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State of the art modeling of soil–tillage interaction using discrete element method

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ABSTRACT

Soil–tillage interaction presents a continuous challenge for researchers, developers and manufacturers. However, modeling soil–tillage interaction is a complex process due to the following: the spatial variability of the soil media; the nonlinearity of soil material; and the contact phenomenon and flow that occur at the interface zone between the soil and the tillage tool.

The need for a sound modeling technique for soil–tillage interaction is the motivation for the present work. The discrete element method (DEM) seems to be a promising approach for constructing a high-fidelity model to describe the soil–tillage interaction and may serve as a predictive simulation tool in the process of designing the tillage shape. The paper will explain, in general, the method and provide comprehensive state of the art studies of soil–tillage interaction based on 2D and 3D DEM simulations. The limitations and advantages of the method are demonstrated. The potential of the DEM to serve as an engineering tool for an optimization of soil–tillage interaction is presented by several case studies. Finally, future considerations and recommendations of improving the use of the DEM techniques are presented.

1. Introduction

Soil tillage interactions present a continuous challenge for researchers, developers and manufacturers. Modeling field machines for earthmoving and farming operations is an important engineering task. However, modeling soil tillage interactions is a complex process due to the spatial variability of soil properties, the nonlinear and dynamic behavior of soil, and the interaction between particles contact phenomenon such as, slippage, particles re-arrangement due to stress and flow that occur at the interface zone between the soil and the tillage tool. The paper presents a novel approach – the discrete element method (DEM) – to model soil–tillage interactions.

According to Gill and Vanden Berg (1968) generally, no effort is made to describe the reaction of the soil due to tillage operation. Consequently, design today merely accepts what occurs; it does not control what occurs. Thus, even though the need for design is great, design in the true sense of the word is not accomplished and probably will not be accomplished until quantitative information is available such as stress distribution on the tillage tool and local changes in soil properties such: soil porosity. According to the Gill and Vanden Berg (1968) soil manipulation and the performance of a specific tillage tool could not be predicted accurately, this statement is still true today.

Analytical models based on Terzaghi's (1943) passive soil pressure theory have been used to investigate soil–tillage interaction with some success. A preliminary assumption of the soil failure pattern (Hettaratchi et al., 1966; McKyes and Ali, 1977; Perumpral et al., 1983) is required for an analytical model of soil–tillage interactions. These models are limited because of their assumptions as engineering tools for the design and optimization of soil–tillage interaction processes that include tools of more complex shapes.

Based on Terzaghi's theory, Karafiath and Nowatzki (1978) presented a finite difference approach to model soil–implement interaction without a need to assume the shape of failure planes. However, a priori assumption on the soil–implement interface was needed.

Modeling soil–implement interactions using the finite element analysis produces some advantages over the modeling methods described above. In this case, any implement geometry and the nonlinear behavior of the soil–tillage tool interaction can be modeled if a proper constitutive law is chosen (Kushwaha and Zhang, 1998). Upadhyaya et al. (2002) presented an extensive review of the utilization of finite element models for soil–implement interactions, and concluded that the finite element model is suitable mostly for continuum analysis. However, soil deformation, especially in the tillage process, involves the separation and mixing of soil layers, the formation of cracks, and the flow of soil particles, which cannot be modeled appropriately by the finite element method (Plouffe et al., 1999).

The discrete element method (DEM), as it is called by engineers, or granular dynamics (GD), as it is called by physicists, is a particle

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based simulation (PBS) technique or, according to Cundall (1988), a general particle flow model that simulates the mechanical behavior of a system comprised of a collection of arbitrarily-shaped particles and their interaction with rigid or flexible bodies.

The DEM is particularly suitable for modeling granular materials and for studying the relationship between 'micro' and 'macro' behavior. The DEM allows contacts between elements to be created or broken and can therefore be used to gain insight into the processes of nucleation and the growth of a crack. Over the past 30 years, numerous researchers have reported good performance of the DEM to simulate micro-mechanics of the dynamic behavior of particles that constitutes the material in a wide variety of engineering and scientific disciplines. The advantage of the DEM to simulate various soil formation behaviors under dynamic load is clear. Therefore, using the DEM technique, one can analyze the mechanical micro and macro-properties of soil. The capability of focusing on the microstructure level enriches the understanding of soil–tool interaction process and enables the improvement of agricultural machinery design.

In spite of the frequent use of the method in grain processing and handling, and simulation of soil–implement/structure interaction in tillage tools, the method has not been widely used yet in engineering practice because of several limitations. Although there are many researchers that report good, qualitative agreement between DEM simulations and experimental work, the method is still in its infancy, primarily because of the lack of a robust method to determine values of the micromechanical model parameters that represent the mechanical properties of soil. Moreover, the micro-DEM properties, which connect the particles, do not necessarily follow the macro-physical definitions of the entire material. It is important to determine the interpretation of the DEM parameters in terms of fundamental physical properties.

