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Rake Angle Influence of the Vibrating Subsoiler Arm in Cutting Forces and Soil Failure

Influencia del ángulo de ataque del brazo de un subsolador vibratorio en las fuerzas de corte y la falla del suelo

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ABSTRACT: In the present work is analyzed the rake angle influence of the vibrating subsoiler arm in the cuttings forces, as well as the soil failure behavior, tilling a silt loam soil (ferralitic), by a soil-tillage tool interaction simulation model, developed applying the Finite Element Model and using the linear elastoplastic Drucker-Prager constitutive model. For modeling was used the Solid Works design software. It was assigned to model the parameters and properties of soil required for simulation, the boundary conditions and acting loads were applied as well as the meshing of the model. As well, several running of the model was realized for three rake angle (15°, 25° y 35°). The results showed the quadratic behavior of draft force with the increasing of subsoiler arm rake angle.
Keywords: FEM, Draft Force, Simulation Model, Rake Angle.

RESUMEN: En el presente trabajo se analiza la influencia del ángulo de ataque del brazo de un subsolador vibratorio en las fuerzas de corte, así como el comportamiento de la falla del suelo a diferentes ángulos de ataque, labrando un suelo arcilloso limoso (ferralítico), mediante un modelo de simulación de la interacción suelo-herramienta de labranza, el cual fue desarrollado aplicando el Método de Elementos Finitos y la forma lineal del modelo constitutivo elastoplástico de Drucker-Prager. Para la modelación del mismo fue utilizado el software de diseño *Solid Works*. Se asignaron al modelo las propiedades y parámetros del suelo requeridos para la simulación, se aplicaron las condiciones de frontera y cargas actuantes, así como la discretización del mismo. Fueron realizadas, además, las corridas del modelo de simulación para tres valores distintos del ángulo de ataque (15°; 25° y 35°). Los resultados mostraron el comportamiento cuadrático de la fuerza de tracción con el aumento del ángulo de ataque del brazo del subsolador.
Palabras clave: MEF, fuerza de tracción, modelo de simulación, velocidad de avance.

INTRODUCTION

Tillage is one of the important field operations for the production of agricultural crops (Zhu *et al*., 2020), is the practice of modifier the soil state to achieve suitable conditions for growing of crops (Meselhy, 2020). The draft force is affected by three parameters, namely: soil conditions, tool shape and operational parameters (Li *et al*., 2014; Armin *et al*., 2015; Ibrahmi *et al*., 2015; Tagar *et al*., 2015; He *et al*., 2016).

The effects of rake angle over the soil and it influence in cutting forces has been analyzed by some researchers (Li *et al*., 2014; Armin *et al*., 2015; Ibrahmi *et al*., 2015; Tagar *et al*., 2015; He *et al*., 2016).

The Finite Element Method (FEM) is a numerical technique for the analysis of complex problems of engineering, specially for dynamic systems with big deformations and failures (Rosa y Wulfsohn, 2002). Este método ha sido utilizado por numerosos investigadores

This method has been used by several researchers to analyze problems related with the soil mechanic and the interaction soil- farming tool (Abo *et al*., 2003; 2004; Topakci *et al*., 2010); and it has shown to be able to simulate different forms of farming tools and the effect of the geometry in the cutting forces (Abu & Reeder, 2003). However, for a precise tool modeling, important physical and mechanical properties should be kept in mind (Dehghan & Kalantari, 2016).

The aim of this study is to analyze, using the Finite Element Method, the rake angle influence of a farming tool (vibrating subsoiler) in cutting forces (draft force and vertical force), as well as the soil failure behavior to different rake angles, tilling a clay loam soil (ferralitic), with forward speed and working depth assigned, as well as soil physical properties (humidity, density) and soil mechanical properties determinates.

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METHODS

Soil model

The soil was classified as elastoplastic material, as Rhodic Ferralsol according to FAO- UNESCO (1988); Oxisol según Soil Survey Staff (2014); Oxisol according Soil Survey Staff (2014) and typical red ferralitic soil according to the Third Genetic Classification of Soil in Cuba (Hernández *et al.*, 1999). It was considered as a loam clay very plastic, with 15% of sand, 38 of lime %, 47 of clay% and organic matter content of 2,59% (Herrera *et al.*, 2008b; 2008a).

