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Modelling approach for soil displacement in tillage using discrete element method

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ABSTRACT

The majority of studies dedicated to the dynamic behaviour of agricultural soils are basically focused on prediction of physical conditions within the soil-tool interface whereas the dynamic soil response, such as soil displacement, has not attracted sufficient attention. Considering its importance for engineering applications, the objective of the presented study was to develop a modelling approach to study the soil displacement due to soil interaction with operating tool during sweep cultivation. The developed approach employs the similarity criteria to account for the effect of scaling-up soil particle sizes on model quality and combines (i) an empirical study of soil displacement during a sweep operation and (ii) related numerical simulations using a discrete element model. Soil displacement for three different soil types in soil bins was measured using a tracer methodology. The discrete element model was formulated for cohesive soils with parallel bond contacts between aggregates. The model allows simulation of mechanical tests (used for calibration purposes) and simulation of soil interaction with operating tool during sweep cultivation. This work shows that due to the necessary change in particle sizes of model soil, the conditions of physical equivalence between the model and natural soil can be difficult to satisfy. Such condition can cause significant dissimilarity between measured and simulated soil displacement. However, this can be overcome if the model scaling does not exceed a certain limit which is determined by soil structure and the potential contact density on a tool's contact surface during the soil-tool interaction. By using these findings, our simulations demonstrate that prediction of soil displacement is possible within the suggested approach with sufficient accuracy.

1. Introduction

Predictions of the dynamic behaviour of granular media, such as agricultural soils, have been of particular interest to engineers and researchers since the late 1970 s (Godwin and Spoor, 1977; McKyes and Ali, 1977). There is a strong demand for accurate predictions of soil-tool interface conditions (stress loads, draught forces etc.) during an agricultural operation. The state of such conditions is crucial for optimization of operation management and tool design.

Accurate predictions of soil movement as a response to the impact of a particular tool would be a major step forward in agricultural machinery design. This would strongly improve the ability to evaluate the performance of a tool as affected by its geometry which has to be optimized not only for soil-tool interaction forces but also for required soil displacement.

The majority of the existing empirical and numerical studies have focussed on prediction of physical conditions within the soil-tool interface (in particular, draught and vertical forces, energy consumption etc.) (Abo-Elnor et al., 2004; Chen et al., 2013; Godwin and O'Dogherty, 2007; Godwin and Spoor, 1977; Obermayr et al., 2011, 2014; Tamas et al., 2013; Ucgul et al., 2014, 2015). In addition, soil stress-strain state during tillage operation were studied (Horn and Rostek, 2000; Pytka, 2001; Pytka and Konstankiewicz, 2002; Pytka et al., 2003; Wiermann et al., 1999) where the authors were mainly focused on dynamic compaction processes. However, the larger scale spatial soil displacement due to strains induced by operating tools has not attracted much attention despite its importance. In (Rahman et al., 2005) the authors implemented a tracer-based method to study soil translocation during an injection tool operation and reported mainly empirical results on tool-induced soil movement. Discrete element modelling of soil—sweep interaction has been previously published e.g. (Chen et al., 2013; Tamas et al., 2013). However, those authors

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simulated soil disturbance during the tool operation only, and the reported simulations focussed mainly on predicting interaction forces at the soil-tool interface.

Several modelling approaches have been used extensively to study soil-tool interactions. Analytical methods based on the passive soil failure theory are commonly used for predictions of soil disturbance and soil cutting forces (Godwin and O'Dogherty, 2007; Godwin and Spoor, 1977; Hettiaratchi et al., 1966; McKyes and Ali, 1977). Although these models have proven to be simple to use and fairly accurate in predicting soil cutting forces, their application is limited to simple blades and assumed soil failure patterns. Neither are they always suitable for tool rake angles less than 20°. In (Godwin and O'Dogherty, 2007) the analytical theory has been extended to more complex tools like the disc and mouldboard plough, but the assumption of soil failure pattern and the range of rake angles remain limitations. In addition, the common limitation of the analytical approach is that it cannot consider soil behaviour at a particle-scale.

Another modelling approach, the finite element method (FEM), has been broadly used to study soil-tool interactions (Abo-Elnor et al., 2004; Fielke, 1999; Plouffe et al., 1999). Compared with the analytical methods, FEM has the advantage of being able to model complicated tool shapes without the abovementioned limitations for analytical models. However, the FEM approach considers soil as a continuous medium, whereas it is in fact a discontinuous medium, especially the topsoil. Such discontinuity involves large soil fractures and displacements. Due to such nonconformity between FEM assumptions and real soil properties, this method is not suitable for the cases where accurate prediction of soil deformation is important; moreover, in some cases, numerical convergence problems can occur (Abo-Elnor et al., 2004).

To model and adequately simulate discontinuous granular materials such as soil, the discrete element method (DEM) introduced in (Cundall and Strack, 1979) is one of the most advanced and proper numerical methods. In the DEM, soil is treated as an assembly of individual particles and each particle interacts with its neighbouring particles under external forces, such as the tillage action. As a result, forces arise at the contact between particles and cause stress and strain distribution in the soil body. The magnitude of the stress is determined by the particle stiffness and the overlap between particles in contact. The motion of particles obeys the principles of classical mechanics.

