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Araştırma Makalesi/*Research Article (Original Paper)*

Modeling the Effects of Narrow Blade Geometry on Soil Failure Draught and Vertical Forces Using Discrete Element Method

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Abstract: In most earth moving machinery, such as bulldozers or tillage tools, the working tool is a tine. Thus, for tillage systems, accurate predicting of the forces acting on the tine is of prime importance to enhance their productivity. The initial conditions (i.e., blade geometry or soil type) and operating conditions (i.e., cutting speed and cutting depth) have been shown experimentally a great effect on machinery efficiency. Although experimental studies provide valuable information, they are expensive, time-consuming, and limited to certain cutting speeds and depths. Results obtained from experimental studies are also highly dependent on the accuracy of the measuring devices. However, with the increasing computational power and the development of more sophisticated mathematical models, numerical methods and in particular discrete element method (DEM) have shown great potential in analyzing the factors affecting soil-blade interaction. In this study, the effects of different rake angles, forward speed, working depth, and depth/width (d/w) ratio were investigated on a tine draught and vertical force using DEM modeling. Simulation results were also compared with the test results. It was found from the results that increasing travel velocity, tine rake angle, d/w ratio, and working depth increased draught and vertical force. Overall, based on the results of this study, DEM is able to predict soil reaction forces with an accuracy of more than 90%.

Keywords: DEM, Draught, Simulation, Tillage

Dar Kanat Geometrisinin Ayrık Eleman Yöntemi Kullanılarak Toprak Bozulma Derinliği ve Çekme Kuvveti Üzerindeki Etkilerinin Modellenmesi

Öz: Buldozerler veya toprak işleme araçları gibi çoğu toprak işleme makinesinde, çalışma aleti bir çatal dişidir. Bu nedenle toprak işleme sistemleri için, bıçak üzerinde etkili olan kuvvetlerin doğru tahmin edilmesi, üretkenliklerini arttırmak için çok önemlidir. Kesme hızı ve kesme derinliği gibi bıçak geometrisi veya toprak tipi ve çalışma koşulları gibi başlangıç koşulları deneysel olarak makine verimliliği üzerinde büyük bir etkiye sahip olduğu gösterilmiştir. Deneysel çalışmalar değerli bilgiler verir, ancak pahalı olabilir ve belirli kesme hızları ve derinlikleri ile sınırlı olabilir. Sonuçlar aynı zamanda ölçüm cihazlarının doğruluğuna oldukça bağlıdır. Ancak artan hesaplama gücü ve daha sofistike modellerin geliştirilmesinde, ayrık eleman analizi (AEA), toprak bıçağı etkileşimini etkileyen faktörleri analiz etmede daha fazla umut vermektedir. Bu çalışmada, farklı eğim açıları, ileri hız, çalışma derinliği ve derinlik/ sürat oranının, ayrı bir eleman yöntemi kullanılarak dik bir çekme ve düşey kuvvet üzerindeki etkileri araştırılmıştır. Sürüş hızı arttıkça tırmık açısı, d / w oranı ve çalışma derinliği çekme kuvvetinin arttığı görülmüştür. AEA, toprak reaksiyon kuvvetlerini bir diş üzerinde öngörebilir ve simülasyon ile deney sonuçları arasında iyi bir uyum bulunmuştur. Genel olarak, bu çalışmanın sonuçlarına dayanarak, AEA toprak reaksiyon kuvvetlerini % 90'dan fazla bir doğrulukla tahmin edebilir.

Anahtar kelimeler: AEA, Derinlik, Simülasyon, Toprak İşleme

Introduction

Soil-tillage has been a challenging issue for many researchers, developers, manufacturers, and farmers. The seed-imbedding preparation, soil structure correction, and sub-soiling are of great importance for farmers. To decrease soil-tool energy requirement, special attention should be given to tillage management. Economic and environmental constraints force the farmers to use well-designed tools for soil-tillage. Soil cultivating process consumes more than half of the energy needed to grow agricultural products (Kushwaha and Zhang 1998). Understanding the interaction between the soil and tillage tool can help designers to increase the energy efficiency in tillage operation. Accurate simulation of the soil-blade interaction can also reduce the need for cost in-situ tests. Moreover, by choosing the appropriate simulation model, the required time can be decreased for developing the proper model.

