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Determining parameters of a discrete element model for soil–tool interaction

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ABSTRACT

The discrete element method (DEM) has been recognized as an effective tool to simulate soil–tool interactions. However, most existing discrete element models were for cohesionless soils, and in those models there were limited discussions on selections and calibrations of model parameters. In this study, a soil–tool interaction model was developed using a commercial DEM software, Particle Flow Code in Three Dimensions (PFC^{3D}). In the model, soil particles were defined with the basic PFC^{3D} model particles, which consisted of balls with cohesive bonds between balls. The model parameters, bond normal and shear strengths, were determined based on intrinsic stresses of soil. The most sensitive model parameter, ball normal stiffness, was calibrated for two contrast soils: coarse and fine soils. The calibrations were performed through comparing the draught forces of a simple soil engaging tool simulated with the PFC^{3D} soil–tool interaction model and those estimated with the Universal Earthmoving Equation. The calibrated ball normal stiffness is 6×10^3 N m^{-1} for coarse soil and 2×10^4 N m^{-1} for fine soil.

1. Introduction

Several methods, including analytical and numerical methods, have been used to model soil–tool interactions for improving design of soil engaging tools. One of the analytical methods is the Universal Earthmoving Equation (UEE). The UEE was developed and modified based on the theory of passive soil failure by several researchers (Hettiaratchi and Reece, 1967; McKyes and Ali, 1977; Godwin and Spoor, 1977). The term earthmoving came from construction equipment, such as bulldozers and excavators and was extended to agricultural soil engaging tools such as tillage and seeding tools. A numerical method, finite element method (FEM), has also been used intensively for modelling soil–tool interaction and this area has been well documented (Plouffe et al., 1999; Shen and Kushwaha, 1998; Abo-Elnor et al., 2004). Latterly, a new numerical method, the discrete element method (DEM), has been applied to simulate soil–tool interaction. The DEM was first introduced by Cundall and Strack (1979) in the field of rock mechanics. Since then the DEM has been used to simulate the flow of many other materials with the objective of improving the design and performance of material handling and processing machines (Tijskens et al., 2003; Landry et al., 2006). In the DEM, the material of interest (e.g., soil) is modelled as collections of discrete particles. Each particle interacts with its neighbouring particles. As compared with the FEM, the DEM can handle large particle displacement and crack propagation involved in the field operation of a soil engaging tool. The FEM may have numerical convergence problems when soil loses contact with the cutting tool (Abo-Elnor et al., 2004).

There have been several studies using the DEM to simulate soil–tool interactions in applications such as bulldozing (Franco et al., 2007; Momozu et al., 2003; Shmulevich et al., 2007) and agricultural operations (van der Linde, 2007). The general concept of the DEM and modelling soil–tool interactions using the DEM have been discussed in Shmulevich et al. (2009) and Shmulevich (2010). Researchers have concluded that the DEM is a promising method for simulating soil–tool interaction; the DEM model parameters significantly affect the accuracy of the model outputs; and the major challenge remains to be the determination of model parameters (also termed as micro-properties of model particles) so that model particles represent the real material particles to be simulated.

This study used the Particle Flow Code (PFC) (Itasca Consulting Group, Inc., Minneapolis, MN) in simulating soil–tool interaction. PFC is a common DEM software. The basic particles are disks in the two dimensional PFC (PFC^{2D}) and they are spheres in the three dimensional PFC (PFC^{3D}). PFC has been used to simulate many granular materials, such as flows of grain in a silo (Lu et al., 1997) and separation of grain in a shaker (Sakaguchi et al., 2001), and spreading of solid manure (Landry et al., 2006). Fewer studies were found for simulating soil–tool interactions using PFC. Franco et al. (2007) and Shmulevich et al. (2007) simulated interactions of bulldozer blades with cohesionless soil using PFC^{2D}. In both studies, draught forces (soil cutting forces in the horizontal

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Nomenclature

c	soil cohesion (Pa)
D	tool working depth (m)
g	gravitation acceleration (m s^{-2})
F	draught force of tool (N)
K_n	particle normal stiffness (N m^{-1})
K_s	particle shear stiffness (N m^{-1})
$\overline{K_n}$	bond normal stiffness (Pa m^{-1})
$\overline{K_s}$	bond shear stiffness (Pa m^{-1})
N_γ	N factor related to soil weight
N_c	N factor related to soil cohesion
N_a	N factor related to tool working speed
P	soil cutting force (N)
$\bar{R}_m$	bond radius multiplier
v	tool working speed (m s^{-1})
w	tool width (m)
α	tool rake angle (°)
δ	soil–tool friction angle
ϕ	soil internal friction angle (°)
γ	specific soil weight (kg m^{-3})
μ	particle friction coefficient
$\overline{\mu}$	bond normal strength (Pa)
$\overline{\tau}$	bond shear strength (Pa)

direction) of wide blades from simulations were compared with the predictions using the UEE, and good agreements were found between simulations and predictions. Another study carried out by Zhang and Li (2006) also simulated soil–bulldozer interaction using PFC^{2D}, but that study was rather qualitative than quantitative in nature. Even fewer studies were found for simulating agricultural soil engaging tools. van der Linde (2007) used PFC^{3D} to simulate the soil cutting process of a powered subsoiler, and the simulated draught forces of the subsoiler were comparable with measurements in a sandy soil. However, powered subsoilers are not common and most soil engaging tools in agriculture are non-powered. Shmulevich et al. (2009) indicated that although some researchers have reported good agreements between DEM simulations and measurements, this area still remains as its infancy because of lack of robust method to determine the model parameters.

