Sensitivity Analysis of Factors Affecting on Finite Element Analysis in Soil- Tool Interaction

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Abstract

In the present study a finite element investigation of the soil tillage process is described using the elastic-plastic constitutive material model. For tillage systems, accurately predicting the forces acting on the blade is of prime importance in helping to enhance productivity. The soil properties, such as soil cohesion, internal friction and Poisson's ratio and the analysis conditions like mesh density in finite element analysis were investigated and its effect on reaction forces were calculated. A 3D finite element analysis of soil–blade interaction was carried out to investigate the behavior of the soil–blade interface and study the effect of soil properties on predicted forces. Results reveal the soil cohesion and soil internal friction has a significant effect on the cutting forces. The soil Poisson's ratio has no significant effect on the reaction forces. Increasing the mesh density cause an increase the accuracy of the analysis and increase the solution time. Results showed that the trend of variation of soil reaction forces with respect to tool displacement is the same at all level of the independent variables.

Keywords: Soil modeling; Sensitivity Analysis; Soil–blade interaction simulation; finite element method

1. Introduction

A tillage operation is a procedure of breaking and loosening of soil. The soil failure mainly depends upon the soil properties, tool geometry and cutting speed. Soil failure under a narrow tillage is a three-dimensional problem. Previous studies on such a problem were usually based on Terzaghi's passive earth pressure theory. Several different analytical models were developed by different researchers [1-4]. These models usually provided fairly simple equations to predict the soil forces on tillage tools. Limit equilibrium principles were applied in developing the soil force equations. These models usually simplified the soil failure ahead of tillage tool into one center wedge and two side crescents. Some models [5, 6] proposed a plane failure surface at the bottom in order to solve the limit equilibrium equation.

In the real situation, when initial cutting begins, the shear failure develops progressively to a total failure ahead of the tillage tool. During cutting, the configuration of soil ahead of the tillage tool and soil-tool interface changes continuously. The relationship between relative displacement and shear stress also varies during soil cutting. All these characteristics of soil-tool interaction during the tillage can not be considered by the models described above. Yong and Hanna [7] proposed for the first time a finite element model for two-dimensional plane soil cutting. This model took into account the effect of the progressive cutting of the soil. Since plane strain was assumed, the Yong-Hanna model was essentially developed for the soil cutting under a wide blade. Many researches have done to model the cutting process using finite element approach [1, 2, and 8]. In order to verify the results of theoretical methods, the experimental tests were done by the researchers. The main question is that how is the reliability of the 3D finite element model results in soil- tool interaction problems. This paper describes a three-dimensional non-linear finite element model for three-dimensional soil cutting under a narrow tillage tool to investigate the effect of independent variables like soil properties on finite element output.

The objective of the present study is to investigate the effects of the soil–tool interface properties on cutting forces using the finite element technique. Also the other aim of this study is to investigate the sensitivity of the input data of the FEM technique on the soil reacting forces.

2. Material and methods

The soil media is modeled as 100×70×80 Cm, (length× width× height) cube of solid material (fig.1). At the places that the cutting blade contacts with soil, the shape of the blade is carved into the soil. For both soil and blade, element solid 45 is used. Solid 45 is a brick element with 8 nodes and 3 degrees of freedom at each node (Ux, Uy, Uz). This element comes in several shapes (Tetrahedral, Hexahedral…). Simulating the blade using the rigid body feature in ANSYS software enables the calculation of the resultant reaction forces acting on the entire blade at a single reference node (pilot point).

Due to the symmetric geometry of the model, one half of the model was simulated but all the results consider the complete model. Two failure surfaces were predefined, one along the horizontal plane in front of the blade-cutting tip and the other along a vertical plane at a distance of 100mm from the symmetric plane and of height 200mm, i.e. along the blade vertical boundary, as shown in Fig. 1. The concept of master and slave contact in ANSYS (contact and target element) was used to simulate the interface between the cutting blade and the soil; and soil itself along the predefined failure surfaces [9]. Relative motion was allowed with friction along the soil–tool and soil–soil interface surfaces. The model was meshed in a manner that increased the mesh density near the blade and the predefined failure surfaces as shown in Fig. 2.

