CFD SIMULATION OF SOIL-TOOL INTERACTION

SIMULAREA CFD A INTERACŢIUNII ORGAN ACTIV-SOL

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Abstract. *The study of tillage tool interaction centers on soil failure patterns and development of force prediction models for design optimization. The force-deformation relationships used in models developed to date have been considering soil as a rigid solid or elasto-plastic medium. Most of the models are based on quasi-static soil failure patterns. In recent years, efforts have been made to improve the conventional analytical and experimental models by numerical approaches. This paper aims at reviewing the existing methods of tillage tool modeling and exploring the use of computational fluid dynamics (CFD) to deal with unresolved aspects of soil dynamics in tillage. The soil was characterized as having a rheological behavior by modeling as a visco-plastic Bingham material. The soil was characterized for its rheological behavior as a Bingham material. Three-dimensional analyses were carried out by the finite volume method with using FLUENT v.6.3, a commercial CFD code. The results indicated that due to tool movement into soil the pressure on the tool active area is highest in the edges region decreasing to central region. The drag force (draught) is shown as the sum of the pressure and the friction between the tool and soil.*

Key words: CFD, tillage tool, soil dynamic

Rezumat. *Studiul interactiunii organ activ de prelucrare-sol se centreaza pe domeniul fisurarii solului si dezvoltarea modelelor de predictie a fortei de tractiune pentru o proiectare optima. Relatia forta-deformatie utilizata in modelele dezvoltate pana acum au considerat solul ca un solid rigid sau mediu elasto-plastic. Mai multe modele propuse au la baza conceptul de fisurare cvasistatica a solului. In ultimii ani eforturile cercetatorilor au fost facute in dezvoltarea modelelor conventionale analitice si experimentale dar prin abordare numerica. Acest articol urmareste sa revizuiasca metodele existente de modelare a organelor active de prelucrare a solului si explorarea utilizarii CFD pentru tratarea aspectelor nerezolvate de dinamica solului in prelucrarea lui. Solul a fost caracterizat ca avand un comportament reologic prin modelarea ca un material viscoplastic Bingham. Analiza 3D a fost realizata prin metoda volumelor finite utilizand programul FLUENT v. 6.3. Rezultatele indica ca datorita miscarii organului activ in sol presiunea de pe suprafata organului activ este mai ridicata in zona taisului scazand spre regiunea centrala. Forta de tractiune este redata ca suma dintre componenta de presiune si cea de frecare dintre organul activ si sol.*

Cuvinte cheie: CFD, organ activ prelucrare sol, dinamica solului

INTRODUCTION

Tool interaction with agricultural soil basically deals with soil cutting, with the objective of attaining suitable conditioning for crop production. Tillage is the mechanical manipulation of the soil in the tillage layer in order to promote tilt, i.e.

desired soil physical condition in relation to plant growth. Performance efficiency of tillage is measured in terms of draft or input energy. Optimization in tillage tool design necessitates minimization of the input energy. It is estimated that tillage accounts for about one half of the energy used in crop production.

Methods of classical soil mechanics are often applied to agricultural soil mechanics with little modification for studying soil deformation. Soil mechanics dealing with agricultural soil has the distinction from those of civil and geotechnical engineering problems in the context of the soil behavior. Tillage is mostly concerned with soil loosening at shallow depths with the interaction of relatively low loads. In addition the depth of agricultural soil tillage is up to 0.5 m. During the last four decades, much research has been conducted on parametric studies for soil–tool interaction with different approaches. These parameters have primarily been studied in a quasi-static condition considering the equilibrium of the soil–tool system. The engineering soil mechanics approach is based on equilibrium state stress–strain relationships for the study of soil deformation, while deformations in agricultural soils rarely reach equilibrium [2]. In soil tillage, the soil is lifted and accelerated and thereby given potential and kinetic energies, and it is manipulated such that a change of state occurs. These processes occur under non-equilibrium conditions. Thus, tillage is a non-equilibrium process.