The lineal form of the extended Drucker-Prager model according to De la Rosa *et al.* (2016) it was used to model the same one (Fig. 1). According to Arefi *et al.*, (2022) this model is the most appropriate for modeling the soil material, because it can be gauged obtaining data of triaxial tests. The yield function of the Drucker y Prager (1952) is expressed as:

$$f(\sigma_1, \sigma_2, \sigma_3) = t - \sigma . tan\beta \quad c \tag{1}$$

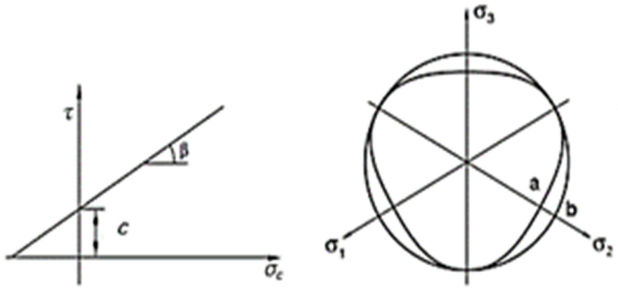


FIGURE 1. Yield surface and flow direction in meridional plane of extended linear Drucker-Prager model.

Properties and soil parameters

The elastic modulus (E) was determined by the slope of a tangential line of a stress- strain curve in straight section, obtained by Herrera *et al.* (2008b; 2008a) for this soil type. The Poisson rate was determined by the following equation:

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

The shear modulus (G) is determined by:

$$G = \frac{E}{2 \times (1 + \nu)} \tag{3}$$

The properties and soil parameters required by the FEM model (Table 1) has been obtained in the soil mechanic laboratory of Applied Investigations National Enterprise to construction (ENIA. VC).

Finite element model

Is formed by scarifier arm (threated as rigid body) and the soil block (deformable in interaction with the arm). Both were modeled using the design software Soil Works and its complement Simulation. The soil block dimensions are: length (L= 2 m), width (B = 1 m) and height (H = 0,9 m), was considered as isotropic and homogeneous, have movement restrictions by lateral, bottom and back surfaces (Fig. 2a), to which constraints pressures were applied.

Over the model acting the gravidity force and atmospheric pressure. Is assumed that the growing of the dimensions of sheared soil prism beyond those assigned, does not affect the draft forces (Bentaher *et al.*, 2013; Marín *et al.*, 2019).

The soil-tool interaction was modeled tangent to the tool attack surface, with contact model surface to surface. The model was discretized with element size (e) maxim of 0,006 m and the Newton-Raphson iterative method was used.

The contact surfaces, both tool and cut soil prism were discretized applying mesh control, with element size of 0.004 m (Fig. 2b). The arm cut the block soil a constant forward speed (*Vm*) in axis X direction, working depth of 0,3 m and cutting wide 0,081m. The soil cut after the flaw slips over the surface of the tool.

RESULTS AND DISCUSSION

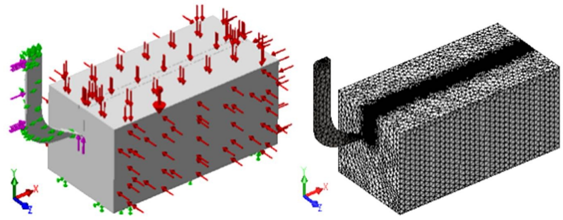
Attack angle influence α in the cutting forces

Several running of the simulation model was realized (Figs. 3, 4 y 5) with different attack angle (15; 25 y 35°), f= 14 Hz, peak amplitude Y_{Peak} =11mm, Vm = 0,8 m·s^{-1}, using the same properties and parameters of the Table 1.

The results showing the growing of *Fx* in polynomic form of second order with the growing of the attack angle α (Fig. 6a), showing coincidence with other authors Abbaspour *et al.* (2014) & Lamia (2020).

TABLE 1. Properties and soil parameters required by model

Propertie or parameter	Symbol	Dimension	Font
Internal friction angle	υ	33º	(Herrera *et al.*, 2008a; 2008b).
Elasticity modulus	E	44 000 kPa	(Herrera *et al.*, 2008a; 2008b).
Shear modulus	G	15 909 kPa	(Herrera *et al.*, 2008a; 2008b).
Poisson's ratio	v	0,32	Calculated
Cohesion	c	50 kPa	(Herrera *et al.*, 2008a; 2008b).
Shear efforts resistance	τ	295 kPa	Herrera, 2006
Traction limit of soil	σ_t	20 kPa	García de la Figal, 2022
Compression limit of soil	σ_c	750 kPa	García de la Figal, 2022
Soil-metal friction angle	ϕ	25º	Herrera, 2006



a) b)

FIGURE 2. Finite element model: a) Boundary conditions b) Model mesh.

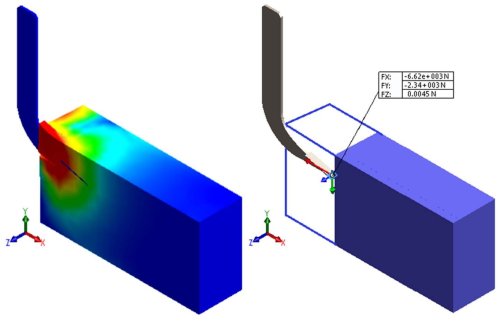


FIGURE 3. Draft force with arm attack angle, α = 15°.

