Simulation of Draft Forces of a Sweep in a Loamy Sand Soil Using the Discrete Element Method

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INTRODUCTION

In agriculture, soil-engaging tools are used for tillage, seeding, manure injection, and other field operations. Examples of soil engaging tools include moldboard plows, sweeps, chisels, and seed openers. Draft force is an important performance indicator for those soil-engaging tools, as it determines the requirement for tractor power. Although experimental studies of draft force have been well documented in the literature (e.g. Hasimu and Chen 2014), measurements of draft force are time consuming and require special equipment, such as large capacity dynamometer and data acquisition system. Several methods have been used for predicting draft force, and they are analytical, empirical, and numerical methods, including Finite Element Method (FEM), Discrete Element Method (DEM), and Smoothed Particle Hydrodynamics (SPH) method. A common analytical method of predicting draft force is the Universal Earthmoving Equation (Hettiaratchi and Reece 1967; Godwin and Spoor 1977; McKyes and Ali 1977). This method was developed based on passive earth pressure theories. The method is simple to use for force prediction and can also be used to examine effects of soil and tool parameters on draft forces (Chen et al. 2013b). However, the assumption of passive failure does not always reflect the nature of soil failure around a soil-engaging tool. The empirical method has drawbacks of being time-consuming for data collection, and the results can be highly variable. For numerical methods, the FEM has been intensively used in the past to model soil-tool interactions (Plouffe et al. 1999; Shen and Kushwaha 1998; Abo-Elnor et al. 2004). However, this method is suitable only for small soil deformation or large deformation with shear failure mode only. Both the SPH and DEM can address large deformation of soil particle, and these methods do not employ meshes and treat soil as an assembly of individual particles. The SPH method is more suitable for modeling soil-water interaction in geomechanics applications, for example, soil excavation using water jets (Bui and Fukagawa 2007) and dynamic loading of geomaterial (Blanc and Pastor 2011). Whereas the DEM is more suitable for modeling soil-tool interaction.

Keywords: Sweep, soil, draft force, DEM, measurement, simulation.
The DEM is a very promising tool in simulating the cutting process of a soil-engaging tool. However, the progress of using this numerical method to simulate soil-tool interactions has been limited for many years, primarily due to the facts that defining the constitutive laws of particle contact and calibrating particle parameters are extremely challenging. It has been found that dynamic behaviours of soil particles are significantly affected by the particle parameters (Masson and Martinez 2000; Shmulevich 2010) and constitutive laws of particle contact (Renzo and Maio 2004). Addressing these issues is imperative in advancing the field of soil-tool simulation using the DEM. Also, most existing studies focused on applications other than agriculture, for example bulldozing where soil was often cohesionless (Franco et al. 2007; Obermayr et al. 2011). Only few existing studies dealt with cohesive agricultural soil (e.g. van der Linde 2007; Mak et al. 2012; Chen et al. 2013a; Tamás et al. 2013; Sadek and Chen 2014). Currently, two common commercial DEM softwares, EDEM and PFC3D (Particle Flow Code in Three Dimension) are being used in developing soil-tool interaction models. For information regarding using EDEM for soil-tool simulation, the reader is referred to Ugul et al. (2014) and Fielke et al. (2013). This study used PFC3D developed by Itasca (Itasca Consulting Group, Minneapolis, MN).

The magnitude of draft force varies with the type of tool and soil condition. Therefore, the draft force of a specific tool needs to be modeled and the model needs to be calibrated for a specific soil condition. The objectives of this study were to (1) measure draft forces of a sweep in a loamy sand soil under different cutting depths and travel speeds, (2) calibrate a soil cutting model developed for the sweep using PFC3D, and (3) evaluate the model performance for the simulation of draft force.

