Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA)
Available online at www.inia.es/sjar
http://dx.doi.org/10.5424/sjar/2014121-4437

Spanish Journal of Agricultural Research 2014 12(1): 44-51
ISSN: 1695-971-X
eISSN: 2171-9292

The behavior of tillage tools with acute and obtuse lift angles

Mohammad Hossein Abbaspour-Fard[1]*, Sayed Ali Hoseini[1],
Mohammad Hossein Aghkhani[1] and Ahmad Sharifi[2]

[1] *Department of Agricultural Machinery Engineering. College of Agriculture. Ferdowsi University of Mashhad. Mashhad, Iran.* [2] *Agricultural Engineering Research Institute (AERI). Karaj, Iran*

Abstract

An experimental investigation was conducted to study the trend of draft force against forward speed and working depth for a range of lift angles beyond acute angles for a simple plane tillage tool. The experiments were performed in an indoor soil bin facility equipped with a tool carriage and a soil preparation unit propelled by an integrated hydraulic power system. The system was also equipped with electronic instrumentation including an Extended Octagonal Ring Transducer (EORT) and a data logger. The factorial experiment (4 × 3 × 3) with three replications was used based on Randomized Complete Block Design (RCBD). The independent variables were lift angle of the blade (45, 70, 90 and 120°), forward speed (2, 4 and 6 km h^{-1}) and working depth (10, 25 and 40 cm). The variance analysis for the draft force shows that all independent variables affect the draft force at 1% level of significance. The trend of the draft force against working depth and forward speed had almost a linear increase. However, the trend of the draft force against the lift angle is reversed for lift angles > 90°. This finding, conflicts with the results of analytical and numerical studies which extrapolate the results achieved for acute lift angles to obtuse lift angles and have not been reported experimentally.

Additional key words: blade; draft force; lift angle; numerical prediction; soil bin.

Introduction

In addition to reclamation and earth moving activities, it is estimated that about 50% of the energy consumed in agriculture is used for mechanical soil manipulation which is performed by various tillage tools and implements (Davoudi *et al.*, 2008). The intensity of this energy consumption is largely influenced by their draft requirements. The importance of tillage draft and energy requirements has continuously forced the researchers to investigate draft requirements for these tools, with different approaches, which is traced back to almost the early decades of the 20th century (*e.g.* Soehne, 1956) and gradually continued (*e.g.* Stafford, 1979; McKyes & Desir, 1984; Fielke, 1996) in a worldwide scale up till now (*e.g.* Manian *et al.*, 2000; Gratton *et al.*, 2003; Mamman & Oni, 2005; Manuwa & Ademosun, 2007). These efforts have been carried out by employing different techniques including experimental, analytical and numerical approaches (*e.g.* McKyes & Ali, 1977; Chi & Kushwaha, 1990; Oni *et al.*, 1992; Zeng & Yao, 1997; Shrestha *et al.*, 2001).

The high demand of energy in tillage operations is not only because of the work done on a large amount of soil volume (100 m^3 ha^{-1} cm^{-1}) but is also related to inefficient methods of energy transfer to soil, mainly because of the lack of relevant data and knowledge (Davoudi *et al.*, 2008). Despite providing a large number of relations on the mechanical behavior of tillage tools, full understanding of their mechanics has not been achieved yet and a lack of sufficient knowledge in the literature is observed.

It can be concluded from the summary review of the literatures that the draft force is affected by three parameters, namely: soil conditions, tool configuration, and operating conditions (Godwin & Spoor, 1977; Godwin

* Corresponding author: abaspour@um.ac.ir
Received: 30-04-13 Accepted: 15-01-14.

This work has two Supplementary Figures that do not appear in the printed article but that accompany the paper online.

Abbreviations used: AERI (Agricultural Engineering Research Institute); CI (Cone Index); EORT (Extended Octagonal Ring Transducer); PC (Personal Computer); RCBD (Randomized Complete Block Design).

& O'Dogherty, 2007; Godwin *et al.*, 2007). In this regard, the blade geometry (including: lift angle, width, depth, and sharpness) is an issue that many researchers have brought their attention to it (Godwin, 2007). The lift angle or rake angle, as defined by others (*e.g.* Godwin, 2007), is the angle between the soil surface and the top surface of the tillage tool.

