DEM-based parameter optimization and tests of digging green onions

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Abstract: In view of the problems of easy damage and high digging resistance in the process of green onion harvesting, a mechanical model of digging green onions was established by taking the moment of digging and drawing green onions as the research object, and the main factors affecting the digging and harvesting effect were determined as the angle of digging, the dip angle of clamping carrier and the length of shovel. Thus, a complex simulation model of soil-green onion-digging mechanism system reflecting the state of harvesting was established, and the model was verified by testing soil compactness. The simulation tests were carried out by means of the complex simulation model of soil-green onion-digging mechanism system, making it clear that digging angle and the length of shovel have a extremely significant impact on the digging resistance, and the dip angle of the clamping carrier had a significant impact on the digging resistance. Through target optimization, the optimal combination of digging parameters was obtained, namely, the digging angle of 20°, the dip angle of clamping carrier of 25° and the shovel length of 70 mm, with the digging resistance of 1394 N at this moment. The field digging resistance test has showed that the average digging resistance is 1543 N with the average clamping damage rate of 1.27% and the average clamping loss rate of 0.44%, which can meet the requirements of green onion harvesting.

Keywords: harvesting, clamping force, digging resistance, discrete element method (DEM), simulation model, green onions
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1 Introduction

Both the output and export of Chinese green onions rank first in the world. However, due to the backward mechanized technology and equipment of green onion harvesting, easy damage in clamping, large digging resistance and other problems exist, which restricts the standardized production of green onions and the improvement of cropping economic benefits[1]. It is of great significance to explore the mechanized harvesting structure of green onions, so as to realize the smooth digging and orderly conveying of green onions.

Developed countries have adopted advanced design technologies such as virtual assembly and simulation analysis to shorten the design cycle of agricultural equipment and achieved the combine harvesting of green onions[2,3]. However, due to the differences in varieties and cropping patterns, mature technologies and equipment have not been widely promoted and applied in China. On the basis of referring to the relevant harvesting technologies and models abroad, China has developed harvesting implements mainly characterized by plough-shovel type, cutter-disc type and combined type digging devices, but they can only complete simple digging of green onions, and have not yet broken through the key technologies of combined harvesting of green onion[4-9].

DEM (Discrete element method) is widely used in the study of agricultural machinery system to obtain appropriate digging mechanism and structural parameters. Conducted DEM simulation parameter calibration on peanut seed particles[10-12], and conducted simulation experiment for mechanical peanut seed-metering device[13], which could represent the actual sowing operation. Peng Caiwang et al. used the discrete element method to model the organic fertilizer of pig manure treated by the black water fly[14], and there was little difference between the established model and the actual material properties. Conducted discrete element calibration on key parameters and contact model of farmland soil particles in arid region of northwest China[15], and conducted digging resistance simulation test. The test results showed that the change rule of digging resistance was basically consistent with the actual digging resistance. Carried out an experimental study on the seed picking and cleaning process of garlic seed picking device through DEM[16].

Therefore, with the help of discrete element method (DEM), the digging moment after the stabilization of green onion clamping was selected as the research object, and the main influencing factors of green onion harvesting were explored through the analysis of the digging process and research of the digging resistance. By means of both simulation test and field test, the interaction among soil, digging device and green onions in the process of green onion harvesting was explored and the appropriate combination of digging parameters was sought, which could provide theoretical basis for the realization of low resistance and low loss harvesting of green onions.

2 Experiment materials and methods

2.1 Digging device

The harvesting device of green onions is shown in Figure 1, which is mainly composed of digging device and clamping device. During harvesting, guide wheels are located on both sides of green onion ridge to prevent deviation of the implements. The angle of digging into the soil can be controlled by the regulating cylinder to realize the adjustment of digging depth. The rotary cutter separates the soil on both sides of the green onion ridge, and the digging shovel cuts the bottom of the green onions to realize the initial

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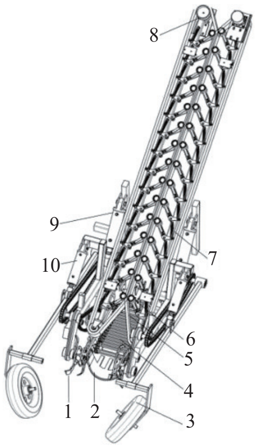
lifting of them. The V-shaped feeding inlet structure of the clamping carrier can effectively avoid the congestion during green onion feeding. The tensioning spring adjusts the tensioning force of clamping carrier made of the flexible sponge, effectively reducing the damage in green onion clamping.



