Tarım Makinaları Bilimi Dergisi (Journal of Agricultural Machinery Science)
2009, 5 (4), 435 - 444

FEM Analysis of the Soil-Tool (Sweep) Interaction

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Abstract: The analysis of soil profiles and soil redistribution by tillage has progressed slowly due to its complexity which involves many factors, such as soil types and properties, types of tillage tools and their operational parameters. In this paper we will introduce the methods of soil bin study, FEM approach was used in developing a modell for the prediction of draught on cultivator sweeps. A verified finite element model is a cheap and useful tool in the development procedure of cultivators and can be used for research and analyse the performance of resulting prototype. Model tools were designed for the experimental verification of the predicted FEM. There are some factors that we can determine the soil and the cultivator tool. The influences of cultivator sweep geometry was researched by the FEM and compared to results of soil bin tests to validate the sweep shares. And as the result of the methodology we can validate the optimal sweep parameters for each type of soil, that we can determine the measurements parameters.
Key words: Soil, Cultivator, FEM, Modeling, Tillage, Soil Bin, Forces

INTRODUCTION

The environment-friendly tillage methods get more emphasis nowadays, thanks to the economical production and the environment load of tillage and its harmful effects. One of the most important environment-friendly tools is the field mulch cultivator. During the last years I have studied the geometry of the cultivator tillages and measured the energy consumption in the soil bin with the most general sweep tools. I defined that most influencing for the energetic property is the tools inclined angel (β). Before further soil bin study and field experiment I studied the Finite Element Method for recognizing the soil-tool interaction. The analysis of soil profiles and soil redistribution by tillage has progressed slowly due to its complexity which involves many factors, such as soil types and properties, types of tillage tools and their operational parameters.

The study of tillage tool interaction focuses 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 an elasto-plastic medium.

Fig.1. The soil bin test

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 soil mechanics with VCCT (Virtual Crack Closure Technic) to deal with unresolved aspects of soil mechanics in tillage.

The previous experimental and finite element studies have shown the influence of both soil initial conditions and sweep operating conditions on cutting forces. Most of these finite element analysis are limited to small blade displacements, to reduce element distortion. In this study a dynamic two dimensional FEM of soil-tool interaction was carried out based on predefined initial cracks to investigate the effect of cutting speed, the angle of cutting forces and the influences of the soil parameters. This method does not depend on the displacements.

MATERIALS AND METHODS

There are several theoretical and experimental methods to study and measure the impact of the soil-tool interaction. The experimental measures can be made in a field test, and then we can mix the theoretical and experimental aspects in a soil bin and in a finite element method (FEM) on PC. Although, experimental study of soil-tool interaction is expensive and limited to certain cutting speeds, the results are highly dependent on the accuracy of the measuring devices. With increasing computing power and the development of more sophisticated material models, the finite element technique is showing more results in analyzing soil- tool interaction.

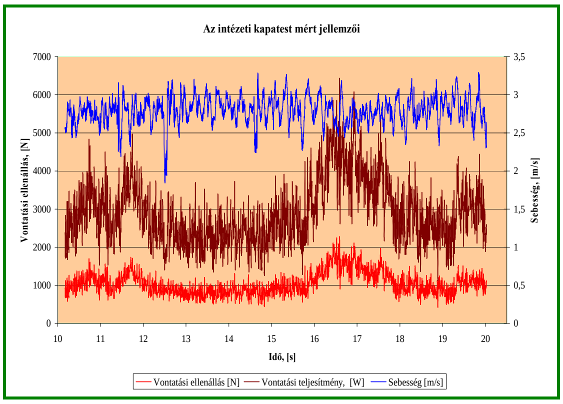

Fig. 1. Sweep measured propertis in the soil bin test

Soil cutting process has been studied by many researchers. The conventional analytical method has been used to develop two- and three-dimensional models based on Terzaghi's passive earth pressure theory (Terzaghi, 1943). These models are based on the assumptions that soils are homogeneous, isotropic, semi-fininite and ideal plastic. As a result of the previous measurement in the soil bin study, some previous models were elaborated. The operations of these models are wearisome and the accuracy is not sufficient. On the basis of general use and successes of the FEA methods, some previous researchers (Liu Yan, Zhi-Min, Xie Xiao-Mi, Kuswaha, Kerényi etc.) began adopting the adjustment to describe the soil-tool interaction. The developments of the FEM programs have made sophisticated models to introduce the soil-tool interaction.

