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Study the effect of tool geometry and operational conditions on mouldboard plough forces and energy requirement: Part 1. Finite element simulation

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A B S T R A C T

The finite element method (FEM) is commonly used to study the soil cutting process with tillage tools. This paper illustrates the use of FEM to model interaction of a mouldboard plough used in northern Africa. A Drucker–Prager elasto-plastic model was used to simulate the material behavior of a sandy loam soil. The mouldboard was considered as a discrete rigid body with a reference point at the tip, at which the three orthogonal force components (vertical, lateral, and draught) were calculated. The effects of the mouldboard depth of cut, speed of operation, cutting angle (α) and the lifting angle (β) on the tillage forces were investigated in this study. Results showed that draught force increased with a second order polynomial function with depth, whereas the vertical and lateral forces had a linear relationships with depth. Moreover, these forces increased linearly with speed. For the effect of the cutting angles, results showed that the draught force increased linearly with the cutting and the lifting angles. The vertical force decreased linearly with these angles. Whereas, the lateral force decreased with a polynomial trend with the cutting angle and increased linearly with the lifting angle. It was found that the minimal energy consumption can be achieved by a combination of a working depth of 150 mm, a speed of 1 m/s, low lifting angle (25°), and cutting angle (from 30° to 45°). This combination also resulted in a good soil inversion. It can be concluded that FEM can be used to understand the effect of mouldboard design and operational conditions on tillage forces, energy requirements, and quality of soil inversion.

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1. Introduction

Tillage is a very important operation in conventional and reduced tillage systems, which is required to improve soil physical characteristics for a better aeration, permeability, root development, and as a result plant growth and yield. However, primary tillage requires large amount of energy and time, and can be a costly operation for the farmers, particularly when concerning conventional tillage with mouldboard ploughs. Some researchers attempted to optimize the geometry of the tillage tool using physical experiments (Owende and Ward, 1996; Soni et al., 2007), while mathematical simulations were also considered by many researchers (Ros, 1978; Shrestha et al., 2001; Shahmirzae and Ghanbarian, 2009). Other researchers studied the influences of operational conditions on the energy consumption of tillage tools including depth, speed, and cutting angles (Al-Janobi and Al-Suhaibani, 1998; Gill and Vanden Berg, 1967). Studies also showed that theoretical modeling approaches for the estimation of tillage forces can be very helpful tools for estimating the energy consumption for different tools geometries (Bentaher et al., 2013; Mouazen and Nemenyi, 1999). However, a key success in mathematical simulation relay on accurate modeling based on correct assumptions, and the use of appropriate material and interface models. If successfully validated under controlled conditions, these mathematical simulations can result in significant reduction in the cost of the numerous expensive field tests used to run for prototype development and verification.

In traditional mathematical simulation of soil–tool interaction, models were developed based on the Terzaghi's passive earth pressure theory (Wismer and Luth, 1972; McKyes and Ali, 1977; Godwin and Spoor, 1977; Hettaratchi, 1993). These models are well reviewed in the literature (Upadhayaya et al., 2009). In addition, numerical approaches, such as computational fluid dynamic (CFD) (Karmakar and Kushwaha, 2006), the discrete element

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method (DEM) (Hofstetter, 2002; Shmulevich, 2010; Tamas et al., 2013; Chen et al., 2013), and the finite element method (FEM) (Mouazen and Nemenyi, 1999; Rosa and Wulfsohn, 1999; Chi and Kushwaha, 1990) were also intensively used to study the soil-tillage tools interaction with more complex tool geometries. Soil behaviors under loading are generally considered as having non-linear elastic–plastic properties with a large strain deformation (Upadhyaya et al., 2002, chapter 2). Plasticity theory applicable to soil mechanics is well reviewed in the work of Wulfsohn and Adams (2002). Modeling the soil-tillage tools interaction with the FEM, some researchers modeled the soil as a continued material with non-linear elastic behavior (Duncan and Chang, 1970; Bailey et al., 1984; Chi and Kushwaha, 1990), whereas others considered the soil as an elastic–perfectly plastic material (Fielke, 1999; Bentaher et al., 2013) and as an elasto-plastic with hardening behavior (Li et al., 2013). Studies accounted for simple shape tools such as blades (Chi and Kushwaha, 1990; Abo-Elnor et al., 2004; Davoudi et al., 2008), or more complex tools such as sweeps (Fielke, 1999), disc plough (Abu-Hamdeh and Reeder, 2003), bent leg plough (Jafari et al., 2006) or mouldboard plough (Plouffe et al.,1999; Formato et al., 2005; Jeshvaghani et al., 2013). Indeed, the effects of the speed, depth, and the angle of the tool on the tillage forces were also studies (Abo-Elnor et al., 2003, 2004; Yong and Hannaj, 1977; Chi and Kushwaha, 1990). Generally, researchers reported increase in draught force with cutting angle (rake angle), speed, and depth. Furthermore, other researcher expanded the simulation to assess the quality of soil loosening (Mouazen and Nemenyi, 1999; Abo-Elnor et al., 2004). Both CFD and DEM allowed large displacement of the soil and the tool, respectively. However, the majority of the FEM studies are limited to small displacements (e.g. in the range of few centimetres) due to simulation problems related to mesh distortion.