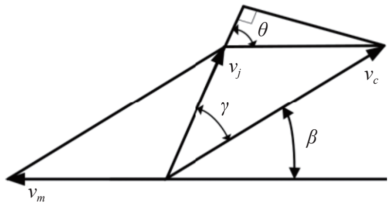
1. Rotary cutter 2. Digging shovel 3. Guide wheel 4. Rod conveying chain 5. Clamping carrier 6. Tensioning wheel 7. Tensioning spring 8. Hydraulic motor 9. Cylinders for regulating guide wheels 10. Cylinders for regulating digging device

Figure 1 Structure diagram of harvesting device

Only the effective cooperation of digging shovel and clamping carrier can ensure the smooth digging of soil and orderly conveying of green onions.

2.2 Green onion movement and digging resistance

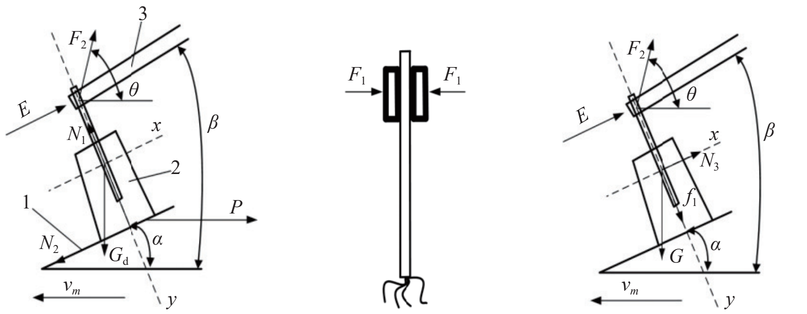
Assuming that the position of green onions and the clamping carrier are stable at the same velocity, the drawing force F2 and VJ of green onions from the clamping carrier are in the same direction. The velocity of the clamping carrier is shown in Figure 2.



Note: v_m is the forward velocity of the implement, m/s; v_c is the conveying velocity of the clamping carrier, m/s; β is the angle of the clamping carrier, (°); v_j is the absolute velocity of green onions, m/s; γ is the angle between the absolute velocity of green onions and the velocity of clamping carrier, (°); θ is the drawing angle, (°).

Figure 2 Velocity decomposition of clamping carrier

The green onions and soil furrow are regarded as excavations and the coordinate system shown in Figure 3 is established.



a. Stress analysis of excavations b. E-direction view c. Stress analysis of green onions

1. Digging shovel 2. Soil furrow after digging 3. Clamping and conveying devices Note: α is the digging angle of digging shovel, (°); N_1 is the supporting force of the shovel against the furrow after digging, N; N_2 is the friction force of the shovel against the soil, N; G is the gravity of green onions, N; G_d is the furrow gravity after digging, N; N_3 is the supporting force of soil to green onions, N; F_1 is the friction between soil and green onions, N; P is the force required for the motion of soil, N; F_1 is the clamping force of green onions, N; F_2 is the digging force of green onions, N.

Figure 3 Stress analysis of the excavations

Equation (1) was established according to the force balance of the excavations.

$$\begin{cases} x: N_2 + G_d \cdot \sin\alpha = F_2 \cdot \cos(\theta-\alpha) + P \cdot \cos\alpha \\ y: G_d \cdot \cos\alpha + P \cdot \sin\alpha = F_2 \cdot \sin(\theta-\alpha) + N_1 \end{cases} \quad (1)$$

where, N_1 is the supporting force of the digging shovel to the excavations, N; N_2 is the friction force of the digging shovel against the excavations, N; G_d is the gravity of the excavations, N; P is the force of the excavations when moving along the shovel, N.

$$\begin{cases} F_2 = \mu_1 \cdot F_1 \\ N_2 = \mu_2 \cdot N_1 \\ G_d = G + g\rho \cdot (BhL - \pi R^2 h) \end{cases} \quad (2)$$

where, μ_1 is the static friction coefficient between the clamping carrier and green onions; μ_2 is the static friction coefficient between soil and digging shovel; G is the weight of green onions, kg; L is the shovel length, mm; ρ is the soil bulk density, g/cm³; B is the digging width, mm; H is the height of soil furrow after digging.

