Mechanism analysis and performance improvement of mechanized ridge forming of whole plastic film mulched double ridges

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Abstract: In order to achieve high-performance and mechanization construction standard of whole plastic mulched double ridge seedbed, and to meet its forming process and corresponding agronomic requirements of the mechanized double ridge seedbed, the key working parameters such as the speed of rotary blade group, the thickness of upturned sod and the power consumption of rotary blade group under different parameters were analyzed based on related working performance in ridge forming. Also, the test factors and their range of values were finally determined in this study. Discrete element method (DEM) simulation was applied in the numerical simulation of the mechanized ridge forming process of whole plastic mulched double ridges, and the ridge forming effect and digging resistance variation characteristics of different types of shovels were compared. Taking the forward speed of the combined machine, the penetration angle of the arc-shaped shovel and the depth of rotary tillage as independent variables, and the qualified rate of seedbed tillage as the response value, the mathematical model between the test factors and the qualified rate of the seedbed tillage was established, to explore the influence sequence of the factors on the qualified rate of seedbed tillage, and obtained the following optimal working parameters of the ridge forming device: the advancing velocity of the combined machine of 0.50 m/s, penetration angle of the arc-shaped shovel of 31°, rotary tillage depth of 140 mm, and average qualified rate 95.20% of seedbed tillage in corresponding simulation verification test. Field test showed that the average qualified rate of seedbed tillage in ridge forming device was 93.60%, which was close to that of the simulation results. The actual working condition of the sample machine was basically in line with the simulation process and could relatively precisely reflect the mechanized ridge forming mechanism of whole plastic double ridges. The results showed that the established DEM model and its parameter setting were relatively accurate and reasonable.

Keywords: whole plastic film mulched double ridges, mechanized ridge forming, DEM, numerical simulation, parameter optimization

1 Introduction

Furrow sowing technology with whole plastic film mulching on double ridges is a breakthrough and innovative technology in dry farming in Northwest China, which serves as an integration of the functions of evaporation suppression, rainfall collecting and ridge and furrow planting[1,2]. By applying the principle of runoff generation on double ridges and flow concentration in furrows, it can store natural precipitation and reduce evaporation from farmland to the greatest extent, and transform precipitation into effective soil moisture to the crop root, thus has improved the efficient water use mechanism in the dry-farming region of the Loess Plateau in Northwest China, and significantly improved the comprehensive agriculture productivity in northwest arid areas, marking great significance in ensuring food security and increasing

farmers' income[3].

Furrow sowing technology with whole plastic film mulching on double ridges was first proposed for maize planting, requiring finishing mechanized tillage and forming of big and small ridges and furrows of seedbed before mulching and soil covering, to prepare for sowing seeds on the film in the small ridges[4]. Therefore, it is necessary to construct high-performance seedbed with film-mulched double ridges to ensure efficient sowing of the mulched seedbed. If the shape of double ridges is irregular, it will result in malfunction of the film mulching and soil covering device and poor fitting between mulching film and ridges. Therefore, the stability and reliability of the mechanized forming of irregular-shaped double ridges are directly related to the implementation of furrow sowing of the whole plastic film on double ridges. Thus, mechanized ridge forming is the key factor influencing the quality of seedbed. It is necessary to analyze the working mechanism of the technology to ensure the high-performance of double ridges on irregular-shaped seedbed[5,6].

In this study, based on the designed crosswise belt type ridge forming and film-mulching combined machine for whole plastic film mulched double ridge tillage[7], the working performance of the machine in big and small ridges was further improved based on numerical simulation and the actual test. Taking related parameters in tillage as the independent variables, the qualified rate of double ridge tillage was measured under different factor combinations through tests, then response surface method was applied to determine the influence of the factors and their

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interaction effect on the qualified rate of tillage and obtain the optimal combination of working parameters of the machine, to achieve the optimal mechanized ridge forming effect of the whole plastic film on double ridges.

2   Machine structure and working principles

2.1   Structure

The designed crosswise belt type ridge forming and film-mulching combined machine for whole plastic film mulched double ridge tillage is mainly composed of the suspension device, fertilizer distribution system, spraying system, mechanized ridge forming device, ridge and crosswise belt type soil digging and covering device, ridge film-mulching device, drilling-suppressing device and walking ground wheel.   The structure of the machine and key parts in double ridge tillage is shown in Figure 1[7].
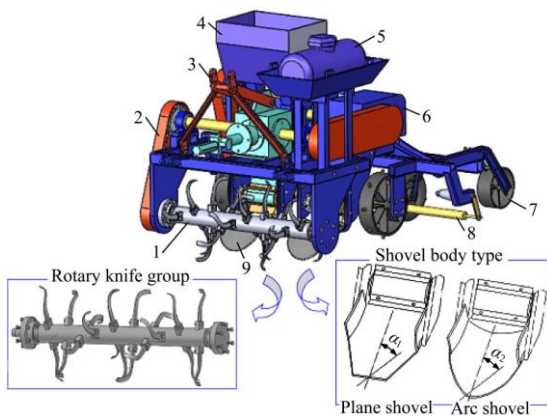

1. Rotary blade group   2. Transmission device   3. Suspension frame   4. Fertilizer device   5. Spraying device   6. Ridge and crosswise belt type soil digging and covering device   7. Compression device   8. Film-mulching device   9. Digging shovel

Figure 1   Structure of the crosswise belt type whole plastic film ridging and mulching machine on double ridges

A four-wheel tractor is mounted in the rear suspension of the combined machine.   The tractor power is input into the gearbox and further transmitted to the rotary blade group to cut the soil, and the digging shovel finishes ditching and ridge forming with the advancing of the rotary blade group.   When the rotary blade group cuts and pushes soil to the center, the digging shovel digs ditch, so as to form a double ridge of irregular shape in a mechanized way.

