INFLUENCE OF THE SWEEP ANGLE OF THE CROSS KNIFE OPENER ON SOIL DISTURBANCE
/
十字槽开沟器横刀后掠角对土壤扰动的影响

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ABSTRACT

The cross-slot opener is a new type of seeding opener. The sweep angle, which is a key structural parameter of the cross knife, has an important influence on soil disturbance. In this paper, discrete element method and tracer method are used to study the conditions of working speed of 0.83m/s and ditching depth of 130mm, the sweep angles of the transverse knife are 0°, 10°, 20°, 30°, 40°, respectively. The influence of time opener on soil disturbance and working resistance. The simulation analysis of the operation process of the cross groove opener shows that the trenching process under different sweep angles of the transverse knife is basically the same, and the standing knife is the main cause of soil disturbance; both the tracer method and the simulation results show the surface and shallow soil particle disturbance. The proportional and horizontal working resistance first decrease and then increase with the increase of the sweep angle of the cross-slot opener. When the sweep angle of the cross-slot opener is 20°, the micro-disturbance of soil particles and the horizontal work resistance are the least; The relative error of the soil disturbance ratio obtained by the tracer method and the discrete element method are both within 15%, and the relative error of the horizontal working resistance is 6.5%. The established discrete element simulation model can more accurately simulate the soil disturbance process of the cross-slot opener.

摘要

十字槽开沟器是一种新型播种开沟器，作为横刀关键参数的后掠角对土壤扰动具有重要影响。本文应用离散元法和示踪法，研究了横刀后掠角分别为 0°, 10°, 20°, 30°, 40°时开沟器对土壤扰动和工作阻力的影响。示踪法与仿真结果皆显示表层和浅层土壤颗粒扰动比例和水平工作阻力随着横刀后掠角的增加先减小后增大，当十字槽开沟器横刀后掠角为 20°时，对土壤颗粒微观扰动和水平工作阻力均最小；通过示踪法与离散元法获取的土壤扰动比例相对误差均在 15%以内，水平工作阻力的相对误差为 6.5%，建立的仿真模型能够准确模拟十字槽开沟器的工作过程。

INTRODUCTION

At present, most of the research on soil contact parts focuses on improving the design through experimental methods (*He J et al., 2018*). In order to study the performance of soil-contacting parts, we must first explore the law of soil movement and the force exerted on the soil during its work (*Jia H L et al., 2017*). The discrete element method (DEM) can be used to simulate the microscopic and macroscopic deformations of granular materials and study materials, allowing the formation and destruction of contact between granular materials, and is also suitable for simulating the interaction between soil and rigid bodies. Scholars have conducted extensive studies on the interaction process between soil and farming tools based on DEM. These studies have confirmed that discrete element simulation can simulate the farming process (*Hang C.G. et al. 2018; Tanaka H. et al., 2000*). In the discrete element, the movement of soil particles can be tracked, and the forces and disturbances of the soil particles during the cultivation process can be analysed (*Fang H.M. et al. 2016b*). The tracing method can also measure the change of soil displacement, which can reflect the mixing condition of the upper and lower dry and wet soil layers after the opener is operated. The tracer method is mainly to arrange the tracer in the soil to replace the fixed-point soil particles before operation. By observing the position change and movement process of the tracer before and after the operation, infer the position change of the soil particle and the movement law of the soil particle at the replacement point of the tracer. *Aliakbar Solhjou et al.* studied the influence of openers with different structural parameters on the amount of soil side throw, and used the tracker tracing method to record the position changes of the tracer (*Barr J et al.*

2016; Solhjou A et al. 2013; Solhjou A et al. 2012; Solhjou A et al. 2014). When *Cao X.D.* improved the design of the traditional core-shaft opener, he used the discrete element method and the tracker tracing method to study the soil microscopic movement changes after the trenching operation and determined the optimal structural parameters. *James Barr et al.* combined the two methods to analyse the influence of the structural parameters of the open-leg opener on soil disturbance (*Barr J B et al. 2020*). These two methods can accurately analyse the soil disturbance quantity. In a comprehensive analysis, domestic scholars mainly use discrete element method in their research on the optimization of soil touching parts, but few use tracer method to study the soil touching parts, and even fewer study the combination of the two aspects of discrete element method and tracer method to optimize the structural parameters of soil touching parts.

