A nonlinear 3-D finite element analysis of soil forces on curved tillage tools

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Chi, L. and Kushwaha, R.L. 1993. **A nonlinear 3-D finite element analysis of soil forces on curved tillage tools**. Can. Agric. Eng. **35**: 011-015. A three-dimensional non-linear finite element model was used to study the effect of blade curvature on tillage tool draft. Two types of curved tools were considered. The hyperbolic constitutive model was used in the analysis. The results from the finite element model show that the draft decreased with increasing curvature for a constant tool angle at the soil surface, and increased with increasing curvature for a constant angle at the furrow bottom.
Keywords: Finite element method, tillage tools, curved blade, soil forces
Un modèle à éléments finis non-linéaire et tridimensionnel a été utilisé pour étudier l'effet de la courbure de la lame d'un instrument de travail du sol sur l'effort de traction. Deux types d'outil courbé ont été considérés. Le modèle constitutif hyperbolique a été utilisé pour l'analyse. Les résultats obtenus avec le modèle à éléments finis ont montré que l'effort de traction augmentait avec l'accroissement de la courbure d'un outil à angle constant à la surface du sol, et augmentait avec l'accroissement de la courbure à angle constant sous le sillon.

INTRODUCTION

Tillage is a procedure of breaking and loosening of soil. The soil failure mainly depends upon the soil properties, tool geometry, and cutting speed. Soil dynamics research was conducted as early as about 1920 and a large research effort has been continued since 1950. In spite of advances made in recent years, tillage is still not an exact science. Almost all of the soil cutting tools used in agriculture have been developed by field experiment and designed by trial and error of field prototypes.

Initially, a theoretical approach to the soil cutting problem was based on the well-known Terzaghi's passive earth pressure theory (Terzaghi 1943). Several three-dimensional soil cutting models were proposed by different researchers (Hettiaratchi and Reece 1967; Godwin and Spoor 1977; McKyes and Ali 1977; Perumpral et al. 1983; Swick and Perumpral 1988) based on Terzaghi's passive earth pressure theory. These models usually provided fairly simple equations to evaluate the soil forces on the tool. However, most of the above models can only be used for a static situation. Because of the simplifications made during modelling, none of the above models could account for the effect of different tool shapes, especially if the tools were curved.

As computers became more accessible, the numerical method was developed to solve the soil cutting problem. Yong and Hanna (1977) proposed a finite element model for two-dimensional soil failure with a wide blade. Chi and Kushwaha (1989) developed a three-dimensional finite element model for a narrow cutting blade. The finite element method showed a capability of simulating different tool shapes. Chi and Kushwaha (1991) studied soil forces on flat and triangular blades. Measurement of soil forces in the soil bin showed a close agreement with practical results.

The objectives of this project were (1) to study the effect of tool curvature on soil forces using the finite element method; (2) to develop the finite element procedure for different tool curvatures and operating angles; and (3) to compare the results from finite element analysis for curved blades with the results from straight flat tools.

PROCEDURE

Finite element model

A three-dimensional finite element model for predicting soil forces with simple tillage tools was developed by Chi and Kushwaha (1989). The model employed an incremental procedure to solve the nonlinear behavior of soil and the interaction between the soil and the tool surface. The finite element model used is described by:

$$\int_{\Omega_e} (D\Phi)^T C D\Phi \, \Delta u_j^e d\Omega_e = \int_{\Omega_e} (D\Phi)^T \sigma_o d\Phi_e + \int_{\Omega_e} \Phi^T f d\Omega_e - \int_{\Gamma_e} \Phi^T p d\Gamma_e \tag{1}$$

where:

D = differential operator matrix,
Φ = shape function matrix,
C = constitutive matrix,
Δu_{je} = nodal displacement increment vector,
σ_o = initial stress vector,
f = body force vector,
p = surface compression vector,
Ω_e = element domain, and
Γ_e = boundary surface of the element.

