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Simulation of non-inverted soil tillage using the discrete element method

Simulación de la labranza sin inversión del suelo empleando el método de los elementos discretos

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ABSTRACT: In the present work, a simulation model is developed by the discrete element method (DEM) for tillage without soil prism inversion with a paratill type implement. The virtual soil block was generated with macro-particles that respond to the simplified geometry of soil fragments with attributes and physical-mechanical properties of a cohesive soil of the vertisol type. For the virtual model of the implement, the design and resistive study of the paratill is carried out using the finite element method (FEM). The simulation of the interaction between the implement and the soil block made it possible to determine the movement and velocity patterns of the particles, as well as the magnitude of the draft force, and the results showed that the design of the implement fulfills the tensile requirements that allow it to support the tillage activity without permanent deformations. On the other hand, the dynamics of the tillage process allowed establishing the final position of the particles, as well as the specific pressures between them and with the implement. Finally, the average value of the draft force was obtained by simulation, being in correspondence with the soil cohesion and the design of the tillage implement. The analytical validation, by means of the classical mechanics equations, showed adequate results of the draft force.
Keywords: Model, Numerical, Virtual, Force, Particles.

RESUMEN: En el presente trabajo se desarrolla un modelo de simulación por el método de los elementos discretos (DEM) para la labranza sin inversión del prisma con un apero tipo paratill. El bloque virtual de suelo se conformó con macro-partículas que responden a la geometría simplificada de los fragmentos del suelo con atributos y propiedades físico-mecánicas de un suelo cohesivo del tipo vertisol. Para el modelo virtual del apero se realizó el diseño y estudio resistivo del paratill mediante el método de elementos finitos (FEM). La simulación de la interacción del apero y el bloque de suelo permitió determinar los patrones de movimiento y velocidad de las partículas, así como la magnitud de la fuerza de tiro. Los resultados mostraron que el diseño del apero cumple con las exigencias tensionales que le permiten soportar sin deformaciones permanentes la actividad de labranza. Por su parte la dinámica del proceso de labranza permitió establecer la posición final de las partículas, así como las presiones específicas entre ellas y con el apero. Finalmente se obtuvo el valor promedio de la fuerza tiro mediante la simulación, estando en correspondencia con la cohesión del suelo y el diseño del paratill. La validación analítica, mediante las ecuaciones de la mecánica clásica, mostraron adecuados resultados de la fuerza de tiro.
Palabras clave: modelo, numérico, virtual, fuerza, partículas.

INTRODUCTION

The introduction of implements for vertical tillage of the soil, and thus the non-inversion of the prism, favors soil conservation. This type of implement avoids burying the fertile layer and maintains an adequate amount of crop residues on the surface, which makes it possible to reduce the effects of erosion, carbon release and compaction (Topa *et al.*, 2021; Zeng *et al.*, 2021; Liebhard *et al.*, 2022; Tan *et al.*, 2025).

The Paratill type implements, fragment the soil without destroying its structure or altering its properties. This implement has an arm or support with an angle of inclination of 45 degrees with respect to the horizontal. The dynamics of the process involves gently lifting the soil, fracturing it along its original fault planes and depositing it fluffy while maintaining its original position. The non-inversion of the prism avoids contamination of the fertile layer with the subsoil, for which work is carried out in correspondence to the arable layer. This method favors the reduction of the size of the clods and the burial of residues from previous harvests, it also improves water infiltration and absorption, stimulates root development and allows the placement of fertilizers in deeper areas (Zeng *et al.*, 2021).

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Moreover, several numerical modeling techniques, related to the prediction of draft forces and soil movement, have been employed to predict the performance of tillage equipment (Zein El-Din *et al.*, 2021; Cabrera *et al.*, 2022; Marín Cabrera *et al.*, 2022). Using computational models, where experimental results and theoretical knowledge are combined, simulations have been carried out that offer sufficiently accurate forecasts, thus making it possible to reduce the time and resources of the experimental stage. Methods such as finite element analysis (FEM), discrete element modeling (DEM), artificial neural networks (ANN) and computational fluid dynamics (CFD) have been used to simulate the processes taking place in the soil. DEM modeling is characterized by the use of a discrete medium of particles that interact independently according to the equations of classical mechanics, thus offering sufficient resources to achieve a representation of the dynamics of soil interaction in tillage processes and the variation of its properties (Sun *et al.*, 2018; Patidar *et al.*, 2024; Sedara *et al.*, 2025).

