Mechanical properties analysis and experiment on Multi-order excavation shovel of Ophiopogon japonicas harvester

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Abstract. Aiming at the poor soil crushing capacity and low operating efficiency of the Ophiopogon harvester, reference to potato, panax notoginseng and other block root excavation device. Based on the soil crushing theory, mechanical analysis of the excavation shovel was performed, and the multi-order excavation shovel of Ophiopogon japonicas harvester was designed. Through ANSYS Workbench Mechanical properties analysis of the excavation shovel, obtained the inclination stress-strain cloud map of soil inlet angle and shovel surface. Combined with the stress-strain results, production suggestions were proposed. Binary regression analysis, response surface analysis and reoptimization design of mining parameters were conducted through field test and Design-Expert 12 software. Test results show that when the inlet angle was 25 °, inclination angle was 170 °, tool forward speed was 0.35m/s, Harvest rate was 98.37% and damage rate was 1.35%, ophiopogon japonicas Harvest worked efficiency. Meet the relevant operating requirements of Ophiopogon japonicus harvester.

1. Introduction

Ophiopogon japonicas is a well-known authentic Chinese medicinal material at home and abroad, and it is also one of the 50 basic medicinal materials in the National Pharmacopoeia of my country. my country is rich in Ophiopogon resources. Over 70% of Ophiopogon japonicus is produced in Santai County, Sichuan. Santai County has a long history of Ophiopogon japonicus planting. The annual planting area is more than 2667hm², which is known as the "Hometown of Ophiopogon japonicas in China"[1-2]. Compared with other rhizome plants, Ophiopogon japonicus has a deeper growth depth and special soil composition. Therefore, the shovel body needs to consume a lot of power when working, and it is difficult to dig. This has the basic design parameters of the shovel body, such as entering the soil. Angle, shovel surface inclination and mechanical properties of shovel body put forward higher design requirements.

Scholars at home and abroad have conducted a lot of researches on the drag reduction, confined soil, broken soil and mechanical properties of various excavating shovel. In order to better study the influencing factors of excavation resistance, Hu Xiong, Wenfei Song [3] used discrete element simulation software EDEM to carry out numerical simulation and experimental verification on the excavation resistance of bucket wheel stackers when excavating materials of different shapes. The shovel surface structure under the best digging resistance; Zhang Zhaoqiong,Zhang Yongcheng [4-5] used ANSYS finite element simulation software to study the stress, strain and deformation theory of the digging system of the notoginseng harvester. After field tests, the digging system was improved to meet the application requirements of the notoginseng harvester; Lang Chongchong, Xu Lulu [6] aimed at the problems of
large digging resistance, poor soil performance and viscosity reduction of the existing panax notoginseng seedling shovel, through ANSYS, DEDM simulation and experimental analysis, they found that the bionic digging resistance is smaller than that of a flat shovel. 18.78%, the average rolling angular velocity of soil particles during operation is 27.13% higher than that of a flat shovel, and it has a better viscosity reduction effect; Wang Tao and Liao Yulan \[7\] designed a multi-stage digging shovel and compared it with ordinary flat shovel towing resistance. They found that the inclination angle of 30° is more reasonable. At this time, the traction resistance is reduced by 6.93%, which is the next step for cassava. The design of digging shovel for harvesting machinery provides a basis.

From the research status of domestic and foreign scholars, relevant researches have been carried out on the various performances of excavating shovel, but the research on the excavating shovel of Ophiopogon japonicus harvesting machinery is indeed rarely reported. In this paper, the basic structure design of the shovel of the Ophiopogon japonicus harvester is carried out, and the parameters such as the angle of entry, the width, thickness, length and the inclination of the shovel surface of the multi-level curved shovel are determined, and a three-dimensional model is established by Solidwork; Analyze the mechanical characteristics of the excavating shovel through Ansys Workbench to determine that the stress and strain meet the design requirements; Finally, through the Design-Expert 12 optimization design software, the soil angle, shovel surface inclination and forward speed are used as test factors, and the obvious rate got and damage rate are used as the test targets for field tests. The response surface three-dimensional curve and regression fitting equation are established, and finally formed Optimize the plan to improve the mining efficiency, stability and reliability of the Ophiopogon japonicus harvester.

