Structural parameter optimization of a furrow opener based on EDEM software

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Abstract: To reduce the ditching resistance of a furrow opener during operation, single-factor and multiple-factor combinations were used to explore the influence of the furrow opener's advance speed, blade opening angle, and width on the ditching resistance based on the discrete element method (DEM). A DEM simulation of the furrow opener was developed. Upon changing these influencing factors, the parameters with the least resistance to operation were identified. Furrow openers were fabricated according to the optimized results, and soil trench tests were carried out. Simulations and soil groove tests showed that the minimum ditching resistance was 58.54 N when the current advance speed was 4.47 m/s, the blade opening angle was 32.02°, and the furrow opener width was 51.45 mm. The error between the simulated value of the ditching resistance and the soil trench test was within 10%, and the trends of resistance change were essentially the same, indicating that it is feasible to optimize the structural parameters of a trench furrow opener using DEM. These research results can provide a reference for the parameter optimization of furrow openers.

Keywords: furrow opener, discrete element, optimization, ditching resistance
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1 Introduction

Furrow openers are important tools that farmers use to sow and fertilize. Their performance significantly affects farming work efficiency[1]. Soil conditions, furrow depth, forwards speed and structure of the furrow opener can all affect the furrow resistance and then affect the operation efficiency. The optimization of the furrow opener structure can reduce the furrow resistance in the process of furrow opening and improve the operation efficiency. It is thus very important to accelerate agricultural production efficiency and reduce energy consumption by optimizing the structure of furrow openers.

The most common furrow openers are disc furrow openers, rotary cutter disc furrow openers, loose soil shovel furrow openers, and plough furrow openers[2-7]. Although there are many kinds of furrow openers, many shortcomings are found in the current designs. Therefore, many efforts have developed preferable designs of furrow openers[8]. Wan et al.[9] analysed the furrow opener stress distribution from the aspects of dynamics and energy consumption and optimized its structural parameters through ANSYS software. However, this optimization method only analysed the working condition of furrow openers, and a large error associated with their actual working processes occurred. Pan et al.[10,11] used the discrete unit method to establish a stable layer soil model and modified the discrete cell simulation model by using the glass earth box and high-speed camera technology. The comparison results with the discrete element simulation showed that the two openers have a good correlation. Barr et al.[12] designed an opener and analysed its performance using the discrete element method (DEM); moreover, the modelling results show that the soil disturbance of the bent leg opener is minimized by streamlining the opener, reducing its thickness and maximizing its forwards inclination. These results add to the understanding of bent-leg openers and provide design recommendations for optimal high-speed performance based on the target depth and speed range.

Karmakar et al.[13] used DEM based on a contact model between the furrow openers and soil, analysed the pressure distribution of furrow openers on soil, and established a variety of differences between the soil and furrow openers. The structural parameters of the furrow openers were optimized according to the relationship between them. Zhao et al.[14] obtained the optimal structural parameters of a slider, developed single factors and response surfaces, and performed validation tests. The results indicated that the main and secondary factors affecting the soil return were sliding angle and top width. The factors affecting the positive resistance were similarly found to be sliding angle and then top width. Abo-Elnor et al.[15] established a model for furrow openers and soil and analysed the relationship between the forwards speed and resistance in the process of ditching, which provided a reference for furrow opener optimization. Ma et al.[16] established the soil particle model and the soil trench device interaction model by using discrete unit simulation software and studied the influence rules of the structural

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parameters and working parameters on the operating power consumption of the segmented trench device. The greatest influence trends of the parameter on the working power consumption was found for the forwards speed, knife plate combination and knife plate speed. Pan et al.[17] and Zheng et al.[18] used a core-share type furrow opener and determined the optimal combination of parameters, such as the opening angle and width of the blade, through experiments. In summary, there has been no systematic study on the structural and working parameters of trenchers at this stage, especially on the trenching process of trenchers under orchard soil characteristics. Therefore, it is necessary to further study the ditching resistance of the furrow opener.

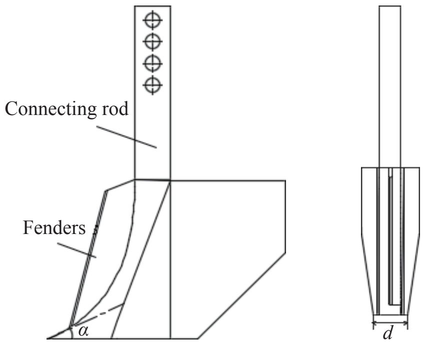
Here, the feasibility of discrete element optimization of the furrow opener is proposed. EDEM software is used to simulate the influence of different parameters on the working resistance of the furrow opener through single factor and orthogonal experiments, and experiments are carried out to verify the resistance of the optimal parameter furrow opener.

