Influence of tillage depth, penetration angle and forward speed on the soil/thin-blade interaction force

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Abstract: In this study, an experimental investigation regarding the influence of three independent variables including tillage depth (10, 15, 20 cm), angle of attack (60, 75, 90 degrees) and forward speed (0.5, 1, 1.35, 1.7 m/s) on draft force of a thin blade is presented. Chisel plow in this research was constructed in two furrows with a blade width of 3 cm and a maximum depth of 25 cm (the distance between two blades was 1 m). Some changes were made in the chassis of the chisel plow in order to obtain different attack angle of the blade. The experimental work was then complemented with a new theoretical model for predicting the blade force using dimensional analysis method. The final expression for estimating the pull resistance is as a function of several soil engineering properties (soil bulk density, soil adhesion and cohesion coefficients), blade parameters (blade width and blade rake angle) and operational conditions (tillage depth and forward speed). Finally constants of the model were computed based on obtained experimental data. The proposed model properly estimated the draft force of a thin blade. Results obtained in this study indicate the stronger influence of tillage depth on the pulling force of a thin soil-working blade compared to the penetration angle and forward velocity. The average error for the vertical blade with depth of 20, 15 and 10 cm were obtained equal to 4.5%, 4% and 1.5%, respectively.

Keywords: tillage, thin blade, chisel plow, interaction force, dimensional analysis

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1 Introduction

One of the criteria used to assess the suitability of a tool for soil manipulation is the force required in pulling the tool through the soil (McLaughlin et al., 2008; Olatunji et al., 2009; Mamman and Oni, 2005; Gill and Vanden Berg, 1967; Arvidsson et al., 2004; Khanghah, 2009). The dynamic response of soil to farm implements is amain factor in determining their performance (Tong and Moayad, 2006). The interaction between tillage tools and soil is of a primary interest to the design and use of these tools for soil manipulation (Shen and Kushwaha, 1998). The tillage operation requires the most energy and power spent on farms. Therefore, draft and power requirements are important in order to determine the size of the tractor that could be used for a specific implement. The draft required for a given implement will also be affected by the soil conditions and the geometry of the tillage implement (Taniguchi et al., 1999; Naderloo et al., 2009; Olatunji et al., 2009). To reduce tillage, it is important to know the draught requirement for different implements. Most of the research on draught in soil tillage has concerned forces on narrow tines (Arvidsson et al., 2004). Based on the conducted researches, three factors of weight, velocity, blade cut angle and their interactions have significant effect on the tensile strength and with increasing these three factors, the tensile strength significantly increases (Aykas et al., 2004). Kuczewsk

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and Piotrowska (1998) introduced a new model for forces on narrow soil cutting tinestaking into account variability of the inclination angle of bottom failure surface in the side segment and inertial forces for different side segments. Draft force and power requirement for tillage implements were considerably affected by implement design and conditions of soil. In terms of effects on draft force and soil disturbance, Rahman and Chen (2001) reported that the working depth of tillage implement was more critical than the working speed. Kheiralla et al. (2004) formulated a draft force models for ploughs based on traveling speed and tillage depth. Abo-Elnor et al. (2004) concluded that the bladecutting width had a significant effect on cutting forces so that the cutting forces increased but not in linear proportion as the cutting width increased. McKyes and Maswaure (1997) demonstrated that designing a tillage tool for minimum draft requirement and high soil cutting efficiency called for a shallow operating depth and rake angle of 30°. Mulqueen et al. (1977) found that cohesion and penetration resistance increased as the soil bulk density increased. Dahab and Mutwalli (2002) reported that the traction force for chisel plough was higher in a soil of higher bulk density and the traction power increased as traction force increased. The effects of soil conditions, tillage depth and forward speed on soil translocation by chisel plow were studied by Van Muysen et al. (2000). The specific draft (force per cross sectional area of worked soil), energy use for moldboard plow, chisel plow and disc harrow at different soil conditions were investigated by Arvidsson et al. (2004). They found that the specific draft was generally the highest for the chisel plow and the lowest for the moldboard plow and the disc harrow and referred that to the differences in implement geometry and mode of soil break-up. Several models were developed to predict draft for tillage tools based on soil condition, soil properties and implement width (Sahu and Raheman, 2006). Taniguchi et al. (1999) reported an increase in draught with increases in travel speed for a mouldboard plough and the relationship between speed and draught was linear. Owen (1989) studied the force-depth relationship of a chisel plow tine with three different wing types in a compacted clay loam soil and found the vertical force on the tine to increase linearly with the operating depth while the horizontal force, moment and total force to increase quadratically with operating depth. Mamman and Qui (2005) studied the draft performance of a chisel plow model using a soil bin. The design parameters considered were: nose angle, slide angle, depth and speed. The draft increased with increases in tillage depth and the levels of nose and slide angles and the cutting edge height. Grisso et al. (1996) determined the draught of a tandem disk, chisel plough and field cultivator in a silty clay loam soil on wheat stubble field. Travel speed and tillage depth were used to study the draught of the tillage implements. They found the draught of the tillage implements to be significantly affected by both travel speed and tillage depth. The draught for the tandem disk varied quadratically with depth when used as a primary tillage implement. The tillage depth mostly influenced the draught of the chisel plough. Although the linear effect of travel speed was found significant, speed showed little effect on chisel plough draught. The field cultivator draught was linearly dependent on speed and speed by depth interaction, and quadratic dependent on depth. Fielke (1996) studied the effect of the cutting edge geometry of tillage implements on tillage forces, soil failure and soil movement below the tillage depth in the field and in a laboratory soil bin. Experimental sweeps that were standardized with 400 mm width; 32 mm lift height, 10º rake angle and 70º sweep angle were used. The authors reported that increasing the speed of operation consistently increased the draught but had little effect on the vertical force. An increase in cutting edge height increased the forward and downward movement of soil at the cutting edge, and an increasing draught and vertically upward forces accompanied this. The sharp cutting edge of the tillage tool minimized the draught and vertically upward forces and it also gave a minimum of soil disturbance below the tillage depth. Basically dimensional analysis is known to be a strong analytical tool which is designed to find or check relations among physical quantities by using their dimensions. It makes possible to generalize the experimental results. General analyzing the phenomena without limiting to a special state of the performed experiments causes less experimental requirements and also time and expense consuming. Obtained results can be provided to engineers more practically and more compacted for easier application (Murphy, 1950).