Equation 1 can be written in short form as:

$$K^e \Delta u_j^e = F^e \tag{2}$$

where K^e is element stiffness matrix and F^e is element load vector. The element load vector includes three terms: 1) initial stress term, 2) body force term, and 3) the surface compression term.

The constitutive relationship of soil

As the soil is a non-linear stress-strain material, the tangent modulus (E_t) changes with the state of stress. Kondner and Zelasko (1963) proposed a hyperbolic model to represent a typical stress-strain relationship of the soil. Duncan and Chang (1970) developed an equation of the tangent modulus (E_t) based upon Kondner's model which is :

$$E_t = \left[1 - \frac{R_f(1-\sin\phi)(\sigma_1+\sigma_3)}{2c\cos\phi + 2(\sigma_3+P_a)\sin\phi}\right]^2 KP_a\left[\frac{\sigma_3+P_a}{P_a}\right]^n \quad (3)$$

where:

E_t = tangent modules of soil (kPa),
c = cohesion of soil (kPa),
ϕ = internal friction angle of soil (degrees)
P_a = atmospheric pressure (kPa),
σ_1 = major principal stress (kPa),
σ_3 = minor principal stress (kPa),
R_f = failure ratio, and
K, n = dimensionless numbers.

This tangent modulus equation and the constitutive matrix used in the model are described by Chi and Kushwaha (1991). The soil parameters for the constitutive equation were obtained from triaxial tests. The soil and tool parameters used in the analysis are listed in Table I. The soil used in these tests was clay loam.

Table. I. Soil properties for nonlinear finite element analysis

Terms	Value
Parameters of initial modulus of soil:	
K	18.10
n	0.0
cohesion of soil, c	7.19 kPa
internal friction angle of soil ,	34.5 degree
soil density,	1.46 Mg/m^3
Poisson's ratio,	0.329
failure ratio, R_f	0.800
Parameters of interface of soil-tool:	
K_i	26.57 kPa/mm
n_i	0.8437
adhesion, c_a	3.288 kPa
external friction angle,	23.5 degree
failure ratio, R_{fi}	0.887
Tillage blade parameters:	
depth, d	100 mm
width, w	50 mm

Interface element

Adhesion and friction exists between the soil and the surface of the cutting blade. These friction forces affect the draft and lift forces significantly. One effective way to investigate these effects in the finite element method is to introduce an interface element between the soil and the tool surface.

Several constitutive models have been developed for soil-tool interface. Desai et al. (1984) developed an elasto-plastic interface model. In this model, the shear stress increases linearly with the relative displacement before the shear stress reaches its maximum failure value. After reaching its maximum value, the shear stress remains constant. The tangent shear modulus becomes zero after the maximum shear stress is reached. Bekker (1960) proposed an exponential stress-relative displacement function for loose soil. Clough and Duncan (1971) proposed a hyperbolic model for the interface between the soil and wall structure.

Laboratory tests were conducted in a modified shear box to study adhesion and friction characteristics between soil and the tillage tool metal. The shear stress and relative displacement curves obtained from shear box tests were largely nonlinear. The results also show that the hyperbolic model (Clough and Duncan 1971) provided a better prediction of the test data; therefore, the hyperbolic model was used in the finite element analysis.

The tangent modulus of the interface element was derived using the hyperbolic model by Chi and Kushwaha (1991) which is:

$$K_\tau = K_i\left(\frac{\sigma_n + P_a}{P_a}\right)^{n_i}\left(1 - \frac{R_{fi}\tau}{\tau_{max}}\right)^2 \quad (4)$$

where:

K_τ = tangent modulus of soil-tool interface (kPa),
R_{fi} = failure ratio of soil-tool interface,
τ_{max} = maximum shear stress (kPa),
τ = shear stress (kPa),
K_i, = parameters obtained from tests (kPa/mm), and
n_i = parameters obtained from tests (dimensionless).

The maximum shear stress was defined as:

$$\tau_{max} = C_a + \sigma_n \tan\delta \quad (5)$$

where:

C_a = adhesion between soil and cutting blade (kPa),
σ_n = normal stress (kPa), and
δ = friction angle between soil and blade (degrees).