The boundary conditions of the model are (Fig. 2)

1. Bottom base nodes, at Y=0, are fully constrained.
2. Nodes on vertical boundaries parallel to the Y–Z plane, at X=0 and X=1000mm, are constrained in the horizontal direction along X axis.
3. Nodes on vertical boundaries are constrained in the lateral direction along z axis.
4. The blade is constrained in the vertical direction and from any rotation but it is free to move in the horizontal direction along X axis.

Gravity effect was taken into account by applying the gravity acceleration as a body load to simulate the soil weight for a single step. This allowed contact to establish between the soil–blade and soil–soil interface.

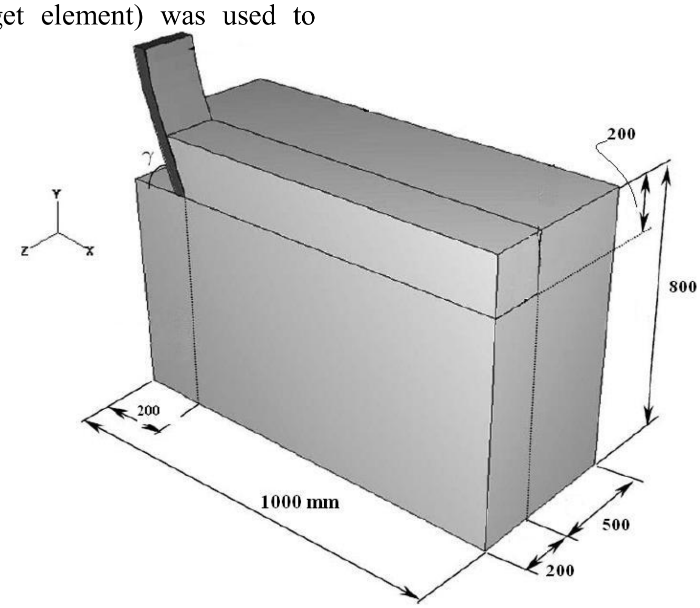

Fig.1. Soil–tool interface model dimensions.

To model the contact surfaces between BL plow and soil media, flexible surface to surface contact elements are used. This kind of contact lets the soil slip on the BL surface and also transfer the loads (forces and displacements) between soil and tillage tool. It also lets the soil separate from blade. All these processes are controlled by parameters like Normal and tangential stiffness. These parameters control the separation and slippage of soil relative to blade, respectively. Furthermore, these two parameters play an important role in convergence of the analysis. Strength behavior of contact is controlled by contact cohesion and friction coefficient and maximum shear stress. Tangential stiffness is measured by direct shear box and coulomb's friction laws. To make a target element it is necessary to put a target element on target surface and a contact element on contact surface as a result the contact element will be automatically produced between these two superficial elements. Targ170 and Cont174 elements are used to produce contact.

The effects of variables on the soil reaction forces were investigated. Variables are: Soil cohesion in three levels (10, 25 and 40 kpa), Soil internal friction in two levels (20° and 30°), Soil Poisson ratio in three levels (0.1, 0.25 and 0.35) and Mesh density in two levels (fine and coarse meshing)