In this study, an experimental investigation regarding the influence of tillage depth, penetration angle and forward speed on the soil/thin-blade interaction force is presented. Influence of three independent variables including tillage depth, angle of attack and forward speed on draft force were measured. The experimental work was then followed by a new theoretical model for predicting the blade force using dimensional analysis method. Finally constants of the model were computed based on the obtained experimental data.

2 Material and methods

In this study, the factors influencing the forces acting on the blade are presented in Table 1 as a function of soil engineering properties, tool design parameters and operating conditions, (Abo Al-Kheer et al., 2011).

Table 1 The effective factors of soil force acting on blade

Effective factors	Definition	Symbol
Soil engineering properties	soil bulk density (g cm^{-3})	γ
	Angle of internal friction of soil (deg)	φ
	Cohesion (kPa)	c
	Adhesion (kPa)	c_a
	Angle of soil metal friction (deg)	δ
Tool design parameters	Tool width (m)	w
	Rake angle (deg)	α
	Tool depth (m)	d
Operational conditions	Surcharge (kPa)	q
	Speed (m s^{-1})	v

Field experiments of the research were performed in the Research Station of the SANRU (Sari Agricultural and Natural Resource University). Engineering characteristics of the examined soil are given in Table 2.

In this study, three independent variables of speed, tillage depth and penetration angle of the plow blade were considered with 36 treatments: 3 tillage depths, 3 penetration angles, and 4 forward speeds in three replications. Influence of three independent variables including tillage depth (10, 15, 20 cm), angle of attack (60, 75, 90 degrees) and forward speed (0.5, 1, 1.35, 1.7 m/s) on tractive force were measured. Chisel plow was constructed in two furrows with a blade width of 3 cm and a maximum depth of 25 cm (the distance between two blades was 1 m). Some changes were made in the chassis to create different attack angle of the blade (Figure 1). Two-tractor according to RANM method was used with drawbar dynamometer (Figure 2) to measure the force exerted on the blade.

Table 2 The properties of testing soil

Soil texture	Silt-Sand
Percentage of clay (<0.002 mm)	47%
Percentage of silt (0.002±0.05 mm)	43%
percentage of sand (>0.05 mm)	10%
Cohesion (c)	2.3 kPa
Angle of internal friction	35°
Moisture content	250 g/kg
The dry density for experiment	1.19 g/cm^3
Humidity for experiment	250 g/kg

Figure 1 The used Arvid 354 tractor together with the examined chisel plow

Figure 2 Two-tractor method with drawbar dynamometer for measuring the force exerted on the blade

3 Model Construction

Regarding the listed factors in Table 1, variables involving in the applied force of a soil working blade (p)

can be written in the form of:

$$p = f(v, d, w, \alpha, \gamma, c, c_a, \varphi, \delta, q) \quad (1)$$

Assuming that q is generally absent in working of a thin soil blade and influences of angles φ and δ are considered in cohesive properties of the soil, therefore their direct presence in the model can be neglected. Also both adhesive and cohesive soil properties will be merged together due to their similar dimensions.

According to Buckingham's theory, the number of invariants and repetitive invariants were seven and three respectively, so four constant pi-values are obtained. In this research, three repetitive invariants are velocity (v), specific weight (γ) and tool width (w).