The dynamic interaction happening in the soil-tillage process includes a high amount of plastic deformation and soil failure due to the soil flow. The soil-tool interaction associated with various parameters, such as the soil failure profile, soil resistance, soil lifting on the device, the soil flow, and its cracking, is a complicated phenomenon. In this connection, developing a numerical model will help researchers to observe how the soil resistance changes under different rake angles, traveling speeds, depths, and widths of the tilling tool.

Almost 40 years ago, Gill and Vanden Berg (1968) stated that the performance of a specific tillage tool could not be calculated. This comment still is true on the final soil condition. However, today much information about the methods used to measure reaction forces on the tillage tools is available. Although prediction accuracy of analytical and experimental methods in predicting the soil-tool interaction is acceptable, these methods can be used for simple tools. Some numerical theories, such as the finite element method (FEM) or computational fluid dynamics (CFD), have been used in this regard. However, due to the continuity hypothesis of these methods, none of these methods can predict changes in soil structure such as the creation of crack on soil and soil flow in the border region between the tool and soil particles (Shmulevich et al. 2007).

Discrete element method (DEM) is a discrete numerical approach capable of examining the granular and distinct materials. In this method, objects are considered as discrete elements and the mechanical relations between them are determined by the normal and shear spring constants and by the friction parameters. This approach is based on the laws of physics and the element displacements are given by the equations of motion. The elements transfer the inserted force of tilling time to the neighboring elements. The tangential force is applied by the relative displacement and relative velocity of the elements. It has been supposed that overlapping occurs between the elements and the interface forces are calculated accordingly. In order to find the equation of motion, it is needed to approximate the forces on the elements. In this method, the active forces of each element on the others are simulated using a vibratory model system (Khot et al. 2007).

Modeling of the interaction between soil and tillage tool is a complex process. Granular materials were modeled using the DEM (Cundall and Struck, 1979), as a suitable tool for simulating soil-tool interaction. Nonlinear soil behavior and soil-tool interactions can be simulated and optimization of tillage equipment can be carried out using DEM. Over the past 10 years, many studies have shown the potential of this DEM method for simulation the interaction between soil and tillage tools.

According to Mak et al. (2012), the existing studies on DEM models are for cohesionless soils and do not discuss the selections and calibrations of model parameters. They developed a soil-tool interaction model using a commercial DEM software, Particle Flow Code in Three Dimensions (PFC3D). In the model, soil particles were defined with the basic PFC3D model particles, which consisted of balls with cohesive bonds between balls. The model parameters including bond normal and shear strengths were determined based on intrinsic stresses of soil. The most sensitive model parameter, ball normal stiffness, was calibrated for two contrast soils: coarse and fine soils. The calibrations were performed through comparing the draught forces of a simple soil-engaging tool simulated with the PFC3D soil-tool interaction model and those estimated with the Universal Earthmoving Equation.

Sun et al. (2018) applied a bionic design method to reduce subsoiler energy consumption and soil disturbance. The bionic structural elements, including a triangular prism (BTP) and partial circular column (BPCC), were inspired by the placoid scale rib structure of shark skin. These elements were then applied to the subsoiler to reduce energy consumption. Six types of bionic subsoilers were designed. The DEM was used to simulate and analyze the interactions of the bionic subsoilers and an ordinary subsoiler (O-S) with the soil. The results showed that bionic subsoilers with a shank and BTP in the horizontal direction of motion (S-T-H) and tines with the BTP parallel to the centerline (T-T) had lower draft requirements and energy consumption than the other designs. The draft requirements and energy consumption of S-T-H subsoilers with different height-to-lateral-rib-spacing (h/s) ratios were then compared. The subsoiler with a bionic element h/s of 0.57 (S-T-H-0.57) had a lower draft requirement (1292.59 N) and a lower total energy requirement (23.48 J) than the other designs.