The 3D theories of the soil cutting with FEM were researched by Yong and Hanna. In this theory they postulated the cutting process as a quasi static question. They created a 2D model, in which they validated with shearing experiment the non-linearity of the soil properties (Mohr-Coulomb-theory), they computed with hyperbola function the received displacement- shearing tension diagram. They validated the soil-tool properties in the same way. They determine these soil parameters for clay.

Theirs models used cutting elements, that they determined the formations direction of the slip lines. They used element with four nodes, and modeled the soil with triangle elements. They took the geometric nonlinearitis into consideration, which after each of the load increments the coordinates of the noods would be the basis of the next steps. Actually under a load increment they applied the law of small deformations that is they determine the deformations with the derived of the rewrited coordinates. They validated the traction force along the tool. They drew the strain dispersion and the displacement of the field. We made a comparison between the obtained numeric results, and the soil bin test, with glass wall. The applied Finite Element Models gave information for the traction force requirement.

In another 2D model on the basis of the pressure test the soil was pure cohesive (that is the internal friction angle nearly zero). The material non-linearity and the contact between the soil and the tool converge with hyperbolic function. They generate the load with displacement increments and for each increments the linear Hook law was valid, each increment was calculated with different deformation modulus. Therefore, that the load increment didn't cause large volume change, they determine the volume of the Poisson number as a function of the current Young- modulus. They use two nodes rub elements between the soil and the tool, because the rewriting was convenient. They divide the soil to linear triangles. In acute-angled tool angle to the horizontal direction of the tool edge they determine the fracture line. These models determine the expectable volume of traction force and the deformed shape. The 3D models of LIU YAN, ZHI-MIN are similar to the 2D models, because of the quasi static task.

The researchers developed the specific soil properties experimental data that describe the proviso of the rigid-plasticity of the CAP model. They defined the soil-tool friction with the Mohr-Coulomb Law, in which the constant had defined with shear examinations. As the result showed, they determined the direction of the horizontal fracture plane. It is not clear from the study, what kind of soil they applied in this theory and what kind of inclined angle they used. They verificated only the theory not the value.

XIE XIAO-MI and ZHANG DE-LUN made the first finite element soil cutting model that takes the dynamic effects in consideration. We get the parameters to describe the material model and the friction from the established triaxial sear research. They used CAP model, but they didn't consider the yield surface as a straight line. To determine the dynamic effect the D'Alembert theory was applied in the FEM so they solved a static task. The big deformation with rewriten Lagrange- formula. The numerical and the experimental results were so similar. It is the most detailed model, but these models need the greatest number of defined parameters.

CHI and KUSWAHA researched the straight and wedge shape tools with FEM. They used the most important mechanical properties from the above mentioned triaxial test. They consider the soil as non-linear elasticity material. They determinated the touching elasticity modulus as a hyperbolic function. They performed the computing as small deformations, so they didn't take the geometrical nonlinearity into consideration. They used tetrahedron elements with four nodes. Tool angle was applied at: 30°, 45°, 60°, 90°. They represented the horizontal and the draft force as a function of the tillage displacement. The obtained curves showed the required force for soil cracking. The stress field was drawn, which gave information about the line of fracture. The numerical and the experimental results were compared, and verified, that the two measurement methods were converged.

The surface of sliding in the backfill of a real retaining wall is slightly curved. In order to simplify the computations, Coulomb assumed it to be plane. The error due to disregarding the curvature is, however, quite small.

To recognize and analyze the Finite Element Analysis Methods we decided to satisfy our purposes by the Parabolic Mohr-Coulomb theory.