2.2   Mechanized ridge forming process and agronomic requirements

As shown in Figure 2, the seedbed of whole plastic-film mulching on double ridges has a big ridge and a small ridge, covering a total width of 1100 mm.   The big ridge is 700 in width and 100-150 mm in height; the small ridge is 400 mm in width and 150-200 mm in height.   The ridges are all covered by film and seeds are sown in the ditches.   The agronomic cultivation mode of whole plastic film mulching on double ridges is shown in Figure 2[5,8-9].
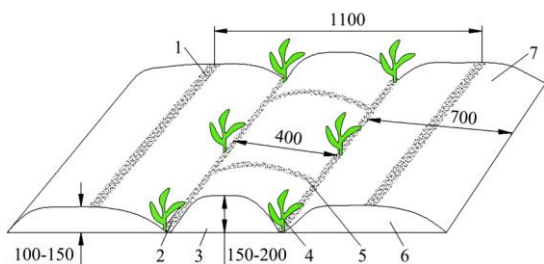

1. Central soil belt on mulching film   2. Soil belt on ridge   3. Small ridge   4. Fertilizer device   5. Crosswise soil belt   6. Big ridge   7. Mulching film

Figure 2   Agronomic cultivation mode of whole plastic film mulching on double ridges

3   Analysis of key working factors

3.1   Ridge forming device

As shown in Figure 3, the ridge forming device of the combined working machine is mainly composed of a rotary tillage cutter group, a digging shovel and a frame connecting them.   The rotary tillage blade is arranged in a double helix on the blade shaft, and the digging shovel of mainly two types (arc-shaped and plane shove) can be replaced in work as required.   Meanwhile, the penetration angle of the shovel can be adjusted within the range of 15 °-45 °according to the mechanized ridge forming effect.
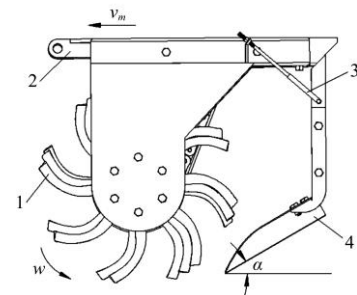
1. Rotary blade group   2. Body frame   3. Penetration angle adjusting device   4. Digging shovel

Note: v_m is the advancing velocity of the combined machine; w is the angular velocity of the rotary blade group; α is the penetration angle of the digging shovel into the soil.

Figure 3   Structure diagram of ridge forming device

When the ridge forming device goes forward with the combined machine, the rotary blade group turns at a high speed, throwing the soil backward and pushing it to the middle.   At this time, the shovel completes ditching and realizes the construction of the small ridge and 1/2 big ridge on both sides.   Meanwhile, in the ridge forming of the next group, the left side 1/2 big ridge connects with the right side 1/2 big ridge of the last group, and the big ridge is constructed with the connecting and suppression of the central film-mulched soil belt.   Therefore, it can be concluded by analyzing the working principle of the ridge forming device that, the advancing velocity of the ridge forming device, the depth of rotary tillage, and the type of shovel and penetration angle have some influence on the quality of the mechanized double ridge forming of the seedbed.
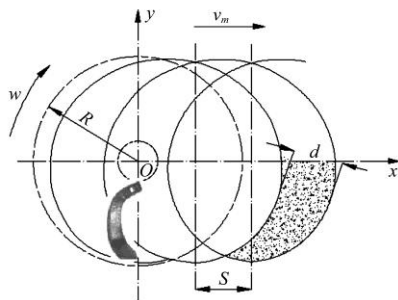
3.2   Rotary blade group

As shown in Figure 1, in order to improve the balance of the blade shaft in rotation, 10 blades on the left side of the blade shaft are arranged in dextrorotation, and 10 blades on the right side are arranged in levorotation.   In addition to rotating around the axis, the rotary blade also moves at a uniform speed along with the advance of the machine.

In order to let the rotary blade group cut the soil effectively, the movement trajectory of the end point of the rotary blade is a trochoid (rotary speed ratio $\lambda>1$), the rotation direction of the rotary blade is clockwise, and the working process of the rotary blade group is shown in Figure 4[10].

Taking the rotation center of the rotary blade as the origin point O, the movement coordinate system of the rotary blade group was established, and the absolute velocity of the end point of the rotary blade group and the thickness of the upturned sod during positive rotary tillage are:

$$\begin{cases} v_1 = v_m\sqrt{1+\lambda^2-2\lambda\sin(wt)} \\ d = \dfrac{2\pi v_m}{zw}\sin\dfrac{\lambda\cos(wt)}{\sqrt{\lambda^2-2\lambda\sin(wt)+1}} \end{cases} \quad (1)$$

where, v_1 is the absolute speed of the end point of the rotary blade group, m/s; v_m is the advancing velocity of the combined machine, m/s; λ is the rotary speed ratio; w is the angular velocity of the rotary blade group, rad/s; z is the number of rotary blades in the same plane.

Note: v_m is the advancing velocity of the combined machine; w is the angular velocity of the rotary blade group; R is the turning radius of the rotary blade; S is the bite length; d is the thickness of the upturned sod.

Figure 4   Schematic diagram of working process of rotary blade group

It can be obtained from Equation (1) that, both the absolute speed of the end point of the rotary blade group and the thickness of the upturned sod during positive rotary tillage are related to the advancing velocity of the combined machine v_m, so the advancing velocity of the combined machine is another key factor affecting the performance of ridge forming. According to preliminary research, the advancing velocity of the combined machine is between 0.5-1.0 m/s.

In the process of mulching and soil covering, most of the power of the rotary blade group is consumed in entering the soil, soil turning and pushing[11], then the power consumption of the rotary blade group can be estimated approximately as follows[12]:

$$\begin{cases} P = 0.1K_\lambda v_m b d_1 \\ b = 2b_1 + b_2 \end{cases} \quad (2)$$

where, P is the power consumption of the rotary blade group, kW; K_λ is the resistance on unit area of rotary tillage, and let K_λ= 6.3 N/cm²[13]; b is the tillage width of the rotary blade group, mm; d_1 is rotary tillage depth, and d_1=10-15 cm; b_1 is the width of the 1/2 big ridge, according to cultivation model of the whole plastic film on double ridges (Figure 2), b_1=0.35 m; b_2 is the width of the small ridge, and b_2=0.40 m according to cultivation model of the whole plastic film on double ridges (Figure 2).
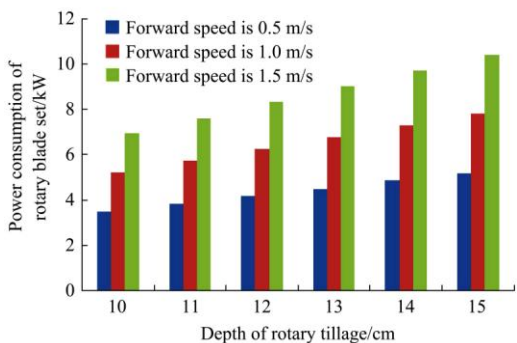

Figure 5   Comparison of power consumption of rotary blade group under different tillage depths and working speeds

When the advancing velocity of the combined machine was 0.5 m/s, 0.75 m/s, 1.0 m/s, and the rotary tillage depth was 10 cm, 11 cm, 12 cm, 13 cm, 14 cm and 15 cm, then the power consumption of the rotary blade group in ridge forming was calculated based on Equation (2), and results are shown in Figure 5.