In this study, the effects of the blade rake angle, traveling speed, depth and width of the blade, and slenderness ratio (the ratio of depth to the width of the blade) on the draught and vertical forces were analyzed by DEM using PFC3D software.

The main goals of this paper were as follows:
1. Modeling the soil- blade interaction using DEM
2. Analyzing the effects of forward speed, working depth and the width of the blade on the draught and vertical force

Materials and Methods

Experiments were conducted in a loam soil with a content of 25% clay, 29.34% silt, and 45.66% sand. The tests were conducted using an MF285 tractor equipped with single rear wheels (18.4R30 radial-ply) and a weight of 1694 kg on the rear axle. The inflation pressure of the rear wheel was 100 kPa during all tests. Experimental runs were randomized and blocked to control variation. To do so, treatments at three replications were arranged in a complete randomized block design. Minitab 2017 software was used to analyze the data. To determine the effect of depth on the draught and vertical forces, field trials were conducted at four different depths of 50, 100, 150, and 200 mm. In order to investigate the effect of depth to width (d/w) ratio on tillage forces, a 90° rake angle blade with d/w ratios of 1, 2, 3, and 4 was modeled (at 50 mm operation depth). For evaluating the effect of rake angle on tillage forces, four different rake angles of 22.5, 45, 67.5, 90, and 112.5° in the constant working depth of 150 mm were examined. A 1 m long and with different width were used in trials. Tine was mounted on a chassis equipped with 2 wheels to control working depth (Fig. 1).

Figure 1. The tine was used in trials (left). The tractor and chassis combination during field trial.

A three-point hitch dynamometer was used to measure required draught and vertical forces (Fig. 2). The dynamometer consists of three octagonal rings, each having eight resistance strain gauges. Draught and vertical forces for the total of three horizontal and vertical forces were measured by three octagonal rings.

The Hertz contact model is a nonlinear contact formulation based on an approximation of the theory of Mindlin and Deresiewicz (1953) and described in Cundall (1988). For Hertz contact, the parameters k_n and k_s are ignored. Instead, the model is defined by the following two parameters: shear modulus (G) and Poisson's ratio (v) of the two contacting particles.

Figure 2. Three-point hitch dynamometer was used to measure draught and vertical force.

Simulation was developed using 3 dimensional particle flow code (PFC3D) created by ITASCA Company. Considered soil in this research was loam and linear contact model and hertz contact theory was used for its simulation. The contact stiffnesses relate the contact forces and relative displacements in the normal and shear directions via Eqs. 1 and 2. The total normal force (F_i^n) and the total normal deformation (U^n) are expressed Eq. 1. Then normal stiffness is a secant Stiffness. The shear stiffness is a tangent stiffness (Eq. 2), since it relates the increment of shear force (ΔF_i^s)to the increment of shear displacement ($k^s \Delta U_i^s$).

$$F_i^n = K^n U^n n_i \tag{1}$$
$$\Delta F_i^s = -k^s \Delta U_i^s \tag{2}$$

The linear contact model is defined by the normal and shear stiffnesses k_n and k_s [force/displacement] of the two contacting entities. The contact stiffnesses for the linear contact model are computed assuming that the stiffnesses of the two contacting entities act in series. The contact normal secant stiffness is given by:

$$K^n = \frac{k_n^{[A]} k_n^{[B]}}{k_n^{[A]} + k_n^{[B]}} \tag{3}$$

and the contact shear tangent stiffness is determined using Eq. 4:

$$k^s = \frac{k_s^{[A]} k_s^{[B]}}{k_s^{[A]} + k_s^{[B]}} \tag{4}$$

Where the superscripts $[A]$ and $[B]$ denote the two entities in contact.

The Hertz contact model is a nonlinear contact formulation based on an approximation of the theory of Mindlin and Deresiewicz (1953) and described in Cundall (1988). For Hertz contact, the parameters k_n and k_s are ignored. Instead the model is defined by the following two parameters: shear modulus *G* (stress] and Poisson's ratio *ν* of the two contacting particle.