The present work was aimed at determining the soil dynamics and the draft force during the discrete element simulation of a soil tillage process without prism inversion.

MATERIALS AND METHODS

The soil block for the virtual model was obtained by generating 85000 particles, using the graphical editor of the EDEM Solution software, Altair Engineering Inc, as shown in Figure 1 (a). The soil particles were generated following a random order, which made it possible to fill without position patterns. As the particles fell due to the effect of gravity, contacts were determined through the model for cohesive soils based on the Mohr-Coulomb theory developed at EDEM, thus activating the cohesive forces between particles until the soil block reached a total height of 0,4 m. The particles used in the macro-scale soil model were spheres of radius 2 mm with mass 8.4 x 10-5 kg, volume 3.3 x 10-8 m3 and moments of inertia in the x, y and z axes of 1.3 x 10-10 kg/m2.

The physical properties assigned to the virtual particles respond to the conditions of a vertisol type soil with a moisture content of 22% and bulk density of 1.18 g/cm3. The physical parameters used in the model are shown in Table 1.

The paratill design (Figure 1b) and the strength study were carried out using SolidWorks 3D CAD software using the Finite Element Method. For this purpose, AISI 1045 steel was used as the tool material, where restrictions were established at the base of the tool and on the lateral

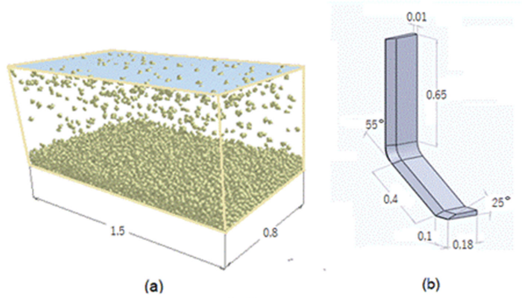

FIGURE 1. a) Generation of the soil block, b) geometry of the implement.

surface of the tool, corresponding to its attachment to the frame. The forces were applied on the front surface along the cutting edge, where the interaction of the soil with the tool takes place. Von Mises stresses and displacement were determined on the implement as an indicator of resistance to plastic deformation. The stresses were applied in steps until the magnitude of 0.6 kN was reached.

For the analytical verification, the semi-empirical model of Perumpral *et al.* (1983) was used, which includes the parameters defined in the soil model, in which the pulling force is determined by the following equation:

$$D = w_t\left(\gamma z^2 N_\gamma + czN_c + c_\alpha z N_\alpha\right) \qquad (1)$$

where:
D = pulling force [N],
wt = width of implement [mm],
γ= densidad [g/cm3],
z = depth [mm],
c = cohesion [Pa],
ca = adhesion [Pa],
N_γ, Nc, Na = coefficients

The model parameters were plotted a sequence of the simulation of the soil interaction with a simple tool and thus the value of the pulling force was determined using equation 1.

RESULTS AND DISCUSSION

Tool stiffness analysis

The figure 2 shows the location of the constraints and the reactions in terms of resistance and displacement of the material, corresponding to the application of the distributed stress in the cutting edge area of the tool where the interaction with the soil block takes place.

TABLE 1. Physical parameters of the soil model

Parameters	Simb	Values	Units
Failure stress	τ_{50}	539.9	kPa
Modulus of Elasticity	E	53.9	MPa
Poisson's ratio	ν	0.28	
Cohesion	X	72.6	kPa
Adhesion	χ_α	5.42	kPa
Internal soil friction	φ	22.2	°
Soil-metal friction	δ	15.3	°

The analysis of the displacement of the tool, as a result of the application of the forces, showed values between 1.5 and 1.7 mm corresponding to the far end of the tool (Figure 2a); this deformation decreases considerably as it approaches the area of fixation in the structure. On the other hand, the calculation of the failure stress from the Von Mises theory shows that the maximum values are found in the curved surface of the implement (Figure 2b). It is the arm supports of the horizontal cutting segment and generates a bending moment that increases the concentration of stresses in the bending radius and is transmitted to the support of the implement through the horizontal section; however, these stresses are considerably lower than the safety coefficient of the material; the other sections do not present significant values. Thus, it is verified that the structure of the body resists the stresses of the interaction with the soil without plastic deformation and with a high safety coefficient.

