Large deformation modeling in soil-tillage tool interaction using advanced 3D nonlinear finite element approach

R. Jafari, T. Tavakoli Hashjin,S. Minaee, M.H. Raoufat
The authors are Ramin Jafari, Ph.D. Student, Department of Agricultural Machinery, College of Agriculture, Tarbiat Modares University, Tehran, Iran, and Teymour Tavakoli Hashjin, Associated Professor, Department of Agricultural Machinery, College of Agriculture, Tarbiat Modarres University, Tehran, Iran, Saeed Minaee, Assistant Professor, Department of Agricultural Machinery, College of Agriculture, Tarbiat Modarres University, Tehran, Iran, Mohammad Hosein Raoufat, Associated Professor, Department of Agricultural Machinery, College of Agriculture, Shiraz University, Iran, Corresponding author: Ramin Jafari, Department of Agricultural Machinery, College of Agriculture, Tarbiat Modares University, Tehran, Iran; phone: +989173131241; fax: +98-21-6026524 ;

Abstract: - This paper aims to introduce a finite element model to investigate the performance of bent leg (BL) plow and investigate the performance of new design as compared to a conventional one using finite element method approach (FEM).The difference between the modified and conventional BL plows is the direction of angle between the projection of cutting blade on horizontal plane normal to plow shank and the line perpendicular to the plow shank in the same plane. The effects of BL plow geometry on plow performance for both plows were studied and the results were verified experimentally. Conventional (B1), and modified (B2) designs of BL plow were modeled at three rake angles (R1= 7.5°, R2= 15° and R3= 22.5°), therefore a total six treatments were considered for both theoretical and experimental studies. A three dimensional non linear finite element model was developed using appropriate FEM software (ANSYS 8.1). The soil media was considered as elastic-perfectly plastic with Drucker-Prager material model. Soil meshing, contact elements and soil frictional properties were updated after each incremental time step. Variation of draft force as calculated by the FEM model indicates that the minimum and maximum draft forces correspond to B2R2 and B1R3 treatments respectively. The experimental results of draft force were in good agreement with predicted data.

Key-Words: - finite element method; large deformation; Modified bent leg plow; soil forces

1. Introduction

Several researchers have developed FEM models of soil cutting by simple tillage tools, subsoilers and disk plows (Yong and Hanna, 1977; Kushwaha, 1995; Fielke, 1999; Mouazen and Nemenyi, 1999; Abo-Elnor et al., 2004; Abu hamed and Reeder, 2003). However available literatures on 3D FEM analysis of soil tillage by unsymmetrical tillage tools are scarce. The unsymmetrical shape of BL plow and a narrow thickness of its blade requires that the analysis to be nonlinear in both geometrical and material aspects. Furthermore large deformation imposes geometrical nonlinearity in the present analysis. Geometrical nonlinearity happens when a node corresponding to an element in FE analysis moves larger than its elemental size. Also nonlinear soil material model and the nature of contact element increase the degree of nonlinearity of analysis.

It is note worthy that during soil failure by tillage tool; cracks propagation as well as soil separation is generated at different locations throughout the entire soil body. But as the FEM tends to discrete the material domain into finite number of elements (connected by finite number of nodes maintaining the continuity at all times throughout the analysis). The modeling of cracks in FE analysis is practically impossible. Therefore positions where soil failure may occur are located by recognizing the shear distribution field. A high shear stress generated at any given point indicates the locations where the soil failure happens as cracks separations. This will be followed in this study at the determination of soil failure positions in order to overcome the disadvantage of the FEM in doing so.

This paper aims to:

1. Develop a modified model of BL plow to consume low draft force and increase soil disturbance efficiency.
2. Model the tillage process by BL plow in conventional and modified designs using FEM approach.
3. Compare draft and vertical forces of BL plow calculated by FEM and measured experimentally.
4. To investigate the effect of design parameters of BL plow on the variation of tensile, compressive and shear stress in soil.

2. Materials and Methods

2.1. Blade geometry

The difference between conventional and modified bent leg plows is the angle between the projection of cutting blade on horizontal plane and the line normal to the plow shank. This angle in conventional model is inclined toward the front of the shank where for modified plow this angle is inclined toward rear of the shank. The dimension of shank and blade assembly is seen in fig.1.