The required model parameters included normal and shear stiffness coefficients, the friction coefficient between particles, Poisson's ratio, elasticity modulus, and density of the soil. Time step was adjusted automatically by software. Due to computational restrictions, particles sizes were three times greater than real soil particles (Ting et al. 1989). Therefore, soil parameters were calibrated appropriately based on soil particles size. For the calibration of required parameters, direct shear was conducted. The internal friction angle and simulation particle adhesion were calibrated by direct shear testing simulation. The modeling box included a top piece and a lower piece, each with a height of 100 mm. The movement of the upper piece of the box was controlled so that a steady vertical force could be applied to the whole set of particles in the simulation. Vertical forces on the particle were thousands of times of actual shear test so that the same stresses could be achieved. The vertical stresses used were 27.5, 55.3, and 82.6 kPa, respectively. The lower piece of the box was moved at a constant speed of 1.5 mm/s to cut the particle set. The simulation cutting speed was also 10 times faster, so the simulation time was 100 times faster than the shear test speed. Then, the forces on the lower piece were measured to measure the maximum shear stress in the particle set. The friction coefficient of particles, particle size, and bond strengths were adjusted to achieve the friction angle and adhesion similar to that of the actual shear test. Table 1 shows soil parameters were used for simulation.

Table1. Input parameters used for simulation

Parameters	Parameters value
Normal spring constant (Kn)	1e8(N/m)
Tangential spring constant (Ks)	1e8(N/m)
Bulk density of particles	3000(kg/m^3)
Particles radius	0.01-0.015(m)
Friction coefficient	0.5
Gravity	9.81(m/s^2)

Soil box length, width and height were 2, 0.5 and 1 m, respectively (Fig. 3). It was filled with sphere balls up to height of 60 cm. Blade was created using wall function by PFC3D. Fig. 4 shows as blade cutting soil and how cracks were created.

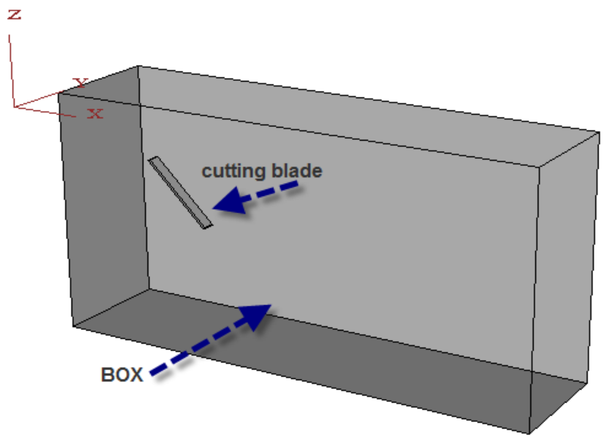

Figure 3. Soil box and blade inside box.

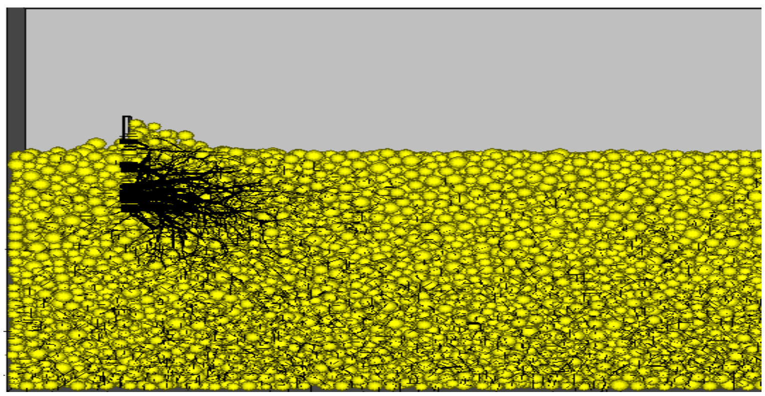

Figure 4. Soil cutting and cracks creation inside soil.

