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Finite element simulation of soil failure patterns under soil bin and field testing conditions

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ABSTRACT

Finite element modeling (FEM) of soil physical behavior can provide information which is difficult or impossible to obtain experimentally. This method has been applied by many researchers to study soil compaction, acting forces on tools, stress distribution in soils and soil failure patterns. The great majority of studies that have investigated soil failure patterns have been limited to in-laboratory soil bins, with few tests being done under field conditions. However, it is difficult to simulate actual soil conditions in a soil bin. This study used FEM for the simulation of the soil failure patterns as linked to consistency limits and sticky point of soil, comparing the simulation results with soil failure patterns observed in the soil bin and in the field. Results showed that FEM is a useful tool to simulate soil failure patterns; however, simulation models correlated better with soil bin than with field test results. The results also showed the presence of a direct relationship between soil failure patterns and the consistency limits of the soil, both in the soil bin and in the field. However, soil bin results were not satisfactorily verified in the field, in particular as the failure patterns were also found to be affected by the roots of the stubbles in the field. It is concluded that FEM can provide accurate simulation of soil failure patterns under soil bin test conditions, but that soil bin results did not satisfactorily represent results from the field.

1. Introduction

Numerical methods are helpful in understanding and describing soil cutting processes and soil–tool interactions. Karmakar and Kushwaha (2006) identified three numerical methods to model the soil cutting process, namely the finite element method (FEM), the discrete element method (DEM) and computational fluid dynamics (CFD). The discrete element method (DEM) is based on a promising approach for constructing a high-fidelity model to describe the soil-tillage tool interaction (Shmulevich, 2010). However, the determination of model parameters to control the soil void ratio and the shape of particles, as well as the modeling of breakage and the formation of aggregates of varying sizes and shapes, remain significant challenges and limit the application of DEM for practical engineering problems (Abo Al-Kheer et al., 2011b). Computational fluid dynamics (CFD) can be used to model soil–tool interactions (Karmakar and Kushwaha, 2006). Soil dynamic behavior using the CFD simulation will help in tool design and its optimization with different shapes in order to reduce tool draft and energy demand over a wide speed range, and help model different types of soils based on their visco-plastic parameters. However, further research is needed before CFD can be used to model soil–tool interactions with confidence (Coetzee and Els, 2009). On the other hand, the finite element method (FEM) has been used by many researchers in order to design tillage tools and to investigate the interaction between soil and tillage implements. FEM can be used to study soil compaction, acting forces on tools, stress distribution in soil and soil failure patterns (Raper and Erbach, 1990; Aluko and Chandler, 2004; Shahab Davoudi et al., 2008); however the continuity assumption in FEM does not allow crack propagation in soil (Jafari et al., 2006). Coleman and Perumpral (1974) pointed out that in soil mechanics research, the FEM method is capable of providing information which is difficult or impossible to obtain experimentally. Later, Yong and Hanna (1977) modeled soil cutting by simple plane (two-dimensional) blades, and Liu Yan and HouZhi-Min (1985) and Chi and Kushwaha (1987, 1989) applied FEM to the study of three-dimensional soil cutting with narrow blades. FEM is also appropriate for the analysis of soil cutting problems where shear failure with significant plastic deformation occurs (Aluko, 2008).

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The performance of agricultural implements and the resulting soil tilth depend largely on the mechanical behavior of soils (Rajaram and Erbach, 1998). Soil failure patterns are one of the most important indices to assess the mechanical behavior of soils under varied soil and tool conditions. Indeed, Abo Al-Kheer et al., (2011a) concluded that the variation in soil failure patterns can be attributed to the wide variations in mechanical behavior of the soil. Previous studies of soil cutting have identified six types of soil failure patterns, namely collapse, brittle, chip-forming, bending, flow and flow with considerable bending in different soil types (Elijah and Weber, 1971; Rajaram and Gee-Clough, 1988; Rajaram and Erbach, 1996; Tagar et al., 2014). Collapse failure, which occurs in dry soils, involves the collapse of soil structure when a mass of a soil in front of the tool is crushed (Rajaram, 1990) and is similar to the shear plane-type failure as described by Elijah and Weber (1971). Brittle failure occurs in moist soils due to the propagation of tensile cracks (Chandler, 1984; Hatibu, 1987). Chip-forming failure, or plastic type failure, occurs in wet unsaturated soil conditions when the soil is removed in the form of chips similar to the chips formed in metal cutting (Rajaram and Erbach, 1996; Rajaram and Gee-Clough, 1988). Flow failure occurs in wet saturated soil conditions due to the mere physical displacement of the soil (Rajaram and Erbach, 1996), and bending failure is similar to flow failure but also shows some strain in the vertical direction (Elijah and Weber, 1971). Flow with considerable bending failure occurs at the sticky point of soil and is similar to flow failure but with considerable bending and no strains of elements (Tagar et al., 2014).

