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Applications of the Finite Element Method in Simulation of Soil-Tillage Tool Interaction

Aplicaciones del Método de Elementos Finitos en la simulación de la interacción suelo-herramienta de labranza

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ABSTRACT: This work develops tridimensional simulation models of the soil-tillage tool interaction applying the Finite Element Method (FEM), tilling clay loam soils (ferralitic). The elastoplastic model of constitutive relation (Drucker-Prager) was used for modeling and Solid Works design software, 2021 version and its complement Simulation. To ensure optimal connection between surfaces of the soil blocks and the tillage tools, contact elements and Coulomb theorem were used to achieve adequate movement of soil elements over the working surface of tillage tools. The geometric parameters of tillage tools were defined as well as parameters and dimensions of soil blocks. The results showed that, both models simulate, in appropriate way, the movement of soil blocks in its interaction with tillage tools. The values of cutting forces, obtained for both models, are similar to values obtained in previous researches.
Keywords: Finite element, soil-tillage tool interaction, elastoplastic model, tridimensional simulation model.

RESUMEN: Este trabajo desarrolla modelos de simulación tridimensionales de la interacción suelo-herramienta de labranza aplicando el Método de Elementos Finitos (MEF), labrando suelos arcilloso-limosos (ferralíticos). Se utilizó el modelo elastoplástico de relación constitutiva (*Drucker-Prager*) para la modelación y el software de diseño *Solid Works,* versión 2021 y su complemento *Simulation*. Para una mejor conexión entre las superficies, tanto de los bloques de suelo como de las herramientas de labranza, fueron utilizados elementos de contacto y el teorema de Coulomb para lograr el movimiento adecuado de los elementos del suelo sobre la superficie de trabajo de las herramientas de labranza. Fueron definidos los parámetros geométricos de las herramientas de labranza, así como las dimensiones y parámetros de los bloques de suelo. Los resultados obtenidos muestran que, ambos modelos simulan, de forma adecuada, el movimiento de los bloques de suelo en su interacción con las herramientas de labranza. Los valores de las fuerzas de corte, obtenidos para ambos modelos, son similares a los obtenidos por otros autores en investigaciones previas.
Palabras clave: Elementos finitos, interacción suelo- herramienta, modelo elastoplástico, modelo de simulación tridimensional.

INTRODUCTION

The soil-tillage tool interaction is characterized by two phenomena: forces arisen in soil-tillage tool interfase (draft, lateral and vertical forces) and displacement of soil particles (Ani *et al.*, 2014).

An important part of researches related with soil-tillage tool interaction has focused on to development of simulation models to predict the cutting forces under different conditions of soil (Torotwa *et al.*, 2022), tool geometry and operation parameters (Lamia *et al.*, 2020; Kuře *et al.*, 2021; Workesa y Alemu, 2021; Marín *et al.*, 2020, 2021 y 2023), impact of agricultural machinery in soil compaction (Mileusnić *et al.*, 2022).

The Finite Element Method (FEM) has been utilized to a great extent at international level in the soil-tillage tool interaction, because of its potential to describe it in three dimensions (Marín *et al.*, 2019).

For the soil-tillage tool interaction by FEM has been realized several researches at international level, namely Abu Hamdeh y Reeder (2003); Armin *et al.* (2016); He *et al.* (2016), to aim develop models, in two or three dimensions, both linear and no linear; elastic, plastic and elastoplastic models, for predict the soil efforts on tillage tool, the geometry influence in cutting forces, as well as the energy consumption of tillage tools.

For the agricultural soils of Cuba, mainly clay soils, the researches involving simulation models of soil tillage-tool interaction by FEM for disc plough and winged subsoilers for this type of soil scarcely exist. The researches have been realized mainly for sand soils and for other numerical methods.

The aim of this work is develop tridimensional simulation models of soil-tillage tool interaction process, permitting the analyses of tillage tool movement crossing the soil, distribution and magnitude of stresses and strains, as well as the cutting forces.

