The Simulation and Parameter Optimization of the Hole-Forming Process of a Duckbilled Hole-Forming Device

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Abstract: This paper addresses the hole-forming process of a duckbilled hole-forming device. Based on a coupled simulation using the multi-body dynamics software RecurDyn and the discrete element software EDEM, the hole-forming mechanism of a duckbilled hole-forming device and the influence of control parameters on the hole-forming performance of the hole-forming device were studied. In this paper, we analyze the direction and speed of soil particles transported under soil disturbance by a hole-forming device through the simulation and study of the hole-forming mechanism of the hole-forming device. By controlling parameters such as the traction angle, forward speed, and mass of the hole-forming device, the influence of the control parameters on the hole-forming trajectory of the duckbilled hole-forming device was investigated. Orthogonal tests determined the optimal combination of control parameters. The results show that the hole-forming process of the hole-forming device mainly comprises squeezing and shearing the soil to form holes, and the hole-forming performance of the hole-forming device was optimal when the traction angle was 17.3°, the forward speed was 1.11 m/s, and the mass of the hole-forming device was 17.9 kg.

Keywords: duckbilled hole-forming device; hole-forming trajectory; coupling simulation; parameter optimization

1. Preface

Xinjiang is a vital cotton-planting base in China, and a large amount of cotton is planted and harvested annually. Sowing is one of the critical aspects of determining yield in cotton planting. Traditional manual seeding is time-consuming, labor-intensive, and inefficient, and it cannot meet the needs of large-scale cotton planting. Mechanical seeding can significantly improve the efficiency of cotton planting, reduce the grower's physical labor, and enable accurate control over the depth of planting, row spacing, and the number of seeds [1–3]. Cotton planting in Xinjiang is mainly dominated by hole sowing on the membrane, which has the advantages of heat preservation, moisture retention, and reducing weed growth [4–6], which are new requirements for seeding machinery.

In order to improve the performance of hole-forming devices, relevant scholars at home and abroad have researched hole-forming devices through analyses of the hole-forming process, structural optimization, and interactions with soil. Concerning motion analysis of the hole-forming process of hole-forming devices, Quan et al. [7] took different shapes and different hole-forming methods (soil extraction and extrusion) as their research objects, and their results showed that the hole-forming process of soil extraction was better than the hole-forming process of extrusion; the method had higher requirements for the mechanical structure of hole-forming devices, and the holes were
quickly backfilled in soft soil due to the backflow of soil particles. Zhou et al. [8,9] took different slip rates, forward speeds, and depths of entry as their objects of study, and their results showed that the slip rate was 11%, the forward speed of the machine was 0.5 m/s, and the depth of penetration of the hole-forming device was 0.03 m. The hole-forming device had a minor slip and was less likely to produce phenomena such as picking and tearing of the film. In terms of structural optimization, Hou et al. [10] designed a side-opening, slip-cutting, film-breaking precision seeding monobloc to address the problems of the considerable size and irregular shape of film holes and poor seeding quality when sowing in mulching film, which would significantly reduce the seeding efficiency of the hole-forming device. Liao et al. [11] examined existing sowing methods for the film of hole-punching devices in the actual operation of the process regarding membrane hole size, irregularly shaped membrane hole sticking, and other issues. Based on the principle of slip cutting, they designed a rolling film-cutting and punching device to determine the structural parameters of the punching device and its profiling mechanism, establish a kinematic model of the punching device, and analyze and determine the main factors affecting the length of the membrane holes and its range of values [11]. In terms of soil interaction, Bao et al. [12] used the discrete element method (DEM) to analyze the tillage process of a deep pine shovel to select the model with the best drag-reduction effect. They explored the drag reduction mechanism of a biomimetic prismatic deep pine shovel from macroscopic and microscopic perspectives. Macroscopically, the shovel and soil model were used as research objects to compare the horizontal plowing resistance and soil force; microscopically, the horizontal and vertical soil particle layers were intercepted, and the arching angle and a velocity trajectory cloud map of the particle layer were investigated. Yeon-Soo Kim developed a comprehensive geotechnical soil–mechanical coupled model based on coupling of the discrete element method (DEM) and multi-body dynamics (MBD) to predict traction forces during plowing, by considering the target tillage depth, which reflects the distribution of soil properties with the change in soil depth, the DEM soil foundation bed was simulated [13]. Regarding soil disturbance, Aili Hasimu and Zhao et al. [14–16] studied the soil disturbance mainly in terms of the entry earth resistance of the hole-forming device and the transport speed and trajectory of the soil particles.

Scholars at home and abroad mainly study transplanting machines and soil tillage. There are few studies on the influence of the hole-forming trajectory and the parameters of the hole-forming device, giving the research presented in this paper specific value.

