ORIGINAL ARTICLE

# Draft Force Prediction of Narrow Tillage Tool Using the Finite Element Method

## Predicción de Fuerza Traccional de herramienta de labranza estrecha mediante el Método de Elementos Finitos

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**ABSTRACT:** The Finite Element Model (FEM) has been used to predict the soil behavior disturbed by tillage tool, as well as the necessary draft force to break it. The aim of the present work is to analyze, by a simulation model of soil-tillage tool interaction in finite element, the draft force behavior of the vibratory subsoiler bent leg (narrow farming tillage tool), tilling a Ferralitic soil block, using the linear form to the extended Drucker-Prager elastoplastic constitutive relation model. The software used was Solid Works and its complement *Simulation* to model the vibratory bent leg and the soil block. The mechanical properties of soil were determined in the soil box CS-CEMA-25 and assigned to simulation model which was analyzed in function of moisture, bulk density, working depth and forward speed. The results showed the FEM reliability to predict the draft forces behavior of narrow tillage tool.

***Keywords*:** FEM, Simulation Model, Soil Mechanical Properties.

**RESUMEN:** El Método de Elementos Finitos (MEF) ha sido utilizado para predecir el comportamiento del suelo removido por la herramienta de labranza, así como la fuerza de tracción necesaria para su rompimiento. El objetivo del presente trabajo es analizar, mediante un modelo de simulación de la interacción suelo-herramienta de labranza en elementos finitos, el comportamiento de la fuerza de tracción de la herramienta de labranza estrecha de un subsolador vibratorio, labrando un bloque de suelo Ferralítico (Rhodic Ferralsol) y utilizando la forma lineal del modelo elastoplástico de relación constitutiva de Drucker-Prager extendido. El software empleado fue *Solid Works* y su complemento *Simulation* para modelar, tanto la herramienta del subsolador como el bloque de suelo. Las propiedades mecánicas del suelo fueron asignadas al modelo de simulación, en función de la humedad, densidad, profundidad de trabajo y velocidad de avance de 0,65 $ms^{-1}$. Los resultados mostraron la confiabilidad del MEF para predecir el comportamiento de los esfuerzos de tracción de esta herramienta de labranza.

***Palabras clave*:** MEF, fuerza de tracción, modelo de simulación, propiedades mecánicas del suelo.

## INTRODUCTION

Tillage, in agricultural sense, is the physical management of soil to get the conditions required for proper plant growing and crop production (Rao & Chaudhary, 2018). It is one of the most energy consuming processes of agricultural production (Dehghan & Kalantari, 2016), around half of the energy used is consumed in tillage operation due to the magnitude of the draft force generated for breaking the soil (Armin *et al.*, 2015) affected by the agricultural machinery traffic and the compaction (Mileusnić *et al.*, 2022).

Draft force prediction, clod size and distribution and erosion damage by soil tillage are among the major motivations for modelling soil-tillage interaction. Combining field data and laboratory experiments with mathematic models, allow quicker and accurate predictions of the interaction of the new tool design with soil (López, 2012).

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In soil tillage modelling, experimental and analytic models arisen in the 40s of last century (Terzaghi, 1943). Later, the tillage forces prediction was investigated by numerical methods, which have acquired importance in the latest years because of the accelerate development of computing techniques (Herrera *et al.*, 2015). Among the numerical methods, the Finite Element Method (FEM) has great acceptation for the computational simulation of soil-tillage tool interaction (González *et al.*, 2013a; 2013b), because of the power for describing it in 3D (Herrera *et al.*, 2013; Naderi *et al.*, 2013; Ibrahmi *et al.*, 2015; Marín & García de la Figal, 2019). Some authors report satisfactory results in modeling tool structural resistance (Biriș *et al.*, 2016; Constantin *et al.*, 2019; Gheorghe *et al.*,2019), tillage tool efforts prediction over the soil (Arefi *et al.*, 2022) and draft force in static condition (López *et al.*, 2019). It can be used to simulate cohesive soils, getting both the resistance characteristics and data in breaking process and movement of soil mass (Lysych, 2019).

The FEM is appropriated for continuous analyses, although the soil deformations, mainly in tillage process, including separation and mixes of its layers, the appearance of cracks and the flow of particles, cannot be modeled appropriately by this method (Jakasania *et al.*, 2018). However, the results in the direction of forward movement (draft) under tillage depth are more reliable using FEM (Ucgul *et al.*, 2018).