Since the back of every real retaining wall is more or less rough, the boundary conditions for the validity of Rankine's theory are seldom satisfied, and earth-pressure computations based on this theory usually involve an appreciable error. Most of this error can be avoided by using Coulomb's theory (Coulomb 1776). Coulomb's method can be adapted to any boundary condition, but, in exchange, it involves a simplifying assumption regarding the shape of the surface of sliding.

The experimental results also showed that the relation between soil shear strength and normal pressure is non-linear at high shear rate. This suggested that the Mohr- Coulomb criterion could only be applied under low shear rate conditions. To demonstrate the effect of the shear rate on soil shear strength and soil- metal friction, dynamic models for soil- tool interaction have been developed by Drucker-Prager.

Both Coulomb's and Rankine's theories are based on the assumptions that the wall is free to move into or beyond the position of the tool surface and that the water contained in the voids of the soil does not exert any appreciable seepage pressure. It is also quite obviously assumed that the soil constants that appear in the equations have definite values that can be determined.

Parabolic Mohr-Coulomb Material (Hydrostatic Stress Dependence)

The MSC Marc includes options for elastic-plastic behavior based on a yield surface that exhibits hydrostatic stress dependence. Such behavior is observed in a wide range of soils. These materials are generally classified as Mohr-Coulomb materials (generalized von Mises materials). The generalized Mohr-Coulomb model developed by Drucker and Prager is implemented by the FEM software. We adapted the Parabolic types of Mohr-Coulomb materials.

The yield function of the Drucker-Prager elastic perfectly plastic material model can be expressed as follows (MSC Marc). The hydrostatic dependence is generalized to give a yield envelope which is parabolic in the case of plane strain (see in figure 3.)

$$f = (3J2+\sqrt{3}\beta\sigma J2)^{1/2} - \sigma = 0 \qquad (1.)$$

The parabolic yield surface is obtained through the isotropic model definion option. Enter the values σ and β through the isotropic model definition option.

$$\sigma^2 = 3(c^2 - \frac{\alpha^2}{3}) \qquad (2.)$$

$$\beta = \frac{\alpha}{\left(3\left(3c^2 - \alpha^2\right)\right)^{1/2}} \qquad (3.)$$

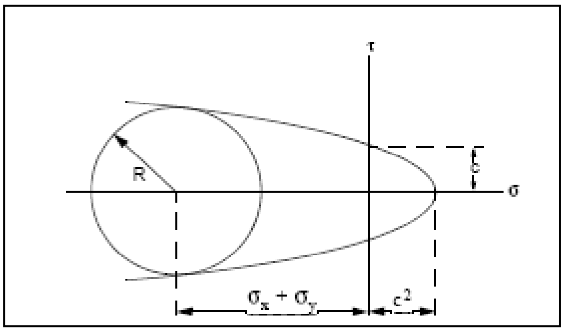

Fig. 3. Resultant Yield Condition of Plane Strain (Parabolis Mohr-Coulomb Material)

We made some trials of the modern FEM softwares, namely the Cosmos, Ansys, MSC Marc. We used the MSC Marc for modeling the soil-tool interaction, because this program had the greatest number of methods to describe the tillage operation.

Two sources of non-linearity are to be expected when a soil is under external load, namely material and geometrical non-linearity. Material non-linearity can be fully described by the stress-strain relation. More than one stress-strain coefficient is required to represent fully the mechanical behaviour of any material under a general system of changing stresses. These coefficients are Young's modulus and Poisson's ratio. In order to deal with the material non-linearity of soil, an incremental analysis technique was used. Inside each, the Newton- Raphson iteration method was applied (Chen and Mizuno, 1990). The increment size was selected to be moderate, in order to improve the accuracy of the solution obtainable in an acceptable computation time. The geometrical parameters of the subsoiler studied were given by Kerényi (1996) and Neményi- Mouazen (1999).