2. Analysis of the Hole-Forming Device Structure and Hole-Forming Process

2.1. The Hole-Forming Device Structure

A duckbilled hole-forming device is an essential component of film sowing, and its working performance directly affects sowing quality. A duckbilled hole-forming device is composed of a hole-forming mechanism (moving duckbill, fixed duckbill, duckbill hinge, and spring), belt, dividing grid, seed baffle, chock, pressure plate, dynamic disk, arc-shaped seed blocking ring, and axis, and its structure is shown in Figure 1. This duckbilled hole-forming device consists of 15 hole-forming mechanisms and has an individual spacing of 85–100 mm, and a planting depth of 23–28 mm [17,18].
2.2. Analysis of the Motion Process of the Hole-Forming Device

The movement process of a duckbilled hole-forming device during operation is shown in Figure 2, where $V$ is the forward speed, m/s; $R$ is the radius of the hole-forming device, mm; $R_r$ is the radius of the apex of the fixed duckbill, mm; $\alpha_1$ is the angle between the fixed duckbill AB and OA, °; $\alpha_2$ is the angle between the moving duckbill AC and OA, °; $H$ is the hole sowing depth, mm; $\Psi$ is the duckbill movement angle, °. $R_0$ is the rolling radius of the hole-forming device, $r = R/(1 - \mu)$, mm; and $\mu$ is the slip coefficient.

2.2.1. Analysis of Duckbill Motion Trajectory

The motion equation of the duckbill is as follows:

The equation of motion for the fixed duckbill is

$$\begin{align*}
x &= R_0 \psi - r \sin(\psi + \phi_1) \\
y &= R_r - r \cos(\psi + \phi_1)
\end{align*}$$ (1)

The equation of motion before the opening of the moving duckbill is

$$\begin{align*}
x &= R_0 \psi - r \sin(\psi + \phi_2) \\
y &= R_r - r \cos(\psi + \phi_2)
\end{align*}$$ (2)

The equation of motion for the points after the opening of the moving duckbill is

$$\begin{align*}
x &= R_0 \psi - r \sin(\psi + \phi'_2) \\
y &= R_r - r \cos(\psi + \phi'_2)
\end{align*}$$ (3)
The equation of motion of the points on the face of the moving duckbill during its opening is

\[
\begin{align*}
\begin{cases}
  x &= x_c + r' \sin(\alpha_1 + \alpha_2 - \theta) = R_d \psi - R_c \sin(\psi - \phi_{1c}) + r' \sin(\alpha_1 + \alpha_2 - \theta) \\
y &= y_c - r' \sin(\alpha_1 + \alpha_2 - \theta) = R_c \cos(\psi - \phi_{1c}) - r' \cos(\alpha_1 + \alpha_2 - \theta)
\end{cases}
\end{align*}
\] (4)

In the formula, \(\phi_{1c}\) is the central angle of any point on the fixed duckbill, \(\psi\); \(\phi_{2c}\) is the center angle of the moving duckbill at one point before it opens, \(\psi\); \(\phi_{2c}'\) is the center angle of the movable duckbill at any point after opening, \(\psi\); \(\theta\) is the angle of rotation of the moving duckbill around the point C of the pin, \(\psi\); \(r\) is the radius of any point of the hole-forming device, mm; and \(r'\) is the radius of rotation from any point on the movable duckbill to point C, mm.

2.2.2. Soil Hole Contour Analysis

Soil holes are formed by the shearing and squeezing action of the duckbill on the soil. The role of the external surface of the fixed duckbill is as follows: the upper left contour (a–b section of Figure 3) and the lower right contour (d–e section of Figure 3) of the soil hole are formed during the soil piercing process, and the lower left contour of the soil hole is formed during the unearthing process (b–c section of Figure 3). The role of the moving duckbill is as follows: during the opening of the moving duckbill, the lower contour of the hole is formed (c–d section of Figure 3), and the soil is squeezed at the later stage of the unearth and continues until the end of the unearth process, forming the upper right contour of the soil hole (e–f section of Figure 3).

![Figure 3. Contour diagram of soil hole.](image)

From the trajectory of the hole-forming device and the process of hole-forming, it can be seen that the soil hole contour is composed of five curves, namely a–b, b–c, c–d, d–e, and e–f in Figure 3. The soil hole point in the diagram is taken as the coordinate origin O, and the rectangular coordinate system is established. The b–c and d–e segments are the motion trajectories of the tip point A of the fixed duckbill. Substituting \(r = R_c\) into Equation (1), the parametric equations of the b–c and d–e segments can be obtained as follows:

\[
\begin{align*}
\begin{cases}
  x &= R_d \psi - R_c \sin(\psi + \phi_{1c}) \\
y &= R_c - R_c \cos(\psi + \phi_{1c})
\end{cases}
\end{align*}
\] (5)

The c–d segment is the contour formed during the opening process of the moving duckbill tip D. Substituting \(r = r_d'\) into Equation (4), the parametric equations of the c–d segments can be obtained as follows:

\[
\begin{align*}
\begin{cases}
  x &= R_d \psi - R_c \sin(\psi - \phi_{2c}) + r_d' \sin(\alpha_1 + \alpha_2 - \theta) \\
y &= R_c - R_c \cos(\psi - \phi_{2c}) + r_d' \cos(\alpha_1 + \alpha_2 - \theta)
\end{cases}
\end{align*}
\] (6)