MATERIALS AND METHODS
Measurement of draft forces of a sweep

Description of the sweep and testing facility The sweep studied had a 330-mm wide V-foot (Fig. 1a). The V-foot had a sweep angle of 70º and a lifting height of 84 mm. The rake angle (between the cutting face and travel direction) of the sweep was 18.5º. The sweep was tested in an indoor soil bin (Fig. 1b) located in the Department of Biosystems Engineering, University of Manitoba. The sweep was mounted onto the soil bin carriage through a C-shank (70 mm wide). The soil bin was 1.5 m wide, 15 m long, and filled with loamy sand soil (10% clay, 4% silt, and 86% sand) to a depth of 0.6 m. The average soil moisture content in the soil bin was 11.3%, and the average soil dry bulk density was 1,320 kg/m³, measured using the soil core and oven-dry method. Between tests runs, the soil was tilled with a rotary tiller, levelled with a blade, and packed with a roller.

(a)    (b)

Fig. 1. Testing tool and soil bin; (a) the sweep (top view); (b) the sweep mounted on the soil bin carriage through a dynamometer
Experimental design and measurements The sweep was tested in the soil bin to measure its draft forces under different travel speeds and cutting depths. A factorial experiment (3x4) was designed with three travel speeds (0.61, 1.22, and 1.83 m/s) and four cutting depths (50, 100, 150 and 200 mm), consisting of a total of 12 treatments. Higher speeds could not be tested due to the speed limit of the soil bin carriage. Each treatment was replicated three times. Thus, a total of 36 test runs were performed. The draft force of the sweep was measured using a frame-type dynamometer, which was installed between the soil bin carriage and the sweep (Fig. 1b). Force signals of the dynamometer were recorded at 35 Hz by a data acquisition system. The draft force was taken as the average of the data points over the section where the force variation was stable.

Data analysis Analysis of variance was performed on the data obtained from the soil bin tests to examine the effects of cutting depth and tool travel speed on the draft force of the sweep at a significance level of $p = 0.05$. Coefficient of correlation and relative error were used to evaluate the degree of agreement.

Development and calibration of soil cutting model Model particles and model sweep A soil-cutting model was developed using PFC$^{3D}$. The model components included a soil box, soil particles, and a simplified model sweep (Fig. 2). The model sweep was constructed using the PFC$^{3D}$ “walls”, and its general dimensions were the same as the sweep used in the soil bin experiments. Walls were used to form a soil box which contained a particle assembly of 0.4 m wide, 0.3 m deep, and 2.0 m long. There were a total of approximately 27,000 spherical particles in the assembly. A larger soil box would be more desired to avoid wall effects. However, that would increase the number of particles, and therefore, the computing time. The particle assembly had a bulk density similar to that of the soil used in the experiments. The particle density was assumed to be the soil particle density: 2,650 kg/m$^3$. The model sweep was positioned at the desired cutting depth at one end of the box. Simulation of the soil cutting process was performed by assigning the desired travel speed to the model sweep.

![Fig. 2. Soil cutting model showing the soil box, model particles, and model sweep prior to the operation.](image)

The particle diameter varied from 10 to 20 mm with a uniform distribution. This particle size range was considered to reflect the size range of field aggregates (from 1 mm to 49 mm) for a sandy soil reported by Okunola and Payne (1991). The PFC$^{3D}$ linear stiffness model with Parallel Bond Model (PBM) was selected to define the contacts between particles. In the PBM, bonds are added between particles at the contacts, which mimicked soil cohesion and aggregates of agricultural soil. For details regarding the PBM, readers are referred to Potyondy and Cundall (2004). The model parameters included particle normal stiffness $K_n$ (N/m), particle shear stiffness $K_s$ (N/m), particle friction coefficient $m$, bond normal strength $\sigma$ (Pa), bond shear strength $\tau$ (Pa), bond normal stiffness $R_n$ (Pa/m), bond shear stiffness $R_s$ (Pa/m), radius multiplier of the bond $R_m$ (dimensionless), and three damping coefficients.