In the process of extraction, the separation moment of green onions and soil was studied for carrying out the stress analysis of green onions, as shown in Figure 3c, and the balance Equation (3) was established.

$$\begin{cases} x: F_2\cos(\theta-\alpha) + N_3 = G\sin\alpha \\ y: F_2\sin(\theta-\alpha) = G\cos\alpha + f_1 \\ f_1 = \mu_3 \cdot N_3 \end{cases} \quad (3)$$

where, N_3 is the supporting force of soil on green onions, N; F_1 is the friction between soil and green onions, N; μ_3 is static friction coefficient between soil and green onions. Equation (4) was obtained by simplifying Equation (3).

$$F_2 = \frac{G\cos\alpha + \mu_3 G\sin\alpha}{\sin(\theta-\alpha) + \mu_3\cos(\theta-\alpha)} = \mu_1 F_1 \quad (4)$$

Simultaneous simplification of Equations (1), (2) and (4) can be obtained as follows:

$$P = \frac{G(\mu_3\sin\alpha + \cos\alpha)[\mu_2\sin(\theta-\alpha) + \cos(\theta-\alpha)]}{[\sin(\theta-\alpha) + \mu_3\cos(\theta-\alpha)](\mu_2\sin\alpha - \cos\alpha)} \\ \frac{[G + g\rho(BhL - \pi R^2 h)](\sin\alpha + \mu_2\cos\alpha)}{\mu_2\sin\alpha - \cos\alpha} \quad (5)$$

According to Equation (5), when the type of soil and green onions is determined, the parameters of soil bulk density ρ, friction coefficient μ_1 between green onions and clamping carrier, friction coefficient μ_2 between green onions and soil, and friction coefficient μ_3 between green onions and soil are basically determined. The force P of soil furrow moving along the shovel is mainly affected by the digging angle, the shovel length L, and the drawing angle θ. According to experience, the angle γ is 10°-20°[17], so the angle θ can be achieved by adjusting the clamping angle. The working resistance of the digging shovel mainly consists of the resistance caused by the movement of the shovel moving the soil furrow and the resistance caused by separating the soil[18-21]. The digging resistance should meet the requirements of

$$R = P + kA_s \tag{6}$$

where, R is digging resistance, N; A_s is the cross-sectional area of the dug-up furrows, mm²; K is the specific resistance coefficient of digging the furrows, N/dm².

3 Simulation model of soil-green onion-digging mechanism system

3.1 Determination of soil physical properties

Five test regions were randomly selected in the green onion planting area, and the test was repeated for 10 times to determine the soil parameters. According to GB7833-1987[22], soil moisture content was measured, cutting-ring method[23] was adopted to measure soil bulk density, and soil compactness meter was used to measure soil compactness. The specific results are listed in Table 1.

Table 1 Parameters of soil physical properties

Value	Moisture content /%	Bulk density/ g·cm⁻³	Compactness/ MPa
Maximum	21.99	1.78	1.40
Minimum	14.37	1.11	0.71
Average	17.45	1.36	1.13
Standard deviation	2.24	0.21	0.20
Coefficient of variation	0.13	0.16	0.17

As can be seen from Table 1, soil moisture content is (17.45±6.72)%, bulk density is (1.36±0.63) g/cm³, and compactness is (1.13±0.6) MPa.

3.2 Determination of physical and mechanical properties of green onion

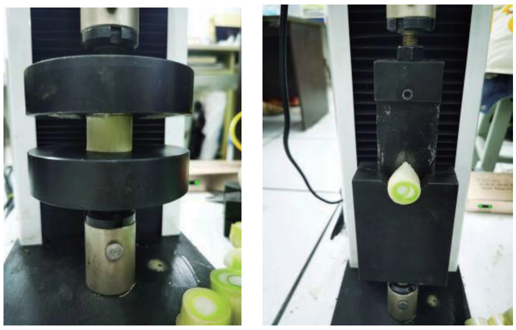
The physical property indexes of scallions in harvest were measured, and the measurement results are shown in Table 2.

