Effects of key design parameters of tine furrow opener on soil seedbed properties

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Abstract: The structural parameters of tine furrow openers have significant effects on soil property of seed furrow in no-till planting, thereby affecting crop growth and yields. In order to analyze the effects of key parameters of tine furrow openers on soil properties (soil bulk density, soil water-stable aggregates (WSA), and soil disturbance) of the surface soil layer of 0-10 cm and surface straw disturbance, the tine furrow openers with different structural parameters, including cutting edge thickness, cutting edge curve, penetration clearance angle and rake angle, were designed and tested under no-till conditions. Orthogonal test and single factor test were performed to analyze the effects of different parameters. Results showed that the rake angle, cutting edge thickness and cutting edge curve had significant effects on cross-sectional area of furrow (A_f) and disturbance of surface straw; the rake angle had a significant effect on soil bulk density. Soil types and operating depth had significant effects on soil disturbance caused by tine furrow openers. The concave type tine furrow opener produced the lowest soil disturbance and soil bulk density of seed furrow, the highest surface straw disturbance and the greatest content of WSA (>0.5 mm). With increasing rake angles of tine furrow opener, the width of seedbed (W_{sb}) and the A_f decreased first and then increased, respectively, while the width of soil throw (W_{st}) and the height of ridge (H_r) increased. The W_{sb} and A_f created by tine furrow opener with 60° rake angle were significantly lower than that with others, respectively. The tine furrow opener with rake angle ranged from 45° to 60° created the lowest soil bulk density. As the penetration clearance angle increased, the content of WSA (>0.5 mm) decreased, but the effect of penetration clearance angle on the content of WSA (<0.5 mm) was not significant. The cutting edge thickness (<2 mm) had no significant effects on soil properties of seedbed. This study could provide a reference for optimal design of the tine furrow opener to create more suitable seedbed environment, and promote the application of the light no-till planters.

Keywords: tine furrow opener, key parameter, no-till planter, soil disturbance, straw cover, bulk density, soil water-stable aggregates

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1 Introduction

Furrow openers are the key component for no-till planter to create suitable seedbeds[1]. Good soil conditions in seedbeds can provide a suitable temperature regime and soil water content for crop germination and growth. Two main types of furrow openers, tine and

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disc, may have different performances in creating seedbeds[2]. Generally, disc openers, which need a larger vertical force to penetrate hard soil, are mainly used on large no-till planters, while tine furrow openers are mainly used on small and medium no-till planters because of its better ability of soil penetration. Comparing with disc furrow opener, the tine opener requires lower vertical force and larger traction force[3].

In China, the disc type planters are too large, heavy, and expensive for popularization and application, while the tine based, small and inexpensive no-till planters are widely used[4]. Reasonable structures of tine furrow openers for these planters are required to create suitable seedbed environment and reduce operation resistance in the no-till straw-mulched fields[5]. The no-till seedbed can improve moisture holding capacity and promote the crop growth[6]. According to the requirements of no-till planting, the seedbed with fewer soil disturbance produced by tine furrow opener, is conducive to crop growth[7,8]. However, the existing research of agronomic characters showed that seedbed with suitable soil disturbance can promote crop emergence and obtain high yield under no-till planting conditions. And the seedbed quality is affected by different structures of tine furrow opener. Currently, many researchers designed various furrow openers with different structural parameters[9-11], and studied their operation performances in fields covered by residues. The influences of seedbeds in the early growth stage of wheat were studied by Yao et al.[12], and these seedbeds were created by different furrow openers (the tine opener, the single disc opener, and the rotary opener). It was found that the soil disturbance and the counts or the number of the adventitious root in the soil layer created by rotary opener were larger than that with others. The single disc opener created the lowest soil disturbance. The rotary opener was a strip-till device which used the powered rotary blades to chop soil, crop residues and straws, and made the better passing capability on seeding and fertilizing furrow openers. Godwin[13] demonstrated that structural parameters of the opener were the main factor on affecting the soil loosening and movement. Solhjou et al.[14] analyzed the effects of rake angle of furrow opener on soil disturbance of seedbed. It was shown that the lower rake angles increased the movement from deeper soil layers into the seed zone. The larger rake angle opener disturbed a smaller furrow size and achieved slightly more furrow backfill.

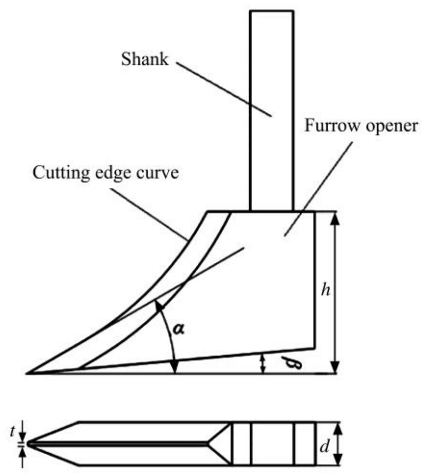
Others studied the effects of furrow openers and its key design parameters on draft force and soil disturbance under different operation conditions. The cross-sectional area increased with the increase of rake angle and wedge angle. Many researchers[15-18] built the mathematic and discrete element model of furrow openers to analyze the draft force and soil disturbance under different conditions of opening speeds, soil bulk density, and moisture content. Hasimu and Chen[19] studied the effects of three different seed openers (hoe, winged hoe, and spoon) on soil disturbance and draft force through soil bin test. With the increase of working depth, soil disturbance and force created by openers increased. The hoe opener had better performance than the others. Ebubekir et al.[20] studied the influences of different types of furrow openers (hoe, shoe, and shovel type) and operation speeds on soil properties and draft force. For all the types of furrow openers, the draft force increased and ridge height decreased with the increase of operational speed. Shovel type furrow opener required the least draft force. Chaudhuri[21] stated that the furrow openers affected the backfill of the soil with increased depth in laboratory and field experiments. The soil disturbance of disc-type furrow opener was also less than that of hoe-type furrow opener. After harvesting the previous crops, the crop straw and stubble were used to cover the ground surface. Disc-type openers did not perform well in no-till field with hard soils and residue cover because the disc-type openers need a larger vertical force to squeeze into the soil and easily pushed the dry soil, straw and stubble into furrow, while hoe-type openers generally performed better on penetration capacity. Mohler et al.[22] and Karayelet al.[23] analyzed the influences of different types of furrow openers on horizontal and vertical distribution of seedbed soil. The existing researches mainly analyzed the properties of seedbed created by different type furrow openers and how these openers affect crop growth under various field conditions. Few studies of the key structural parameters of tine furrow openers, mainly focused on analyzing the effects of openers on draft force. Furthermore, there was no comprehensive analysis of soil properties affected by the key structural parameters of tine furrow openers.

The objective of this study was to determine which key structural parameters (including cutting edge thickness, cutting edge curve, penetration clearance angle, and rake angle) of tine furrow opener had significant effects on soil properties (soil bulk density, soil water-stable aggregates, and soil disturbance) and surface straw disturbance of the seed furrow under no-till conditions.

2 Materials and methods

2.1 Description of test furrow opener

The test tine furrow openers were designed to analyze their effects on soil properties and straw disturbance of seed furrow. To eliminate the interference of other factors, all designed tine furrow openers (Figure 1) had the same structural parameters except the four variable parameters (including rake angle, penetration clearance angle, cutting edge thickness, and cutting edge curve).



Note: *α*: Rake angle; *β*: Penetration clearance angle; *h*: Height of the furrow opener; *d*: Width of the furrow opener; *t*: Cutting edge thickness.

Figure 1 Schematic diagram of tine furrow opener

Rake angle (*α*): It is the angle between the working edge of furrow opener and the ground surface, which has certain effects on the penetration performance and working resistance of furrow opener. The rake angle was determined to be greater than 30 °[14].