Stress correction

The tangent modulus was calculated from the element stresses. In the incremental procedure, the soil stress increases with the increase in the blade displacement. The soil stress should not fall outside the failure surface during loading. However, since a residual modulus was assigned to the element after the element failure, a stress level outside of the failure surface occurred sometimes. This incorrect stress level could affect the boundary forces calculated for the later increments. Therefore, the stress level was corrected back to the failure surface. During the stress correction, the stress state was brought back to the failure surface in the normal direction according to the procedure described by Chi and Kushwaha (1991). An iteration method was used and the procedure was repeated until a satisfactory convergence was reached.

Finite element mesh

The tool angle of a curved blade at the soil surface changes with depth. To simplify the problem, circular curves were used for the blade shape. Two sets of finite element analyses were conducted. In the first set, the tool angle at the soil surface was selected as vertical (90 degree rake angle) and the tool angle at the furrow bottom was changed as 90 degree (straight blade), 60 degree, 30 degree and 0 degree (most curved blade) as shown in Fig. 1. In second set of finite element analysis, the tool angle was set at 30 degree at the furrow bottom and the tool angle at soil surface was changed from 30 degree (straight blade) to 90 degree (most curved blade) (Fig. 1). Figure 2 shows a typical finite element mesh with 60-degree tool angle at the soil surface and 30-degree tool angle at the furrow bottom.

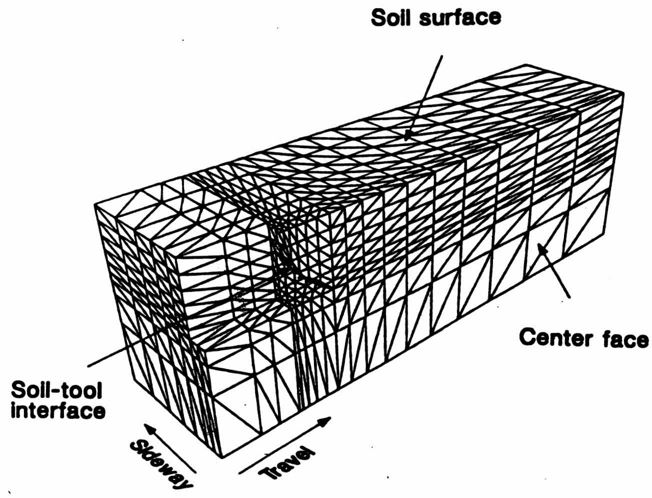

Fig.. 2 Finite element mesh with tool angle of 60-degree at soil surface and 30-degree at the furrow bottom.

RESULTS AND DISCUSSION

A force-displacement curve was obtained from the incremental finite element analysis as shown in Figs. 3 and 4. Displacement loading was used in the finite element analysis. The draft force increased as the tool moved along the direction of travel. When the displacement increased to a certain point, the soil ahead of the tillage tool collapsed. A maximum draft force was obtained at this failure point (Figs. 3 and 4). At this failure point, a failure zone ahead of the tillage tool was obtained by marking the failed elements as shown in Figs. 5 and 6. This failure zone indicates a pattern of soil failure in front of the tool. These failure zones are similar to those assumed by Godwin and Spoor (1977) and McKyes and Ali (1977) in their soil failure analysis. The draft force at this failure point was used as the required draft for tillage operation.