Recently few studies have been conducted taking the dynamic feature of soil–tool interface due to machine interaction by numerical modeling. These studies, in contrast to the conventional assumption of passive earth pressure theory (quasi-static), considered velocity and acceleration of the tool during the soil–tool interaction. However, the large scale deformation of soil is still an area in which little research has been conducted. Force prediction models for tillage tools have been relying on the classical soil failure theory for quasi-static conditions.

So far, five major methods, namely empirical and semi-empirical, dimensional analysis, finite element method (FEM) [1], discrete or distinct element method (DEM) [4] and artificial neural network (ANN) [7], have been used as approaches to solve problems in the area of soil–tool interaction and failure mechanism. A better understanding of the soil–tool interface mechanism can be obtained by correlating soil rheological behavior with its dynamic characteristics.

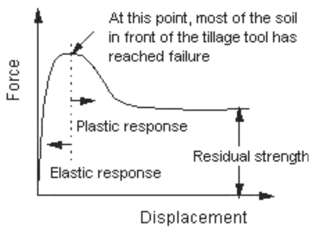
This article attempts to briefly review a new approach to the soil-tool dynamic interaction where occur large and irrecoverable soil deformation the use of computational fluid dynamics (CFD).

MATERIAL AND METHOD

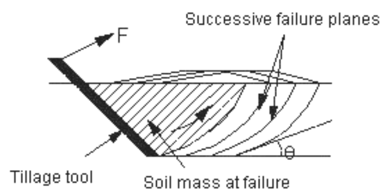
1. FORMULATION OF THE PROBLEM

In order for a tillage tool to perform according to its desired criteria, tool geometry is an important factor. Typically, the criteria used for tillage tool design include draught to operate the tool the volume of soil loosened and total the energy requirement. The condition of the tilled soil due to the tool action depends on the soil

mechanical behavior, its initial condition and tool operating parameters. Soil is a very complex material and its behavior is not understood completely. The complexity grows further when soils of different places with different agro-climatic conditions are taken into considerations. For the purpose of developing prediction models, soil mechanical behavior has been descried in different ways represented by combination of elastic spring, dashpot and slider in the perspective of elasticity, plasticity and viscosity.
Many agricultural soils exhibit a highly nonlinear mechanical behavior and should thus be characterized as nonlinear plastic or visco-plastic materials. Soil deformation under steady-state stress can be described by a simple linear model of viscoplasticity, the Bingham rheological model [5]. The force requirement to pull the tool is a function of the soil pressure exerted on the tool. Soil pressure on tillage tools and its distribution with respect to tool wear is an important parameter in determining tool size and shape. In earlier studies, soil has been considered as a rigid body, elastic solid or elasto-plastic material [2]. According to these studies the force by a tillage tool is influenced by both the stiffness and the strength of the soil (figure 1 a). At the beginning of the tilling activity, most of the soil is elastic and offers significant resistance. Therefore, the force required to till soil is quite high. As the tool moves, more and more soil begins to yield and fail, resulting in the propagation of failure planes or cracks from the tip of the tillage tool to the surface (figure 1 b).



a



b

Fig. 1. (a) Force required for tillage; (b) Successive failure planes in front of the tool.

Once the soil begins to yield, the magnitude of the required force drops and reaches a residual level as the soil in front of the tool reaches a steady state in terms of crack propagation. As the tillage tool is dragged further, new failure planes are initiated in the soil in front of the tool and this cycle of peak and residual force repeats itself (figure 2).

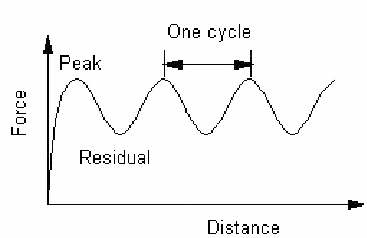


Fig. 2. Fluctuations in the tillage force due to formation of failure planes in the soil.