It is shown by comparing the power consumption of rotary blade group under different tillage depths and working speeds that, tilling depth of the rotary blade group had an influence on power output, working performance and construction cost of the seedbed to some extent, and it is one of the key factors affecting the working performance of the ridge forming device.

4   Simulation test of the mechanized ridge forming of whole plastic film mulching on double ridges

4.1   Numerical simulation of mechanized ridge forming process

In order to further analyze the dynamic characteristics of the ridge forming and ditching by rotary tillage of the ridge forming device, Discrete Element Method (DEM) was adopted for numerical simulation of the working process of the ridge forming device. For convenience in calculation and analysis on the model, also refer to existing research, spherical particles with a diameter of 3 mm were adopted as soil particles in the modeling, Hertz-Mindlin (no-slip) was adopted for soil particle-soil particle, soil-particle-rotary blade group models, and contact model of the digging shovel. According to references [5,14-17], the simulation model was set, the parameters in the simulation test are shown in Table 1.

Table 1   Parameters of materials and contact

Items	Parameters	Numerical values
Soil particles	Poisson's ratio	0.4
	Shear modulus/Pa	1.0×10^6
	Density/kg m^{-3}	1364
Rotary blade group, digging shovel	Poisson's ratio	0.28
	Shear modulus/Pa	3.5×10^{10}
	Density/kg m^{-3}	7850
Soil particle-soil particle	Recovery coefficient	0.2
	Static friction coefficient	0.4
	Dynamic friction coefficient	0.3
Particle-rotary blade group, digging shovel	Recovery coefficient	0.3
	Static friction coefficient	0.4
	Dynamic friction coefficient	0.1

In order to reduce the running time and storage space of the software, a virtual soil bin (2600 mm (length)×1400 mm (width)× 600 mm (height)) with discrete element mulched film was established for ridge forming. The software Solidworks was used to create the geometric simulation model of the ridge forming device and import it into the EDEM software. The numerical simulation process of mechanized ridge forming is shown in Figure 6, the simulation time step is 1.23×10^{-5} s, and the total simulation time is 2.40 s[18,19].

As shown in Figures 6a-6i, when the advancing velocity of the combined machine is 0.75 m/s, the penetration angle of the arc-shaped shovel is 30°, the rotary tillage depth is 12 cm, and the time t=0.21-2.40 s, the mechanized ridge forming process of whole plastic film mulching on double ridges was numerically simulated. The observation of the interaction of the rotary blade group, digging shovel and seedbed soil should be started after stable contact was achieved between rotary blade group and soil, therefore, from t = 0.21 s, the DEM numerical simulation approached the working status of mechanized ridge forming, as shown in Figure 6a. When t=0.36-0.63 s, the arc-shaped shovel followed the rotary blade group to dig the soil and turn it over to form ridges and furrow; when t=0.86 s, the arc-shaped shovel fully entered the soil and dug up the soil particles, which were mixed

with the high-speed soil particles after cutting and throwing by the rotary tiller group, resulting in a relatively complicated flow field (Figure 6d); from $t=1.16$-2.16 s (Figures 6d-6g), the boundary between the particle flow field of soil by high-speed rotary cutting and that by digging shovel became clear gradually, and the small ridge in the middle and two 1/2 big ridges on both sides were formed. Also, the positions of soil particle flow by the rotary

blade group and dispersion degree were higher than that by the shovel, and that is the main reason of dust flying in the process of rotary tillage and ridge forming. When $t=2.40$ s, the simulation process of mechanized ridge forming was finished, and a double-ridge seedbed of irregular shape was formed to meet the agronomic requirement of whole plastic film mulching on double ridges.
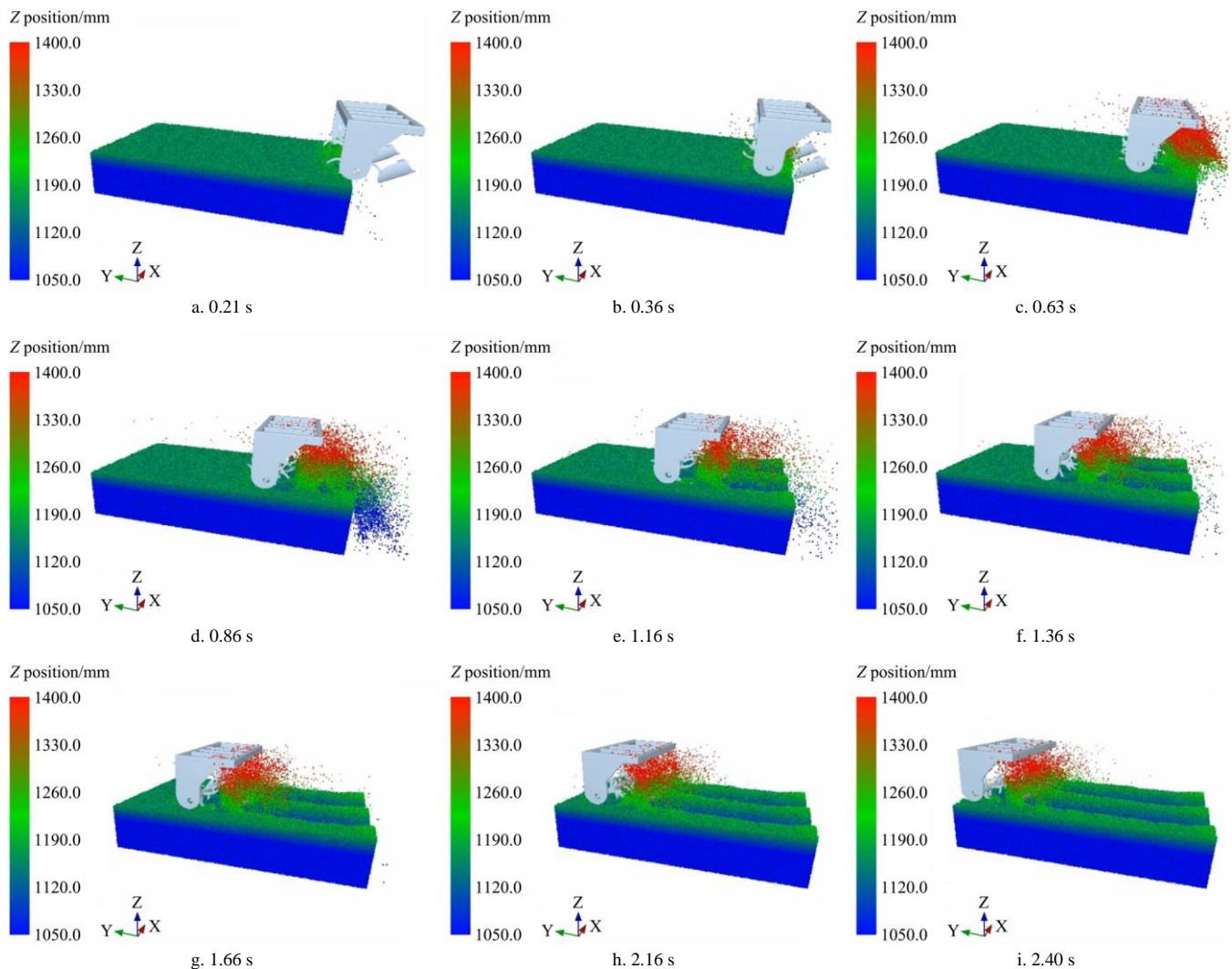

