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Analysis of Soil Dynamic Behavior during Rotary Tillage Based on Distinct Element Method

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Abstract: The interaction of soil-tillage tool plays a pivotal role in analysis and optimization of the tillage process. The dynamic behavior of soil needs to be developed primarily when studying the soil-tillage tool interaction. The simulation of soil-rotary blade interaction using distinct element method (DEM) and indoor soil bin experiment were conducted to provide a better understanding of the soil movement. Firstly, DEM model of soil-rotary blade interaction was established. Secondly, comparison of experimental results and simulation results were done, positions before and after tillage of surface soil particle were used as soil displacement in simulation, and tracer method was employed to measure soil displacement in experiment. Then, the movement of soil which belongs to different positions was analyzed. The results showed that soil forward and side displacement in experiment increased with increasing rotational speed of blade, the forward displacement was larger than the side displacement. The displacement of shallow soil was the largest, and then middle soil and deep soil had the minimum displacement. The closer the soil to the rotational point was, the larger the forward and side displacement of soil were. For the particles in tillage scope, the percent of particles which moved to the opposite direction were 26.2%, 72.1% and 48.4% for shallow soil, middle soil and deep soil, respectively. Most soil particles moved backward in horizontal direction during tillage process. The direction of side force and side displacement depended on the situation that the soil particle lay in the left or right side of the lengthwise edge axis. If the soil lay in the left side of the lengthwise edge axis, the side displacement was towards the left and vice versa. The soil particle moved downward with the rotary blade at the beginning of soil cutting, and later it slipped from the border of blade and being tossed up. The average error of soil displacement between simulation results and experimental results was 24.9% for soil forward displacement while 15.3% for soil side displacement. The paper studied the macro- and meso- movement of soil particles during rotary tillage, which is helpful to understand the interaction between rotary blade and soil and develop the mechanism of rotavator design and optimization.

Key words: rotary blade; soil movement; discrete element simulation; dynamic mechanism

0　Introduction

Tillage practices account for about half of the energy consumed in crop production[1]. Soil-tool interaction is a complex process because of the spatial variability of soil, tool dynamics and soil movement. Soil movement and disturbance caused by four different tools were tested in an indoor soil bin by RAHMAN et al.[2-3]. LIU et al.[4-5] conducted a study on soil displacement under controlled conditions, and pointed out that the forward speed affected the forward and side movement of soil. CHANDIO et al.[6] studied the effect of working depth and speed of disc tool on soil displacement and observed an increasing trend of displacement. PENG[7] discussed the velocity, acceleration and displacement of surface, middle and deep soil. However, soil movement during rotary tillage is not yet fully understood, especially for the soil movement in different positions.

Knowledge of the soil-tillage tool interaction is important for the design and selection of tillage tool. Soil-tool interactions are usually characterized by forces arising at the soil-tool interface and soil movement. The dynamic behavior of soil and force exerted on the

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soil needs to be developed primarily when studying the soil-tillage tool interaction. For this purpose, distinct element method (DEM) is suitable for modeling granular materials and the relationship between the micro and macro behaviors of materials. DEM allows the creation or breakage of contacts between elements and is also highly suitable for modeling the interactions between soil and rigid or flexible bodies. Many studies have employed DEM for modeling soil-tillage tool interaction[8-13] and these researchers concluded that DEM model could closely simulate the tillage process. The movement of particles could be traced to analyze the dynamic behavior of particle during the tillage process[14].

Therefore, a study was designed to investigate the macro- and meso- movement of soil particles during rotary tillage, which is helpful to understand the interaction between rotary blade and soil, and develop the mechanism of rotavator design and optimization.

1 Indoor experiment

The experiment was conducted in an indoor soil bin at the Soil Mechanics Laboratory of Nanjing Agricultural University, Jiangsu, China. The IT225 rotary blade was fixed on test bench, as described in our previous work[14]. The $2\ \text{cm}^3$ tin cubes were labeled and inserted into the soil to trace the movement of the surface soil. For this purpose, 30 cubes were arranged in 10 lines perpendicular to the direction of blade travel. The arrangement of soil tracers is shown in Fig. 1a, the original soil bin is shown in Fig. 1b and the device for recording tracer positions is shown in Fig. 1c.

2 Distinct element method

2.1 Basic hypotheses

We do following hypotheses in this paper.

(1) The soil particle was simplified as spherical particle group and defined with quality and velocity.

(2) Hertz – Mindlin bonding model was used as contact model in simulation.

(3) Tillage was defined as the controlled movement of rotary blade on soil.

The particle dynamic behavior is a reflection of impact way of rotary blade on soil and can be used to analyze soil disturbance and movement.

(a) Arrangement of soil tracers

(b) Original soil bin

(c) Device for recording tracer positions

Fig. 1 Soil tracers and soil displacement measurement device

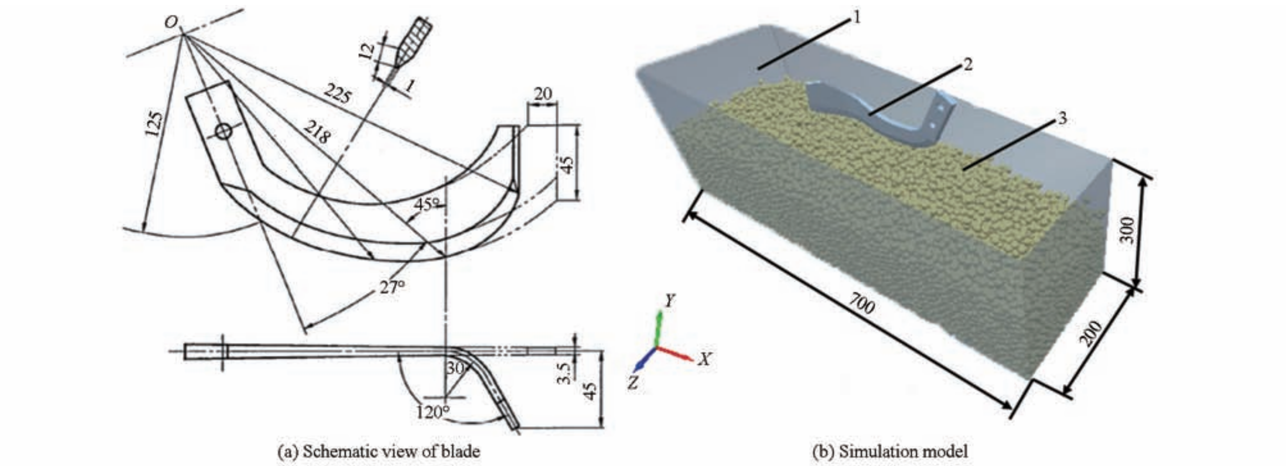
2.2 DEM model

The blade and soil bin were constructed using Pro/E and then imported to EDEM. Soil particles (24 000) were generated in the soil bin. EDEM allows specification of the rotary speed and forward speed of the blade, which were chosen to simulate the operations of the rotary blade in indoor soil bin experiments. Note that due to simulation time and computational limitations, the size of the simulated soil particles is significantly larger than the actual soil particles[15]. The radius of the soil particles was set at 5 mm, the selected blade was IT225 (as shown in Fig. 2a), and the dimensions of soil bin are 0.7 m × 0.2 m × 0.3 m. The simulation model is shown in Fig. 2b, the main parameters used in the simulation were as detailed in FANG et al.[14].

Based on the coordinate system in simulation, the direction of particle motion is described as follows: the horizontal movement happens in X direction, the vertical movement happens in Y direction, and side movement is in Z direction. The forward travel of rotary blade is in $-X$ direction.