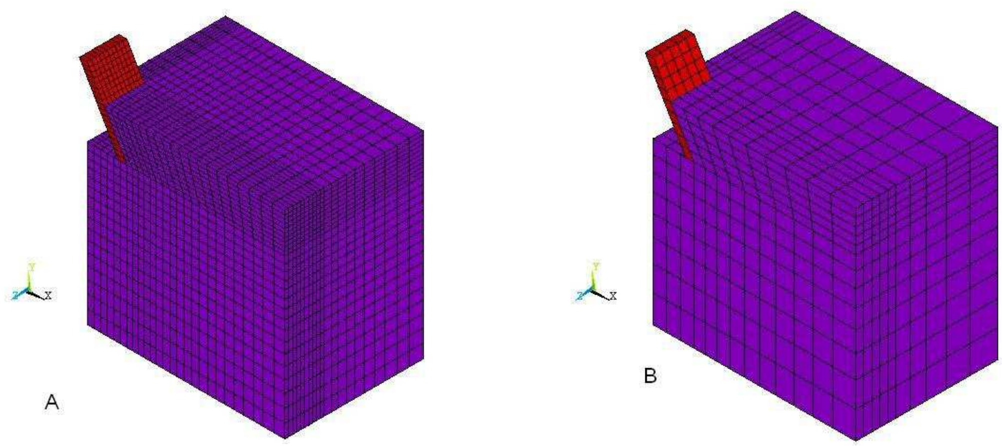

Fig.3. Meshing the soil- blade interface, fine meshing (A) and coarse meshing (B).

3. Results and discussion

The finite element results extracted from sensitivity analysis were calculated. The sensitivity of the reacting forces with respect to the input data was measured. The rate of increase of draught force is relatively high at low displacement, and levels out as displacement further increases. The reason for this process is that the plastic strain in each element occurs under very low displacement. In the next step of tool motion, the yielded elements transfer forces to their adjacent element and their force tends to become constant. The trend of reaction force variation with respect to the tillage tool displacement in different level of soil cohesion, soil internal friction, soil Poisson's ratio and the mesh density was calculated and compared. The results in summery are:

3.1. 3.1 The effect of soil cohesion

The variation of draft force with respect to tool displacement at three level of soil cohesion showed that any increase in soil cohesion cause an increase in the steady state level of horizontal draft force. The maximum horizontal draft force has seen in the maximum level of soil cohesion. The direct relation between the soil cohesion and soil stiffness might be the main reason of such difference (fig.3). The trend of horizontal draft force variation with respect to tillage tool displacement is similar to the hyperbolic stress- strain curve. In the loosen soils the draft force will be reached to the

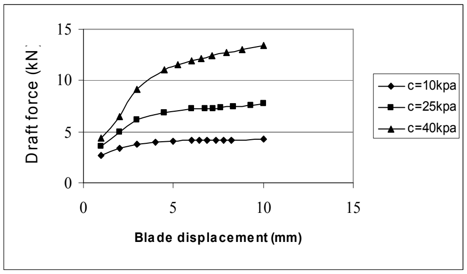

Figure.3. Variation of horizontal draft force according to the tool displacement at various level of soil cohesion.

maximum level sooner than that of in the soil with higher cohesion. This is the main reason that the finite element analyses were diverged in the loosen soil sooner than the hard soil, because the soil elements will reach to the maximum allowable plastic strain in a lower displacement.

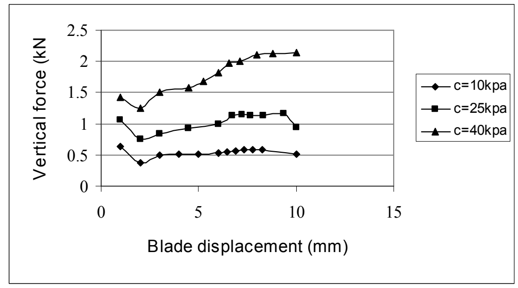

Figure.4. Variation of vertical reaction force according to the tool displacement at various level of soil cohesion.

The variation of vertical reacting force according to the tool displacement at three levels of soil cohesion showed that the force will level out after initial fluctuations. The trend of the variation of the vertical force is the same at different level of soil cohesion but the steady state vertical force level is higher in more cohesive soils than less cohesive soils. The calculated results showed that in the range of 15-40 kg/cm3 soil cohesion, the sensitivity of the variation of draft force and vertical force are 26.6 $\frac{kN}{kg/cm^2}$ and 0.05 $\frac{kN}{kg/cm^2}$ respectively.