Figure 6   Numerical simulation of the mechanized ridge forming of whole plastic film mulching on double ridges

4.2   Comparison of the effect of two types of shovels

Digging shovel is the key component and connecting part in ridge forming and ditching and for the soil digging device. During the operation, it is necessary to make sure that the curve of the formed ridge and furrow is smooth and their shape meets the relevant agronomic requirements, and that the resistance in digging should not be too large.

Two types of shovels, arc-shaped and plane shovels were selected (Figures 7a and 7b), and the penetration angle of both types of shovels were 30° (ditching shovel is a part of digging soil, so the tilt angle should not be too large, and the preliminary experimental study shows that the tilt angle ≤45° is appropriate), the advancing velocity of the combined machine was 0.75 m/s, and the depth of rotary tillage was 12 cm, the specific operation process of the ridge forming device and the effect of double ridge tillage are shown in Figure 7. As shown in Figures 7c and 7d, with the same working parameters on the ridge forming device, shapes of shovels had a great influence on the parameters of the double ridge seedbed structure of irregular shape. The plane digging shovel

aroused great disturbance in seedbed soil, while the formed ridges had little difference in size. Compared with the working effect of the plane digging shovel, the arc-shaped shovel proved a better ridge forming effect. Since the angle of inclination of the small ridge in the middle was high, and the sunken bottom of the furrow was obvious, it was good for the collection of invalid rainfall under 10 mm and film-mulching.

Meanwhile, it can be seen from the variation curve of digging resistance of both shovels (Figure 8) under different penetration angles (15°, 30°, 45°) that, under the same working conditions, the digging resistance of the arc-shaped shovel is slightly higher than that of the plane shovel, mainly because the arc-shape can improve the soil fluidity, also can increase the angle between the shovel bottom plate and the side plate, so as to avoid soil accumulation, and ensure the double effect of ridging and ditching quality. It can be found through the comparison of curves in Figures 8a and 8b that, the digging resistance of the plane shovel was not very sensitive to the variation of penetration angles, which had a more significant influence on the digging resistance of the arc-shaped

shovel. Therefore, in combination with the characteristics of forming effect and digging resistance of two types of shovels, the arc-shaped shovel is more suitable for double ridge forming of

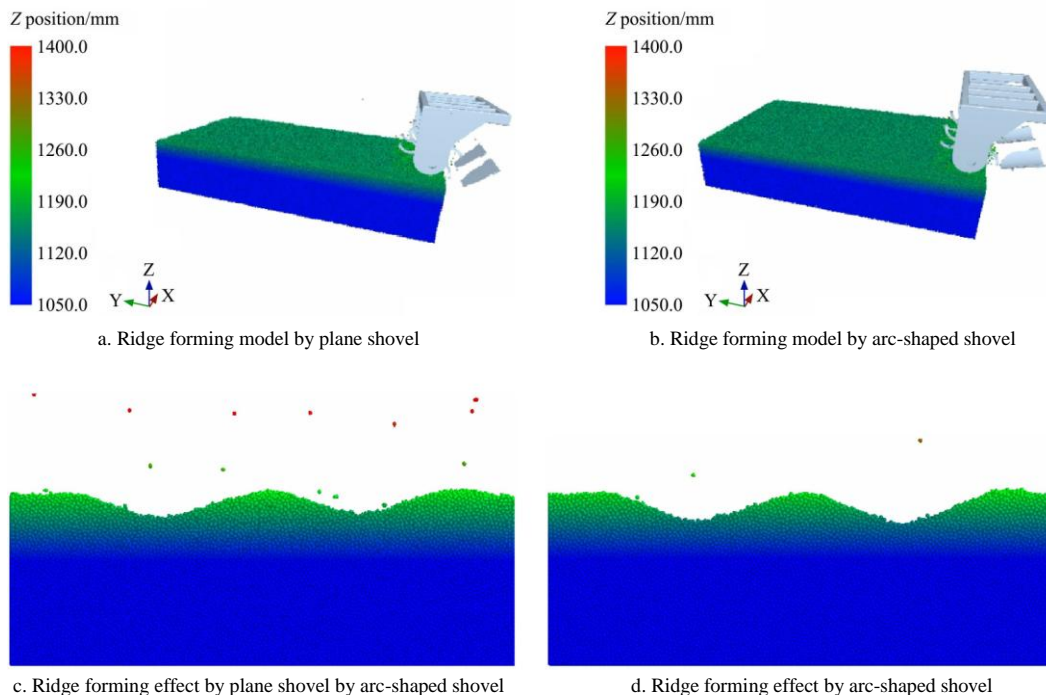whole plastic film mulching, but the penetration angle still needs to be further optimized by test[20,21].