The distribution of kinetic energy during the filling procedure of the soil block is shown in Figure 3. The particles experience an increase in energy from the initial generation position when subjected to free fall. This gravitational energy is used in the model to activate the contact forces responsible for activating the cohesion between particles and forming the structure of the block,thus returning the particles to the state of rest, forming a structured body capable of resisting external stresses.

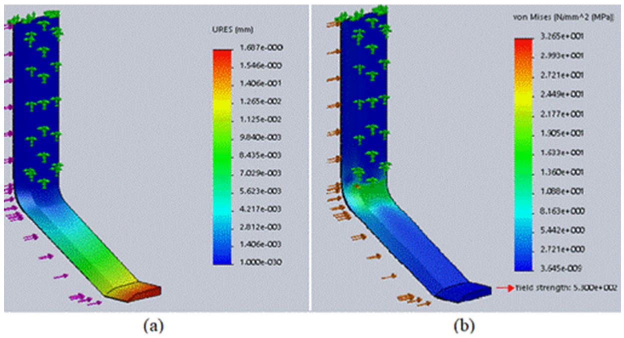

FIGURE 2. FEM study: a) Displacement analysis; b) Failure stress.

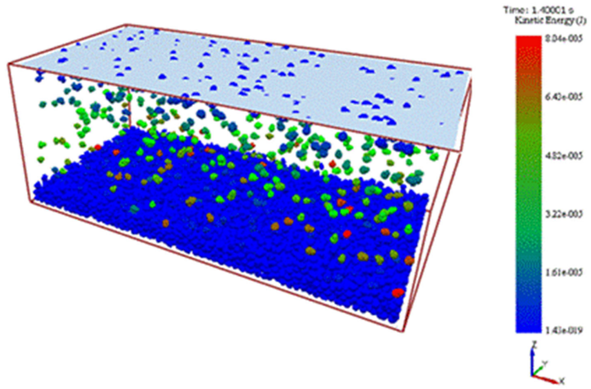

FIGURE 3. Kinetic energy during the fall of soil particles.

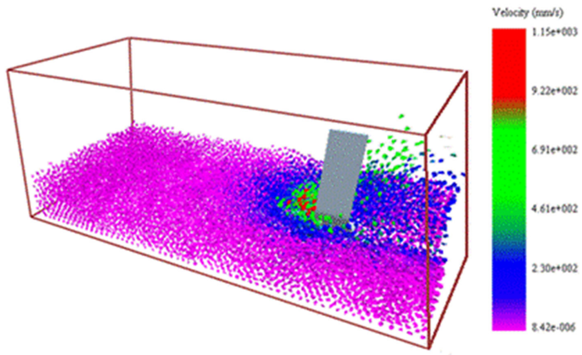

FIGURE 4. Particle velocity variations.

Analysis of the particle motion pattern

The movement pattern of the soil particles, due to the contact between them and with the implement, is shown in Figure 4. The displacement of particles describing spatial trajectories as a consequence of the dragging caused by the tool, the average displacement speed for those that are directly in contact with the implement is 0.6 m/s and maximums of 1.1 m/s, for those that are adjacent and only in contact with each other the values are 0.23 m/s. The particles in contact with the horizontal cutting zone of the paratill shows a vertical displacement, they are deposited on the surface of the block after the passage of the implement. The movement area of the particles does not exceed the nominal width of 0.8 m of the block, however, with a working width of 0.5 m of the implement, an area of approximately 70% of the soil block is mobilized. All this demonstrates the soil fragmentation capacity of implements that move below the surface without causing prism inversion, as well as the possibility of their use in tillage and localized cultivation operations (Zeng *et al.*, 2021).