Penetration clearance angle (*β*): It is the angle between the subsurface of furrow opener and the ground surface, which affects the penetration performance and the flatness of furrow bottom. The penetration clearance angle was determined to be less than 12 °.

Cutting edge thickness (*t*): With the increase of the thickness of cutting edge, the abrasion resistance of furrow opener improved and the working resistance also increased. The determined thickness was less than 2 mm.

Cutting edge curve: The cutting edge of furrow opener is used to cut soil and affects the movement of soil and surface straw. Four types of cutting edge curve including lineartype (T_1), convex type (T_2), concave type (T_3), and linear-curvilinear combination type (T_4) were selected to analyze the impacts on operation effect.

Four levels were set for each of the four structural parameters according to the above analysis, shown in Table 1.

Table 1 Factors and levels of orthogonal experiments

Levels	Factors			
	Rake angle A /(°)	Cutting edge curve B	Cutting edge thickness C/mm	Penetration clearance angle D /(°)
1	30	T_1	0.5	0
2	45	T_2	1.0	4
3	60	T_3	1.5	8
4	75	T_4	2.0	12

The height (*h*) of tine furrow openers was determined by depth of the furrow. Meanwhile, the growth of wheat can be affected by seeding depth. The shallower seeding depth was beneficial for crop emergence, and degraded the drought resistance and cold resistance performance. With the increase of the seeding depth, the effect of water retention and heat preservation was reinforced, however, the deeper seeding depth will lead to lower emergence rate. Studies showed that, the seeding depth of 5 cm was beneficial for crop emergence[24,25]. Meanwhile, the fertilizer should be placed below the seed in the furrow, and the suitable distance between the seeds (GBT20865-2007) and the fertilizer is about 3 cm to 5 cm. So the maximum opening depth was about 10 cm that can place seed and fertilizer in the appropriate place of furrow.

According to the different structural parameters determined by the $L_{16}(4^5)$ orthogonal table[26], 16 types of furrow opener were designed (Table 3). To eliminate the influences from other factors, sizes of the furrow opener were consistent except the above four structural parameters. The height (*h*) and the width (*d*) of tine furrow openers were designed as 15 cm and 4 cm respectively. Furrow openers were fabricated using 65Mn steel plate (5 mm in thickness) with conditioning treatment. The different shapes and parameters of furrow openers were shown in Figure 2.

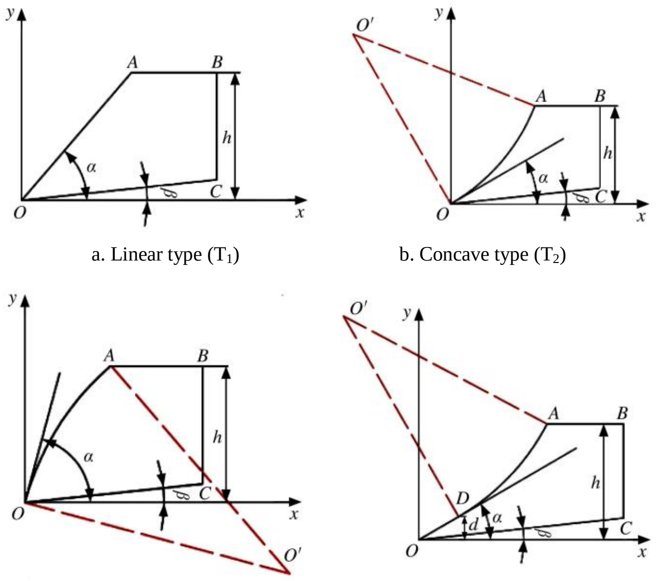
The point *O* at the bottom of the furrow opener was assumed as the origin of coordinate system, then the two end points of the cutting edge curve were point *O*(0, 0) and point $A(x_a, h)$.

(1) When the cutting edge curve was linear type (Figure 2a), the relationship among rake angle (α), height of furrow openers (*h*) and *x*-coordinate value of point *A* was:

$$\tan\alpha = \frac{h}{x_a} \tag{1}$$

Thus the *x*-coordinate value of point *A*, calculated by Equation (1), was shown in Equation (2).

$$x_\alpha = \frac{h}{\tan\alpha} \tag{2}$$



a. Linear type (T_1) b. Concave type (T_2)

c. Convex type (T_3) d. Linear-curvilinear combination type (T_4)

Note: α: Rake angle; β: Penetration clearance angle.

Figure 2 Structural diagram of tine furrow opener

(2) When the cutting edge curve was concave type or convex type (Figures 2b and 2c), the circle, where the cutting edge curve was in, passed through the ordinate origin *O*(0, 0). The point $O'(x_{O'}, y_{O'})$ and *R* were the center and the radius of the circle, respectively. Then the equation of the circle was assumed as:

$$(x - x_{O'})^2 + (y - y_{O'})^2 = R^2 \tag{3}$$

If the cutting edge curve was concave type (Figure 2b), the *x* and *y* values of the center point $O'(x_{O'}, y_{O'})$ were presented in the following equations.

$$\begin{cases} x_{O'} = -R\cos[\pi - (\frac{\pi}{2} + \alpha)] = -R\sin\alpha \\ y_{O'} = R\sin[\pi - (\frac{\pi}{2} + \alpha)] = R\cos\alpha \end{cases} \tag{4}$$

So the equation of the circle was,

$$(x + R\sin\alpha)^2 + (y - R\cos\alpha)^2 = R^2 \tag{5}$$

The *x*-coordinate value of point A was calculated by *y*-coordinate ($y_a = h$). It was

$$x_a = \sqrt{R^2 - (h - R\cos\alpha)^2} - R\sin\alpha \tag{6}$$

Similarly, if the cutting edge curve was convex type (Figure 2c), equations of the circle and x-coordinate value of point *A* were calculated by Equation (7) and Equation (8) as concave type curve edge in Figure 2b.

$$(x - R\sin\alpha)^2 + (y + R\cos\alpha)^2 = R^2 \tag{7}$$

$$x_a = \sqrt{R^2 - (h + R\cos\alpha)^2} + R\sin\alpha \tag{8}$$

where, Equation (7) represents the equation of the circle where convex type cutting edge curve was in, Equation (8) represents the *x*-coordinate value of point *A*.

(3) When the cutting edge curve was linear-curvilinear combination type (Figure 2d), the segment *OD* and segment *DA* of cutting edge curve were a straight line and circular arc which was a part of the circle. The segment *OD* was tangent to segment *DA* and the tangent point was $D(x_{d'}, y_{d'})$. The *x*-coordinate value ($x_{d'}$) of point *D* was calculated by the *y*-coordinate value ($y_{d'}$) which was set up to be the constant value (d'). The circle, where the segment *DA* of cutting edge curve was, did not pass through the ordinate origin *O*(0, 0). The equations of the circle and *x*-coordinate value of point *A* were determined by the same analysis mentioned above.

$$[x - (R\sin\alpha - \frac{d'}{\tan\alpha})]^2 + [y - (R\cos\alpha + d')]^2 = R^2 \tag{9}$$

$$x_a = \sqrt{R^2 - [h - (R\cos\alpha + d')]^2} + (R\sin\alpha - \frac{d'}{\tan\alpha}) \tag{10}$$

where, Equation (9) represents the equation of the circle where segment *DA* of cutting edge curve was, Equation (10) represents the *x*-coordinate value of point *A*.