In the formula, \(R_c\) is the radius of point C of the center of rotation of the moving duckbill; \(r_d'\) is the radius of the end point of the moving duckbill from point C of the pin;
The e–f segment is formed by extruding the outer surface CD of the moving duckbill during the unearthing process. The parameter equation is

\[
\begin{align*}
    x &= R_0 \psi - [R_0 \sin(\theta + \alpha + \lambda) - R_1 \sin(\alpha + \lambda)] \cos(\theta + \alpha + \lambda) \\
    y &= R_1 - R_0 + [R_0 \sin(\theta + \alpha + \lambda) - R_1 \sin(\alpha + \lambda)] \sin(\theta + \alpha + \lambda)
\end{align*}
\] (7)

The a–b section is the trajectory line formed by AB on the outer surface of the fixed duckbill during the process of soil piercing, and its parameter equation is

\[
\begin{align*}
    x &= R_0 \psi - [R_0 \sin(\theta + \lambda) - R_1 \sin(\lambda)] \cos(\theta + \lambda) \\
    y &= R_1 - R_0 + [R_0 \sin(\theta + \lambda) - R_1 \sin(\lambda)] \sin(\theta + \lambda)
\end{align*}
\] (8)

2.2.3. Dynamic Analysis of the Hole-Forming Device

The traction machinery mainly drives the movement of the hole-forming device, and the different traction angles affect the trajectory of the duckbill of the hole-forming device. The hole-forming device rolls on the soil when the whole machine moves forward. The forces on the hole-forming device can be simplified as gravity, friction, support between the hole-forming device and the soil, and traction. The forces on the hole-forming device are shown in Figure 4.

![Figure 4. The force of the hole-forming device.](image)

The forces in the horizontal and vertical directions are analyzed:

\[
\begin{align*}
    F \cos \alpha &= F_f \\
    F_n + F \sin \alpha &= G \\
    F_f &= \mu F_n
\end{align*}
\] (9)

In the formula, \( G \) is the gravitational force of the hole-forming device itself; \( F_n \) is the support force of the soil on the hole-forming device; \( F \) is the traction force of the hole-forming device; \( F_f \) is the friction force of the ground on the hole-forming device; and \( \alpha \) is the angle between the traction force and the direction of advance. It is obtained according to Equation (9):

\[
F = \frac{\mu G}{\cos \alpha + \mu \sin \alpha}
\] (10)
From Equation (10), the traction force $F$ increases with the increase in $\alpha$ after the hole-forming device reaches equilibrium. From Equation (11), the support force $F_n$ decreases as $\alpha$ increases. As $\alpha$ increases, the traction force $F$ increases, and the support force $F_n$ decreases.

3. Simulation Analysis of Hole-Forming of the Hole-Forming Device

3.1. Multi-Body Dynamics Modeling

To ensure the accuracy of the simulation results, the hole-forming device was modelled in a 1:1 scale using Solidworks 2021 software. We save in the s_t format imported into RecurDyn V9R5 software; to reduce the number of operations, the hole-forming device structure parts that do not affect the simulation results are simplified, and the motion is added to the parts, as shown in Table 1.

Table 1. The movement of the hole-forming device model.

<table>
<thead>
<tr>
<th>Serial Number</th>
<th>Unit</th>
<th>Kinematic Pair</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ground, coupling shaft</td>
<td>Translate</td>
</tr>
<tr>
<td>2</td>
<td>End cap assembly, coupling shaft</td>
<td>Fixed</td>
</tr>
<tr>
<td>3</td>
<td>Dividing grid combination, coupling shaft</td>
<td>Revolute</td>
</tr>
<tr>
<td>4</td>
<td>Moving duckbill combination, dividing grid combination</td>
<td>Revolute</td>
</tr>
<tr>
<td>5</td>
<td>Moving duckbill combination, dividing grid combination</td>
<td>Spring</td>
</tr>
</tbody>
</table>

3.2. Soil Discrete Element Modelling

The discrete element method is a numerical computational method commonly used to study the problems of particle accumulation, particle flow, collision process, particle deformation, etc. By simulating the particle system, the discrete element method can predict and analyze the mechanical properties, deformation behaviors, particle gap changes, and other information of the particle system [19]. It can simulate the interaction of the hole-forming device with the soil in reality more accurately. The EDEM software can accurately obtain the hole-forming device forces and the disturbance to the soil during the rolling process. In the modeling, in order to make the model close to reality, the soil particles were selected as spherical particles with a radius of 3 mm [20,21], and the particle contact model was selected as Hertz–Mindlin with bonding; the modeling parameters [22–25] are shown in Table 2.