The majority of these research works were generally focused on lift angles of, or less than 90° (*e.g.* Payne & Tanner, 1959; Ruciņš, & Arvīds, 2006; Tong & Moayad, 2006; Godwin & O'Dogherty, 2007). One of the earliest attempts was work of Soehne (1956) who analytically derived a 2-dimensional model to predict the draft requirement of a rectangular blade which was later modified by others to 3-dimensions (Tong & Moayad, 2006). The exception is the work of Gebresenbet & Jönssonm (1992), who studied the effect of lift angle on draft force for a wider range up to 130°. However their work was limited for very tiny blades of seed drills with working depth ranging from 20 to 80 mm. The results of this work obviously cannot be easily extended to the blades of those implements used for tillage operation with working depth ranging from 200 to 300 mm (known as primary tillage implements) by extrapolation of the results. Two main reasons might be behind these general attitudes:

1) Analytical and mathematical models are generally based on some assumptions that may cause unrealistic results and predictions. In these models, usually when the lift angle of the blade approaches 90°, the model becomes mathematically unstable and ambiguous; hence, the predicted draft force approaches infinity, which is very far from reality. For this reason, researchers have limited the lift or rake angle to less than 90° in their models and extended the results beyond this angle by extrapolating their simulated results. Obviously, because of the exponential trend of the models before 90°, the extrapolation leads to a large error. Suppl. Fig. 1 [pdf online] shows a typical curve for the predicted blade draft, drawn based on such models. Clearly the exponential approach of the curve in Suppl. Fig. 1 [pdf online], towards the lift angle of 90° is due to unrealistic assumptions of the models which resulted in a mathematical ambiguity at this lift angle.

2) Most of the existing blade type tillage tools work under a lift angle of less than 90°. Implements, such as chisels and sweeps which are spread all around the world, are examples of tillage machines employing blades with lift angles from 20° to 70°. Therefore, it is primarily expected that researchers focus on this range of lift angles.

Although many tillage tools are pulled with lift angles of less than 90°, some other implements can also be found which work under obtuse lift angles for soil compaction and disintegration purposes. Most of tooth type and finger type secondary tillage implements, pulling rotary hoe in reverse direction for clod breaking, some heavy subsoilers with curved shank, scrubber boards, and backhoes are some examples. Because these implements work under lift angles around or above 90° and lack of knowledge is observed in the literature before and especially above lift angles of 90°, more research is needed on this range of angles.

This paper presents the results of experiments which were conducted with a wide range of lift angles (acute and obtuse angles) to investigate the impact of the lift angle on the draft force under different conditions in a controlled soil bin laboratory condition.

Material and methods

The experiments were conducted in an indoor soil bin facility of dimensions of length, width and height of 25.0 × 1.5 × 1.0 m, located in the tillage laboratory of the Iranian Agricultural Engineering Research Institute (AERI), Karaj, Iran. The soil bin is comprised of two rails on the top, one on either side, on which the tillage tool carriage was made to ride (Suppl. Fig. 2 [pdf online]).

Soil preparation and measurements

The soil preparation unit was a self-propelled machine composed of a scraper with spreading mechanism, a tooth type roller, a packer, an electric motor as prime mover, and an integrated hydraulic power system. Hence, the unit can simulate and prepare the field condition of soil in the soil bin with desired bulk density and compaction. The working depth and forward speed can be easily adjusted by a built-in controller. An overview of the soil bin, soil preparation unit, and the propulsion unit is shown in Suppl. Fig. 2 [pdf online]. The soil used for the experiments was loam according to the USDA (1987) textural classification of soils.

The dry basis soil moisture content (d.b.) was calculated using the so-called weighing method and was

Table 1. Soil parameters and properties

Replicate	Cohesion (C) (kPa)	Internal (Φ) (°)	Adhesion (C_a) (kPa)	Soil-blade friction (δ) (°)
1	10.2	35.3	1.4	32.6
2	12.3	32.7	2.4	33.8
3	6.2	36.3	3.4	34.9
4	5.7	36.3	3.9	34.5
5	5.3	35.6	3.8	33.3
6	6.0	35.3	4.1	32.7
Average	6.7	35.3	3.2	33.6

suitably constant during the tests and in the range of 10-12%, with an average of 11.66% from 10 points in the soil bin. The surface of the soil was leveled prior to each experiment. The soil was compacted in 50 mm deep layers by subjecting it to a given number of passes of the soil preparation unit. The soil's dry bulk density was measured prior to each test run, up to 40 cm depth, with 10 cm depth interval, using cylindrical soil samples. The samples were oven dried and having known the volume and the dried weight of the samples, their dry bulk density was calculated. In general, the average bulk density and true density of the soil were 1.23 and 2.14 g cm^{-3}, respectively. A penetrometer (Eijkelkamp™ Penetrologger, model 6.15) was also used to measure the cone index (CI) of the soil prior to each test for random measurement of compaction and to ensure the consistency of soil condition throughout the soil bin. The test runs started whenever the average CI at 10 points reached 1.40 MPa. The other physical properties of the soil were measured with six replications by standard techniques. The measurement results are shown in Table 1.

