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Review Article

Soil - Tillage Tool Interaction Using Numerical Methods - A Review

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Abstract

The mechanical soil tillage operations are performed using force, commonly by using a tractor drawn tool to achieve cutting, inversion, pulverization and movement of the soil. The energy required for tillage is a significant percentage of the total energy used in agricultural production from land preparation to harvest of crop. With high oil prices and increasing pressure on greenhouse gasses (GHG) emissions, it is important to minimize the energy used in agricultural production. Soil tillage is an energy-intensive operation and design improvements have been sought to reduce forces for many different tools. Due to the high cost of prototyping and testing, computer modeling was used to design soil processing equipment. To model soil tool interaction two methods namely; finite element method (FEM) and discrete element method (DEM) have been used. This paper investigates the ability to apply these modeling techniques to study the soil tillage process. A short comparison of the results calculated using both methods is also presented. A review of several previous studies shows that both hypotheses are adaptable to simulate the behavior of soil materials. However, the discrete element method provides a more accurate estimate of draught and uplift forces.

Keywords: Modelling; Tillage; FEM; DEM

Introduction

Agriculture is the oldest and most important economic activity of humanity, because it provides the food, fiber and the fuel necessary for our survival. With the world population expected to reach 9 billion by 2050, agricultural production must double to meet the growing demand for food and bioenergy. This has also been highlighted in the United Nations Sustainable Development Goals (SDGs). Targets 2.3 and 2.4 of the SDG 2 (end hunger, achieve food security and improved nutrition and promote sustainable agriculture), commits by 2030 double the agricultural productivity ensuring sustainable food production systems respectively.

Taking into account the limited resources of arable land, water scarcity and climate change impact, it is estimated that the efficiency of agricultural productivity should increase by 25% to achieve this goal by limiting the growing pressure exerted by agriculture on the environment [1,2].

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Plowing, defined as the physical handling of farmland to improve soil tilth, is an extremely vital part of agricultural production for weed control and seed bed creation. Cultivation of agricultural land is usually accomplished by cutting, mixing and/or inverting the land using towed tools. Manual soil tillage by using manpower and animal driven plough is now seen an obsolete practice when larger farms are to be cultivated. However, in many developing countries like India, Pakistan, Africa the subsistence small farmers still use this practice. In larger farms soil tillage is one of the major energy consumers in agricultural production. Energy (especially fossil fuels) currently plays a key role in the tillage process. Due to the rapid increase in fuel costs, the power optimization of tillage is a necessity. Some researchers have worked on reduced tillage practices [3,4]. These techniques are limited to areas of high rainfall where water is not a limiting factor for crop growth. However, in arid and semi-arid regions, a significant decrease in land productivity is to be expected [5].

Tillage practices represent around half of the energy used in agricultural production [6]. Several researchers have sought to optimize the energy consumption of the tillage by reducing the draught force [7-12]. This force is related to the mechanical properties of the soil, to the working parameters (depth and speed of plowing) and to the geometry of the soil tillage tool.

Optimizing the design of soil tillage tools will help improve energy efficiency. Accurate modeling of soil-tool interaction is key to this optimization and can eliminate the need for numerous expensive field tests and reduce prototype development and verification time. However, soil-instrument interaction is a complex process due to spatial variability of soil, dynamic effects, flow and mixing occurring in the soil as a result of this interaction.

In general, three types of modeling approaches have been used to model the interaction between soil and instrument, namely: empirical, analytical, and numerical methods [13-15]. The empirical modeling approach is efficient over time and provides practical information. However, the experimental procedures involved are expensive and the extrapolation of the results for all conditions is uncertain. Analytical methods have received a lot of attention in recent decades from many researchers [16]. However, the soil structure and texture are not always homogeneous, so it is not realistic to develop a single equation for the calculation of the tillage forces during the tillage process. With the rapid development of computer science, the researchers used numerical methods to model the interaction between the soil-tool. Two types of numerical methods were used, the finite element method (FEM) [17-19]. and the discrete element method (DEM) [20]. To simulate the interactions of the soil instrument. More recently, 3D discrete element method (DEM) has become accessible and feasible with desktop computing. A brief review of previous research has been incorporated into this paper.

