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Modeling the Effect of Soil-Tool Interaction on Draft Force Using Visual Basic

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Abstract

In tillage systems, accurate predicting of the forces acting on the blade is of prime importance to enhance their productivity. The soil, tool, and operational parameters have been shown experimentally a great effect on draft of tillage tools. Several ways can be used to determine the performance of tillage tools. These are field experiments, soil bin experiments, mathematical models and numerical models. Although experimental studies provide valuable information, they are expensive, time-consuming, and limited to certain cutting speeds and depths. On the other hand, the developments of mathematical models and numerical methods have shown great potential in analyzing the factors affecting soil-tool interaction. Under this study, Sohne's mathematical model was selected, simulated using Visual Basic and validated. Results indicated model was able to predict draft for simple tillage tools with an accuracy of 86% 95%, and 85% for rake angle, tool depth, and tool speed, respectively.

Keywords: Tillage, Draft, Simulation Model, VB.

Introduction

Egyptian agriculture is considered as one of the most intensive in the world where tillage process is of prime importance. There are about 6.5 million hectares of cropping area must be cultivated each year. This means turning an estimated mass of about 6500 million Mgr of soil when the depth of soil cultivation will be 100 mm (Rosa, 1997).The most popular plow used by Egyptian farmers is the chisel plow which is considered a simple tillage tool. The factors affecting forces required for tillage operation include type of soil, rake angle, forward speed, depth, width of cut, soil density and others as reported by many studies (Ismail, 2002; and Abu–Hamdeh and Reeder, 2003). Mouazen and Ramon (2002) reported that draft of tillage tools reflects the soil physical conditions and the degree of soil compaction. For unique soil type, plowing speed and tool design, draft varies with bulk density, moisture content and plowing depth. Field experiments are needed to determine draft of tractor-implement combination. This is time consuming and generally is complex and expensive work. Numerous research works have shown that simulation models are an efficient alternative for experimental work. Models could be a good tool to participate in resource management in scientific applications (Graves et al., 2002).There are four criteria that can be used to select the preferable model. These are: prediction precision, model simplicity, evenness of parameter estimates and sensitivity of results to change in parameter (Hesse and Keuper, 2001). In spite of these criteria are granted the suitable selection of a model for specific case, a model to evaluate the draft force of farm implements with good accuracy is often complicated (Amara et al., 2013). Kheiralla et al. (2004) formulated polynomial draft models from orthogonal regression analyses based on linear and quadratic functions of travel speed and tillage depth. Mathematical solutions of soil-tool interaction based on empirical and semi-empirical models may be of help to tool for designers and researchers in the field of tillage implements (Sohne; 1956; Gebresenbet; 1989 and Karmakar, 2005).Different empirical models developed by statistical analysis to predict the required draft of tillage implements are available in literature (Rashidi et al., 2013.). Draft models could be also developed by dimensional analysis (Moeenifar et al., 2014) or by fuzzy table look-up scheme (Mohammadi et al., 2012). Therefore, the objective of this study was to choose, develop, test and validate a model to predict draft of simple tillage tools such as chisel plows.

Materials and Methods

Model Selection

After studying the various models available in the literatures, it was decided to choose Sohne's model as it is the most suitable model for the simple tillage tool similar to the chisel plow. Amathematical analysis of this model is presented. Sohne's classified the forces resulting from soil-tillage tool interactions into four forces. These were interface, soil strength, acceleration, and gravitational forces. The interface forces are expressed in terms of adhesion and soil metal friction angle. In soil mechanic applications, it is not possible to differentiate between friction and adhesion force. Therefore, the following model has been proposed to include adhesion force (Gill and Vanden Berg, 1968).