Table 2. Soil discrete element modeling parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil particle density/(kg·m⁻³)</td>
<td>1569</td>
</tr>
<tr>
<td>Density of steel/(kg·m⁻³)</td>
<td>7801</td>
</tr>
<tr>
<td>Soil particle radius/mm</td>
<td>3</td>
</tr>
<tr>
<td>Soil Poisson’s ratio</td>
<td>0.36</td>
</tr>
<tr>
<td>Steel Poisson’s ratio</td>
<td>0.29</td>
</tr>
<tr>
<td>Shear modulus of soil/MPa</td>
<td>$1 \times 10^6$</td>
</tr>
<tr>
<td>Shear modulus of steel/MPa</td>
<td>$8.02 \times 10^{10}$</td>
</tr>
<tr>
<td>Restitution coefficient between soil particles</td>
<td>0.4</td>
</tr>
<tr>
<td>Restitution coefficient of soil and steel</td>
<td>0.5</td>
</tr>
<tr>
<td>Static friction coefficient between soil particles</td>
<td>0.49</td>
</tr>
<tr>
<td>Static friction coefficient between soil and steel</td>
<td>0.46</td>
</tr>
<tr>
<td>Dynamic friction coefficient between soil particles</td>
<td>0.29</td>
</tr>
<tr>
<td>Dynamic friction coefficient between soil and steel</td>
<td>0.15</td>
</tr>
</tbody>
</table>
Normal contact stiffness coefficient between soil–soil particles/(N/m²) \[1.9 \times 10^5\]
Tangential contact stiffness coefficient between soil–soil particles /(N/m²) \[1.4 \times 10^5\]
Critical normal stress between soil and soil particles/Pa \[55,000\]
Critical tangential stress between soil and soil particles/Pa \[55,000\]
Bonding radius/mm \[3.5\]

3.3. Coupling Simulation

3.3.1. Coupling Simulation of a Single Duckbill

During the rolling process, the hole-forming device interacts with the soil, causing the velocity of the soil particles to change, and the velocity size of soil particles is a direct response to the degree of disturbance of the soil during the hole-forming process. In order to visualize the disturbance of the duckbill on the soil particles, a duckbill model was imported into the EDEM 2022 software during the coupling process [15,26–28]. The simulation time is set to 1 s, the step length is \(2 \times 10^{-4}\) s in the EDEM software, and the simulation time is set to 1 s. The step length is set to 500 in the RecurDyn V9R5 software; the traction angle is 20°, the mass of the hole-forming device is 17 kg, the forward speed of the hole-forming device is 1.11 m/s as the parameter, and the specific process is shown in Figure 5.

![Figure 5. Coupling simulation flowchart.](image)

3.3.2. Integral Simulation of the Hole-Forming Device

In order to investigate the influence of different parameters on the hole-forming trajectory of the hole-forming device, the forward speed, traction angle, and mass of the hole-forming device were used as control parameters, and the hole-forming process of the hole-forming device was simulated in a coupled manner. The simplified burrower model is imported into EDEM software, the simulation time is set to 1 s, and the time step is \(2 \times 10^{-4}\) s in EDEM software. The simulation time is set to 1 s, and the step is 500 in RecurDyn software, and the hole-forming process of the hole-forming device is coupled and simulated through the coupling interface.

3.4. Model Validation

The research team conducted a series of field tests to verify the accuracy and reliability of the simulation model in practical application. The critical operating...
parameters were strictly set as follows: traction angle of 17.3°, forward speed of 1.11 m/s, and mass of the hole-forming device of 17.9 kg. The test site was selected in a test field belonging to Shihezi University in Shihezi City, Xinjiang Uygur Autonomous Region, where the typical soil and climatic conditions provided an ideal natural environment for the tests.

During the trial’s preparation phase, the research team carried out ground preparation work on the trial field to ensure that the surface was flat and free of obstacles and to eliminate factors that might impact the trial’s results. The flatness of the ground is crucial for the stable operation of the traction equipment and the hole-former, which ensures the uniformity of the operation and the mass of the hole-former.

For the accuracy of the measurement results of field trials, five groups of tests were conducted to reduce the impact of random error and systematic error. The experimental field was divided into several areas, each measured in a group. Each group of tests measured the sowing depth and plant spacing. Each group of tests measured individual spacing and planting depth. The average of the measurement results of each test index was taken as the result of each group of tests. Figure 6 shows the field trials.

![Field trials](image)

Figure 6. Field trials.

The measured planting depth, individual spacing simulation value, and actual value are shown in Table 3.

<table>
<thead>
<tr>
<th>Number</th>
<th>Simulated Values for Planting Depth</th>
<th>Real Values of Planting Depth</th>
<th>Simulated Values for Individual Spacing</th>
<th>Real Values of Individual Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>27.47</td>
<td>27.62</td>
<td>89.17</td>
<td>89.21</td>
</tr>
<tr>
<td>2</td>
<td>27.56</td>
<td>26.98</td>
<td>88.95</td>
<td>88.73</td>
</tr>
<tr>
<td>3</td>
<td>27.53</td>
<td>27.41</td>
<td>89.26</td>
<td>89.05</td>
</tr>
<tr>
<td>4</td>
<td>27.9</td>
<td>27.88</td>
<td>88.70</td>
<td>89.12</td>
</tr>
<tr>
<td>5</td>
<td>27.42</td>
<td>27.56</td>
<td>89.02</td>
<td>88.97</td>
</tr>
</tbody>
</table>