Experimental tillage blade

The blade was a simple plane steel tine, prepared from a flat and thick enough (40 mm) plain carbon steel plate to provide sufficient mechanical strength, with a width of 10 cm and length of 70 cm in order to satisfy the definition of a narrow blade as defined by Godwin (2007), for all test runs. It was mounted to the propulsion unit via a holder with some extra holes to provide different lift angles (acute and obtuse angles) for the blade at different working depths. In each case, the adjustment was made to give the required lift angle and depth of operation. The propulsion unit was also equipped with instrumentation, including an Extended Octagonal Ring Transducer (EORT) and data logger with RS-232 port to directly import data from the instrumentation unit to a personal computer (PC) and statistical software (*e.g.* MS Excel) to measure and record the horizontal and vertical components of the draft force (Fig. 1). The built-in triple Watson Bridge, having the total of 12 strain gauges, enables the EORT to measure the horizontal and vertical forces acting on the tillage tool. The strain gauges on EORT are arranged in such a way that enables the measurement of the torque as well as the forces acting on the blade. The British made data logger (CAMPBELL, Model CR23X) is in charge of recording, digitizing and transmitting the EORT data to the PC via a standard RS232 port; which

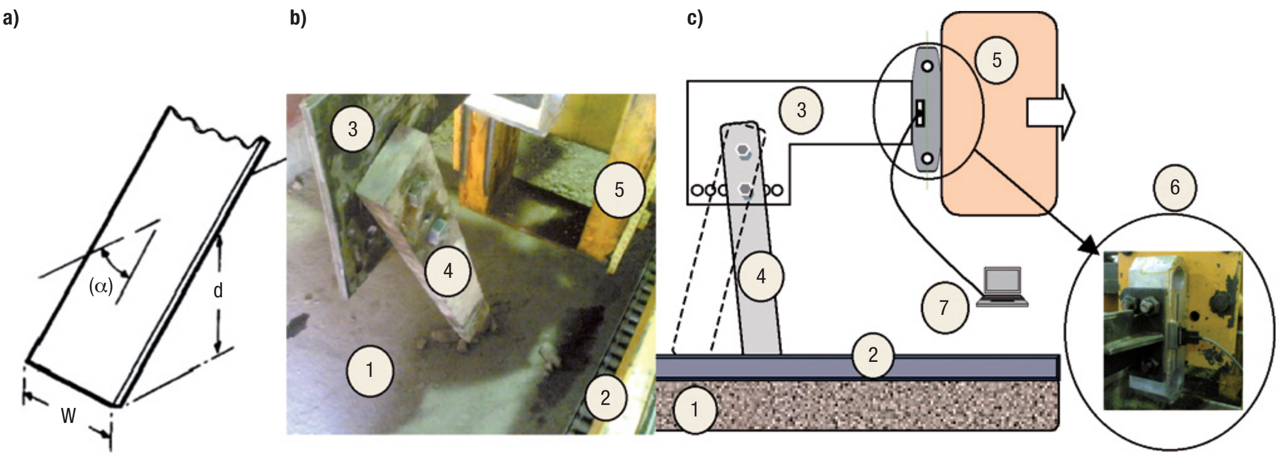

Figure 1. a) blade geometry including width (W), lift angle (α) and working depth (d); b) blade configuration and measuring rig; c) schematic diagram of its side view. 1) soil bin; 2) soil bin side rail; 3) blade holder with extra holes; 4) blade; 5) propulsion unit; 6) EORT (extended octagonal ring transducer); 7) PC (personal computer).