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MATERIALS AND METHODS

Soil model

In the present work the soil-tillage tool interaction is modeled by the yield Drucker-Prager linear function, which may be expressed as:

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

Where: σ_1, σ_2, σ_3 -are the principal efforts *t*, is the deviatory effort and can be calculated by:

$$t = \frac{q}{2} \times \left[1 + \frac{1}{K} - \left(1 - \frac{1}{K}\right)\left(\frac{r}{q}\right)^3\right] \quad (2)$$

K: is the ratio of the yield stress to the compression yield stress in triaxial test, calculated as:

$$k\frac{3 - sen(\varphi)}{3 + s\ \ en(\varphi)} \quad (3)$$

Where: φ is the internal friction angle of soil p is the normal effort acting on the soil, defined as:

$$p = -\frac{1}{3} \times (\sigma_1 + 2\sigma_3) \quad (4)$$

β lifting angle referred commonly to material internal friction angle in the Drucker-Prager model (Figure 1) and may be calculated as:

$$tan\beta = \frac{6 \times sen(\varphi)}{3 - sen(\varphi)} \quad (5)$$

Q is the Von Misses equivalent stresses, expressed by:

$$q = \sigma_1 - \sigma_3 \quad (6)$$

r^3 is the third invariant of deviatory efforts

$$r^3 = -(\sigma_1 - \sigma_3)^3 \quad (7)$$

The cohesion d, when the hardening is defined by the same, is calculated as:

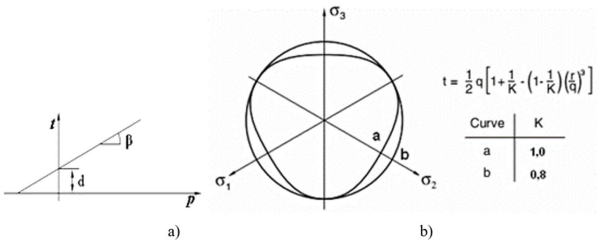


Figure 1. Yield criterion of the Extended Drucker-Prager model. a) Southern plane b) Principal stresses plane.

$$d = \frac{\sqrt{3}}{2} \times \tau\left(1 + \frac{1}{k}\right) \quad (8)$$

Soil properties

The soil was classified as red Ferralitic, according to Second Genetic Classification of Soils in Cuba (Hernández *et al.*, 1975), as Oxisol (Cid *et al.*, 2011), as Rhodic Ferralsol (Hernández *et al.*, 2015). Its density was 1 200 kgm^{-3}, its plasticity ratio was 36, 2% and its organic matter content was 2, 7%. The modulus of elasticity was determined by the slope of a tangential line of a stress- strain curve in straight section. The Poisson rate was determined by the equation:

$$G = \frac{E}{2(1 + \nu)} \quad (9)$$

The cohesion and internal friction angle were determined by the Mohr graphical solution. The Table 1 shows the properties and parameters of soil required by the finite element model.

Finite element models

Two tridimensional simulation models of the soil-tillage tool interaction by finite elements have been developed using the *Solid Works* design software (Fig. 2). One model, formed by a broad tillage tool (disc plow) and a block soil. The other model, formed by a narrow tillage tool (winged subsoiler with logarithmic shape arm) and a block soil.

In both models, the tillage tool is moving a constant speed. Both block soils are deformable interacting with tillage tools and the assigned dimensions to both models let the adequate volume for simulations.

Table 1. Properties and parameters of soil required by the FEM model

Property or parameter	Symbol	Dimension	Font
Friction internal angle	φ	33º	Herrera *et al*. (2008)
Modulus of elasticity	E	44 000 kPa	Herrera *et al*. (2008)
Shear modulus	G	15 909 kPa	Herrera *et al*. (2008)
Poisson ratio	ν	0.32	Calculated
Cohesion	c	50 kPa	Herrera *et al*. (2008)
Shear resistance	τ	295 kPa	Herrera *et al*. (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 *et al*. (2006)

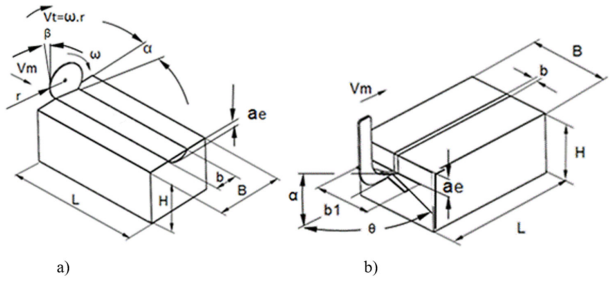


Figure 2. Simulation models of soil-tillage-tool interaction: a) Disc plow; b) Winged subsoiler.