$$\mathrm{F} = \mathrm{A_o C_a} + \mathrm{N}\tan\psi \qquad (1)$$

The soil strength component is expressed using cohesion and soil internal friction angle. The cohesion force is the force required to overcome the internal force of the soil at the shear failure surface to break the soil slice off. When the tool exerts force, and compresses the soil, a failure surface makes an angle (β) from the horizontal. The angle could be calculated from Mohr`s circle diagram for the principal stresses at soil failure using the following equation:

$$\beta = (90 - \phi)/2 \qquad (2)$$

When force exerted by the tool exceeds the cohesion force, the soil slice is cut off. The magnitude of these forces depends on soil conditions and the type of soil failure. Soil cohesion strength and the internal friction angle were expressed by Coulomb, (1776) in reference to soil shear strength using following equation:

$$\tau = C + \sigma \, tan\phi \qquad (3)$$

The acceleration force is due to the soil mass being constrained to move over the tool surface, and has been expressed by using Newton`s Second Low of Motion as the following (Sohne, 1956):

$$B = \frac{\gamma}{g} bd{V_0}^2 \frac{sin\delta}{\sin(\delta + \beta)} \ (4)$$

The gravitational force is due to the weight of soil and may be calculated from the volume of the soil. The volume of the soil depended on the tool width and the surface area that may support by the tool. It could be expressed using the following equation.

$$W = \gamma \, b \, A_o \qquad (5)$$

Draft of Soil-Tool Interaction

Figure 1 shows the free body diagram of a segment of soil as it reacts to the advancing tillage tool.

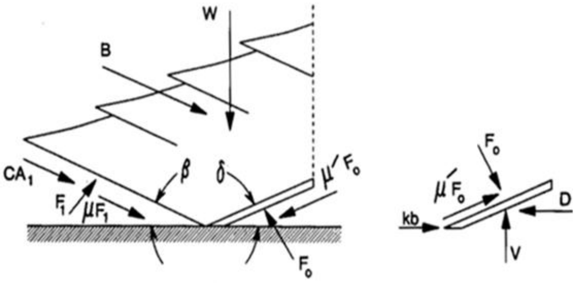


Figure (1): Free body diagram of soil-tool reaction forces (after Sohne, 1956, cited in Gill and Vandenberg, 1968).

By summing forces resulting from soil-tillage tool interactions in the horizontal and vertical directions, and equating them to zero, the following equation was obtained to predict the draft for simple tillage tools (Rowe and Barnes, 1961).

$$\mathrm{D} = \frac{W}{Z} + \frac{CA_1 + B}{Z(sin\,\beta + \mu \cos\beta)} + \frac{C_a A_0}{Z(sin\,\delta + \mu`\,cos\,\delta)} \ (6)$$

The tool surface and failure plane areas were calculated from the geometry of free body diagram for soil-share reactions forces using the following equations:

$$\mathrm{A}_1 = \mathrm{b\,d}/(\sin\beta) \qquad (7)$$

$$\mathrm{A_o} = \mathrm{b\,d}^* \left[L_o + \frac{L_1 + L_2}{2}\right] \qquad (8)$$

Roza, (1997) concluded that the adhesion increased from 0.6 to 8.3 kPa when the soil moisture and soil bulk density increased from 11% and 1.3 Mg/m^3 to 19% and 1.49 Mg/m^3, respectively. They also added that there is no appreciable changes in the interface friction angle as the increasing in soil moisture and soil bulk density for the same soil. The interface friction angle range ranged from 23.8° to 24°. Therefore, the pervious equations for determining the draft force of tillage tools have been modified to be as the following:

$$\mathrm{D} = \frac{W}{Z} + \frac{CA_1 + B}{Z(sin\,\beta + \mu \cos\beta)} (9)$$

Table 1. List of symbols used under this study.

Sym.	Definition	Sym.	Definition
A_0	tool surface area, (m2)	l_2	d×Tan(δ), (m)
A_1	**area of forward shear failure surface, (m^2)**	m	mass of soil moved, (kg)
B	soil acceleration force, (N)	N	normal force to the sliding surface, (N)
b	tool width, (m)	t_0	average time a particle of soil engaged by the tool, (s)
C	Soil cohesion strength, (kPa)	V	soil velocity (uniform within the mass), (m/sec)
C_a	soil adhesion strength, (kN)	V_0	tool speed, (m/sec)
D	draft force, (N)	W	Weight of soil, (kg)
d	tool depth, (m), and	Z	$\frac{cos\delta - \mu`\,sin\delta}{\sin\delta + \mu`\,cos\delta} + \frac{\cos\beta - \mu\,sin\beta}{\sin\beta + \mu\,cos\beta}$
d*	d {[sin(δ+β)]/sin β}, m	β	angle of the forward failure surface, (deg.)
dv/dt	acceleration of soil mass, (m/s2)	δ	rake angel, (deg.)
F	frictional force tangent to the sliding surface, (N)	σ	normal stress, (kPa).