The frequency of the cycle and the magnitude of the peak tillage force are influenced by the speed at which tilling is carried out [6].

These quasi-static analyses generally do not take into account the dynamics of tillage.The dynamic visco-plastic nature of soil during tillage has not been given proper consideration. The soil deformation pattern around a tillage tool was studied considering the soil as a visco-plastic material using computational fluid dynamics (CFD) simulations. The results showed that the Bingham model could successfully depict the pattern of soil plastic failure with respect to the yield stress. However, very little data are available from studies that relate soil deformation with the pressure on tool while it moving.

Using FLUENT software can do an assessment on traction forces and pressure distribution on a narrow tillage tool by considering the dynamics of soil – tool interaction using a fluid flow soil approach.

2. CFD SIMULATION

In this study, soil–tool interaction was analyzed from fluid flow perspective. A narrow, rigid and vertical blade was considered as stationary tool in the middle of the visco-plastic soil flow domain (soil bin) (figure 3). The narrow tool acted as an obstruction (the bluff body) in the flow field with 140 mm length (T), 200 mm width (W), operating at 100 mm depth (H), was considered for the study. The flow geometry consisted of an open channel of 940 mm length (8H+T), 1400 mm width (7W), and 300 mm depth (3H). The side and bottom walls were so placed that the effects of the boundary wall on the flow characteristics were negligible.

During the CFD simulations, it was observed that a channel width of seven times the tool width eliminated the effect of the channel wall on the flow pattern with respect to tool influence.

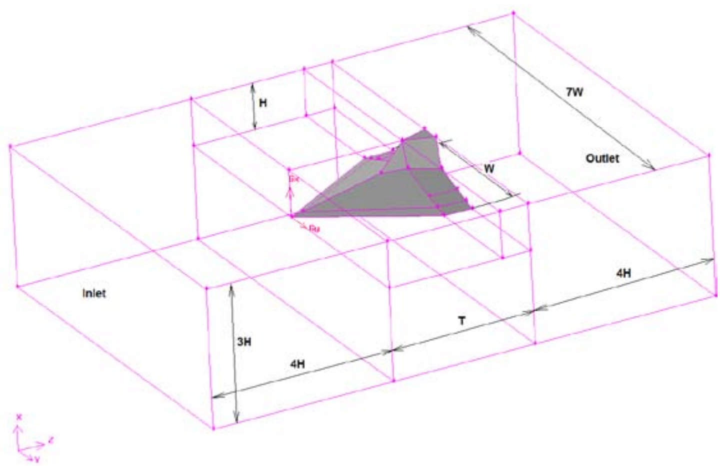


Fig. 3. Schematic of the flow field (soil bin).

The soil was assumed to be an incompressible, isotropic and homogeneous Bingham material with a single-phase laminar flow. If one assumes that soil behaves as a non-Newtonian fluid with a definite yield stress, then the motion of a tillage tool through the soil can be hypothesized as a fluid flow interaction with immersed body. This concept has been implemented in this research through the use of computational fluid dynamics. Soil yield stress in shear was considered to be the failure criterion.

2.1 General and Boundary Conditions

Three-dimensional CFD simulations were carried out in isothermal conditions for a clay loam soil (29% clay, 24% silt and 47% sand). Soil visco-plastic parameters, soil viscosity η, and yield stress τ_0 required for the simulations have been found using a constant-rate soil rheometer [3]. Input parameters for the soil considered in a simulation with 17% moisture content (dry basis) and 400 [kPa] cone index were: ρ = 1250 [Kg/m^3] bulk density, η = 900 [Pa s] viscosity, τ_0 = 12 [kPa] yield stress. Fluid inlet velocity for soil flow domain v = 3 [m/s].

The system was idealized with the following assumptions: the tool is narrow, rigid, and works at a constant depth; flow is symmetrical about the vertical section of the tool; soil failure is three-dimensional; the soil is an isotropic and homogeneous continuum; the soil behaves as a Bingham visco-plastic material with definite yield stress; soil pore spaces are negligible, and the soil is an incompressible material.