The cross-slot opener is a new type of opener developed by our research team. One-time ditching can realize the double-sided application of corn seeds and seed fertilizer and the layered application of seed fertilizer and base fertilizer, reducing the operation of the opener (*Zhang J C et al., 2019*). The sweep angle of the cross knife is a key structural parameter of the cross-slot opener, which has a great influence on soil disturbance and horizontal working resistance during the working process. However, the influence of the sweep angle of the cross-slot opener on soil disturbance and working resistance is still unclear. Therefore, this research takes the cross-slot opener as the object and uses the discrete element method and the tracer method to study the influence of the sweep angle of the transverse knife on the soil disturbance and horizontal working resistance during the trenching process, so as to provide a reference for the determination of the sweep angles of the transverse knife.

MATERIALS AND METHODS

Tracer test

- **Experiment material**

The cross-slot opener is mainly composed of a vertical knife and a horizontal knife on both sides, as shown in Fig.1. In the process of corn sowing and fertilization, the opener uses a vertical knife to open the base fertilizer ditch to realize the deep application of base fertilizer. A horizontal knife is installed on both sides of the vertical knife, and a seed ditch and a seed fertilizer ditch are opened on both sides of the upper part of the base fertilizer ditch in the lower layer of the soil. The falling soil above affects seeding and fertilization, realizing the two-sided application of seed and seed fertilizer.

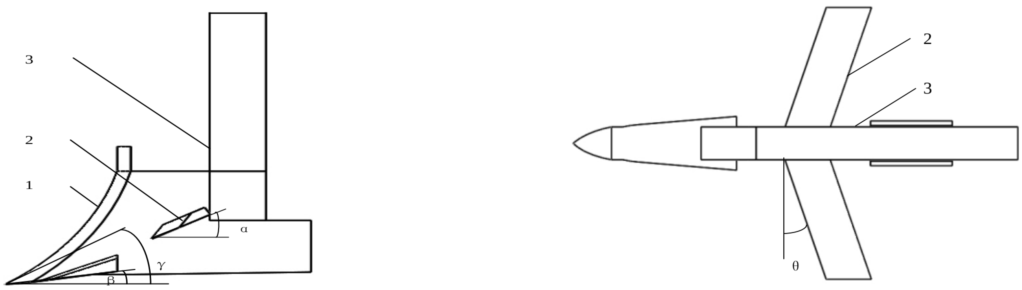


Fig. 1 - Cross-slot opener

1. Vertical knife; 2. Horizontal knife; 3. Column

Li G.H., (2018), Zhang J.C. et al., (2019), studied to determine the structural dimensions of the cross-slot opener, the horizontal knife entry angle α is 30°, the vertical knife entry angle γ is 31°, and the vertical knife entry clearance angle β is 8°. In order to loosen the seed bed and facilitate ditching and fertilization, the projected length of the unilateral transverse knife in the direction of the seed furrow section is 80mm. From a theoretical analysis, when the sweep angle θ increases, the soil changes from cutting to sliding, and the resultant horizontal force decreases; when the sweep angle θ is too large, the projected length of the transverse knife on the seed trench section remains unchanged. The total length of the horizontal knife will increase, and the area of soil disturbance will increase. In order to reduce working resistance and soil disturbance, combined with the spacing of corn seed fertilizer and the installation position of the cross knife of the cross-slot opener, the maximum sweep angle of the cross knife is determined to be 40°.

Li G.H. (2018) and *Zhang J.C. (2019)* only theoretically and partially analysed the influence of the sweep angle of the transverse knife on the working resistance, but the influence of the sweep angle of the transverse knife on the soil disturbance is still unclear. Therefore, this study determines that the sweep angle θ of the transverse knife is 0°, 10°, 20°, 30°, and 40°.

