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A novel approach for simulation of soil-tool interaction based on an arbitrary Lagrangian–Eulerian description

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ABSTRACT

Simulation of soil-tool interaction is a challenging task due to the large deformation of soil around the tool, the unconstrained deformation of the free soil surface and the dynamic soil-tool interaction behavior at the interface. In this paper, a novel approach based on an arbitrary Lagrangian-Eulerian finite element (ALE-FE) formulation is used for simulating the soil-blade interaction. Problems associated with severe mesh distortions in a Lagrangian description and those associated with deformable material boundaries in an Eulerian description can be solved by this formulation. By introducing the Eulerian boundaries, the cutting action is simulated as the flow of soil against a stationary blade. No element deletion is needed in ALE-FE method and thus the complete contact surface of soil is retained. The extended Drucker-Prager constitutive law is used to simulate the mechanical behavior of soil. Results indicate that the ALE-FE approach is a useful tool in investigating soil-tool interaction and it is especially suitable for cases where large plastic deformation of soil occurs. Simulations under different cutting conditions demonstrate the robustness and effectiveness of the proposed ALE-FE method. The influences of cutting angle and depth on cutting are also investigated. The failure angle, soil deformation and draft force predicted by ALE-FE model are in good agreement with the published experimental data.

1. Introduction

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 optimization of tillage implements (Ucgul et al., 2014). However, accurate simulation of soil-tool interaction is a complex process due to the large deformation of soil around the tool, the unconstrained deformation of the free soil surface and the dynamic soil-tool interaction behavior at the interface.

Finite element method is today an exciting approach for understanding soil-tool interaction processes. It can provide information which is difficult or impossible to obtain experimentally (Tagar et al., 2015) and significantly reduce the cost of expensive and time-consuming experimental tests (Ibrahmi et al., 2015).

Due to relative ease in formulation and implementation, the pure Lagrangian finite element method has been used by many researchers to investigate the soil-tool interactions (Chi and Kushwaha, 1990; Fielke, 1999; Mouazen and Nemenyi, 1999; Abo-Elnor et al., 2004; Bentaher et al., 2013; Li et al., 2013; Naderi-Boldaji et al., 2013; Ibrahmi et al., 2015; Tagar et al., 2015). In a pure Lagrangian finite element method, a natural approach for solid-mechanics analysis, 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 are exactly the material boundaries. However, this also means the Lagrangian method is very sensitive to the quality of mesh. Consequently, with the large deformation of the material, the elements are greatly distorted such that the analysis is often terminated. The mesh distortion problems can be overcome to some extent by element deletion (Bentaher et al., 2013; Li et al., 2013; Ibrahmi et al., 2015; Tagar et al., 2015). However, this element-deletion method affects the accuracy in simulating the soil-tool interaction since the elements of contact surface are partially deleted. Recently, Armin et al. (2014) develops a new finite element procedure for soil-tool interaction without deleting any element. The draft forces predicted by this method show a good correlation with the results from analytical method and filtered experimental results (Armin et al., 2017). However, in this finite element procedure the cutting action is simulated by way of separating the nodes in front of the tool along predefined surfaces. Therefore, the continuous process of cutting the soil is modeled ‘discretely’ (Armin et al., 2014).

On the other hand, the pure Eulerian description is more suitable for fluid-flow problems. In a pure Eulerian description nodes are fixed in space, and material flows through elements that do not deform. Computational Fluid Dynamics (CFD) method which typically adopts

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the Eulerian description has also been used to simulate soil-tool interactions (Karmakar and Kushwaha, 2005, 2006; Karmakar et al., 2007; Karmakar et al., 2009; Bartzanas et al., 2013; Zhu et al., 2016; Zhu et al., 2017). The mesh distortion is not a concern any longer in the pure Eulerian description since the mesh is completely fixed in space and the cutting action is modelled as the flow of soil around a stationary tool. However, the fact that the mesh is spatially fixed means that it is not suitable for cases where there are deformable material boundaries. Therefore, it has difficulty in simulating the unconstrained deformation of the free soil surface during the cutting process.

For soil-tool interaction in practical engineering, the large deformation and the unconstrained deformation of soil occur simultaneously. Therefore, both the pure Lagrangian and the pure Eulerian descriptions are inappropriate in simulating some of the characteristics of soil deformation and failure. In this paper, a more general approach, the arbitrary Lagrangian-Eulerian finite element (ALE-FE) method is adopted to simulate the soil-tool interaction. By introducing the Eulerian boundaries, the cutting action is simulated as the continuous flow of soil against a stationary tool and thus the continuous process of cutting the soil is modeled continuously. The free deformation of the soil is simulated by using the merits of the Lagrangian description and the large deformation of soil is simulated by flow of material using Eulerian description. Moreover, no element deletion is needed in the ALE-FE formulation and thus the complete contact surface of soil is retained.

The main objective of this study is to provide a novel method for the simulation of soil-tool interaction and thereby contribute to a better understanding of soil deformation and failure. To further demonstrate the robustness and effectiveness of the proposed ALE-FE method, the cutting processes under different cutting conditions are simulated. The influences of cutting angle and depth on cutting are also investigated.

2. Material and methods

2.1. ALE formulation

The ALE description combines the advantages of both the pure Lagrangian description and the pure Eulerian description. In the ALE description, the grid points are neither constrained to remain fixed in space nor to move with material. In fact, the grid points can be moved arbitrarily independent of the underlying material and have their own motion governing equations. Detailed formulation of the ALE-FE method can be found in many books and papers, see for instance (Belytschko et al., 2013). A brief summary of ALE formulation is presented below.