2 Materials and methods

2.1 Furrow opener structure and test platform

2.1.1 Furrow opener structure

Furrow openers are connected to machines by connecting rods. During operation, the furrow openers are immersed in soil to open trenches, and a baffle blocks the soil on both sides to avoid soil backfilling[19]. The structure diagram is shown in Figure 1.



a. Front view b. Left view

Note: α is the opening angle of the furrow opener blades, and d is the width of the furrow openers.

Figure 1 Schematic diagram of the two-dimensional structure of the furrow opener

2.1.2 Test platform

A soil tank vehicle was obtained from the soil tank laboratory of Tarim University and used for the test. This vehicle is mainly composed of a test bench, suspension frame, and console, as shown in Figure 2.

Figure 2 Soil trough test run

The sensor was bolted to the hanger and furrow opener, as shown in Figure 3. The resistance of the furrow opener was measured during the ditching process.

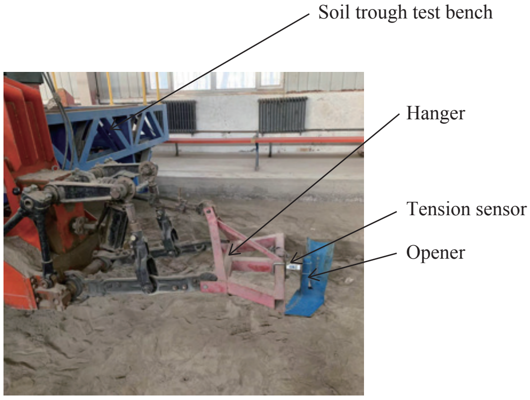


Figure 3 Ditching resistance system

2.2 Optimization and simulation of the furrow opener structure based on EDEM

2.2.1 Furrow opener modelling

The main parameters of the furrow opener are retained in simulation, and the model of the furrow opener is established as shown in Figure 4.

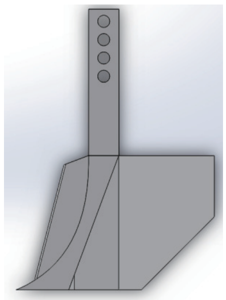
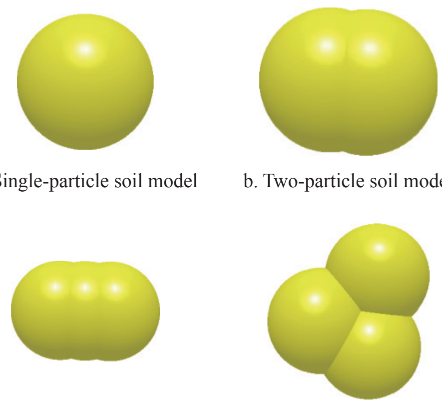


Figure 4 Simulation model of the furrow opener

2.2.2 Soil particle modelling

The soil particle model details influence the simulation process because the interaction between the soil particles and the furrow opener directly affect the opening resistance during the ditching process[20]. Due to the diversity of soil particles, four models were established as shown in Figure 5.



a. Single-particle soil model b. Two-particle soil model

c. Three-particle soil model

Figure 5 Soil particle model

2.2.3 Contact model selection

The soil channel model established in this paper is the Hertz-Mindlin bond model, and a soil channel model is correspondingly established as shown in Figure 6. The parameters of the soil particles and the simulated soil tank model are listed in Table 1[21].

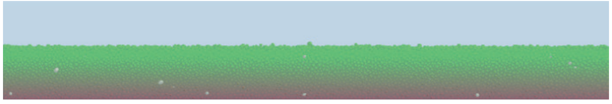


Figure 6 Soil trough simulation model

Table 1 Simulation parameter table

Soil simulation parameters	Parameter value
Simulation soil tank model/mm^3	3300×500×500
Speed of work v/km·h^{-1}	3-7
Working depth h/mm	30
Soil density ρ/kg·m^{-3}	1400
Soil shear modulus G/MPa	1.06×10^6
Soil Poisson's ratio v	0.37
Restitution coefficient between soil particles	0.19
Static friction factor between soil particles	0.4
Coefficient of kinetic friction between soil particles	0.23
Density of steel/kg·m^{-3}	7800
Steel Poisson's ratio v_1	0.3
Steel shear modulus G/MPa	7.27×10^{10}
Coefficient of kinetic friction between soil particles and steel	0.32
Static friction factor between soil particles and steel	0.5
Coefficient of restitution between soil particles and steel	0.24
Normal contact stiffness coefficient between particles/N·m^{-3}	19 000
Interparticle tangential contact stiffness coefficient/N·m^{-3}	14 000
Critical normal stress between particles/kPa	53
Critical tangential stress between particles/kPa	30