- **Experimental procedure**

The tracer test was carried out in the digital soil tank of the Agricultural Machinery Laboratory of Northwest A&F University. The soil is loess with granular structure. The parent material is secondary loess and loamy clay. It belongs to the agricultural soil developed on the loess parent material (*Ding S.P. et al., 2018*). In the tracer test, according to the soil parameters in the field when the corn was sowed, the soil in the soil trough was prepared by a layered preparation method to ensure that the soil trough test was basically consistent with the soil parameters of the field environment (*Zhang J C et al., 2016*). After preparation, the average moisture content of the soil in the soil tank was 16.2%, and the soil hardness was 1447 kPa. Rotary tillage and soil compaction are shown in Fig.2.

With the opener working centre as the X-axis direction as the reference, tracers are arranged within 150mm on the left and right. The tracer uses a PVC cube with a material density of 1.2g/cm3 and a side length of 10mm. Use a soil drill to drill a 150mm deep circular hole vertically downward at each location. First put the light blue tracer in the round hole, then put the soil taken out by the soil extractor, and after compacting it to the same layer of soil hardness, keep the upper and lower layer tracers 30mm apart. The depths are 120mm, 90mm, 60mm, 30mm, 0mm, respectively, fill in pink, yellow, green, blue and red tracers, put in an appropriate amount of soil and compact to close to the hardness of the same layer of soil, after tilling, use three-dimensional positioning. The measuring instrument measures the position of the tracer in the X, Y, and Z directions, and studies the position changes of the tracers in each layer, as shown in Fig.3.

The experiment was carried out under the conditions of a tillage depth of 130mm and a speed of 0.83m/s, using an electric variable frequency four-wheel drive soil tank test vehicle (*Hang C G et al., 2018*). In order to ensure the consistency of the test process and the reliability of the data, the first 3m of the soil-bin is the acceleration stage, the last 3m is the deceleration stage, and the middle area is the test area and the data collection area.

a) Rotary tillage and crushing process in soil trough

b) Soil compaction process

Fig. 2 - The soil preparation process of the soil trough

Fig. 3 - Tracer layout and position measurement

Discrete element simulation analysis of cross-slot opener

The interaction between the cross-slot opener and the cultivated soil is a complex movement process. Discrete element simulation can study the interaction between the cross-slot opener and the soil from a macro and micro perspective.

- **Simulation modelling**

In order to ensure the reliability of the simulation results, the Solidworks2018 software is used to establish a 3D model of the cross-slot opener with 5 different horizontal knife sweep angles in the test at a 1:1 ratio, and save it in the *.IGS* format and import it into EDEM2018.The decrease of soil particle size in EDEM simulation will cause the simulation time to increase geometrically. Therefore, the particle size in the simulation is limited by calculation time and computer performance, and is always larger than the real soil particle size (*Ucgul M. et al., 2014; Fang H.M et al., 2016a*). In this paper, the soil particle model has a spherical particle with a radius of 3mm, and the Hertz-Mindin with bonding model is selected (*Chen Y. et al. 2013*). The model is to bond two particles together through a bond, which can withstand a certain tangential force and normal force. When the tangential force and normal force both reach the maximum value, the bond between the two particles is damage. After that, the separated particles are treated as rigid spheres, and contact solutions are performed.

- **Soil model parameters**

In EDEM simulation software, model parameters mainly include material parameters and contact parameters. The material parameters mainly include the density, Poisson's ratio and shear modulus of soil and cross-slot opener (65Mn). The contact parameters mainly include the coefficient of restitution, dynamic friction factor and static friction factor between materials. The basic parameter references of the discrete element simulation model are shown in the table (*Ding S.P. et al. 2018; Wang X.Z. et al. 2018*).

Basic parameters of the discrete element model **Table 1**

PARAMETER	VALUE
Density of 65Mn steel /(kg·m^{-3})	7830
Poisson's ratio of 65Mn steel	0.35
Shear modulus of 65Mn steel	7.27×10^{10}
Soil particle density /(kg·m^{-3})	1404
Poisson's ratio of the soil particles	0.40
Shear modulus of the soil particles /Pa	6×10^{7}
Coefficient of restitution between soil and soil	0.6
Coefficient of rolling friction between soil and soil	0.4
Coefficient of static friction between soil and soil	0.58
Coefficient of restitution between soil and 65Mn steel	0.6
Coefficient of rolling friction between soil and 65Mn steel	0.5
Coefficient of static friction between soil and 65Mn steel	0.34
Normal Stiffness per unit area (N m^{-1})	2400000
Shear Stiffness per unit area (N m^{-1})	1700000
Critical Normal Stress (Pa)	235000
Critical Shear Stress (Pa)	186000
Bonded Disk Radius (mm)	3.5

