 1)B_1 < B, C > \mathrm{D} \tag{25}$$

where: λ is the number of digging shovels (pieces); B_2 is the width of digging shovels, mm; B_1 is the slide gap of digging shovels, mm; B is the width of digging device, mm;

This design adopts the multi-face digging shovel combination, the digging shovel piece quantity λ takes 8 pieces.

Calculated: $B_2 < 66.875$ mm

A certain gap is reserved between the shovels, the digging shovel is assembled reasonably, and the width of the shovel surface at the front end is 60 mm. The distance between the two sides of the shovel is determined according to the slip clearance. For the convenience of assembly, there is a certain gap between the shovels. The blade clearance on both sides is 15 mm.

Calculated: B_H=90 mm

Design of dip angle of shovel blade

The force on the shovel blade is shown in Fig. 10.

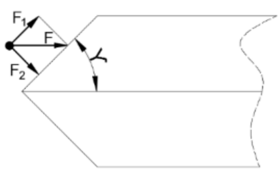


Fig. 10 - The force diagram of digging shovel blade

$$F\sin(90^{\circ}-\gamma)=F_1 \tag{26}$$

$$F\cos(90^{\circ}-\gamma)=F_2 \tag{27}$$

$$F_1=F_2\tan\varphi \tag{28}$$

where: F is the total resistance to shovels; F_1 is the friction on the blade of a shovel; F_2 is the vertical splitting force on the blade surface of the digging shovel; γ is the digging shovel blade dip angle; φ is the inner friction angle of soil.

In the process of digging, the soil at the bottom of the planting ridge is cut smoothly, and the cross section of the digging blade is in direct contact with the soil. According to the corresponding friction law, the friction force overcome by the digging shovel needs to be greater than the total resistance of the digging shovel.

$$F_2\tan\varphi < F\sin(90^{\circ}-\gamma) \tag{29}$$

$$\cos(90^{\circ}-\gamma)\tan\varphi < \sin(90^{\circ}-\gamma) \tag{30}$$

Calculated: $\varphi < 90^{\circ}-\gamma$

The larger the dip angle of the shovel blade, the more soil the ridge has, the flatter the ridge bottom and the greater the resistance of the digging; the smaller the dip angle of the shovel blade, the more serious the wear of the shovel tip. When the internal friction angle of the soil is 20º, digging shovel blade dip angle γ<70º.In this paper γ is set to 45º.

Design of dip angle of shovel surface

According to the conclusion of the force analysis of the shovel above, the digging resistance of the shovel is mainly related to the mixture of potato and soil and the dip angle of the shovel. The relationship between shovel dip angle and digging resistance is shown in Fig. 11.

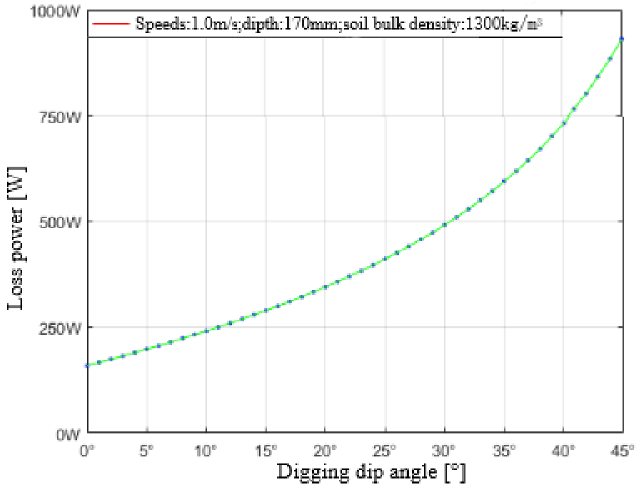


Fig. 11 - Relationship between inclination angle of shovel surface and digging resistance

It can be seen from the diagram that the surface digging shovel is used to minimize the digging resistance under the condition of a certain dip angle of the digging shovel surface. In order to meet the requirements of small digging resistance and backward transportation height, the digging shovel is designed with two sections, the front section dip angle is small and the back section of dip angle is large. The detailed size of the shovel is shown in Fig.12.