Another major limitation of the DEM is the modeling of the real particle size and shape which may affect soil model parameters. Due to computational limitations, it is necessary to use much larger particles than in reality, especially when dealing with soil. In fact, in almost all soil models reported in the literature, authors have used large particles. Therefore, it may be necessary to calibrate the soil parameters to make them compatible with this difference in particle size and shape.

Numerical schemes may frequently reduce the computational complexity and considerations of symmetry or meaningful assumptions may reduce the problem being investigated from 3D to 2D. This reduction, which is very common in a continuum mechanics approach, may not be straightforward in the DEM.

The objectives of the current paper are to present the general concepts of the DEM technique for investigating dynamic soil–tillage interaction problems, its advantages when compared to other techniques by demonstrating several case studies in 2D and 3D.

2. Discrete element modeling

2.1. General concept

A key aspect of the DEM is the formation of the contact rules among particles. According to these rules, the equations of motion of the particles are developed by considering the body forces and external forces that act on the system. The behavior of the system is determined by the solution of these equations of motion. There are two distinct approaches based on the interaction between particles. These two approaches are:

- Describing the particles as "hard". In this case the collision between two particles is momentary; there is no overlapping between the particles at the time of the collision, and the particle trajectory after the collision is determined by its trajectory before the collision and the rules that govern contact process-friction, elasticity, plasticity, and coefficient of restitution, etc. (Moreau, 1994; Walton, 1987; Laniar and Jean, 2000).
- Describing the particles as "soft". It is assumed that the collision is a continuing process, which takes place along several time steps, and the forces created in the collision are caused by the extent of penetration or the deformation of the particles (soft-contact). The rules in this case determine the connection between the deformation in the particle and the created forces (Cundall and Strack, 1979; Walton, 1987; Duran, 1999).

Modeling by "hard" collision is used mainly for describing inter-molecular phenomena (Cundall and Hart, 1992; Cundall and Strack, 1979; Walton, 1987). To describe the behavior of granular material such as soil, the accepted model is the "soft" collision (Anandarajah, 1994; Cundall and Hart, 1992; Taylor and Preece, 1992).

Most of the DEM formulations follow the Cundall and Strack (1979) approach. This model is based on the following assumptions.

1. The particles are treated as rigid bodies.
2. The contacts occur over a vanishingly small area (i.e., at a point).
3. Behavior at the contacts is through a soft-contact or "soft" particles approach wherein the rigid particles are allowed to overlap one another.
4. The magnitude of the overlap is related to the contact force via the force displacement law and all overlaps are small in relation to particle sizes.
5. Bonds can exist at contact points between particles.
6. For simplicity of calculation all particles are assumed to be spherical; however, the clump and cluster logic supports the creation of super-particles of arbitrary shape. Each clump consists of a set of overlapping particles that act as a rigid body with a deformable boundary.
7. The velocity and acceleration are assumed to be constant during each time step.
8. During a single time step, disturbance cannot be propagating from any particle farther away than the immediate neighbors.

According to Newton's approach, the motion of a single rigid particle is determined by the resultant force and moment vectors acting upon it and can be described in terms of the translational motion of a point, which is the center of the mass of the particle and rotational motion of the particle about that point according to Newton's and Euler's approaches.

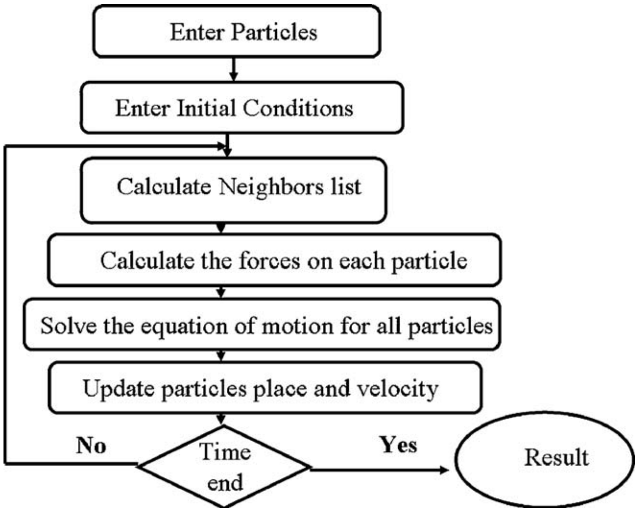

Fig. 1. Flow-chart of the simulation process.