3.2 The effect of soil internal friction

The variation of horizontal draft force according to tool displacement in various frictions is similar to an elastic-plastic material model graph. Results showed that the trend of force variation is merely the same at 20°, 30° and 35° soil friction angle (figures 5 and 6).

3.3.3.3 The effect of soil Poisson's ratio

Poisson's ratio is one of the most important parameters witch affect on elastic volumetric soil strain. Figures 7 and 8 showed that the Poisson's ratio has no significant effect on the soil reaction forces. As a matter of fact the sensitivity of the reaction forces with respect to Poisson's ratio is near zero. The reason is that the Poisson's ratio has affected on the elastic volumetric strain while the amount of soil reaction forces is depend on plastic strain.

Results revealed that the soil internal friction has affect on the position of maximum level of the force. For example for 35° soil friction angle the analysis have diverged after 3mm tool displacement while this value is near 8mm for 20° soil friction angle. The main reason of such divergence is that the tangential component of friction force in frictional soils is approached to its maximum level and the normal component is approached to its minimum level. Decreasing the normal force may cause the analysis to diverge. The other reason of such divergence is using the non-Associated flow rule during the present study. The analyses with associated flow rule concept in which the soil friction angle is equal to flow angle, have diverged after longer tool displacement than non associated one. Increasing the volumetric plastic strain in soil due to associated flow rule analyses is the main reason of increasing the soil reacting forces.

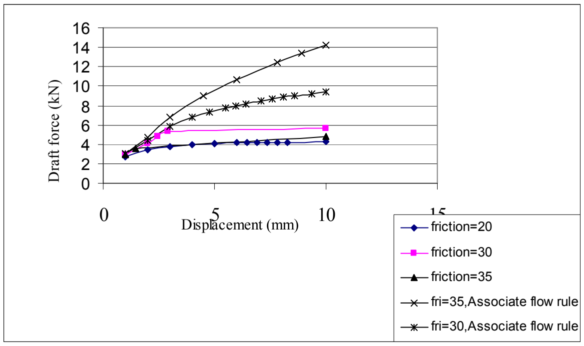

Figure.5. Variation of horizontal draft force according to the tool displacement at various level of soil friction.

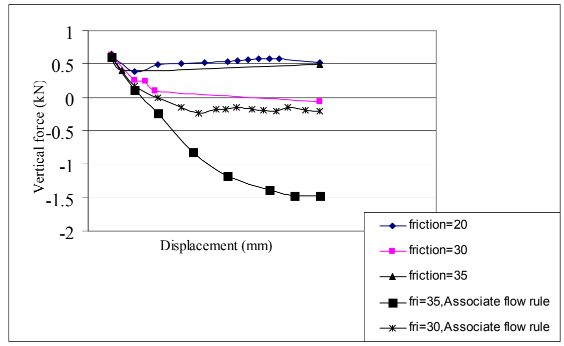

Figure.6. Variation of vertical reaction force according to the tool displacement at various level of soil friction.

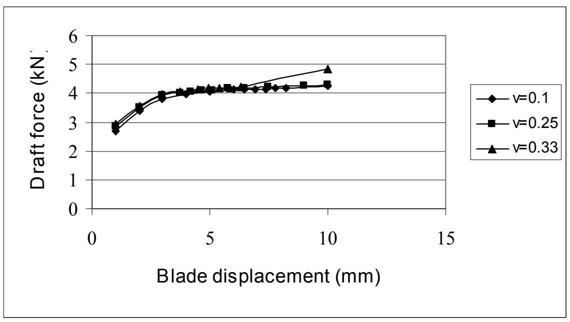

Figure.7. Variation of horizontal draft force according to the tool displacement at various level of soil Poisson's ratio.