Results and discussion

Table 2 shows statistical variance analysis (Anova) results of the effect of tine depth, its rake angle and d/w ratio of draught requirement were measured by conducting field experiments. Effects of the three main factors at the 1% level on tine's draught changes were significant.

Table 2. Anova statistics for the effect of depth, rake angle and d/w ratio on draught requirement

Factor	DOF (degree of freedom)	Sum of squares	Mean square	F
Block	2	0.03	0.015	2.11^{ns}
depth	3	22.813	7.6	1070.42**
Error	6	0.043	0.0071	
Total	11	22.88		
Block	3	0.056	0.028	2.74^{ns}
Rake angle	4	16.27	4.068	398.82**
Error	8	0.082	0.0102	
Total	14	16.35		
Block	2	0.008	0.0044	0.66^{ns}
d/w ratio	3	28.55	9.518	1416.57**
Error	6	0.0403	0.0067	
Total	11	28.6		

** Highly significant ($p < 1\%$), ns= not significant

The effect of tine depth, its rake angle and d/w ratio on the vertical force of tine was presented in Table 3. All of them showed significant effect on the vertical force.

Table 3. Anova statistics for the effect of rake angle on vertical force

Factor	DOF (degree of freedom)	Sum of squares	Mean square	F
Block	2	0.018	0.0092	1.17^{ns}
Rake angle	4	7.44	1.86	234.82**
Error	8	0.063	0.0079	
Total	14	7.52		
Block	2	0.001	0.0005	12.5**
d/w ratio	3	2.77	0.926	23150**
Error	6	0.00024	0.00004	
Total	11	2.77		
Block	2	0.0025	0.00125	5.34^{ns}
depth	3	1.597	0.532	2265.3**
Error	6	0.0014	0.00023	
Total	11	1.6		

** Highly significant ($p < 1\%$), ns= not significant.

The effect of depth on draught force is presented in Fig. 4. Both simulation and experimental results showed that with increasing the depth both vertical and draught forces increased. Draught force was increased with depth increment due to the increase in soil density and surcharges, leading to the increase in soil-tool friction and cohesion. Other researchers showed that the draught force was the second-order function of the depth (Owen 1989). Based on Mckeys and Ali (1997) equation for narrow tools, the required draught is a second-order function of depth. The difference between the discrete element predictions using spherical particles and experimental results can be due to greater rolling resistance between model particles in comparison with the actual behavior of soil, soil particles size (considered larger than the actual value), and considered soil parameters which were different than real soil parameters due to lack of calibration.

Rake angle is an important tool geometry factor significantly affecting tool draught and vertical force requirements. This parameter is defined as the angle contained between the tool travel direction (traditionally draught) and the active tool face (Payne and Tanner 1959; Freitag 1988). These works and other ones (Söhne 1956; Dransfield et al. 1964) highlighted that the optimum rake angle values for minimum draught are within the range of 20 to 30° (Fig. 6). Draught and vertical forces requirement increased with tine rake angle increment. As illustrated in Fig. 6, soil vertical force on tine increased with increasing tine rake angle. A good correlation between the experimental and simulation results was found for the effect of the rake angle on draught and a vertical force (Fig. 6). The draught force is not minimum at rake angles less than this range (20-25°) due to a gradually overriding effect of increased soil/tool interface area with its associated adhesive and frictional forces, and the practical issues associated with significant cutting edge thickness at low rake angles inducing soil compaction (Fielke, 1996 and 1999). A 5-fold increase in draught requirement was reported by Payne and Tanner (1959) over the 20° to 160 ° rake angle range.