F_1	normal force on the forward failure surface, (N)	τ	shear strength, (kPa),
F_0	normal load on the inclined plane, (N)	φ	internal friction angle, (deg.)
K	soil cutting resistance, (N/cm^2)	Ψ	interface friction angle
L_0	tool length, (m)	γ	soil bulk density, (Kg/m3)
L_1	d {[cos(δ+β)]/sinβ} , (m)	μ`	coefficient of external friction angel, no units
		μ	coefficient of internal friction angel, no units

Devolving the Model Using Visual Basic

Under this study, Visual Basicwas used as a computer programing langue to develop a model based on Sohne's model for simple tillage tool.The effect of soil-tool interaction on predicting draft of tillage tools was investigated. The model is an interactive program where the user is prompt to enter his relevant input data for the model. A set of screens, object buttons, scroll bars, and menus which available at Visual programming were used to design the form. The objects can be positioned on a form, and their behaviors are described through the use of a scripting language associated with each one.

Procedures of Building the Model

The structure of building the model consisted of interrelated screens and tasks arranged in a logical and easily understandable in order to form an integrated and complete unit as showed in Figures (2 and 3). All variables used to calculate the draft were defined using the Visual Basic language. The procedural code that performs actual data processing tasks is most often created in program units called function procedures. After creating the procedures and functions, the equations that link the variables are written in a logical and correct order. Equations from mathematical analysis of Sohne's model were used to calculate the draft of tillage tools. The following two figures show the screenshots of the input and output interfaces of the program for prediction the draft.

Verifying the Model

Implementing a test program involves three basic steps desk-checking and debugging and running real-experimental data to make sure that the program works (Bol and Mohamed, 1997).These three steps must be conducted to make sure that is realistic works and it’s free of errors.Data of soil physical and mechanical properties (from tri-axial tests) which used to test the model were taken from the results obtained by Afify, (1999) and from the results obtained by Roza, (1997) for clay-loam soil.Model also tested using real data in terms of soil and tool parameters affecting on draft.These data were obtained under soil bin condition for clay-loam soil (Afify, 1999).

Validating the Model

Once any model is built, it must be validated before use (Brown, 2005). To correctly validate a model, the actual system is tested over the range of values that the model will be used to predict. If acceptable agreement between the test data and the model is obtained that means, the model is validated. Results from previous studies in terms of the factors affecting on draft indicated that draft of different tillage tools varies with variations in soil conditions, tool design and operational parameters. Therefore, under this study three parameters were used as variable factors influenced on draft of tillage tools. These were tool rake angle (index of tool design), and both tool depth and tool speed (index of the operational tool). Data of draft of tillage tools which obtained from the model were validated by comparing them with results of real experiments which chosen from available in literatures (Akbarina et al., 2014; Ibrahmi et al., 2014; Ucgul et al., 2014; Shahgholi et al, 2019; Aboukarima, A.M, 2007; Al-Hamed et al., 2014; and Tong et al., 2006). The validation was carried out using an appropriate statistical method (SPSS Statistical Software).

