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Introduction to the study of Soil-Tool modeling

Adib Neisy*, Elham Tayari, Amin Reza Jamshidi, Peyman Attaie

Department of Agricultural Mechanization, Collage of Agriculture, Shoushtar Branch, Islamic Azad University, Shoushtar, Iran

Abstract: Agricultural tillage involves soil cutting, soil turning, and soil pulverization and thus demands high energy, not just due to the large amount of soil mass that must be moved, but also due to inefficient methods of energy transfer to the soil. The most widely used energy-transfer method is to pull the tillage tool through the soil. Various methods have been attempted to improve efficiency such as vibratory tillage tools. However, development of more efficient methods effectively depends upon the necessity for improved understanding of tillage tool mechanics. Complete tillage mechanics is far from being realized, although generalized relations have been proposed. Draft and energy requirements, based on current soil and operating conditions, are considered important parameters for design and manufacture of improved tillage is a literature review that addresses fundamentals of soil mechanics regarding main issues such as speed, depth, soil and tool specifications affecting draft and energy requirements, operational conditions, and the interactions among these factors.

Key words: *Soil-Tool Modeling; Agricultural tillage*

1. Introduction

Analytical approach is one of the first methods that have been used to predict the interaction between soil and a tillage tool. This approach has been employed by many researchers in the field of soil tillage for about 5 decades. The results of this approach are still valid to some extent and its governing rules are sometimes used in other approaches such as empirical and numerical approaches. Reece equation formed a basis in analytical approach and has been used by several investigators (Reece, 1965; Hettiaratchi and Reece 1966, 1967; Hettiaratchi et al. 1974). Two-dimensional cases are approximately valid for soil cutting tools with wide blades relative to their depths of operations (width/depth greater than unity). When a cutting tool is not very wide, a large proportion of the cut soil moves sideways (Payne 1956). Since more soil must be moved per unit width of the tool in the 3-D cases compared to the wide blades (2-D), a larger draft is expected for 3-D cases than that of wide blades.

Payne (1956), O'callaghan-Farrelly (1964), Hittiaratchi-Reece (1967), Godwin Spoor (1977), McKyes-Ali (1977), and Perumpral etal. (1983) are the researchers who have employed a static 3-D soil failure model to investigate soil-tool interaction. In all these models, the effect of travel speed on draft requirement has been ignored.

2. Analytical Models

2.1. Payne model

By observing the upward displacement of soil ahead of the tillage tool, Payne (1956) assumed a failure zone for tines with a width/depth ratio less than 1:1. Payne and Tanner (1959) found out that in addition to the complexity of the equations, tool geometry such as rake angle, depth, and width can change the shape of the failure zone.

2.2. O'Callaghan-Farrely model

Based on Payne model and experimental data, O'Callaghan-Farrely (1964) developed a model. Several assumptions were made in this model; (1) A critical depth equal to 0.6, tine width was assumed; (2) Failure surface above the critical depth was described by a 2-D approach; (3) Two side crescents were neglected; (4) All tines were flat; (5) Rake angle was equal to 90°; (6) Mass of the soil wedge was neglected; and (7) Adhesion and external friction between soil and tool surface were not counted. Two equations to calculate draft requirements for shallow and deep tines were developed by the researchers that are not mentioned here. According to Shen and Kushwaha (1998), predictions from those equations are very close to the experimental data except for an underestimation when a very hard soil is encountered. Shen and Kushwaha (1998) expressed that part of shortcomings of this model returns to its assumptions particularly assumptions number 4, 5, and 7 above.

2.3. Hettiaratchi-Reece model

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* Corresponding Author.

Hettiaratchi and Reece (1967) developed another model that was similar to the O'Callaghan-Farrely model in some aspects. This model also assumed a critical depth for the operating tool and two traversal failure zones only below the critical depth. In the model, 2-D equations are used to calculate the forward failure forces ahead of a soil-tool interface and 3-D equations for the transverse failure away from the center line of the interface. The equations were used in the same way as for the O'Callaghan-Farrely model except that the mass of soil was counted in this model. According to Grisso and Perumpral (1985), this model overestimated forces for vertical tools ($\alpha = 90^{\circ}$), yet the model underestimated inclined tools.

2.4. Godwin-Spoor model

Godwin and Spoor (1977) suggested a circular shape for the soil failure crescents on the surface and for the sides of a narrow tillage tool to predict the volume of displaced soil by the tool. In this model, r was defined as the total forward distance of soil failure on the surface from the tool face, and soil in front of the tool was analyzed by a 2-D failure region using the N-factors of Hettiaratchi and Reece (1974).