To have the model behave the same as the soil to be simulated, the model parameters had to be properly selected and calibrated. In this study, $K_n$ was chosen to be calibrated, as it was the most influential parameter for the draft force (Sadek and Chen 2014). According to the literature (e.g. Asaf et al. 2007; van der Linde 2007), particle normal stiffness ($K_n$) and shear stiffness ($K_s$) can be considered to be the same, i.e. $K_n/K_s = 1$. According to Mak et al. (2012), bond shear strength was equal to soil cohesion $(c)$: $\tau = c$; bond normal strength was a function of $c$ and soil internal friction angle $(\phi)$: $\sigma = c \cot \phi$. The $c$ and $\phi$ of the experimental soil were previously measured using direct shear tests within the scope of another study (Chen and Ren 1998), and their corresponding values were 13.9 kPa and 20.0°. Thus, the derived bond normal and shear strengths were 13.9 and 382 kPa respectively. Chen and Ren (1998) also reported an average vertical displacement of 4.2 mm under an average normal stress of 208 kPa measured in the direct shear tests. These were used to determine the bond normal stiffness: $K_n = 49500$ (kPa/m) in this study. The ratio of bond normal and shear stiffness ($K_n/K_s$) was set as 1, and the bond radius multiplier ($R_m$) was set as 0.5. Particle friction coefficient $(m)$ was 0.36 from the measured soil internal friction angle of 20.0°. For the damping coefficients, the PFC$^{3D}$ default values were used.

Calibration of particle stiffness ($K_n$) Particle stiffness, $K_n$, is a soil property. Therefore, it was expected that $K_n$ would not be affected by the tool travel speed. Thus, a constant travel speed (0.61 m/s) was used to run the model at different soil cutting depths. The total force acting on the model sweep in the horizontal direction was recorded over the length of the soil box. The average value of the forces over the middle section of the soil box was taken as the simulated draft force of the model sweep. In the calibration process, the draft force was monitored for an assumed value of $K_n$ at each of the four cutting depths (50, 100, 150, and 200 mm); then the value of $K_n$ was altered and the model was run again for the four cutting depths. This was repeated until the best match
between the simulated force and that predicted from the Universal Earthmoving Equation (UEE) was found. The UEE has reasonably good accuracy for predicting draft force of a soil-engaging tool. It relates draft force with soil and tool parameters, such as soil weight, cohesion, adhesion, surcharge, and tool travel speed. As soil adhesion is very small (Godwin 2007), particularly for sandy soil, its effect can be neglected. Surcharge of soil surface is zero for typical agricultural fields. According to McKyes (1985), the UEE is expressed as

\[ D = (\rho_0 g d^2 N_a + c_d N_c + \rho_b v^2 d N_b) w \sin(\alpha + \delta) \] (1)

where,

- \( D \) = draft force (N),
- \( \rho_b \) = soil bulk density (kg/m³),
- \( g \) = gravitational acceleration (m/s²),
- \( d \) = cutting depth (m),
- \( v \) = tool travel speed (m/s),
- \( w \) = cutting width of tool (m),
- \( \alpha \) = tool rake angle (°),
- \( \delta \) = soil-tool friction angle (°),
- \( N_a, N_c, \) and \( N_b \) = the N factors (dimensionless).

The N factors are functions of \( \alpha, \delta, \phi, w, \) and \( d \) and they were determined using the wedge method (McKyes, 1985).

RESULTS AND DISCUSSION

Measured draft forces as affected by the cutting depth and travel speed

The draft force of the sweep significantly increased with cutting depth from 50 to 200 mm, regardless of travel speed (Fig. 3). As for effects of speed, increases in draft force were observed at all the cutting depths when the speed increased from 0.61 to 1.22 m/s. Further increase in speed to 1.83 m/s did not cause any increases in the draft force. Draft force data measured by Al-Janobi and Al-Suaibani (1998) and Onwualu and Watts (1998) also showed that effects of depth were more pronounced than those of speed.