The predicted draft forces for different curvatures were compared, as shown in Figs. 7 and 8. For a 90-degree tool angle at the soil surface, increasing curvature decreased the tool angle at the furrow bottom. Therefore, the resistance to soil movement was reduced and lower drafts were obtained

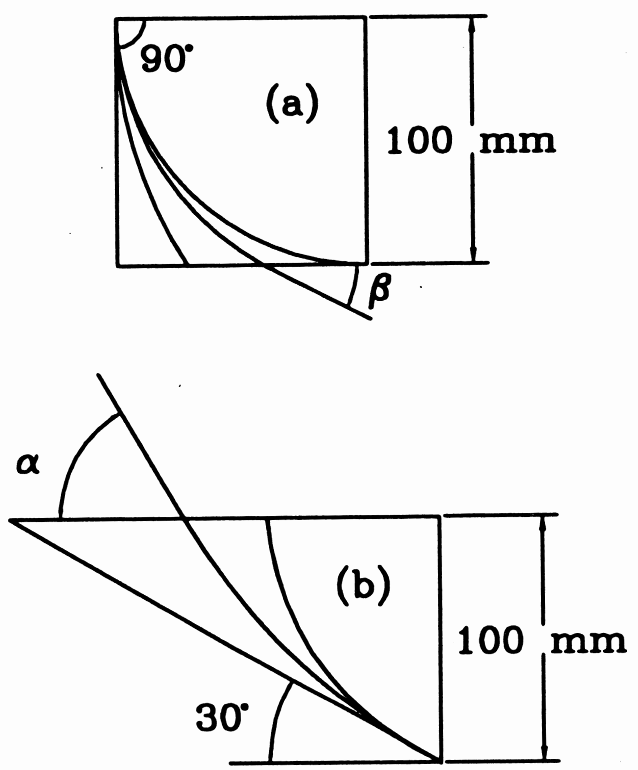

Fig. 1. Curved tools (a) with a 90-degree angle at soil surface and (b) with a 30-degree angle at the furrow bottom.

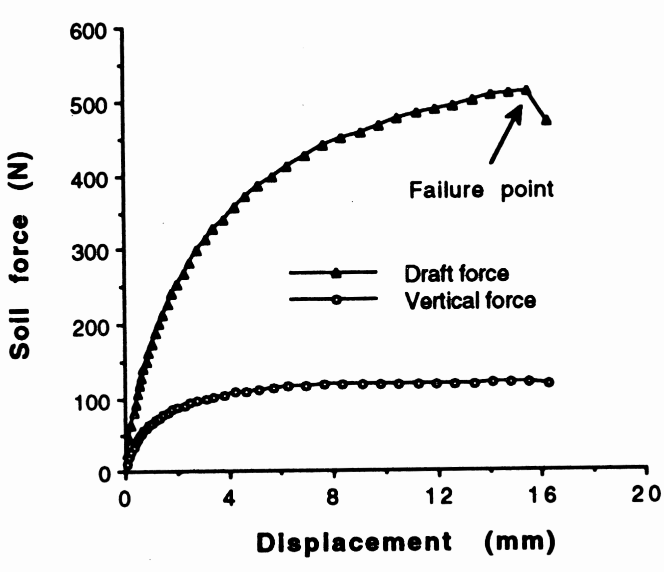

Fig. 3. Force-displacement curve of a curved blade with 90-degree tool angle at tool surface and 30-degree tool angle at the furrow bottom.

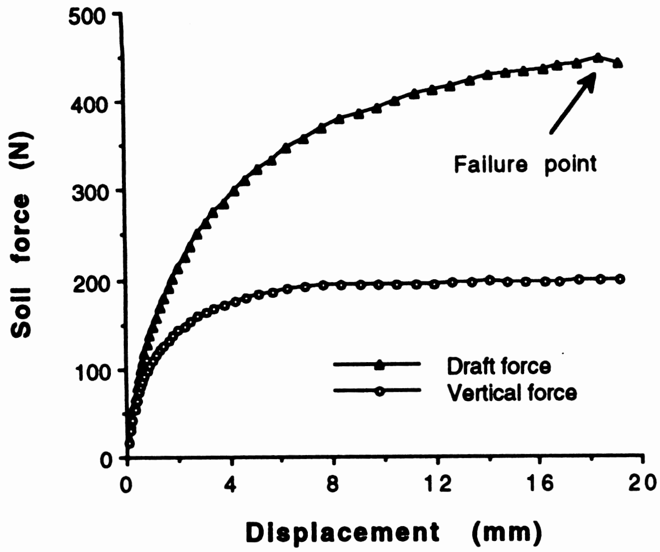

Fig. 4. Force-displacement curve of a curved blade with 60-degree tool angle at tool surface and 30-degree tool angle at the furrow bottom.