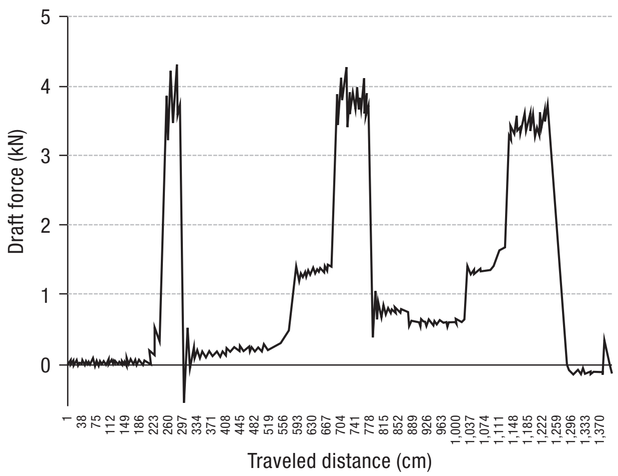

Figure 2. A sample of data obtained from data logger for three replications of an experimental run.

is equipped with 12 input ports and hence it can be simultaneously connected to several sensors. Prior to any experimental run, the independent variables, including blade lift angle, working depth and forward speed, were adjusted and double checked. The replications of experiments were performed along the soil bin by alternating the penetration of the blade up to the working depth. A sample of data acquisition is shown in Fig. 2. In this figure the horizontal axis is the traveled distance along soil bin and the vertical axis represents the draft force of the blade in kN. The peak points represent the magnitude of draft force for each replication. The draft force for each replication was calculated from the average of corresponding peak points. For each replication, the average draft force was calculated from peak points. To ensure the accuracy of measurements, the system was calibrated prior to each experiment.

Analysis of data

The factorial experiment (4 × 3 × 3) was used based on a Randomized Complete Block Design (RCBD) with three replications (Montgomery, 1991). Lift angle of the blade, forward speed of the tillage operation and working depth were considered as independent variables with the following levels: Four lift angles of the blade (45, 70, 90 and 120°), three forward speeds (2, 4 and 6 km h^{-1}) and three working depths (10, 25 and 40 cm). The draft force was measured and considered as dependent variable. Since many other parameters act as disturbing variables and may affect the results (*e.g.* soil moisture content, soil compaction etc.), we tried these variables remaining constant during the experiments. The program Statistical Analysis Software (SAS) was used to analyze the data and extract the draft model. The least significant difference (LSD) was applied to compare the mean values.

Results

The results of this analysis show that the impacts of all independent variables and their interactions on the draft force are significant at the 1% level of significance (Table 2). In other words, a direct correlation exists between the draft force and all studied parameters.

The coefficient of variations (4.98%) in Table 2 indicates that experiments were performed with high precision. As expected, among the independent variables the effect of the working depth on the draft is higher than the effects of the other variables (*i.e.* lift angle and forward speed).

Draft force-working depth relationship

As expected, the results of the variance analysis for the draft force shows that the working depth has a significant effect on the draft force at the 1% level of significance (Table 2). Fig. 3 also shows the effect of the working depth on the draft force for different lift angles of the blade at different forward speeds. In general, for all conditions, a linear correlation exists between the working depth and draft force, with a corre-

Table 2. Variance analysis of the draft force

Surface of variation	DF	Sum square	Mean square	F-test
Replicate	2	0.06	0.03	2.14**
Treatment	35	472.62	13.50	1,029.08**
Lift angle	3	27.86	9.29	707.72**
Working depth	2	416.86	208.43	1,5884.24**
Forward speed	2	19.15	9.58	729.87**
Lift angle-depth	6	5.24	0.87	66.57**
Lift angle-speed	6	0.41	0.07	5.15**
Depth-speed	4	2.77	0.69	52.69**
Lift angle-depth-speed	12	0.33	0.03	2.10*
Error	70	0.92	0.01	
Total	107	473.59		
Coefficient of variation 4.98%				

*,** Significant at the 5% and 1% level of significance, respectively.