Boundary conditions imposed in the simulation with respect to the flow domain are: the velocity component normal and uniform to the inlet boundary; the outlet was specified as pressure boundary; no-slip wall boundaries were specified at the bottom and the sides of the channel; the top of the flow domain was specified as free-surface.

2.2 Processing

The Navier-Stokes equation is the basis of numerical solutions of any fluid flow by assuming the conservation of mass through the control volume. In this way, the fluid flow approach addresses different aspects of dynamic soil-tool interaction, such as forces due to the velocity and acceleration of the tool, soil pressure on the tool surface considering the weight of the soil mass, and soil failure due to visco-plastic soil deformation. The following constitutive relation for the Bingham model represents the shear stress tensor in the momentum equation:

$$\tau = \tau_0 + \eta\gamma \text{ for } \tau > \tau_0 \text{ ; } \gamma = 0 \text{ for } \tau \le \tau_0 \quad (1)$$

where τ_0 [Pa] yield stress; γ [s^{-1}] shear rate; η [Pa s] viscosity.

During tillage, as the tool encounters stiff soil, there is no soil failure until the applied stress exceeds the soil yield stress. A continued applied force that exceeds the threshold yield stress results in visco-plastic soil flow due to soil shear failure. In the CFD processing a value of 10^{-4} has been employed as the convergence criterion at every step of the iteration for the sum of the normalized residuals over the whole fluid domain for all the governing fluid flow equations. A relaxation factor less than 0.3 was found to be a good value for attaining stable convergence, although it increased the computation time compared to larger relaxation factors.

RESULTS AND DISCUSSIONS

Post-Processing

Dynamic soil-tool interactions were carried out by the control volume method with fluid flow phenomena. Simulations were carried out with the soil flowing as a Bingham material in an open channel with an obstruction or bluff body in the flow domain. Results of the simulation were interpreted with the soil as stationary and the tool moving at a constant velocity. Some significant results are discussed below. The pressure distribution on the narrow surface was found to vary with the position of the blade surface and with the type of soil. Maximum pressure was observed at the tool cutting edge. The average normal pressure varied from 4.5 to 53.5 kPa at the tool edge for soil used in simulation (figure 4).

Drag on an immersed narrow tool into fluid (soil) is comprised of two components, pressure drag and viscous or friction drag. This total drag depends on the shape of that tool. Therefore, the total draught is in direct relationship with drag and therefore is divided into two components: pressure and friction or viscous (*table 1*).

Table 1

Total draught

Zone Name	Pressure force [N]	Viscous force [N]	Total force [N]
Narrow surface	95.6	520.4	616
Vertical device	36.3	42,5	78.8
Net	131.9	562.9	694.8

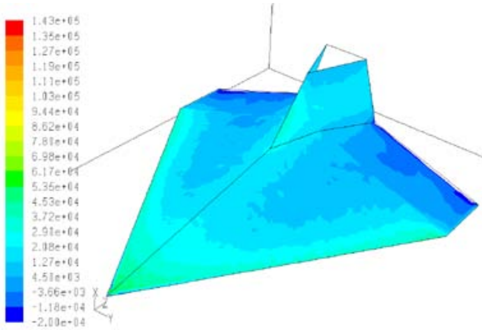


Fig. 4. Contours of Total Pressure [Pa]

CONCLUSIONS

Existing soil-tool modeling techniques have been reviewed with their relative merits and weaknesses. A wide range of such models is available to predict the force required to operate a tillage tool. Preliminary investigations using computational fluid dynamics showed promising results for modeling soil–tool interaction to determine the tillage forces (draught), distribution of pressure on the tool surface. Application of CFD in the area of tillage is anticipated to bring a new dimension to the tool design and study of soil failure behavior for different agro-climatic conditions.

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