- **Simulation test method**

After the soil parameter setting is completed, a virtual soil trough with a length × width × height of 1000mm×800mm×150mm will be generated by the pellet factory dynamically generating and accumulating pellets. In order to meet the requirements of corn planting and fertilization operations and the working depth of the cross-slot opener, the virtual soil slot model is divided into surface soil (above-10mm), shallow soil (-10mm~-40mm), middle and lower soil (-40mm~-70mm) and bottom soil (-70mm~-150mm) four parts, as shown in Fig.4. Based on the coordinate system in the simulation, the three-dimensional movement direction of the particles is explained as follows: horizontal movement occurs in the X direction; lateral movement occurs in the Y direction; vertical movement occurs in the Z direction. The forward direction of the cross-slot opener is -X direction, the forward speed is 0.83m/s, the total simulation time is 8.5s, and the depth of the opener is 130mm.

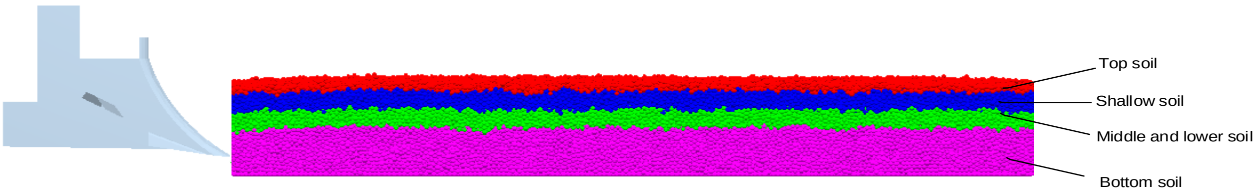


Fig. 4 - Discrete element farming model

RESULTS

Comparative analysis of soil disturbance state

It was difficult for the traditional test methods to determine the soil disturbance process during the operation of the cross-slot opener, in order to determine the changes of soil disturbance state at different depths with the different horizontal knife sweep angles (*Hang C G et al. 2018*). Using the discrete element method, a lateral cross-sectional view of the soil model at 7.6s (the cross-slot opener is in the middle of the tillage stroke) was carried out, and the cross-slot opener's lateral centre was at 0mm of the cross-sectional view, according to the projection length of the cross knife 80mm and the lateral disturbance of the opener to the soil, the section spacing in the vertical tillage direction was selected to be 40mm, and the tillage direction section under different horizontal knife sweep angles was shown in Fig.5.