Numerical prediction

The experimental study of soil-blade interaction is difficult to achieve and therefore, can be limited to certain speeds and depths of cut. The results also depend on the accuracy of the measuring devices. However, with the increase in computing power and the development of more sophisticated material models, finite element analysis is more promising in the analysis of factors that influence soil-blade interaction. Several researchers have conducted finite element simulations of soil-blade interface processes and investigated factors influencing cutting forces [19,21,22]. However, the results of a numerical procedure that can be used according to the appropriate behavioral laws may be limited or doubtful validity. Therefore, selecting the most appropriate material model is most likely to produce reasonable results. The mechanical behavior of granular soils, generally from silt to gravel, can be modeled by various theories. Hypo plasticity derives from the structure of rational mechanics from the main requirements on the properties of the model; a single equation has been obtained that describes many important characteristics of the granular behavior of the soil [24]. Based on the general concept of hypo plasticity, various aspects of the mechanical behavior of granular materials have been studied in recent years, for example, shear [25,26]. and the rate of dependence and cohesion [27]. Critical conditions have been incorporated to better describe the influence of the level of pressure and density on the behavior of materials [26,28,29].

Finite Element Method (FEM)

A numerical method, the finite element method (FEM), has been developed for soil cutting processes since the 1960s [7]. This method has received much attention as a powerful tool to investigate soil-tool interaction. FEM has been used to model plowing using simple tools such as blades [7,9,30], sweeps [31]. Bent leg plow [10] or a plowed disk [32]. However, little work has been carried out on the numerical modeling of tillage with curved geometry like the moldboard [33]. The Drucker-Prager elastic-perfectly plastic model is one of the material models that has been adopted for conducting a FEM analysis of the soil cutting process [19].

Modeling the soil-tool interaction with finite element analysis has some advantages over the modeling methods described above. Upadhyaya., *et al.* [34] presented an in-depth review of the use of finite element models for soil-tool interaction and concluded that the finite-element model is primarily suited for continuous analysis. However, soil deformation, especially in the tillage process, involves the separation and mixing of soil layers, the appearance of cracks, and the flow of soil particles, which cannot be modeled appropriately by the finite element method [35].

Mootaz., *et al*. [36] carried out experiment on simulation of soil–blade interaction for sandy soil using advanced 3D finite element analysis. The soil selected for this study was a sand type commonly found in the Egyptian desert. In their study, a 3D finite element analysis of soil–blade interaction was carried out based on predefined horizontal and vertical failure surfaces, to investigate the behavior of the soil–blade interface and study the effect of blade-cutting width and lateral boundary width on predicted forces. Sandy soil was considered in this study and modeled using the hypoplastic constitutive model implemented in a commercial finite code, 'ABAQUS'. They find out the validity of the concept of predefined failure surfaces in simulating soil–blade interaction and the significant effect of blade-cutting width, lateral boundary width and soil swelling on cutting forces.

Bentaher., *et al.* [17] reported on the numerical modeling of soil tillage. The finite element method (FEM) was used to model the cutting process of the soil using a moldboard. The surface geometry of the moldboard was measured with a 3D touch probe bench, also called coordinate measuring machine, and these data were used to construct the shape with SolidWorks design software. An elasto-plastic constitutive model was used for the soil. The generated surface of the plow was imported to ABAQUS software as a discrete rigid body with a reference point at the tip of the moldboard. At this tip the reaction force with its three orthogonal components was calculated. The impact of the cutting angle (angle between the horizontal generatrix and the tillage direction) and the lift angle (angle between the moldboard surface and the horizontal line in an orthogonal section to the cutting edge) on draught force was investigated. The optimal values concerning the draught minimization are 44º and 22º, respectively, for the inclination angle of the horizontal generatrix and the lifting angle.