2.2 Site and equipment description

The field experiments were conducted from 2012 to 2014 at Zhuozhou Experiment Station (39°28′N, 115°56′E), Hebei, China. The soil types were sandy loam and loam. The soil pH value was 7.8 and the soil organic contents ranged from 1% to 1.9%. The annual average rainfall is 617 mm, which always concentrates in summer. In this annual double cropping regions, two crops are planted in sequence each year (October for wheat and June for maize). Before the field experiment, the field was covered by corn stover which was chopped by smashed straw machine and evenly threw to the soil surface. Penetration resistance, an indicator of soil compaction, was measured by a soil compaction meter (Field Scout™ SC900) with 60° apex angle, 12.83 mm cone base diameter, and 45 cm maximum measuring depth. The value of penetration resistance was recorded at each 2.5 cm interval. At the same depth, the undisturbed soil samples were randomly collected with a manual stainless steel core samplers, and the samples were used for measuring moisture content (db) of dry soil and soil dry bulk density by oven drying method. The disturbed soil samples were collected with sealable plastic bag, and the proportions of soil water-stable aggregates of the disturbed soil was measured by the wet-sieving method. Soil conditions of the experiment field were tabulated in Table 2.

Table 2 Soil conditions of experiment field

Soil type	Depth /cm	Soil penetration resistance/kPa	Soil moisture content(db)/%	Soil dry bulk density/g cm^{-3}	Proportions of soil water-stable aggregates/%				
					0.106-0.25 mm	>0.25-0.5 mm	>0.5-1.0 mm	>1.0-2.0 mm	>2.0 mm
Sandy loam	0-5	78	9.75	1.318	14.83	29.67	6.86	2.12	4.59
	5-10	215	12.21	1.408	14.96	28.17	4.06	1.77	3.39
	10-15	531	10.16	1.437	14.60	26.46	8.33	2.85	2.38
Loam	0-5	280	9.63	1.346	7.63	18.66	7.18	4.53	3.93
	5-10	561	12.25	1.424	10.62	19.16	7.01	3.58	3.64
	10-15	877	10.31	1.445	8.15	18.95	5.68	2.95	2.63

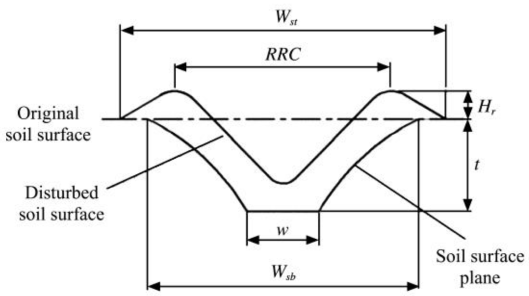
Field experiments were carried out using a field integrated testing system and a furrow opener suspension bracket (Figure 3) designed by China Agricultural University[27]. The system consisted of rear suspension test platform and data collecting section. Parameters such as draft force, fuel consumption, and operating speed can be measured by the test platform hauled by tractor. Experimental data were collected by data collecting section of the system. The operating speed can be set up and adjusted to meet with experimental requirement by the system. In the experiment, the suspension bracket was connected to the test platform by three-point hitch. The experimental furrow openers were mounted on traverse beam of the suspension bracket by U-shaped bolt and can be adjusted up and down according to the operating requirement.

If the seeding speed was too high (>7 km/h), it might result in the decline of metering device performance[28,29] and then increase the seed breaking rate. With the increase of seeding speed, the distance of soil lateral throwing increased and the wet and dry soil mixed which affected the performance of backfill soil and the seeding quality. Studies showed that the seeding speed less than 7 km/h was better for improving the seeding performance and opening quality.

Figure 3 Furrow openers tested by field integrated testing system

2.3 Measurements

Soil disturbance quantity: During the opener was operating in the field, the soil was disturbed and most of the disturbed soil was turned over, which formed two ridges on both sides of the seeding furrow. The distance between the outer edges of the two ridges was defined as W_{st}. The distance between the two peaks of the ridges in both sides of furrow was the ridge to ridge distance (RRD). The rest of the disturbed soil formed the shallow groove in the furrow. The profile of the groove was represented by the second line (the disturbed soil surface) in Figure 4. The disturbed soil was carefully removed until the contour of the furrow was clearly observed. The disturbed soil surface and the contour of the furrow were drawn on a transparency paper for measuring easily. The width of the furrow top was the maximum width of seedbed (W_{sb}) on the original soil surface. The distance from the peak of the ridge to original soil surface was the height of ridge (H_r). The above soil disturbance parameters[30] were illustrated in Figure 4.



Note: W_{st}: Maximum width of soil throw; H_r: Height of the ridge; *RRD*: Ridge to ridge distance; W_{sb}: Maximum width of seedbed; *w*: Tool width; *t*: Depth of furrow.

Figure 4 Parameters used to define soil disturbance

Among these parameters, the A_f was calculated by the following equation:

$$A_f = \frac{w + W_{sb}}{2} t \tag{11}$$

where, *w* is the width of furrow opener, cm; W_{sb} is the maximum width of seedbed, cm; *t* is the depth of furrow, cm. All the measurements were replicated for five times and the average value was calculated.

Straw disturbance quantity: The disturbance of surface straw was measured by the difference of the straw coverage rate before and after tests. The straw coverage rate was measured by meter stick method[31]. First, the meter stick (which was marked at every 0.5 m interval) was placed on the ground surface. Second, the number of all marks on the meter stick was counted as the total number (*N*). When the marks on the meter stick covered on the straw, the marks were counted as the record number (*n*) in measuring area. This study mainly analyzed the effects of different tine furrow openers on straw disturbance quantity. The result was directly measured after the opening operation and the furrow was open. The meter stick was placed along the two diagonals of the measuring area. The length and the width of the measuring area were determined by the maximum distance of soil throw (W_{st}) and the length of meter stick respectively. Straw coverage rate, calculated as the ratio of the record number (*n*) and the total number (*N*), was shown in Equation (12).

$$\Delta = \frac{n}{N} \times 100\% \tag{12}$$

The difference of straw coverage rates before and after each test, used to show the effect of furrow opener on straw disturbance during the opening operation, was defined as the straw disturbance quantity (η), as shown in Equation (13).

$$\eta = \Delta_0 - \Delta \tag{13}$$

where, Δ_0 is the straw coverage rate before test; Δ is the straw coverage rate after test.

Soil bulk density: As mentioned, seeding depth was set as 5 cm to improve the crop emergence rate and crop yield[25]. Soil bulk density of seedbed was analyzed because loose soil can promote emergence rate and root growth. Soil samples at 10 cm depth were randomly collected with a manual stainless steel core samplers (size: ϕ50.4 mm × 50 mm) to measure the soil bulk density. All the soil cores were weighed and dried at 105℃ for 48 h. Dry soil cores were weighed again to determine dry bulk density[7].

Soil water-stable aggregate: The disturbed soil samples were collected from seed furrow (after each test) for measurement of soil aggregate stability. Each soil sample was first passed through an 8 mm sieve which helped break the soil clods and separate pebbles and stable clods (>8 mm). Before analysis, soil samples were air-dried for 24 h in the laboratory with room temperature. Soil water-stable aggregate distribution was determined by placing the soil sample on a nest of sieves, immersing directly in water, and agitating the sieves up and down 35 mm for 15 min in water (30 cycles per minute). Proportions of stable aggregates of >0.106-0.25 mm, >0.25-0.5 mm, >0.5-1.0 mm, >1.0-2.0 mm, and >2.0 mm were calculated by drying and weighing the soil remaining on each sieve[32].

2.4 Experimental design

Orthogonal test: Under the operating speed of 4 km/h and the depth of 10 cm, 16 types of furrow openers were tested to analyze the effects of tine furrow opener on soil dry bulk density, cross-sectional area of furrow (A_f), and surface straw disturbance, and determine the key parameters of furrow opener. The effect was studied in the loam soil with straw coverage rate of 93%.