The main objective of this work is to analyze the prediction of cutting forces behavior in the direction of the forward movement of a tillage tool (vibrating bent leg subsoiler) while tilling a clay loam soil (Ferralitic) with forward speed and working depth assigned, as well as physical properties (moisture and density) and certain mechanical properties, by means of the FEM.

## METHODS

***Soil Model.*** The linear form of the extended Drucker-Prager model (De la Rosa *et al.*, 2016) was used for modelling the soil (Figure 1). It is classified as an elastoplastic material, as a Rhodic Ferralsol (FAO-UNESCO, 1988); Oxisol according to USDA Soil Survey Staff (2010); typical red Ferralitic, according to the third genetic classification of soils in Cuba (Hernández *et al.*, 1999).

For its texture, it can be considered like a clay loam very plastic, with 17% of sand, 36% of loam, 47 of clay% and 2.58% of organic matter (Herrera *et al.*, 2008b; 2008a). According Naderi *et al.* (2013); Ibrahmi *et al.* (2017); Arefi *et al.*, (2022), this model is the most appropriate for modelling the soil material, because it can be gauged obtaining data of triaxle tests.

The yield function of the linear Drucker-Prager model (Drucker and Prager, 1952) can be expressed as:

$$f(\sigma_1, \sigma_2, \sigma_3) = t - p \times tan\beta\ d \quad (1)$$

***Properties and Soil Parameters.*** The elasticity module (E) was determined as the tangent module to the elastic deformation section of strain stress curve in the right tract, obtained by Herrera *et al.* (2008b; 2008a) for this kind of soil.

The Poisson coefficient was determined by the following equation:

$$\nu = \frac{E}{2 \times G} - 1$$

The shear module G was calculated by:

$$G = \frac{E}{2 \times (1 + )}$$

Table 1 shows the properties or parameters required by the FEM model which were obtained in the laboratory of mechanics of soils from the Company of Investigations Applied to Construction, Villa Clara Province (ENIA.VC).

***Finite Element Model.*** It was formed by the farming tool (curved bent and front shear wedge) which was considered as rigid body and the soil block (deformable in interaction with the bent leg). The bent leg and the soil block were modeled using the design software *Solid Works* and its complement *Simulation*. The soil block dimensions were: length (2 m), width (1 m) and height (1 m). The soil block was considered isotropic and homogeneous, it had movement restrictions for the side, bottom and later surfaces

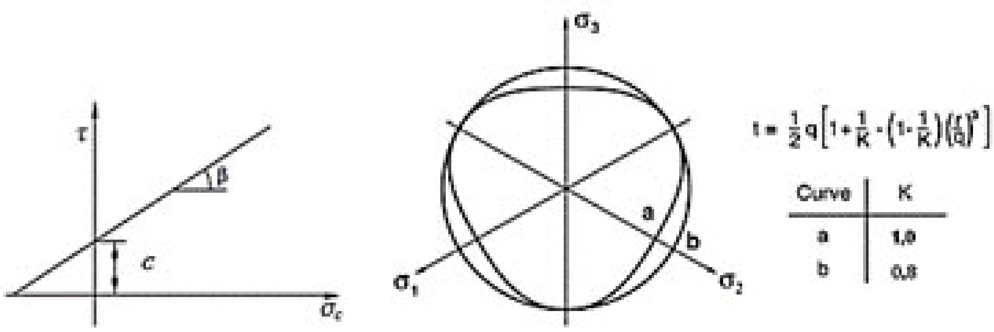



**FIGURE 1.** Yield Surface and flow direction in the southern plane of the extended lineal Drucker-Prager model.

(Figure 2a) to which constraints pressures were applied. Over the model act the gravity force and the atmospheric pressure. It is assumed that the increase in the dimensions of the prism of soil cut beyond those assigned, does not affect the draft forces (Bentaher *et al.*, 2013). The interaction soil-farming tool was modeled tangent to the attack surface of the tool, with contact model surface to surface. The general mesh of the model was carried out with an elements size (**e**) maximum of 0,008 m, minimum size of 0,006 m and the Newton-Raphson iterative method was used. The surfaces in contact, the farming tool and the prism of soil cut, were refined applying mesh control with elements size of 0,004 m (Figure 2b). The bent leg cuts the soil block to a constant forward speed of 0.65 $m \cdot s^{-1}$ in the direction of the axis X, to a working depth of 0.3 m and cut wide 0.081 m. The soil cut after the flaw slips over the surface of the tool.