As can be seen from Figure 7, in the hole-forming process of the hole-forming device, the maximum error between the simulation value of individual spacing and the test value is 1.15%, and the average relative error is about 0.48%; the maximum relative error between the simulation value of the planting depth and the test value is 2.89%, and the average relative error is about 1.53%. The maximum error between the simulation value of individual spacing and planting depth and the test value of the model is less than 3%, and the model is reliable and can simulate the real hole-formation process of the hole-forming device.
4. Analysis of Simulation Results

4.1. Soil Disturbance by a Single Duckbill

The simulation results are shown in Figure 8, and the time points of 0 s, 0.13 s, 0.2 s, 0.24 s, 0.3 s, and 0.4 s are selected for analysis. It was observed that before 0.13 s, as the duckbill had no contact with the soil, the soil particles had no perturbation, and the velocities were all 0 m/s; at 0.13–0.2 s, the duckbill broke through the soil, and the velocities of some of the soil particles became bigger; at 0.2–0.24 s, the duckbill was inserted into the soil, and the moving duckbill beak was opened, and the perturbation to the soil reached the maximum; at 0.24–0.3 s, the duckbill slipped out from the soil, and the disturbance gradually decreased; at 0.3–0.4 s, the duckbill left the soil, there was no contact with the soil, and the velocity of soil particles gradually decreased to 0 m/s.

Figure 7. Simulation and experimental measurement results.

Figure 8. Soil particle velocity diagram.
To further investigate the direction of soil particle movement and the variation patterns of the particle velocities in various axial directions under the action of the hole-forming device, a simulation analysis was conducted to examine the average combined velocity of soil particles and the average component velocities along each axis throughout the process from the duckbill’s entry into the soil to its emergence. The simulation results are shown in Figure 9; before 0.13 s, the average combined velocity and the average partial velocity of each axis were 0 m/s. From 0.13 s to 0.4 s, the average combined velocity and the average X-axis partial velocity changed obviously, and the average X-axis partial velocity was negative, the velocity in the Y-axis direction increased first in the negative direction, then in the positive direction and then in the negative direction, and then finally became 0 m/s, and the velocity in the Z-axis direction did not fluctuate; at 0.4-1 s, the average combined velocity and the average partial velocity of each axis returned to 0 m/s. The results show that during the process of duckbill hole forming, the disturbance of the soil is mainly concentrated in the X-axis direction, and the rolling process of the duckbill squeezes the soil and drives the soil particles to move along the negative direction of the X-axis to cause hole formation.

![Figure 9. Average velocity of each axis of soil particles.](image)

4.2. Effect of Parameters on Hole-Forming Trajectory

4.2.1. Effect of Forward Speed on Hole-Forming Trajectory

At different forward speeds, the amount of slip of the hole-forming device and the time of action with the soil varies, resulting in different planting depths and individual spacing; during the movement of the cavity-forming apparatus, there is always slip. In order to analyze the change rule of the hole-forming trajectory of the hole-forming device under different forward speeds, the traction angle is 20°, the mass of the hole-forming device is 17 kg, and the forward speed of the hole-forming device is 0.69, 0.83, 0.97, 1.11, and 1.25 m/s as the parameter. The simulation results are shown in Table 4.

<table>
<thead>
<tr>
<th>Forward Speed (m/s)</th>
<th>Planting Depth (mm)</th>
<th>Individual Spacing (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.69</td>
<td>30.67</td>
<td>92.43</td>
</tr>
<tr>
<td>0.83</td>
<td>26.78</td>
<td>89.73</td>
</tr>
<tr>
<td>0.97</td>
<td>29.08</td>
<td>89.48</td>
</tr>
<tr>
<td>1.11</td>
<td>29.19</td>
<td>89.91</td>
</tr>
<tr>
<td>1.25</td>
<td>29.32</td>
<td>91.01</td>
</tr>
</tbody>
</table>

With the increase in speed, the pressure of the hole-forming device on the soil first reduced until the vertical direction reached equilibrium, the planting depth decreased, and then because of the continued increase in speed, the hole-forming device appeared to slip,
and the planting depth increased; with the increase in speed, the angular velocity of the duckbill rotating also gets bigger and bigger as shown in Figure 10, the individual spacing decreases, the forward speed continues to increase, the duckbill and the role of the soil are not enough, resulting in duckbill slipping, and the individual spacing increases.

At 0.8–0.9 s, the angular velocity of the hole-forming device fluctuates wildly when moving at a forward speed of 0.69 m/s. This is because the duck’s beak disturbs the soil more when the speed is too low, pulling up the small pieces of soil, resulting in a minor rolling resistance and an instantly more significant angular velocity, which then comes into contact with the soil. The angular velocity decreases to an average value.

![Figure 10. Angular velocity change diagram of the hole-forming device.](image)

4.2.2. Effect of Traction Angle on Hole-Forming Trajectory

In the simulation test, the mass of the hole-forming device’s mass is 17.9 kg and the forward speed is 1.25 m/s. The traction angle is set at 0° as the low-level value and 10° as the difference value, and five simulation tests are carried out. The results of the simulation tests are shown in Figure 11.