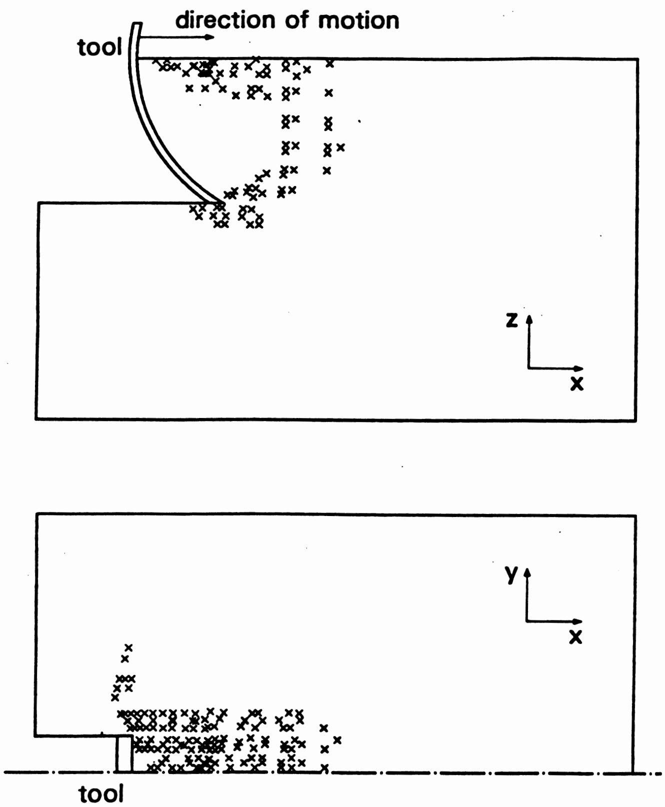

Fig. 5. Soil failure zone of a curved blade with 90-degree tool angle at soil surface and 30-degree tool angle at the furrow bottom; (a) vertical soil failure and (b) horizontal soil failure.

by using curved blade as shown in Fig. 7. Figure 7 also indicates that the minimum daft was obtained for a curved blade with a 30-degree tool angle at the furrow bottom. When the tool angle was fixed as 30-degree at the furrow bottom, increasing curvature increased the tool angle at the soil surface. The increase in tool angle at the soil surface resulted in the increase in resistance to soil movement in front of the tool. In this case, the draft was increased by using the curved blade as shown in Fig. 8. The straight blade with tool angle of 30-degree at both top and bottom provided minimum

