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Discrete element simulation of the interaction between a granular material and a three-dimensional cutting blade

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ABSTRACT

The Discrete Element Method (DEM) is emerging as a powerful predictive tool for numerical simulation of large-scale industrial processes involving discrete and discontinuous media [1]. One such application involves soil-tillage interaction which is complex due to cohesive non-homogeneous materials, high strain rate plastic deformation, convoluted flow paths resulting in potential mixing, friability, aggregation, frictional interfaces and failure at the tip of the cutting tool. Over 40 years ago Gill and Vandenberg stated that the specific performance of a ground-engaging implement could not be predicted [2]. This statement is still true today if one is aiming to predict the evolution of damage that occurs to the soil structure. However, there is a demanding need to address this problem since tillage practices account for about half of the energy used in crop production alone [3]. The problem is even more acute if soil tillage interaction is considered from a mining perspective where billions of tonnes of over-burden and minerals are moved annually. These complexities present a significant challenge to researchers, developers, manufacturers and end-users of equipment who need to improve industrial processes. Possible modelling strategies involve analytical models [4], experimental methods [5], finite element continuum models [6] and discrete particle methods [7]. Analytical models such as the fundamental equation of earth mechanics provide a plane strain plastic equilibrium solution of a failed region of soil. The models are based on critical state mechanics and are useful for simple geometric configurations and small strain. Full-scale experimental methods can be used to study the forces acting on tools. However, it is difficult to extract the cause-effect relationships and the experiments are prohibitively expensive for alternate geometric configurations. Small-scale laboratory experiments are more cost effective but it is difficult and sometimes impossible to scale variables to industry scale due to body force effects [8]. Finite element continuum models (predominately critical state) suffer from mesh adaptation problems, and have difficulty in prediction of changes in soil structure configuration in the tilth zone [3]. Coping with evolution of damage at the tool interface is also complex. This leaves DEM as a possible technique to gain insight in this area through micro and macro modelling. DEM is a numerical technique that treats granular material as an assemblage of 2-D or 3D particles (rigid or deformable) with an appropriate rheological prescription for inter-particle and particle-to-wall contact

behaviour. The method was originally used to analyze the stability of fractured rock slopes before being extended to model soil materials. Modelling involves simulation of the trajectories, spin, and orientation of every particle, and the interaction of particles with their neighbours and environment. All researchers recognize the immense computations required with industrial problems, and excluding problems involving continuum to discrete fracture, most utilize rigid particles with an elastic (not necessarily linear) contact layer.

In this paper DEM is used to study the interaction of a three-dimensional dozer blade with coal. The coal is modeled as an ensemble of rigid spherical particles, normally distributed between an upper and lower bound on diameter. Blade geometry is industry scale and modeled as a rigid tool with a frictional interface. A major challenge with DEM is determination of inter-particle properties and prescription of particle shape. In this research, inter-particle properties (normal and tangential stiffness, damping and friction) are derived from a plane strain DEM model of a simplified geometry validated against the fundamental equation of earth mechanics. Particle shape is spherical (computationally efficient) but particle spin is inhibited for a statistical proportion of all particles. This represents an approximation to macro-roughness. Predictions are presented for traction force as a function of coal moisture, blade speed and blade friction. For the first time a numerical measure of blade capacity is presented. Particular emphasis is placed on graphical post processing to aid with discovery of dominant mechanisms.

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