a. Ridge forming model by plane shovel

b. Ridge forming model by arc-shaped shovel

c. Ridge forming effect by plane shovel by arc-shaped shovel

d. Ridge forming effect by arc-shaped shovel

Figure 7   Models of ridge forming device with different types of shovels

a. Variation of digging resistance under different penetration angle of the plane shovel

b. Variation of digging resistance under different penetration angle of the arc-shaped shovel
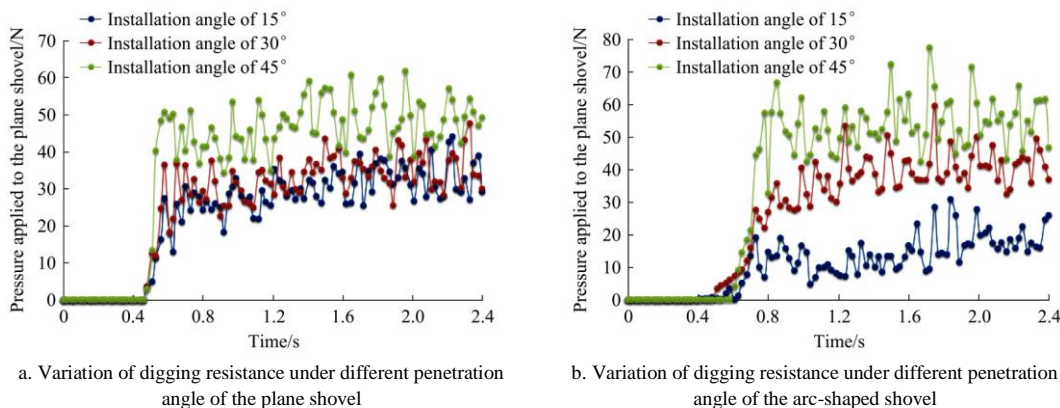
Figure 8   Variation curve of digging resistance under different penetration angle of the two types of shovel

5   Parameter optimization of ridge forming by arc-shaped shovel

5.1   Test design and method

According to the standard of NY/T 987-2006 of working quality of the plastic film mulching planter and tillage requirement for seedbed of whole plastic-film mulching on double ridges (the total width of ridges is 1100 mm, of which the width of the big ridge is 700 mm and the height is 100-150 mm; the width of the small ridge is 400 mm and the height is 150-200 mm, which can be recognized as qualified for the cultivation of double ridges of

irregular shape). The tillage qualified rate of the ridge forming device is taken as the evaluation index for the simulation test on working parameter optimization. Based on the simulation model established in Figure 9, the cross-section of seedbed at different positions was solved at random after each simulation test, and the tillage qualified rate of the seedbed was determined. The formula for determining the qualified rate of seedbed tillage is

$$Y = \frac{N_1}{N} \times 100\% \qquad (3)$$

where, Y is the seedbed tillage qualified rate, %; N_1 is the test points in seedbed tillage; N is the total test points.
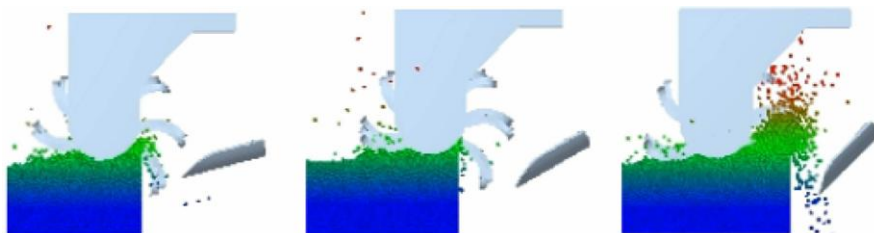

Figure 9   Simulation model of ridge forming by arc-shaped shovel

Based on the analysis of the working parameters of the arc-shaped shovel in ridge forming, the advancing velocity x_1 (0.50-1.00 m/s), the penetration angle of the arc-shaped shovel x_2 (15°-45°) and the depth of rotary tillage x_3 (100-150 mm) were selected as test factors, and the qualified rate of seedbed tillage Y was taken as the evaluation index. Three-factor three-level response surface analysis method was used in the test, and 17 sets of response surface analysis tests (Table 3) were carried out according to the coded levels of each test factor shown in Table 2. Each group of tests was repeated three times, and the average value of the three tests was taken as the test result, then data processing was done by using Design-Expert 8.0.6.1.

Table 2   Coding of factors and levels

Coding table	Factors		
	Advancing velocity of the combined machine x_1/m s^{-1}	Penetration angle of the arc-shaped shovel x_2/(°)	Rotary tillage depth x_3/mm
−1	0.50	15	10.0
0	0.75	30	12.5
1	1.00	45	15.0

5.2   Establishment and test of regression model

As shown in Table 3, the qualified rate of seedbed tillage could reach 64.5%-91.3%, but the performance stability of double ridge tillage and the quality of mechanized ridge forming varied greatly during the test.

Design-Expert 8.0.6.1 was used to analyze test results, and the quadratic regression model of qualified rate Y of seedbed tillage expressed by coding values was obtained.

$$Y = 85.32 - 4.40X_1 + 5.81X_2 + 0.84X_3 - 2.47X_1^2 -$$
$$7.30X_2^2 - 2.15X_3^2 + 3.85X_1X_2 - 1.90X_1X_3 - 1.48X_2X_3 \quad (4)$$

where, Y is the qualified rate of seedbed tillage, %; X_1 is the coded value of the advancing velocity of the combined machine; X_2 is the coded value of the penetration angle of the arc-shaped shovel into the soil; X_3 is the coded value of the rotary tillage depth.

Table 3   Results of response surface analysis

Test No.	X_1	X_2	X_3	Y/%
1	−1	1	0	78.9
2	1	−1	0	64.5
3	0	0	0	84.4
4	−1	0	1	91.3
5	−1	0	−1	82.8
6	1	0	−1	73.9
7	0	0	0	83.6
8	1	0	1	74.8
9	0	−1	−1	68.2
10	0	1	−1	84.9
11	0	−1	1	69.8
12	−1	−1	0	77.1
13	1	1	0	81.7
14	0	0	0	87.4
15	0	0	0	84.1
16	0	0	0	87.1
17	0	1	1	80.6

The variance analysis and the significance test of regression coefficients were carried out for the above quadratic regression model. The results are shown in Table 4.

According to the analysis in Table 4, the p-value (0.0045) of

the quadratic regression model is less than 0.01, which indicates that the regression model is very significant; the missing P value (0.0578)>0.05, i.e., the misfit is not significant, which indicates that the quadratic regression equation fitted by the model is consistent with the actual situation, and can correctly reflect the relationship between the qualified rate of seedbed tillage Y and factor X_1, X_2 and X_3. The regression model can be used to predict the results of various experiments in the optimization test. The effects of the first item X_1 (the advancing velocity of the combined machine), the second item X_2 (the penetration angle of the arc-shaped shovel) and the second item X_2^2 (the penetration angle of the arc-shaped shovel) on the qualified rate of the seedbed tillage were significant; the interaction item $X_1 X_2$ (the interaction between the advance speed of the combined machine and the angle of the arc shovel) was significant, and the other items were not significant. According to the regression coefficient of each factor of the model, the main order of the influence of each factor on the qualified rate of seedbed tillage is X_2, X_1, X_3, that is, the penetration angle of the arc-shaped shovel into the soil, the advancing velocity of the combined machine and the depth of rotary tillage.