![Figure 11. Hole-forming trajectory under traction angles.](image)

As shown in Table 5, the trajectory of hole-forming under different traction angles shows that the individual spacing increases and then decreases with the increase in traction angle, with the highest value of 10°; the planting depth gradually decreases with the increase in traction angle. According to the agronomic specification of cotton sowing, the range of traction angle is 10°~30°.

### Table 5. Effect of traction angle on hole-forming trajectory.

<table>
<thead>
<tr>
<th>Traction Angle (°)</th>
<th>Planting Depth (mm)</th>
<th>Individual Spacing (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>29.78</td>
<td>88.78</td>
</tr>
<tr>
<td>10</td>
<td>29.46</td>
<td>89.59</td>
</tr>
<tr>
<td>20</td>
<td>26.71</td>
<td>89.41</td>
</tr>
<tr>
<td>30</td>
<td>26.68</td>
<td>89.36</td>
</tr>
<tr>
<td>40</td>
<td>26.50</td>
<td>89.50</td>
</tr>
</tbody>
</table>
4.2.3. The Effect of the Holes-Forming Device on Holes-Forming Trajectory

A duckbill holes-forming device in the rolling process relies on the holes-forming device’s gravity and soil interaction; the moving duckbill spring is compressed, the moving duckbill opens and completes the seeding, and the holes-forming device’s gravity directly affects when the moving duckbill can open. In this study, the mass of the holes-forming device was set at 15, 16, 17, 18, and 19 kg, respectively. The mass of the holes-forming device was adjusted using a user-defined change in model mass in the RecurDyn software, setting the forward speed to 0.97 m/s and the traction angle to 20°. The simulation results are shown in Table 6: As the mass of the holes-forming device increases, the pressure of the holes-forming device on the soil becomes more extensive, and the longer the size of the duckbill inserted into the soil, the more the depth of the burrow hole also increases; the individual spacing fluctuates less with the increase in the holes-forming device mass.

Table 6. The influence of the mass of the holes-forming device on the holes-forming trajectory.

<table>
<thead>
<tr>
<th>Mass of the Hole-Forming Device (kg)</th>
<th>Planting Depth (mm)</th>
<th>Individual Spacing (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>27.50</td>
<td>89.31</td>
</tr>
<tr>
<td>16</td>
<td>28.12</td>
<td>89.44</td>
</tr>
<tr>
<td>17</td>
<td>28.27</td>
<td>90.03</td>
</tr>
<tr>
<td>18</td>
<td>28.73</td>
<td>89.70</td>
</tr>
<tr>
<td>19</td>
<td>29.18</td>
<td>89.18</td>
</tr>
</tbody>
</table>

5. Simulation Optimization

5.1. Optimization Methods

The holes-forming trajectory is affected by several influencing factors. If different factors and different levels are combined as samples for numerical simulation, the computational time cost is too high and the efficiency is low. The orthogonal test effectively reduces the number of samples while ensuring that the weights of the factors and levels on the results are balanced. In this paper, the holes-forming device forward speed, traction angle, and mass of the holes-forming device were used as the test factors, and the planting depth and individual spacing were used as the indexes for evaluating the holes-forming performance. Using the one-factor test and the analysis of the simulation process as a reference, the levels and coded values of each factor were set, as shown in Table 7.

Table 7. Test factor level and coding.

<table>
<thead>
<tr>
<th>Coding</th>
<th>Experimental Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Traction Angle $X_1$/°</td>
</tr>
<tr>
<td>−1.682</td>
<td>3.2</td>
</tr>
<tr>
<td>−1</td>
<td>10</td>
</tr>
<tr>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>1.682</td>
<td>36.8</td>
</tr>
</tbody>
</table>

Using Design-Expert 13.0 software to design a three-factor, five-level quadratic rotation orthogonal combination test program, the simulation test results under each parameter combination were filled in, as shown in Table 8.

Table 8. The results of quadratic rotation orthogonal center combination test scheme.

<table>
<thead>
<tr>
<th>Test Serial Number</th>
<th>Experimental Factors</th>
<th>Evaluating Indicator</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$X_1$</td>
<td>$X_2$</td>
</tr>
<tr>
<td>1</td>
<td>−1</td>
<td>−1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>−1</td>
</tr>
</tbody>
</table>
5.2. Analysis of Test Results

The recorded data sets were analyzed and processed through the experimental design software, and the effects of the hole-forming device forward speed, traction angle, and hole-forming device mass are shown in Table 9. The $F$-value can identify the primary and secondary influence evaluation indexes, and the ANOVA results show that the primary and secondary influence on planting depth is forward speed > hole-forming device mass > traction angle; the primary and secondary influence on individual spacing is hole-forming device mass > forward speed > traction angle. The $R^2$ coefficient of determination, an essential indicator for determining the linear fit of the regression equation, was 0.97 for the planting depth equation and 0.9811 for the individual spacing equation. From this, it can be judged that 97% of the variation in $Y_1$ is due to $X_1$, $X_2$, and $X_3$, and 98.11% of the variation in $Y_2$ is due to $X_1$, $X_2$, and $X_3$, and the predicted values of the regression equations are highly correlated with the measured values [29].