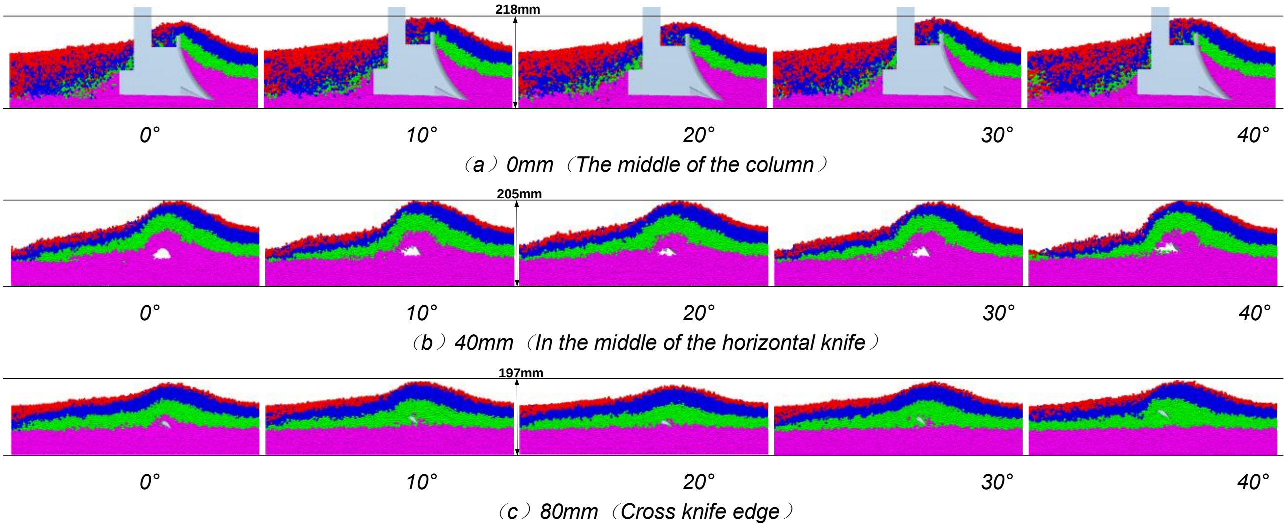


Fig. 5 - Effect of the back-inclining angle on portrait disturbance quality of soil in different layers

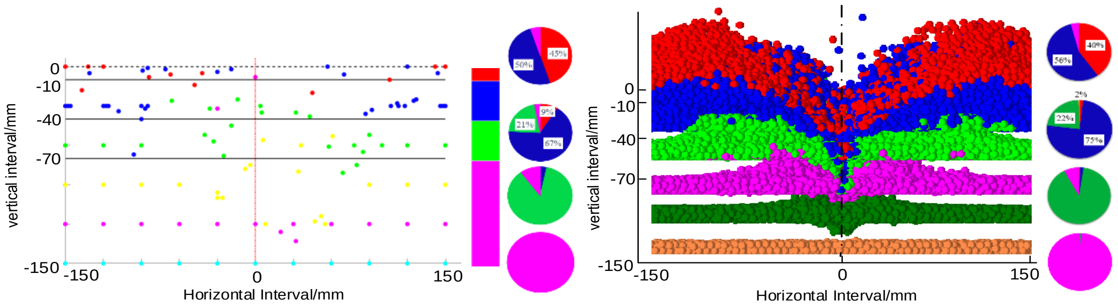
It could be seen from Fig.5 that in the middle of the vertical knife, the vertical uplift of the soil by the cross-slot opener and the mixing degree of the upper and lower soil layers were the largest. The soil disturbance area was mainly concentrated near the vertical knife, and the horizontal knife disturbance was small. With the increase of the lateral distance from the middle of the vertical knife, the vertical lifting height of the opener to the soil and the mixing degree of the upper and lower soil layers gradually decreased, and the vertical lifting height of the soil in the middle of the vertical knife was larger than the edge of the horizontal knife 21mm. With the increase of the sweep angle of the cross-slot opener, the disturbance range of the opener to the shallow and middle and lower soil layers gradually increased. As the sweep angle of the horizontal knife increased, the height of the soil lifted by the opener decreased and then increased in the middle of the vertical knife and the edge of the horizontal knife. When the sweep angle of the horizontal knife was 20°, the height of the soil lifted by the opener was the smallest (Fig.5a, c). In the middle of the horizontal knife, the influence trend of the horizontal knife sweep angle on the soil uplift height remained basically unchanged, but the slope of the ridge formed after the soil uplift gradually increased (Fig.5b).

Comparative analysis of the effect of sweep angle on soil microscopic movement

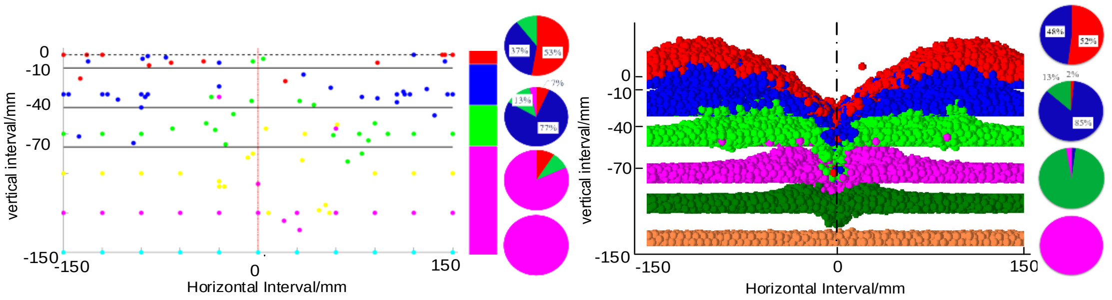
It could be seen from Fig.6 that the soil particles moved upward as a whole when the cross-slot opener was working. After work, the surface soil was mainly composed of surface and shallow soil particles. The shallow soil was mainly composed of surface, shallow and middle and lower soil particles. The middle and lower soil was mainly composed of shallow, middle and lower soil particles.