2.3 Distribution of soil particles

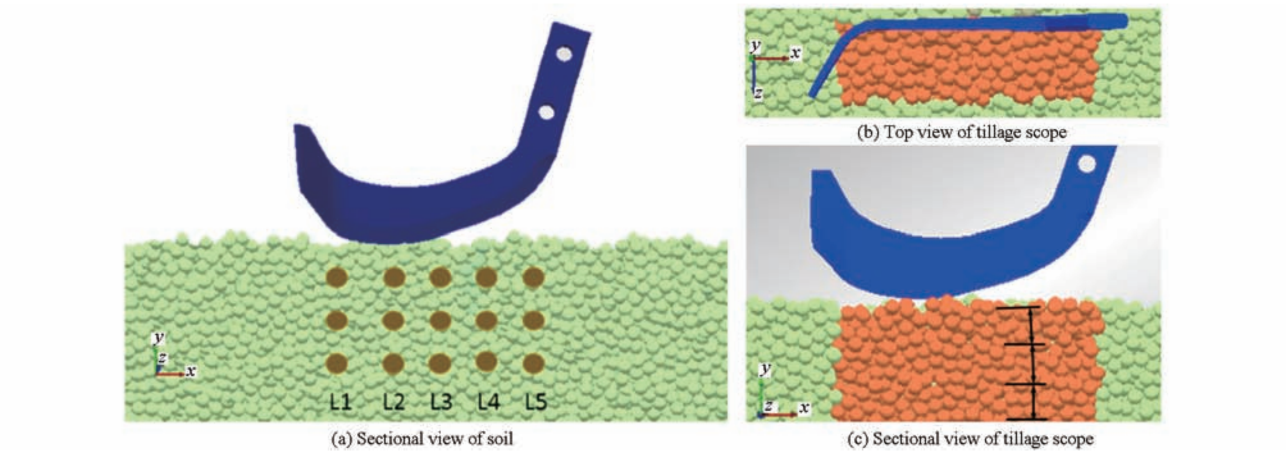
Soil particles in 15 positions, 3 depths under the lengthwise edge with 5 positions in each depth, were selected to analyze the difference of particle movement. The selected depths were 0 ~ 30 mm, 30 ~ 60 mm and 60 ~ 90 mm, as shown in Fig. 3a. The soil particles in Fig. 3b and 3c lay in the tillage scope were used to



(a) Schematic view of blade (b) Simulation model

Fig. 2 Schematic of rotary blade IT225 and simulation of soil bin with rotary blade

1. Soil bin 2. Rotary blade 3. Soil



(a) Sectional view of soil

(b) Top view of tillage scope

(c) Sectional view of tillage scope

Fig. 3 Layout of soil particles

analyze soil side movement at different depths.

3 Results and discussion

3.1 Impact of rotational speed on soil displacement

The forward and side displacements of the soil at rotational speeds of 77, 100, 123, 146 r/min are shown in Fig. 4. The forward displacements of the soil were 51.7, 146.7, 325, 366.7 mm at 77, 100, 123, 146 r/min, respectively, while the side displacements of the soil were 18.3, 36.7, 56.7, 83.3 mm at 77, 100, 123, 146 r/min, respectively, in the soil bin. It is evident that the soil displacement increased with increasing rotational speed of the blade. The higher the rotational speed was, the greater area of the soil being scattered was. The increasing ration of forward displacement was larger than that of side displacement revealed that rotational speed had more impact on soil forward displacement. Besides, the displacement in the forward direction was larger than that in the side direction at all rotary speeds due to stronger effect of soil throwing in the horizontal direction.

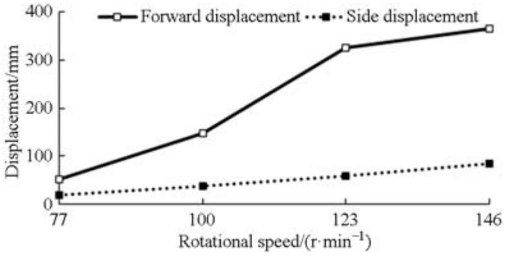


Fig. 4 Soil moving displacement with different rotational speeds

3.2 Movement of soil particles in different positions

The forward and side displacements of the selected 15 positions are shown in Fig. 5. As for the middle and deep soil, the closer the soil to the rotational point was, the larger the forward and side displacements of soil were. The middle and deep soil in L1 had small displacements because they did not contact blade directly as blade cutting the soil. The same situation occurred to deep soil in L2, its displacements were caused by minor disturbance of soil. The movement of shallow soil was complex; the soil lay in L3 touched the blade earlier than other soil due to its special position. The displacement of shallow soil in L3 moved more than other soil particles. Moreover, soil movement in deeper layer was restricted by the gravitational effect of upper soil, the displacement of shallow soil was the largest, and then middle soil and deep soil had the minimum displacement. Besides, no matter what depth and position of soil particles were, the forward displacement was larger than side displacement, this is in agreement with the experimental results. The shallow soil was disturbed more during tillage; the soil permeability is good and is suitable for seed germination.

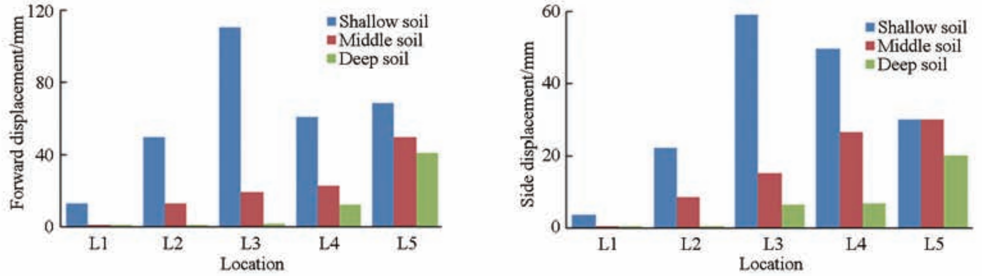


Fig. 5 Moving displacement of soil particles with different positions

3.3 Soil side movement in tillage scope

The side displacements of soil in tillage scope were calculated. The percent of soil particle which moved to the opposite side were 10.1%, 28.2% and 27.0%, respectively, for shallow, middle and deep soil (as shown in Fig. 6). The shallow soil moved to the opposite side with a minimum portion while the maximum portion of the middle soil. The percent of soil which moved in $-Z$ direction were 26.2%, 72.1% and 48.4%, respectively, for shallow, middle and deep soil. The shallow soil also had a minimum portion while the maximum portion of the middle soil to move in $-Z$ direction, which revealed that middle soil was resettled in side direction with the largest portion.

The variations of soil particle side displacements within the tillage scope were calculated, then variations of shallow, middle and deep soil were ordered and plotted into 3 lines. The side displacement variations of shallow soil were the biggest and most of shallow soil moved in Z direction. The displacement variations of middle soil were smoother than that of shallow soil and most of the soil moved in $-Z$ direction. The deep soil had the same trend of displacement variations as middle soil, but many displacement variations of deep soil were near zero, which means these soil particles had minor displacements.

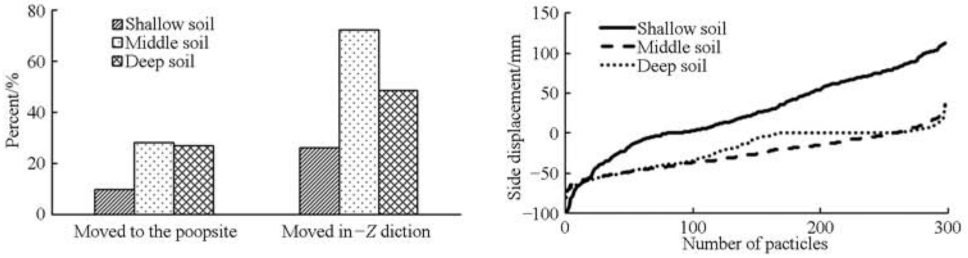


Fig. 6 Percent of soil particles moved to the opposite direction

3.4 Dynamic behavior of soil particles

At the beginning, no soil was cut, all the soil particles remains static. Subsequently, the soil particles began to contact with rotary blade from point contact to face contact and contact area increased gradually. The soil moved under the effect of shearing and squeezing from soil-blade interface. The soil disturbance, amount and height of soil particles being tossed up increased with increasing embedded depth of blade during cutting process. A series of pictures in Fig. 7 shows the movement process of soil particles in horizontal and vertical directions.