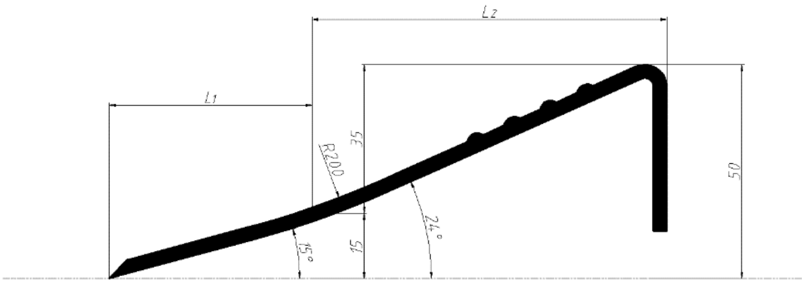


Fig. 12 - Inclination of digging shovel

In the first part of digging shovel, the angle is 15º, the shovel height is 15 mm. In the second part, the angle is 24º, the shovel height is 35 mm, the total shovel height is 50 mm. The front and rear sections of the shovel have rounded corners, R=200 mm.

Design of Length of Digging Shovel

In the Fig. 12.

L_1 is the length of first part digging shovel; L_2 is the length of second part digging shovel;

According to the angle of the digging shovel surface and the height of the cross section of the two sections of the shovel surface can be calculated:

$$L_1 = \frac{15}{\tan 15^\circ} \tag{31}$$

$$L_2 = \frac{35}{\tan 24^\circ} \tag{32}$$

Calculated: L_1=55.98mm; L_2=78.61mm

The total shovel length: L=L_1+L_2=134.59mm

Simulation model

The soil model and potato model were established by EDEM, in order to increase the accuracy of the simulation experiment, the soil particles use the soil model library in the material library, and the potato particles were conducted by SolidWorks, and then the particle unit is filled, and the degree of filling meets the triaxial size of the particles. Four kinds of soil particles were set up in the simulation experiment to represent surface soil, middle soil, deep soil and ground soil respectively. the model shape of each layer of soil particles was the same, but the physical parameters were different.

According to the measured triaxial size of potato particles, the average triaxial size of potato particles was 80×50×40 mm. Create a 3D model of potato by SolidWorks. Soil particle model and potato particle model are shown in Fig. 14 and Fig.15. According to the actual situation, the potato-soil mixture is modeled by simulation. The potato-soil mixture consists of compacted soil particles, ridge bottom sparse soil large particles, middle layer tight soil particles, surface layer small particles and potato particles. The ground size was set to 3000×1500×100 mm. The ridge width is 620 mm, the ridge height is 210 mm, the ridge length is 2800 mm.

The potato ridge model is shown in Fig. 16:

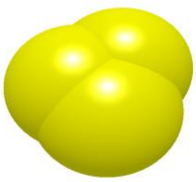


Fig. 14 - Soil particle model

Fig. 15 - Potato particle model

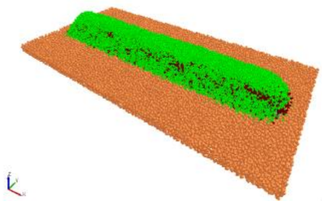


Fig. 16 - Ridge Model of potato

The simulation parameters and characteristics were set as shown in Table 2 and Table 3.

Table 2

Simulation parameters

Items	Poisson's ratio	shear modulus [Pa]	Density [kg·m^{-3}]
Surface soil	0.32	3×10^6	800
Middle soil	0.4	5×10^6	900
Deep soil	0.5	10×10^6	1000
potato	0.4	1.99×10^6	1200
Shovel	0.3	7.8×10^{10}	7850

Table 3

Simulation characteristics of soil, potato and shovel

Items	Coefficient of restitution	Coefficient of static friction	Coefficient of dynamic friction
Surface Soil - Middle Soil	0.145	0.52	0.245
Surface Soil -Deep Soil	0.150	0.53	0.250
Middle Soil -Deep Soil	0.155	0.54	0.255
Potato - potato	0.13	0.2	0.01
Potato -shovel	0.523	0.644	0.0221
Potato -surface soil	0.06	0.48	0.01
Potato -middle soil	0.06	0.50	0.01
Potato -deep soil	0.055	0.51	0.01
Shovel-surface soil	0.17	0.49	0.39
Shovel-middle soil	0.18	0.50	0.40
Shovel-deep soil	0.19	0.51	0.41