A PFC^{3D} model can be successful only if its model parameters are determined correctly. In most existing simulations, model parameters were arbitrarily selected. In only few simulations, they were calibrated. Franco et al. (2007) performed calibrations in simulating soil–bulldozer blade interactions. The method was based on the interlocking property of the particles. The maximum error of the parameters obtained by the method compared with the actual soil parameters was 22.8%. To serve simulations of the dynamic interaction in soil tillage process, Asaf et al. (2007) modelled soil particles using clumps of two disks using PFC^{2D} and calibrated model parameters based on in situ field sinkage tests using different soil penetration tools. The calibrated model parameters were later used by Shmulevich et al. (2007) to simulate wide blades having different shapes in cohesionless soils. In simulation of a powered subsoiler, van der Linde (2007) modelled soil particles as basic spheres with breakable bond between particles using PFC^{3D}, and calibrated model parameters using lab compression tests and direct shear tests for a specific sandy soil.

In summary, there were only few existing PFC models which were developed for simulations of soil–tool interaction and most of them were two dimensional and were for cohesionless soils. Soil–tool interaction simulations and determinations of model parameters should be further studied in three dimensions for different agricultural soils. The existing calibrations were carried out using trial and error processes, and to date, no robust standard calibration methods have been developed in simulations of soil–tool interaction. Another challenge of using the DEM is that a DEM model has several model parameters which cannot be all calibrated and some of them have to be determined with knowledge, experience, and logics (Potyondy and Cundall, 2004). Continuous research efforts are required towards determinations of model parameters for soil–tool simulations.

The objectives of this study were to (1) develop a soil–tool interaction model to simulate a simple engaging tool and its interaction with soil using PFC^{3D} and (2) determine the model parameters for two contrast soils: coarse soil and fine soil.

2. Development of soil–tool interaction model

2.1. Description of PFC^{3D}

PFC^{3D} focuses on two basic elements: *balls* and *walls*. Balls or a cluster of balls represent material particles, such as soil particles, while walls represent physical boundaries around the particles, such as a soil bin. Walls can also be used to construct machines, such as a soil engaging tool. In simulating soil–tool interaction, an assembly of balls is contained within walls. As a soil engaging tool moves through the balls, each ball will contact with several other neighbouring balls, and the dynamics (displacements and forces) of the ball assembly changes. Several models are implemented in PFC^{3D} to describe the different contacts between balls to simulate the behaviour of different materials. Among those models, the parallel bond model (PBM), in which balls are held together by bonds, is suitable for materials exhibiting internal forces between particles (Itasca, 2008), such as agricultural soil particles in which cohesive forces exist between particles. van der Linde (2007) also mentioned that PBM is more suitable for simulations of agricultural soil. The parallel bond in the PFC^{3D} is depicted as a cylinder of cementitious material installed between balls (Fig. 1). The cylindrical bond is able to transmit both forces and moments. Bond break when the respective strengths at the contact area have exceeded the set limits, and the contact forces and moments would become zero until another contact point has been established. For details regarding the PFC^{3D} PBM, readers are referred to Itasca (2008).

2.2. Soil–tool interaction model

A simple soil engaging tool (a narrow blade) was simulated in this study. This type of simple tool has been used by many researchers for fundamental studies of soil–tool interactions in the past (McKyes, 1985; Chi and Kushwaha, 1991; Abo-Elnor et al., 2004; Godwin, 2007). The basic tool geometric parameters are tool width (w) and rake angle (α). The basic tool operational parameters are working depth (D) and working speed (v). For this simple tool, draught force is the most critical soil cutting force, and it reflects the power required from the tractor to pull the tool.

In the model, PFC^{3D} flat walls were used to represent the soil engaging tool. The tool was assigned constant geometrical and working parameters: too width (w) = 0.1 m; rake angle (α) = 45°; working depth (D) = 0.15 m. All these parameters are within the typical ranges of tillage tools and their field operations. Five PFC^{3D} walls were used to construct a soil bin to contain a soil particle assembly. To avoid the edge effect of the bin walls on soil particle flows during the operation of the tool, the vertical dimension of the soil bin was set greater than the working depth of the soil engaging