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Research Paper

Measurement and modelling of soil displacement from sweeps with different cutting widths

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Soil dynamic properties are important performance indicators for soil-engaging tools. In this study, soil displacement and cutting forces of selected sweeps were measured and simulated. The sweeps had different cutting widths: 153, 280, and 330 mm, and they were tested in an indoor soil bin with a sandy loam soil at a working depth of 50 mm and a travel speed of 1.53 m s^{-1}. A discrete element model was developed using PFC^{3D} (Particle Flow Code in Three Dimensions) to simulate soil-sweep interactions. With the measured soil cutting forces, the model particle stiffness was calibrated to be 3×10^3 N m^{-1}. Results from modelling and measurements showed a general trend of the highest displacements around the centre of the path of sweep, reducing at the further distance away from the centre. Among all directions, measured soil displacements were the highest in the forward direction, up to 608 mm. Measured results showed that forward soil displacements were smaller for smaller sweeps, and lateral soil displacements were lower at a greater depth regardless of the sweeps. Simulated forward and lateral displacements did not contradict these results. Among all the sweeps, the 153-mm wide sweep had significantly higher vertical displacements at all depths as compared to the other sweeps, demonstrated by both measurements and simulations. Overall, the simulated soil displacements were lower than the measured values in all three directions. The accuracy of the model needs to be improved for predictions of soil displacements.

1. Introduction

Sweeps are common soil-engaging tools for many field operations, such as mechanical weed control, tillage, and seeding. Soil displacement is an important performance indicator for these field operations. For example, minimum soil lateral throw is desired to obtain uniform seeding depth and sufficient soil backfilling to cover the seeds (Hasimu & Chen, 2014). Also, excessive soil movement will increase moisture loss and weed seed germination (Solhjou, Fielke, & Desbiolles, 2012). Therefore, understanding soil displacement resulting from

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sweeps is very important for designing effective soil-engaging tools for these field operations.

Existing studies on soil disturbance characteristics focused on soil disturbance areas and surface profile (Chen, Munkholm, & Nyord, 2013; Hasimu & Chen, 2014). Displacement of soil particles has not been well documented due to the difficulties associated with its measurement. Soil displacement resulting from a soil-engaging tool is a complicated soil dynamic behaviour and is affected by a large number of factors (Sharifat & Kushwaha, 1997), such as soil types and properties, types of soil-engaging tools and their operational parameters (Dowell, Siemens, & Bode, 1988; Hanna, Marley, Erbach, & Melvin, 1993; Liu & Kushwaha, 2006). For example, increasing the travel speed of no-till openers resulted in greater lateral soil throw (Barr & Fielke, 2016). Another affecting factor is soil condition. Sharifat and Kushwaha (1999) studied a sweep and a furrow opener under different soil conditions, and found that soil bulk density and moisture content significantly affected soil lateral movement. Rake angles of tool significantly affected soil movement and layer mixing. Solhjou et al. (2012) tested flat-faced narrow openers with different rake angles in a soil bin. They concluded that smaller rake angles moved deeper soil up to the surface, which would favour seed germination in a dry soil condition. Tool face geometry also influences soil movement, and reduced soil forward and lateral movements were observed for an opener with face chamfers as compared with an opener with a blunt face (Solhjou, Desbiolles, & Fielke, 2013). The other tool geometries also affected the soil movement, found by Solhjou, Desbiolles, and Fielke (2014) in a study of six openers with different bent leg geometries. Understanding the effects of tool geometry on soil movement is important to guide selection and design of soil-engaging tools.