Dimensionless parameters were formed in a matrix form and the following dimensionless parameters were extracted.

$$\begin{cases} \Pi_1 = [(\gamma)^{a_1} \cdot (v)^{b_1} \cdot (w)^{c_1}]p = M^0L^0T^0 \\ \Pi_2 = [(\gamma)^{a_2} \cdot (v)^{b_2} \cdot (w)^{c_2}]c = M^0L^0T^0 \\ \Pi_3 = [(\gamma)^{a_3} \cdot (v)^{b_3} \cdot (w)^{c_3}]\varphi = M^0L^0T^0 \\ \Pi_4 = [(\gamma)^{a_4} \cdot (v)^{b_4} \cdot (w)^{c_4}]\delta = M^0L^0T^0 \\ \Pi_5 = [(\gamma)^{a_5} \cdot (v)^{b_5} \cdot (w)^{c_5}]c_a = M^0L^0T^0 \\ \Pi_6 = [(\gamma)^{a_6} \cdot (v)^{b_6} \cdot (w)^{c_6}]d = M^0L^0T^0 \\ \Pi_7 = [(\gamma)^{a_7} \cdot (v)^{b_7} \cdot (w)^{c_7}]\alpha = M^0L^0T^0 \end{cases} \quad (2)$$

The combination of extracted Π-numbers can be written as a functional equation in the form of:

$$\begin{cases} \Pi_1 = \dfrac{P}{v^2\gamma w^2} \\ \Pi_2 = \dfrac{c + c_a}{v^2\gamma} \\ \Pi_3 = \dfrac{d}{w} \\ \Pi_4 = \sin\alpha \end{cases} \quad (3)$$

After substituting the obtained Π-numbers in Equation (3), one obtains

$$\frac{P}{v^2\gamma w^2} = f(\frac{c + c_a}{v^2\gamma}, \ \frac{d}{w}, \ \sin\alpha) \quad (4)$$

The final form of the function to estimate the pull resistance is considered in this study in the following form.

$$P = (v^2\gamma w)(\frac{c + c_a}{v^2\gamma})^{n_1}(\frac{d}{w})^{n_2}(\sin\alpha)^{n_3} \quad (5)$$

In Equation (5), the constant values of n_1, n_2, and n_3 can be obtained by statistical computation of the measured experimental data.

4 Results and discussions

In this study, a factorial experiment was used in a randomized complete block design with 36 treatments (3 tillage depth × 3 penetration angle × 4 forward speed) in three replications. Influence of three independent variables including tillage depth (10, 15, 20 cm), angle of attack (60, 75, 90 degrees) and forward speed (0.5, 1, 1.35, and 1.7 m/s) on tractive efficiency as the dependent variable was evaluated. The obtained results were analyzed based on the factorial experiment using analysis of variance. Treatment means were compared by Duncan's multiple range test using SAS software. Table 3 shows the comparison of the mean force exerted on the blade (in kN) at different levels of plowing depth, speed and angle of attack.

The data presented in this table indicate the significant influence of tillage depth, penetration angle, and forward speed on the draft force of the examined chisel plow with tin blades.

Table 3 Comparison of mean draft force of the examined chisel plow containing two tin blades (kN) at different levels of plowing depth, angle of attack and forward speed

Speed/ (m/s)	Penetration angle (degree) 60			75			90			
	Tillage depth (cm)			Tillage depth (cm)			Tillage depth (cm)			
	10	15	20	10	15	20	10	15	20	Average(X)
0.75	$0.4^{z\alpha}$	0.64^{pqr}	1.01^{hij}	$0.45^{yz\alpha}$	0.811^{m}	1.2^{fg}	0.58^{tuv}	1.04^{hi}	1.56	0.859^{A}
1.00	$0.43^{xyz\alpha}$	0.78^{mnop}	1.1^{def}	0.5^{vwxy}	0.88^{kl}	1.29^{cde}	0.65^{qrt}	1.15^{fg}	1.67	0.934^{B}
1.35	0.47^{xyz}	0.8^{lmn}	1.2^{fg}	0.56^{uvw}	0.97^{hij}	1.4^{a}	0.72^{opq}	1.3^{cd}	1.85	1.024^{C}
1.70	0.51^{vx}	0.91^{k}	1.35^{bc}	0.62^{ru}	1.06^{h}	1.6	0.78^{mno}	1.38^{bcd}	2.1	1.146^{D}
Average(X)	0.4525^{E}	0.7825^{F}	1.165^{G}	0.5325^{H}	0.93^{I}	1.3725^{J}	0.6825^{K}	1.218^{L}	1.795^{M}	

Note: The means indicating with the common letters are not significantly different at 5%.

The means X indicating with the common letters are not significantly different at 5%.