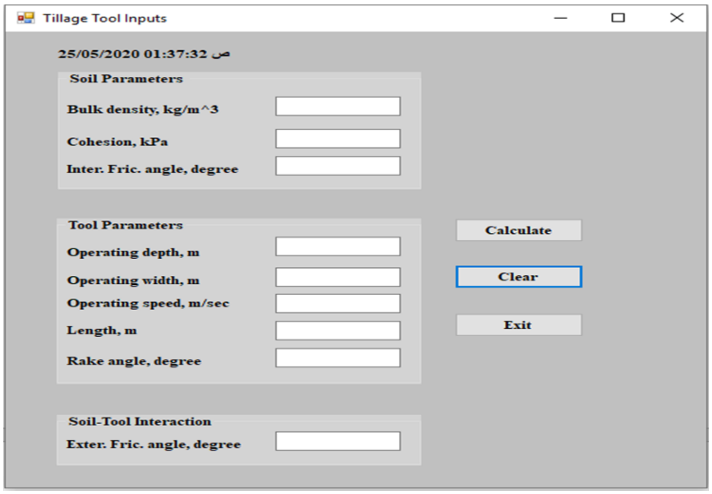
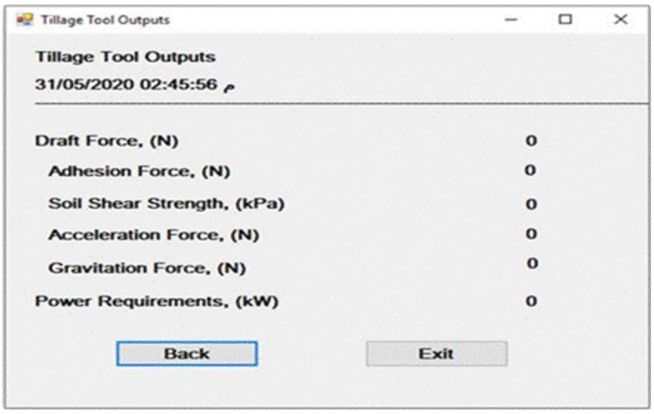


Figure (2): Screenshot of the input interface of the program for predicting the draft force.



Tillage Tool Outputs
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Draft Force, (N) 0
Adhesion Force, (N) 0
Soil Shear Strength, (kPa) 0
Acceleration Force, (N) 0
Gravitation Force, (N) 0
Power Requirements, (kW) 0

Figure (3): Screenshot of the output interface of the program for predicting the draft force.

Results and Discussion

Model verifying of draft with respect to the tool rake angle

A multi-regression analysis was performed to make a comparison between the draft from the model and with the draft from experimental results obtained by Zhang, (2018), Ibrahmi, (2014), and Fielke (1988). Data in Table 2 show the results of draft force from the model and from experimental results. It can be seen that, as expected the draft force increased with an increase in the tool rake angle for the three experiments and consequently, for the model. Figure 4 shows the relation between measured and predicted draft at different values of tool rake angles using the data from three real experiments. It showed that the predicted draft resulted in an agreement with measured draft with a correlation coefficient of 0.86 as a power function. Analysis of variance was performed for measured and predicted draft in relation to tool rake angle. It showed that there is a significant difference between both measured and predicted draft forces with tool rake angle. Results of the least significant difference (LSD) test indicated that there were significant differences on the measured and predicted draft force for the values of tool rake angles of (10°, 15°, 25°, 60°, and 75°).

Effect of tool rake angle on the predicted draft force

Figure 5 shows the effect of tool rake angle on predicted draft force using data of three real experiments conducted by Zhang, (2018), Ibrahmi, (2014), and Fielke (1988). It showed that the increase in tool rake angle caused increasing in predicted draft force for the three experiments. The highest values of predicted draft force were obtained with the results from Zhang and Fielke under various tool rake angle. However, the lowest values of predicted draft under different tool rake angles were obtained from Ibrahmi data. The change in tool rake angle from 30° to 60° caused an increase in predicted draft force by 48%, 49%, and 49% at 300, 350, and 400 mm tool tillage depths, respectively. These results are similar to those obtained by Gebresenbet, (1995), and Tong and Moayad, (2006).

Table 2. Results of draft force from the model and from experimental results with respect to tool rake angle.