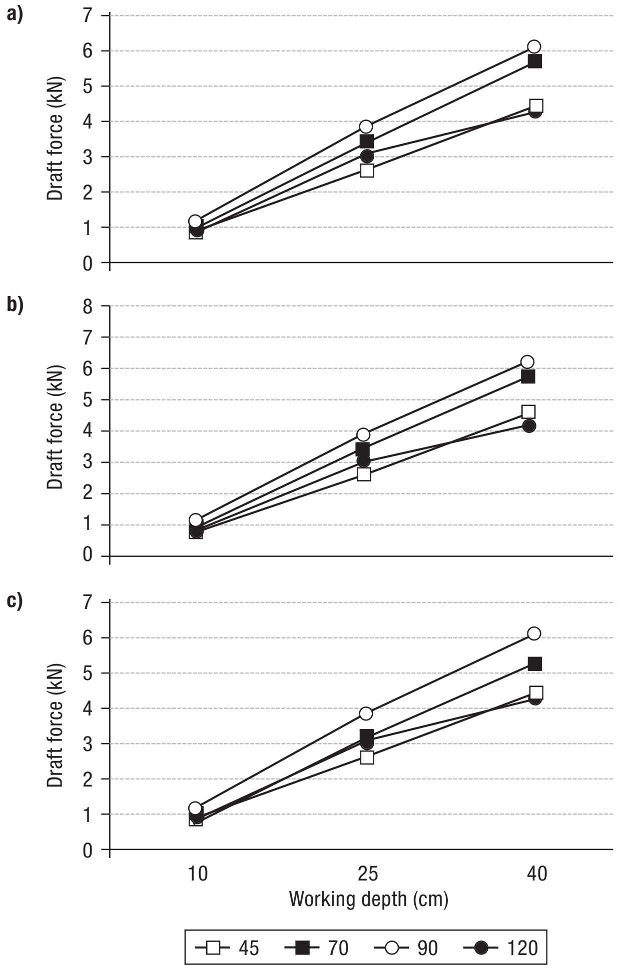

Figure 3. The effect of working depth on the draft force for different lift angles of the blade at forward speeds of: a) 2 km h^{-1}, b) 4 km h^{-1} and c) 6 km h^{-1}.

lation coefficient (R^2) of at least 0.98 and the generic form of:

$$D_f = a \cdot d + b \qquad [1]$$

where D_f, and d are the draft force in kN and working depth in cm, respectively. a and b are coefficients of the trend line. The trend lines of correlation between draft force and working depth show that for all conditions a varied between 1.15 and 1.35 and b between 0.03 and 0.21.

We also found that by increasing forward speed the linearity of the correlation between the draft force and working depth increased. Moreover, we observed for all lift angles increasing trends in the relations between the draft force and forward speed. In all experiments, in the acute range of lift angles, the draft force increased with the increase of lift angle. Moreover, as working depth increased, the difference between draft

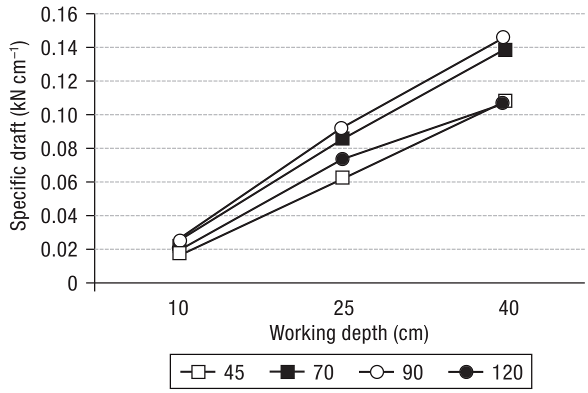

Figure 4. The effect of the working depth on the specific draft force for different lift angles of the blade at a forward speed of 2 km h^{-1}.

forces of different acute lift angles increased. Interestingly this trend was reversed beyond a lift angle of 90° so that the draft force was nearly equal for a lift angle of 40° and 120°.

To evaluate the effect of the working depth on the draft force, the draft force was normalized for different test runs, and we named this normalization *specific draft,* which is the draft force per unit of working depth (kN cm^{-1}) and was considered for all test runs. Studies show that this parameter is dependent on several factors, mainly the soil type and condition (Godwin, 2007). Fig. 4 shows the rate of change of specific draft for a forward speed of 2 km h^{-1} against different lift angles. For all lift angles, constant increasing trends for the draft force were found. However, as lift angle increased, a slight increase was observed in the rate of change of specific draft with working depth. This can be seen from the slope of the trend lines of the graph.

Draft force-forward speed relationship

The results of the variance analysis for the draft force show that forward speed has also a significant effect on the draft force at the 1% level of significance (Table 2). In general, increasing linear trends for the draft force for different lift angles are observed with forward speed as for the working depth (Fig. 5). However, the figure shows that the shallower the working depth, the steeper the slope of the trend lines.

