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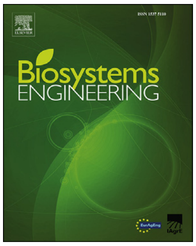

Research Paper

Simulating the effect of rake angle on narrow opener performance with the discrete element method

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Narrow openers are widely used in Australia to place seed and fertiliser into furrows under no-tillage seeding operations, but excessive soil disturbance often limits their performance. The discrete element method (DEM) and a hysteretic spring contact model can be used to model soil-tool interactions, although previous work has been limited in its evaluation of soil disturbance. A new approach was used to evaluate soil disturbance in DEM simulations using a voidage grid binning technique to identify loosened soil after tillage and therefore paralleling soil bin and field testing methodologies. The effect of opener rake angle (35–90°) was simulated and compared to previous soil bin studies in a sandy loam soil predicting furrow profile parameters loosened area, ridge height, dip area, furrow backfill and lateral soil throw with relative errors of 9%, 16%, 14%, 0.8%, and 9%, respectively. Soil layer mixing trends also followed those measured in soil bin experiments-low rake angle openers moving deep soil up the furrow profile and maximising the furrow mixing effect. Additionally, predicted soil failure (critical depth and forward rupture ratio m) and tillage force rake trends followed those expected from classic empirical based soil mechanics studies. DEM predicted approximately a twofold draught penalty with increasing rake angle as well as a vertical force transition at 71°—closely matching trends consistently reported in literature. The approach followed demonstrated an improved potential for DEM simulations to optimise the performance of narrow openers.

1. Introduction

Narrow openers (also known as hoe openers) are widely used in Australian no-tillage farming systems to open a slot and place fertiliser and seeds in the soil. However, they can create a large amount of soil disturbance. Excessive soil disturbance limits practical operating speed, reduces seed placement accuracy, stimulates weed seed germination, increases seedbed moisture loss, and can cause pre-emergent herbicide contaminated soil to be thrown onto adjacent seed rows (Baker et al., 2006; Barr, Desbiolles, & Fielke, 2016; Chauhan, Gill, & Preston, 2006; Desbiolles & Saunders, 2006). It is therefore advantageous to optimise narrow opener design to better control soil disturbance and hence improve the performance of no-tillage seeding.

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Nomenclature

A_1	Backfilled furrow area
A_2	Dip Area
d_c	Critical depth (mm)
E_r	Relative average error (%)
f	Forward rupture distance, (mm)
i	Original depth layer
L	Length of voidage grid bin (mm)
m	Forward rupture Distance Ratio
M	Experimental measured value
N	Total number of tracers found in seed zone
n_i	Number of tracers from depth layer i
P_{ti}	Proportion of tracers in a seed zone originating from original depth layer i
S	DEM simulated value
$S_{\#\#}$	Percent soil cover index
r	Radius of DEM particles, (mm)
V_P	Total volume of particles whose centroids are located within the grid cell
W	Voidage grid bin square cell width (= height) (mm)
Δ	Voidage ratio

Soil disturbance can be defined as the loosening (a reduction in bulk density), movement (a change in position along three dimensional directions) and mixing (a relative exchange of positions, particularly in the vertical direction) of soil caused by an opener passing through soil. The key soil disturbance parameters for opener design optimisation include:

a) the soil failure mechanisms and in particular the critical depth at which they change from a crescent failure zone with three dimensional (forward, lateral and vertical) soil movement, to a two dimensional (forward and lateral) soil movement (Godwin & Spoor, 1977);
b) the resulting furrow profiles (Solhjou, Fielke, & Desbiolles, 2012); lateral soil throw (Desbiolles & Saunders, 2006; Hasimu & Chen, 2014); and,
c) vertical soil layer mixing (Sharifat, 1999).

The associated draught and vertical force requirements are also important for energy efficiency and penetration ability (Barr et al., 2016; Hasimu & Chen, 2014).

In terms of experimentation, each measured performance parameter is resource intensive and this limits the number of opener designs, operational settings and soil conditions for which an opener can be optimised. Computer-based modelling, as in many engineering applications, has the potential to reduce the resources required to thoroughly test, evaluate and optimise opener design.

Modelling soil tool interaction has been attempted by empirical, analytical, continuum and dis-continuum methods of analysis, but each has their limitation. Empirical models formalise relationships observed within specific data sets, with limited predictive capabilities outside their contexts. Analytical models are often based on classical soil mechanics theories to quantify mechanistic relationships, providing a useful basis for the prediction of draught and vertical forces. However, their use is limited to simple design parameters such as opener depth, width, rake angle and they are unable to predict the flow of loosened soil as an outcome of furrow loosening. Continuum method of analysis such as finite element analysis (FEA) (Aluko, 2008; Armin, Szyszkowski, & Fotouhi, 2016; Fielke, 1999; Raper & Erbach, 1990; Tagar et al., 2015) and computational fluid dynamics (CFD) (S. Karmakar, Ashrafizadeh, & Kushwaha, 2009; S Karmakar & Kushwaha, 2006)have been used to analyse more complex geometries and accurately model soil failure patterns and forces. However, continuum methods do not account for soil layer mixing, flow of soil particles or the cracks formed by the tillage process (Plouffe, Lague, Tessier, Richard, & McLaughlin, 1999) and they can fail to compute large deformations and displacements.

The discrete element method (DEM) is a discrete method of analysis that can overcome the shortcomings of the methods described above. DEM calculates the interactions between a series of discrete particles which are governed by contact models. The potential of DEM for modelling soil tool interactions has been demonstrated and utilised over the last two decades. However, most research has centred around simulating the resultant forces acting on the tool (Bravo, Tijskens, Suárez, Gonzalez Cueto, & Ramon, 2014; JianQun et al., 2009; Obermayr, Dressler, Vrettos, & Eberhard, 2011; Obermayr, Vrettos, Eberhard, & Däuwel, 2014; Ucgul, Fielke, & Saunders, 2014b), and less on soil disturbance characteristics.

Recent studies have looked at soil disturbance characteristics. Ucgul et al. (2014b) qualitatively compared sandy-loam soil forces acting on sweeps and the resulting soil failures with various DEM contact models, achieving the best fit with the elastic–plastic hysteretic spring contact. Obermayr et al. (2011) predicted a similar soil wedge (15% relative error) ahead of a wider cutting tool to that expected from calculations using the Coulomb theory. Ucgul, Fielke, and Saunders (2014a) initially underpredicted the lateral soil throw with various sweep geometries due to large 10 mm radius particle sizes, but they were able to improve results by reducing the particle size to 1.5 mm radius within the 20 mm thick surface layer. Murray (2016) used 2.5 mm radius DEM particles to simulate the operation of a hoe opener. Lateral soil throw was assessed using a cross sectional profile and measuring to the edge of the bulk soil throw section. Outlier DEM particles thrown further than this width were omitted from the lateral soil throw measurement, resulting in a 14% relative error between the DEM simulation and field measurements. Ucgul, Saunders, and Fielke (2017) predicted trends for top soil burial with a mouldboard plough (relative error of 14%), the major source of error was reported to be from larger than actual DEM particles (2–5 mm radius) affecting soil flow at the cutting edge. Cross sectional scalar velocity and displacement profiles have been used to define failure boundaries profiles in DEM for 80 mm wide sweeps (Chen, Munkholm, & Nyord, 2013) and a range of hoe openers (Murray, 2016). However, scalar velocity and displacement profiles assume particle movement results in soil loosening, when in reality particle movement can act to loosen or compact the soil profile as highlighted in Barr, Desbiolles, and Fielke (2017). Considering only the positive vertical velocity, or displacement