Exp.	Zhang, (2018)		Ibrahmi, (2014)		Fielke, (1988)	
Rake angle (deg.)	Measured (N)	Predicted (N)	Measured (N)	Predicted (N)	Measured (N)	Predicted (N)
10	440*	330	85*	64	510	350
15	570*	390	126*	85	500	415
25	680*	470	211*	94	560	578
30	974	554	260	100	640*	660
45	853	727	380	163	750	949
60	1016	1033	585	230	810*	835
75	1112	1150	920	484	915	945
Equation	$\mathbf{Y} = 145.09\, e^{0.0018\, X}$		$\mathbf{Y} = 0.0004\, X^2 + 0.05\, X + 64.5$		$\mathbf{Y} = -0.004\, X^2 + 6.5\, X - 1961$	
R²	**0.85**		**0.99**		**0.95**	

*Data calculated by SPSS software.

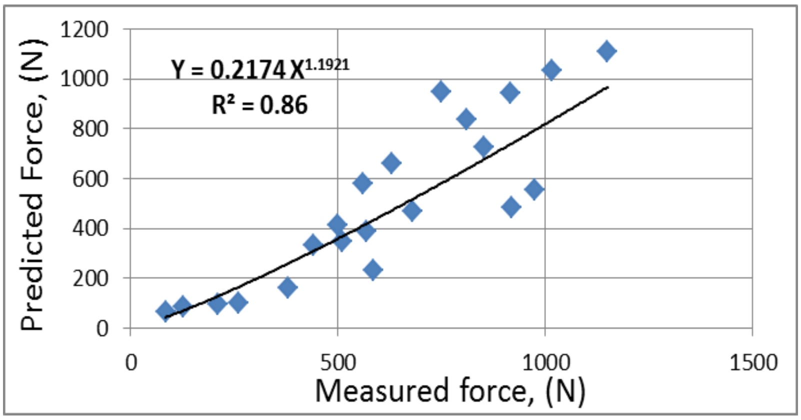

Figure (4): Relative the measured and predicted draft at different tool rake angles using experimental results.

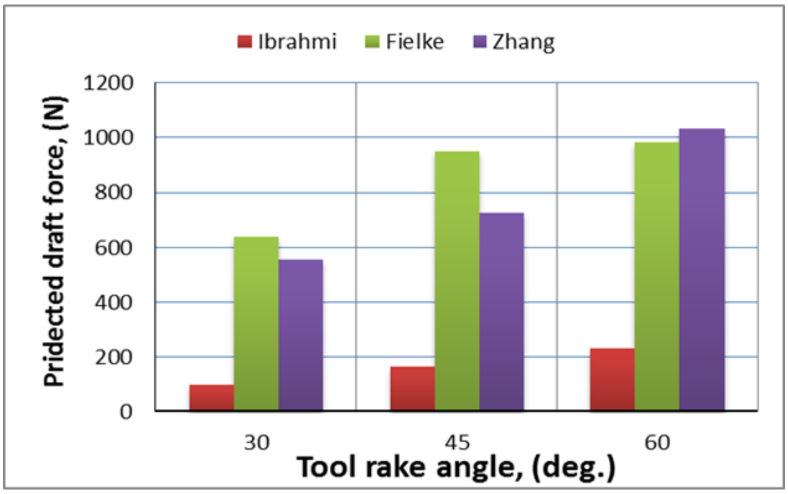

Figure (5): Effect of tool rake angle on predicted draft force using three experimental results.

Model verifying of draft with respect to the tool operating depth

Data in Table 3 show the results of draft force from the model and from experimental results. It can be seen that, as expected the draft force increased with an increase in the tool operating depth for the three experiments and consequently, for the model. Figure 6 shows the relation between measured and predicted draft at different tool operating depths. It clear that the predicted draft showed an agreement with measured draft with a correlation coefficient of $R^2 = 95\%$ as a power function. Analysis of variance was performed for measured and predicted draft in relation to tool operating depths. It showed that there is no significant difference between both measured and predicted draft forces with tool operating depths. Results of the least significant difference (LSD) test indicated that there is no significant difference on the measured and predicted draft force with respect to tool operating depth.