Virtual Crack Closure Technique

The crack growth is modeled by the VCCT which is based on the Griffith crack growth criterion. According to the Griffith crack growth criterion, a crack grows if the energy released at crack propagation is equal to or larger than the energy required to create new crack surface. The latter is called "critical energy release rate" and can be derived from experiments. The central assumption of the VCCT is, that the energy is released when the crack is extended by a length and the energy is required to close the crack over a length. The energy rate for closing the crack is computed from the force at the crack tip and the crack opening displacement. If the computed energy rate is equal to or greater than the critical energy release rate, the crack propagates.

Griffith stated that, for crack propagation, the rate of elastic energy release should be at least equal to the rate of energy needed for creation of a new crack surface. This concept was extended by Irwin to include limited amounts of ductility. In Irwin's considerations, the inelastic deformations are confined to a very small zone near the tip of a crack. The basic concept presented by Griffith and Irwin is an energy balance between the strain energy in the structure and the work needed to create a new crack surface. This energy balance can be expressed using the energy release rate *G* as

$$G = G c \quad (4.)$$

G is defined as $G = -\frac{d\Pi}{da}$ (5.)

where *Π* is the strain energy and *a* is the crack length. *G* depends on the geometry of the structure and the current loading. *Gc* is called the fracture toughness of the material. It is a material property which is determined from experiments.

In this modell was it used to representing a simplified soil cracking process. The experimented initial cracks were set in the deformable body, then under a crack process was the produced force measured.

Model description

A two-dimensional FEM mesh was generated within two perpendicular line, to which we glued it. The FEM mesh of the soil-tool system could be seen in the figures (in different tool angles and soil propertis). In this modell I postulated, that the soil is homogene, isotrophic and the Parabolic Mohr-Coulomb method was applied. Four-node, quad shell elements were selected to represent the soil material.

Table 1. Soil and soil-tool interface properties for the finite element analysis

Soil material propertis	Compacted	Loose
Wet bulk density (kg/m3)	1840	1610
Soil water content d.b. (g kg -1)	145	145
Cohesion (kPa)	20,4	15,3
Internal fiction angle (deg.)	34	30,3
Poisson's ratio	0,385	0,339
Modulus of elasticity (kPa)	20000	5000

In the contact we defined the soil as deformable. Simulating the blade using the rigid body feature in MSC Marc enables to calculation of the resultant reaction forces acting on the entire blade at a single reference node. The cracks were predefined by means of the experimental way. The linear stress- strain relationship is not suitable for the analysis of soil deformation. The analyses were performed by using MSC Marc 2007r1 non- linear FEM programm.

The gravity effect was taken into account by applying the gravity acceleration as a body load to simulate the sand weight in the boundary condition.

The cuttting speed in the finite element model was carried out at one constant cutting speed (v=1m/s) in the horizontal direction along the X axis. The sweeps displacement hold on 2-7,5s, but if we set the next crack, the process could be infinite (not steady state).

We used steady motion for cutting acceleration in the model through the sweep displacement in the horizontal direction along the X axis.

To research the effect of tool incline angle (β) on sweep cuttin forces, a series of finite element models were carried out at different constant incline angle (β= 15°, 30°, 45°)

Under the simulation the deformable body (soil) was meshed in a manner of Automatic Global Remeshing.

In the analysis for example the soil, the materials may be deformed from some initial (maybe simple) shape to a final, very often complex shape. During the process, the deformation can be so large that the mesh used to model the materials become highly distorted, and the analysis can not go any further without using some special techniques. Remeshing/rezoning is a useful feature to overcome the difficulties. Although global remeshing can be done manually by using the Rezone option, the automatic global remeshing procedure is recommanded. Global remeshing can only be carried out on a contact body. Therefore, contact bodies are expected in the analysis with global remeshing. When remeshing/rezoning in 2-D Marc finds the outline of the body to be rezoned and repairs the outline to remove possible penetration. Marc then use the mesher to create a new mesh based on the clean outline. This function make the crack growing, and soil failure possible.

RESEARCH RESULTS

As mentioned before, the Drucker- Prager model described sand behaviour through a rate independent constitutive relation. In the cutting process the tools incline angles should show significant effect on the cutting forces. Moreover we postulated, that the moving the sweeps with different constant velocities should not affect the cutting forces but vary the β angle (incline angle) at different rates should affect the cutting forces.