Simulation process

(1) Experimental particle contact model using Hertz-Mindlin with JKR model, The Surface Energy between particles is set to 3.75 J/m^3;

(2) Importing the 3D model of potato digging device and setting up the material parameters and contact model of digging device. Set the speed of digging device to 0.8 m/s, lifting-chain line speed of 2 m/s (*Li Xiaopeng et al., 2019*). A Hertz-Mindlin with JKR model is used to simulate the contact model between potato digging device and particle, Surface Energy is set to 3.5 J/m^3.

The simulation process of the potato digger is shown in Fig.17.

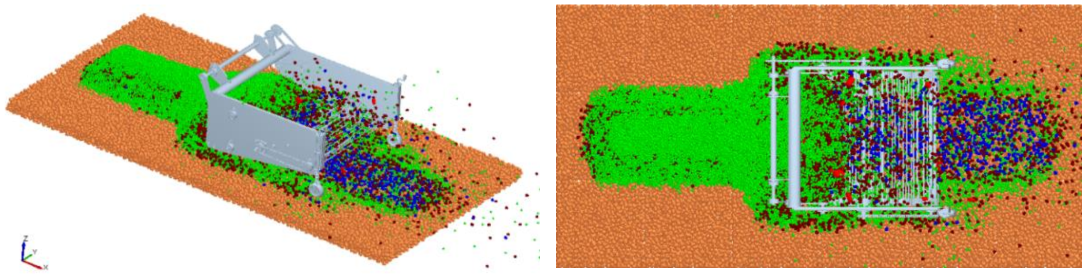


Fig. 17 - The simulation process of the potato digger

According to the figures above, after the digging device slowly shovel into the ridge, the potato ridge section began to deform slowly; The potato particles and soil particles are mainly concentrated between the vibrating shovel and the lifting chain, and start conveying backward under the rotation of the lifting chain. During the transportation process, part of the surface soil particles falls to the ground along the lifting chain, and the middle soil particles and the deep soil particles fall less due to the large particle size. Potato particles and soil particles will beat during the rise of the lifting chain, and the contact between the particles and the lifting chain causes a certain impact. Therefore, a reasonable control of the line speed of the lifting chain is an important measure to reduce the potato damage.

RESULTS

Simulation Results

The experimental results of potato mining simulation are shown in Fig.18.

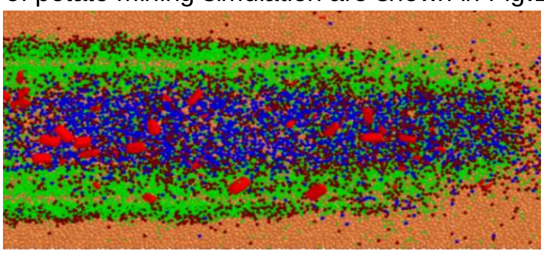


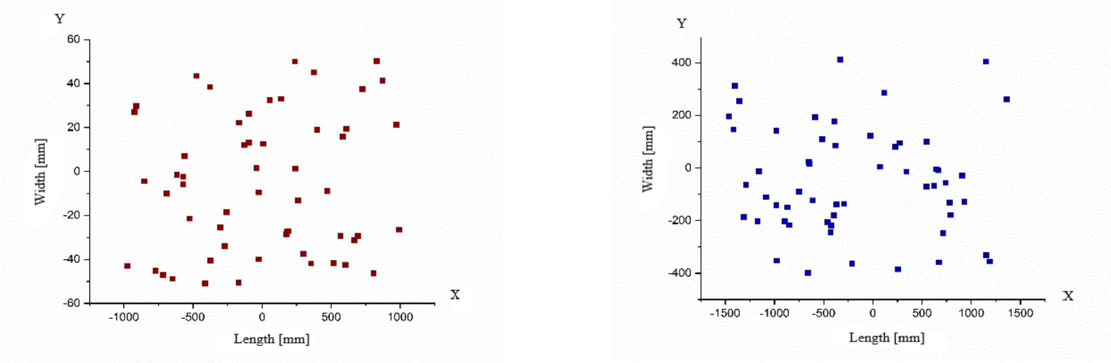
Fig. 18 - Experimental results of potato digging simulation

Simulation results show that the total number of potatoes is 55, 48 were exposed after shovel digging, and 7 potatoes were not exposed. The exposed potato rate was 87.3% and the buried potato rate was 12.7%. The potato digging effect was good.