Table 3. Results of draft force from the model and from experimental results with respect to tool operating depth

Experiments	Akbarina, (2014)		Ibrahmi, (2014)		Fielke, (1988)	
Tool depth (mm)	Measured (N)	Predicted (N)	Measured (N)	Predicted (N)	Measured (N)	Predicted (N)
150	1010	762	600	523	190	197
200	1500	1060	610	560	350	415
250	1900	1325	700	600	590	697
300	2300	2023	750	630	900	908
Equation	$Y=-0.0008X^2+3.15X-958.8$		$Y=0.011X^2-11.1X+3414.9$		$Y=0.011X^2-11.2X+3414.9$	
R^2	0.99		0.97		0.99	

* Data calculated by SPSS software.

Effect of tool operating depth on the predicted draft force

Figure 7 shows the effect of tool operating depth on predicted draft using results of Akbarina (2014), Ibrahmi (2014) and Fielke (2014). It showed that the increasing in tool operating depth caused an increase in the predicted draft force obtained from the model. The highest values of predicted draft force were obtained with the results of Akbarina at various levels of tool operating depths. However, there were no appreciable change in the predicted draft force with the results from Ibrahmi and Fielke. The increase in tool operating depth from 150 mm to 300 mm resulted in increasing of predicted draft force by 56%, 17%, and 78% for Akbarina, Ibrahmi, and Fielke, respectively. These results may be attributed to the variation on soil physical conditions, the degree of soil compaction, tool geometry, tool travel speed and tool width (Mouazen and Ramon, 2002).

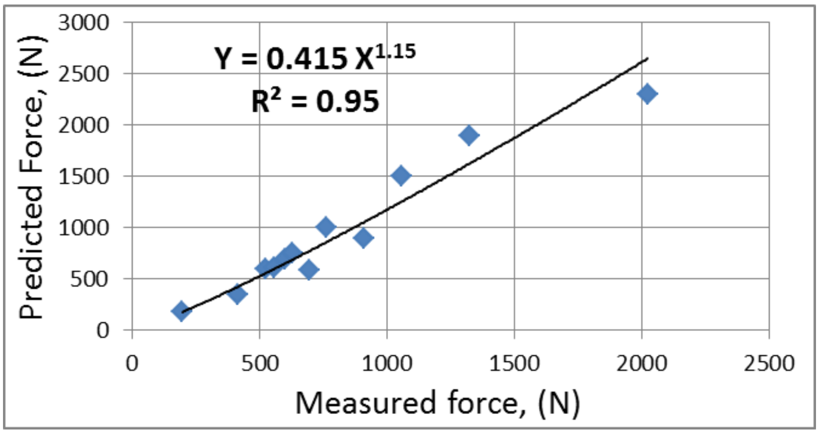

Figure (6): Relative the measured and predicted draft at different tool operating depths**.**

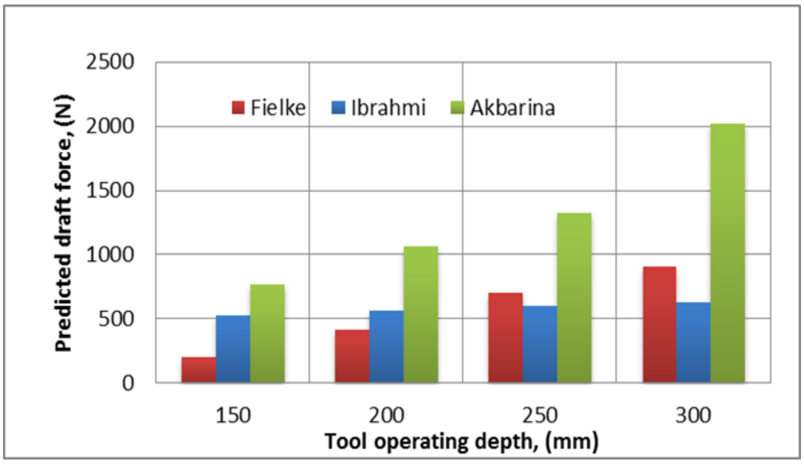

Figure (7): Effect of tool operating depth on predicted draft force using various experimental results.

