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Research Paper

Discrete element simulations and experiments of soil disturbance as affected by the tine spacing of subsoiler

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Tine spacing is a key parameter for the design of a subsoiler and has a significant effect on soil disturbance, which is a critical performance indicator of subsoiling. In this study, a subsoiling model was developed using the discrete element method (DEM). A subsoiling experiment was also conducted in a field with a loamy clay soil to serve the model development and model validations. In both the simulation and experiment, two V-shaped subsoiling tines were investigated at five different tine spacings (300, 350, 400, 450, and 500 mm), a constant working speed (0.83 m s^{-1}) and a constant working depth (300 mm). The results showed that the 400 mm tine spacing resulted in the highest particle forces in the middle and deep soil layers. The height of the unloosened soil between two adjacent subsoilers increased as tine spacing increased. When the tine spacing was varied from 300 to 500 mm, the undisturbed soil height was changed from 100 to 226 mm in the experiment, and from 79 to 170 mm in the modelling. When the tine spacing was 400 mm, the number of soil particles disturbed in the shallow soil layer accounted for 45.6% of the total soil particles disturbed, which was the least among all the tine spacings. Considering the characteristics of soil disturbance, the tine spacing of 400 mm appeared to outperform the other spacings.

1. Introduction

Long-term rotary tilling and ploughing operations at shallow depths result in severe degradation of the soil structure and the formation of a dense plough pan under the plough layer. This affects the development of the root system of crops and their absorption of water and nutrients, and thereby significantly hinders sustainable crop productions. Deep tillage, such as subsoiling, can effectively improve the physical properties of the soil, particularly the soil porosity and its distribution, which improves the moisture, nutrients, porosity and thermal conditions of the soil, and increases the crop yield (Arvidsson & Hillerstrom, 2010; He et al., 2007; Shi et al., 2016). Regardless of the types of tillage equipment that

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are used, it is necessary to consider the disturbed state of the soil to ensure the effectiveness of tillage (Guo, Tong, Zhou, & Ren, 2001).

Previous studies have demonstrated that three main factors affect the characteristics of soil disturbance: the structural parameters of the tool, the operational conditions, and the physical and chemical properties of soil (Li, Liu, Mu, Chen, & Han, 2014; Tamas & Jori, 2010). For example, the addition of chisel tines in front of winged tines had a significant effect on the tillage resistance and the amount of soil disturbed (Spoor & Godwin, 1978). Using simulations, Badegaonkar, Dixit, and Pathak (2010) studied the effect of the bend angle and bend length of the cultivator shank on the tillage performance. Celik and Raper (2012) studied the effects of four coulters with different shapes on several indicators, such as soil disturbance, cone index, bulk density, and volume of soil disturbed, at tillage depths of 25 and 38 cm. Tamas, Jori, and Mouazen (2013) found that sweeps disturbed soil in a similar manner to chisel tines. Effects of shanks with different width-to-depth ratios at different bend angles have been also studied on the macro-scale failure of a dry loam (Makanga, Salokhe, & Gee-Clough, 1996; Makanga, Salokhe, & Gee-Clough, 1997). These previous studies focused on analysing the effects of the tine shape, penetration angle, working speed, and tillage depth on disturbance behaviours of soil, but no studies have investigated effects of the tine spacing of a subsoiler on the disturbance characteristics of soil.

Tine spacing is a key parameter for the design of subsoilers and has significant effects on the disturbance range of tilled soil (Godwin & O'Dogherty, 2007; Zhu, Zhang, Yao, Li, & Deng, 2009). Tine spacing is generally determined empirically based on the shape of the tine; there are relatively large variations in the selected tine spacings. Therefore, examining effects of tine spacing on disturbance characteristics is the key in determining the optimal tine spacing. However, subsoiling is a complicated process, and the soil disturbance is affected by many factors, such as the spatial variation of the soil, the dynamics of the tillage machinery, and the complexity of the soil dynamics. Conventional experimental methods were time-consuming and cannot fully describe the disturbance regime of deep soil layers (Fang, Ji, Ahmed, Zhang, & Guo, 2016). Therefore, numerical simulation methods were used to simulate a subsoiling process in this study.