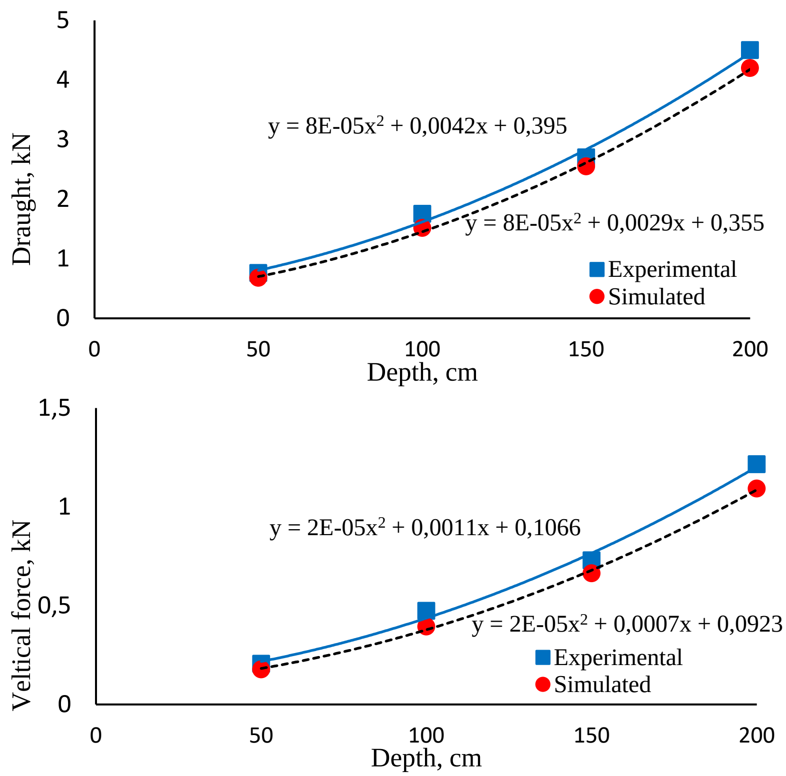

Figure 4. Draught and vertical force vs. working depth.

Fig. 5 shows that with increasing d/w ratio draught and vertical force increased and DEM simulation confirmed this.

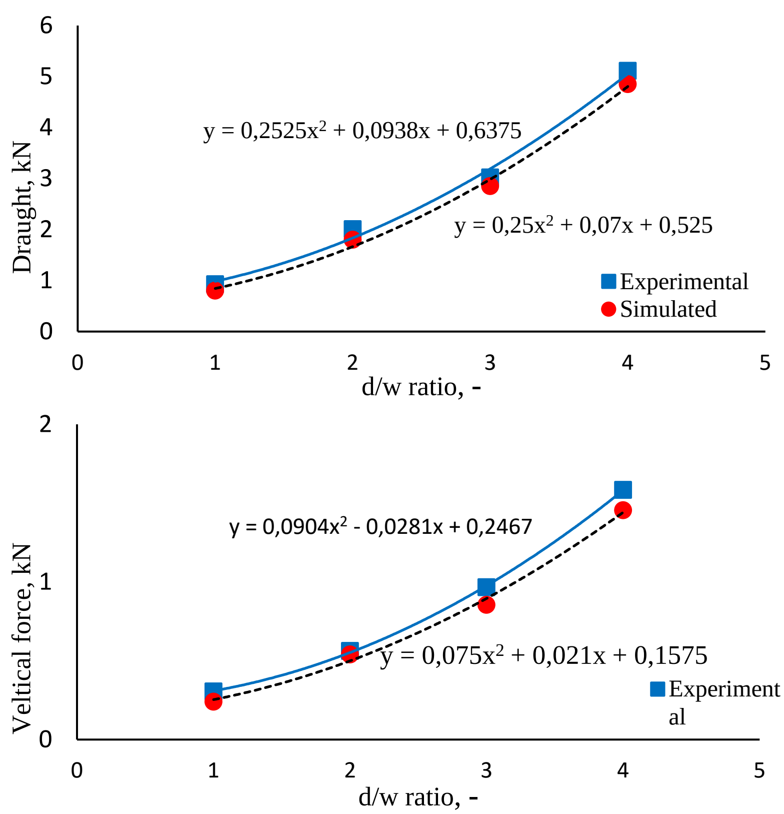

Figure 5. The effect of (depth/width) ratio on draught and vertical force.