Single factor test: Four structural parameters (including cutting edge thickness, cutting edge curve, penetration clearance angle and rake angle) of tine furrow opener were studied to analyze their effects on soil bulk density, WSA, and the soil and surface straw disturbance, respectively. Those experiments were conducted in two soil types (sandy loam and loam) with different straw coverage rates of 43%, 68% and 93%, respectively. According to the above analysis, the operating speed was selected as 4 km/h and the operating depths were selected as 5 cm and 10 cm for putting the seed and fertilizer into the furrow.

2.5 Data analysis

To reduce experimental error and ensure the accuracy and reliability of the experimental data, all the trials were replicated in triplicate and averaged. An ANOVA was used to assess the effects. When the ANOVA indicated a significant F-value, multiple comparisons were performed by the least significant difference method (p<0.05). The SPSS software package (19.0) was used for all the statistical analyses. Figures were generated by Origin9.1 software.

3 Results and discussion

3.1 Analysis of orthogonal experiment

As indicated in Tables 3 and 4, the order and contribution rate of every experimental factor on each target index was determined by orthogonal experiment and range analysis.

The contribution rate order of the factors' effects on both soil bulk density and soil disturbance (A_f) was the same as follows: rake angle > cutting edge thickness > cutting edge curve > penetration clearance angle. The order of four factors' effects on the surface straw disturbance quantity was cutting edge curve > rake angle > cutting edge thickness > penetration clearance angle.

Table 3 Results of the $L_{16}(4^5)$ orthogonal experiments

Test No.	*A*	*B*	*C*	*D*	Soil bulk density /g cm^{-3}	Cross-sectional area of furrow /cm^2	Disturbance of surface straw/%
1	1	1	1	1	0.941	76.7	58.71
2	1	2	2	2	1.087	74.3	65.01
3	1	3	3	3	1.213	85.1	52.01
4	1	4	4	4	1.062	81.5	80.83
5	2	1	2	3	1.010	86.1	65.17
6	2	2	1	4	1.145	92.2	81.48
7	2	3	4	1	0.980	89.6	88.89
8	2	4	3	2	1.250	110.1	75.86
9	3	1	3	4	1.304	108.8	82.76
10	3	2	4	3	1.153	90.5	74.07
11	3	3	1	2	1.098	84.1	50.12
12	3	4	2	1	1.074	71.8	86.21
13	4	1	4	2	1.100	93.9	68.97
14	4	2	3	1	1.080	76.0	79.31
15	4	3	2	4	1.003	73.4	82.35
16	4	4	1	3	0.940	61.5	62.50

Table 4 Extreme analysis of orthogonal experiment

Index	Level	A	B	C	D
Soil bulk density	k_1	1.076	1.088	1.031	1.019
	k_2	1.096	1.116	1.044	1.134
	k_3	1.156	1.074	1.211	1.078
	k_4	1.031	1.082	1.073	1.128
	R	0.125	0.042	0.180	0.056
Cross-sectional area of furrow	k_1	79.400	91.375	78.625	78.525
	k_2	94.500	83.250	76.400	90.600
	k_3	88.800	83.050	95.000	80.800
	k_4	76.200	81.225	88.875	88.975
	R	18.300	10.150	18.600	12.075
Disturbance of surface straw	k_1	64.140	68.903	63.203	78.280
	k_2	77.850	74.968	74.685	64.990
	k_3	73.290	68.343	72.485	63.438
	k_4	73.283	76.350	78.190	81.855
	R	13.710	7.447	14.987	18.417

The result of variance analysis was tabulated in Table 5. Rake angle significantly (p<0.05) affected the soil bulk density. Marginal effects of cutting edge thickness and cutting edge curve were not significant (p<0.05). All the factors except penetration clearance angle had significant influence on both of soil disturbance (A_f) and surface straw disturbance.

As shown in Tables 4 and 5, rake angle was determined as the main factor which affected soil bulk density and soil disturbance. The significant effects of cutting edge curve and cutting edge thickness on disturbance of surface straw resulted from their direct contact with the soil and the surface straw, which was in accordance with the research by Yao[10].

Table 5 Variance analysis of orthogonal experiments

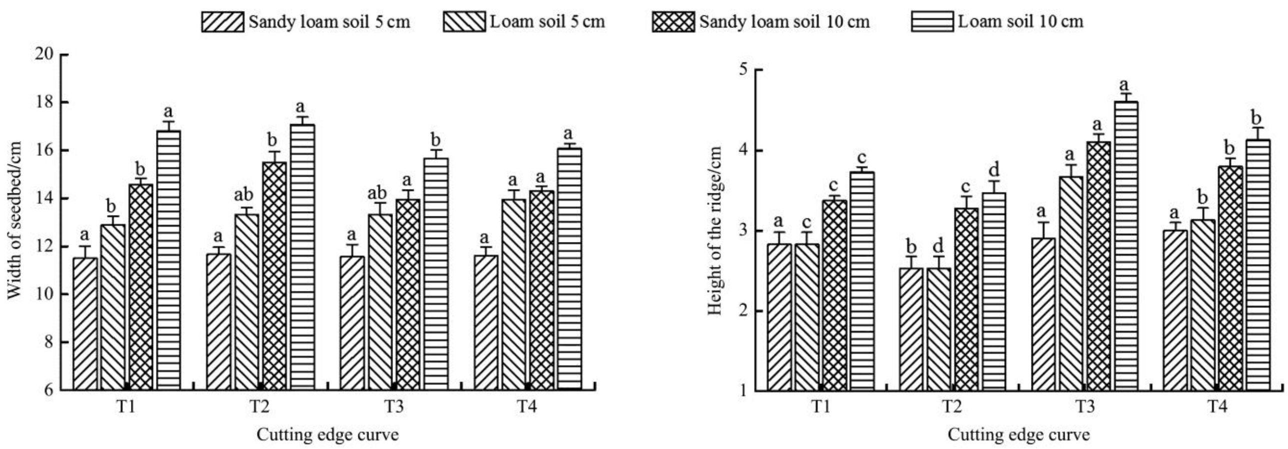
Index	Source	Squares sum	Freedom	Mean square	*F*-value
Soil bulk density	*A*	0.032	3	0.011	2.876
	B	0.004	3	0.001	0.357
	C	0.082	3	0.027	7.336
	D	0.034	3	0.011	3.052
	Error	0.011	3	0.004	
	Total	0.164	15		
Cross-sectional area of furrow	*A*	852.750	3	284.250	11.236
	B	245.815	3	81.938	3.239
	C	917.255	3	305.752	12.086
	D	425.695	3	141.898	5.609
	Error	75.895	3	25.298	
	Total	2517.410	15		
Disturbance of surface straw	*A*	396.928	3	132.309	5.462
	B	202.485	3	67.495	2.786
	C	492.310	3	164.103	6.775
	D	1035.747	3	345.249	14.253
	Error	72.668	3	24.223	
	Total	2200.138	15		

Note: $F_{0.05}(3, 3)$=9.28, $F_{0.10}(3, 3)$=5.39, $F_{0.25}(3, 3)$=2.36.