Soil particles in 15 positions as defined before were traced to analyze the moving mechanism of soil at different depths and positions. The horizontal, side and vertical displacement and force curves of soil particles were obtained from cutting process (as shown in Figs. 8 and 9). It concluded that the shallow soil was exerted more force and moved more than middle and deep soil.

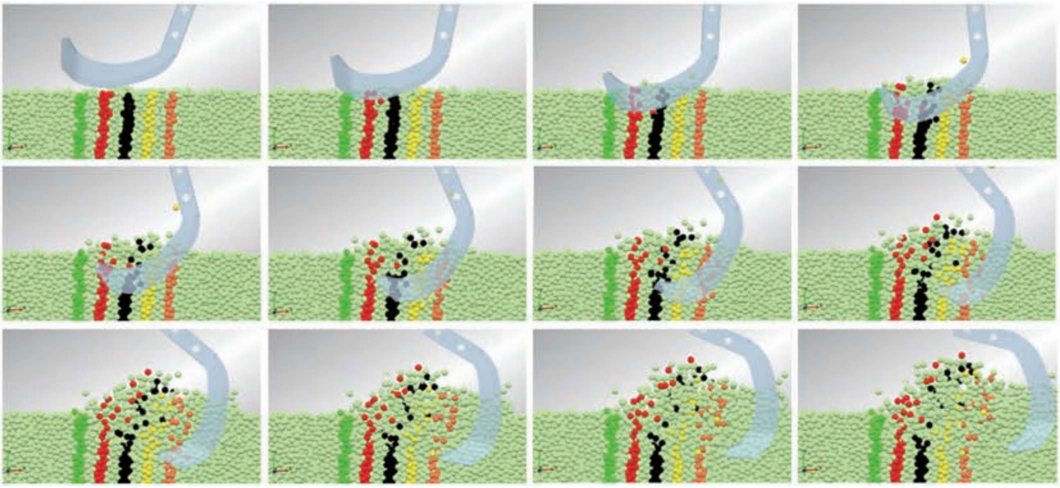
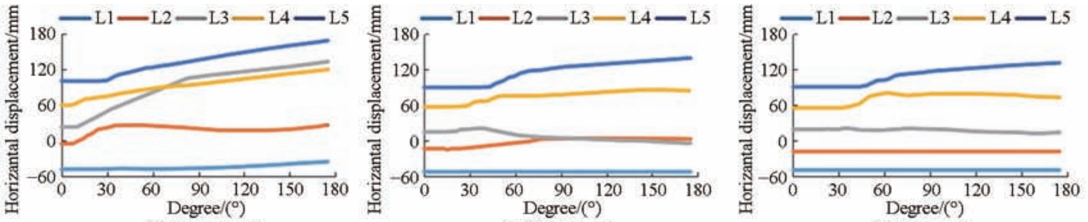
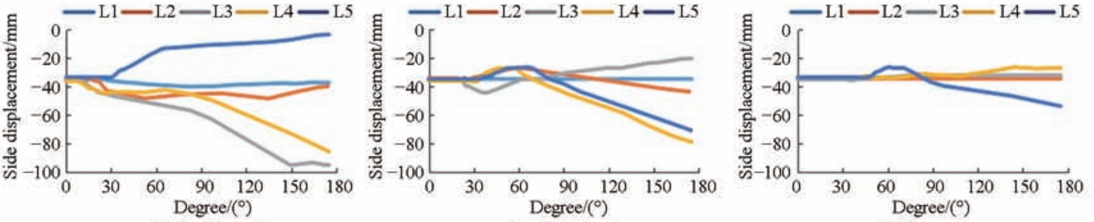


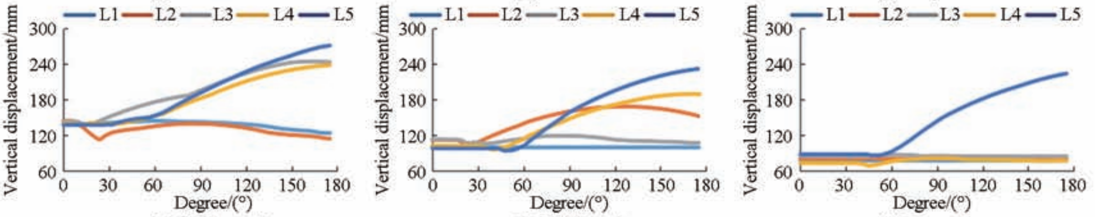
Fig. 7　Movement of soil particles under lengthwise edge



(a) Shallow soil　(b) Middle soil　(c) Deep soil



(d) Shallow soil　(e) Middle soil　(f) Deep soil

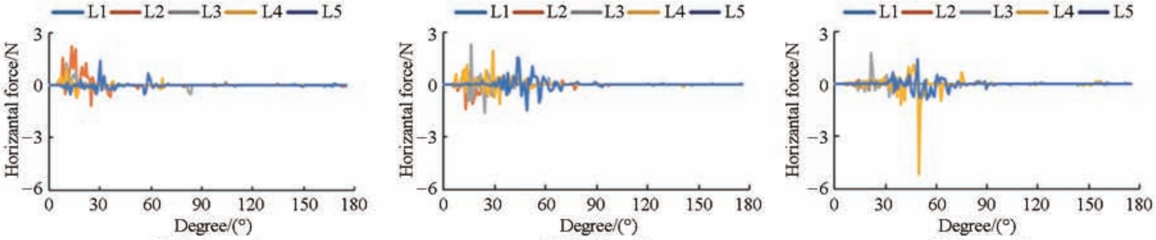


(g) Shallow soil　(h) Middle soil　(i) Deep soil

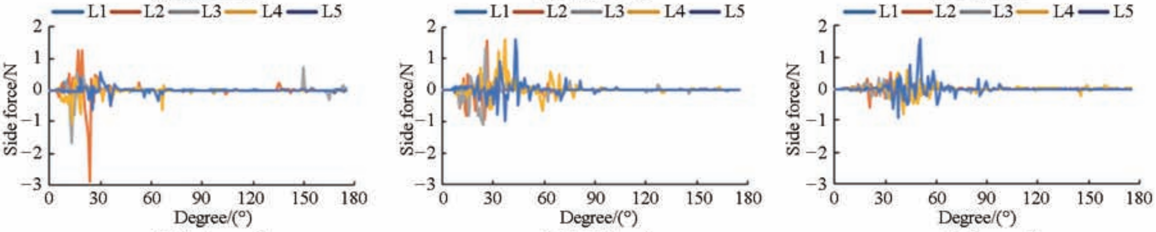
Fig. 8　Moving displacement curves of different positions and different layers during tillage process

Dynamic sliding cutting effect of lengthwise edge made soil particles moved backwards. Figs. 8a ~ 8c revealed that the soil in L1 did not contact blade directly as blade cutting the soil, so it got small displacement and force. The same situation occurred to deep soil in L2. Other soil particles were exerted transient force when they got contact with blade and moved backwards under the effect of horizontal force. The aforementioned results indicated that the horizontal displacement increased with increasing rotational speed, so the soil would be scattered in a larger area under higher rotational speed.