A number of studies have been conducted so far in the field of soil-tool interaction simulations using DEM: on general earth moving machines (Franco et al., 2007; Momozu et al., 2003; Shmulevich et al., 2007) and agricultural machines (Asaf et al., 2007; Ucgul et al., 2017). The general concept of the DEM and the numerical modelling of the soil-tool interaction have been discussed in (Shmulevich, 2010). In (Asaf et al., 2007) DEM has been used to model the dynamic interaction in the soil tillage process with focus on calibrations of model parameters. In that 2D study, soil particles were modelled by clumps of two discs and the soil was cohesionless. Calibrations were based on in-situ field sinkage tests using different penetration tools. The calibrated model parameters and similar particle shapes were used by (Shmulevich et al., 2007) to simulate the interaction between soil and a wide cutting blade using the DEM.

The abovementioned studies demonstrate that DEM is a well-tested numerical approach allowing satisfactory simulation of the behaviour of granular materials in general and prediction of soil-tool interaction. However, one of the major challenges in its application in the study of soil behaviour is correct model calibration because of the vast number of parameters, some of which cannot be calibrated and have to be determined using knowledge, experience, and logic (Potyondy and Cundall, 2004).

Model calibration is not the only challenge limiting the application of DEM in soil modelling. The high computational demand of DEM is also a limit that invokes the necessity to reduce the number of contacting particles by the scaling-up of soil particle sizes. This means that, it is not possible to exactly represent a soil structure within a DEM model. As a result, the similarity criteria (Feng et al., 2009), especially the geometrical similarity, can be difficult to satisfy. All this imposes an additional simulation error which has to be handled and considered in advance if accurate DEM predictions are to be achieved.

The similarity principles (Landau and Lifshitz, 1982; Sedov, 1993) in relation to the DEM approach have been theoretically discussed and addressed in several studies (da Cruz et al., 2005; Feng et al., 2009; Leuenberger, 2001; Obermayr et al., 2011, 2014). Unfortunately, these studies do not consider the problem of DEM model applicability when some of the geometrical similarity criteria cannot be satisfied, either in general form or in relation to a particular application. With regard to the current work, it is essential to understand how the initial errors, due to partial geometrical non-equivalence of modelled soil to real physical soil object, effect the soil displacement during its interaction with an operating sweep tool.

Therefore, the objective of this work was to develop a modelling approach, which takes the similarity criteria into account, to study the soil displacement due to soil interaction with operating tool during sweep cultivation.

2. Methods

2.1. *Field experiment*

The empirical part of the study took place in the large-scale, semi-field experimental facility located at Research Centre Foulum, Denmark (56°30′ N, 9°35′ E). The facility (Fig. 1a) consisted of four outdoor soil bins (Fig. 1b) containing three typical Danish soil types (Table 1): a coarse sand from Jyndevad, a loamy sand (two bins) from Foulum, where only one of the two bins was used in this study, and a sandy loam from Rønhave. All three bins had barley stubble (height 60–70 mm) harvested a month before the experiment. The soil bins measured 40 *x* 2.7 *x* 1.5 m (length, width, depth). For the past 13 years, the soil has been conventionally tilled and cropped with mainly cereals. The automatic open-close roof (Fig. 1a) allows irrigation to be controlled.

Each soil bin was divided into three plots (in order to avoid interactions between consecutive experimental runs) (Fig. 1b). The plot width was 0.7 m. The same sweep was operated at a 100 mm working depth and a constant tractor travel velocity of 3.2 km/h (which is typical Danish sweep tillage speed), the same for all plots and bins.

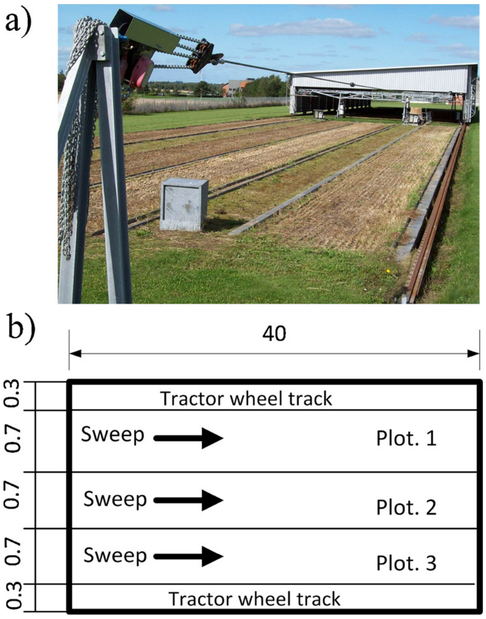

Fig. 1. Semi-field research facility. (**a**) Soil bins and roofing system. (**b**) The scheme of three plots in one soil bin. All dimensions are in meters.