Mouazen and Nemenyi [19] used finite element method for the calculations of draught and vertical forces, soil deformation and normal pressure distribution on subsoiler face for four subsoiler types. A non-linear, three-dimensional, finite element analysis of the soil cutting process by a standard medium-deep subsoiler based upon the Drucker-Prager elastic-perfectly plastic material model was used. The mathematical construction of the Drucker-Prager model was presented. The material non-linearity of soil was dealt with using an incremental technique. Inside each step, the Newton-Raphson iteration method was utilized. The geometrical non-linearity was solved by using the small strain assumption. A comparison of subsoiler forces for calculations made with the small strain assumption and the updated Lagrange formulation of large displacement was reported for subsoiler cutting in a sandy soil. It was shown that the small strain assumption was more convenient for solving the geometrical non-linearity of a soil tilled down to relatively deep horizons.

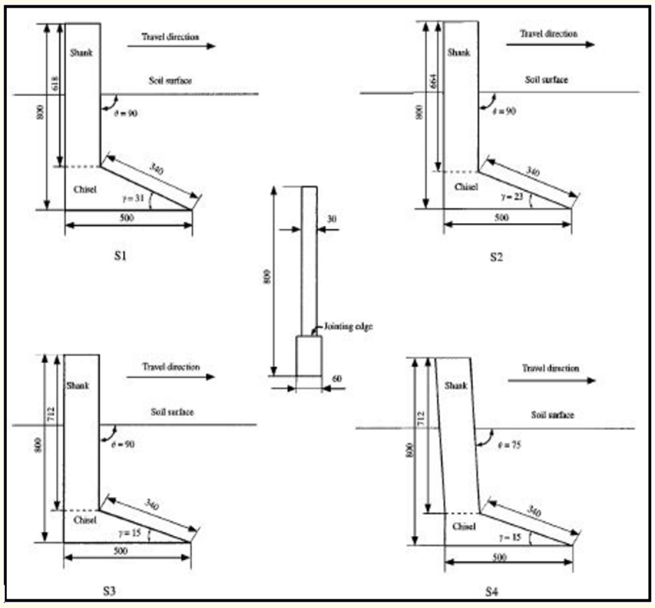

Figure 1: Illustration of different geometrical types of subsoiler. (S1) subsoiler with 90º rake angle shank and 31º inclined chisel; (S2) subsoiler with 90º rake angle shank and 23º inclined chisel; (S3) subsoiler with 90º rake angle shank and 15º inclined chisel; (S4) subsoiler with 75º rake angle shank and 15º inclined chisel.

The theoretical results showed that a well-coordinated angle combination of the two parts of the subsoiler made a large reduction in the draught and vertical forces of the subsoiler with a shank angle of 75º and a chisel angle of 15º. On the soil surface in front of the shank, the soil was deformed to produce a wedge-shaped soil upheaval. A maximum upward surface movement of 23.7 cm was calculated when soil tilling was performed with this design of subsoiler. For all the geometrical types of subsoiler studied, concentrations of normal pressure at the outer linking edges between the two parts of the subsoiler, as well as on the bottom corners of the chisel, indicated that during manufacturing these parts should be better supported against wear and deformation. The smallest chisel angle of 15º reduced considerably the pressure values at these two parts, whereas changing the shank rake angle from 90 to 75º only assisted in reducing the pressure values at the outer linking edges [19].

Finite element method predictions of the subsoiler draught force as well as the extent of surface soil failure agreed well with measurements made in the soil bin. The predicted draught force for all subsoiler types exceeded the measured ones. The over prediction error ranged from 11.76 to 20.04% [19]. The finite element model provided a good approximation to the maximum upward soil movement for the experiments. Better finite element method predictions of the front soil failure were obtained for the two subsoiler designs with a small chisel angle of 15º than for the designs with chisel angles of 23 and 31º. Among the four investigated subsoiler types the best subsoiler design was devised, which required the lowest draught and developed good soil loosening qualities as estimated by soil volume change. This subsoiler had a shank of 75º rake angle and an inclined chisel of 15º angle. Keeping a good soil loosening performance was attributed to the smaller shank rake angle of 75º, which indicated that the shank played an important role for the determination of the quality of soil loosening.