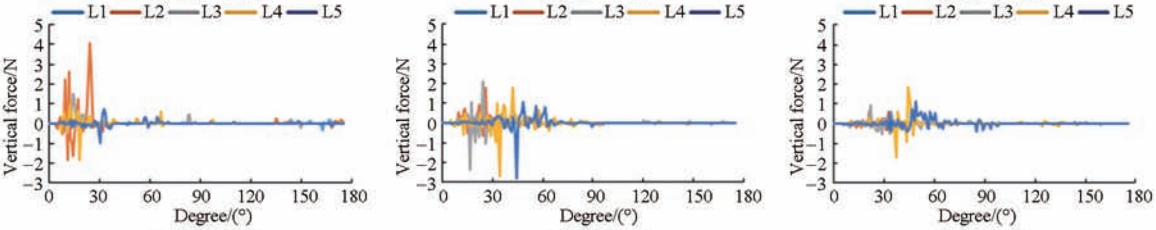
Though all of the 15 soil particles lay under the lengthwise edge of blade, the direction of side force and side displacement depended on the situation that the soil particle lay in the left or right side of the lengthwise edge axis before simulation. The side force of shallow soil in L5 in the beginning was in *Z* direction due to its position was in the left side of lengthwise edge axis, namely the *Z* direction. The middle soil of L2, L4 and L5, and deep soil of L5 were exerted in *Z* direction at the initial, so all of them moved in *Z* direction in the beginning. The force exerted on shallow soil was larger than middle and deep soil, thus the side displacement of shallow soil was the largest. The aforementioned results indicated that the side displacement increased with increasing rotational speed, so the soil would be disturbed more in side



(a) Shallow soil (b) Middle soil (c) Deep soil



(d) Shallow soil (e) Middle soil (f) Deep soil



(g) Shallow soil (h) Middle soil (i) Deep soil

Fig. 9 Force curves of different positions and different layers during tillage process

direction under higher rotational speed.

The soil particle moved downward with the rotary blade at the beginning of soil cutting, and later it slipped from the border of blade and being tossed up. The shallow soil in L1 just moved down with blade, but not be tossed up because it lay in the border of edge. The deep soil was affected by the gravitational effect of shallower soil and moved a little, only soil in L5 moved more due to it is near rotational point of blade. Besides, the shallow and middle soil got more vertical force and moved more in vertical direction.

3.5 Comparison of experimental and simulation results

The horizontal and side displacements of soil tracers are 366.7 mm and 83.3 mm in experiment. 10 surface soil particles were selected in simulation and their forward and side displacements were calculated. The average horizontal and side displacements of these 10 particles were 275.5 mm and 70.6 mm and they were used as simulation results. The simulation results were a little smaller than experimental results, the same findings were also reported by FANG et al.[14], UCGUL et al.[15], and COETZEE and ELS[16-17]. The absolute difference of simulation results and experimental results and then divided by experimental results is defined as relative error. The relative error of forward and side displacement of soil were 24.9% and 15.3%. Besides, the horizontal displacement was larger than side displacement both in experiment and simulation.

4 Conclusions

(1) This paper studied the macro- and meso-movement of soil particles during rotary tillage with the help of indoor soil bin experiment and DEM simulation. The average error of soil displacement between simulation results and experimental results were 24.9% for soil forward displacement while 15.3% for soil side displacement.

(2) The soil forward and side displacement in the experiment increased with increasing rotational speed of blade, the forward displacement was larger than the side displacement. It concluded that the higher the rotational speed was, the larger area of the soil being scattered was.

(3) The percent of soil particles which moved to the opposite side were 10.1%, 28.2% and 27.0%, respectively, and the percent of soil particles which moved in $-Z$ direction were 26.2%, 72.1% and 48.4%, respectively, for shallow, middle and deep soil. The middle soil was resettled in side direction with the largest portion.

(4) The displacement of shallow soil was the largest, and then middle soil and deep soil had the minimum displacement. The closer the soil to the rotational point was, the larger the forward and side displacements of soil were. Most soil particles moved backward in horizontal direction during tillage process. The direction of side force and side displacement depended on the situation that the soil particle lay in the left or right side of the lengthwise edge axis. If the soil lay in the left side of the lengthwise edge axis, the side displacement towards the left and vice versa. The soil particle moved downward with the rotary blade at the beginning of soil cutting, and later it slipped from the border of blade and being tossed up. The soil disturbance, amount and height of soil being tossed up increased with increasing embedded depth of blade during cutting process.

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基于离散元法的旋耕过程土壤运动行为分析

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摘要：土壤与耕作部件间的相互作用规律是设计和选用土壤耕作部件的基础。研究土壤和耕作部件间的相互作用规律就是要研究耕作部件对土壤产生的作用和它们之间的作用力，首先必须探讨耕作部件工作时土壤运动规律和施加于土壤的作用力。为此本文建立基于离散元方法的旋耕工作模型；对比分析实验与仿真的土壤位移：在土槽实验中采用示踪块方法测量土壤位移，仿真中通过追踪表层土壤颗粒的运动获得仿真位移；利用实验和仿真数据对土壤位移和运动机理进行分析。结果表明：土壤水平和侧向位移都随着转速增加呈现增加的趋势；土壤的水平运动位移总是大于同转速下的侧向位移。浅层土壤颗粒的运动位移最大，中层土壤次之，深层土壤最小。较深位置的土壤，距离旋转中心越近的土壤颗粒水平位移和侧向位移越大。在旋耕刀切土范围内的土壤，有向相反方向运动趋势的浅、中、深层颗粒比例分别为26.2%、72.1%、48.4%。在水平力作用下，大部分土壤颗粒随着旋耕刀切土有向后运动的行为；土壤在开始时刻的侧向受力和侧向运动方向，由颗粒的侧向位置是否偏离侧切刃轴线决定，位于侧切刃轴线左侧的颗粒，则其侧向力向左，反之亦然；土壤在垂直方向先随着刀具入土向下运动，然后滑出刀刃边界被抛起。本文建立的仿真模型得到的土壤水平位移和侧向位移与相应实验值的误差为24.9%和15.3%。本文运用离散元法进行旋耕过程中土壤宏观和细观运动行为的分析，有助于理解旋耕刀与土壤的相互作用机理，为旋耕机械的设计与优化提供理论依据。

关键词：旋耕刀；土壤运动；离散元仿真；运动机理

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Abstract: The interaction of soil-tillage tool plays a pivotal role in analysis and optimization of the tillage process. The dynamic behavior of soil needs to be developed primarily when studying the soil-tillage tool interaction. The simulation of soil-rotary blade interaction using distinct element method (DEM) and indoor soil bin experiment were conducted to provide a better understanding of the soil movement. Firstly, DEM model of soil-rotary blade interaction was established. Secondly, comparison of experimental results and simulation results were done, positions before and after tillage of surface soil particle were used as soil displacement in simulation, and tracer method was employed to measure soil displacement in experiment. Then, the movement of soil which belongs to different positions was analyzed. The results showed that soil forward and side displacement in experiment increased with

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increasing rotational speed of blade, the forward displacement was larger than the side displacement. The displacement of shallow soil was the largest, and then middle soil and deep soil had the minimum displacement. The closer the soil to the rotational point was, the larger the forward and side displacement of soil were. For the particles in tillage scope, the percent of particles which moved to the opposite direction were 26.2% , 72.1% and 48.4% for shallow soil, middle soil and deep soil, respectively. Most soil particles moved backward in horizontal direction during tillage process. The direction of side force and side displacement depended on the situation that the soil particle lay in the left or right side of the lengthwise edge axis. If the soil lay in the left side of the lengthwise edge axis, the side displacement was towards the left and vice versa. The soil particle moved downward with the rotary blade at the beginning of soil cutting, and later it slipped from the border of blade and being tossed up. The average error of soil displacement between simulation results and experimental results was 24.9% for soil forward displacement while 15.3% for soil side displacement. The paper studied the macro- and meso- movement of soil particles during rotary tillage, which is helpful to understand the interaction between rotary blade and soil and develop the mechanism of rotavator design and optimization.

