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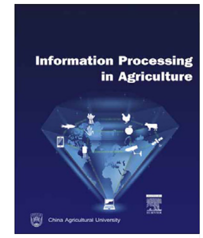

Defining the effect of sweep tillage tool cutting edge geometry on tillage forces using 3D discrete element modelling

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The energy required for tillage processes accounts for a significant proportion of total energy used in crop production. In many tillage processes decreasing the draft and upward vertical forces is often desired for reduced fuel use and improved penetration, respectively. Recent studies have proved that the discrete element modelling (DEM) can effectively be used to model the soil–tool interaction. In his study, Fielke (1994) [1] examined the effect of the various tool cutting edge geometries, namely; cutting edge height, length of underside rub, angle of underside clearance, on draft and vertical forces. In this paper the experimental parameters of Fielke (1994) [1] were simulated using 3D discrete element modelling techniques. In the simulations a hysteretic spring contact model integrated with a linear cohesion model that considers the plastic deformation behaviour of the soil hence provides better vertical force prediction was employed. DEM parameters were determined by comparing the experimental and simulation results of angle of repose and penetration tests. The results of the study showed that the simulation results of the soil-various tool cutting edge geometries agreed well with the experimental results of Fielke (1994) [1]. The modelling was then used to simulate a further range of cutting edge geometries to better define the effect of sweep tool cutting edge geometry parameters on tillage forces. The extra simulations were able to show that by using a sharper cutting edge with zero vertical cutting edge height the draft and upward vertical force were further reduced indicating there is benefit from having a really sharp cutting edge. The extra simulations also confirmed that the interpolated trends for angle of underside clearance as suggested by Fielke (1994) [1] where correct with a linear reduction in draft and upward vertical force for angle of underside clearance between the ranges of −25 and −5°, and between −5 and 0°. The good correlations give confidence to recommend further investigation of the use of DEM to model the different types of tillage tools.

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Nomenclature

a	indices for sphere or implement	r	radius, (m)
Ad	adhesion (kPa)	r_{eq}	equivalent radius, (m)
A_c	contact area, (m^2)	r_{con}	perpendicular distance of contact point from the centre of mass, (m)
b	indices for sphere or implement	t	integration time step (s)
C	cohesion (kPa)	U_{abn}	normal component of the relative displacement (m)
e	coefficient of restitution	U_{abt}	tangential component of the relative displacement (m)
g	gravitational acceleration, ($m\,s^{-2}$)	$\dot{U}_{abn}$	normal component of the relative velocity ($m\,s^{-1}$)
E	Young's modulus, (MPa)	$\dot{U}_{abt}$	tangential component of the relative velocity ($m\,s^{-1}$)
E_{eq}	equivalent Young's modulus, (MPa)	U_0	residual overlap (m)
F_c	cohesion force, (N)	$\ddot{U}$	translational acceleration, ($m\,s^{-2}$)
F_n^d	normal damping force, (N)	Y	yield strength (Pa)
F_t^d	tangential damping force, (N)		
F_n	normal total contact force, (N)	*Greek letters*	
F_n^s	normal contact force, (N)	υ	Poisson ratio
F_t^s	tangential contact force, (N)	μ	coefficient of friction
F_t	tangential total contact force, (N)	μ_r	coefficient of rolling friction
G	shear modulus (Pa)	λ_θ	unit vector of angular velocity
I	moment of inertia, ($kg\,m^2$)	ξ	cohesion energy density ($J\,m^{-3}$)
K_1	stiffness for loading ($N\,m^{-1}$)	$\ddot{\Theta}$	rotational acceleration, ($rad\,s^{-2}$)
K_2	stiffness for unloading/reloading ($N\,m^{-1}$)	ρ	density ($kg\,m^{-3}$)
M	moment, (Nm)		
M_r	moment due to rolling friction, (Nm)		
m	mass, (kg)		
n_c	damping factor		
n_k	stiffness factor		

1. Introduction

Energy (especially fossil fuels) currently plays a key role in tillage systems. In order to reduce energy use, the tillage process must be examined in detail [2]. In tillage processes, decreasing the draft and upward vertical forces is often desired. The study of [3] showed that the cutting edge geometry of the tillage tool has an important effect on draft and vertical tillage forces. When the interaction between the soil and tool cutting edge can be accurately modelled, more energy efficient tools can be designed without performing expensive field tests which may only be undertaken at certain times of the year.

The discrete element method (DEM) is a numerical method used for modelling the mechanical behaviour of granular materials. DEM was developed by [4] in the field of rock mechanics. It is based on the contact between two particles. Interactions between these particles are examined by using contact models governed by physical laws. DEM assumes agricultural soil can be modelled as a granular material. DEM simulations can be run in 2D or 3D. Ideally, to get accurate results, the size and shape of the particles used in the DEM simulations should be as close as possible to actual particle shape and size. However, as the number of particles studied increases, more calculations and a longer simulation time is required. Although specific particle shapes can be used to define the particles, the computationally simplest and hence, the commonly used particle shapes in DEM simulations are circular for 2D simulations and spherical for 3D tillage simulations [5,6]. To date a few attempts have been made to model the soil-implement interaction in 2D DEM, such as; modelling of the cutting blades [7–9,13]; modelling of the soil loosening process caused by a vibrating subsoiler [10]; and modelling of a pendulum type cutting blade test [11]. There are also some 3D studies that provide quantitative results; for instance 3D DEM simulation of a cutting blade [12–16] and 3D simulation of a sweep tool [6]. Although very good correlations were shown between the measured and predicted draft forces, the vertical force results were either not provided or not well correlated with the experimental results. In all this previous work only elastic contact models namely; linear spring contact model (LSCM), Hertz–Mindlin contact model (HMCM) or parallel bond contact model (PBCM) were used. The LSCM is based on the work by [4] and is the simplest method of modelling mechanical relations between spherical particles. In the LSCM stiffness and the damping coefficients are determined for each material as a constant and the collisions between the particles are considered as linear elastic. This model is quite simplistic. In the HMCM, the deformation at the contact point is assumed as non-linear elastic. The stiffness and damping coefficients are calculated using relative displacement based equations. In order to use the HMCM for cohesive particle–particle interactions, the PBCM is used. When the cohesion is zero the PBCM yields the HMCM [17]. None of the contact models used in the previous works considered the plastic deformation behaviour of the soil. So as to consider the plastic deformation behaviour of the soil hysteretic spring contact model (HSCM) developed