Analysis of Simulation Results

1. Analysis on the Distribution of Potato Particles before and after Digging

Refer to Fig.18 to establish a coordinate system, which is X along the direction of the harvester, the Y direction along the ridge section direction. The position distribution before and after potato digging is shown in Fig.19.



before **after**

Fig. 19 - Top view of potato digging before and after

According to the change of the position of the potato before and after digging, it can be seen that the potato particles are concentrated in the X direction in the range of -1000~1000 mm, and in the Y direction in the range of -60~60 mm, which conforms to the position distribution of the potato in the potato cropping ridge; After the potatoes are dug, the X direction is concentrated in the range of -1500~1200 mm, and the Y direction is concentrated in the range of -400~400 mm. It can be seen that the distribution of the positions of the potatoes before and after the digging in both the X and Y directions has increased. The analysis shows that since the forward speed of the digging device is 1 m/s and the linear speed of the lifting chain is 1.5 m/s, the speed direction is opposite to the forward direction of the digging device, and the linear speed of the lifting chain is greater than the forward speed of the digging device; After digging, the Y-direction width is close to the working width of the digging device 780 mm. The analysis shows that the potato moves to both sides of the digging device while moving backwards on the lifting chain. The width of the digging device determines the width of the potato in the Y direction after digging. The increase of the width in the Y direction can increase the landing area of potato, and reduce the collision between the potato and the potato, thereby reducing the damage of the potato.

2. Analysis of Speed Change in Potato particle Digging

The speed changes during potato particle digging are shown in Fig. 20:

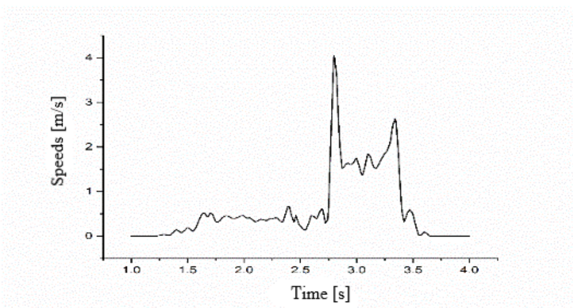


Fig. 20 - Changes of potato particle velocity

According to the diagram, the time experienced by potato particles on the digging device is about 2.5 s, and the speed and state of potato in each time period are shown in Table 4.

Table 4

Changes of velocity and state of potato granules in different time periods

Time period [s]	Changes in potato speed	State
1.25~1.75	A slow increase from 0 to 0.5 m/s	Potatoes in the potato-soil mixture start to contact the shovel
1.75~2.30	At about 0.5 m/s speed	Potato soil mixture moves backward on a shovel
2.30~2.75	Velocity fluctuates greatly, keeping up and down 0.5 m/s	Potato soil mixture moves backward on a vibrating shovel
2.75~2.80	Velocity increases dramatically, reaching maximum speed of 4 m/s	Potatoes are exposed to ascending chains
2.80~2.85	A sharp drop in speed 1.5 m/s	Potatoes are transported backward on the lift chain
2.85~3.30	Velocity fluctuates greatly, keeping up and down 1.5 m/s	The gap between the potato transport chain and the transport chain

Time period [s]	Changes in potato speed	State
3.30~3.40	A sharp increase in speed, maximum 2.7 m/s	Potato contact transport chain
3.40~3.75	The velocity drops sharply and the final velocity is 0	Potatoes are transported backward on the conveyor chain and fall to the ground