Discrete Element Method (DEM)

The DEM method is an explicit numerical technique that treats soil as a collection of individual unconnected particles. Particles interact through a series of contact laws and the motion of the particles is controlled by Newton's laws of motion. This method was employed to study a soil ploughing process. A three-dimensional sphere-based implementation of the DEM was developed and calibrated through simulations of soil test. A simulation of a blade ploughing through soil was performed for various blade designs.

Cundall [37] proposed the DEM method to simulate a granular material. The mechanical behavior of the material is calculated sequentially by solving the equation of motion of each discrete element. This method has recently been used by several civil, geotechnical and agricultural researchers [11,12,38]. In the DEM, the material of interest (e.g., soil) is modeled as collections of discrete particles. Each particle interacts with neighboring particles. As compared with the FEM, the DEM can handle large particle displacement and crack propagation involved in the field operation of a soil engaging tool. FEA can have numerical convergence problems when the soil loses contact with the cutting tool [9].

Ucgul., *et al.* [39] Predicted draft and vertical forces, and the furrow profile for a sweep tool for varying geometries and speeds. The simulation results were compared to Fielke [31] experimental sweep results for varying width and rake angles. A good correlation was obtained between the predicted and measured tillage forces for both draft and vertical forces (R2 = 0.95 - 0.99) using 10 mm radii particles. The DEM simulations were able to be run in under 2h. whilst the use of 10 mm radius particles gave a timely solution and good force predictions the soil flow and resulting furrow profile were less than those measured. Simulations with a 20 mm thick layer of 1.5 mm radii particles over a base of 10 mm radii particles provided a more accurate representation of soil flow and furrow profile but doubled the computation time. The tests were carried out in the University of South Australia Tillage Test Track, with a 2.5 m wide and 300 mm deep sandy loam soil. The sandy loam soil used by Fielke [31] had a low cohesive strength value of 6 kPa. The effect of particle size was found to be a result of differences in response by the soil flow to the impact with the tine on which the sweep blades were mounted. The work also highlighted how multiple tool geometries can be created and simulated to improve a critical tool geometry parameter such as rake angle to achieve a desired result such as minimum draft force or maximum vertical down force.

Mak., *et al.* [40] developed a soil–tool interaction model using a commercial DEM software, Particle Flow Code in Three Dimensions (PFC^{3D}). PFC^{3D} focuses on two basic elements: balls and walls. Balls or a cluster of balls represent material particles, such as soil particles, while walls represent physical boundaries around the particles, such as a soil bin. Walls can also be used to construct machines, such as a soil engaging tool. In simulating soil–tool interaction, an assembly of balls is contained within walls. As a soil engaging tool moves through the balls, each ball will contact several other neighboring balls, and the dynamics (displacements and forces) of the ball assembly changes. Several models are implemented in PFC^{3D} to describe the different contacts between balls to simulate the behavior of different materials. Among those models, the parallel bond model (PBM), in which balls are held together by bonds, is suitable for materials exhibiting internal forces between particles [41]. In the model, soil particles were defined with the basic PFC^{3D} model particles, which consisted of balls with cohesive bonds between balls. The model parameters, bond normal and shear strengths, were determined based on intrinsic stresses of soil. The most sensitive model parameter, ball normal stiffness, was calibrated for two contrast soils: coarse and fine soils. Values of c and Ø of coarse soil (average moisture content: 23.9%) and fine soils (average moisture content: 29.2%) were taken as the averages of the data reported by McKyes [15]. The soil-tool friction angle was taken as 23º [42]. The calibrations were performed through comparing the draught forces of a simple soil engaging tool simulated with the PFC3D soil–tool interaction model and those estimated with the Universal Earthmoving Equation (UEE). The calibrated ball normal stiffness is 6 × 10^3 N/m for coarse soil and 2×10^4 N/m for fine soil. The UEE has the following format [15].

$$P=\left(\gamma g D^2 N_\gamma + cDN_c + \gamma v^2 DN_a\right) w$$

where P is soil cutting force (N), γ is soil specific weight (kg m^{-3}), g is gravitation acceleration (m s^{-2}), D is working depth (m), c is soil cohesion strength (Pa), v is the tool travel speed (m s^{-1}), w is tool width (m), and N_γ, N_c, and N_a are the N factors (dimensionless).