Table 4   Variance analysis of regression equation

Source of variation	Sum of squares	Degree of freedom	Mean square	F	P
Regression	802.54	9	89.17	8.85	0.0045**
X_1	154.88	1	154.88	15.37	0.0057**
X_2	270.28	1	270.28	26.82	0.0013*
X_3	5.61	1	5.61	0.56	0.4798
X_1X_2	59.29	1	59.29	5.88	0.0457*
X_1X_3	14.44	1	14.44	1.43	0.2702
X_2X_3	8.70	1	8.70	0.86	0.3837
X_1^2	25.74	1	25.74	2.55	0.1540
X_2^2	224.23	1	224.23	22.25	0.0022*
X_3^2	19.42	1	19.42	1.93	0.2077
Residual error	70.54	7	10.08		
Lack-of-fit	57.75	3	19.25	6.02	0.0578
Error	12.79	4	3.20		
Sum	873.08	16			

Note: * significant (p<0.05) and ** extremely significant (p<0.01).

As shown in Figure 10, for the fourth group of tests shown in Table 3, when the advancing velocity of the combined machine was 0.50 m/s, the penetration angle of the arc-shaped shovel was 30° and the depth of rotary tillage was 150 mm, the qualified rate of double ridge tillage process of the ridge forming device under different angles of view was 91.3%, as shown in Figure 10e.

As shown in Figure 11, for the 9th group of tests shown in Table 3, when the advancing velocity of the combined machine was 0.50 m/s, the penetration angle of the arc-shaped shovel was 15° and the depth of rotary tillage was 100 mm, the qualified rate of double ridge tillage process of the ridge forming device under different angles of view was 68.2%, as shown in Figure 11e.

It was found in the simulation test that there were some differences in the quality effect of the big and small ridges and the furrow after double ridge tillage under different test factor combinations. From the simulation analysis of response surface in the 4th group and the 9th group (Figures 10a-10c and Figures 11a-11c) and cross-sectional size distribution of double ridge tillage (Figures 10d and 11d), it can be concluded that the effect of the penetration angle of the arc-shaped shovel on the qualified rate of seedbed tillage was significant, which is consistent with the variance analysis of the regression equation.
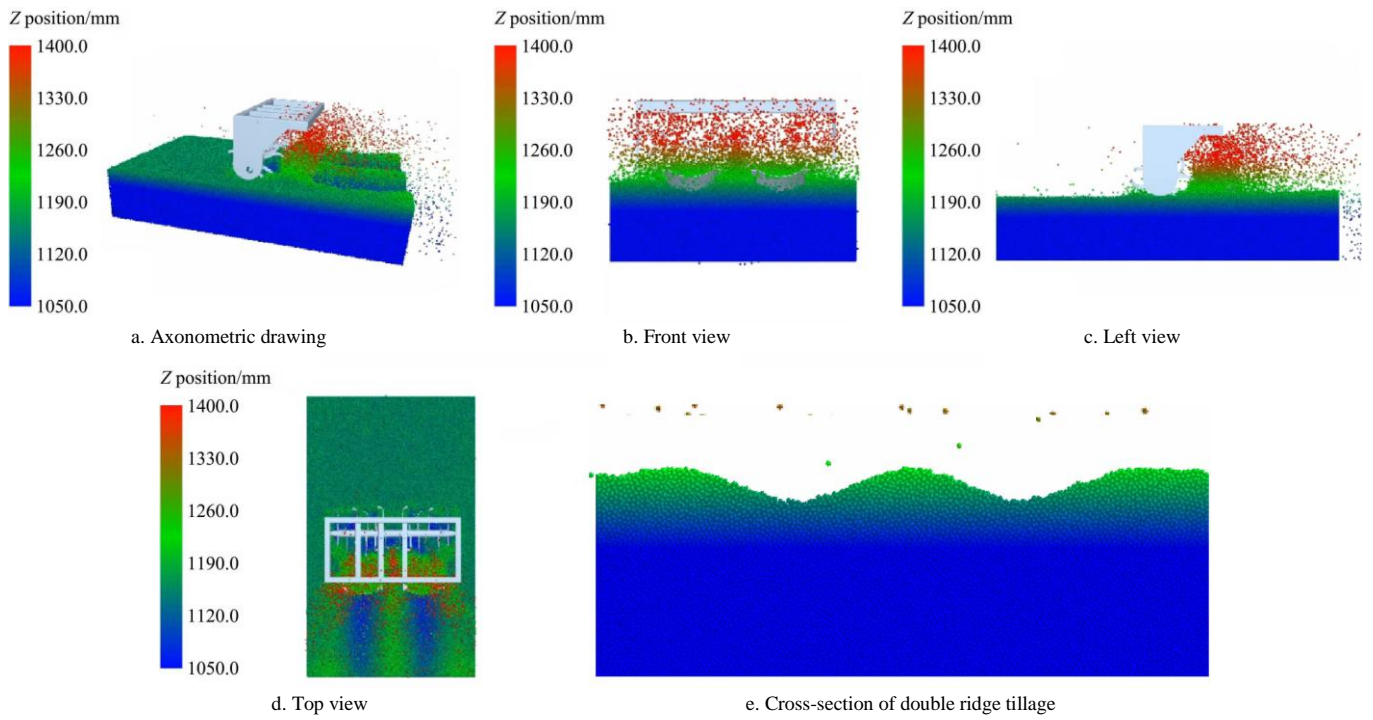
a. Axonometric drawing