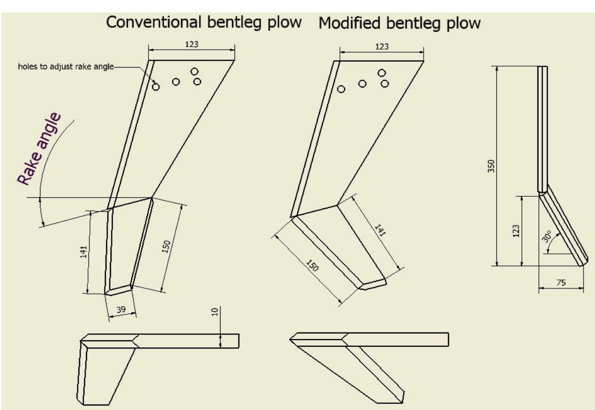

Fig.1. Dimensions in millimeters of the BL plow assembly developed in this study.

Rake angle is defined as an angle between shank- blade interfaces with horizontal line parallel to travel direction. A total of four different rake angles could be obtained by rotating the plow about the horizontal axis (z-axis) using the holes on plow shank. In order to achieve a deeper penetration and reduce the soil resistance, the cutting edge of both plows were sharpened to 45°. Preliminary soil-bin experiments by authors indicate that the modified BL plow tills better than conventional one especially at rake angle of 15° (Jafari *et al*, 2005).

2.2. Finite element formulation

The Elastic-Plastic model describes an elastic, perfectly plastic relationship. Stresses are directly proportional to strain until the yield point is reached. Beyond the yield point, the stress-strain curve is perfectly horizontal. A function which describes the locus of the yield point is called the yield function. The yield function of the Drucker- Prager elastic perfectly plastic material model (F) can be expressed as follows (Ansys documentation):

$$F = 3\beta\sigma_m + [\frac{1}{2}\{S\}^T[M]\{S\}]^{0.5}$$

Where:

σ_m = the mean or hydrostatic stress= $\frac{1}{3}(\sigma_x + \sigma_y + \sigma_z)$

{S}= the deviatoric stress equation

β = material constant and is equal to

$$\beta = \frac{2Sin\varphi}{\sqrt{3}(3 - Sin\varphi)}$$

The material yield parameter is defined as

$$\sigma_y = \frac{6cCos\varphi}{\sqrt{3}(3 - Sin\varphi)}$$

Where:

C and φ are the input soil cohesion value and angle of soil internal friction, respectively.

Soil plasticity is formulated using the theory of incremental plasticity (Hill, 1950). Once a material begins to yield, the incremental strain can be divided into elastic and plastic components.

$$\{d\varepsilon\} = \{d\varepsilon^p\} + \{d\varepsilon^e\}$$

Only elastic strain increments $d\varepsilon^e$ will cause stress changes. As a result, stress increments can be written as follows:

$$\{d\sigma\} = [C_e]\{d\varepsilon^e\} = [C_e](\{d\varepsilon\} - \{d\varepsilon^p\})$$

A yield function, F, is a function of normal and shear stress, so an incremental change in the yield function is given by:

$$dF = \frac{\partial F}{\partial \sigma_x} d\sigma_x + \frac{\partial F}{\partial \sigma_y} d\sigma_y + \frac{\partial F}{\partial \sigma_z} d\sigma_z + \frac{\partial F}{\partial \tau_{xy}} d\tau_{xy} = \{\frac{\partial F}{\partial \sigma}\}\{d\sigma\}$$

The theory of incremental plasticity dictates dF will be equal to zero when the stress state is on the yield surface. This condition is termed the natural loading condition, and can be written mathematically as:

$$dF = \{\frac{\partial F}{\partial \sigma}\}\{d\sigma\} = 0$$

The plastic strain is postulated to be:

$$\{d\varepsilon_p\} = \lambda\{\frac{\partial G}{\partial \sigma}\}$$

Where, G and λ are plastic potential function and plastic scaling factors, respectively.