The growing of the chapped soil prism dimensions beyond the assigned does not affect the cutting forces (Ibrahmi *et al.*, 2014; Marín *et al.*, 2022). The soil tool interaction was modeled tangential to the attack surface with contact model surface to surface.

Loads and Boundary Conditions

The boundary conditions for the models were established in function of acting loads.

Over the block soil of disc plow model (Fig. 3a) act the gravity acceleration (9, 81 $m \cdot s^{-2}$) and the atmospheric pressure (10 1325 Pa). Has moving constrains in below part (Y axis).

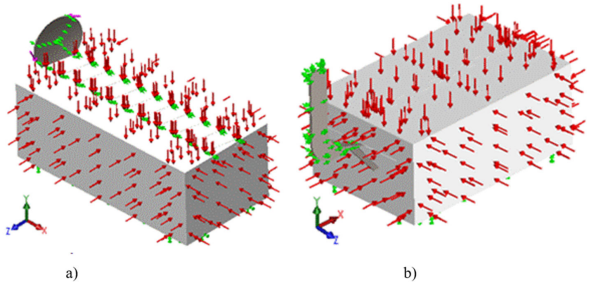


Figure 3. Loads and boundary conditions of the simulation models: a) Disc plow; b) Winged subsoiler.

The disc plow is moving ahead at constant speed (Vm = 0, 8 ms^{-1}) in axis X direction and turn around moving ahead at constant angular speed, working depth (ae = 100 mm) and working width (b = 358 mm). The block soil dimensions are: width (B = 1200 mm); length (L = 2000 mm); high (H = 1 000 mm).

The disc plow vertical tilt angle (β) is 15º, the disc plow lateral tilt angle is 25º, the diameter is 500 mm and the radius of curvature is 40,3 mm. The material used in manufacturing the disc plow is alloy steel.

Over the block soil of winged subsoiler model (Fig.3b) is acting the gravity acceleration (9, 81 ms^{-2}) and the atmospheric pressure (10 1325 Pa). Has a fixed constrain in the below part.

In lateral surfaces act the soil boundary stresses. The winged subsoiler arm is moving ahead at constant speed Vm = 1, 2 ms^{-1} (0, 33 kmh^{-1}) in X axis direction, at working depth (ae = 300 mm) and working width (b = 80 mm).

The block soil dimensions are: width (B = 1500 mm); length (L = 2000 mm); high (H = 1000 mm). The material of winged subsoiler arm is carbon steel and the chisel material is alloy steel. The chisel attack angle is 30º. The lateral arrow width (b1) is 900 mm.

The assigned dimensions, both disc plow model and winged subsoiler model, provide enough soil volume to enclose the movement of the same one during it deformation, without over computer time.

Mesh of the finite element models

The general mesh of both models were realized with maximum element size (e) of 20 mm, minimum element size 6 mm and the Newton-Raphson iterative model was used. The surfaces in touch, both tools and cut soil prism were mesh applying mesh control, with element size 4 mm (Fig. 4).

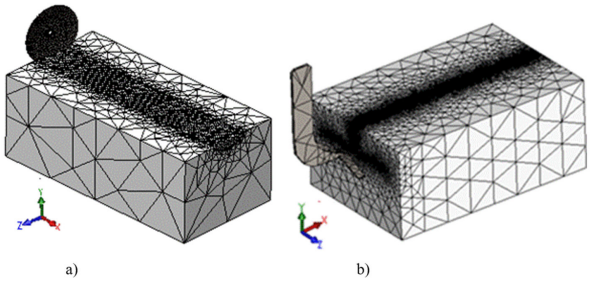


Figure 4. Mesh of the finite element models: a) Disc plow; b) Winged subsoiler.

RESULTS AND DISCUSSION

The results of the developed tridimensional simulation models provide information about the cutting forces, stresses, strains and displacements, both the block soils and tillage tools. Both models simulated, in appropriate way, the movements of both tillage tools across block soils, at 300 mm of displacement of same one.