The validity of the assumed predefined crack initial points was examined first in soil bin with artificial soil.

During cutting the most significant variable that could judge the performance of the contact mechanism is the shear stress with crack occurence.

In the mechanics research of the occurences of the cracks growing are independent from the speed and the acceleration. Some results are shown in the figures.

Subsoiler draught and vertical forces were calculated from the summation of forces from interface elements once for every three-displacement steps. The horizontal and vertical components represented draught and vertical forces, respectively. These forces were separately computed for the chisel and shank. Subsequently, total subsoiler forces at a given increment were obtained by the addition of the particular forces of both parts. Fig. 4 illustrates the FEM calculated components of draught force against displacement for the sweep (45°-rake angle). The rate of increase of total draught force is relatively high at low displacement, but then is decreasing by increasing displacement. A total draught force was estimated for this sweep type. The chisel and shank contributes to the total draught force by nearly 60 and 40%, respectively. At each increment up to a displacement of 2.5 cm, each part comprises approximately half of the sweep tool total draught force. However, the particular draught forces after this stage obviously split into two different paths (Fig. 4). The small increase in total draught beyond this level actually results from small increases in sweep draught. The total vertical force increases in magnitude with subsoiler displacement until it reaches a maximum valu. While the particular vertical force of the chisel tends to increase with displacement, the vertical force of the shank tends to decrease with displacement (Fig. 5). The negative vertical force of the shank is the force tending to lift the shank upwards. The overall vertical force of the subsoiler is positive because the magnitude of the shank negative vertical force is less than the chisel positive vertical force. This positive total vertical force pushes the subsoiler downwards, which may introduce a new compaction initiating from the heel of the subsoiler.

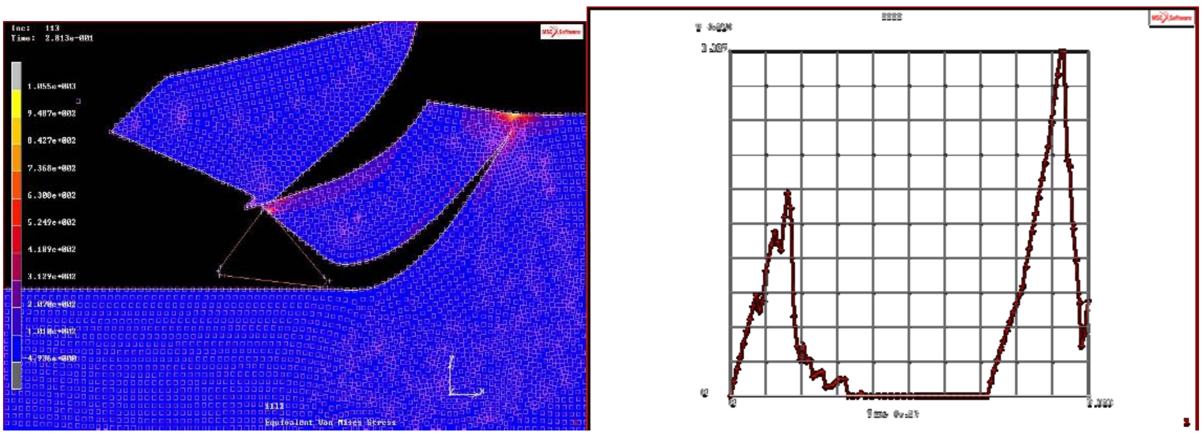

Fig. 4. FEM calculated total sweep draught forces of 45° inclined angle subsoiler and the function of sweep force-displacement. (In loosed soil.)