Model behaviour

In PFC³D models, the mechanical behaviour of particles is described in terms of the movement of each particle and the inter-particle forces acting at each contact point (Itasca 2014). These, in this study, were translated into draft forces acting on the model sweep. The soil-cutting model allowed monitoring the forces and observing the dynamics of model particles over the course of soil cutting. Figure 4 shows some snapshots from the simulations. Initially, particle contact forces started to develop around the sweep where bonds between particles might break (Fig. 4a), which mimicked soil breakage (soil loosening) in a field operation. As the model sweep was being advanced, more and more particles were impacted by the sweep, and contact forces were developed in a larger area around the V-foot of the sweep (Fig. 4b); then spread to a larger area including the surrounding of the C-shank of the sweep (Fig. 4c). It was also observed that some particles were being dislodged above the original soil surface. This type of soil surface disturbance can also be observed in a real field operation. At the stage shown in Fig. 4d, the soil cutting process reached its “stable” status. When comparing Fig. 4d to Fig. 4c, particle-particle contacts were extended farther in the front of the sweep tip, but some particles behind the sweep had lost the contacts. Figure 4d also demonstrates that more soil particles were dislodged above the original soil surface. All the above phenomena reflected the real soil behaviour in field operations.

Figure 5 shows a typical history of draft force monitored from a simulation. As the sweep entered the soil box, its draft force quickly increased and then fluctuated around a constant value; at that stage, the development of draft force was considered to be stable. The fluctuating nature of draft force is also observed in practice. In PFC simulation, the extent of fluctuation is affected by the particle size. As the particles used in this study were fairly large, the simulated draft force exhibited large fluctuations. The simulated draft force was determined by the average force over the stable section of the curve.
Calibration results

Draft forces from the UEE: The cutting width of the sweep in Eq. 1 is not a constant value over the cutting depth. The width of the foot was 0.33 m and that of the shank was 0.07 m. The cutting width depended on whether the cutting involved the V-foot only or both the V-foot and the C-shank. When Eq. 1 was used to calculate the draft force, the cutting width was determined according to the proportion of the V-foot and C-shank that are immersed in soil. This was done using the given rake angle (\( \alpha \)) of 18.5\(^\circ\), the sweep length of 0.25 m, and the cutting depth. Values of the other parameters used are summarized in Table 1. The value of soil-tool friction angle (\( \delta \)) was taken from Shen and Kushwaha (1989). Values of N factors are listed in Table 2. It was noticed that values of N factors varied with the tool working depth, and they did not vary with the travel speed.

Draft forces were monitored during simulations with a series of assumed \( K_n \) values. The results showed that the value of \( K_n \) which resulted in the best match between simulated and calculated draft forces was \( K_n = 3 \times 10^3 \) N/m where the RE was minimum (9%).

Evaluation of the model

The simulation results were compared with those from the experimental results using 1:1 line (Fig. 7). They agreed well at the 150 mm depth; at the smaller cutting depths, the model overestimated the draft force; and at the greater cutting depth, the model underestimated the draft force. Over all four depths, the correlation coefficient between the simulated forces and the measured forces was 0.8.

CONCLUSIONS

The soil bin measurements showed that the draft force of the sweep increased rapidly with cutting depth. Increasing the tool travel speed from 0.61 to 1.22 m/s also resulted in a significant increase in the draft force at all the depths tested. However, there was no further increase in draft force with increasing travel speed.
force at a higher speed of 1.83 m/s. Agricultural soil can be simulated using the PFC$^{3D}$ basic spherical particles with parallel bonds. The soil-cutting model developed using the PFC$^{3D}$ bond model can simulate the draft forces of the sweep. The particle stiffness of the model was $3 \times 10^3$ N/m for the sandy soil, calibrated with the draft forces predicted by the Universal Earthmoving Equation. Over four cutting depths, the correlation coefficient was 0.8 between the draft forces simulated with the soil-cutting model and those measured. It is recommended to conduct further simulations with smaller soil particles and wider soil box.

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**REFERENCES**