To obtain the coefficient n_1, experimental data for the force as dependent variable and speed as independent variable was plotted in the Excel software.

To obtain the n_2 and n_3 coefficients, the same procedure was used except that the independent variables for n_2 and n_3 in each graph were tillage depth and penetration angle, respectively. Finally, the formula for calculating the force exerted on the blade was obtained in the form of

$$P = 0.0082[(v^2\gamma w)(\frac{c+c_a}{v^2\gamma})^{0.84}(\frac{d}{w})^{1.46}(\sin\alpha)^{2.6}] \qquad (6)$$

Results of Equation (6) together with the experimental data for the vertical blade (90°penetration angle) are shown in Figure 3a. As shown in this figure, the estimated data using the Equation (6) (solid lines) has a good agreement with the experimental data. The average error for the depth of 20, 15 and 10 cm were obtained equal to 4.5%, 4% and 1.5%, respectively.

The same qualitatively results were observed for the 75° and 60° penetration angles. These results are illustrated in Figures 3b and 3c, respectively.

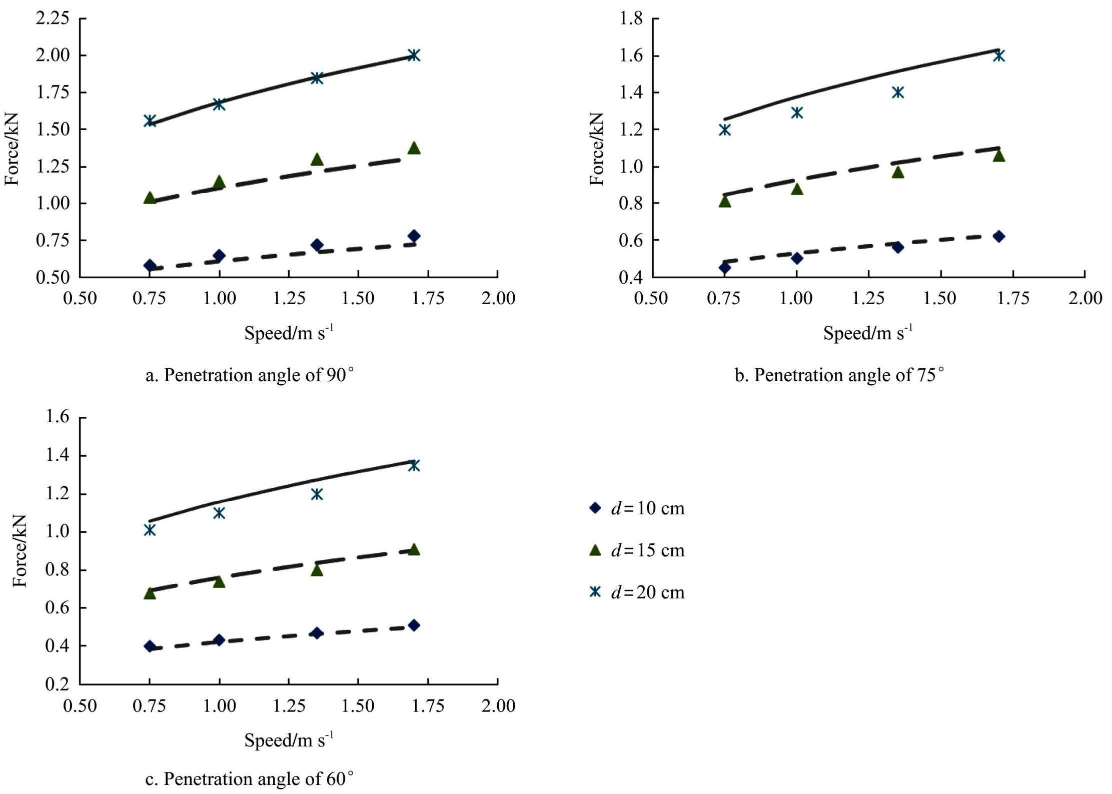

Figure 3 Influence of forward speed and tillage depth on the soil/ thin blade interaction force: penetration angle of 90°, 75°, and 60°; lines are estimation using the Equation (6)

5 Conclusions

Summary of the results obtained in this study are shown in Table 4, indicating the maximum variation of the forces exerted on the blade due to variation of the speed, penetration angle and tillage depth. These data were computed using the data shown in Table 3. Results obtained in this table indicate stronger influence of tillage depth on the pulling force of the blade in compare to the penetration angle and forward velocity. Influences of the penetration angle and forward velocity are in the next step. Forward speed had minimum influence compared to other two examined parameters.

Table 4 Maximum variation of the forces exerted on the blade due to the forward speed, tillage depth and angle of penetration

Level	Force changes due to depth changing/%	Force changes due to speed changing/%	Force changes due to angle changing/%
1	74	9	20
2	159	20	132
3		33	

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