Chen., *et al*. [43] developed a discrete element model to simulate a slurry injection tool (a sweep) and its interaction with soil using Particle Flow Code in Three Dimensions (PFC^{3D}). In the model, spherical particles with bonds and viscous damping between particles were used to simulate agricultural soil aggregates and their cohesive behaviors. To serve the model development, the sweep was tested in three different soils (coarse sand, loamy sand, and sandy loam). In the tests, soil cutting forces (draught and vertical forces) and soil disturbance characteristics (soil cross-section disturbance and surface deformation) resulting from the sweep were measured. The measured draught and vertical forces were used in calibrations of the most sensitive model parameter, particle stiffness. The calibrated particle stiffness was 0.75 × 10^3 N/m for the coarse sand, 2.75 × 10^3 N/m for the loamy sand, and 6 × 10^3 N/m for the sandy loam. The calibrated model was validated using the soil disturbance characteristics measured in those three soils. The simulations agreed well with the measurements with relative errors below 10% in most cases.

Figure 1: Cylindrical bond between two balls in the PFC^{3D} parallel bond model (PBM) [43].

Elvis., *et al.* [44] used the discrete element method for predicting forces reactions and soil behavior during non-inversion tillage. The numerical model at particle level works with a force system integrated by normal, shear, cohesion and friction forces. Macro parameters are defined as the soil mechanical properties obtained by soil mechanical tests. The behavior of soil–soil and soil–metal interface at different dry bulk densities and gravimetric water contents were determined by modified direct shear box and triaxial compression tests. A set of statistical regression equations feasible to estimate the macro values of Young's modulus, shear strength, soil friction and soil cohesion were obtained. The model was also verified in a mathematical study by Feng., *et al.* (2007) with the purpose of validating the DEM prediction capacity. From this model the stiffness in normal direction was determined as:

$$k_n=\frac{E_{ab}\cdot A_{\text{int}}}{D_{eq}}\left[\frac{1+\alpha_k}{b_k\left(1+v\right)+\gamma_k\left(1-\alpha_k\right)}\right]$$

Where, E_{ab} = equivalent Young's modulus of the materials in contact (Pa), A_{int} = interaction surface (m^2), D_{eq} = equivalent distance between the two particles (m), ν = Poison's ratio, α_k = loading path, β_k = softening factor, γ_k = interaction range.

The relationship between macro and micro behavior of soil friction was investigated by means of the simulation of direct shear tests. The discrete soil model was used to simulate soil tillage at conditions called hard-dry, soft-wet and friable state. To calibrate the model, a soil-bin was filled with the soil previously characterized and equipped with a tool similar to the one used for the simulation. The comparison between draft forces from simulation and soil-bin tests showed a small under-predicted behavior of the model for loose soil with high moisture; this behavior was fixed toward compacted and dry soil conditions. Para-plough and moldboard were the tools used for non-inversion tillage simulation at different physical states of the soil. The result shows the pattern of movement and force distribution related with the geometry of the tool.

Ucgul., *et al.* [45] used Discrete Element Modelling (DEM) for the prediction of both tillage forces and soil movement of tillage implements. A one-third scale moldboard plough was constructed and tested in a soil bin where draught force, vertical force and soil movement were measured. A comparison of the measured and simulated draught and downward vertical forces showed a close agreement. A procedure was developed to compare soil movement, percentage burial of top soil and forward soil movement of the soil bin tests and the DEM simulations. The results showed similar trends and patterns for both the percentage of the top soil buried to various tillage depths and the forward soil movement. Due to the larger than actual spherical particles used in the simulation the forward soil movement was greater for DEM. The DEM showed some particles moving below the tillage depth. This shows that further model development is needed with work recommended to look at using both clump particle shapes and smaller particle sizes to improve soil movement predictions.