Table 9. Analysis of variance of regression equations.

<table>
<thead>
<tr>
<th>Source</th>
<th>Planting Depth</th>
<th></th>
<th></th>
<th>Individual Spacing</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>df</td>
<td>Mean Square</td>
<td>$F$-Value</td>
<td>$p$-Value</td>
<td>df</td>
</tr>
<tr>
<td>Model</td>
<td>9</td>
<td>10.46</td>
<td>46.74</td>
<td>0.0001 **</td>
<td>9</td>
</tr>
<tr>
<td>$X_1$</td>
<td>1</td>
<td>1.27</td>
<td>5.67</td>
<td>0.0333 *</td>
<td>1</td>
</tr>
<tr>
<td>$X_2$</td>
<td>1</td>
<td>8.52</td>
<td>38.10</td>
<td>0.0001 **</td>
<td>1</td>
</tr>
<tr>
<td>$X_3$</td>
<td>1</td>
<td>1.40</td>
<td>6.25</td>
<td>0.0265 *</td>
<td>1</td>
</tr>
<tr>
<td>$X_1X_2$</td>
<td>1</td>
<td>26.97</td>
<td>120.56</td>
<td>0.0001 **</td>
<td>1</td>
</tr>
<tr>
<td>$X_1X_3$</td>
<td>1</td>
<td>7.66</td>
<td>34.25</td>
<td>0.0001 **</td>
<td>1</td>
</tr>
<tr>
<td>$X_2X_3$</td>
<td>1</td>
<td>1.49</td>
<td>6.65</td>
<td>0.0229 *</td>
<td>1</td>
</tr>
<tr>
<td>$X_1^2$</td>
<td>1</td>
<td>12.18</td>
<td>54.43</td>
<td>0.0001 **</td>
<td>1</td>
</tr>
<tr>
<td>$X_2^2$</td>
<td>1</td>
<td>34.89</td>
<td>155.94</td>
<td>0.0001 **</td>
<td>1</td>
</tr>
<tr>
<td>Residual</td>
<td>13</td>
<td>0.2238</td>
<td></td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>Lack of Fit</td>
<td>5</td>
<td>0.2455</td>
<td>1.17</td>
<td>0.4014</td>
<td>5</td>
</tr>
<tr>
<td>Pure Error</td>
<td>8</td>
<td>0.2101</td>
<td></td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>Cor Total</td>
<td>22</td>
<td></td>
<td></td>
<td></td>
<td>22</td>
</tr>
</tbody>
</table>

Notes: * indicates significant differences ($p < 0.05$) and ** indicates highly significant differences ($p < 0.01$).
The \( p \)-value can determine whether the effect of regression term parameters is significant or not [30], as shown in Table 8; the effect of \( X_2, X_1^2, X_2^2 \) on planting depth is highly significant \((p < 0.01)\); the effect of rest of the items on individual spacing is significant \((0.01 \leq p \leq 0.05)\); the effect of \( X_4, X_2, X_3, X_1X_2, X_2^2, X_3^2 \) on individual spacing is highly significant \((p < 0.01)\); \( X_1, X_3 \) had an insignificant effect on individual spacing; and the rest of the items had a significant effect on individual spacing \((0.01 \leq p \leq 0.05)\).

The quadratic polynomial regression equation between planting depth, individual spacing and test factor coding was established by eliminating the non-significant phase, as shown in the following formula:

\[
Y_1 = 27.5 - 0.3047X_1 - 0.79X_2 + 0.3201X_3 + 1.84X_1X_2 + 0.9788X_1X_3 - 0.4312X_2X_3 + 0.8755X_2^2 + 1.48X_2^2 \\
Y_2 = 88.54 - 0.637X_1 + 0.7712X_2 + 1.23X_3 + 0.925X_1X_2 - 0.325X_1X_3 - 0.7137X_2^2 + 1.07X_2^2 - 0.8551X_3^2
\]  

\((12)\)

\((13)\)

The response surface can reflect the relationship between the operational performance of the hole-forming device and each experimental factor. The response surface of the hole-forming device’s forward speed, traction angle, mass, and their interactions on planting depth and individual spacing can be obtained using Design-Expert 13.0, as shown in Figures 12 and 13.

\textbf{Figure 12.} Effect of traction angle, forward speed, and mass of the hole-forming device on planting depth, (a) effect of traction angle and forward speed on planting depth; (b) effect of traction angle and mass of the hole-forming device on planting depth; (c) effect of forward speed and mass of the hole-forming device on planting depth.