Table 2 Physical property indicators of green onion

Value	Green onions white diameter/mm	Green onion white long/mm	Plant height/ mm	Individual weight/g	Moisture content/%
Maximum	35.00	495.0	1260.0	349.40	85
Minimum	18.00	320.0	840.0	138.80	91
Average	25.05	406.1	999.1	222.35	87.68
Standard deviation	2.81	3.64	8.40	46.21	1.79
Coefficient of variation	0.11	0.08	0.08	0.20	0.20

It can be seen from Table 2 that Green onions white diameter in harvest period is (25.05±2.81) mm, Green onion white long is (406.1±3.64) mm, Plant height is (999.1±8.04) mm, and Individual weight of a single plant is (222.35±46.21) g; The Moisture content is (87.68±1.79)%. Green onion as a living body is easily affected by environmental factors, which results in a large coefficient of variation of the weight of single onion plant.

The mechanical property indexes of Green onions in harvest period were measured by GHS2000 microcomputer controlled electronic universal testing machine as shown in Figure 4, and the measurement results are listed in Table 3 and Table 4.



a. Compressive strength test b. Shear strength test

Figure 4 Mechanical characteristic test of green onion

Table 3 Compression test and test results

Position	Data indicators	Maximum force/N	Compressive strength/MPa	Elastic modulus/MPa
Upper	Maximum	188.00	0.40	2.99
	Minimum	74.00	0.17	1.35
	Average	128.10	0.30	2.40
	Standard deviation	33.90	0.09	0.49
	Coefficient of variation	0.26	0.30	0.21
middle	Maximum	175.00	0.49	3.59
	Minimum	61.00	0.11	1.92
	Average	102.02	0.29	2.35
	Standard deviation	37.24	0.09	0.49
	Coefficient of variation	0.37	0.31	0.21
lower	Maximum	178.20	0.44	2.92
	Minimum	60.00	0.16	2.19
	Average	105.52	0.31	2.62
	Standard deviation	36.23	0.10	0.26
	Coefficient of variation	0.34	0.32	0.10

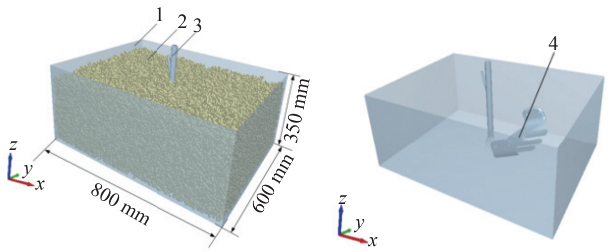
Table 4 Shear test results

Position	Data indicators	Maximum force/N	Maximum shear force/MPa	Elastic modulus/MPa
Upper	Maximum	78.00	0.185	78.00
	Minimum	39.00	0.07	39.00
	Average	56.17	0.10	56.17
	Standard deviation	11.03	0.02	11.03
	Coefficient of variation	0.20	0.20	0.20
Middle	Maximum	53.00	0.185	53.00
	Minimum	35.00	0.06	35.00
	Average	44.50	0.08	44.50
	Standard deviation	4.92	0.01	4.92
	Coefficient of variation	0.11	0.125	0.11
Lower	Maximum	59.00	0.205	59.00
	Minimum	40.00	0.07	40.00
	Average	48.50	0.09	48.50
	Standard deviation	5.71	0.01	5.71
	Coefficient of variation	0.12	0.11	0.12

It can be seen from Tables 3 and 4 that there is little difference in the compressive strength and elastic modulus of the upper, middle and lower parts of scallion; The middle part of spring onion is easy to crush; The growth characteristics of scallions lead to different tissue structures among different parts of scallions, so the maximum stress difference of each part is more obvious. In the shear test, the middle part of the scallion is easy to be damaged, and the shear properties of the upper part and the lower part are similar.

3.3 Geometric model construction of green onion and digging device

According to the size measurement of green onions, the diameter of green onion was (25.05±8.43) mm, the length from green onion neck to green onion root was (406.1±109.2) mm, the length of green onion root was 50-80 mm, and the diameter of green onion root was 1 mm. Solidworks was used to carry out 3d modeling of green onions, and EDEM simulation software was imported through Geomety command. Based on the actual furrow width of green onion planting and the appropriate row spacing of green onion harvester, EDEM simulation soil bin was established, as shown in Figure 5.