Rajaram and Erbach (1996, 1998) concluded that, to better understand tillage, research should be directed towards explaining various soil failure patterns and the resulting physical property changes. Indeed, Mamman and Oni (2005) carried out a study to investigate the effect of draught on the performance of model chisel furrowers. They concluded that there were no optimum values of tool speed or tillage depth for which the draught of the model tools were at a minimum. Therefore they suggested that the choice of model tool should depend on soil failure pattern at shallow depths, as well as on the size and quality of furrows created at deeper depths. Numerous studies have been conducted on soil failure patterns (e.g., Elijah and Weber, 1971; Stafford 1979a; Rajaram and Gee-Clough, 1988; Wang and Gee-Clough, 1993; Rajaram and Erbach, 1997, 1998, 1999; Aluko and Seig, 2000; Makanga et al., 2010); however, despite this large number of studies, a thorough understanding of soil failure patterns has not yet been achieved.

Of the large number of studies having investigated soil failure patterns, the vast majority have been limited to in-laboratory soil bins, with only a few tests being done under field conditions (e.g., Elijah and Weber, 1971; Hemmat et al., 2012). The justifications for soil bin studies include: better control of soil physical parameters (Stafford, 1979b) and the setting of operation variables (Wegscheid and Myers, 1967), as well as the possibility of replicating tests over short periods, independent of weather (Barnes and Bockhop, 1960). However, it is difficult to simulate actual soil conditions in a soil bin. This is consistent with Dexter and Bird (2001), who concluded that the properties of disturbed (remolded) soil are not appropriate for the prediction of the behavior of undisturbed soil in the field. Therefore, the verification of soil bin and laboratory experiments under realistic field conditions is always necessary (McKyes and Desir, 1984). This is consistent with Liu et al. (2007), who compared soil bin and field experimental soils. Overall, while soil bin study results may be extrapolated to the field scale, a great deal of caution must be taken, given the far greater soil heterogeneity at the field scale.

Although the importance of a better understanding of the true failure patterns of soils has been emphasized by a number of authors (e.g., Rajaram and Erbach, 1997, 1998; Mamman and Oni, 2005), the technical methods available to quantify soil failure patterns are limited. For instance, Jayasuriya and Salokhe (2001) concluded that the numerical value of the moisture content does not show any direct relationship with changes in soil failure patterns in different soils. Soil consistency limits could therefore be hypothesized to show a much clearer relationship with soil failure patterns than the simple numerical value of the moisture content, though this has not been previously studied in great detail. Although the study by Stafford (1979a) did indeed report the plastic and liquid limits of the experimental soils, the experimental soil moisture levels employed for testing unfortunately did not correspond to any of these limits.

Thus, the authors of this paper carried out a previous study to investigate soil failure patterns and draft as influenced by the consistency limits of the soil, and the results confirmed that there does exist a direct relationship between these variables (see Tagar et al., 2014). However, it is most important to verify the results in realistic field conditions. To date, most studies have focused on the simulation of soil stresses, soil forces, soil deformation, and soil

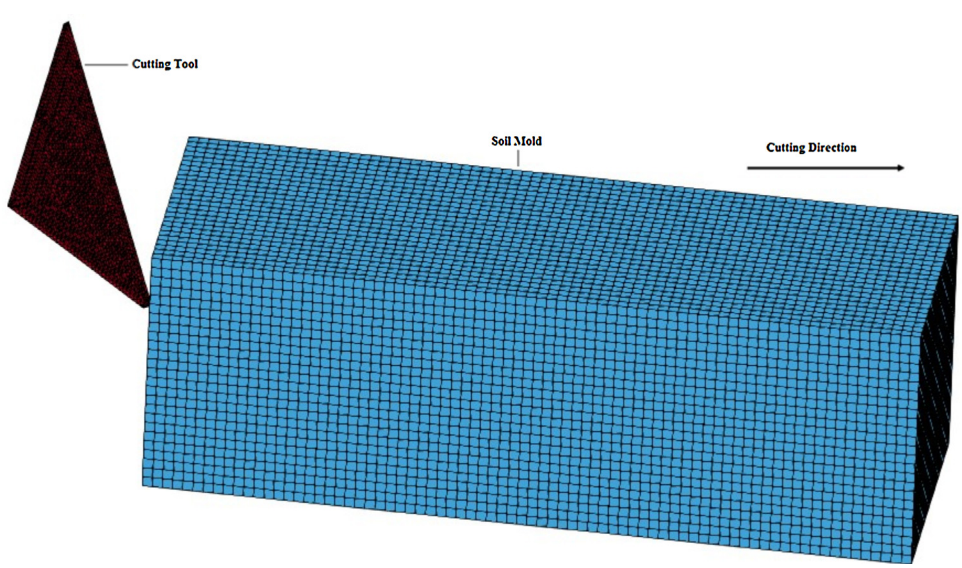

Fig. 1. Finite element meshing of soil and cutting tools before tool operation.