The bottom soil was mainly composed of bottom soil particles, there was almost no disturbance. Surface and shallow soil were used as maize sowing areas, which had higher requirements for soil moisture, especially in arid and semi-arid areas for maize germination and growth. The middle, lower and bottom soils were mainly composed of soil particles in the wet soil layer, which had little effect on the growth of corn. Therefore, the analysis of the particle composition in the surface and shallow soils was mainly carried out. It could be seen from the test results of the tracer method in Fig. 6(a) that with the increase of the sweep angle of the horizontal knife, the proportion of the shallow and middle-lower soil particles in the surface soil first decreased and then increased, and the proportion of the surface soil particles in the shallow soil decreased first and then increased.

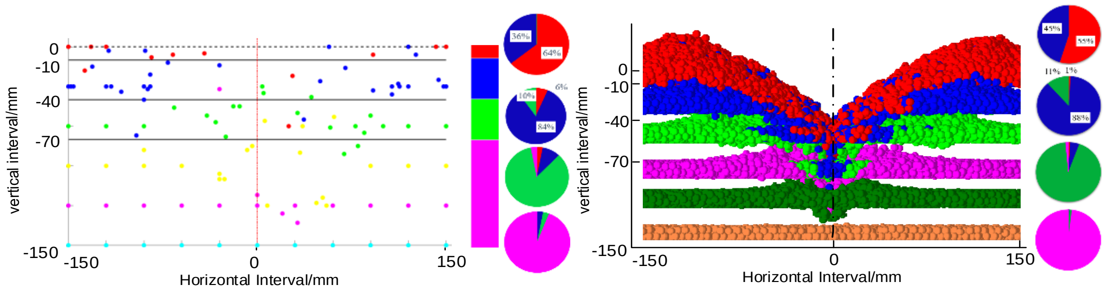
When the sweep angle of the transverse knife was 40°, the proportion of surface soil particles was 18%, and the proportion of surface soil particles in the other transverse knife sweep angles was not much different, all below 10%. When the sweep angle of the horizontal knife was 20°, the proportion of the shallow and middle-lower soil particles in the topsoil was at least 36%, which was 24%. From the simulation results in Fig. 6(b), it could be seen that with the increase of the sweep angle of the transverse knife, the proportion of the shallow and middle-lower soil particles in the surface soil first decreases and then increases.