Key words: rotary blade; soil movement; discrete element simulation; dynamic mechanism

引言

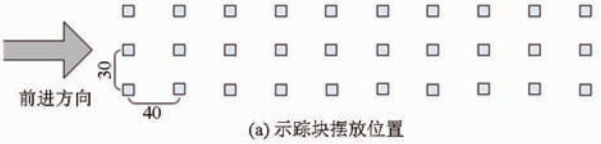
耕作过程的能量消耗很大,几乎占到整个农业生产过程能耗的一半[1]。由于土壤的空间差异性、耕作机械的动力学因素及土壤本身的运动及破碎等原因,耕作过程相当复杂。RAHMAN 等[2-3]在土槽中测量了 4 种机具耕作时土壤运动和扰动情况。LIU 等[4-5]研究了特定情况下土壤的运动,指出机具前进速度影响土壤水平和侧向位移。CHANDIO[6]探究了圆盘犁作用下土壤位移受耕深和耕作速度的影响。彭彬[7]对微耕机切土过程中的表层、中层和深层土壤粒子的运动速度、加速度和位移情况进行了研究。但迄今为止,旋耕过程的土壤运动研究得还不够充分,尤其是不同位置土壤受到机具作用后的运动差异和机理。

土壤与耕作部件间的相互作用规律是设计和选用土壤耕作部件的基础。研究土壤和耕作部件间的相互作用规律就是要研究它们之间的相互作用力和耕作部件对土壤产生的作用。为研究耕作部件的性能,首先必须探讨耕作部件工作时土壤运动规律和施加于土壤的作用力。离散元法(DEM)可用来模拟颗粒材料和研究材料间的细观宏观变形,允许颗粒材料间存在接触的形成和破坏,也适合仿真土壤和刚性体间的相互作用。学者基于 DEM 对土壤与耕作机具间的作用过程进行了广泛研究[8-13],这些研究都证实离散元仿真能够模拟耕作过程。而且在离散元中可以追踪颗粒的运动[14],从而对土壤颗粒在耕作过程中的受力和运动情况进行分析。

因此,本研究旨在利用实验方法和离散元方法对旋耕刀耕作过程进行研究,探究不同位置土壤的宏观和细观运动,明确作用过程和机理,为旋耕机械设计提供合理的依据。

1　室内旋耕实验

在南京农业大学工学院的土壤动力学实验室内进行土壤旋耕实验,旋耕刀 IT225 安装在自制的实验台架上,台架的详细描述参见文献[14]。体积为 2 cm^3 的立方体锡块,做标记后嵌入土中作为表面土壤运动的示踪块;30 个锡块分别摆成 10 列,与机具前进方向垂直。示踪块的摆放位置见图 1a,土槽实验图如图 1b 所示,示踪块的位置由图 1c 的装置进行标记。



(a) 示踪块摆放位置

(b) 土槽实验台

(c) 土壤位移测量装置

图 1　土壤示踪块和土壤位移测量装置

Fig. 1　Soil tracers and soil displacement measurement device

2　离散元仿真

2.1　基本假设

为了保证仿真的可行性和可重复性，对仿真过程作如下假设：

（1）耕作中涉及的土壤简化为足够多的球颗粒群，颗粒赋予物性并给予一定的质量和速度等。

（2）颗粒接触模型选用 Hertz – Mindlin 粘结模型。

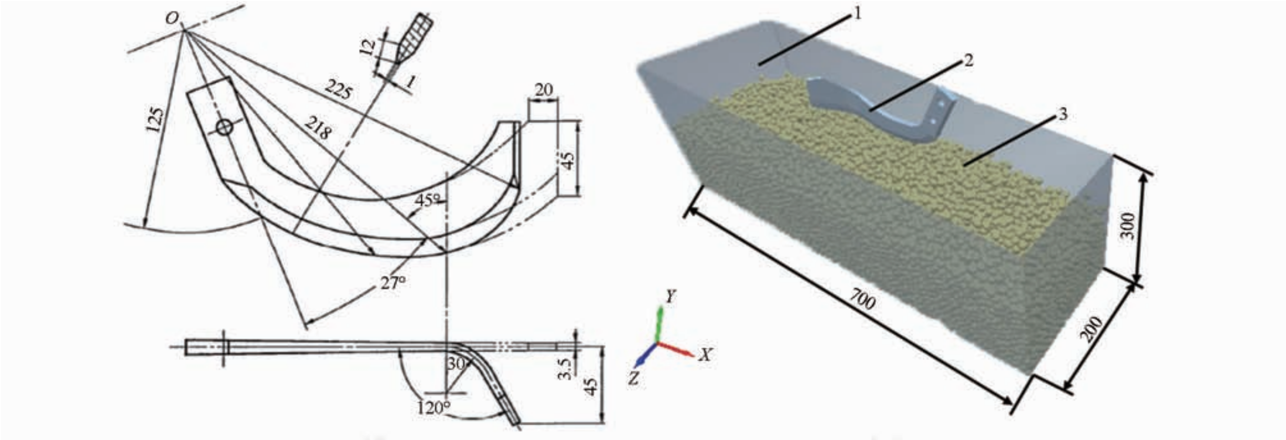
（3）耕作过程是旋耕刀以规定的运动方式对土壤颗粒作用的过程。

颗粒的运动反映了旋耕刀对土壤的影响方式，是进行耕作机具设计和优化的依据。可根据耕作过程中土壤颗粒的运动数据，分析土壤扰动区域和运动方式。

2.2　DEM 模型

将 Pro/E 中建好的旋耕刀和土槽模型导入 EDEM 中，设置生成满足耕深条件的土壤颗粒（24 000 个）；然后对旋耕刀设置前进速度及旋转速度等。离散元仿真中颗粒尺寸减小会导致仿真耗时呈几何级数增加，故仿真中的颗粒尺寸受计算时间和存储空间限制，总是比真实土壤颗粒尺寸大[15]。本文选定土壤颗粒半径为 5 mm；所用旋耕刀为 IT 系列 225 式旋耕刀（图 2a）；土槽尺寸为 0.7 m × 0.2 m × 0.3 m（长 × 宽 × 高）。仿真模型见图 2b，仿真中涉及的所有参数见文献[14]。

基于仿真中的坐标系，对颗粒三维运动方向作如下说明：水平运动发生在 X 方向；垂直运动发生在 Y 方向；侧向运动发生在 Z 方向。旋耕刀前进方向为 $-X$ 方向。