Model verifying of draft with respect to the tool operating speed

Data in Table 4 show the results of draft force from the model and from experimental results under different tool speeds. It can be seen that, as expected the draft force increased with an increase in the tool operating depth for the three experiments and consequently, for the model. Figure 8 shows the relation between measured and predicted draft at different tool operating speeds. It shown that the predicted draft showed an agreement with measured draft with a correlation coefficient of R^2 = 86% as linear function. Analysis of variance was performed for measured and predicted draft in relation to tool operating speeds. It showed that there is no significant difference between both measured and predicted draft forces with respect to tool operating. Results of the least significant difference (LSD) test indicated that there were a significant differences on the measured draft force for the values of operating speeds of (0.75, 1.1, and 3.3 m/s.). However, there is no significant difference from LSD test on the predicted draft force with respect to tool operating speed.

Table 4. Results of draft force from the model and from experimental results with respect to tool operating speeds.

Experiments	Akbarina, (2014)		Moeenifar, (2014)		Ucgul, (2014)	
Tool speed (m/s)	Measured (N)	Predicted (N)	Measured (N)		Measured (N)	Predicted (N)
0.75	381*	480	459	342	329*	190
1.1	558*	667	513*	380	375	220
1.5	762	910	580	400	390*	235
1.7	863	1155	600	450	443*	280
2.2	1117*	1275	777*	476	475	300
3.0	1390	1400	856*	520	511*	328
3.3	1676*	1480	993*	580	559	350
Equation	$Y = -0.0006X^2 + 2.06X - 227.4$		$Y = 287.94\ln(X) - 1419.4$		$Y = 0.1864X^{1.1962}$	
R^2	0.98		0.96		0.99	

* Data calculated by SPSS software.

Effect of tool operating speed on the predicted draft force

Figure 9 shows the effect of tool operating speed on predicted draft using the results of Akbarina (2014), Moeenifar (2014), and Ucgul (2014). It showed that the increasing in tool operating speed caused an increase in the predicted draft force obtained from the model. The highest values of predicted draft force were obtained with the results of Akbarinaat various levels of tool operating speeds. However, the middle and lowest values were resulted from the results from Moeenifar and Ucgul, respectively. The increase in tool operating speed from 0.75 m/s. to 3.3 m/s. caused increasing in predicted draft force by 67%, 41%, and 46% for Akbarina, Moeenifar, and Ucgul, respectively. These results may be attributed to the variation on soil physical conditions, the degree of soil compaction, tool geometry, tool operating depth and tool width (Mouazen and Ramon, 2002).

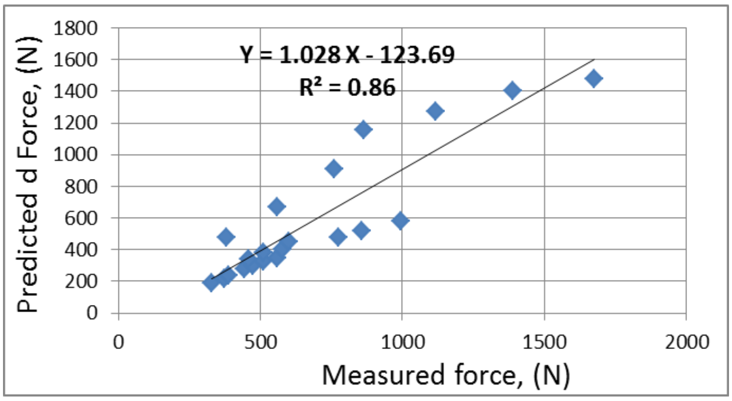

Figure (8): Relative the measured and predicted draft at different tool operating speeds.