2.3 Simulation and verification

2.3.1 Single-factor test for determining the choice of furrow opener parameters

There are many factors that affect the ditching resistance including the opening angle of the furrow opener blade, the width of the furrow opener, the ditching speed, the type of soil, and the degree of soil firmness. Among these, the blade opening angle and forwards speed of the furrow opener, the width of the furrow opener and three other factors are selected as the main test factors, and a single-factor test of the furrow opener is carried out. The trial design is listed in Table 2.

Table 2 Single-factor trial design

No.	Blade opening angle/(°)	Furrow opener width/mm	Forwards speed/km·h^{-1}
1	20	75	5
2	25	75	5
3	30	75	5
4	35	75	5
5	40	75	5
6	30	25	5
7	30	50	5
8	30	75	5
9	30	100	5
10	30	125	5
11	30	75	3
12	30	75	4
13	30	75	5
14	30	75	6
15	30	75	7

2.3.2 Orthogonal test design for determining the structural parameters of the furrow opener

To explore the influence of the forwards speed of the furrow opener, the opening angle of the blade, and the width on the ditching resistance, an orthogonal experimental design is adopted. Combined with the simulation analysis results of the single factor, a quadratic regression orthogonal test with 3 factors and 3 levels is used. The test factor levels are listed in Table 3.

Table 3 Test factor levels

Level	X_1 Blade opening angle/(°)	X_2 Furrow opener width/mm	X_3 Forwards speed/km·h^{-1}
–1	25	50	3
0	30	75	4
1	35	100	5

2.3.3 Verification test design for determining the simulation effect

When the opening angle of the furrow opener was 32.02°, the width of the furrow opener was 51.45 mm, and the forwards speed was 4.47 m/s. Five furrow opening tests were performed.

2.4 Data analysis

Origin software was used to analyse single-factor test data, Design-expert was used to analyse variance and response surface of orthogonal test, and Excel software was used to analyse data of validation test.

3 Results and discussion

3.1 Single-factor test analysis

3.1.1 Influence of the blade angle on the resistance during ditching

The relationship between the blade opening angle and the ditching resistance is shown in Figure 7, which depicts that when the blade opening angle is less than 30°, the ditching resistance decreases with an increasing blade opening angle. However, when the blade opening angle is greater than 30°, the ditching resistance increases with an increasing blade opening angle. This is attributed to the observation that when the ditching resistance is less than 30°, the ground-breaking capacity is not sufficient, which results in high ditching resistance. When the blade opening angle is greater than 30°, the contact area between the grooving blade face and the soil increases, which also increases the ditching resistance[22].

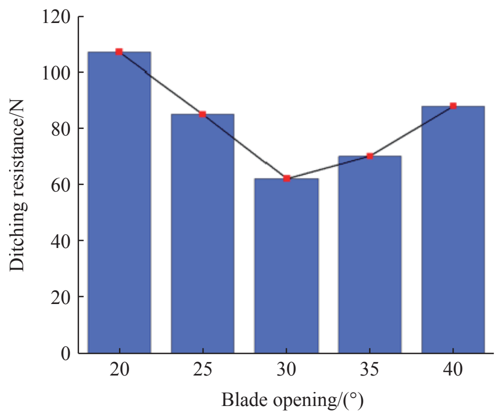


Figure 7 Relationship between the blade opening angle and ditching resistance

3.1.2 Influence of the width on the resistance during ditching

The relationship between the width and ditching resistance is shown in Figure 8, which depicts that when the width of the furrow opener increases, the resistance increases accordingly. This occurs because when the width of the furrow opener is increased, the area of action between it and the soil becomes larger, and the resistance also increases[23].