(a) 结构简图　　(b) 仿真模型

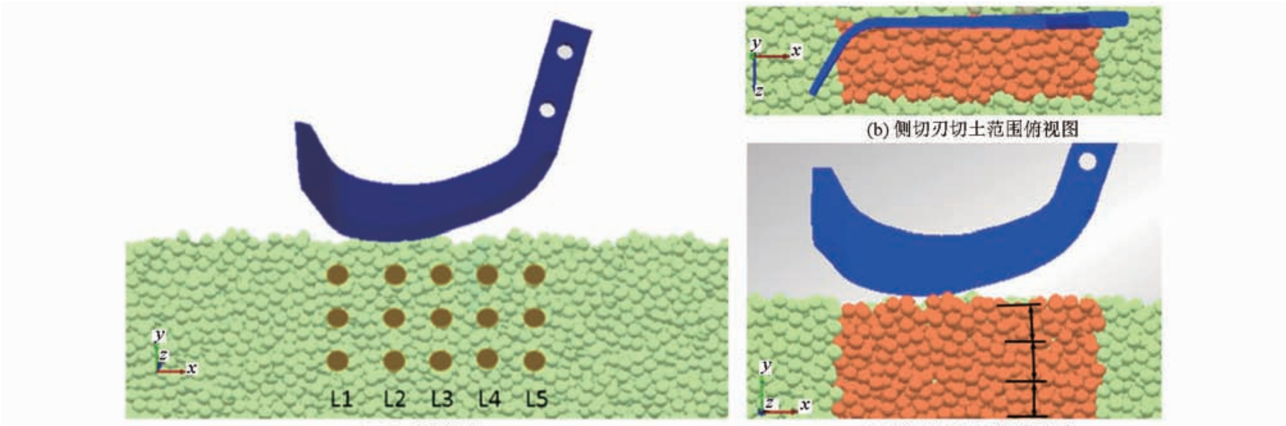
图 2　IT225 旋耕刀结构简图和旋耕过程仿真模型

Fig. 2　Schematic of rotary blade IT225 and simulation of soil bin with rotary blade

1. 土槽　2. 旋耕刀　3. 土壤

2.3　土壤颗粒的分布

为分析不同位置土壤在旋耕刀作用下的运动差异，在旋耕刀侧切刃不同部位的正下方按照不同深度选择土壤颗粒。3 个深度层，即 0 ~ 30 mm、30 ~ 60 mm 和 60 ~ 90 mm，每层选择 5 个位置，共计 15 个位置。颗粒的相对位置见图 3a 的剖视图。



(a) 土壤剖视图　　(b) 侧切刃切土范围俯视图　　(c) 侧切刃切土范围剖视图

图 3　土壤颗粒分布

Fig. 3　Layout of soil particles

图 3b、3c 中选出的颗粒用于探究切土范围内不同深度土壤的侧向运动，分析土壤向背离正切刃朝向方向运动的比例。

3　结果与讨论

3.1　工作参数对土壤宏观运动的影响

根据旋耕前后土壤示踪器的坐标位置，计算与旋耕刀前进方向垂直的各标记点在 4 种转速下的平均水平位移和侧向位移（图 4）。当旋耕转速为 77、100、123、146 r/min 时，土壤水平位移分别为 51.7、146.7、325、366.7 mm，侧向位移为 18.3、36.7、56.7、83.3 mm。土壤的水平和侧向位移都随着转速增加呈现增大趋势。旋耕转速越高，土壤被抛撒的程度越高，所以土壤的运动位移越大。水平位移随着转速的增加程度大于侧向位移随转速的增加程度，说明转速的变化对土壤水平方向运动的影响程度远大于其对土壤侧向运动的影响。此外，土壤的水平位移总是大于侧向位移，这主要是因为切土时旋耕刀对土壤的水平抛撒作用大于侧向抛撒作用。

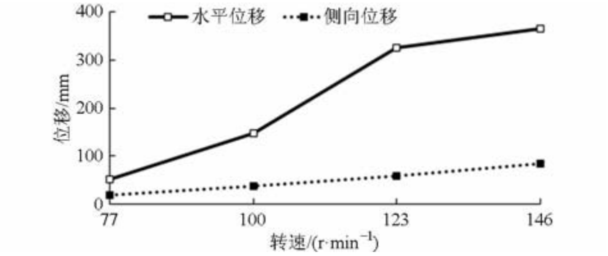
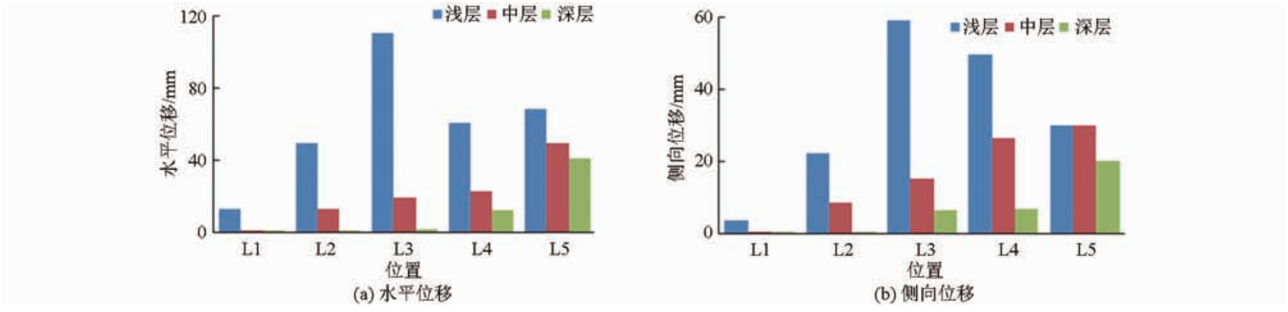


图 4　不同转速下的土壤运动位移

Fig. 4　Soil moving displacement with different rotational speeds

3.2　不同位置土壤颗粒的运动

所选的 15 个位置，每处土壤的平均水平和侧向位移见图 5。就中层和深层而言，距离旋转中心越近的土壤水平位移和侧向位移越大。而其中 L1 处的中层和深层颗粒之所以位移很小，是由于在旋耕刀摆线下切过程中颗粒未与旋耕刀直接接触；深层的 L2 处土壤颗粒亦然；它们的微小运动仅是由旋耕刀切土过程中周围土壤扰动造成。浅层颗粒运动比较复杂，L3 处的土壤颗粒位于侧切刃切土位置，较早与侧切刃接触。在旋耕刀切土过程中，其水平和侧向位移较其他位置土壤最大。此外，由于下层土壤受到上层土壤的重力作用，所以其运动在一定程度上受到上层土壤的阻碍。故浅层土壤位移明显大于中层和深层土壤位移；中层土壤位移次之；深层土壤位移最小。另外，无论土壤颗粒处于何种深度和刀具位置，其水平位移都大于侧向位移，这与实验测量的土壤位移结果一致。旋耕刀切土过程中，浅层土壤受扰动程度较大，故土壤透气性较好，有利于种子发芽生长。



(a) 水平位移　(b) 侧向位移

图 5　不同位置土壤颗粒的运动位移

Fig. 5　Moving displacements of soil particles with different positions

3.3　切土范围内土壤的侧向运动

为考查切土范围内土壤的侧向运动情况，计算了所有颗粒的侧向位移。其中浅、中、深层土壤运动至背离正切刃朝向一侧（外侧）的比例分别为 10.1%、28.2%、27.0%（图 6），浅层土壤运动到侧切刃外侧的比例最小，中层最大。有向外侧运动趋势的浅、中、深层土壤颗粒比例分别为 26.2%、72.1%、48.4%（图 6），同样是浅层颗粒运动比例最