Draft force results

As shown in Figure 5, the draft force increases from the contact of the tool with the soil block and is characterized by the oscillation of the values. This oscillation responds to the intermittency of the force necessary to separate the contacts between the particles according to the frequency of their occurrence, which has been pointed out by other authors (Zhang *et al.*, 2023a). In the initial stage of tool trajectory there is an increase in the value of the forces, which precedes an accommodation of the particle flow that leads to a better stability in the values. The resulting average force value is 0.47 kN, which is in correspondence with the cohesion of the soil and the design of the paratill being the main component during tillage operations which acts in the opposite direction to the movement of the implement.

The results are in agreement with studies carried out by several authors where simulation results have been obtained to determine the variation in soil conditions according to the design of the implement and its subsequent validation in field conditions (Kuře *et al.*, 2021; Kim *et al.*, 2022; Abdeldayem y Tekeste, 2025).

In the contact zone between the implement and the soil block, the specific pressure variations are shown, which identifies the stress state of the cutting zone (Figure 6). The maximum pressures are shown in red and increase as they approach the paratill shaft.

The stress state of the soil particles and the implement depends on the level of cohesion between particles, the geometric constraints imposed by the implement and its translation speed. (Kim *et al.*, 2021; Zhang *et al.*, 2023a). This value shows the stresses at a macro-scale level and that take place in each contact zone, these stresses are responsible for the defragmentation of the soil aggregates into smaller particles in correspondence with several studies (Zhang *et al.*, 2023b; He *et al.*, 2025).

On the other hand, the analytical determination of the value of the draft force, using the specific parameters of the model and the equations proposed by Perumpral *et al.* (1983), had a value of 0.53 kN. This value shows a difference that exceeds by 10.6% the average pull force obtained by the simulation, which is acceptable, considering the oscillation of the main cutting plane that takes place due to the movement of the particles during the simulation as well as the variation of the height of the ground in front of the tool. On the other hand, the results of the empirical models range from 60 to 80% accuracy. However, some studies consider that DEM models show a tendency to overestimate the values of forces (Obermayr *et al.*, 2011).

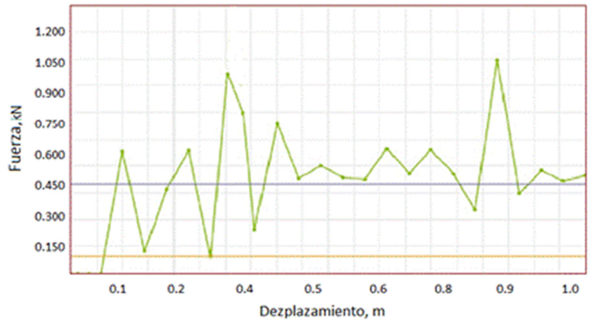

FIGURE 5. Draft force versus displacement.

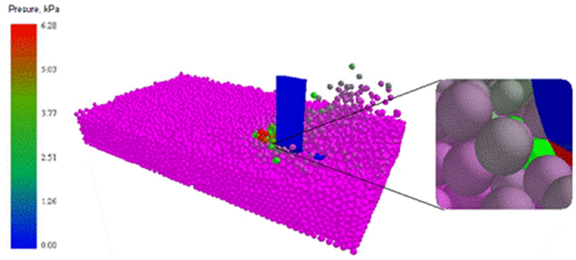

FIGURE 6. Distribution of specific pressures.

CONCLUSIONS

1. In the static study of the strength of the paratill type implement, it was determined that the design of the implement meets the tensile requirements that allow it to withstand without permanent deformations the tillage activity.
2. The simulation of the dynamics of the tillage process showed adequate movement patterns and velocity of the soil particles, allowing to establish their final position, as well as the specific pressures between them and with the implement.
3. The average value of the draft force obtained from the simulation was 0.47 kN, which is in correspondence with the cohesion of the soil and the design of the paratill. This value corresponds to the results of the analytical validation where an error of 10.6% was obtained.

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