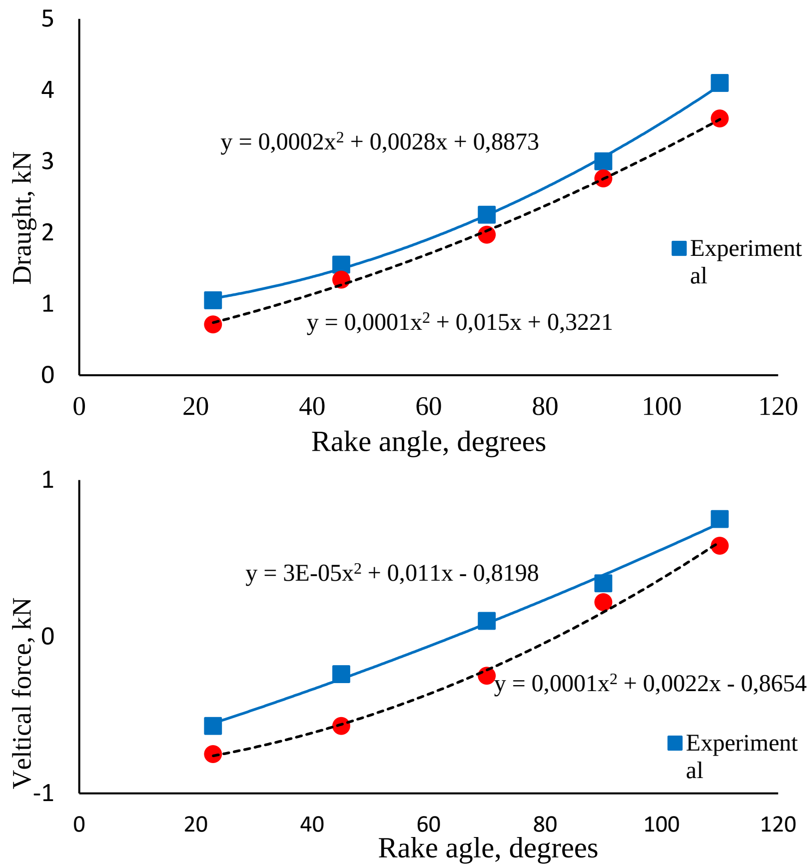

Figure 6. The effect of blade rake angle on draught and vertical force.

Fig. 7 declares that there was good agreement between simulation and experimental results for draught requirement.

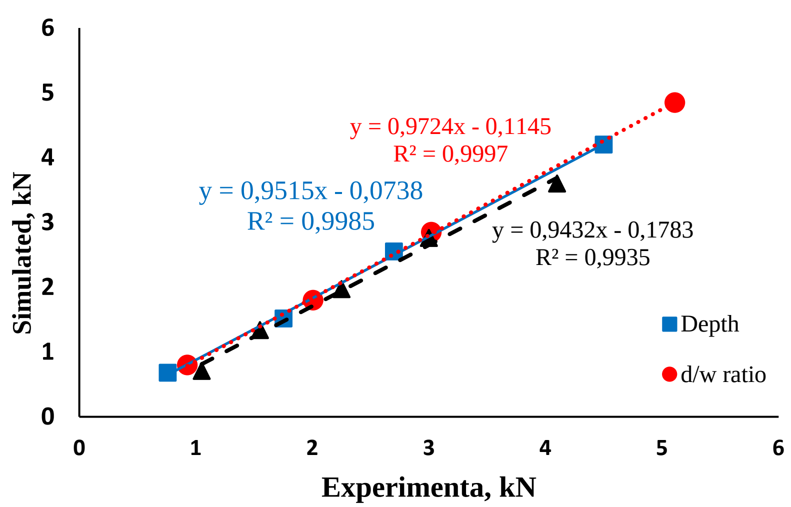

Figure 7. Correlation regression between experimental and simulated results for depth, d/w ratio and rake angle effects on draught.