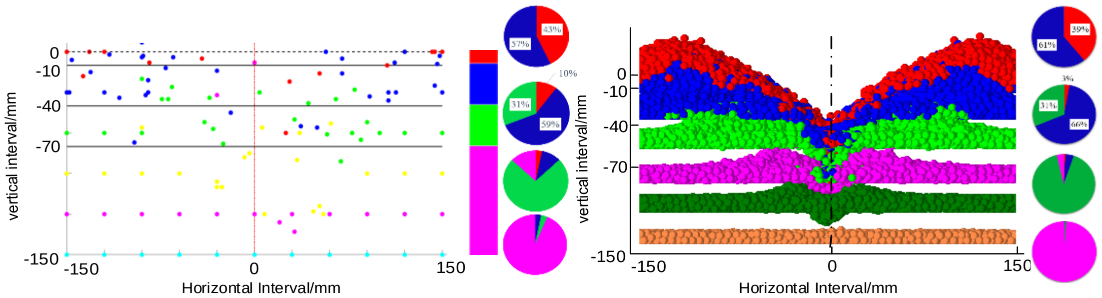
（a）Sweep angle 0°



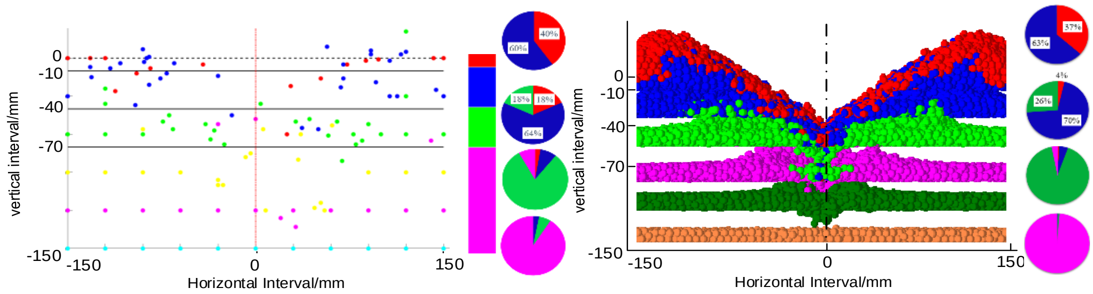
（b）Sweep angle 10°



（c）Sweep angle 20°



（d）Sweep angle 30°



（e）Sweep angle 40°

Tracer *EDEM Predicted*

Fig. 6 - Soil microscopic movement of cross-slot opener

When the sweep angle of the transverse knife was 40°, the shallow and the proportion of middle and lower soil particles was as high as 63%, and the proportion of surface soil particles in the shallow soil first decreased and then increased, but the overall difference was not significant, all below 4%. When the sweep angle of the horizontal knife was 20°, the shallow and middle-lower soil particles in the surface soil were the least, accounting for 45%, which was 18% lower than when the sweep angle was 40°, and accounting for only 1% of the shallow soil.

Influence of the sweep angle of the horizontal knife on tillage resistance

It could be seen from Fig.7 that the horizontal working resistance varied between 275-593N under different sweep angles of the transverse knife. The horizontal working resistance of the cross-slot opener under different sweep angles of the horizontal knife was quite different. When the sweep angle of the cross knife was 0° and 10°, the horizontal working resistance of the cross-slot opener did not change significantly. When the horizontal knife sweep angle increased from 10° to 20°, the horizontal working resistance decreased sharply. When the sweep angle increased from 20° to 40°, the horizontal working resistance increased sharply, mainly because the sweep angle increased, the length of the cross knife increased, which lead to a larger disturbance area, thereby increasing the horizontal working resistance. The average error between the simulated value and the experimental value of the horizontal working resistance of the cross-slot opener with 5 different horizontal knife sweep angles was 6.5%.

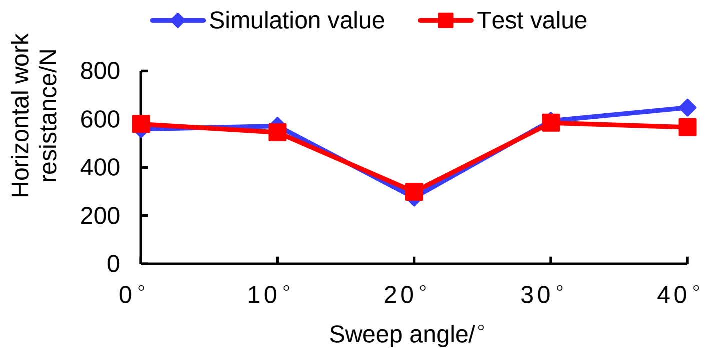


Fig. 7 - The influence of the sweep angle of the horizontal knife on the horizontal working resistance

CONCLUSIONS

(1) The relative error between the tracing method tested results and the discrete element simulation results was less than 15%, indicating that the established discrete element simulation model could more accurately reflect the soil disturbance during the operation of the cross-slot opener.

(2) With the increase of the sweep angle, the action form of the cross knife on the soil changes from cutting to sliding cutting. With the further increase of the sweep angle of the transverse knife, the increase in the total length of the transverse knife gradually increases the range of soil disturbance. With the further increase of the sweep angle, the increase in the length of the cross blade would gradually increase the range of soil disturbance, which would inevitably lead to an increase in working resistance.

(3) There was a certain error between the experimental results of the tracer method and the discrete element simulation results, especially the proportion of other soil particles in the surface soil. The following two reasons could be explained: due to the small layout of the tracer blocks, some tracer blocks would be lost or moved out of the statistical area after the cross-slot opener works; the radius of the soil particles and the tracer blocks in the simulation had a certain difference in size.

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