## RESULTS AND DISCUSSION

***Finite Element Simulation.*** The behavior of the draft force along its travel was analyzed by means of simulations by the FEM. In Figure 3, some steps of the process of soil cut are shown. It can be observed that, as the bent leg is moving through the soil block, big displacements of the soil mass happen, both longitudinally and vertically, overcoming the its internal and external resistance forces and taking place the break of the soil prism. Coinciding with other authors like Bentaher *et al.* (2013); Ibrahmi *et al.* (2015); Arefi *et al.* (2022), it can be observed that the model simulates the cutting process of soil in an appropriate way.

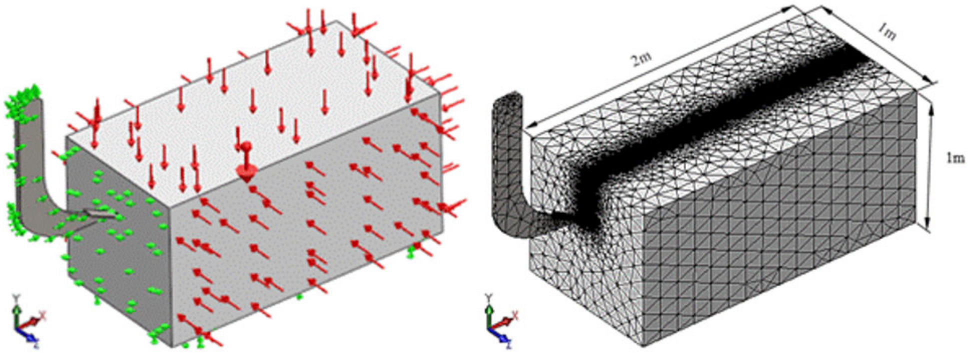
The draft force reaches a maximum value of 14,1 kN to 0,25 m from the beginning of the contact of the tool with the soil block, diminishing first in parabolic form to 1m, as the tool moves through the soil block (Figure 4 ) and next it is practically constant, while it is almost zero when the wedge of tool comes out of the second one. These results are similar to those estimated by the ASAE D497 Dates (2006) for farming tool of narrow tip.

$$m = \frac{14.1 - 12.5}{2 - 0.4} = \frac{1.6}{1.6} = 1\frac{kN}{m} \quad (4)$$

The finite element model verification is based on the analytic model of Swick & Perumpral (1988),

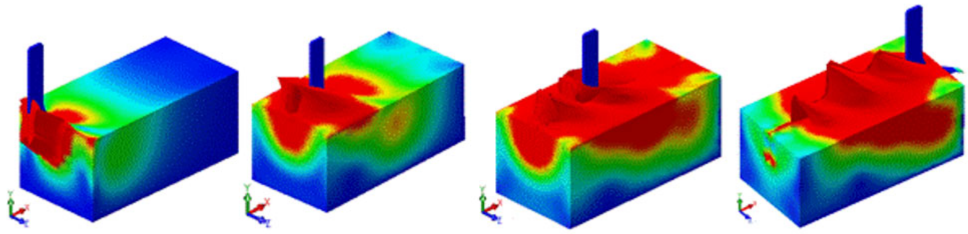
**TABLE 1.** Properties or parameters required by the FEM model

| Properties or parameters | Symbol | Dimension | Source |
|---|---|---|---|
| Internal friction angle | $\varphi$ | 27.19 º | Herrera *et al.* (2015) |
| Elasticity module | *E* | 104272 kPa | Herrera *et al.* (2008) |
| Poisson's ratio | $\upsilon$ | 0,44 | Calculated |
| Flexion stresses | $\sigma_f$ | 693.2 kPa | González *et al.* (2014) |
| Cohesion | *d* | 217.2 kPa | González *et al.* (2014) |
| Dilatancy angle | $\Psi$ | 13º | González, 2011 |
| Resistance to shear effort | $\tau$ | 40 kPa | Herrera, 2006 |
| Shear module | *G* | 1 793 400 Pa | Calculated |
| Kind of soil | | Linear elastoplastic | |
| Traction limit of soil | $\sigma_t$ | 42 000 Pa | Calculated |
| Compression limit of soil | $\sigma_c$ | 48 000 Pa | Calculated |
| Soil-metal friction angle | $\delta$ | 23.68º | Herrera *et al.* (2015) |
| K ratio | *K* | 1 | |
| Soil humidity | *H* | 22.4 % | |
| Density | $\rho$ | 1 120 $kg.m^{-3}$ | (Herrera *et al.*, 2015) |




a) b)

**FIGURE 2.** Finite Element Model: a) Boundary conditions b) Model mesh.



a) b) c) d)

**FIGURE 3.** Steps of the soil cutting process by the farming tool to different distances of displacement: a) 0.15m, b) 0.6 m, c) 1m, d) 2m.