To our knowledge, no previous work taking into consideration both working conditions (depth, speed, cutting angle (α), and lifting angle (β)) and their effect on the quality of soil loosening was published. The scope of this paper is to model the soil–mouldboard plough interaction using FEM, aiming at quantifying the effects of all the pre-mentioned parameters, on acting forces and soil loosening and inversion. A mouldboard plough design used by farmers in North Africa (width less than 250 mm), with arid climate and high evaporative demand, is simulated in this study. A subroutine that removes the elements from the mesh as they fail was used in our numerical model to overcome the mesh distortion problems. The cutting of the whole block of soil (2 m) was considered.

2. Materials and methods

The mouldboard tillage process conducted with finite element method was studied in two parts.

2.1. Soil model and measurement

2.1.1. Soil material model

The mechanical behavior of the soil under the external load of tillage was modeled with different yield criteria. Examples of these models are hypoplastic, Cam-Clay, elastic–perfectly plastic (Abo-Elnor et al., 2004; Poodt et al., 2003; Li et al., 2013). Furthermore, several researchers used the Drucker–Prager and its extend forms (linear, hyperbolic, or general exponential) available in ABAQUS (2010), to simulate the interaction between the soil with different tools used in civil engineering, excavation, and tillage (Li et al., 2013). In the present work, the soil was modeled as a continuum elasto-plastic with hardening property using the linear form of the extended Drucker–Prager model. This model can be defined as follows:

$$F = t - \mathrm{p}\tan\xi - d \tag{1}$$

where F (kPa), t (kPa), p (kPa), ξ (°), and d (kPa) are respectively the yield function, the deviatoric stress, the normal stress, the internal angle of friction, and the cohesion of the material. The normal (p) and deviatoric (t) stresses can be expressed as follows:

$$p = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3) \tag{2}$$

$$t = \frac{1}{2}q\left[1 + \frac{1}{K} - \left(1 - \frac{1}{K}\right)\left(\frac{r}{q}\right)^3\right] \tag{3}$$

$$q = (\sigma_1 - \sigma_3) \tag{4}$$

$$r^3 = -(\sigma_1 - \sigma_3)^3 = -q^3 \tag{5}$$

where

K is the ratio of the tension yield stress tension to the compression yield stress in triaxial test ($0.778 \leqslant K \leqslant 1$) (ABAQUS, 2010). If $K = 1$ then $t = q$ and the yield surface in this case is identical to the Von Mises circle in the deviatoric principal stress plane.

q is the mises equivalent stress.

$\sigma_1, \sigma_2 = \sigma_3$ are compressive stress in triaxial test; r is the third invariant of deviatoric stress.

2.1.2. Measurement of soil material and soil–metal properties

The soil was a sandy loam used in the soil bin of Cranfield University with dry bulk density of 1600 kg/m^3 and a moisture content of 9.5% (d.b.). The soil mechanical properties (Young Modulus and Poisson ratio) were determined by triaxial test. The characteristics of soil–tool interface (angle of soil–metal friction (δ)) and soil internal properties (cohesion (C), the angle of internal friction (ϕ)) were measured through laboratory tests in a shear box at five levels of normal stress (12, 39, 66, 94, and 121 kPa). The cohesion (C), the angle of internal friction (ϕ) and the angle of soil–metal friction (δ) were also evaluated.

The material behavior in ABAQUS numerical model was defined with elastic–perfectly plastic low (no hardening). The yield stress was defined as the precompression stress (σ_{pc}) obtained from uniaxial compression test with Casagrand method (1936) (Naderi-Boldaji et al., 2014). Table 1 list the properties used in FEM model.

Furthermore, to simulate the fracture and failure of soil a damage and failure features module available in ABAQUS/Explicit was used. In addition, a subroutine was used to define the failure when reaching the yield stress (σ_{pc} = 0.145 MPa) and to remove elements from the mesh when reaching a given strain (100% in our case) (Bentaher et al., 2013).

2.2. Finite element model

A 3D soil–mouldboard plough interaction model was developed using ABAQUS toolbox (Fig. 1). The model consisted of three

Table 1
Parameters used in the finite element (FEM) model.

Parameters	Value
Density, (g/cm^3)	1.6
Young' modulus, E (MPa)	7.5
Poisson's ratio, υ	0.3
Friction coefficient angle, ξ (°)	44
Stress ratio, K	1
Dilatation angle, ψ (°)	0
Cohesion, C (kPa)	4.082
Soil–metal friction angle, δ (°)	30.25
Precompression stress, σ_{pc} (MPa)	0.145

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