b. Front view

c. Left view

d. Top view

e. Cross-section of double ridge tillage

Figure 10   The 4th group of response surface simulation analysis tests

a. Axonometric drawing

b. Front view

c. Left view

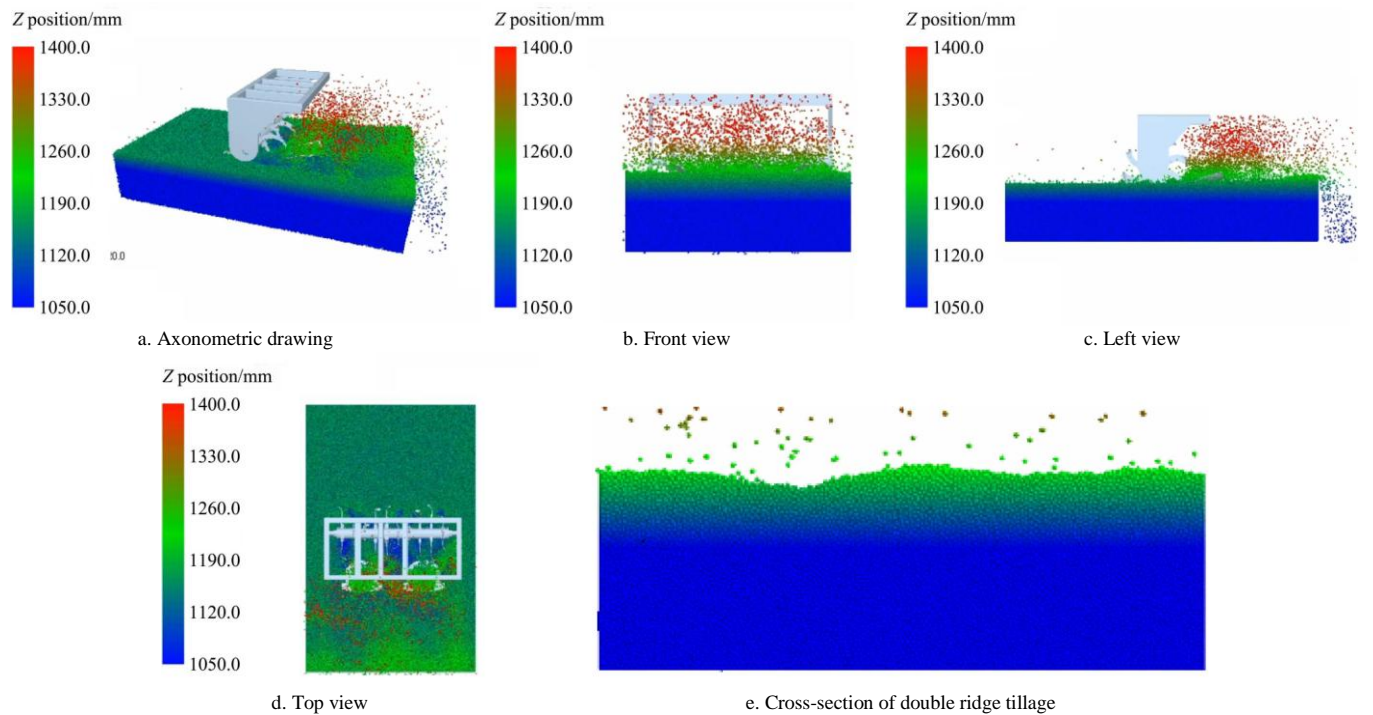d. Top view

e. Cross-section of double ridge tillage

Figure 11   The 9th group of response surface simulation analysis tests

5.3   Analysis of interaction items of the model

According to the quadratic regression model (4), a response surface diagram of the relationship of all test factors can be drawn, and the shape of the response surface can reflect the influence of interaction factors.   From the results in Table 4, it can be found that only the interaction between the advancing velocity of the combined machine and the penetration angle of the arc-shaped shovel had a significant effect on the qualified rate of seedbed tillage, while the influence of other interactive factors was not significant.   Thus a response surface of two interactive factors was made, as shown in Figure 12.

As can be seen from Figure 12, the qualified rate of seedbed tillage dropped gradually when the penetration angle of the arc-shaped
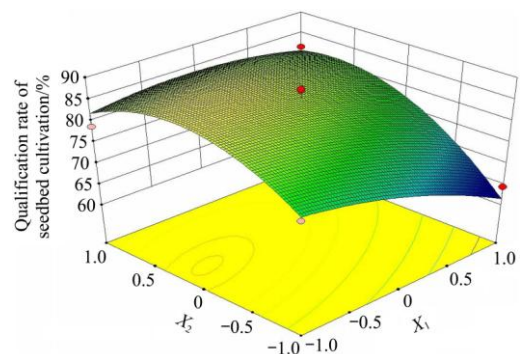

Figure 12   Effects of advancing velocity and penetration angle of arc-shaped shovel on qualified rate of seedbed tillage
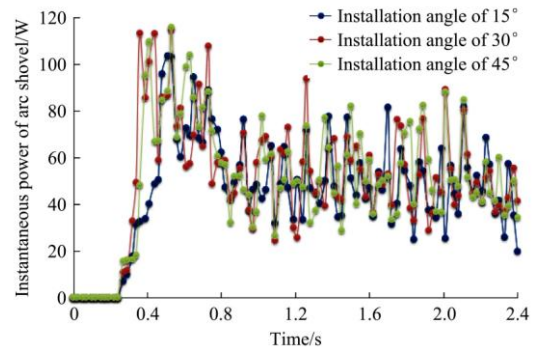
shovel was fixed at a certain level and the advancing velocity of the combined machine increased from 0.50 m/s to 1.00 m/s. The reason is that, with the increase of advancing velocity in ridge forming, the time of soil cutting and pushing as well as digging by the rotary blade group and arc-shaped shovel became shorter, weakening the plasticity of soil, causing falling of soil particles on both sides of the big and small ridges and covering the furrows. As a result, the double ridge tillage of the seedbed could not meet the qualification requirement.

Through the comparative analysis of Figures 13a and 13b, it can be seen that the instantaneous power of the arc-shaped shovel was obviously lower than that at 1.00 m/s when the advancing velocity was 0.50 m/s, indicating that the advancing velocity of the combined machine had an obvious effect on the energy consumption of seedbed tillage by the ridge forming device. When the power of the combined machine is constant, the advancing velocity is the key factor affecting the double ridge tillage performance of the seedbed, showing consistency with the variance analysis of the regression equation. Meanwhile, under the same advancing velocity, the larger the penetration angle of the arc-shaped shovel was, the higher the instantaneous power of the shovel would be, so it is necessary to find out the optimal working parameters of the ridge forming device.
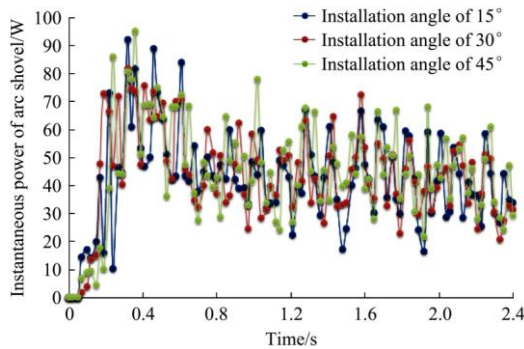
a. Instantaneous power of arc-shaped shovel at advancing velocity of 0.5 m/s   b. Instantaneous power of arc-shaped shovel at advancing velocity of 1 m/s

Figure 13   Instantaneous power variation curve of arc-shaped shovel under different advancing speed

5.4 Optimization of working parameters of the ridge forming device

By taking the 100% qualified rate of seedbed tillage in ridge forming as the target, the Optimization-Numerical module in the software Design-Expert 8.0.6.1 software was used for the optimal solution of the regression equation model, and the optimal working parameters of the ridge forming device were as follows: the advancing velocity of the combined machine was 0.50 m/s, the penetration angle of the arc-shaped shovel was 31°, and the rotary tillage depth was 140 mm.