Good correlation between the experimental and simulation results was found for the effect of the depth, d/w ratio and rake angle vertical force (Fig. 8).

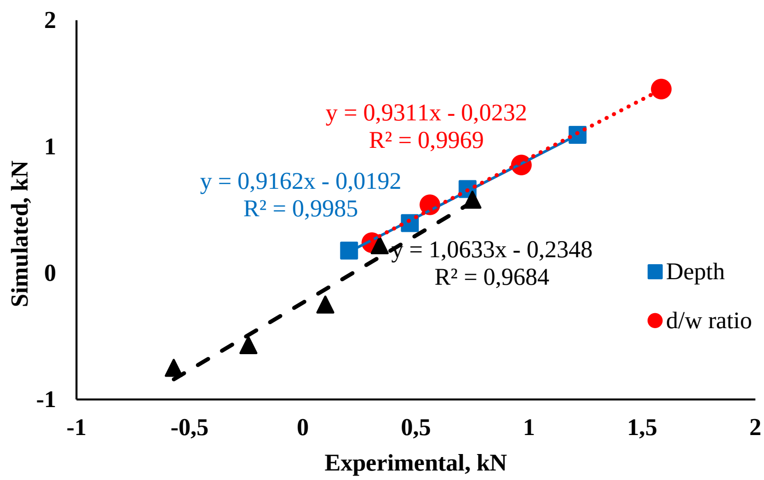

Figure 8. Correlation regression between experimental and simulated results for (d/w) ratio effects on draught force

Simulation and results showed that increasing the tine forward speed increased the draught and vertical force (Fig. 9). Most of the previous studies have shown that forward speed is an important factor in increasing draught force. Söhne (1956) found that the draught force was a function of soil acceleration and consequently acceleration is proportional to the square of velocity. On the other hand, different results about draught force versus velocity can be found in the literature. This difference can be attributed to the different field conditions and the type of tillage tool used in the studies. Owen (1989) found that draught force increase is a quadratic function of velocity; however, Summers et al. (1986) reported a linear relationship between them.

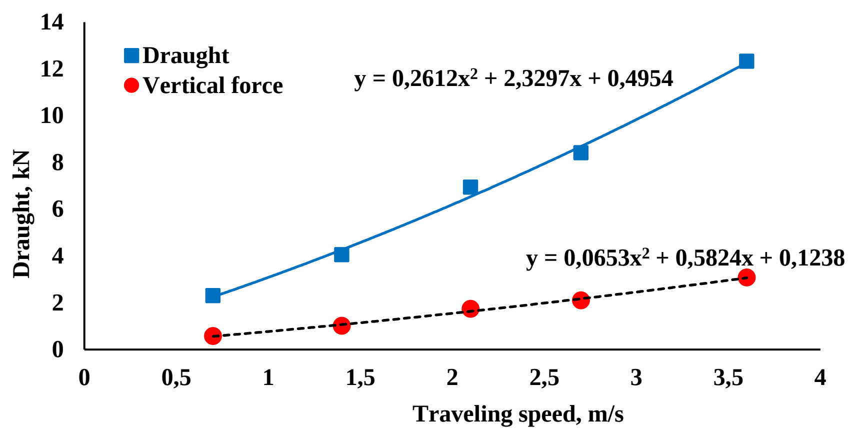

Figure 9. The effect of traveling speed on Draught force.

Conclusion

In this study, the DEM simulation of soil-tine interaction was carried out using a linear contact model. The results of the study showed that DEM could predict the dynamic behavior of granular materials like soil. DEM is able to predict drought and vertical forces on tine at different forward speeds, rake angles, d/w ratios, and depths and good correlation was found between DEM predicted and experimental data. Draught requirement and vertical force on the tine increased with the increase of rake angle. It was also found that increasing d/w ratio increases draught force.

The difference between DEM results using spherical particles and experimental results can be explained by the greater rolling resistance between modeled particles compared with the actual particles of soil, as the soil particles size was greater than the actual particles of the soil

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