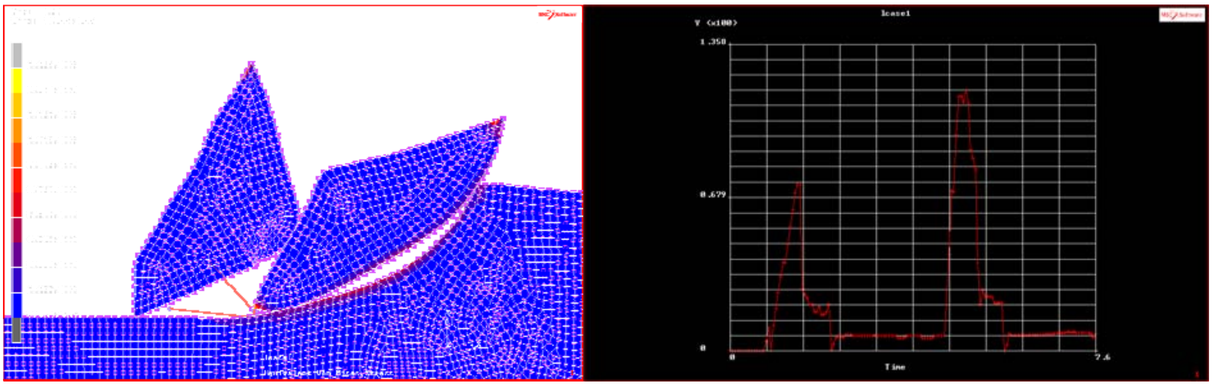

Fig. 5. FEM calculated total sweep draught forces of 45˚ inclined angle subsoiler and the function of sweep force-displacement.

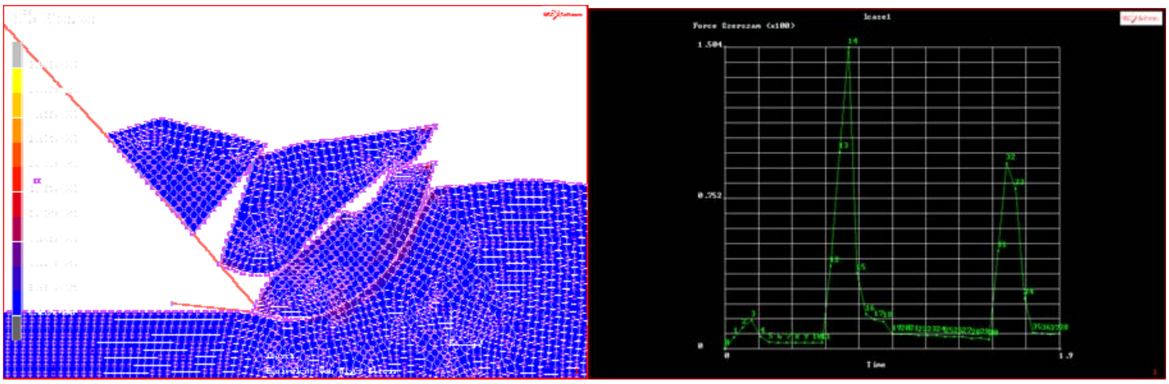

Fig. 6. FEM calculated total sweep draught forces of 40˚ inclined angle subsoiler and the function of sweep force-displacement.

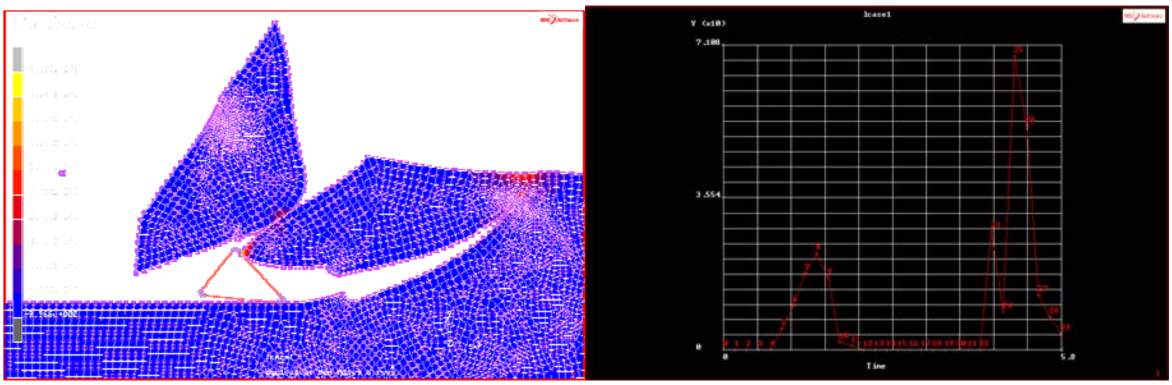

Fig. 7. FEM calculated total sweep draught forces of 45˚ inclined angle subsoiler and the function of sweep force-displacement.