The draft force-forward speed regression models and their coefficient of determination (R^2) at different working depths and lift angles are shown in Table 3. In general, the relation between the draft force and forward speed can be expressed through a linear equation

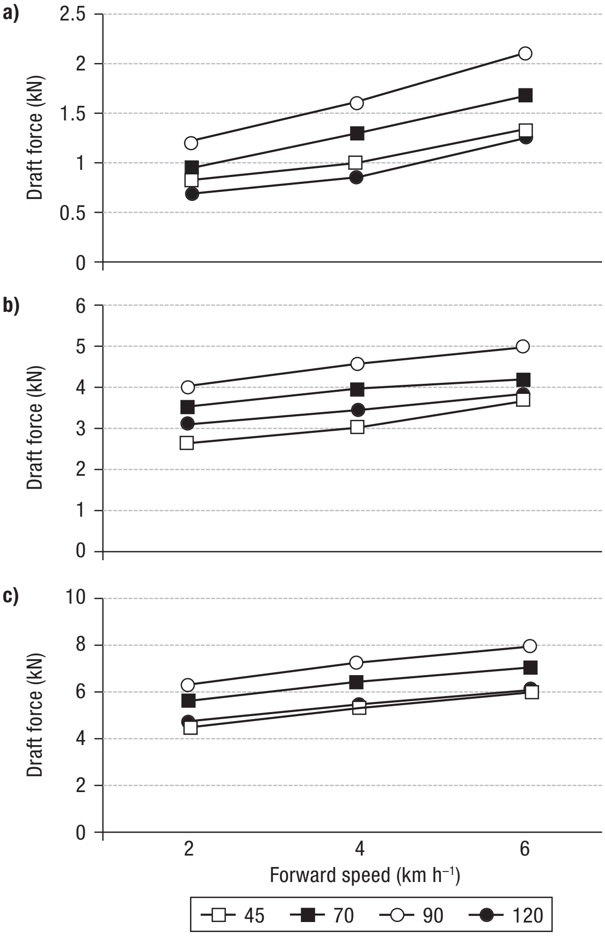

Figure 5. The effect of the forward speed on draft force for different lift angles of the blade at working depths of: a) 10 cm; b) 25 cm; and c) 40 cm.

with a very good correlation. However, nonlinear relations have also been reported (Stafford, 1979). According to Table 3, with the shallow depth (10 cm) the slope of the equations was the highest and general decreasing trends were observed by increasing the working depth. This indicates that at shallower depths much of the soil mass was affected by the kinetic energy of the tillage tool but the movement of the soil was restricted as the working depth increased. So it can be concluded that at a shallower depth the effect of forward speed on draft force is higher.

Draft force-lift angle relationship

The relation between the lift angle of the blade and the draft force is an important issue that many researchers have been focusing on (*e.g*. Godwin, 2007). The variance analysis of the draft force (Table 2) shows that the lift angle had also a significant effect on the draft force at the 1% level of significance (Table 2). The comparison of the mean values of the draft force for different lift angles showed increasing trends of the draft force with lift angles up to 90° and then decreased at 120° for all working depths and forward speeds. These trends are shown in Fig. 6. At all lift angles by increasing the working depth and forward speed the draft force increases. By increasing the lift angle, the applied normal stress on the soil increases and hence the shear strength of the soil increases. Consequently, the draft force tends to increase (Godwin & O'Dogherty, 2007).

Discussion

Draft force-working depth relationship

The increase of the draft force with increasing working depth is usually related to the weight of the soil and thus its further consolidation. Moreover, with increasing working depth, the vertical component of the soil reaction force is increased, causing more compaction effects on upper layers of the soil and thence increasing draft forces (Godwin, 2007). The specific draft, as defined in this paper, provides a better understanding on the effect of the depth on the draft force. This parameter is much higher in sticky clay soils than

Table 3. Force-speed regression models and their coefficient of determination R^2 at different working depths and lift angles

Lift angle (°)	10 cm		25 cm		40 cm	
	Model	R^2	Model	R^2	Model	R^2
45	D = 0.455v + 0.539	0.98	D = 0.282v + 2.147	0.98	D = 0.279v + 3.722	0.99
70	D = 0.474v + 0.677	0.97	D = 0.301v + 2.477	0.98	D = 0.171v + 5.025	0.97
90	D = 0.528v + 0.773	0.99	D = 0.218v + 3.381	0.99	D = 0.222v + 5.322	0.99
120	D = 0.471v + 0.504	0.98	D = 0.215v + 2.590	0.99	D = 0.284v + 3.604	0.99