Numerical simulation methods, including the finite element method (FEM) and the discrete element method (DEM), have been widely used to simulate the interaction between tillage machines and soil as well as soil mechanical properties (Kasisira & du Plessis, 2006; Sadek, Chen, & Liu, 2011). FEM is mainly used for continuum problems of homogeneous material and cannot accurately describe the behaviour of soil that is a discontinuous and non-homogeneous media (Mouazen & Ramon, 2006). DEM can simulate macro-scale and micro-scale deformations of discontinuous media, such as soil particles, and is being widely used in research on tillage processes (Hamza & Anderson, 2008; Shmulevich, Asaf, & Rubinstein, 2007). For example, Li et al. (2014) analysed the effect of working speed and depth on soil cutting forces using the Particle Flow Code in 3 Dimensions (PFC3D), which is DEM software. A sweep–soil interaction model was developed using PFC3D to analyse the soil-cutting forces of the sweep and the disturbance characteristics of soil for three soil types (Chen, Munkholm, & Nyord, 2013). Several other models have been developed using the Experts in Discrete Element Modeling (EDEM) software to study the effects of the width, penetration angle, and working speed of winged tines on the tillage resistance and subsoiling performance; the results provided a basis for the optimisation of winged tines (Ucgul, Fielke, & Saunders, 2014a, 2014b; Ucgul, Fielke, & Saunders, 2015). Tamas et al. (2013) also studied the effect of working speed on the tillage resistance and soil disturbance of a winged tine using the DEM method. Interactions of a bear claw with soil have been also modelled using PFC3D to serve the design of bionic subsoilers (Li, Chen, & Chen, 2016).

The objectives of this study were to (1) investigate the effects of different tine spacings of a V-type subsoiling tool on the characteristics of soil disturbance using discrete element modelling and a field experiment and (2) determine the optimal tine spacing for the subsoiling tool based on the modelling and experimental results.

2. Field experiment

2.1. Experimental materials

The experiment was conducted in a corn stubble field in Zhaixi Village in the Yangling Agricultural Demonstration Area, Xianyang, Shaanxi Province, China, between May 5 and 9, 2016. The soil was a loamy clay (Lou soil) with a granular structure that developed on parent loess (Huang, Hang, Li, Zhang, & Zhu, 2015; Huang, Hang, Yuan, Wang, & Zhu, 2016). The soil had a dry bulk density of 1.346 t m^{-3} measured through the oven-drying method, and a water content of 12.5% measured using a SU-LPC type multi-parameter testing system (Tianjin Hao Ling Technology Co., Ltd., Tianjin, China). The soil internal friction angle and cohesion were 17.0° and 0.0118 MPa respectively, obtained by shear tests of the soil.

V-shaped tines are often used in subsoiling operations for long-term cultivated fields to ensure sufficient soil disturbance in deep soil layer. In this study, a subsoiler with a V-shaped tip was selected for the experiment (Fig. 1). The shank was an arc-shaped shank selected based on the Chinese standards, the *Subsoiler Tines and Subsoiler Tine Shanks* (JB/T 9788-1999). The shank had a cutting edge angle of 60° and a thickness of 30 mm. Both of the subsoiler tip and shank were made of 65Mn Steel.

2.2. Experimental process

A small-scale toolbar was used for the field experiment. The toolbar was powered by a Shanghai-50 tractor through three-point-hitch (Fig. 2a). Two subsoilers were mounted on the toolbar by U-bolts, so that the tine spacing could be easily adjusted. The experiment was performed with five different tine spacings: 300, 350, 400, 450, and 500 mm, at a constant tillage depth of 300 mm, and a tillage speed of 3 km/h. Each test run created two soil furrows (Fig. 2b) where measurements were taken as described in the following section. The