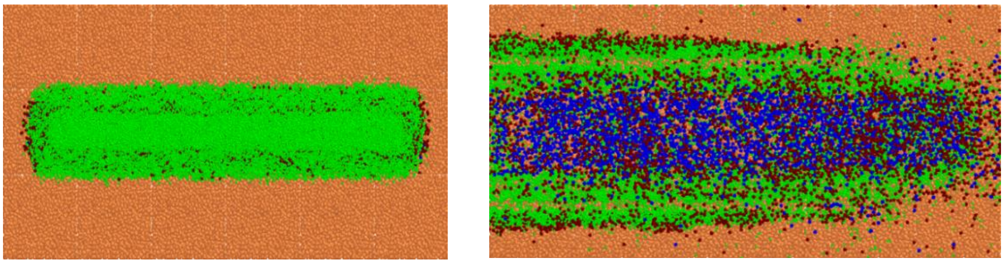
It can be seen from the data in Table 4 that the speed of potato movement has two sharp increases, which are the moment when the potato touches the lifting chain and the moment when it touches the conveyor chain. This is caused by the impact generated by the potato contacting them. When the potato touches the elevator chain, the speed of the potato will increase sharply to about 4 m/s, and then it will drop to the line speed of the lifting chain about 1.5 m/s, and the potato will continue to be lifted. When the potato is in contact with the conveyor chain, the speed of the potato gradually increases from 1.5 m/s to 2.7 m/s, and then decreases to the linear speed of the conveyor chain. Then, under the conveying chain, the potato particles slide down from the end of the conveyor chain until on the ground, the speed drops to 0 m/s.

Analysis of potato particle velocity changes can be concluded:

(1) The conveyor chain added at the back end of the lifting chain can reduce the landing speed of potato particles and reduce the damage to the potato skin; (2) In the process of potato soil separation and transportation, potato particles are impacted and rubbed many times, which is directly related to the linear velocity of the lifting chain, which ensures the good separation of potato soil, and reduces the linear velocity of the lifting chain is helpful to reduce the impact effect of potato; (3) The speed of potato on the conveying chain fluctuates, but the fluctuation times and frequency are small. The combination of straight rod and curved rod can effectively reduce the impact and rolling friction of potato on the conveying chain.

3. Analysis on the Change of Position Distribution before and after Soil Particle Digging

The location distribution of soil particles before and after digging is shown in Fig. 21.



before **after**

Fig. 21 - Location distribution of soil particles digging

According to Fig.21, after digging the soil ridge, most of the soil particles are distributed in a certain regularity. Due to the propulsion of the digging device, the loose soil particles on the surface layer slowly move to both sides; Most of the soil particles are located in the middle of the digging track of the digging device. Since the bulk density of the middle soil and the bottom soil is larger than that of the surface soil, the lifting chain bears a larger load during the transportation process. Therefore, it can be appropriately used to ensure normal digging. In this case, reduce the digging depth, thereby reducing the working load of the lifting chain.

4. Analysis of Potential Energy Change in Soil Particle Digging

The analysis of potential energy changes during soil particle digging is shown in Fig.22.

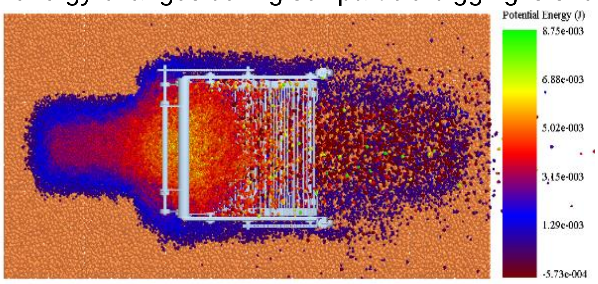


Fig. 22 - Location distribution of soil particles digging

During the process of digging potatoes by the digging device, the overall potential energy of the soil particles changes in a 'T' shape. The maximum potential energy of the soil particles is 8.75×10^3 J, and the minimum potential energy is -5.73×10^4 J. The potential energy of the soil particles in contact with the working parts of the digging device and the soil particles in the middle of the planting ridge along the forward direction of the digging device vary greatly. The potential energy of the soil particles above the working parts of the digging device presents a "circular" shape. The soil particles located in the center above the digging shovel and the vibrating shovel have the largest potential energy, and the potential energy changes in the range of 5.02×10^3~6.88×10^3 J. The surrounding soil includes: the potential energy of the soil at the front end of the lift chain, the soil between the two side plates and the surface soil particles varies in the range of 3.15×10^3 to 5.02×10^3 J. The potential energy of soil particles in the middle of the planting ridge along the forward direction is greater than that on both sides of the ridge. The potential energy of soil particles on both sides of the ridge is maintained at about 1.29×10^3 J, and the potential energy of soil particles in the middle of the ridge is maintained at about 3.15×10^3 J. The analysis shows that the soil particles in the forward direction are propelled by the digging device, and the potential energy of the soil particles in the middle increases.