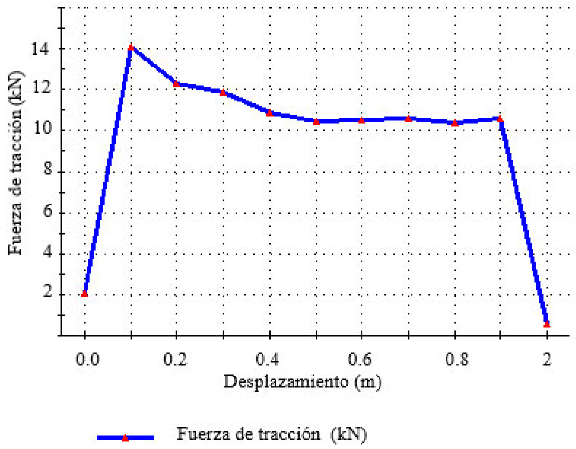



**FIGURE 4.** Draft force behavior along the farming tool displacement.

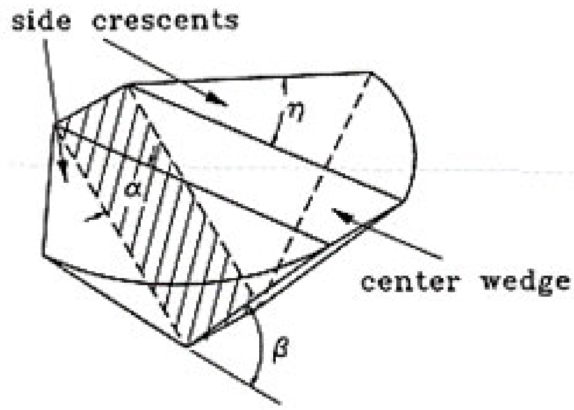
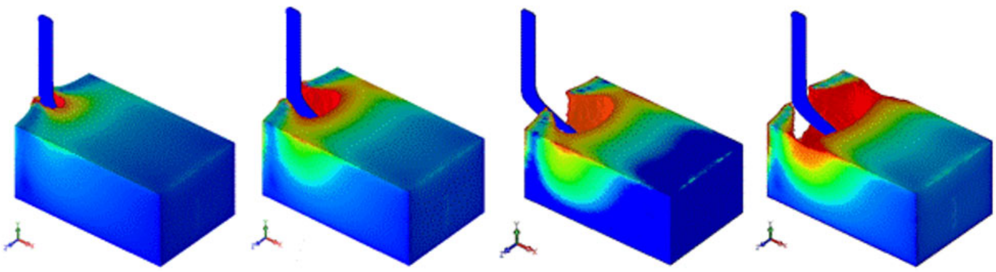



**FIGURE 5.** Analytic model of Swick-Perumpral (Isavi, 2015).



a) b) c) d)

**FIGURE 6.** Finite element model verification: a) Beginning of formation of the soil flaw area, b) c) and d) Soil removed of the flaw area.

which proposes a soil cut dynamic model that takes into consideration the forward speed. Its area of flaw consists on a central wedge and two growing sides (Figure 5) with a right rupture plane in the bottom.

It is observed (Figure 6) that, in the superior diagram (of soil surface) the soil flaw of the model in finite elements of soil, acquires a similar form to Swick Perumpral's analytical model up to 0,6 m of trajectory through the soil block and is removed by the farming tool.

## CONCLUSIONS

The behavior of the bent leg draft efforts along the displacement through the soil block shows coincidence with the works carried out in previous investigations. The force increases abruptly at the beginning of the interaction soil-farming tool, reaching its maximum value (14.1 kN). Then, it is stabilized a little in values smaller than the maximum as the tool moves with tendency to decrease and it diminishes to almost zero at the end of its displacement. The model FEM shows similarity with the analytic model of Swick-Perumpral in the process of formation of the soil flaw area.

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