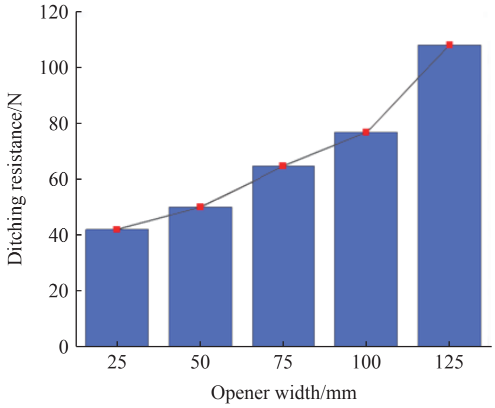


Figure 8 Relationship between the furrow opener width and ditching resistance

3.1.3 Influence of forwards speed on the resistance during ditching

The relationship between the forwards speed and ditching resistance is shown in Figure 9, which depicts that as the speed increases, the resistance increases. When the travelling speed increases, the momentum of the furrow opener increases, and the force acting on it becomes larger; thus, the ditching resistance increases with an increasing furrow opener speed[3,24].

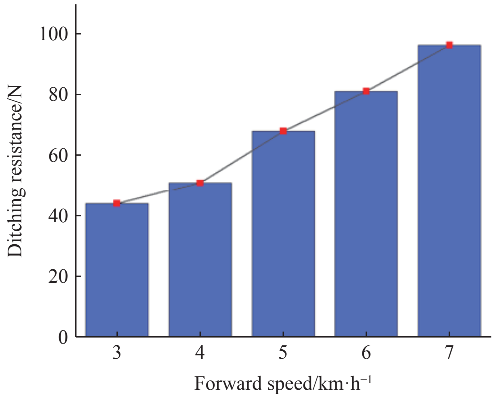


Figure 9 Relationship between the forwards speed and ditching resistance

3.2 Orthogonal test analysis

3.2.1 Test results and analysis of variance

The design and simulation test results are listed in Table 4.

Table 4 Simulation test design scheme and results

Serial number	Blade opening angle X_1/(°)	Furrow opener width X_2/mm	Forwards speed X_3/km·h^{-1}	Resistance value/N
1	–1	–1	0	61.67
2	1	–1	0	68.73
3	–1	1	0	103.21
4	1	1	0	107.34
5	–1	0	–1	80.37
6	1	0	–1	87.28
7	–1	0	1	84.16
8	1	0	1	85.31
9	0	–1	–1	63.42
10	0	1	–1	104.25
11	0	–1	1	67.37
12	0	1	1	106.64
13	0	0	0	85.12
14	0	0	0	86.16
15	0	0	0	85.57

Considering the mean value of the ditching resistance Y as the evaluation index and the blade opening angle X_1, the ditching knife width X_2 and the advancing speed X_3 as the test factors, variance analysis is performed. The relevant results are listed in Table 5.

Table 5 Analysis of the variance

Evaluation indicators	Source of variance	Sum of square	Degrees of freedom	Mean square	F-value	p-value	Salience
	Model	3279.68	9	364.41	421.50	<0.0001	**
	X_1	46.32	1	46.32	53.58	0.0007	**
	X_2	3210.01	1	3210.01	3712.89	<0.0001	**
	X_3	8.32	1	8.32	9.63	0.0268	*
	X_1X_2	2.15	1	2.15	2.48	0.1759	
	X_1X_3	8.29	1	8.29	9.59	0.0269	*
	X_2X_1	0.61	1	0.61	0.70	0.4398	
Y	X_1^2	2.13	1	2.13	2.46	0.1773	
	X_2^2	0.53	1	0.53	0.62	0.4674	
	X_3^2	1.23	1	1.23	1.42	0.2865	*
	Residual	4.32	5	0.13			
	Lack of fit	3.78	3	0.24	4.63		
	Error	0.54	2	0.052			
	Sum	3284	14				

According to the variance analysis, the significance of the mean value Y of the ditching resistance is p<0.001. Therefore, the data is extremely statistically significant. For the mean value of ditching resistance Y, the regression items X_1 and X_2 in the regression model, at p<0.01, also showing a high statistical significance. Moreover, X_3, X_1, X_3, and X_{32}, at p<0.05, also have a significant impact on the model. The rest of the factors are found to be insignificant. The significant term optimizes the regression equation of the mean value of the ditching resistance Y, and the optimized equation is shown in Equation (1).