In the ALE method, material points are represented by a set of Lagrangian coordinates $\boldsymbol{X}$, spatial points with a set of Eulerian coordinates $\boldsymbol{x}$, and grid points with a set of arbitrary coordinates $\boldsymbol{\chi}$. At time t, a spatial point $\boldsymbol{x}$ is simultaneously the image of a material point $\boldsymbol{X}$ by mapping with material motion $\boldsymbol{x} = \boldsymbol{x}(\boldsymbol{X}, t)$, and the image of a grid point $\boldsymbol{\chi}$ by mapping with mesh motion $\boldsymbol{x} = \boldsymbol{x}(\chi, t)$. The material velocity $\boldsymbol{v}$ is obtained using the classical material derivative.

$$\boldsymbol{v} = \dot{\boldsymbol{x}} = \left.\frac{\partial \boldsymbol{x}}{\partial t}\right|_X \tag{1}$$

The mesh velocity $\hat{\boldsymbol{v}}$ is obtained after the introduction of a mixed derivative, which represents the time variation of a physical quantity for a given node.

$$\hat{\boldsymbol{v}} = \dot{\boldsymbol{x}} = \left.\frac{\partial \boldsymbol{x}}{\partial t}\right|_\chi \tag{2}$$

Thus, the ALE method consists of two fundamental tasks: creating a new mesh, and remapping solution variables from the old mesh to the new mesh. The volume smoothing algorithm (Simulia, 2013) is chosen to generate a new mesh because it is very robust and can effectively smooth the mesh. The basic idea of the volume smoothing method is to relocate each node by computing a volume weighted average of the element centers in the elements surrounding the considered node. Node n is relocated by the following equation.

$$x_n^{i+1} = \frac{\sum_{k=1}^{ksur} V_k^i x_k^i}{\sum_{k=1}^{ksur} V_k^i} \tag{3}$$

where x_n^{i+1} is the new position of the node n at the $(i+1)$th iteration, V_k^i is the volume of the surrounding kth element, x_k^i is the position of the center of the kth element and $ksur$ is the number of surrounding elements of node n.

Once the new mesh is created, the solution variables are remapped by performing an advection sweep. The method used in this study for advecting solution variables is the so called second-order method based on the work of Van Leer (1977). It is consistent, monotonic, and conserves mass, momentum, and energy. The mass, momentum and energy conservation laws used in the ALE method are similar with those in the pure Eulerian description. Taking into account the definition of the convective velocity $\boldsymbol{w} = \boldsymbol{v} - \hat{\boldsymbol{v}}$, conservation laws for ALE approach are written as follows.

$$\dot{\rho} + \boldsymbol{w}\nabla\rho + \rho\,\mathrm{div}\boldsymbol{v} = 0 \tag{4}$$

$$\rho\dot{\boldsymbol{v}} + \rho\boldsymbol{w}\nabla\boldsymbol{v} = \boldsymbol{f} + \mathrm{div}\boldsymbol{\sigma} \tag{5}$$

$$\rho\dot{e} + \rho\boldsymbol{w}\nabla e = \boldsymbol{\sigma}:\boldsymbol{D} \tag{6}$$

where ∇ is the gradient operator, ρ is the mass density, $\boldsymbol{f}$ are the body forces, $\boldsymbol{\sigma}$ is the Cauchy stress tensor, e is the specific internal energy, $\boldsymbol{D}$ is the strain rate tensor.

2.2. Model description

A series of 2D soil cutting models based on ALE-FE formulation were established. The solution was achieved using a commercial software Abaqus 6.13 and the explicit direct integration algorithm was adopted (Simulia, 2013). In order to compare with the experimental data, only flat blades were considered for the present study. Combining the merits of both the Lagrangian and the Eulerian formulations, different types of boundary conditions can be flexibly defined in a single ALE-FE analysis.

Using ALE-FE formulation, a boundary type can be either Lagrangian, sliding, or Eulerian. A Lagrangian boundary has the most constraints of all the boundary types. The nodes on a Lagrangian boundary are constrained to move with the material in both the normal and the tangential directions. Besides, no material can flow across a Lagrangian boundary. A sliding boundary is the same as a Lagrangian boundary except that the nodes on it are only constrained to move with the material in the normal direction, and they are completely unconstrained in the tangential directions. An Eulerian boundary allows material flow across it, i.e. flow into or out of the computational domain, and this characteristic distinguishes Eulerian boundary from Lagrangian or sliding boundary.

As shown in Fig. 1, the blade was assumed as a rigid body with a reference point which enabled the calculation of the reaction force acting on the blade. All boundaries of the blade were Lagrangian and the blade was fully fixed during the analysis. The cutting velocity was applied to the soil. At the defined Eulerian boundaries, soil entered the soil domain on the left boundary and exited the soil domain at both the right boundary and the top boundary of the soil chip. In order to retain the Eulerian boundaries, spatial mesh constraints were applied to the left and right sides of the soil in the X direction and to the top area of the soil chip in the direction normal to the top surface. Note that the mesh here is independent of the material, thus the spatial mesh constraints applied to the nodes will not actually affect the material flow or deformation. The bottom of the soil was constrained on material in the Y direction. The other soil surfaces that had no constraints were set to be sliding boundaries. Gravity load was applied to the whole ALE-FE