Finally the incremental stress corresponding to a given incremental strain is obtained as follows:

$$\{d\sigma\} = ([C_e] - [C_p])\{d\varepsilon\}$$

2.3. Finite element mesh and boundry conditions

The soil media is modeled as 100×80×50 Cm, (length× width× height) cube of solid material. At the places that BL contacts with soil, the shape of BL plow 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 (U_x, U_y, U_z). This element comes in several shapes (Tetrahedral, Hexahedral…). For BL and the soil in the vicinity of BL, mapped hexahedral brick elements are used. In other parts of the soil in which this shape of element couldn't be used, free tetrahedral elements are placed. Since the thickness of BL plow is only 1 Cm, the size of elements of BL could be utmost 1 Cm and the size of soil elements in contact with plow should be the same. More than 21000 elements are used in this model. Most of the analysis was carried out through 30 mm of blade displacement in the horizontal plane along the x axis direction. For a typical 3D model, a solution time of about 10 hours was needed to account for whole 30 mm displacement using P5 computer with 1024 MB memory. Another reason for choosing 30 mm blade displacement is the blade forces have reached a steady state during this time period as mentioned by Abo-Elnor, *etal*, 2004. Very dense mesh is used to obtain a highly accurate quantitative analysis.

Each face of soil media is constrained so it couldn't move normal to the face. The nodes on blade- soil interface have a specific displacement along blade surface. Also the internal nodes are free in three directions. The boundary conditions considered on the BL plow is so that prevents all of its displacement and rotation unless in the direction of tool travel. In this direction a controlled displacement is imposed on a pilot point. A pilot point is a point that is joined to some parts of BL and all movement and forces of this point automatically transfer to whole body of BL plow.

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 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.

FE analysis is funded on a small displacement meaning that one can impose a displacement up to 15% of element size to an element. Some programs like ANSYS upgrade the geometry of element during the analysis. Therefore it is possible to have a bit more displacement. Although there are a number of elements that work together and whenever one of them yields, others tolerate the reminder of force, yet those plastic elements couldn't tolerate excessive displacement and cause the analysis to diverge.

FE analysis was carried out in six different treatments (3 rake angle ×2blade geometry). Conventional (B1), and modified (B2) designs of BL plow were modeled at three rake angles (R_1= 7.5°, R_2= 15° and R_3= 22.5°). All analyses were done in 10 incremental time steps (each step 3 mm) and the stresses and forces were recorded at the end of each time step. The working depth for FE model and experimental test was 250 mm.

3. Results and discussion

BL plow draft, vertical and lateral forces were calculated from the summation of the reactions of the contact elements that act on pilot point. Also measured and predicted reaction forces data were compared. The soil stress and strain were compared for both designs.

3.1. Draft force

Fig. 2 shows the FEM calculated component of draft force against displacement for the six treatments studied. The rate of increase of draft force is relatively high at low displacement, and decreases as displacement increase. The reason for this process is that the plastic strain in each element occurs in very low displacement. In the next step of tool motion, the soil plastic yielded elements transfer forces to the next element and its force tends to become constant. The graph of the variation of draft force against blade displacement shows that the draft force of conventional BL plow is more than modified one so that the B_1R_3 treatment consumes maximum draft force. The rate of increasing draft force with increasing rake angle was not noticed in modified BL plow so that the B_2R_2 treatment consumed minimum draft.

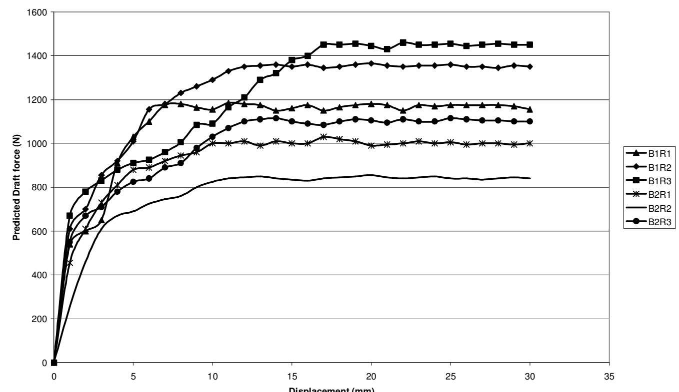

Fig.2. FEM calculated draft force of BL plow as a function of displacement.

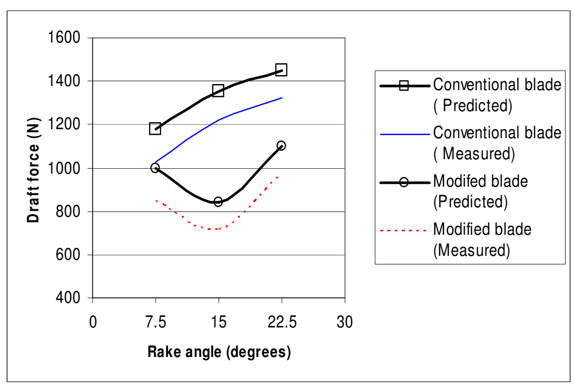

Fig.3. Measured and predicted draft forces of BL plow versus rake angle.

