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Research Paper

Coupled Eulerian-Lagrangian finite element method for simulating soil-tool interaction

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Simulation of soil-tool interaction is challenging due to large deformations of soil around the tool, unconstrained deformation of the free soil surface and the dynamic behaviour of soil-tool interaction at the interface. An application of a coupled Eulerian-Lagrangian finite element (CEL-FE) method to the simulation of soil-tool interaction is presented. By combining the merits of both the Lagrangian and the Eulerian formulations, large deformation and unconstrained deformation of soil and the dynamic behaviour of soil-tool interaction are simultaneously simulated. Firstly, interactions between the soil and vertical tines were simulated. The results showed that the predicted soil deformation and draft force were in reasonable agreement with published data from soil bin tests. Then, in order to further validate the feasibility and effectiveness of the CEL-FE method, interactions between the soil and inclined blades at different operating conditions were simulated. Results showed that the numerically simulated and experimentally measured draft forces exhibited similar trends and average values. In addition, the predicted soil deformation was in general agreement with experimental observations. Finally, an example of simulating soil-mouldboard interaction was given and preliminary results indicated that shape complexity of this tool was not a limitation for applying the CEL-FE method. The proposed CEL-FE method provides new possibilities for simulating soil-tool interaction and it is hoped that this method will help to contribute a better understanding of the soil-tool interaction process thereby improving the design of tillage tools.

1. Introduction

Numerical simulation of soil-tool interaction for earthmoving and farming operations is an important engineering task (Shmulevich, 2010) and it is vital to the design and optimise tillage implements (Ucgul, Fielke, & Saunders, 2014a). If the soil cutting process is successfully simulated, expensive and time consuming experimental work for prototype development and verification can be reduced. However, the accurate simulation of soil-tool interaction is a complex process due to

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Nomenclature

ϕ	arbitrary solution variable
$\boldsymbol{v}$	material velocity, m s^{-1}
ρ	density, kg m^{-3}
$\boldsymbol{\sigma}$	Cauchy stress, Pa
$\boldsymbol{b}$	body force, N
E	total energy per unit volume, J
e	internal energy, J
$\mathbf{D}$	velocity strain
$\boldsymbol{\Phi}$	flux function
$\mathbf{S}$	source term
ξ	small penetration, m
f	contact force, N
κ	penalty stiffness, N m^{-1}
F	yield function
p	equivalent pressure stress, Pa
q	von Mises equivalent stress, Pa
φ	internal friction angle, Degree
c	cohesion, kPa
θ	deviatoric polar angle, Degree
r	third invariant of deviatoric stress, Pa

Abbreviations

CEL-FE	coupled Eulerian-Lagrangian finite element
FEM	finite element method
CFD	computational fluid dynamics
DEM	discrete element method
VOF	volume of fluid
EVF	Eulerian volume fraction

large deformations of soil that occur around the tool, unconstrained deformation of the free soil surface and the dynamic soil-tool interaction behaviour at the interface.

Three types of numerical simulation methods, namely the finite element method (FEM), computational fluid dynamics (CFD), and the discrete element method (DEM), have been applied by researchers to simulate soil-tool interaction.

Due to relative ease in formulation and implementation, Lagrangian FEM which is a natural approach for solid-mechanics analysis has been widely used to investigate the soil-tool interaction (Chi & Kushwaha, 1990; Fielke, 1999; Mouazen & Nemenyi, 1999; Naderi-Boldaji et al., 2013). In a Lagrangian FEM nodes are fixed within the material, and elements deform as the material deforms. This method is particularly effective when unconstrained deformation of material is involved, since the mesh boundaries coincide with the material boundaries. However, this also means the Lagrangian method is very sensitive to the quality of mesh. Consequently, large deformations of material often lead to severe mesh distortions which affect the accuracy of the solution and can even lead to the termination of the calculation. The mesh distortion problems can be overcome, to some extent, by element-deletion (Bentaher et al., 2013; Ibrahmi, Bentaher, Hbaieb, Maalej, & Mouazen, 2015; M. Li, Chen, Zhang, & Tong, 2013; Tagar et al., 2015). However, element-deletion affects the accuracy in simulating soil-tool interaction since the elements of contact surface are partially deleted. Recently, Armin, Fotouhi, and Szyszkowski (2014) develops a new finite element procedure for simulation of soil-tool interaction without deleting elements, but the separation surfaces of the soil need to be predefined.

However, CFD has also been used to simulate soil-tool interaction (Bartzanas et al., 2013; Karmakar, Ashrafizadeh, & Kushwaha, 2009; Karmakar & Kushwaha, 2005, 2006; Karmakar, Kushwaha, & Lague, 2007; Zhu et al., 2016, 2017). For this kind of analysis, an Eulerian description is adopted. Mesh distortion is no longer a concern since the computational domain is fixed in space and cutting action is modelled as the flow of the soil around a stationary tool. Thus, large deformations of material can be easily simulated. However, the fact that the mesh is spatially fixed means that it is not suitable for cases where there are deformable material boundaries. Therefore, CFD has difficulty in simulating the unconstrained deformation of free soil surface that occurs during the cutting process.

Unlike continuum numerical methods such as FEM and CFD, DEM is a meshless numerical discontinuum method. It was originally proposed by Cundall (1971) for rock mechanics but has recently been adopted by researchers simulating soil-tool interactions (Barr, Ucgul, Desbiolles, & Fielke, 2018; Coetzee & Els, 2009b; Gürsoy, Chen, & Li, 2017; Hang, Gao, Yuan, Huang, & Zhu, 2017; Hang, Huang, & Zhu, 2017; B. Li, Chen, & Chen, 2016; Mak, Chen, & Sadek, 2012; Milkevych, Munkholm, Chen, & Nyord, 2018; Obermayr, Vrettos, Eberhard, & Däuwel, 2014; Ono, Nakashima, Shimizu, Miyasaka, & Ohdoi, 2013; Shmulevich, Asaf, & Rubinstein, 2007; Ucgul, Fielke, & Saunders, 2014b, 2015; Ucgul, Saunders, & Fielke, 2017a,b; Ucgul, Saunders, Li, & Lee, 2018; Zeng, Chen, & Zhang, 2017). Currently the main difficulty in applying DEM is the calibration of material microparameters that represent the real material properties, i.e. material macroproperties (Coetzee & Els, 2009a; Shmulevich, 2010). These parameters significantly affect the accuracy of the simulation results but their accurate calibration is still a challenge. No standardised calibration methods, or measuring procedures, are available and researchers often apply different approaches to determine the same parameter value (Coetzee, 2017).

In order to break the limitations of the current numerical methods, an arbitrary Lagrangian–Eulerian approach was presented in a previous work for the two-dimensional simulation of soil-tool interactions (Zhang, Cai, & Liu, 2018). The predicted soil deformation and draft force were in good agreement with the published experimental data. In this paper, another advanced approach, a coupled Eulerian-Lagrangian finite element (CEL-FE) method is presented. This method is more convenient for the three-dimensional numerical simulation of soil-tool interaction. Using the CEL-FE method arbitrarily large deformations of soil can be handled without mesh distortion, because the soil material adopts the Eulerian description and the Eulerian mesh is spatially fixed. The unconstrained deformation of the free soil surface can also be captured by employing Eulerian material tracking algorithms. Also, in CEL-FE simulation, material property parameters can be conveniently calibrated since the traditional constitutive laws of soil mechanics can be applied directly. These advantages make the CEL-FE method appear a very promising approach for the simulation of soil-tool interaction.