The tracer method has been commonly used for soil displacement measurements. In this method, tracers are placed in the soil before a tillage operation, and the displacement of tracers after tillage is considered to be the displacement of the soil (Home, 2003; Rahman, Chen, & Lobb, 2005; Sharifat & Kushwaha, 1997). Different materials have been used as tracers, such as gravels, steel, ceramic, plastic aluminium. Plastic tracers were selected for measuring soil movement resulting from a sweep and a knife opener, due to the similar density of plastic and soil (Sharifat & Kushwaha, 1997). Cube tracers of different sizes (10, 15, 20 mm) and materials (wooden, PVC, aluminium, and steel) were compared (Rahman et al., 2005), and 10-mm PVC or aluminium cubic tracers were recommended for soil movement studies. Subsequently, 10-mm PVC cube tracers were used by Solhjou et al. (2012, 2013, 2014) in studies of soil translocation as affected by geometrical parameters of openers. The drawbacks of the tracer method include the soil disturbance associated with the tracer insertion before tillage and the time consuming nature of the measurement. Another drawback was the difficulties in locating tracers after tillage. Flat steel washers were also used for soil movement measurements, as they could be easily located by a metal detector (Montgomery, McCool, Busacca, & Frazier, 1999). With the availability of numerical modelling tools, such as the finite element method and discrete element method (DEM), simulation has become a promising solution for more effective and accurate predictions of soil displacement.

Soil displacement resulting from a soil-engaging tool can be effectively handled by software, such as Particle Flow Codes in Three Dimensions (PFC^{3D}) (Itasca™, Minneapolis, USA) which was developed based on the DEM. In the DEM, soil is treated as an assemblage of individual particles that interact with each other at the contact point between particles. The external forces, such as tillage action, induce forces at the contact points between particles and cause displacement of particles. The particle dynamics are governed by Newton's second law of motion and the linear force-displacement law. Using the PFC^{3D}, detailed particle-scale information, such as the position of each particle at any given time can be obtained; the contact forces between particles and a tool surface can be monitored (Cundall & Strack, 1979; Manne & Satyam, 2015). These features enable the user to predict particle displacement and soil cutting forces resulting from a soil-engaging tool.

One of the disadvantages of the PFC^{3D} is its low computation efficiency. This limits the number of particles, and in turn, the domain size and particle size that can be used in the model. A suitable timestep is also required for the numerical integration of Newton's laws to update the dynamic state of each particle during the computation. Selection of timestep is dictated by the stability constraints of the model. Although adjusting timestep on-the-go can sometimes improve the computation efficiency, it can also lead to an undersized timestep and cause instability. Damping is another parameter to adjust in PFC^{3D} simulations. There are two types of damping: local damping and viscous damping which act to obtain a stable system by dissipating energy among particles and contacts between particles respectively. The magnitudes of the damping coefficients should be decided based on the nature of model simulated, e.g., static, quasi-static, or dynamic simulations. In this study, an automatically fixed timestep determination algorithm built in the software was used and damping coefficients were taken from Sadek and Chen (2015) who used the same soil as this study.

Most existing PFC^{3D} models focused on soil cutting force predictions and soil disturbance. Chen et al. (2013) developed a model to simulate a slurry injection tool and its interaction with soil. The model was calibrated by draft and vertical forces measured through a field experiment. The calibrated model was used to simulate the soil disturbance area. Through simulation, Tamás, Jóri, and Mouazen (2013) found that soil porosity and cutting forces of sweeps increased as the sweep rake angle was increased. They suggested a further study soil particle displacement to better understand particle behaviours. In a soil-tool model, which simulates the soil throw distance resulting from a simple soil-engaging tool, Sadek and Chen (2015) studied soil throw as affected by model parameters. These existing studies have quantified the dynamic characteristics of bulk soil, i.e. movement of soil body, but not displacement of individual soil particles. Until recently, displacement of individual particles was qualitatively highlighted by observing the soil mixing among different soil layers in the DEM modelling of an opener (Barr & Fielke, 2016). This was further advanced by Ucgul, Saunders, and Fielke (2016) who tracked the percentage of soil particles buried in each of three soil layers (0–100, 100–200, and 200–300 mm). These previous studies have demonstrated that the DEM is