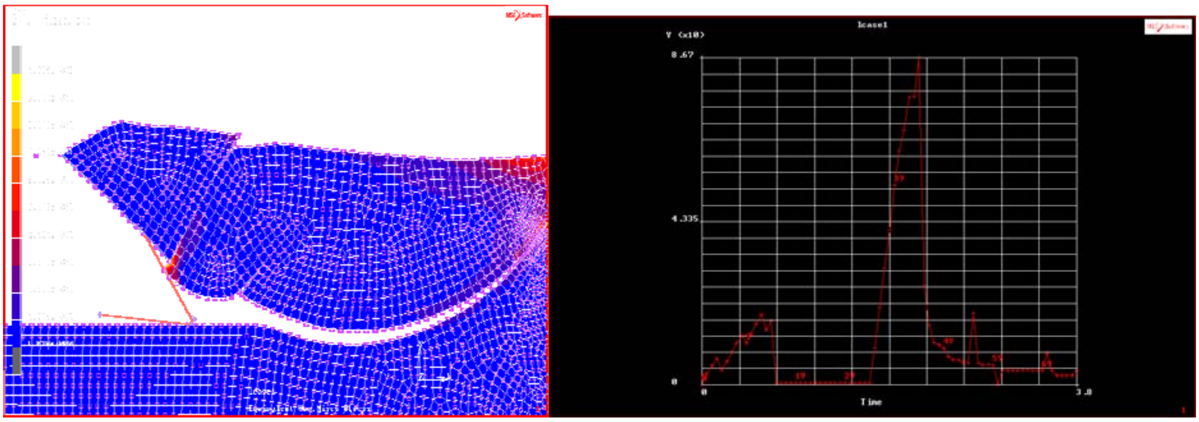

Fig. 8. FEM calculated total sweep draught forces of 60˚ inclined angle subsoiler and the function of sweep force-displacement. (In property of loosed soil.)

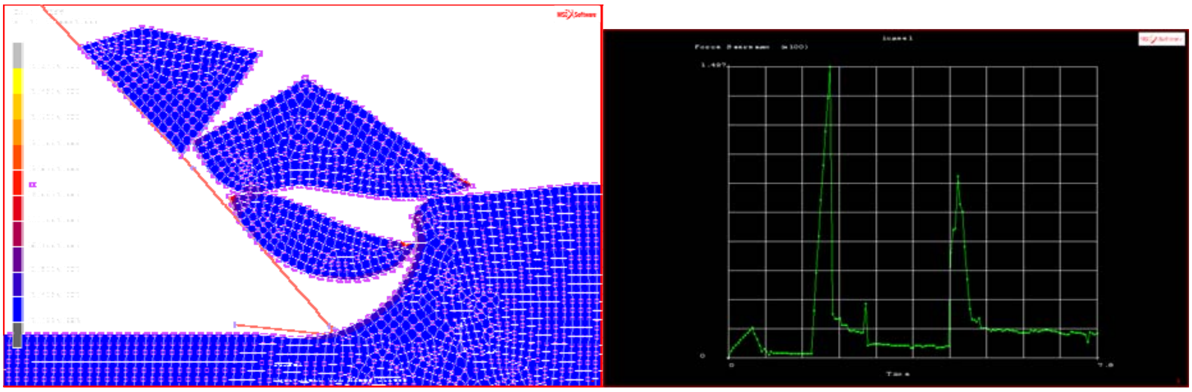

Fig. 9. FEM calculated total sweep draught forces of 45˚ inclined angle subsoiler and the function of sweep force-displacement. (In a hard compacted soil.)

