Available online at www.sciencedirect.com
ScienceDirect
journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Comparison of the discrete element and finite element methods to model the interaction of soil and tool cutting edge

*Mustafa Ucgul**, *Chris Saunders*, *John M. Fielke*

Agricultural Machinery Research and Design Centre, School of Engineering, University of South Australia, Mawson Lakes, SA 5095, Australia

ARTICLE INFO

Article history:
Received 22 September 2017
Received in revised form
14 February 2018
Accepted 1 March 2018

Keywords:
Discrete element method (DEM)
Finite element method (FEM)
Tillage
Draught force
Vertical force
Soil movement

Soil tillage is an energy intensive operation and design improvements that reduce forces have been pursued for many different tools. Due to the high cost of prototyping and testing, computer modelling has been adopted to design tillage equipment. In order to model soil-tool interaction two methods namely; finite element method (FEM) and discrete element method (DEM) have been used. Fielke (1994 and 1996) found that for shallow working low rake angle tools the cutting edge geometry of a tillage tool has a major effect on tillage forces and soil movement. FEM modelling of the tests was also carried out in Fielke (1999). In this paper the experimental work of Fielke (1994) was simulated using DEM techniques and the results were compared to both the measured data and FEM predicted results. The results of the study showed that better vertical force prediction was obtained using DEM whereas forward soil movements below the tillage depth were simulated more accurately using FEM. This can be attributed to the larger size of particles used in DEM simulation than needed to pass around the cutting edge. It was also shown that DEM can be used to accurately predict soil failure planes.

1. Introduction

Tillage operations are carried out using a mechanical force, commonly by using a tractor drawn tool to achieve cutting, inversion, pulverisation and movement of the soil. The energy required for tillage processes accounts for a significant proportion of total energy used in crop production. With high oil prices and increasing pressure on emissions, minimising the energy used in crop production is important. In the tillage process, decreasing the draught and upward vertical forces is desired to reduce energy consumption. Fielke (1996) showed that the cutting edge geometry of a sweep tool has a significant effect on draught and vertical tillage forces. If the interaction between the soil and tool cutting edge can be accurately modelled, more energy efficient tools can be designed without performing costly field tests which may only be undertaken at certain times of the year. In addition, as the purpose of tillage using a low rake angle sweep tool is to cut and lift the soil with minimum draught force, a simulation technique that has the capability of simulating soil cutting and soil lifting would be beneficial.

* *Corresponding author.*
E-mail address: Mustafa.Ucgul@unisa.edu.au (M. Ucgul).
https://doi.org/10.1016/j.biosystemseng.2018.03.003

In general, three types of modelling approaches have been used to model soil-implement interaction, namely; empirical, analytical, and numerical methods. The empirical modelling approach (e.g. Pytka & Konstankiewicz, 2001; Zhang & Kushwaha, 1999) is time effective and gives practical information. However, the experimental procedures involved have high cost and extrapolation of the results to all conditions is uncertain (Raji, 1999). Analytical methods have received much attention over the last decades from many researchers (e.g. Godwin, O'Dogherty, Saunders, & Balafoutis, 2007; McKyes, 1985). However, the structure of the soil is not homogenous, so development of just one governing equation to calculate the tillage related forces during the whole tillage process is not realistic. With the rapid development in computer technology, numerical methods have been employed by researchers to model the soil-tool interaction. Two types of numerical methods, namely the finite element method (FEM) (Bentaher et al., 2013; Fielke, 1999; Kushwaha & Shen, 1995 (for modelling tillage forces) and Armin, Fotouhi, & Szyszkowski, 2014; Mouazen & Nemenyi, 1999; Tagar et al., 2015 (for modelling crack or soil failure)) and the discrete element method (DEM) (Asaf, Rubinstein, & Shmulevich, 2007; Barr, Fielke, & Desbiolles, 2017; Bravo, Tijskens, Suárez, Gonzalez Cueto, Ramon, 2014; Obermayr, Vrettos, Eberhard, & Däuwel, 2014; Sadek & Chen, 2015; Ucgul, Fielke, Saunders, 2014a, 2014b, 2015b; Ucgul, Saunders, Fielke, 2017a, 2017b) have been used to simulate soil-tool interactions. More recently 3D discrete element method (DEM) has become accessible and achievable with desktop computing. This paper compares FEM and DEM in the case of soil-tool interaction. In this study the interaction between soil and varying sweep tillage tool cutting edge geometries (varying cutting edge height, varying length of underside rub and varying underside clearance) were simulated using DEM and the results were compared to Fielke (1994 and 1996)'s soil bin and FEM results.