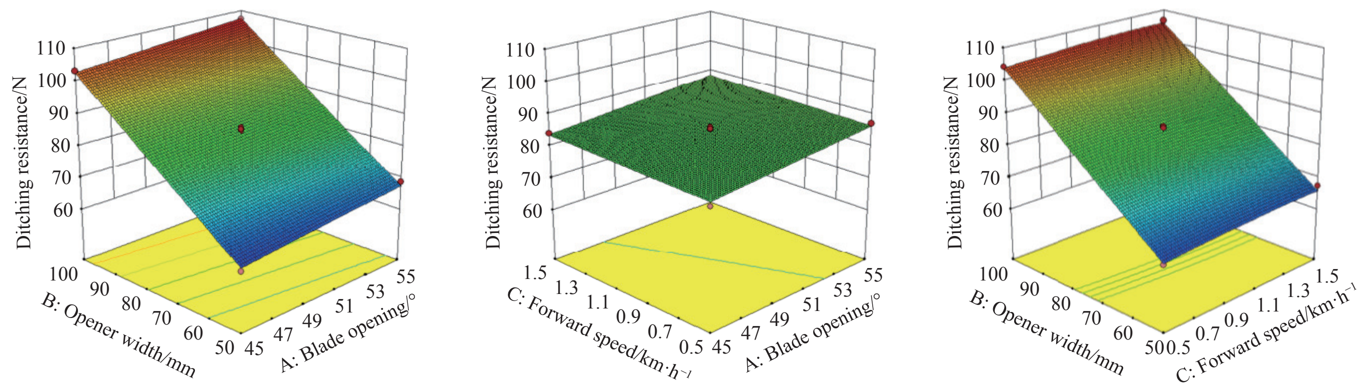
$$Y = 85.40 + 2.41X_1 + 20.03X_2 + 1.02X_3 - 1.44X_1X_3 - 0.55X_3^2 \quad (1)$$

3.2.2 Response surface analysis

The response surfaces of the forwards speed, blade opening angle, and furrow opener width to the mean values of the ditching resistances are shown in Figure 10. Figure 10a shows that when the forwards advance speed is at the zero level, under the same furrow opener width, the ditching resistance also increases with an increasing blade opening angle. When the width of the furrow opener increases, the ditching resistance increases. This occurs because when the width of the furrow opener is increased, the area of action between it and the soil becomes larger, and the resistance also increases. In Figure 10b, when the width of the furrow opener is at the zero level at the same forwards speed, the resistance also increases with the increase in the blade opening angle. The resistance increases because when the speed of the furrow opener increases, the momentum of the furrow opener increases, and the force on the furrow opener also increases; thus, the resistance of the furrow opener increases. In Figure 10c, when the blade opening angle is at the zero level, the grooving resistance varies with its width at the same advancing speed. Under the same width, the resistance also increases when the forwards speed increases; however, the resistance change is minimal.

3.3 Validation test analysis

According to the optimization simulation results, when the forwards advance speed is 4.47 m/s, the blade opening angle is 32.02°, the furrow opener width is 51.45 mm, and the ditching resistance is 58.54 N. The test results are listed in Table 6. After calculations are performed, the relative errors are determined to be 6.4%, 7.7%, 4.9%, 9.1%, and 2.6%, and the relative errors are all less than 10%. Thus, the simulation results are reliable.



a. $Y=f(X_1, X_1, 0)$ b. $Y=f(X_1, 0, X_3)$ c. $Y=f(0, X_2, X_3)$

Figure 10 Response surface of the test factors on the evaluation index

Table 6 Test results of soil trench ditching under the optimal parameter combination

Test serial number	1	2	3	4	5	Average
Resistance value/N	62.6	63.5	61.6	64.4	60.1	62.4

3.4 Discussion

Through the optimization simulation and verification of the structural parameters of the furrow opener, it is further confirmed that the optimized furrow opener has smaller ditching resistance. It is also confirmed that EDEM simulation is reliable.

Compared with similar works, this paper optimizes the plough-type furrow opener, solves the problem of selecting parameters to reduce the furrow resistance during the manufacture of the plough-type furrow opener, and provides a certain reference for the manufacture of the furrow opener.

In this study, the validation test was only carried out in the soil trough laboratory, and the effect of ditching for different soils was not verified. At the same time, only the opening angle, width and forwards speed of the furrow opener were optimized, and no more parameters were selected for the optimization test.

4 Conclusions

Through simulation test and verification of the structural parameters of the furrow opener, the optimal parameter combination was obtained with a blade opening angle of 32.02°, furrow opener width of 51.45 mm, and forward speed of 4.47 m/s. Under these parameters, the lowest ditching resistance of 58.54 N was obtained. Furrow openers with optimal structural parameters were processed and tested in soil trenches, and the average resistance value of 62.4 N was obtained. The errors between the simulation experiment and the soil trench test were all less than 10%. Furthermore, the optimized furrow opener exhibited a lower ditching resistance than the pre-optimized furrow opener.

Acknowledgements

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