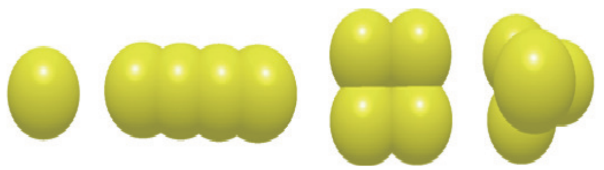
a. Complex model of green onion-soil-digging shovel   b. Geometric model of digging shovel

1. Soil-bin 2. Soil particles 3. Geometric model of green onions 4. Geometric model of digging shovel

Figure 5 Complex simulation model of soil-green onion-digging mechanism system

3.4 Simulation model of soil particles

The soil particle radius was set to 5mm, and different types of soil particles were established by EDEM[24,25]. The soil was established with spherical block, columnar, massive, and nuclear particles as shown in Figure 6.



a. Spherical particles   b. Columnar particles   c. Massive particles   d. Nuclear-shaped particles

Figure 6 Soil particle model

The value range of the necessary parameters of discrete element simulation was determined through the actual soil test, mechanical properties test of green onions and parameter references[26-30], as listed in Table 5.

3.5 Contact model setting

In order to ensure the accuracy of simulation results, the contact model between green onions and soil particles and between soil and soil particles was set as Hertz-Mindlin with Bonding model[31-34]. When the normal and tangential stresses exceeded the predefined values, the bond broke, i.e

$$\sigma_{\max} < \frac{-F_n}{A} + \frac{2M_t}{J}R_B \tag{7}$$

Table 5 Parameters of discrete element simulation model

Parameter	Value
Soil trough size (length×width×height)/mm×mm×mm	800×600×350
Excavation depth/mm	250
Soil particle density/kg·m^{-3}	1360
Poisson's ratio of soil	0.40
Soil shear modulus/MPa	1
Coefficient of restitution between soil particles	0.60
Static friction coefficient between soil particles	0.45
Dynamic friction coefficient between soil particles	0.21
Poisson's ratio of scallion	0.30
Scallion density/kg·m^{-3}	800
Shear modulus of scallion/MPa	0.90
Coefficient of restitution between scallion and soil	0.40
Static friction coefficient between scallion and soil	0.30
Dynamic friction coefficient between scallion and soil	0.28
Recovery coefficient between soil and 65Mn	0.30
Static friction coefficient between soil and 65Mn	0.50
Dynamic friction coefficient between soil and 65Mn	0.05
Particle filling radius/mm	5
Simulation time/s	3.2

$$\tau_{\max} < \frac{-F_t}{A} + \frac{M_n}{J}R_B \tag{8}$$

where, $\sigma_{\max}$ is normal stress, N; $\tau_{\max}$ is tangential stress, N; A is the cross-sectional area of particles, m^2; F_n is the normal force for the particles, N; F_t is the tangential force for the particles, N; M_n is the normal moment for the particles, N/m; M_t is the tangential moment for the particles, N/m; J is moment for inertia of bonding pole. Determined the unit normal stiffness of 240 kN/m^2, unit tangential stiffness of 170 kN/m^2, normal critical stress of 17.5 kPa, tangential critical stress of 11.6 kPa, bond radius of 6 mm.

Soil particle model and cone-shaped model of soil compactness meter were established to conduct compactness test simulation, as shown in Figure 7.

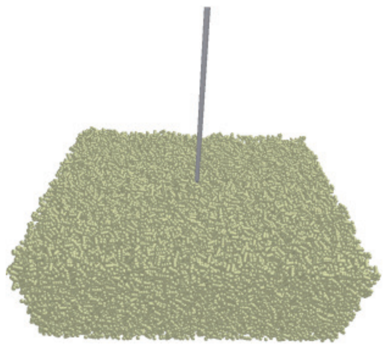


Figure 7 Simulation test of soil compactness

When the depth is 300 mm, the soil particle compactionness is 1.25 g/cm^3, and the actual soil compactionness is 1.36 g/cm^3. Thus, the error is 8%, which confirms that the established soil particle model is similar to the actual soil.