Von Misses stresses, displacements and strains

For the disc plow model, the maximum value of von Misses stresses obtained is 206, 5 MPa (Fig. 5) and was met in the inner diameter of the same one. In this area are concentrated the biggest flexure and torque moments. Similar results (222 MPa) were obtained by Dehghan-Hesar & Kalantari (2016) for a conventional disc plow, with disc plow diameter 300 mm, working depth 70 mm, disc thickness 3 mm and radius of curvature 53 mm. It can be observed that, the cut soil is lifted, pulverized, partially inverted, and displaced to one side (Abu Hamdeh & Reeder, 2003).

For the winged subsoiler model, the maximum value of von Misses stresses (Fig. 6) is located in the chisel attack surface (79, 65 MPa). In this zone, the stresses values are bigger than tillage tool tip because of the contact area in this zone is big (Marín *et al.*, 2019), showing also, the attack angle influence in the cutting efforts of tillage tools (Marín, 2023).

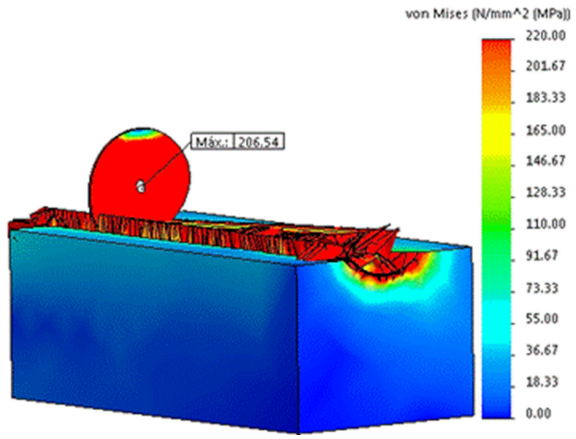


Figure 5. Von Misses stresses of disc plow model to 300 mm of displacement.

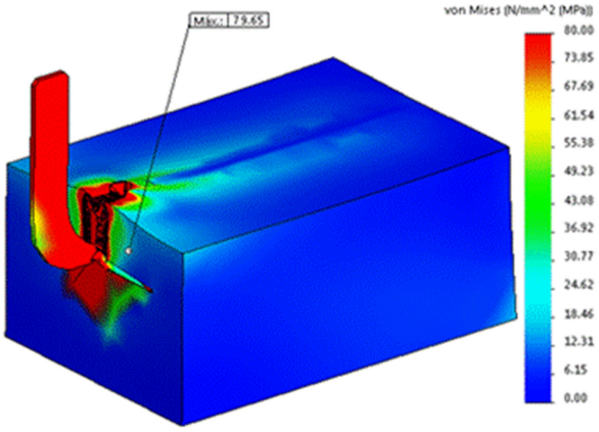


Figure 6. Von Misses stresses of winged subsoiler model at 300 mm of displacement.

Coinciding with other authors in previous researchers (Marín *et al*., 2022; Arefi *et al*., 2022; Marín, 2023), it can be observed that, as time goes by the winged subsoiler moving ahead over the soil block, big displacements taking place in all directions, overcoming the soil resistant forces and breaking the soil.

The Von Misses stresses, displacements and strains of disc plow at working depth (ae=100 mm) are showed in the figure 7. The applied force is 0, 9 kN and torque moment is 80 Nm. Of the finite element analyses it can be observed that, the maximum von Misses stresses obtained (206, 48 MPa) not surpass the elastic limit of material used in the manufacturing of same one (620, 4 MPa), thence the disc plow resist the efforts during the working order. Likewise, the maximum values of displacements and strains are unappreciated and not affect in significant way the working of disc plow.

For the winged subsoiler (Fig. 8), the von Misses stresses reach the maximum value (79 MPa) in chisel attack surface. Of the winged subsoiler finite element analyses, it can be observed that, the maximum von Misses stresses obtained not surpass the elastic limit of material, resisting the efforts during it working order. The displacements and strains are unappreciated.

CONCLUSIONS

Two tridimensional simulation models of soil-tillage tool interaction, using FEM have been developed, demonstrating the validity of this method in simulate, in appropriate way both models.

The elastoplastic model of Drucker-Prager constitutive relation used in simulation was able to predict the soil behavior interacting with utilized tillage tools.

The values of resulting stresses of both models are similar to other found in previous researches. For the disc plow, the highest stresses values were obtained in the inner diameter of disc plow. For the winged subsoiler, were obtained in the attack surface.