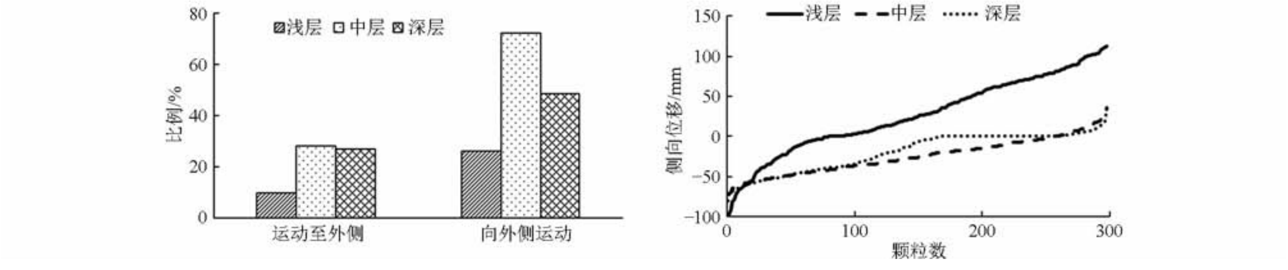


图 6　土壤颗粒侧向运动比例

Fig. 6　Percent of soil particle moved to the opposite direction

小，中层比例最大。说明在耕作过程中，中层土壤被侧向重置的数量最多。将选中区域内所有颗粒的侧向位移变化量从小到大进行排序后作成3条位移线。浅层土壤侧向位置前后变化较大，且土壤大多向正切刃朝向方向运动；中层土壤的侧向位置前后变化趋势相对浅层颗粒的变化趋势较平缓，且中层土壤的侧向位移变化值以负值较多；深层土壤的侧向位置前后变化趋势与中层颗粒的变化趋势相近，但有较大一部分深层土壤颗粒位移变化值在零值附近，这也进一步说明深层土壤受上层土壤影响不大，部分颗粒位移较小。

3.4 土壤运动机理分析

刀具未接触表层土壤时，所有土壤颗粒保持静止；随着刀具入土，侧切刃与土壤依次从点接触到面接触再逐渐增大接触面积，刀刃周围的土壤颗粒在刀刃剪切和挤压作用下开始运动。随着刀刃入土深度增加，土壤受扰动面积增加，土壤被抛起的数量和高度也逐渐增加。图7的一系列剖视图展示了位于侧切刃正下方的土壤颗粒在旋耕刀作用下的水平和垂直方向运动过程。

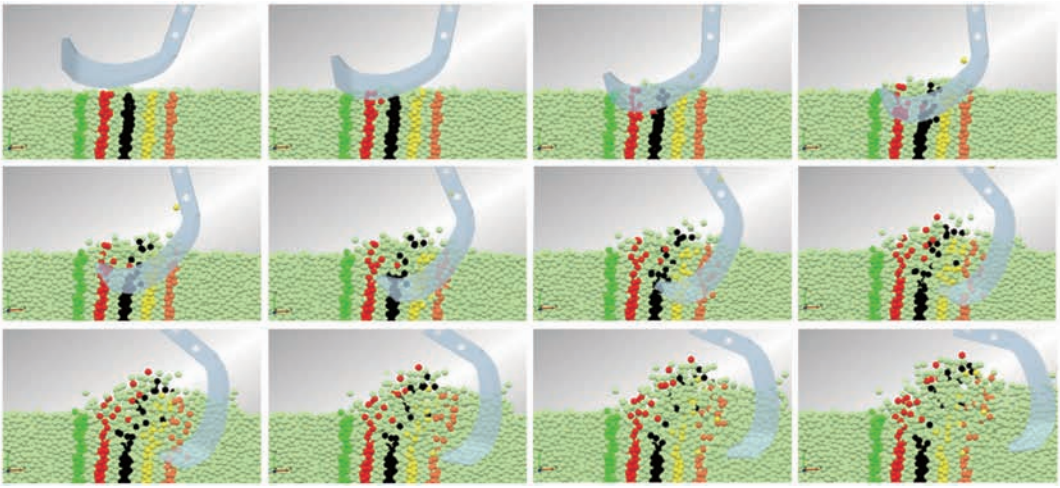


图7 侧切刃正下方土壤的运动仿真结果

Fig.7 Movement of soil particles under lengthwise edge

为了探究不同位置和不同深度土壤在旋耕刀作用下的运动机理，在前述15个位置的每处各选择一个土壤颗粒进行其三维运动的追踪。通过求解切土过程，得到土壤颗粒的水平、侧向和垂直方向运动位移曲线及受力曲线（图8和图9）。通过对比图8和图9中对应位置土壤的受力和位移曲线，发现浅层土壤的运动位移和受力总是大于较深层的土壤位移和受力。

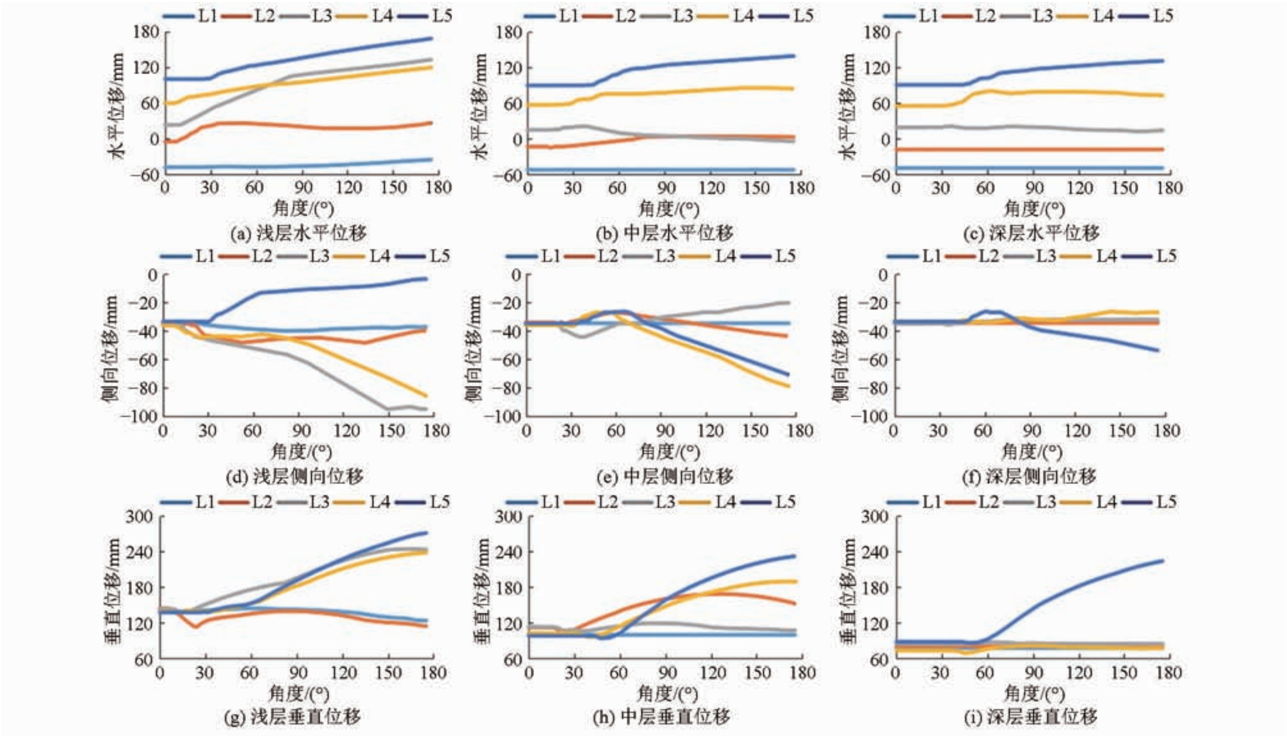
土壤颗粒在侧切刃的动态滑切作用下，随着旋耕刀切土有向后运动的行为。图8a～8c表明L1由于处于远离旋转中心的侧切刃端下方，在刀旋切过程中并未与刀有直接接触，故土壤几乎不受力而保持水平方向静止；深层的L2处同理亦然。其余土壤颗粒与刀接触时受到短暂的水平力，在水平力作用下几乎都随着旋耕刀切土有向后运动的行为。前述结果表明转速越高，土壤水平位移也越大，即土壤旋耕后在水平方向越分散，故可以提高刀轴转速使土壤在耕作后尽可能分散。