Chengguang., *et al*. [46] developed subsoiling model using the discrete element method (DEM) in EDEM. A subsoiling experiment was also conducted in a field with a loamy clay soil (Lou soil) to serve the model development and model validations. In both the simulation and experiment, two V-shaped subsoiling tines were investigated at five different tine spacings (300, 350, 400, 450, and 500 mm), a constant working speed (0.83 m/s) and a constant working depth (300 mm). The results showed that the 400 mm tine spacing resulted in the highest particle forces in the middle and deep soil layers. The height of the unloosened soil between two adjacent subsoilers increased as tine spacing increased. When the tine spacing was varied from 300 to 500 mm, the undisturbed soil height was changed from 100 to 226 mm in the experiment, and from 79 to 170 mm in the modelling. When the tine spacing was 400 mm, the number of soil particles disturbed in the shallow soil layer accounted for 45.6% of the total soil particles disturbed, which was the least among all the tine spacing. Considering the characteristics of soil disturbance, the tine spacing of 400 mm appeared to outperform the other spacing.

Ucgul., *et al*. [47] developed a full scale mouldboard plough and tested in the field and then simulated using DEM. The draught forces predicted by DEM were of similar magnitude to those calculated using ASABE's Agricultural Machinery Management Data (D497.7 R2015). The DEM model predicted top soil burial to a similar depth in the soil profile as was measured in the field. However, DEM predictions of lateral and forward soil movements of the buried top soil were greater than that measured in the field. The DEM predictions showed that increasing speed from 5 to 15 km/h gave a 40% increase in draught and a significant reduction in the depth of top soil burial. Increasing the tillage depth from 200 to 350 mm gave a 270% increase in draught but very little change in depth of burial of the top soil. The use of a skimmer was predicted to increase the draught by 4% and increase the amount of top soil buried below 100 mm depth.

Summary and Conclusion

The finite element method (FEM) is a powerful numerical technique that can be used to analyze complex engineering problems. It is particularly useful for problems that include geometric nonlinearities, as well as situations in which the underlying differential equations describing physical or biological phenomena are not linear. Since most soil-tool/soil-plant interaction problems involve both nonlinear materials and geometries, the EFM has been widely used to analyze soil-tool and soil-plant interaction problems. For example, in a root growth or a tillage problem interface element are necessary to properly model the soil-root or soil-tillage tool interface. Furthermore, the soil is an elasto-plastic material that causes non-linearity of the material. A problem of interaction between a ground traction device (for example a pneumatic one) implies a geometric non-linearity due to the soil-tire interaction (contact problem) and to the elasto-plastic behavior of the ground and of the tire material (composite material, incompressible). Furthermore, these problems include significant displacements and deformations. The availability of many generic commercial software such as ANSYS and ABAQUS, which integrate the elasto-plastic behavior of the terrain and includes a wide range of element types, including contact and interface elements, makes the FEM a particularly interesting technique for analyzing problems of soil-tool interaction.

Alternative methods that do not require continuum assumptions, such as the discrete element method (DEM), have been used with some success in soil mechanics. Their main disadvantage is the requirement of a huge computer memory, also to solve a very small problem, since the equations of the movement of each particle in the system and its interaction with its neighbor are continuously taken into consideration. Calculation costs can be reduced by exploiting the DEM functionalities to model fractures by combining the FEM and DEM methods. The original DEM formulations have been obtained for purely frictional materials and have been used to analyze the behavior of the sand. Soil tillage is an energy-intensive operation and design improvements have been sought to reduce forces for many different tools. Due to the high cost of prototyping and testing, computer modeling was used to design soil processing equipment.

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