2. Multi-stage excavating shovel structure design

2.1. Design basis
Ophiopogon japonicus is a perennial herb, as shown in Figure 1, the plant height is 14-30cm, the average leaf length is 22.35cm, the rhizome is a mass-shaped rhizome, the average root length is 21.13cm, the average number of roots is 20.29, and the average root weight is 5.98g \[8-9\]. The growth depth of Ophiopogon japonicus is between 10cm-20cm, the growth soil texture is loam, the water content is 20%-40%, and the soil firmness is about 900kPa.

![Figure 1. Ophiopogon seedlings](image)

2.2. Design of shovel surface
The traditional digging shovel for Ophiopogon japonicus is a first-order triangular digging shovel, which makes full contact with the soil after cutting into the soil. Not only does it have high resistance, but the soil is easy to adhere, resulting in poor soil crushing ability. In this paper, considering various factors such as soil penetration performance, soil crushing ability, stress and strain, etc., a multi-stage excavating shovel for the Ophiopogon japonicus harvester is proposed, that is, on the basis of the first-order inclination angle of the triangular plane shovel, an inclination plane is added, and Combined with the soil crushing performance of the convex shovel, the soil pressure is dispersed, the soil adhesion is reduced, and the work performance of the digging shovel is improved\[10-11\].

The multi-stage excavating shovel model is shown in Figure 2 below.

![Figure 2. Three-dimensional model of multi-stage excavating shovel](image)

1. Front end crushing plowshare (left side panel)
2. Front end crushing plowshare (right side panel)
3. Lower shovel plate
4. Shovel tip

2.3. Parameter determination

According to the research of domestic and foreign scholars, the structural parameters that affect the performance of excavating shovel mainly include soil entry angle, digging depth, shovel face inclination, shovel face width, etc. Under the condition that the obvious rate got and damage rate of Ophiopogon japonicus are qualified, the above parameters are designed.

2.3.1. Angle of entry and inclination of shovel face

Since the force analysis and mechanical characteristics of multi-stage excavating shovel are affected by many factors and the degree of complexity is relatively high, this paper introduces virtual theoretical shovel surface for force analysis. The force diagram is shown in Figure 3 below:

![Figure 3. Force analysis of digging shovel](image)

The force analysis of the shovel of the Ophiopogon japonicus harvester obtains the following formula:

\[
\begin{align*}
P \cos \alpha - \mu N_0 - C_a A_0 - B \cos(\beta + \alpha) - G \sin \alpha - K_\theta &= 0 \\
N_0 - G \cos \alpha - P \sin \alpha - B \sin(\beta + \alpha) &= 0
\end{align*}
\]  

among them:
- \(P\) —— The driving force of the shovel, \(N\);
- \(N_0\) —— Digging shovel normal load, \(N\);
- \(G\) —— Soil gravity of shovel shovel surface, \(N\);
Due to the slow running speed of the Ophiopogon japonicus harvester and the sharper blade of the excavating shovel, under the condition of loamy soil, ignoring acceleration resistance $B$, cutting resistance $C_a A_0$ and soil shearing force $T$, the following formula is given:

$$
\alpha = \arctan \frac{P - \mu G}{\mu P + G}
$$

Scholars have studied [14-16] that the size of the entry angle has a greater impact on the performance of the excavating shovel. When the entry angle is designed between 20°-50°, the resistance of the excavating shovel is within a reasonable range, which is too large or excessive. A small amount will cause the performance of the excavating shovel to decrease. This paper obtains the optimal soil inclination angle of the multi-stage excavating shovel of the Ophiopogon japonicus harvester through mechanical performance analysis and test response surface analysis.

The inclination angle of the shovel will affect the mechanical properties, soil performance, obvious rate got and damage rate of Ophiopogon japonicus seedlings during the excavation process. In the next section, this article will use the inclination angles of the shovel to be 160°, 165°, 170° and 175°. Perform finite element mechanical analysis for 10°, 20°, 30° and 40° in order to determine the stress and strain under the combination of shovel face inclination angle and soil entry angle.

2.3.2. Digging depth and shovel width
Since the growth depth of Ophiopogon japonicus is between 10cm-20cm, in order to ensure the obvious rate got of Ophiopogon japonicus and reduce the mechanical power consumed by digging, the digging depth of Ophiopogon japonicus is defined as 20cm.