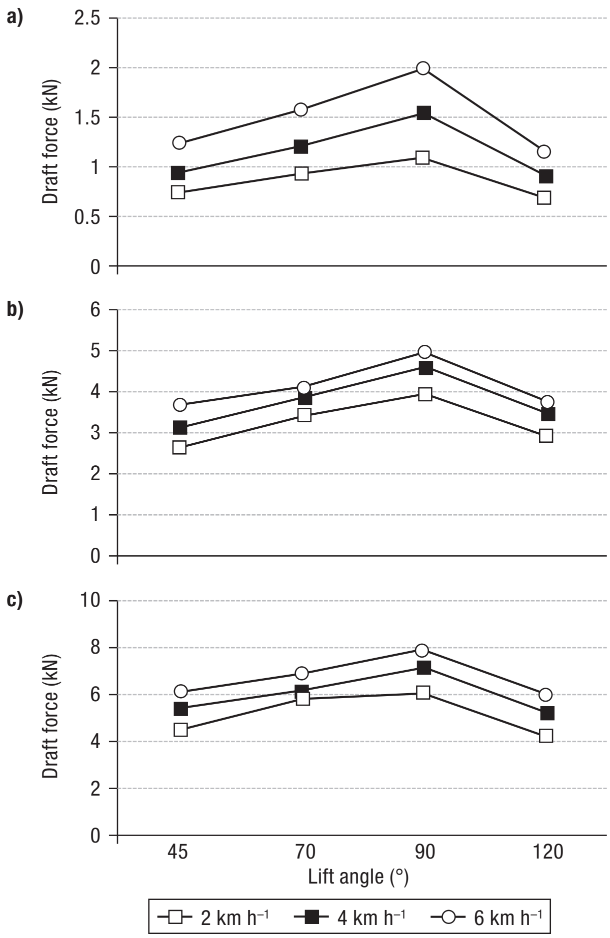

Figure 6. The effect of the lift angle on the tillage tool draft force at different working depths: a) 10 cm, b) 25 cm, c) 40 cm and different forward speeds.

sandy soils (Payne & Tanner, 1959). In general, with increasing cohesiveness of soil and degree of soil compaction, the specific draft increases with the depth which is related to the self consolidation phenomenon in such soils. As the soil used in this study was loam with some degrees of cohesion, in all test runs an almost linear increase was observed for the specific draft against the working depth. Similar increasing trends of the specific draft force for different lift angles (Fig. 4) show that this parameter is less dependent on geometric and dynamic properties of the blade, but greatly affected by consolidation of the soil.

Draft force-forward speed relationship

Swick & Perumpral (1988) stated that the relation between the draft force and the forward speed is affected by the inertia of the accelerated soil mass and the rate of shear by the tillage tool which are both dependent on the soil type and condition. In general, the acceleration of soil mass increases by increasing the forward speed and the result is an increase in draft force. The soil shear resistance increases by increasing the shear rate and hence the forward speed. However, the effect of shear rate on soil shear resistance is greater with heavier soil texture. The greater effect of the forward speed on the rate of draft force at a shallower depth can be related to the more free movement of soil mass and more dynamic condition of these layers.

Draft force-lift angle relationship

As mentioned, most of the research works has been carried out on tillage tools performed with acute lift angles, but the results were sometimes extended to obtuse angles by extrapolation. The works of Payne & Tanner (1959) and Godwin & O'Dogherty (2007) are two examples of such works. However, the results of this study (see Fig. 6) indicate that the trend of change in draft force against lift angle is reversed beyond a lift angle of 90°. Therefore, the extension of the results of the acute angles to obtuse angles (as it has previously been done) may be inappropriate.

The review of literature also indicates that there are differences in the prediction of draft forces between theoretical and numerical approaches. Much of these differences may be related to the employed assumptions and the way in which the approach is established. As some of the results of this article are in conflict with some of the previous findings, they need more investigation, specifically for lift angles beyond 90° to establish a comprehensive and robust prediction model for the blade's draft.

As final conclusions, the results show that all independent variables under study and their interactions had a significant effect on the draft force. The draft force acting on the tool increases with increase of lift angles up to 90° and then it decreases. The decreasing trend of the draft force against the lift angle beyond 90° has not been yet reported elsewhere. This finding needs to be approved via more extensive future works. This conflict can be effectively investigated using some new techniques such as the so-called discrete element method (DEM) which deals with the macro behavior of particulate materials, *e.g.* soil mass at bulk scale by tracking the movement of individual particles.