Taking into account the obtained results of numerical simulation by FEM of both models, geometric parameters and operational conditions of the utilized tillage tools, is recommended for future works the experimental validation.

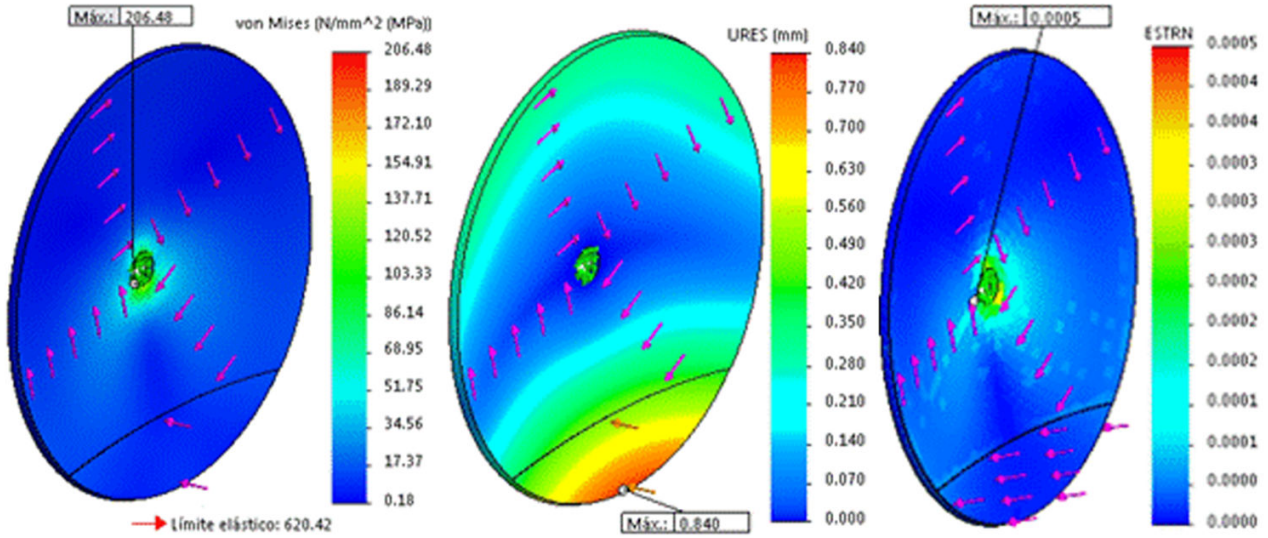


Figure 7. Von Misses stresses, displacements and strains of the disc plow.

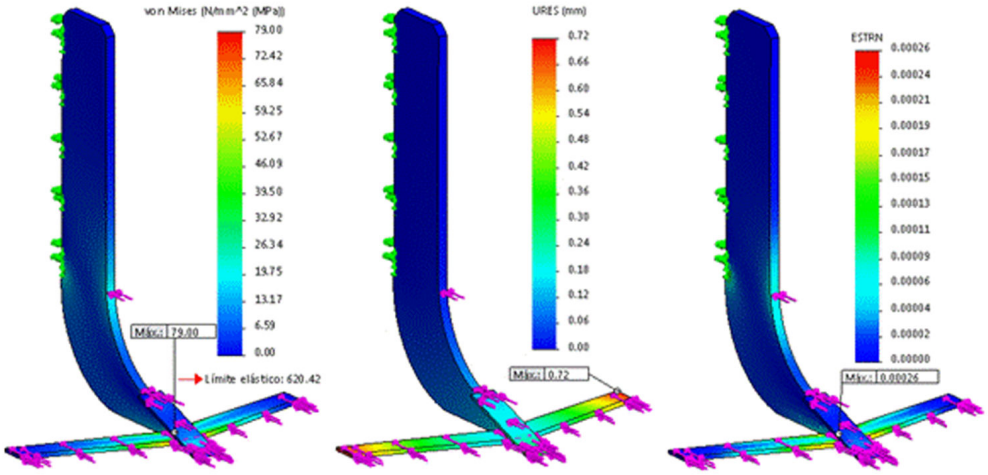


Figure 8. Von Misses stresses, displacements and strains of the winged subsoiler.

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