According to Ophiopogon japonicus planting agronomy, the plant spacing of Ophiopogon japonicus is 6.0-7.5cm, the row spacing is 8.0-10.0cm, the average root length of Ophiopogon japonicus is 21.13cm, and the average number of roots is 20.29. Under the premise of ensuring that the fast roots of Ophiopogon japonicus are as complete as possible during the harvesting operation, the damage rate and the soil condition should also be reduced. The design shovel width is 100cm.

2.3.3. Analysis of soil stress on the shovel
The digging shovel of Ophiopogon japonicus is subjected to a variety of forces during the excavation process, and the force analysis is carried out. The force diagram is shown in Figure 4 below [17-18].
The traction force equation is obtained from the force diagram above:

\[ W = N_0 (\sin \alpha + \mu \cos \alpha) + C_s A_0 \cos \alpha \]  

(3)

The force analysis on the excavated soil is used to obtain the force balance equations on the x and y axes as follows:

\[
\begin{align*}
N_0 (\sin \alpha + \mu \cos \alpha) - N_1 (\sin \beta + \mu \cos \beta) - (T + B) \cos \beta &= 0 \\
G - N_0 (\cos \alpha - \mu \sin \alpha) - N_1 (\cos \beta + \mu \sin \beta) + (T + B) \sin \beta &= 0
\end{align*}
\]  

(4)

among them:

- \( G \) — The gravity of the soil on the shovel surface of the digging shovel, \( N_0 \);
- \( T \) — Soil shear resistance, \( N_1 \);
- \( \mu_1 \) — Soil internal friction factor;
- \( \mu \) — The internal friction factor of soil and metal;
- \( N_1 \) — Normal load of soil, \( N_1 \);
- \( \beta \) — Effective front angle of soil.

The formula is:

\[ Q = \frac{\cos \alpha - \mu \sin \alpha}{\sin \alpha + \mu \cos \alpha} + \frac{\cos \beta - \mu_1 \sin \beta}{\sin \beta + \mu_1 \cos \beta} \]  

(5)

Combining the above equations (3), (4), and (5), the working parameters of the shovel of the Ophiopogon japonicus harvester and the physical and mechanical properties of the soil establish a functional relationship with the horizontal force pushing the shovel to obtain the traction of the shovel in the soil. The mathematical model of resistance is \([19-20]\):

\[ W = \frac{G}{Q} + \frac{T + B}{Q(\sin \beta + \mu \cos \beta)} + \frac{C_s A_0}{Q(\sin \alpha + \mu \cos \alpha)} \]  

(6)

From the above force analysis, it can be seen that the friction and adhesion of the soil can neglect the force of the shovel relative to the normal force of the shovel surface. Therefore, the calculation and analysis of the normal force of the soil can be mainly carried out, and the traction force is used to calculate the normal force of the shovel surface. Finally, the pressure values of different entry angles and shovel surface inclination angles are obtained. The respective parameter values and corresponding pressure values are as follows, Table 1 and Table 2:

Table 1. Relevant parameter values of digging shovel

| parameter | Soil density (/kg×m\(^{-3}\)) | Friction factor in soil | Soil cohesion/Pa | Soil adhesion factors | Soil and metal friction factor |
|-----------|-----------------------------|------------------------|-----------------|-----------------------|-----------------------------|
| Numerical value | 1360 | 0.276 | 15855 | 2.2 | 0.7 |

Table 2. Pressure values of different entry angles and shovel surface inclination angles

| Entry angle | Shovel surface inclination (°) | Pressure (Pa) |
|-------------|-------------------------------|---------------|
| 10          | 160                           | 1114.424      |
|             | 165                           | 1185.341      |
|             | 170                           | 1287.742      |
|             | 175                           | 1358.119      |
|             | 160                           | 962.050       |
| 20          | 165                           | 1023.264      |
|             | 170                           | 1111.655      |
3. Analysis of finite element mechanical characteristics of shovel