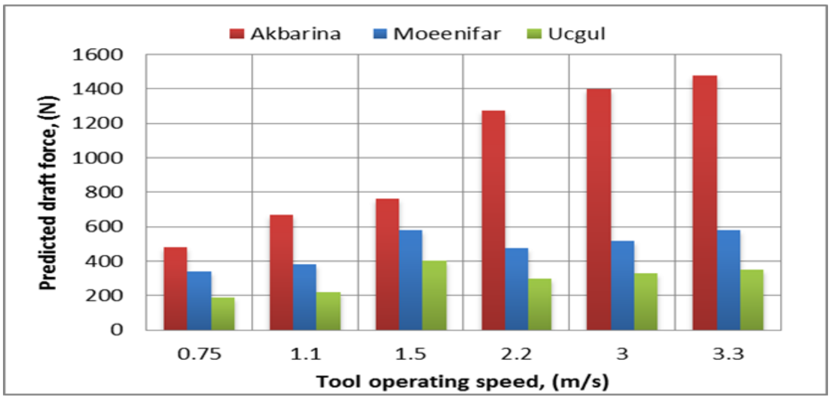

Figure (9): Effect of tool operating speed on predicted draft force using various experimental results.

Conclusion

In this study, simulation model of soil-tool interaction was carried out based on Sohne's model using Visual Basic. Results showed that the model could predict the draft of simple tillage tools, i.e., chisel plows. This predication could be done at varying operating and soil conditions. The model was validated using real data under different tool rake angles, tool operating depths and tool operating speeds. Good correlations, almost 90%, were obtained between the predicted draft from the model and measured draft from experimental data. Predicted draft force of tillage tools increased with the increasing in rake angles, tool depths, and tool speeds. Also, results obtained from the model could be used by those interested in modern soil tillage systems to make the appropriate decision regarding determining the draft force required for tillage equipment.

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نمذجة تاثير التفاعل بين التربة والسلاح على قوة الشد باستخدام فيجوال بيسك

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تشير كل الدراسات والاحصائيات إلى أن الزراعة المصرية تعتبر واحدة من أكثف الزراعات في العالم، وحيث أن عملية الحراثة تحتل المرتبة الأولي من حيث الطاقة المطلوبة لإجراءها مقارنة بباقي العمليات الزراعية الأخرى وذلك لوجود حوالي 6.5 مليون هكتار من المساحة الزراعية يتم حراثتها كل عام وهذا يعني إثارة كتلة تقدر بنحو 500 6 مليون طن من التربة عندما يكون عمق الحراثة 100 مم فقط (Rosa, 1997). النماذج الرياضية وكذلك نماذج المحاكاه او النماذج العددية تعتبر البديل الأمثل للدراسات التجريبية سواءا الحقلية أو صناديق التربة فبالرغم من أنها توفر بيانات قيمة ، إلا أنها مكلفة وتستغرق وقتا طويلا وتقتصر على دراسة بعض العوامل التي تؤثر على آداء معدات الحراثة كسرعات وأعماق التشغيل. وقد أظهرت تطورات النماذج الرياضية التي تعتمد على التحليل الرياضي ونماذج المحاكاه التي تعتمد على إستخدام برامج الحاسب الآلي إمكانيات كبيرة في تحليل واستخدام كثيرا من العوامل التي تؤثر على التفاعل بين التربة وأسلحة الحراثة لقياس الأداء لمعدات الحراثة. يضاف إلى ذلك أن نظم الزراعة الحديثة في الوقت الحالي في مجال حراثة التربة تتطلب معرفة المعلومات المتعلقة بالطاقة المطلوبة للحراثة ، الأمر الذي يحفز على استخدام نماذج المحاكاة كتقنية بديلة مثلى لتقدير الطاقة المطلوبة لمعدات الحراثة. لذا ، فإن الهدف من هذه الدراسة هو إختيار وتطوير واختبار وكذلك التحقق من صحة المخرجات لنموذج محاكاه يستند إلى Sohne's Model للتنبؤ بقوة الشد لمعدات الحراثة البسيطة مثل المحاريث الحفارة باستخدام برنامج Visual Basic. وبمقارنة نتائج النموذج بالنتائج المقاسة تجريبيا أظهرت صلاحية النموذج للإستخدام بدقة تصل إلى 90%. كما إن النموذج يمكن أن يستفيد به المهتمين بنظم الزراعة الحديثة في مجال حراثة التربة لاتخاذ القرار المناسب فيما يتعلق بتحديد قوة الشد المطلوبة لمعدات الحراثة.