2. Methodology

2.1. Soil bin tests and FEM simulation of the tests

To investigate the interaction between soil and cutting edge of a low rake angle sweep tillage tool, a series of soil tests were performed by Fielke (1994). The tests were performed in a glass-sided bin using a soil sample of 800 mm length, 110 mm width, and 300 mm depth. In order to measure the draught and vertical forces two 1 kN capacity transducers were fitted to the test equipment (Fig. 1). Ten experimental tillage tools based on dimensions given in Fig. 2 were constructed using AISI 1040 steel. The cutting edge thickness, underside rubs and underside clearance of the tools used in the tests are shown in Fig. 3. The experimental tools were mounted to a linear bearing that ran along a rail and was pushed through the soil by a 1300 mm stroke hydraulic cylinder at a speed of 33 mm s^{-1}. All experiments were performed at 70 mm operation depth. A video camera was also used to record the soil movement. For the experiments, 10% moisture content sandy loam soil (85% sand, 3% silt and 12% clay) at 1670 kg m^{-3} bulk density was used. The particle size distribution of the soil, obtained by sieving, is given in Table 1.

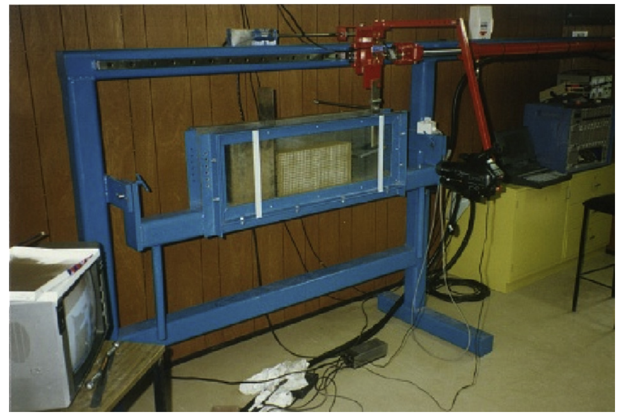

Fig. 1 – Glass sided soil bin test equipment (Fielke, 1994).

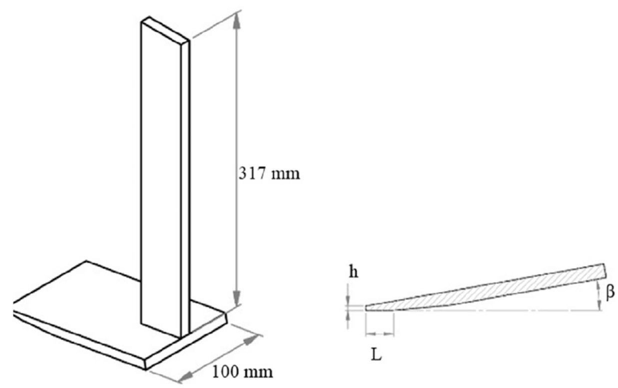

Fig. 2 – Definition of the experimental sweep wing geometry. Cutting edge parameters of h is cutting edge height, L is underside rub length and β is angle of underside clearance, as per Fielke (1994).

In the tests, draught force increased rapidly as the tool entered the soil (Fig. 4) and the draft and vertical force was soon stabilised until the failed soil reached the tine and then started to wedge between the tine and the glass wall and the forces then continued to rise again to form a second stable value. Hence, in order to eliminate the effect of the restriction in soil flow by the vertical tine, Fielke (1994) only compared the draught and vertical forces for the first 150 mm of travel prior to the soil wedging between the tine and the glass walls.

The draught and vertical forces were taken from the peak forces prior to the tool having travelled 150 mm into the soil which are marked with "O" in Fig. 4.

In order to measure the soil movement, a 10 mm × 10 mm square grid with 0.5 mm thick lines was applied to the soil using a template in the horizontal and vertical directions (Fig. 5). The lines were formed by dusting the template with talcum powder. The soil failure was recorded in each test using a video recorder and deformed grids were determined. Maximum depths below tillage where the soil was moved forward greater than 1 mm were measured to examine and compare soil smearing and plough pan formation.

For the FEM predictions a 2D linear elastic–plastic model was employed and the classical Mohr-Coulomb failure theory was used for the failure criterion. The soil was modelled using