3.1. Establishment of the finite element model of the shovel

Three-dimensional models with different inclination angles of 160°, 165°, 170° and 175° were drawn by Solidworks 3D drawing software, and the drawn models were imported into ANSYS Workbench finite element analysis software for mechanical analysis. The thickness of the second-order curved excavating shovel designed according to the actual working conditions is 10 mm. According to the practical manual of mechanical design, the stress yield limit of Q235 carbon structure pole steel is 235 MPa. The material parameter settings of the multi-stage excavating shovel are shown in Table 3 below:

| material | Elastic Modulus /Pa | Poisson's ratio | density (kg/m³) |
|----------|---------------------|----------------|-----------------|
| Q235     | 2.09×10¹¹           | 0.33           | 7890            |

The material setting, mesh division, fixed constraint and load addition are carried out for the multi-stage excavating shovel, and the finite element mechanical characteristic analysis is carried out for different combinations of soil entry angle and shovel surface inclination angle.

3.2. ANSYS Workbench finite element analysis

The finite element model is solved by 16 combinations of the soil entry angle and the shovel surface inclination angle in Table 2, and the stress-strain excavating shovel deformation cloud diagram is obtained. The following figures 5 to 6 show the stress and strain cloud diagrams of the soil entry angle of 30° and the shovel surface inclination angle of 170°. Organize the stress and strain table as shown in Table 4:

| Table 3. Material parameter settings of excavating shovel |
|----------------------------------------------------------|
| material | Elastic Modulus /Pa | Poisson's ratio | density (kg/m³) |
|----------|---------------------|----------------|-----------------|
| Q235     | 2.09×10¹¹           | 0.33           | 7890            |

Figure 5. Stress distribution diagram with 30° soil penetration and 170° shovel surface inclination

Figure 6. Deformation cloud diagram with 30° soil penetration and 170° shovel surface inclination
Table 4. Stress and strain values

| Entry angle | Shovel face inclination | Stress (MPa) min | Stress (MPa) max | Deformation (mm) max |
|-------------|-------------------------|------------------|------------------|---------------------|
| 10          | 160                     | 3.0977*10^{-3}   | 21.877           | 0.44928             |
|             | 165                     | 3.16*10^{-3}     | 25.793           | 0.4549              |
|             | 170                     | 5.4592*10^{-3}   | 18.101           | 0.4981              |
|             | 175                     | 5.451*10^{-3}    | 19.679           | 0.5269              |
|             | 160                     | 2.6741*10^{-3}   | 18.886           | 0.3878              |
| 20          | 165                     | 2.72*10^{-3}     | 22.266           | 0.3927              |
|             | 170                     | 4.713*10^{-3}    | 15.626           | 0.42997             |
|             | 175                     | 4.71*10^{-3}     | 16.988           | 0.4549              |
| 30          | 160                     | 2.4173*10^{-3}   | 17.072           | 0.3506              |
|             | 165                     | 2.46*10^{-3}     | 20.128           | 0.35498             |
|             | 170                     | 4.26*10^{-3}     | 14.125           | 0.38867             |
|             | 175                     | 4.25*10^{-3}     | 15.356           | 0.4112              |
| 40          | 160                     | 2.269*10^{-3}    | 16.022           | 0.32903             |
|             | 165                     | 2.311*10^{-3}    | 18.899           | 0.3331              |
|             | 170                     | 3.998*10^{-3}    | 13.255           | 0.3647              |
|             | 175                     | 3.991*10^{-3}    | 14.41            | 0.3859              |

The histogram of the stress and strain values corresponding to different entry angles and different shovel surface inclination angles is shown in Figure 7-8 below:

Figure 7. Corresponding stress diagrams of different entry angles and shovel surface inclination angles

Figure 8. Corresponding deformation cloud diagrams with different entry angles and shovel surface inclination angles

According to the finite element analysis of the mechanical characteristics of 16 different combinations of digging shovel entry angles and shovel face inclination angles, the stress-strain cloud
diagram is obtained and the table 3 and column diagrams 5-6 can be seen: The maximum stress of the Ophiopogon japonicus harvester's multi-stage excavating shovel shows a trend of first increasing and then decreasing with the increase of the soil entry angle and the inclination of the shovel surface. There are inflection points at 30° and 170°, respectively, and the maximum stress value is 14.125MPa. The minimum stress value is 4.26*10^{-3}MPa, and the maximum stress value is concentrated at the link between the shovel plate and the left and right side plates; The maximum deformation of the multi-stage shovel is 0.38867mm, which appears at the tip of the shovel. Check the mechanical design manual to know the elongation of Q235 and the yield strength of 235MPa. Therefore, the stress intensity and deformation of the excavating shovel are within the upper limit of the material requirement range when the soil entry angle is 30° and the shovel surface inclination angle is 170°.