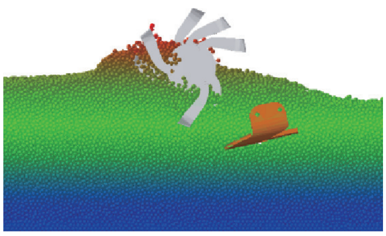
4 Simulation test of digging and harvesting

4.1 Test program and results

In the process of digging green onions, green onions were affected by soil and clamping carrier. Combined with the results of stress analysis of green onions, digging resistance indirectly affected the damage of green onions, which was the main index for the effect of green onion harvesting. Therefore, the digging angle of shovel, the length of the shovel and the inclination angle of the clamping carrier were determined as test factors, which were represented by x_1, x_2, x_3 respectively. Digging resistance was the test index, represented by y. In order to adapt to different soil types and operating conditions, the range of α value was determined as 20°-30° by referring to the range of commonly used digging angles[35-38]. According to the preliminary test, the range of digging shovel length was 40-200 mm, and the forward speed of the machine is 0.2 m/s. The dip angle of the clamping carrier was greater than the digging angle of the shovel. Affected by angle γ, the dip angle of the clamping carrier was 25°-40°. Design-Export 12 software was used to design simulation experiment of orthogonal combination of three factors and three levels with quadratic rotation. The factor and level coding is listed in Table 6. It simulation process at a certain time is shown in Figure 8. The test results are listed in Table 7.

Table 6 Factor and level coding table of digging resistance test

Code	Experimental factors		
	Angle of penetration x_1/(°)	Clamping belt inclination x_2/(°)	Length of shovel face x_3/mm
−1.682	17	20	43
−1	20	25	70
0	25	32.5	110
1	30	40	150
1.682	33	45	177



x_1=20°, x_2=25°, x_3=70 mm

Figure 8 Simulation process at a certain moment

Table 7 Scheme and results of digging resistance test

Serial number	Experimental factors			y/N
	x_1/(°)	x_2/(°)	x_3/mm	
1	30	40	150	1587
2	25	32.5	177	1527
3	25	32.5	110	1353
4	20	25	150	1163
5	25	32.5	110	1356
6	20	25	70	820
7	25	32.5	43	807
8	30	40	70	1086
9	30	25	150	1673
10	25	32.5	110	1352
11	25	32.5	110	1359
12	25	20	110	1139
13	30	25	70	989
14	25	32.5	110	1352
15	25	45	110	1381
16	25	32.5	110	1200
17	33	32.5	110	1519
18	20	40	150	1359
19	17	32.5	110	1139
20	20	40	70	1357

4.2 Establishment of regression equation and variance analysis

The test results were analyzed and fitted by multiple regression by means of Design-Expert 12 software, and multiple regression quadratic equations of digging shovel angle, clamping angle, shovel length and digging resistance were obtained:

$$y = 1328.50 + 94.32x_1 + 85.23x_2 + 201.65x_3 - 91.88x_1x_2 + 103.37x_1x_3 - 67.13x_2x_3 + 1.23x_1^2 - 23.16x_2^2 - 56.04x_3^2 \quad (9)$$

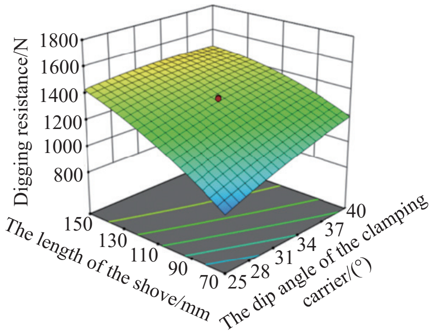
The variance analysis is listed in Table 8. The p value of y model of digging resistance is less than 0.0001, indicating that the model is effective. The p values of digging angle x_1 and shovel length x_3 on digging resistance are both less than 0.0001, indicating that digging angle has a significant effect on digging resistance. The p value of dip angle x_2 of the clamping carrier on the digging resistance is less than 0.05, indicating that the digging angle has a significant impact on digging resistance. It can be seen from the F value that the impact of digging angle x_1, dip angle x_2 of the clamping carrier and shovel length x_3 on digging resistance is in a descending order of x_3, x_1, x_2.