In order to verify the reliability of the regression model (4), the optimal working parameters of the ridge forming device were used to simulate the tillage performance of the seedbed (Figure 14). In order to ensure that the simulation model approaches the actual test conditions, the lifting device model that could disturb soil was mounted on the top of the arc-shaped shovel. Test results showed that the qualified rate of seedbed tillage was 95.2%, which was obviously improved before the optimization. The results showed that with the optimized operation parameters, soil cutting and pushing effect in ridge forming could be improved, the depth of furrow excavation could be increased, the disturbance to seedbed soil could be alleviated, the tillage quality of double ridges could be improved, so as to meet the agronomic requirements in furrow sowing on whole plastic film mulching on double ridges. Therefore, the established regression model is reliable.
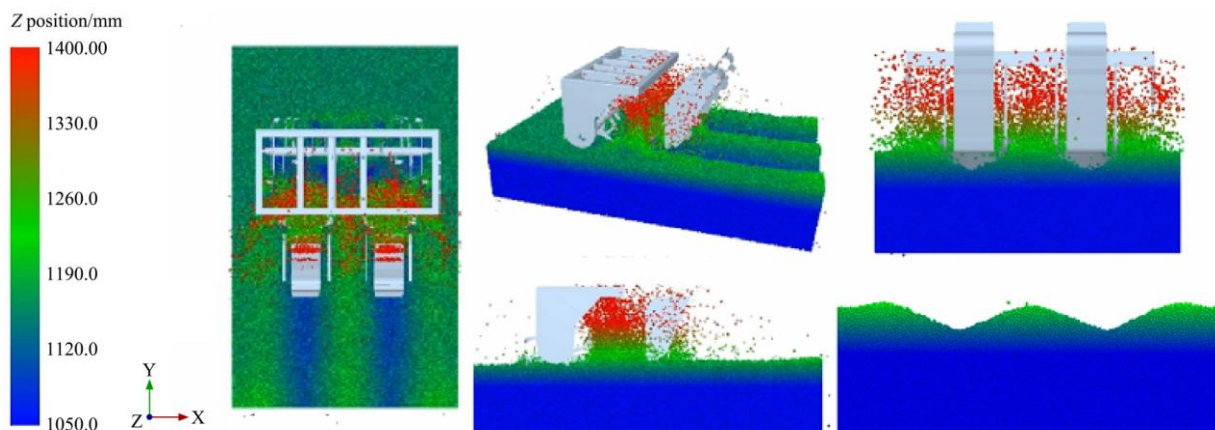

Figure 14   Simulation test on tillage performance of ridge forming device under optimal working parameters

6   Field verification test

In order to further verify the tillage performance of the ridge forming device under the optimal working parameters, the test was carried out in the experimental field of Taohe Tractor Manufacturing Co., Ltd. of Lintao County, Dingxi City, Gansu Province in June 2019 (Figure 15). The soil in the test site was loessal soil with the soil moisture content of 16.86%, the soil bulk density was 1300 kg/m³, soil compactness<0.20 MPa. The test field was flat, loose with few preceding crops. By referring to the standard NY/T 986-2006 of "Working quality of film mulching machine" and DB62/T 1935-2010 Operation procedure and

operation quality acceptance of whole plastic double ridge mulching machine", the 15-meter seedbed tillage performance with whole plastic film on double ridges after the operation was tested. The average values of six working areas were taken as the test result, and the qualified rate of seedbed tillage was 93.6%.

Figure 15   Field performance test

It was found in the test that when the surface of the field is rugged with many soil and stone pieces and the soil moisture content is high, it may easily undermine seedbed tillage quality due to imbalance in cutting of the rotary blade group and the arc-shaped shovel and soil adhesion. The actual working condition of the sample machine was basically the same as the simulation process, which can reflect precisely how the ridge forming device can realize the construction of double ridge seedbed. The result shows that the discrete element simulation model is relatively accurate, and it is feasible to use the discrete element method to simulate and study the ridge forming process through rotary tillage and ditching. At the same time, due to the great difference between the parameters setting of discrete element soil particles and the actual aggregation degree in rotary tillage, and the wide variation of soil moisture content, the actual interaction between the rotary blade group, the arc-shaped shovel and the seedbed soil can not be fully reflected, therefore, it is necessary to further set and optimize the parameters of the model.

7 Conclusions

1) According to the structure and working principle of the ridge forming device, the key factors affecting its performance were analyzed and determined. Numerical simulation was carried out on the mechanized ridge forming process on the whole plastic mulched double ridges, in combination with the characteristics of ridge forming effect and digging resistance of two types of shovels, the arc-shaped shovel proved to be more suitable for double ridge forming.

2) Response surface analysis method was applied to establish a quadratic polynomial regression model on the qualified rate of seedbed tillage, the advancing velocity of the combined machine, the penetration angle of the arc-shaped shovel and the depth of rotary tillage. Taking the full qualified rate of seedbed tillage as the target, the optimal working parameters of the ridge forming device were as follows: the advancing velocity of the combined machine was 0.50 m/s, the penetration angle of the arc-shaped shovel was 31°, and the rotary tillage depth was 140 mm. Under the optimal working parameters, the average qualified rate of seedbed tillage was 95.2%.

3) Field verification test showed that the average qualified rate of seedbed tillage in ridge forming device was 93.6%, which was 1.6% than that of the simulation results. The actual working condition of the sample machine was basically in line with the simulation process and could relatively precisely reflect the

mechanized ridge forming mechanism of whole plastic double ridges. It shows that the established DEM model and its parameter setting were relatively accurate and reasonable.

The research conclusions will effectively promote the entire mechanization level of the production system of whole plastic-film mulching on double ridges, which have great significance to safeguard agricultural productivity in the arid area of Northwest China.

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