4. Field test and result analysis of Ophiopogon japonicus digging device

4.1 Prototype trial production
In order to more effectively test the two important indicators of the Ophiopogon japonicus harvester excavating device-the obvious rate got and damage rate of the Ophiopogon japonicus harvester, the excavating device and the lifting device are prototyped, and the harvesting effect of the excavating device is mainly studied. Modeling was carried out by Solidwork 3D software. After several scheme improvements, the structure of the excavation device and the lifting device was determined, and finally the trial production of the 4WM-100B prototype of the Ophiopogon japonicus harvester was completed. The prototype is shown in Figure 9 below:

![Figure 9. Ophiopogon harvesting machine 4WM-100B prototype](image)

4.2 Field test conditions and methods
Field trials were conducted in Qintai Village, Huayuan Town, Santai County, Mianyang City, Sichuan Province. The obvious rate got and loss rate of the 4WM-100B prototype digging device of the Ophiopogon japonicus harvester were tested. Test tools include: steel tape measure, electronic stopwatch, electronic balance, temperature and humidity meter, soil moisture tester, digital display soil hardness meter, etc. The investigation of the field conditions during the harvest of Ophiopogon japonicus is as follows: the test soil is loam, the terrain slope is flat, the soil firmness is 942kPa, the soil moisture content is 23.3%, the ambient temperature is 17.4℃-20.8℃, the relative humidity is 40%-42%, and the Ophiopogon japonicus planting method for artificial planting, the plant spacing is 6.0-7.5cm, the row spacing is 8.0-10.0cm, the unit area mass of Chinese medicinal materials is 1.79kg/m^2, and the excavation depth is set to 20cm. The excavation test site diagram is shown in Figure 10:
According to the relevant technical regulations and test methods of the national industry standard DG/T 189-2019 "Medicinal Material Excavator" and NY/T 3481-2019 "Technical Specification for Quality Evaluation of Root and Stem Chinese Medicinal Materials", consider the main parameters that affect the harvesting and digging device of Ophiopogon japonicus, with the soil angle, the inclination angle of the shovel surface and the forward speed as the test factors, the obvious rate got and the damage rate as the evaluation indicators, and the second orthogonal combination test was carried out [21-22].

4.3. Experimental analysis

4.3.1. Test program
In order to explore the impact of the excavation device on the harvest of Ophiopogon japonicus, an experimental design was carried out through Design-Expert 12. The main parameters of the test are: soil entry angle, soil shovel surface inclination angle and forward speed. The test factor level coding is shown in Table 5 below:

| Level | Entry angle (°) | Shovel face inclination (°) | Forward speed (m/s) |
|-------|----------------|-----------------------------|---------------------|
| -1    | 10             | 165                         | 0.2                 |
| 0     | 20             | 170                         | 0.35                |
| 1     | 30             | 175                         | 0.5                 |

The obvious rate got and damage rate of Ophiopogon japonicus are important indicators that affect the mining system of Ophiopogon japonicus. The corresponding factors in this experiment are set as the obvious rate got and the damage rate. The test plan and results are shown in Table 6 below:

| Serial number | Entry angle (°) | Shovel face inclination (°) | Shovel face inclination (m/s) | Harvest rate (%) | Damage rate (%) |
|---------------|----------------|-----------------------------|-----------------------------|-----------------|----------------|
| 1             | -1             | 0                           | 1                           | 93.60           | 1.39           |
| 2             | 0              | 0                           | 0                           | 98.61           | 1.46           |
| 3             | 1              | 1                           | 0                           | 94.22           | 1.38           |
| 4             | 0              | -1                          | 1                           | 95.47           | 1.41           |
| 5             | 1              | 0                           | 1                           | 95.14           | 1.39           |
| 6             | -1             | 0                           | -1                          | 91.21           | 1.36           |
| 7             | 0              | 0                           | 0                           | 97.98           | 1.45           |
| 8             | 0              | 1                           | 1                           | 97.51           | 1.45           |
| 9             | 0              | 0                           | -1                          | 95.81           | 1.44           |
4.3.2. Analysis of test results