3.2 Soil disturbance

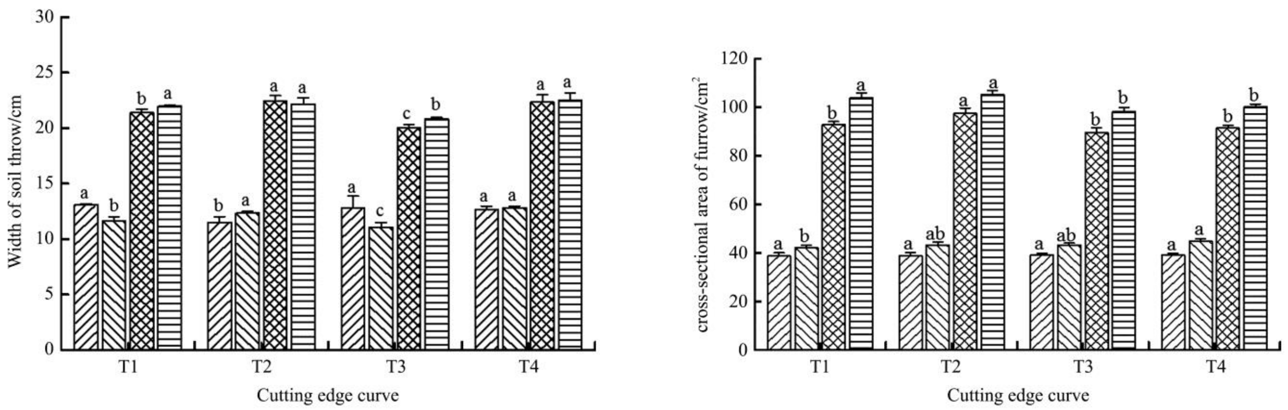
The indexes of soil disturbance affected by cutting edge curve and rake angle were shown in Figures 5 and 6. The quality of soil disturbance increased with increasing operating depth in both loam soil and sandy loam soil, and that was more significant in loam soil. It was because the adhesive force and shear strength are larger in loam soil which promoted the disturbance quality to the side soil[15,18]. Concave type furrow opener had the lowest W_{sb}, W_{st} and A_f, and the largest H_r, as shown in Figure 5.

Compared with linear type (T_1), convex type (T_2) and combination type (T_4), the W_{sb} caused by concave type (T_3) tine furrow opener decreased by 6.73%, 8.20% and 2.49% in loam soil at 10 cm depth, respectively; and decreased by 4.39%, 1.01% and 2.59% in sandy loam soil at 10 cm depth, respectively. However, the W_{sb} caused by linear type (T_1) was lower than that of others in loam soil, and there was no significant difference in sandy loam soil at 5 cm depth (Figure 5a).



a. Effects of different cutting edge curves on width of seedbed

b. Effects of different cutting edge curves on height of the ridge



c. Effects of different cutting edge curves on with of soil throw

d. Effects of different cutting edge curves on cross-sectional area of furrow

Figure 5 Effects of different cutting edge curves on soil disturbance

Compared with linear type (T_1), convex type (T_2) and combination type (T_4), the concave type (T_3) tine furrow opener increased the H_r by 18.9%, 24.6% and 10.2% in loam soil at 10 cm depth; 17.8%, 20.2% and 7.3% in sandy loam soil at 10 cm depth; 41.9%, 49.8% and 17.5% in loam soil at 5 cm depth, respectively. However, the H_r caused by combination type (T_4) was greater than that of others in sandy loam soil at 5 cm depth (Figure 5b).

Compared with the linear type (T_1), convex type (T_2) and combination type (T_4), the W_{st} caused by concave type (T_3) tine furrow opener decreased by 5.3%, 6.2% and 7.7% in loam soil at 10cm depth, respectively; decreased by 6.4%, 10.7% and 10.3% in sandy loam soil at 10 cm depth, respectively. A similar trend was observed in loam soil at the depth of 5 cm, concave type (T_3) tine furrow opener decreased by 5.9%, 8.9% and 11.6%, respectively. There was no significant difference in sandy loam soil at 5 cm depth (Figure 5c).

Compared with the concave type (T_3) tine furrow opener, the W_{st} caused by linear type (T_1), convex type (T_2) and combination type (T_4) increased by 7.0%, 3.2% and 5.4% in loam soil at 10 cm depth, respectively; the W_{st} caused by linear type (T_1), convex type (T_2) and combination type (T_4) increased by 7.1%, 3.5% and 5.3% in sandy loam soil at 10 cm depth, respectively. However, there was no significant difference at 5 cm depth (Figure 5d).

In addition, it was concluded that concave type cutting edge curve helped to reduce soil disturbance. Sánchez-Girón et al.[33] found that the shape of opener and it's rake angle affected the A_f. The study confirmed that soil was influenced by the squeezing and cutting action of furrow opener's cutting edge and moved along the edge direction in the opening operation.

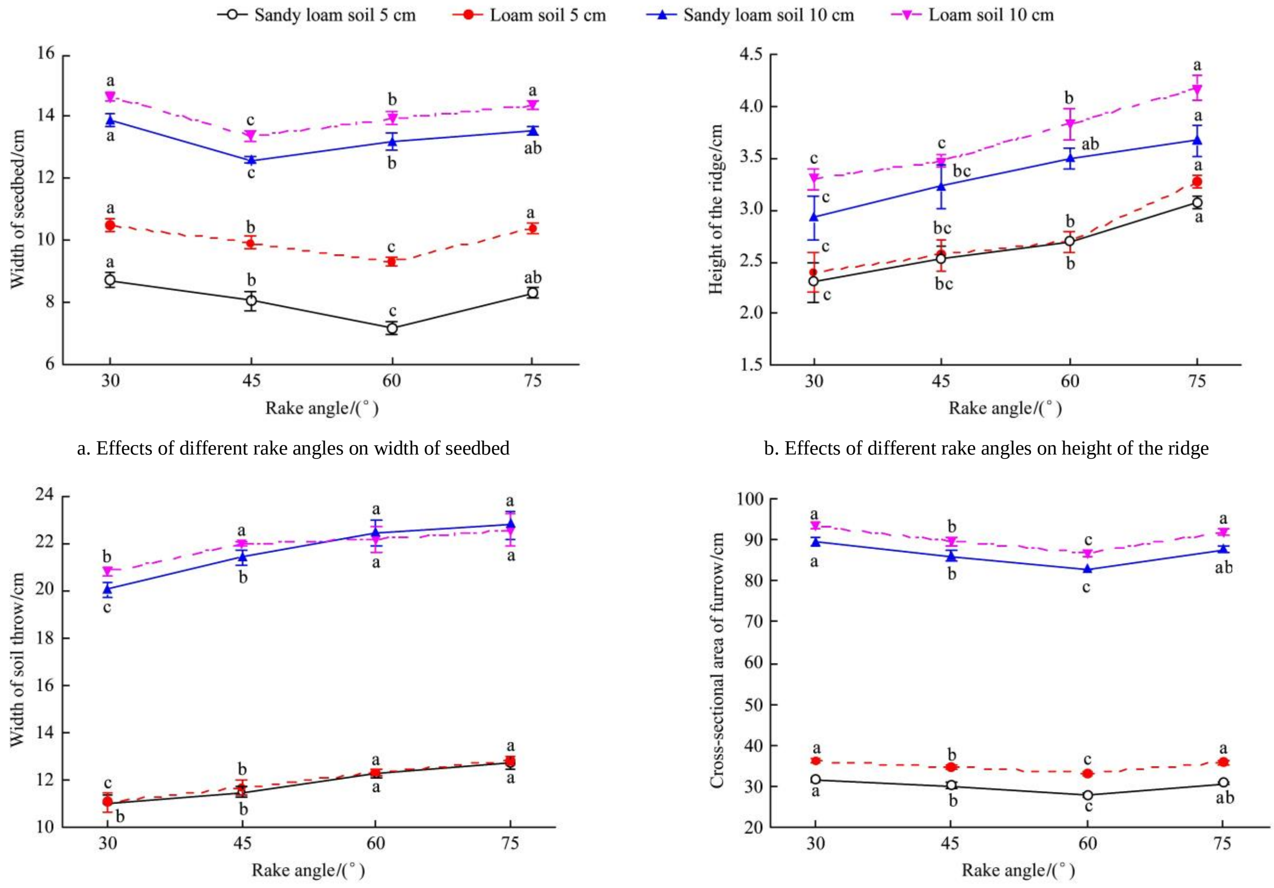
It had significantly greater soil disturbance at the depth of 10 cm than that at the depth of 5 cm, and there were significant differences among those openers with different rake angles (Figure 6). The W_{sb} increased first and then decreased with increasing rake angles. The lowest W_{sb} appeared with 45° and 60° rake angle at 10 cm and 5 cm depth, respectively (Figure 6a). The H_r and W_{st} increased with increasing rake angles. The H_r was larger by 7.4%-13.6% and 1.6%-6.6% in loam soil than that in sandy loam soil at the depth of 10 cm and 5 cm, respectively (Figure 6b). Tine furrow opener with 75° rake angle increased W_{st} by 8.3% and 15.4%, compared with 30° rake angle at the depth of 10 cm and 5 cm, respectively (Figure 6c). With the increase of rake angle, A_f increased first and then decreased. The A_f had the smallest value when the rake angle was 60° (Figure 6d). It was concluded that tine furrow opener with rake angle ranged from 45° to 60° created the lowest soil disturbance because soil was lifted up by furrow opener with smaller rake angle and pushed with larger rake angle.