In the soil bin test the maximum draft force was seen after longer displacement than that predicted by FEM. The extension of loose horizon might interpret such divergence, because the soil within this loose horizon might have

been compressed for longer displacement before it collapsed. On the other hand, for the FEM model the homogeneous compacted body collapsed after shorter BL plow displacement. Hence it can be concluded that maximum draft force have been occurred earlier.
The comparison of the measured and predicted draft force of conventional BL plow as a function of rake angle shows that any increase in rake angle results in an increase in tool draft force (fig.3). The predicted BL plow horizontal reaction force from the FEM model exceeded the measured ones for both plow designs. The over prediction error of draft force can be attributed to soil failure mechanism. Crack formations and fragmentation of the soil during the soil bin test were not properly accounted for in the FEM model, where the Drucker-Prager elastic-perfectly plastic model with the general flow rule of associated plasticity was adopted. The amount of draft over prediction ranged from 9.9 to 18.3%.

Changing the direction of angle between projection of cutting blade on horizontal plane and the line normal to the shank causes the surface of the soil to be the first point to come in contact with cutting edge. This backward rotation causes the soil cutting processes start from surface and propagate to the sub soil, as a result the surcharge pressure which applies to the blade is merely the weight of loose soil. Therefore reduction in the amount of surcharge pressure acting on the blade is considered as the most important cause of draft force reduction in the modified model, furthermore tensile cracks appears instead of compressive ones in modified BL plow, which alleviate the draft force. Also the same results were seen for vertical force.

3.3. Soil displacement

The distribution of the vertical and forward soil displacement fields calculated from the FEM model after 20 mm blade displacement. In the zone cited in front of the BL plow shank and above the cutting blade, the soil moves upward, forward and sideways with respect to the original position. Such arbitrary motions indicate that shear distortion occurred throughout the zone. Figs.4 shows upward soil displacements distribution contour due to typical BL plows. Maximum upward soil displacement usually occurs within a little distance in front of the plow shank, and makes a wedge shape soil upheaval. The soil slope in the small gap from the maximum surface upheaval point down to the front edge of the shank can be interpreted by the resistance action of the interface friction against the upward sliding of the shank adjacent soil particles.

The maximum upward soil displacement shows the ability of plow to cut, loose and turn the soil. The comparison of the amount of maximum upward soil displacement in front of the shank show that the modified BL plow can move the soil upward more than conventional one (Table.1).

Table.1. Comparison of maximum upward soil displacement in front of plow shank (displacements are in millimeter).

Rake angle	**Blade design**	
	B1(Conventional blade)	B2(Modified blade)
R_1(7.5°)	**2**	**15.273**
R_2(15°)	**8.07**	**18.083**
R_3(22.5°)	**9.34**	**16.683**
Mean soil upward displacement	**6.47**	**16.68**

The FEM results indicate that the maximum soil loosening and upward displacement is seen in modified BL plow at rake angle of 15°.

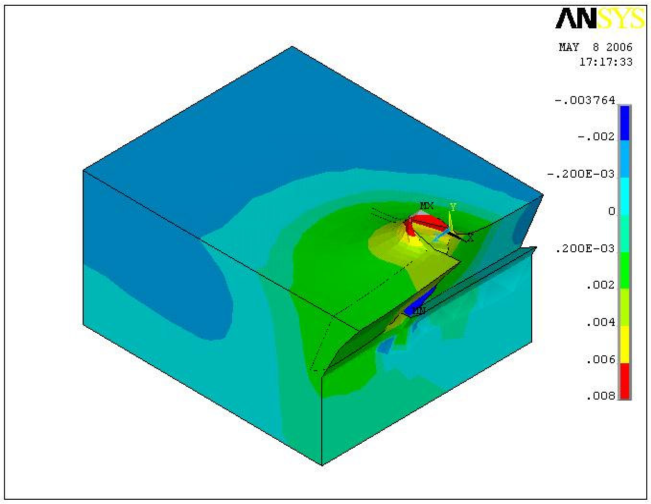

Fig.4. Typical upward soil displacement distribution contour for conventional BL plow at 22.5° rake angle after 20mm blade displacement (displacements are in meter).

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