Use Design-Expert software to perform binary regression equation analysis, multiple regression fitting and significance test on the test results of Ophiopogon japonicus multi-stage digging shovel, and obtain the regression equation of obvious rate got Z and damage rate Y. The variance analysis of obvious rate got and damage rate is as follows Table 7 and Table 8 show:

Table 7. Variance analysis of obvious rate got Z

| Source of variation  | sum of squares | Degree of freedom | Mean square | F     | P      | Significance |
|----------------------|---------------|------------------|------------|-------|--------|-------------|
| Model                | 86.33         | 9                | 9.59       | 52.13 | 0.0002 | ***         |
| A- Entry angle       | 1.23          | 1                | 1.23       | 6.66  | 0.0494 | **          |
| B- Shovel face inclination | 10.93      | 1                | 10.93      | 59.39 | 0.0006 | ***         |
| C- Forward speed     | 6.36          | 1                | 6.36       | 34.55 | 0.002  | ***         |
| AB                   | 2.39          | 1                | 2.39       | 12.97 | 0.0155 | **          |
| AC                   | 0.0176        | 1                | 0.0176     | 0.0955| 0.7697 |             |
| BC                   | 0.0081        | 1                | 0.0081     | 0.044 | 0.8421 |             |
| A²                   | 43.65         | 1                | 43.65      | 237.19| < 0.0001| ***         |
| B²                   | 4.45          | 1                | 4.45       | 24.19 | 0.0044 | ***         |
| C²                   | 7.55          | 1                | 7.55       | 41.01 | 0.0014 | ***         |
| Residual             | 0.9201        | 5                | 0.184      |       |        |             |
| Lack of Fit          | 0.7063        | 2                | 0.3531     | 4.96  | 0.112  |             |
| Pure Error           | 0.2138        | 3                | 0.0713     |       |        |             |
| Cor Total            | 87.25         | 14               |            |       |        |             |

Note: P indicates whether it is significant or not the probability level standard. P<0.01 means extremely significant (***) , 0.01<P<0.05 means significant (***), 0.05<P<0.1 means more significant (*).

It can be seen from Table 7 that for the test index obvious rate got Z, B, C, A², B², and C² have extremely significant effects on the obvious rate got Z (P<0.01); A and AB have significant effects on the obvious rate got Z (0.01<P<0.05);The binary fitting regression equation to get the influence of each factor on the obvious rate got Z is:

\[
Z = 98.31 + 0.4794A + 1.17B + 1.09C - 0.7725AB + 0.0938AC - 0.045BC - 3.69A^2 \\
-1.18B^2 - 1.54C^2
\]  

(7)

Table 8. Damage rate Y variance analysis

| Source of variation        | sum of squares | Degree of freedom | Mean square | F     | P      | Significance |
|----------------------------|---------------|------------------|------------|-------|--------|-------------|
| Model                      | 0.0223        | 9                | 0.0025     | 132.42| < 0.0001| ***         |
| A- Entry angle             | 0.0002        | 1                | 0.0002     | 9     | 0.0301 | **          |
| B- Shovel face inclination | 0.0036        | 1                | 0.0036     | 192.67| < 0.0001| ***         |
| C- Forward speed           | 0.0004        | 1                | 0.0004     | 18.78 | 0.0075 | ***         |
| AB                         | 0.0009        | 1                | 0.0009     | 48    | 0.001  | ***         |
| AC                         | 0.0001        | 1                | 0.0001     | 4.17  | 0.0967 |             |
It can be seen from Table 8 that for the test index damage rate Y, B, C, AB, A2, and B2 have extremely significant effects on the obvious rate got Y (P<0.01); A and C2 have significant effects on the obvious rate got Y (0.01 < P < 0.05); The binary fitting regression equation to obtain the influence of various factors on the obvious rate got Y is:

$$Y = 1.45 + 0.0056A + 0.0212B + 0.0081C - 0.015AB - 0.0062AC - 0.0025BC - 0.0619A^2 - 0.0206B^2 - 0.0999C^2$$

From the comparison of the F value, it can be seen that the order of the factors affecting the obvious rate got and the damage rate is: shovel surface inclination> soil entry angle> forward speed.