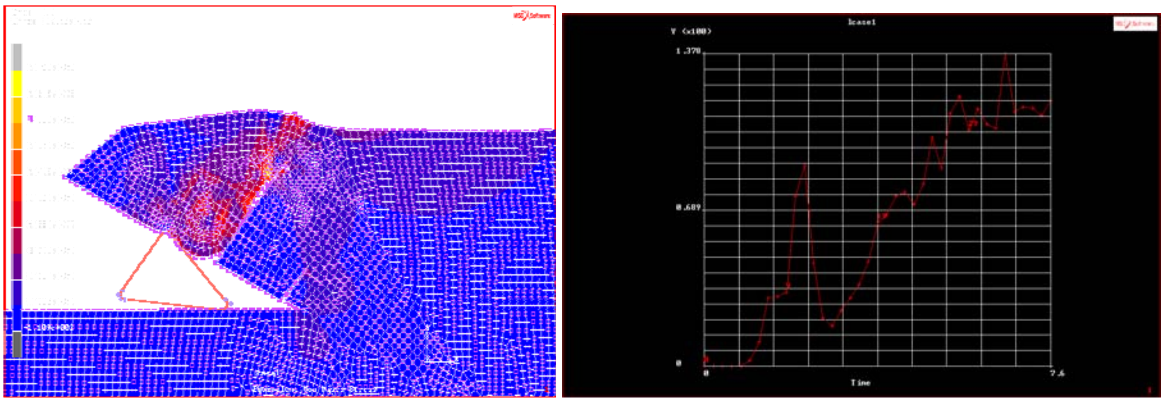

Fig. 10. FEM calculated total sweep draught forces of 45˚ inclined angle subsoiler and the function of sweep force-displacement. (In loamy clay configuration.)

DISCUSSION AND CONCLUSIONS

Results calculated from the FEM model support the following conclusions: 1. The FEM model proved to be an appropriate tool in development and analysis of the performance of cultivator sweeps in particular and soil loosening processes in general.

2. Total draught force calculated from the FEM model for different sweep geometrical types ranged from 10 kN to 250 kN.

The two- dimensional dynamic finite element analyses carried out to simulate soil-tool interaction and the effect of soil properties and the tool inclined angle on predicted cutting forces was studied. The so called Drucker- Prager constitutive model was used to describe the behavior of the simulated sand (isortophic soil) during soil-tool interface process. A series of models were analysed with various soil properties and inclined angles using two- dimensional models. The results showed the significant effect of the tool incline angles on cutting forces.

Therefore, in this study we did the analysis to the second and third cracks, not only to the first fracture (in quasi static), this result could be the draft force in virtual reality.

From the various 2D analysis carried out, some concluding remarks can be made as follows: The concept of VCCT (Virtual Crack Closure Technic) seems to be suitable for modeling the 2D soil-tool interaction problem. The tool incline angle has a significant effect of the cutting forces (increasing).

The varying soil properties (increase of the propertis) results significant effect of cutting forces (increasing).

It can be concluded that the finite element method can be used for simulating the soil cutting processes in non-homogeneous soils and investigation of soil deep loosening and sweep performance. The model can be used in development procedures of soil loosening devices. The amount of prototypes and tests in a soil bin and in the practice can be reduced, because most promising designs can be selected based on FEM simulations. The performance of the prototypes can be analysed with the model and improvements of the prototypes can be made based on this analysis. This will result in a faster and cheaper development procedure with a better chance for successful design.

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. Improvements have been achieved by the recent numerical methods. However, the behavior of large soil deformation during tillage needs to be explored. Problem areas and information gaps existing with regarding soil–tool interaction have been identified

Acknowledgements

The authors wish to acknowledge the instrumentation and the assistance in the field test for the Hungarian Institute of Agricultural Engineering Gödöllő, for offering the possibility of carrying out the soil bin tests and for their kind help and the grant from National Office for Research and Technology.

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