Table 8 Analysis of variance

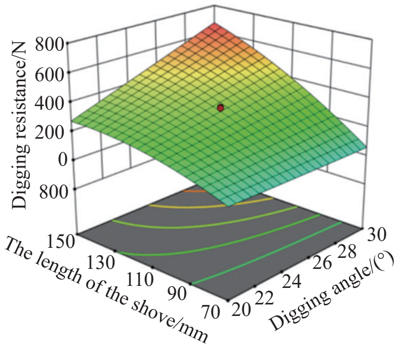
Source	Digging resistance d/N			
	Sum of squares	Mean square	F	p
Model	1.004×10^6	1.116×10^5	37.08	<0.0001
x_1	1.190×105	$1.190\cdot10^5$	39.58	<0.0001
x_2	97 005.27	97 005.27	32.25	0.0002
x_3	5.501×10^5	5.501×10^5	182.87	<0.0001
x_1x_2	65 160.50	65 160.50	21.66	0.0009
x_1x_3	88 200.00	88 200.00	29.32	0.0003
x_2x_3	34 322.00	34 322.00	11.41	0.0070
x_1^2	35.71	35.71	0.0119	0.9154
x_2^2	7505.46	7505.46	2.50	0.1453
x_3^2	44 713.46	44 713.46	14.86	0.0032
Residual error	30 081.53	3008.15		
Misfit term	10 178.20	2035.64	0.5114	0.7603
Pure error	19 903.33	3980.67		
Total difference	1.034×10^6			

4.3 Analysis of the influence law of interaction terms on test indexes

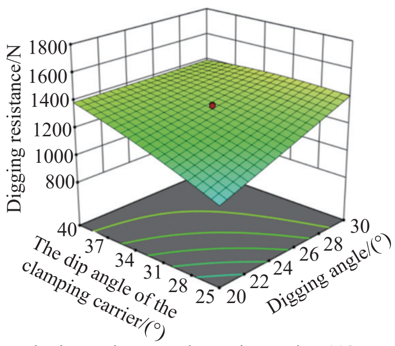
The response surface is shown in Figure 9. It can be seen from Figure 9a that when the digging angle is centrally horizontal, that is, when the digging angle is equal to 25°, the digging resistance can be effectively reduced by reducing the length of the shovel surface and the dip angle of the clamping carrier. It can be seen from Figure 9b, when the dip angle of the clamping carrier is centrally horizontal, that is, when the dip angle of the clamping carrier is 32.5°, the digging resistance can be reduced by decreasing the digging angle and the length of the shovel surface. It can be seen from Figure 9c that when the length of the shovel surface is centrally horizontal, that is, when the length of the shovel surface is 110 mm, the digging resistance should be reduced by decreasing the digging angle and the dip angle of the clamping carrier. By analyzing the response surface of each interaction factor to digging resistance, it can be determined that the smaller the digging angle and the dip angle of clamping carrier, the shorter the length of shovel surface, the smaller the digging resistance.



a. Digging resistance when x_1 is equal to 25°



b. Digging resistance when x_2 is equal to 32.5°



c. Digging resistance when x_3 is equal to 110mm

Figure 9 Influence response surface of test factors on test indexes

4.4 Parameter optimization

As the average weight of single plant of green onion is 0.3 kg, the minimum digging and pulling force of green onion was determined to be 3 N. According to the surface tensile test, the maximum pulling force of the first epidermis in the middle of green onion was 33N, thus, the maximum digging and pulling force of green onion was determined to be 33 N. Objective optimization was carried out by nonlinear programming to find out the optimal combination parameters for digging. The objective function and constraint conditions were as follows:

$$\min y = f(x_1, x_2, x_3)$$

$$\text{s.t.}\begin{cases} 20 \le x_1 \le 30 \\ 20 \le x_2 \le 40 \\ 70 \le x_3 \le 150 \\ 3 \le \dfrac{G\cos x_1 + \mu_3 G\sin x_1}{\sin(x_2+10-x_1) + \mu_3\cos(x_2+10-x_1)} \le 33 \end{cases} \tag{10}$$

Matlab software was used to optimize the parameters as follows: the digging angle was 20°, the dip angle of clamping carrier was 25°, the shovel surface length is 70 mm, with the digging resistance of 1394N.

5 Field tests

5.1 instrument and equipment

Relying on the 4CL-1 self-moving combine harvester of green onions, the tension-compression sensor (range of 0-10000 N, accuracy of 0.1 N) was used to conduct the digging resistance test, and data was collected with data acquisition card, as shown in Figure 10.

Figure 10 Field test of digging resistance

The data acquisition system is mainly composed of computer, 8-channel data acquisition card, BSQ-2 transmitter and tension-compression sensor. The positive pole of the power supply of BSQ-2 transmitter is connected with the positive pole of 24 V DC power supply, and the negative pole of the power supply of BSQ-2 transmitter is connected with the negative pole of 24 V DC power supply; "Signal +" of BSQ-2 transmitter is connected to channel 1 and channel 2 of 8-channel data acquisition card respectively, and "Signal –" of BSQ-2 transmitter is connected to "Signal –" of 8-channel data acquisition card. After completing the above wiring, connect the BSQ-2 transmitter to the pull pressure sensor. At the same time, it is connected with the computer through the signal line to complete the specific wiring, as shown in Figure 11.