Acknowledgments

The authors would like to thank the financial support of the Ferdowsi University of Mashhad (FUM, Mashhad, Iran) and technical supports (soil bin facilities) of the Agricultural Engineering Research Institute (AERI, Karaj, Iran).

References

Chi L, Kushwaha RL, 1990. A non-linear 3D finite element analysis of soil failure with tillage tools. J Terramechanics 27(4): 343-366.

Davoudi S, Alimardani R, Keyhani A, Atarnejad R, 2008. A two dimensional finite element analysis of a plane tillage tool in soil using a non-linear elasto-plastic model. Am-Euras J Agric Environ Sci 3(3): 498-505.

Fielke JM, 1996. Interaction of the cutting edge of tillage implements with soil. J Agr Eng Res 63(1): 61-72.

Gebresenbet G, Jönssonm H, 1992. Performances of seed drill coulters in relation to speed, depth and rake angles. J Agr Eng Res 52: 121-145.

Godwin RJ, 2007. A review of the effect of implement geometry on soil failure and implement forces. Soil Till Res 97(2): 331-340.

Godwin RJ, Spoor G, 1977. Soil failure with narrow tines. J Agr Eng Res 22: 213-228.

Godwin RJ, O'Dogherty MJ, 2007. Integrated soil tillage force prediction models. J Terramechanics 44(1): 3-14.

Godwin RJ, O'Doghertya MJ, Saundersb C, Balafoutisa AT, 2007. A force prediction model for mouldboard ploughs incorporating the effects of soil characteristic properties, plough geometric factors and ploughing speed. Biosyst Eng 97: 117-129.

Gratton J, Chen Y, Tessier S, 2003. Design of a spring-loaded down force system for a no-till seed opener. Can Biosyst Eng 45: 229-239.

Mamman E, Oni KC, 2005. Draught performance of a range of model chisel furrows. Agric Eng Int: CIGR Ejournal, Vol VII, Manuscript PM 05 003.

Manian R, Rao VR, Kathirvel K, 2000. Influence of operating and disk parameters on performance of disk tools. Agricultural Mechanization in Asia, Africa and Latin America 31(2): 19-26.

Manuwa SI, Ademosun OC, 2007. Draught and soil disturbance of model tillage tines under varying soil parameters. Agric Eng Int: CIGR Ejournal, Vol IX, Manuscript PM 06 016.

McKyes E, Ali OS, 1977. The cutting of soil by narrow blades. J Terramechanics 14(2): 43-57.

McKyes E, Desir FL, 1984. Prediction and field measurements of tillage tool draft forces and efficiency in cohesive soils. Soil Till Res 4(5): 459-470.

Montgomery DC, 1991. Design and analysis experiments, 3rd ed. John Wiley & Sons, NY.

Oni KC, Clark SJ, Johnson HW, 1992. The effects of design on the draught of undercut sweep tillage tools. Soil Till Res 22: 117-130.

Payne PC, Tanner DW, 1959. The relationship between rake angle and the performance of simple cultivation implements. J Agr Eng Res 4(4): 312-325.

Euciņš Ā, Arvīds V, 2006. Impact of the share inclination angle on the plough body draft resistance. Zemdirbyste/ Agriculture 93 (4): 166-179.

Shrestha DS, Sighn G, Gebresenbet G, 2001. Optimizing design parameters on a moldboard plough. J Agr Eng Res 78 (4): 377-389.

Soehne W, 1956. Einige Grundlagen für eine landtechnische Boden-mechanik. Grundlagen Landtechnik 7: 1-27.

Stafford JV, 1979. The performance of a rigid tine in relation to soil properties and speed. J Agr Eng Res 24(1): 41-56.

Swick WC, Perumpral JV, 1988. A model for predicting soil-tool interaction. J Terramechanics 25(1): 43-56.

Tong J, Moayad BZ, 2006. Effects of rake angle of chisel plough on soil cutting factors and power requirements: acomputer simulation. Soil Till Res 88: 55-64.

USDA, 1987. USDA textural classification study guide. Soil Conservation Service, United States Department of Agriculture, revised February 1987.

Zeng D, Yao Y, 1997. A dynamic model for soil cutting by blade and tine. J Terramechanics 37(4): 317-327.