4.3.3. Response surface curve analysis

Through the data analysis of Design-Expert 12 software, the significant relationship between soil entry angle A, shovel surface inclination angle B, forward speed C and obvious rate got and damage rate is obtained, and the response surface curve diagram of the corresponding Z test index is obtained as follows:

As shown in Figure 11:

From the analysis of the above response surface graphs, it can be seen that with the increase of the shovel entry angle and the inclination angle of the shovel surface of Ophiopogon japonicus, the obvious rate got Z first increases and then decreases. From the contour line in the figure, the digging rate The slope of the slope in the direction of the shovel face is faster than the rate of change of the angle of soil entry, that is, the influencing factors of the shovel face inclination angle are larger than those of the soil entry angle.
4.3.4 Parameter optimization design

According to the binary regression equation and response surface curve analysis, in order to obtain the best test level combination, the regression model is calculated through the optimization design. According to the actual working conditions and performance requirements of the Ophiopogon japonicus harvester and the above analysis model, the optimization conditions are as follows:

\[
\begin{align*}
\text{max } Z(A, B, C) & \rightarrow \text{min } Y(A, B, C) \\
\text{s.t. } & 10 \leq A \leq 40 \\
& 165 \leq B \leq 175 \\
& 0.2 \leq C \leq 0.5
\end{align*}
\]

After the optimization equation is solved, the digging device of the Ophiopogon japonicus harvester has a soil entry angle of 17°-27°, a shovel surface inclination angle of 167.5°-172.5°, and a forward speed of 0.32m/s-0.38m/s. The excavating device has the best performance, with Harvest rate got of 98.41%-98.61% and damage rate of 1.32%-1.46%.

4.4 Test verification

Taking into account the processing conditions of the digging device of the Ophiopogon japonicus harvester and the actual working conditions, the combined shovel with a shovel angle of 170° was assembled on the 4WM-100B prototype. In the experiment, the shovel's entry angle was set to 25° and the machine forward speed was set at 0.35m/s, the above factor level test is carried out, and the average value of the measurement results is taken 5 times to obtain the following table 9.

| Parameter                          | Entry angle | Shovel face inclination | Forward speed | Harvest rate | Damage rate |
|------------------------------------|-------------|-------------------------|---------------|-------------|-------------|
| Numerical value                    | 25°         | 170°                    | 0.35m/s       | 98.37%      | 1.35%       |

The results of the Ophiopogon japonicus validation test showed that the obvious rate got was 98.37% and the damage rate was 1.35%. The predicted value was very close to the test result, which verified the accuracy of the model optimization. The performance test of the prototype machine shows that the machine has high operating efficiency, a high degree of agreement with the optimized model results, and the relevant technical indicators are better than the qualified standards.

5. Conclusion

(1) In this paper, the digging shovel of the Ophiopogon japonicus harvester was designed based on the agronomy of Ophiopogon japonicus and related design requirements of the digging shovel. An inclination plane was added on the basis of the first-order inclination angle of the plane shovel, and the soil performance was increased through the protrusion of the shovel surface inclination angle to reduce the lost motivation.

(2) The ANSYS finite element mechanical characteristics analysis of the multi-stage excavating shovel was carried out, and the stress and strain analysis cloud diagram was obtained through different combinations of the soil angle and the inclination angle of the shovel surface. The statistical analysis of the stress cloud chart found that there were turning points at the soil entry angle of 30° and the shovel surface inclination angle of 170°. At this time, the mechanical performance of the Ophiopogon shovel was the best. The statistical analysis of the strain cloud chart reveals that the main deformation of the shovel was at the tip of the shovel. In actual production, the strength of the blade tip can be increased, and the deformation can be reduced to increase its reliability.

(3) The machine was tested in the field, and a binary regression model of test indicators and influencing factors was established by Design-Expert 12 software. And conduct response surface analysis, and finally conduct re-optimization design calculations. The results show that when the soil entry angle was 25°, the shovel surface inclination angle was 170°, and the forward speed was 0.35m/s,
the Harvest rate got 98.37%, damage rate got 1.35%, and all indicators were better than the relevant national standards.