According to Payne and Tanner (1956), the difficulty with such a model was that r changed when the aspect ratio of the blade (wd /) varied and soil strength changed. To solve the problem, Payne and Tanner performed some tests with narrow tillage tools in sandy soils in order to estimate r and s for various rake angles α, slenderness ratios wd / , and soil types. Results showed r changed as the rake angle changed, and a graph was developed to describe the relationship between dr /and the tool angle. Accordingto Shen and Kushwaha (1998), the determination of the rupture distance r was still difficult.

2.5. Mckyes-Ali model

Mckyes and Ali (1977) developed an independent analytical model for narrow tools without the need to rely on experimental inputs of soil failure geometry. The model was similar to the Godwin and Spoor model in the shape of the failure zone except that a flat bottom plane for the center wedge was assumed. The straight lines at the bottom of the crescents enabled to define the direction of forces at the bottom of the failure zone.

This model is easier than the Godwin-Spoor model since it does not need prior knowledge of the rupture distance and N-factors are re-evaluated in this model. Moreover, the model uses a technique that increases the magnitude of N factors as the tool becomes narrower. In addition, by setting □□w, the researchers compared the Nfactorswith the N-factors used for 2-D models.

It was found that for smooth blades, the results were very close, yet for the rough blades with α > 90°, rupture angle and the N-factors were much higher than those for the 2-D soil cutting cases. McKyes (1985) published a set of charts to determine the N-factors for some rake and rupture angles.

2.6. Grisso et al. model

With a similar shape of the failure zone to that of the Godwin and Spoor and the Mckyes and Ali models, Grisso et al. (1980), Perumpral et al. (1983), developed a model in which side crescents were replaced by two forces acting on the center wedge. Soil weight of the two side crescents was neglected, and side planes of the center wedge were treated as slip planes; therefore, the failure zone of this model included only a center wedge. As in the Mckyes and Ali model, the bottom slip surface was assumed to be straight. As well, the soil in front of the tool was assumed to move upward. This model produced equal values of$N$ and cN as resulted from the previous two models, but 36caN value of the Grisso et al. model was less than one half of the same quantity resulting from the Mckyes and Ali model.

3. Dynamic models

Based on the Mckyes-Ali model, two dynamic soil failure models have been developed in which the effect of tool speed have been accounted. The first model was introduced by Swick-Perumpral (1988) and the second model by Zeng-Yao (1992). The first model had some assumptions which overestimated the size of the side crescents (researchers). Therefore, a new angle based on the experimental data was proposed, which was a function of the rupture distance r and the rake angle □□. In the Zeng-Yao dynamic model, the acceleration and strain-rate effects were included. Main difference between this model and the Mckyes-Ali model is that this model needs a prior knowledge of shear strain at failure to determine the position of shear failure boundary.

3.1. Finite Element Method (FEM) Models

Finite element method, which was used for the first time in aviation engineering in the middle of the 20 century, developed by extension in the other branches of science such as Physics, electro-magnetic, Mechanics, and civil engineering. Now, it has become a very powerful tool to solve the problems in those sciences.

Any numerical method of soil failure modeling including FEM has to use a constitutive model to describe the relationship between applied stresses and resultant strains within the soil. Different constitutive models have been developed based on the way that researchers have looked at soil. Linear and nonlinear models have been categorized based on using a linear or nonlinear equation to relate stress and strain within the soil where by using theory of plasticity, soil can be viewed as only elastic, or purely plastic, or both elastic and plastic materials during the loading process. And finally, soil is viewed statically, if time is ignored in calculations, and dynamically if time is considered in modeling. Since many different models for different views of soil have been developed, here only the most common models used in soil tillage studies will be briefly introduced.

The hyperbolic model, which determines the hyperbolic relationship between stress and axial strain, was originally proposed by Kondner and Zelasko (1963) and later Duncan and Chang (1970) modified the model to use in a FEM analysis. Bailey's model under hydrostatic compression. Later, the model was modified to include the effect of shear was first proposed by Bailey et al. (1984) to predict volumetric strain stress.

The Cam clay model was originated at the University of Cambridge, England (Roscoe et al. 1958; Schofield and Wroth 1968), and it is one of the simplest elastoplastic models which is very popular among the soil researchers. A modified version of the Camclay modelby Wrothand Houlsby (1980) shows the relationship between stress and strain at the normal consolidation line and the swelling line in terms of specific volume and mean normal pressure. The Cap model for the first time was proposed by Drucker et al. (1955) and then it was developed by Dimaggio and Sandler (1971) based on the work accomplished by a research group at MIT (Christian 1966; Tang and Hoeg 1968).