土壤颗粒虽然都位于侧切刃下方，但其运动开始时刻的侧向受力和侧向运动方向，由颗粒质心的侧向位置是否偏离侧切刃轴线决定。浅层的L5处土壤，由于其位置位于侧切刃轴线左侧，即偏正切刃朝向一侧，故其一开始受到沿Z方向的侧向力，所以沿Z方向运动；中层的L2、L4和L5处土壤一开始受到沿Z方向的侧向力，也是由于其质心位于侧切刃轴线左侧；深层的L5处土壤质心位置在侧切刃轴线左侧，其受力和开始运动方向沿正切刃朝向。浅层土壤受到的作用力较中层和深层土壤作用力大，故浅层土壤位移较大。前述结果也表明转速越高，土壤侧向位移也越大，即土壤越分散，故提高刀轴转速同时也可使土壤侧向受扰动区域增大，从而在耕作后使土壤尽可能地分布在较宽范围内。

土壤先随着刀具入土向下运动，然后滑出刀刃边界被刀刃抛起。浅层L1处的土壤只是随着刀刃下切有轻微的向下运动，并未被抛出，主要是由于其位于刀刃切土边缘；随着刀刃进一步下切，颗粒并未随刀具向后，只是在原位置由于土壤扰动有轻微的下陷。处于深层的土壤由于受上层土壤重力的影响，颗粒的垂直受力很小，仅靠近旋转中心的L5处土壤有较大的位移。此外，浅层和中层土壤都受到较大的向下垂直力。

3.5 仿真与实验的土壤位移

实验中，土壤示踪块的水平位移和侧向位移分别为366.7 mm和83.3 mm。在仿真中取表层的



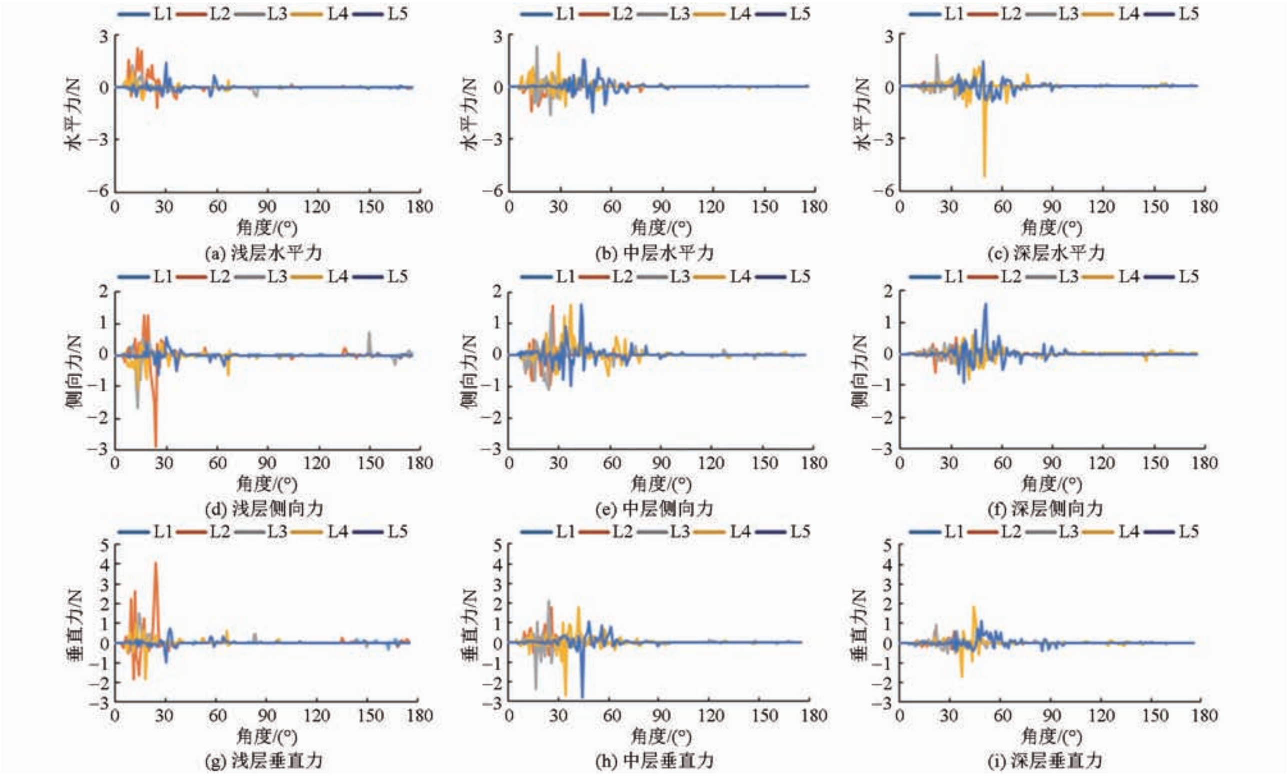
(a) 浅层水平位移　(b) 中层水平位移　(c) 深层水平位移

(d) 浅层侧向位移　(e) 中层侧向位移　(f) 深层侧向位移

(g) 浅层垂直位移　(h) 中层垂直位移　(i) 深层垂直位移

图 8　耕作过程中不同位置和不同层土壤颗粒的运动曲线

Fig. 8　Moving displacement curves of different positions and different layers during tillage process



(a) 浅层水平力　(b) 中层水平力　(c) 深层水平力

(d) 浅层侧向力　(e) 中层侧向力　(f) 深层侧向力

(g) 浅层垂直力　(h) 中层垂直力　(i) 深层垂直力

图 9　耕作过程中不同位置和不同层土壤颗粒的受力曲线

Fig. 9　Force curves of different positions and different layers during tillage process

10 个土壤颗粒，计算仿真初始和结束对应的水平位移之差和侧向位移之差，取水平位移平均值和侧向位移平均值分别作为仿真土壤水平和侧向位移。仿真中水平位移为 275.5 mm，侧向位移为 70.6 mm。仿真的土壤位移结果稍小于实验结果，类似仿真值小于实验值的研究也出现于文献[14 − 17]中。定义仿真与实验结果值的绝对差值与实验值的百分比为仿真相对误差，则水平位移和侧向位移的仿真相对误差分别为 24.9% 和 15.3%。此外，无论是实验结果还是仿真结果，土壤水平位移总是大于侧向位移。

4　结论

（1）在室内土槽实验和相应的离散元仿真基础上，对土壤宏观位移和细观运动机理进行了研究。仿真模型得到的土壤水平位移和侧向位移与相应实验值的误差分别为24.9%和15.3%。

（2）土壤水平和侧向位移都随着转速增加呈现增加的趋势；土壤的水平运动位移总是大于同转速下的侧向位移。说明提高转速可以增加土壤抛撒范围。

（3）在旋耕刀切土范围内，浅、中、深层土壤运动至背离正切刃朝向一侧的比例分别为10.1%、28.2%、27.0%；有向相反方向运动趋势的浅、中、深层土壤颗粒比例分别为26.2%、72.1%、48.4%。在耕作过程中，中层土壤被侧向重置的数量最多。

（4）浅层土壤颗粒的运动位移最大，中层土壤次之，深层土壤最小。较深位置的土壤，距离旋转中心越近的颗粒水平位移和侧向位移越大。在水平力作用下，大部分土壤颗粒随着旋耕刀切土有向后运动的行为；土壤在开始时刻的侧向受力和侧向运动方向，由颗粒的侧向位置是否偏离侧切刃轴线决定，位于侧切刃轴线左侧的颗粒，则其侧向力向左，反之亦然；土壤在垂直方向先随着刀具入土向下运动，然后滑出刀刃边界被刀刃抛起。随着刀刃入土深度增加，土壤受扰动面积增加，土壤被抛起的数量和高度也逐渐增加。

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