The following conclusions can be drawn from the digging of potato soil potential energy:

(1) The potential energy of the soil particles on the potato planting ridge gradually increases from the periphery to the middle of the ridge, and the soil particles gradually move to the surrounding to prevent clogging.

(2) Under the traction of the tractor, the soil particles in the front middle of the digging device are pushed by the digging device. The greater the digging depth, the greater the shovel force required by the soil particles, and the greater the power loss of the digging device. Properly controlling the digging depth of the digging device is the key factor to reduce resistance.

5. Wear analysis of excavating equipment

The digging device is in close contact with soil particles during the digging process, and the digging parts will cause surface wear when working for a long time. It can be analyzed by investigating the pressure of the digging parts during the digging process. The force distribution of the digging parts during the digging process is shown in Fig.23.

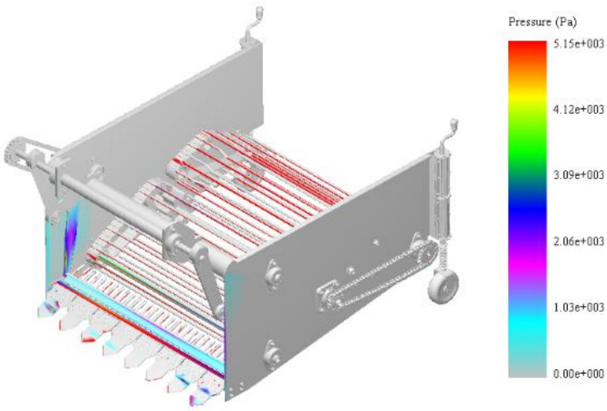


Fig. 23 - Force Wear Distribution of Excavator

During the digging process, each digging component will produce some wear, but the degree of wear is not uniform. The main worn parts of the shovel are at the junction of the shovel tip, the blade and the curve of the shovel surface. The most worn part is subjected to a pressure of 5150.24 Pa. Among them, the tip of the shovel is severely worn. The wear of the digging shovel in the middle is more serious than that of the shovel on both sides. The abrasion effect of the curve connection of the shovel surface is greater.

The analysis shows that due to the change of the curve curvature, the friction of the soil particles on the joints is increased, and the abrasion of the excavating shovel is increased. The wear of the digging shovel shaft is mainly concentrated in the middle, and the pressure range is between 2000-5000 Pa. Long-term wear is easy to cause deformation of the shaft and affect the assembly accuracy between the digging shovel. The chain rods of the rear lift chain are subject to wear, and the pressure range is between 5000-5100 Pa. The wear makes the lift chain thinner and reduces the stability of the lift chain. The pressure range of the two side plates of the digging device is between 500-800 Pa.

CONCLUSIONS

(1) A digging device of potato harvester is designed. The force analysis is carried out on the digging shovel. The relationship between the inclination angle of the digging shovel and the power consumption under different digging speed, digging depth and soil bulk density was analyzed by MATLAB software, and the mathematical models of the three were established.

(2) According to the structure size of potato digging device, the 3D model of key parts and frame of digging device is created by SolidWorks, and the complete potato digging device model is assembled. Using the discrete element analysis method, DEM software was used to create soil particles and potato particles, build a simulation model of potato planting ridges, and conduct simulation experiments for potato digging. the position change, velocity change, soil particle position change, potential energy change and the wear of the digging device before and after the potato particle digging were analyzed. The simulation results show that when the working speed of the digging device is 1 m/s, the digging depth is about 170 mm and the linear speed of the lifting chain is 1.5 m/s, the potato's exposed potato rate is 87.3%, which meets the requirements of potato harvesting operations.

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