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References
[1] Wang YP, Ye JH, Jiang HX, et al. Research and Application of 4WM-100B Ophiopogon japonicas Harvest in Santai[J]. Science and technology of Sichuan agriculture, 2020(08):72-73+76.
[2] Liu W. Analysis of Industry competitiveness of Mail Industry in Santai Mianyang[D]. Sichuan Agricultural University, 2014.
[3] Hu X, Song W, Zheng P. Influence of material shape on excavation resistance of bucket wheel stacker based on EDEM simulation[J]. International Core Journal of Engineering, 2019, 5(8).
[4] Zhang Y. Design and Experiment of Self-propelled Panax notoginseng Harvester[D]. Kunming University of Technology, 2016.
[5] Zhang Z, Wang F, Zhang Y, et al. Design and Experiment of Self-propelled Panax notoginseng Harvester[J]. Agricultural Mechanical Journal, 2016, 47(S1):234-240.
[6] Lang C, Xu L, Pan W, et al. Design and finite element analysis of Panax notoginseng seedlings bionic digging shovel[J]. Journal of Chinese Agricultural Mechanization, 2020, 41(09):82-88.
[7] Wang T, Liao Y, Yang Y, et al. The Design and Mechanical Analysis of Digging Shovel of Cassava Harvest Machine[J]. Journal of Agricultural Mechanization Research, 2015, 37(10):50-53.
[8] Liu J. Comprehensive Study on the Evaluation of Ophiopogon Germplasm Resources in Sichuan Basin[D]. Sichuan Agricultural University, 2020.
[9] Zhang F, Li J, Chen J. A dual-antenna global positioning system (GPS) receiver based automated leveling system for tuber harvesters of Ophiopogon japonicus[J]. Journal of Zhejiang University(Agriculture & Life Sciences), 2018, 44(04):445-450.
[10] Zhang Z, Wang H, Li Y, et al. Design and Experiment of Multi-stage Separation Buffer Potato Harvester[J]. Agricultural Mechanical Journal, 2021, 52(02):96-109.
[11] Zhang J, Wang J, Zhao G, et al. Design of resistance test bench for vibration soil cutting and excavation[J]. Journal of Agricultural Mechanization Research, 2021, 43(09):93-97.
[12] Zhou M. Design and test of vibration excavation shovel of Astragalus harvester[D]. Jiangsu University, 2020.
[13] Fan Y. Study on Potato Mining Mechanism and bionic Shovel Design Based on Discrete Yuan Method[D]. Shenyang Agricultural University, 2020.
[14] Adrianus J, Henderikus K. Agricultural Soil Mechanics[M]. Springer, Berlin, Heidelberg: 1983-01-01.
[15] Lv J, Sun Y, Li J, et al. Design and test of vertical spiral organic fertilizer spreading device[J]. Transactions of the Chinese Society of Agricultural Engineering, 2020, 36(24):19-28.
[16] Lv J, Sun H, He H, et al. Design and Experiment on Conveyor Separation Device of Potato Digger under Heavy Soil Condition [J]. Transactions of the Chinese Society for Agricultural Machinery, 2017, 48(11): 146-155.

[17] Shi L. Research on Biomechanical Properties of Potato and Drag Reduction Mechanism of Mining Shovel [D]. Gansu Agricultural University, 2013.

[18] Science-Applied Sciences; Shihezi University Researchers Publish Findings in Applied Sciences [Bionic Design of a Potato Digging Shovel with Drag Reduction Based on the Discrete Element Method (DEM) in Clay Soil][J]. Science Letter, 2020.

[19] Li J, Jiang X, Ma Y, et al. Bionic Design of a Potato Digging Shovel with Drag Reduction Based on the Discrete Element Method (DEM) in Clay Soil [J]. Applied Sciences, 2020, 10(20).

[20] Duanmu L. Design and research of bionic excavation shovel of cassava harvester [D]. Jilin University, 2020.

[21] Zaverkin V, Kästner J. Exploration of transferable and uniformly accurate neural network interatomic potentials using optimal experimental design [J]. Machine Learning: Science and Technology, 2021, 2(3).

[22] He W, Xue W, Tang B. Optimization Test Design Method and Data Processing [M]. Beijing: Chemical Industry Press, 2012.