3.3 Straw disturbance quantity

Appropriate amount of straw coverage could improve soil moisture content and promote crop growth[34]. However, excessive amount of straw coverage would increase soil temperature and delay the emergence time[35]. The straw disturbance quantities affected by tine furrow opener with different structural parameters (including cutting edge thickness and cutting edge curve) under different straw coverage rates were shown in Figure 7.

Straw disturbance quantity increased with increasing straw coverage rate. The straw disturbance quantity was 11.0%, 12.5% and 17.0% under the coverage rate of 43%, 68% and 93%, respectively. Under the same coverage rate, there were no significant differences (p<0.05) and no obvious variety regulation on straw disturbance quantity among 0-2 mm cutting edge thickness (Figure 7a). Meanwhile, research by Bobobee and Gebresenbet[36] on shear performance of cutting edge indicated that, the draft force and the anti-blocking capacity of furrow opener were improved with the decrease of cutting edge thickness, respectively. The straw disturbance quantity caused by cutting edge curve was 9.3%-13.8%, 11.6%-15.7% and 14.6%-20.7% under the coverage rate 43%, 68% and 93%, respectively. The concave type (T_3) tine furrow opener created the highest straw disturbance quantity. Compared with concave type (T_3), furrow opener with linear type (T_1), convex type (T_2) and combination type (T_4) reduced the disturbance quantity by 25.9%, 32.2% and 11.2%, respectively, under the coverage rate of 43%; reduced by 21.5%, 25.9% and 14.0%, respectively, under the coverage rate of 68%; reduced by 16.3%, 29.3% and 10.6%, respectively, under the coverage rate of 93% (Figure 7b).

Yao[10] had the same results on straw disturbance quantity. There were significant differences among the four cutting edge curves under the same coverage rate because soil moved along the edge direction and affected the straw movement[37]. It was found that cutting edge had significant influence on the disturbance of the soil and surface straw, however, the abrasion should be considered in design.



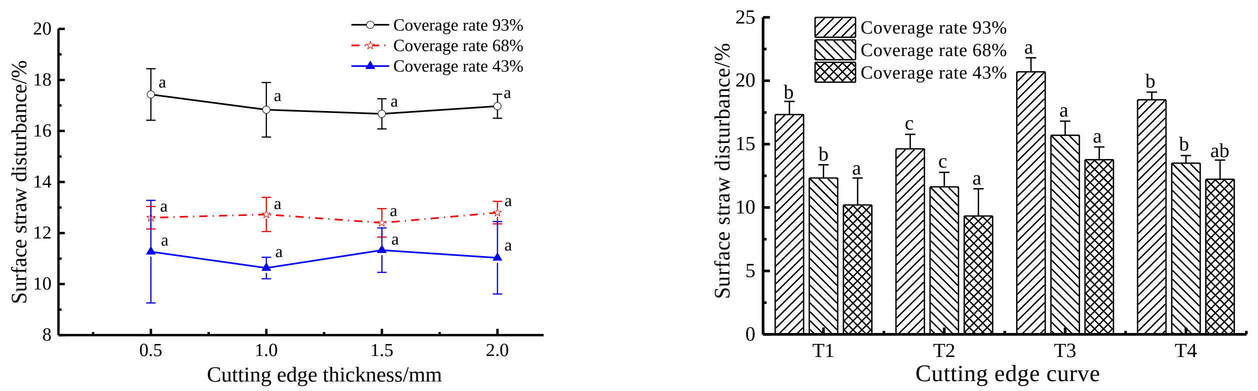
a. Effects of different rake angles on width of seedbed

b. Effects of different rake angles on height of the ridge

c. Effects of different rake angles on width of soil throw

d. Effects of different rake angles on cross-sectional area of furrow

Figure 6 Effects of different rake angles on soil disturbance



a. Effects of different cutting edge thicknesses on surface straw disturbance

b. Effects of different cutting edge curves on surface straw disturbance

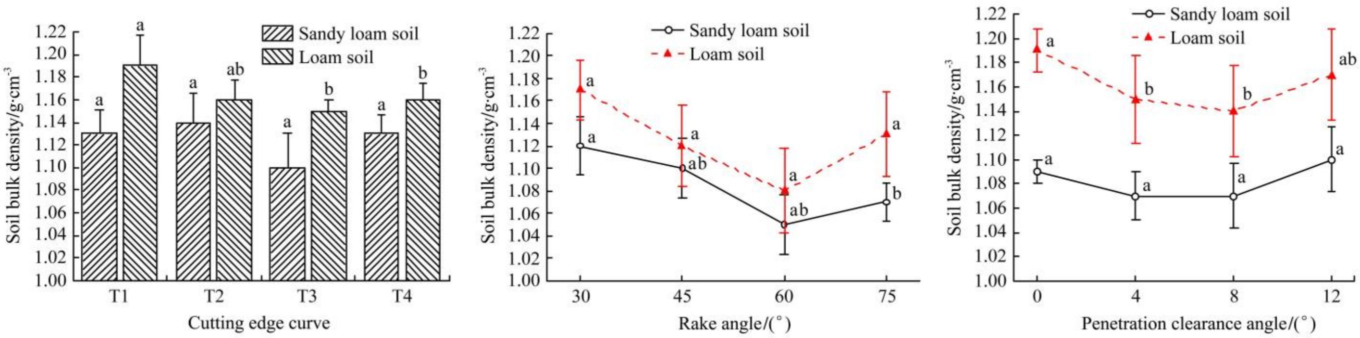
Figure 7 Effects of different structures on straw disturbance

3.4 Soil bulk density

The soil bulk density caused by different tine furrow openers in loam soil was larger than that in sandy loam soil (Figure 8).

Concave type (T_3) furrow opener created the smaller soil bulk density than others. Compared with concave type (T_3), linear type (T_1), convex type (T_2) and combination type (T_4) furrow opener increased the soil bulk density by 3.5%, 0.9% and 0.9% in loam soil, and increased by 2.7%, 3.6% and 2.7% in sandy loam soil, respectively (Figure 8a). With the increasing rake angle, soil bulk density decreased first and then increased. With 60°rake angle, the furrow opener created the lowest soil bulk density of 1.082 g/cm^3 in loam soil and 1.051 g/cm^3 in sandy loam soil. The soil bulk density created by furrow opener with 60° rake angle was lower than that by 30°, 45° and 75° rake angles in loam and sandy loam soil, respectively (Figure 8b). With the increase of penetration clearance angle, soil bulk density decreased first and then increased. Compared with 0°, 4° and 12° penetration clearance angle, furrow opener with 8° penetration clearance angle, which produced the lowest soil bulk density (1.14 g/cm^3) in loam soil, and decreased soil bulk density by 4.4%, 0.9% and 2.6%, respectively. However, furrow opener with penetration clearance angle ranged from 4° to 8°, which created the lowest soil bulk density (1.07 g/cm^3), decreased soil bulk density by 2.0% and 2.8% compared with 0° and 12° penetration clearance angle in sandy loam soil, respectively (Figure 8c).