\textbf{Figure 13.} Effect of traction angle, forward speed, and mass of the hole-forming device on individual spacing, (a) effect of traction angle and forward speed on individual spacing; (b) effect of traction angle and mass of the hole-forming device on individual spacing; (c) effect of forward speed and mass of the hole-forming device on individual spacing.
The response-surface plots of the two-by-two interaction of forward speed, traction angle, and the hole-forming device mass on planting depth and individual spacing can be obtained from Figures 9 and 10: As the forward speed of the hole-forming device increases, the planting depth and individual spacing first decrease and then increase. This is because as the speed increases, the hole-forming device on the soil pressure first decreases until the vertical direction to reach equilibrium, the planting depth decreases, and then due to the speed continues to increase, the hole-forming device appears to glide, and the planting depth increases; As the speed increases, the angular velocity of the duckbill rotation also increases, the individual spacing decreases, the forward speed continues to increase, the duckbill and soil action is insufficient, resulting in duckbill slippage, and the individual spacing increases; With the increase in the traction angle of the hole-forming device, the vertical upward force becomes more extensive, the pressure of the hole-forming device on the soil becomes smaller, the planting depth has been reduced, and the individual spacing first increases and then decreases; As the mass of the hole-forming device increases, the pressure of the hole-forming device on the soil becomes more significant, and the longer the size of the duckbill inserted into the soil, the more the depth of the burrow hole increases. The individual spacing increases with the mass of the hole-forming device and then tends to stabilize.

5.3. Parameter Optimization

The depth and spacing at which cotton seeds are planted have an essential effect on the growth and development of cotton. Sowing at a deep depth may result in delayed or low seedling emergence, as the temperature and oxygen levels below the soil surface are unsuitable for seed germination. Also, even if the seeds can germinate, the seedling emergence process requires more energy, which may affect seedling growth and lead to overall slow plant growth. In addition, the higher moisture content in the deeper layers of the soil may increase the chances of certain soil-borne diseases. Sowing at too shallow a depth may result in poor seedling emergence due to external environmental influences such as temperature fluctuations and soil dryness. Moreover, shallow soil dryness does not favor downward root extension, resulting in a shallow root system, which can affect the plant's wind resistance and water uptake. If the spacing between the plants is too large, the ground will quickly become full of weeds, which will compete with the cotton for nutrients and water, affecting the growth of the cotton. If the spacing is too small, the competition between plants will be intense, which may lead to excess nutrient growth and insufficient reproductive growth, affecting flowering and boll formation. Furthermore, if the plants are too close to each other, this may lead to poor ventilation and light conditions in the field and increasing the incidence of pests and diseases. According to the planting requirements of the local cotton seeds researched, the planting depth of the cotton seeds is 27–28 mm and the individual spacing of the cotton seeds is 85–100 mm.

In order to seek the optimal parameter combinations of the interacting factors, the hole-formation performance regression model was solved by multi-objective optimization, with the constraints shown below:

\[
\begin{align*}
27 \leq Y_1 & \leq 28 \\
85 \leq Y_2 & \leq 100 \\
0.83 \text{m/s} \leq X_1 & \leq 1.11 \text{m/s} \\
st X_1 & \leq 10^\circ \\
16 \text{kg} \leq X_3 & \leq 18 \text{kg}
\end{align*}
\] (14)

To meet the agronomic requirements and increase the cotton germination rate and yield, the minimum planting depth and the minimum individual spacing were taken as the optimization objectives.
Using the optimization module in Design-expert 13.0, the hole-forming performance of the hole-former is optimal when the traction angle is 17.3°, the forward speed is 1.11 m/s, and the mass of the hole-forming device is 17.9 kg.

6. Conclusions

This paper takes a duckbilled hole-forming device as the research object and studies the influence of control parameters such as the forward speed, traction angle, and hole-forming device mass on the trajectory of a duckbilled hole-forming device, optimizes the control parameters through simulation and data processing, and searches for the optimization parameter combinations. The change rule of the control parameters on the influence of the hole-formation trajectory was explored, providing methods and ideas for selecting and optimizing the hole-forming device manufacturing parameters. The following are the main conclusions of this study:

1. Through the method of DEM-MBD coupled simulation, it is found that the disturbance of the soil in the process of hole formation by a duckbilled hole-forming device is mainly concentrated in the forward direction and vertical direction of the hole-former, and the hole is formed by squeezing and shearing the soil;
2. The size of the forward speed of a duckbilled hole-forming device directly affects the hole-forming performance of the hole-forming device, and a forward speed that is too small or too large will result in too large a planting depth and individual spacing, which will not be able to meet the agronomic requirements;
3. Through the optimization of the hole-formation performance parameters of the hole-forming device, it is obtained that the hole-formation performance of the hole-forming device is optimal when the traction angle is 17.3°, the forward speed is 1.11 m/s, and the mass of the hole-forming device is 17.9 kg.

In an environment where labor costs are high, and mechanization is dominant, farmers and machinery companies must complete sowing with high quality. Our team researched the difficulties encountered in the local cotton sowing process. It improved the sowing performance by optimizing the parameters of the hole-forming device. However, there still needs to be a gap between the current sowing efficiency and the performance of the sowing machinery and that of the developed countries. Our team will continue to be dedicated to research on the development of agricultural machinery in the future.

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Conflicts of Interest: The authors declare no conflicts of interest.
References


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