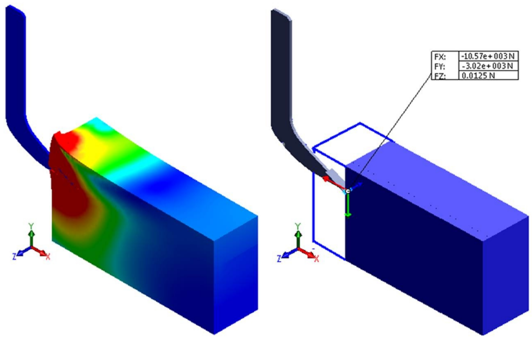


FIGURE 4. Draft force with arm attack angle, α = 25°.

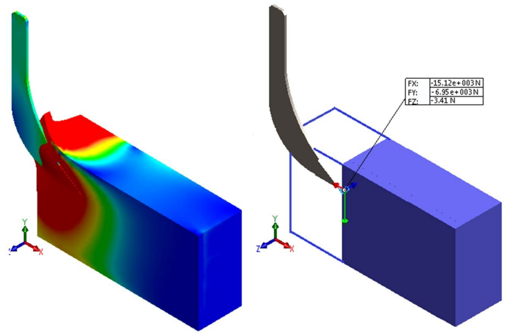


FIGURE 5. Draft force with arm attack angle, α = 35°.

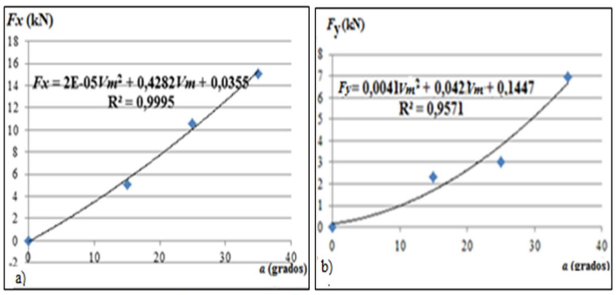
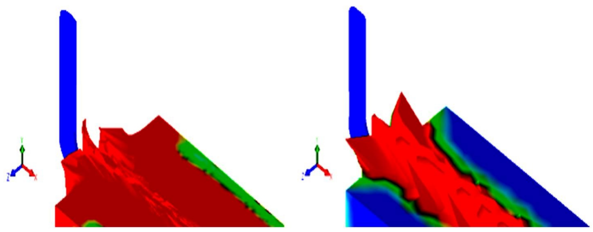


FIGURE 6. Forces behavior: a) draft force F_X; b) vertical force F_Y a to different attack angle α.



a) b)

FIGURE 7. Disruption of the cut soil prism by the scarifier arm: a) α = 15°; b) α = 25°.

Growing in 5 grades of attack angle *α*, increasing the draft force in approximately 4 kN (25 % of growing).

The vertical force of the soil-tool interaction *Fy*, the best adjusts (R^2= 0,957) of your varying concerning the attack angle α was obtained with a polynomic function of second order (Fig. 6b), showing coincidence with other authors (Bentaher *et al.*, 2013b; Odey *et al.*, 2018).

Soil failure

The soil failure process, both in vertical address and forward address, was simulated by several running of the finite element model, along the travel, with mesh density (**e**=6 mm), f= 14 Hz, Y_{Peak}=11mm to different cutting angles *α*: 15 y 25⁰. The properties and parameters of the Table 1 were used.

In the zone over the farming tool (Fig. 7), take place great movements of the cut soil prism, both vertical and horizontal address, as well as displacements in lateral direction.

For α = 15° and the farming tool working with forced vibrations, the disruption of the soil, both horizontal and vertical address is less than α = 25° (Fig. 7a), as well as the draft force required for his breaking.

When α = 25° (Fig. 7b), great disrupting of the cut soil prism is obtained, as well as great displacement of the soil in vertical sense (Abu y Reeder, 2003; Odey y Okon, 2019). It can be observed, as well, the failure plane formation of the removed soil.

CONCLUSIONS

The cutting forces of soil, both draft and vertical, increasing in quadratic form with the growing of the attack angle, being the draft force the greatest.

The attack angle has a great influence in the disruption level, loosing, displacement and turning of cut soil prism.

Increasing the attack angle, increase the turning grade of cut soil, as well as the particles displacement, both in forward direction and vertical.

The FEM has been able to simulate, in adequate form, the effect of the farming tool attack angle in cutting forces of soil.

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