During the opening process, furrow openers with larger penetration clearance angle made soil fall back into the furrow early and broke up soil. And the soil on the sides and bottom of seed furrow was compacted by furrow openers with smaller penetration clearance angle[38]. Chaudhuri[21] found that the operating depth of furrow opener had influences on the width of seedbed and backfilling soil and thus affected the soil bulk density.



a. Effects of different cutting edge curves on soil bulk density

b. Effects of different rake angles on soil bulk density

c. Effects of different penetration clearance angles on soil bulk density

Figure 8 Effects of different structures on soil bulk density

3.5 Soil water-stable aggregates

Soil water stable-aggregate (WSA) reflected the surface area and porosity of soil in field. The WSA (1-10 mm) had good soil porosity which was beneficial to air permeability, water holding capacity of soil and crop growth[39]. At the soil depth of 10 cm, different structures of tine furrow opener affected the percentage of WSA with different particle sizes (Table 6). With increasing particle sizes, the content of WSA decreased first and then increased in the seed furrow. The content of WSA (>0.25-0.5 mm) was higher than others, and the content of WSA (>1.0 mm) was the lowest. That was consistent with the original soil of the operational area. Under the same treatment, the percentage of each particle size of WSA in loam soil was larger than that in sandy loam soil, especially the WSA (>0.25-1.0 mm).

The concave type (T_3) tine furrow opener produced the larger content of WSA (>0.5 mm) and the lower content of WSA (≤0.5 mm) than other types. There were significant differences on WSA (>0.25-0.5 mm), while the differences were in significant on other particle sizes among cutting edge curves (p<0.05).

There were no significant differences on each particle size of WSA with various rake angles (p<0.05). The content of WSA (<2 mm) increased with increasing rake angles, but it was not significant. The content of WSA

(<2 mm) caused by 75° rake angle was 0.1%-3.2% larger than 30° rake angle, because the tine furrow opener with a larger rake angle pushed soil and damaged the WSA. During the process of soil cutting, the tine furrow opener with smaller rake angle caused less damage to WSA.

As penetration clearance angle increased, the content of WSA (>0.5 mm) decreased. There were no significant differences on WSA with various penetration clearance angles (p<0.05).

In conclusion, soil disturbance had larger influence on WSA (>0.5 mm). Less soil disturbance reduced the damage of WSA which was related to the research conducted by Du et al.[40]. Meanwhile, Arvidsson et al.[41] found that different geometric structures of opener and soil conditions had different soil fragmentation.

Table 6 Effects of different structures on soil water-stable aggregates

Design parameters		Proportions of soil water-stable aggregates/%									
		0.106-0.25 mm		>0.25-0.5 mm		>0.5-1.0 mm		>1.0-2.0 mm		>2.0 mm	
		Sandy loam	Loam	Sandy loam	Loam	Sandy loam	Loam	Sandy loam	Loam	Sandy loam	Loam
Cutting edge curve	T_1	14.91^{a}	17.12^{a}	28.92^{a}	30.12^{b}	5.45^{a}	7.81^{a}	3.81^{a}	4.15^{a}	1.27^{a}	2.01^{a}
	T_2	14.89^{a}	17.14^{a}	28.93^{a}	34.13^{a}	5.42^{a}	7.76^{a}	3.66^{a}	4.11^{a}	1.19^{a}	1.97^{a}
	T_3	14.90^{a}	17.02^{a}	28.92^{a}	30.89^{ab}	5.45^{a}	7.74^{a}	3.82^{a}	4.17^{a}	1.33^{a}	2.12^{a}
	T_4	14.90^{a}	17.31^{a}	28.92^{a}	30.71^{ab}	5.45^{a}	7.73^{a}	3.74^{a}	4.08^{a}	1.25^{a}	2.00^{a}
Rake angle	30°	14.89^{a}	17.09^{a}	28.91^{a}	30.13^{a}	5.44^{a}	7.74^{a}	3.86^{a}	4.08^{a}	1.34^{a}	2.01^{a}
	45°	14.89^{a}	17.10^{a}	28.92^{a}	30.15^{a}	5.46^{a}	7.78^{a}	3.80^{a}	4.14^{a}	1.30^{a}	2.14^{a}
	60°	14.90^{a}	17.13^{a}	28.92^{a}	30.15^{a}	5.46^{a}	7.81^{a}	3.76^{a}	4.17^{a}	1.26^{a}	2.09^{a}
	75°	14.92^{a}	17.29^{a}	28.93^{a}	30.17^{a}	5.45^{a}	7.90^{a}	3.73^{a}	4.21^{a}	1.18^{a}	2.11^{a}
Penetration clearance angle	0°	14.91^{a}	17.12^{a}	28.92^{a}	30.14^{a}	5.45^{a}	7.87^{a}	3.91^{a}	4.20^{a}	1.37^{a}	2.12^{a}
	4°	14.92^{a}	17.12^{a}	28.91^{a}	30.13^{a}	5.44^{a}	7.79^{a}	3.87^{a}	4.17^{a}	1.30^{a}	2.11^{a}
	8°	14.91^{a}	17.13^{a}	28.92^{a}	30.14^{a}	5.45^{a}	7.81^{a}	3.86^{a}	4.16^{a}	1.27^{a}	2.05^{a}
	12°	14.92^{a}	17.13^{a}	28.92^{a}	30.13^{a}	5.45^{a}	7.83^{a}	3.85^{a}	4.13^{a}	1.26^{a}	2.07^{a}

Note: In the same structure, means within a column followed by the same letters are not significantly different (p<0.05).

4 Conclusions

In this study, different key structural parameters of tine furrow openers were designed to analyze the effects of soil bulk density, WSA, soil disturbance on soil properties and surface straw disturbance of seedbed. The rake angle had significant effect on cross-sectional area of furrow (A_f), soil bulk density and surface straw disturbance. The cutting edge thickness and cutting edge curve had significant effects on A_f and surface straw disturbance respectively. The cutting edge was the key structural parameter affecting soil and surface straw disturbance. The concave type furrow opener produced the furrow with the lowest width of seedbed (W_{sb}), width of soil throw (W_{st}), and A_f in no-till planting. It also had the highest surface straw disturbance and the H_r. The tine furrow opener with rake angle between 45° and 60° produced the lowest W_{sb} and A_f. The H_r and W_{st} increased with the increasing rake angles. The cutting edge thickness (≤2.0 mm) had no significant effects on disturbance of surface straw. Concave type furrow opener produced the lower soil bulk density and greater content of WSA (>0.5 mm) than others. When the penetration clearance angle ranged from 4° to 8°, the tine furrow opener created the lowest soil bulk density. As the penetration clearance angle increased, the content of WSA (>0.5 mm) decreased, and there were no significant differences on WSA (≤0.5 mm). This study can provide supports for the design of tine furrow opener and promote the application of the light no-till planters.

Acknowledgments

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[References]

[1] Darmora D P, Pandey K P. Evaluation of performance of furrow openers of combined seed and fertiliser drills. Soil & Tillage Research, 1995; 34: 127–139.

[2] Altikat S, Celik A, Gozubuyuk Z. Effects of various no-till seeders and stubble conditions on sowing performance and seed emergence of common vetch. Soil & Tillage Research, 2013; 126: 72–77.

[3] Doan V, Chen Y, Irvine B. Effect of residue type on the performance of no-till seeder openers. Canadian Bio-systems Engineering, 2005; 47: 29–35.

[4] He J, Zhang Z Q, Li H W, Wang Q J. Development of small/medium size no-till and minimum-till seeders in Asia: A review. Int J Agric & Biol Eng, 2014; 7(4): 1–12.