Below, part of research in the area of tillage operations by implementing FEM method has been discussed.

3.2. Kushwaha and Shen model

Kushwaha and Shen (1995) employed FEM to solve the dynamic equation of interaction between the soil and a tool, which was previously used for the similar cases. By using a two-dimensional FEM, it became possible to predict the draft requirement of a vertical blade on soil. Comparison between the results of soil bin tests and the modeling showed that the predicted draft was very close to the experimental data. It was indicated that the method could work for predicting the forces acting between the soil and any other kinds of tillage tools by some modifications.

3.3. Rosa and Wulfsohn model

Finite element method was implemented by Rosa and Wulfsohn (1999) to study a constitutive model for high speed tillage by using narrow tillage tools. Two different tools, including a flat and a triangular edged narrow tool, were used for soil bin experiments to test the effect of forward speeds between 0.5 to 10.0 m s 39-1 over a distance of 1 to 3 m. The model's assumptions were: (1) Tool is narrow, rigid, and working in constant depth and velocity; (2) Failure is a 3-D case; (3) Tool deflection is negligible compared to the soil deflection; (4) Soil-tool interface is either totally smooth or totally rough in order to simulate the extreme cases; (5) Soil is assumed an isotropic and homogeneous medium; and (6) Soil particles are ideally assumed lumped masses and gravity effects are negligible compared to the inertial and strain rate effects or the contributed soil stiffness to draft.

3.4. Chi and Kushwaha model

Chi and Kushwaha (1991) used a non-linear three-dimensional FEM to investigate soil-tool interaction. One of the main goals of this research was the evaluation of the effect of draft requirements of tillage tools on wear and friction losses. Actual tests in the soil bin were conducted to compare with the results of the model. Draft was measured for different rake angles of the tool. Results of both theoretical and experimental methods obviously showed that the draft requirement decreased as the rake angle decreased, but stayed constant for the rake angles less than 45. Results were very close, showing only about 0.8% error for a rake angle of 45 and 10.5% error for a rake angle of 90 when comparing the model with the actual test results of the soil bin. Stress on the edge of the tool was very large, and the maximum stress increased as depth was increased; therefore, the outer edges of the tool at the bottom suffered the greatest stress and wear. As well, this stress increased as the rake angle was increased.

3.5. Mouazen and Nemenyi model

To date, only a few studies have focused on real tillage implements using FEM to investigate the forces interacting between soil and tillage tools. Mouazen and Nemenyi (1999) developed FEM to analyze the reaction of a subsoiler in a nonhomogeneous sandy loam soil. In this research, the effect of tool geometry on subsoiler performance, by implementing a subsoiler shank attached to a chisel with different angles and effective cutting widths, was investigated by implementing a 3-dimensional FEM model. Simulation of soil-tool interaction was developed by adopting the Coulomb's law of friction. The FEM model overestimated the measured draft force in a range between 11 to 16.8% for a non-homogeneous and between 15 to 18.4% for a homogeneous soil for all four different chisel angles when the results were compared to the soil bin test results.

3.6. Fielke model

Fielke (1999) investigated the effect of cutting edge geometry of a 400 mm wide experimental sweep on horizontal and vertical components of forces. As well, he studied soil failure patterns, and soil movement below the tillage depth using a 2-dimensional FEM. The researcher found out that replacing a sharp cutting edge tool with a blunt one can increase draft requirement up to 80%. In addition, the direction of the vertical force can change from one that acts to pull the tool into the soil to a force that provides tool lift. In this study, soil was represented by a linear elasto-plastic model, and the Mohr Coulomb theory was employed as the soil failure criterion. Results of the modeling showed the power of FEM to model soil-tool interaction.

Conclusion

Plouffe et al. (1999) employed a 3-dimensional FEM to simulate forces applied on a moldboard plow during an operation. Three plowing depths of 100, 150, and 200 mm and three forward speeds of 0.25, 1, and 2 m s 41-1 were implemented. A cylindrical plow bottom was fixed on a tri axial dynamometer and its movement in both vertical and lateral directions was controlled by two hydraulic cylinders. The type of soil used in the soil bin was a Sainte-Rosalie clay soil (53% clay, 27% silt, 20% sand, and 2.97% organic matter), which is a typical soil for moldboard plowing in Quebec, Canada. Results showed no significant difference between experimental data and the simulated data for the longitudinal forces (Fx), but for the vertical forces (F), simulated forces were significantly lower than measured forces for the forward speeds of 0.25 and 2 m/s.

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