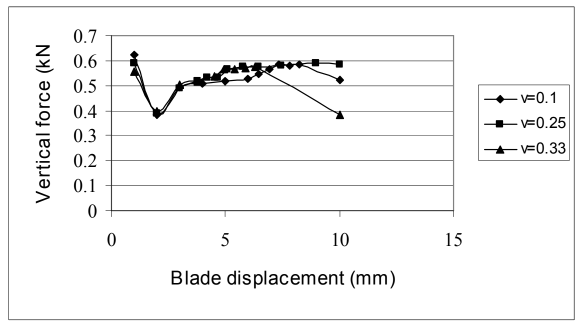

Figure.8. Variation of vertical force according to the tool displacement at various level of soil Poisson's ratio.

3.4 The effect of mesh density

The effect of mesh density on the reliability of the 3D finite element model was investigated at two level of mesh density. The soil was meshed to 10 elements per width of cutting blade in fine meshing while in coarse meshing the width of blade was divided into 5 elements. Mesh density was found to have a very significant effect on the predicted results when using elastic-plastic material models to simulate soil–blade interface problem. To investigate the effect of the mesh density on the predicted finite element results of a 3D soil–blade interaction, a series of 3D finite element models was carried out for different various mesh densities and for 15mm of blade displacement. Predicted cutting forces acting on the blade in both draft and vertical directions were monitored during each finite element analysis and presented in Figs. 9 and 10, respectively, through 15mm of horizontal blade displacement. Fig. 9 represents the progress in draft cutting forces as the blade moves horizontally and Fig. 10 represents the progress in vertical cutting forces as the blade moves horizontally using various mesh densities. From these two figures it is noticeable that the mesh density has a very significant effect on the predicted forces in both draft and vertical directions in that as the mesh density increases the predicted forces decreases. For example, the reduction of the predicted forces can be in the order of 25% with slight increase in the mesh density. Results showed that to obtain a highly accurate quantitative analysis, a very dense mesh should be considered with an expected 2-day run time using a dual xenon 1 GHz processor PC with 500MB of memory.

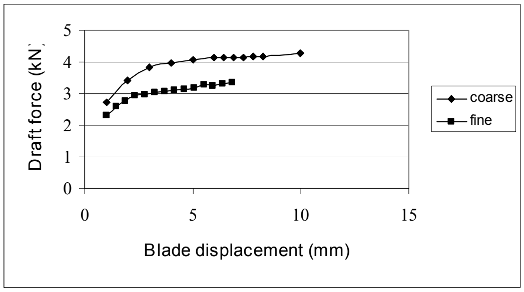

Figure.9. Variation of horizontal draft force according to the tool displacement at various level of mesh density.

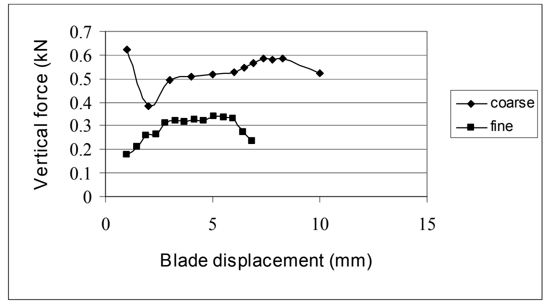

Figure.9. Variation of vertical force according to the tool displacement at various level of mesh density.

4. Conclusion

The 3D finite element analyses have been carried to simulate soil–blade interaction and study the effect of blade soil properties and mesh density on predicted cutting forces in both draft and vertical directions. The so called elastic-plastic constitutive model was used to describe the behavior of the simulated soil in monotonic loading. The mesh density was found to have a significant effect on the predicted results. So only a qualitative study has been reported here. A series of models were analyzed concerning various soil cohesion, soil internal friction, soil Poisson's ratio and mesh densities using 3D models. From the various 3D analyses carried out, some concluding remarks can be made as follows:

1. Soil cohesion and soil internal friction has a significant effect on the cutting forces. The trend of variation of reacting forces according to blade displacement is the same at various levels of cohesion and friction.
2. The mesh density has a significant effect on the predicted results in both draft and vertical directions in that as the mesh increases the predicted forces decreases. Changing the flow rule to associated flow rule cause an increase the reaction forces.
3. The soil Poisson's ratio has no significant effect on the reaction forces.

5. References:

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