[5] Murray J R, Tullberg J N, Basnet B B. Planters and Their Components. Canberra: Elect Printing; 2006. pp. 8–25.

[6] Filho O G, Silva A P, Giarola N F B, Tormena C A. Structural properties of the soil seedbed submitted to mechanical and biological chiseling under no-tillage. Geoderma, 2013; 204-205: 94–101.

[7] He J, Li H W, McHugh A D, Wang Q J, Li H, Rasaily R G, et al. Seed zone properties and crop performance as affected by three no-till seeders for permanent raised beds in Arid Northwest China. Journal of Integrative Agriculture, 2012; 11(10): 1654–1664.

[8] Huang G B, Zhang R Z, Li G D, Li L L, Chan K Y, Heenan D P, et al. Productivity and sustainability of a spring wheat–field pea rotation in a semi-arid environment under conventional and conservation tillage systems. Journal of Integrative Agriculture, 2008; 107(1): 43–55.

[9] Vamerali T, Bertocco M, Sartori L. Effects of a new wide-sweep opener for no-till planter on seed zone properties and root establishment in maize (*Zea mays* L.): A comparison with double-disk opener. Soil & Tillage Research, 2006; 89: 196–209.

[10] Yao Z L. Study on wedge-shaped with front knife no-till opener. PhD dissertation. Beijing: China Agricultural University, 2008. 6; 99p. (in Chinese with English abstract)

[11] Siemens M C, Darnell T J, Hulick D E. Performance of two hoe-type air drills sowing green peasin a conservation tillage system. Applied Engineering in Agriculture, 2009; 23(1): 23–29.

[12] Yao Z L, Li H W, Gao H W, Wang X Y, He J. Crop performance as affected by three opening configurations for no-till seeder in annual double cropping regions of northern China. Australian Journal of Soil Research, 2009; 47(8): 839–847.

[13] Godwin R J. A review of the effect of implement geometry on soil failure and implement forces. Soil and Tillage Research, 2007; 97: 331–340.

[14] Solhjou A, Fielke J M, Desbiolles J M A. Soil translocation by narrow openers with various rake angles. Biosystems Engineering, 2012; 112: 65–73.

[15] Abo-Elnor M, Hamilton R, Boyle J T. Simulation of soil–blade interaction for sandy soil using advanced 3D finite element analysis. Soil and Tillage Research, 2004; 75(1): 61–73.

[16] Shmulevich I, Asaf Z, Rubinstein D. Interaction between soil and a wide cutting blade using the discrete element method. Soil & Tillage Research, 2007; 97: 37–50.

[17] Ucgul M, Fielke J M, Saunders C. Defining the effect of sweep tillage tool cutting edge geometry on tillage forces using 3D discrete element modeling. Information Processing in Agriculture, 2015; 2: 130–141.

[18] Chen Y, Munkholm L J, Nyord T. A discrete element model for soil–sweep interaction in three different soils. Soil & Tillage Research, 2013; 126: 34–41.

[19] Hasimu A, Chen Y. Soil disturbance and draft force of selected seed openers. Soil &Tillage Research, 2014; 140: 48–54.

[20] Altuntas E, Ozgoz E, Taser O F, Tekelioglu O. Assessment of different types furrow openers using a full automatic planter. Asian Journal of Planter Sciences, 2006; 5(3): 537–542.

[21] Chaudhuri D. Performance evaluation of various types of furrow openers on seed drills-a review. Journal of Agricultural Engineering Research, 2001; 79(2): 125–137.

[22] Mohler C L, Frisch J C, McCulloch C E. Vertical movement of weed seed surrogates by tillage implements and natural processes. Soil and Tillage Research, 2006; 86: 110–122.

[23] Karayel D, Özmerzi A. Comparison of vertical and lateral seed distribution of furrow openers using a new criterion. Soil & Tillage Research, 2007; 95: 69–75.

[24] Molatudi R L, Mariga I K. The Effect of mazie seed size and depth of planting on seeding. Journal of Applied Science Research, 2009; 5(12): 2234–2237.

[25] Sanusan S, Polthanee A, Seripong S, Audebert A, Mouret J C. Seedling establishment and yield of direct-seeded rice under different seeding depths. KhonKaen Agriculture Journal, 2009; 37: 15–22.

[26] Li L H, Wang C, Zhang X Y, Li G Y. Improvement and optimization of preparation process of seedling- growing bowl tray made of paddy straw. Int J Agric & BiolEng, 2014; 7(4): 13–22.

[27] Qiao X D. Development and application of the field integrated testing system for the rear suspension tools. PhD dissertation. Beijing: China agricultural university, 2013. 6; 84p. (in Chinese with English abstract)

[28] Zhai J B, Xia J F, Zhou Y, Zhang S. Design and experimental study of the control system for precision seed-metering device. Int J Agric & BiolEng, 2014; 7(3): 13–18.

[29] Yazgi A, Degirmencioglu A. Measurement of seed spacing uniformity performance of a precision metering unit as function of the number of holes on vacuum plate. Measurement, 2014; 56: 128–135.

[30] Manuwa S I, Ademosun O C, Adesina A. Regression equations for predicting the effect of tine width on draught and soil translocation in moderately fine textured soil. Journal of Environmental Science and Engineering, 2012; B1: 820–825.

[31] AlKaisi M, Hanna H M. Resource conservation practices: Residue management and cultural practices. Available at: http://lib.dr.iastate.edu/extension_ag_pubs/156/. Accessed on [2002-03].

[32] Zhou H, Lu Y Z, Yang Z C, Li B G. Influence of conservation tillage on soil aggregates features in North China Plain. Agricultural Sciences in China, 2007; 6(9): 1099–1106.

[33] Sánchez-Girón V, Ramirez J J, Litago J J, Hernanz J L. Effect of soil compaction and water content on the resulting forces acting on three seed drill furrow openers. Soil & Tillage Research, 2005; 81: 25–37.

[34] Singh G. Effects of wheat straw and farmyard manure mulches on overcoming crust effect, improving emergence, growth and yield of soybean and reducing dry matter of weeds. International Journal of Agricultural Research, 2009; 4(12): 418–424.

[35] Yang L, Zhang R, Gao N N, Cui T, Liu Q W, Zhang D X. Performance of no-till corn precision planter equipped with row cleaners. Int J Agric & BiolEng, 2015; 8(5): 15–25.

[36] Bobobee E Y H, Gebresenbet G. Effect of cutting edge thickness and state of wear of ploughshare on draught force and heart rates of Sanga oxen in Ghana. Soil and Tillage Research, 2007; 95(1-2): 298–307.

[37] Wang Q J, He J, Li H W, Lu C Y, Rasaily R G, Su Y B. Design and experiment on furrowing and anti-blocking unit for no-till planter. Transactions of the CSAE, 2012; 28(1): 27–31. (in Chinese with English abstract)

[38] Wang Q J, Yao Z L, Gao H W, Li H W, Wang X Y. Design and experiment on a wedge shaped no-tillage opener. Chinese Journal of Mechanical Engineering, 2008; 44(9): 177–182. (in Chinese with English abstract)

[39] McCarthy J F, Ilavsky J, Jastrow J D, Mager L M, Perfect E, Zhuang J. Protection of organic carbon in soil micro aggregates via restructuring of aggregate porosity and filling of pores with accumulating organic matter. Geochimica et Cosmochimica Acta, 2008; 72(19): 4725–4744.

[40] Du Z L, Liu S F, Xiao X P, Yang G L, Ren T S. Soil physical quality as influenced by long-term fertilizer management under an intensive cropping system. Int J Agric & Biol Eng, 2009; 2(1): 19–27.

[41] Arvidsson J, Keller T, Gustafsson K. Specific draught for mouldboard plough, chisel plough and disc harrow at different water contents. Soil Tillage Res, 2004; 79(2): 221–232.