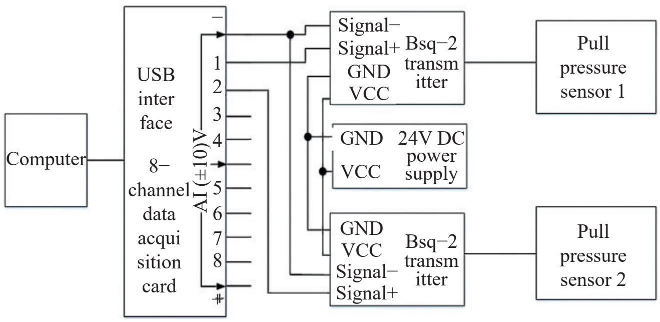


Figure 11 Wiring diagram of data acquisition system

5.2 Test indexes

According to the optimization results of the simulation test, the test was conducted under the conditions of digging angle of 20°, clamping carrier angle of 25° and shovel length of 70 mm. The damage rate, loss rate and digging resistance of green onions were obtained by randomly selecting 5-6 furrows and 5 m distance of green onions in each furrow for the test.

1) Damage rate

$$F_1 = \frac{N_1}{M} \times 100\% \tag{11}$$

where, F_2 is damage rate, %; N_1 is the number of damaged plants; M is the total number of clamped plants.

2) Loss rate

$$F_2 = \frac{M - N_2}{M} \times 100\% \tag{12}$$

where, F_2 is loss rate, %; N_2 is the number of harvest.

5.3 Test results and analysis

The digging and clamping process of green onions is shown in Figure 12. A total of 5 groups of tests were conducted, and the specific results are shown in Table 9. The rubbing injury occurred when the green onions were harvested into the clamping conveyor carrier was the main reason for the damage of green onions. The main reason for the loss of green onions was that the various growth of green onions caused the omitted clamping of the undergrown plants. The other reason was that the state of green onions changed during harvesting, resulting in unstable clamping.

Figure 12 Actual digging process

Table 9 Field test results

Test serial number	Damage rate/%	Loss rate/%	Digging resistance/N
1	1.50	0.50	1623
2	1.23	0.38	1543
3	1.15	0.43	1450
4	1.38	0.53	1472
5	1.07	0.35	1582
Maximum value	1.50	0.53	1623
Minimum value	1.07	0.35	1450
Average value	1.27	0.44	1534
Standard deviation	0.17	0.08	72.81
Variable coefficient	0.14	0.17	0.05

According to (Q/0781QHL01-2019 Enterprise Standard for Green Onion Harvester), the damage rate of spring onion should be less than 5.8%, and the loss rate should be less than 5%. It can be seen from Table 9, the damage rate of green onions was (1.27±0.17)%, the loss rate was (0.44±0.08)%, and the digging resistance was (1534±72.81) N, which met the requirements of green onion harvesting.

6 Conclusions

1) The optimal combination of excavation and drawing parameters is the key to low resistance and low loss harvest of green onions. Through the analysis of digging process and the construction of digging resistance model, it was determined that the digging angle, the dip angle of clamping carrier and the length of digging shovel were the key factors that affect the digging resistance of green onions.

2) Combined with the key parameters of soil and green onions, the complex simulation model of soil-green onion-digging mechanism system was established. Through the virtual simulation test of green onion digging and pulling process, multiple regression equations of the influence of digging angle, dip angle of clamping carrier and the length of digging shovel on digging resistance were obtained. The influence degree of each factor on digging resistance was determined, and the order of influence from large to small is the length of digging shovel, digging angle and dip angle of clamping carrier. Matlab software was used to determine the optimal combination of digging parameters: the digging angle is 20°, the angle of clamping carrier is 25°, and the length of digging shovel is 70 mm.

3) Field tests were carried out to verify the harvesting effect of green onions under the optimal combination of digging parameters. The test results showed that the average value of digging resistance was 1534 N, the average damage rate of green onions was 1.27%, and the average loss rate of green onions was 0.44%, which met the requirements of green onion harvesting.

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