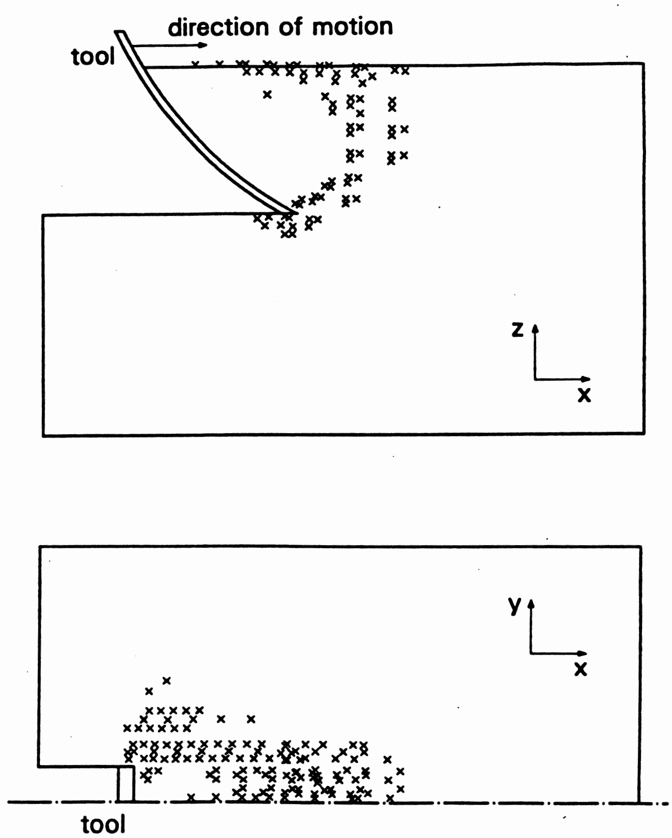

Fig. 6. Soil failure zone of a curved blade with 60-degree tool angle at soil surface and 30-degree tool angle at the furrow bottom; (a) vertical soil failure and (b) horizontal soil failure.

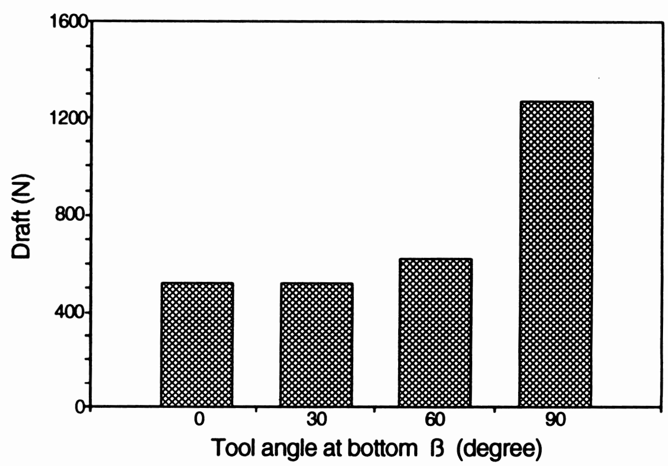

Fig. 7. Draft with various tool angles at the furrow bottom for the blades with a fixed angle (90-degree) at soil surface.

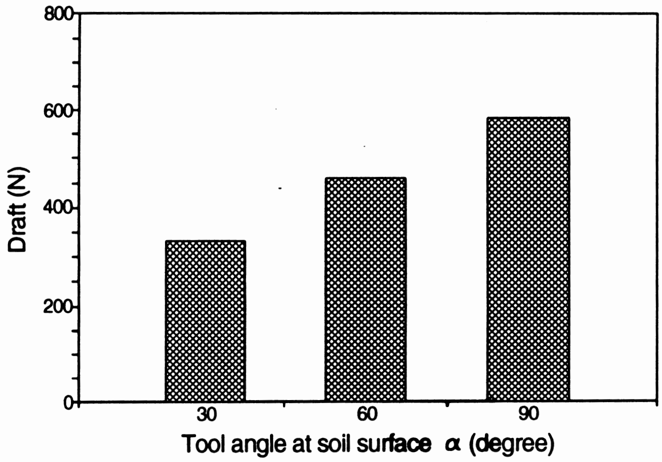

Fig. 8. Draft with various surface angles for the blades with a fixed tool angle (30-degree) at the furrow bottom.

draft (Fig. 8). The finite element prediction of the draft for a straight cutting blade was verified with the results from a soil bin test (Chi and Kushwaha 1991). The comparison of draft force from soil bin tests showed that the finite element model predicted accurate draft force for the straight blade.

The results of the finite element analysis showed that the tool angle of the curved blade played a principal role in determining the extent of the draft forces. Using the curved soil cutting blade did not decrease the draft under all conditions.

CONCLUSIONS

A three-dimensional nonlinear finite element model used to study the effect of blade curvature on tillage tool draft showed good predictions for draft forces similar to the ones obtained in previous research.

For a fixed tool angle at the soil surface, increasing the curvature of the tool decreased the resistance to soil movement and reduced the tillage draft.

For a fixed tool angle at the furrow bottom, increasing the tool curvature increased resistance to soil movement and tillage draft.

The magnitude of the draft of the curved tillage tool operating at a constant depth depended on the tool operating angle.

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