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Modeling of Moldboard Plow Draft Force Based on Tillage Depth and Operation Speed

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Abstract: As tillage depth and operation speed of the implement have the greatest influence on the draft requirement for tillage with the most common tillage tools, this study was conducted to predict draft force (DF) of a moldboard plow (pull-type) based on tillage depth (TD) and operation speed (OS) of the implement. For this purpose, DF of the moldboard plow was measured at three levels of soil moisture content (16.1, 22.0 and 25.4%), four levels of TD (7, 14, 19 and 23 cm) and four levels of OS (1.95, 2.69, 3.80 and 4.50 km/h). Results of DF measurement at soil moisture contents of 16.1 and 25.4% were utilized to determine two-variable regression models and results of DF measurement at soil moisture content of 22.0% were used to verify selected model. The paired samples t-test results showed that the difference between the DF values predicted by selected model and measured by field tests were not statistically significant and to predict draft force of moldboard plow based on tillage depth and operation speed of the implement, the two-variable regression model $DF = 160.0 + 0.760\ TD^2 + 69.02\ OS$ with $R^2 = 0.904$ can be strongly suggested.

Key words: Draft force · Moldboard plow · Tillage depth · Operation speed · Modeling

INTRODUCTION

Tillage involves the movement of soil from one place to another [1, 2]. In conventional farming tillage may consume a major portion of the farm's energy budget. The most convenient method to estimate a given implement's energy requirement is to measure the force required to pull the tillage implement at a desired operation speed [3-5]. The force required to pull a tillage implement through the soil is called draft force. When a tillage implement is pulled through the soil, the power unit (usually a tractor) must overcome draft forces created by soil resistance. The direction of the draft force is in the direction of travel [6]. Accurate knowledge of draft force is useful for optimal matching of power unit to tillage implement [7]. However, draft force varies greatly due to numerous factors that influence it. Since a large number of factors influencing draft requirement and various potential combinations of tillage devices exist, it is prohibitively expensive to test all implements in all conditions for every soil type. Therefore, determining which variables have the greatest influence on the draft requirement for tillage with the most common tillage tools would greatly enhance the process of matching power units to tillage implements [8].

The objective of a large body of existing work has been to study the draft force of a given tillage implement under certain soil conditions and/or operating parameters [4, 5, 9-19]. The ASAE standard D497.4 describes draft force as a function of implement type, soil type, implement width, tillage depth and operation speed [6]. A number of other properties such as static and dynamic component of soil shear stress, soil-metal friction coefficient, soil density and implement geometry are also necessary to consider when analyzing draft force [8, 10, 12, 20]. However, most work that has been done on draft force in the past was focused on specific draft and has concluded that tillage depth is the primary determinant of the amount of force required to pull an implement through soil, with speed often having a significant effect [8, 12, 15, 16, 19].

As tillage depth and operation speed of the implement have the greatest influence on the draft requirement for tillage with the most common tillage tools, this study was conducted to predict draft force (DF) of a moldboard plow (pull-type) based on tillage depth (TD) and operation speed (OS) of the implement.

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MATERIALS AND METHODS

Experimental Site: Experiments were conducted at the Agricultural Research and Experimental Farm of Shahid Beheshti Technical School at Sari, Mazandaran Province, Iran. The experimental site was located at latitude of 36°31' N and longitude of 53° 25' E and was 16.4 m above mean sea level.

Soil Sampling and Analysis: A composite soil sample from 48 points was collected from 0-20 cm depth and analyzed in the Laboratory for particle size distribution (sand, silt and clay). The soil in the experimental site was basically clay in texture. The clay soil was consisted of 49.5% clay, 35.0% silt and 15.5% sand.

Tillage Implement: A two-bottom moldboard plow (pull-type) with width of 96 cm was used in this study (Fig. 1). This implement is representative of the standard primary tillage implement most commonly used for turning over the upper layer of the soil, bringing fresh nutrients to the surface, while burying weeds and the remains of previous crops.

Field Methods: There was no crop grown and the field was left fallow. Prior to performing the experiments, the field was irrigated by using a sprinkler irrigation system. Soil samples were collected and weighed during the experiments to determine soil moisture content. The samples were placed in an electric oven maintained at 110°C for 48 hours. The dried soil samples were reweighed and the soil moisture contents were calculated on a dry weight basis. A factorial experiment based on randomized complete block design (RCBD) with three replications was used to evaluate the effect of tillage depth (TD) and operation speed (OS) of the implement on draft force of moldboard plow (pull-type). Draft force measurement at three soil moisture contents (16.1, 22.0 and 25.4%), four levels of TD (7, 14, 19 and 23 cm) and four levels of OS (1.95, 2.69, 3.80 and 4.50 km/h) were used in a combination resulting in a total of 48 treatments. The treatments were randomly distributed in the field tests.

Experimental Procedure: An experimental block 75 m × 5 m was used for each treatment. A small block of approximately 15 m long by 5 m wide in the beginning of each tested block was used to enable the tractor and implement to reach the required tillage depth and operation speed. Tillage depth was measured as the vertical distance from the top of the undisturbed soil surface to the implement's deepest penetration. During field operations, the tractor was operated at the same tillage depth but at different operation speeds. A Universal 650 tractor with 48.5 kW and in good condition was used in all the experiments. The implement draft force, tillage depth and operation speed during field operations were measured and recorded by an onboard data logger in the tractor cab.

Fig. 1: Two-bottom moldboard plow (pull-type) used in this study

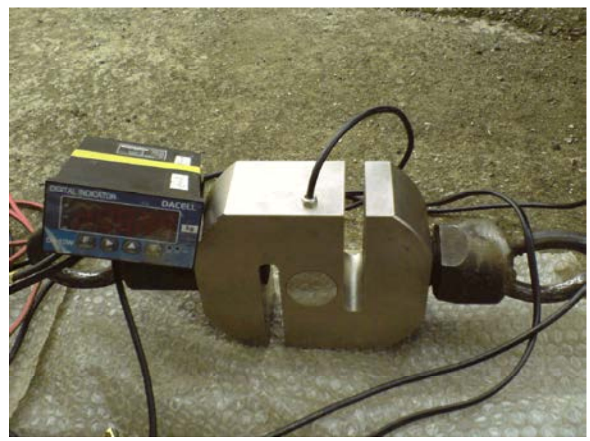

Fig. 2: Towed linkage load cell used in this study

Data Acquisition System: The data acquisition system consisted of a data logger, a towed linkage load cell (Fig. 2), a depth position transducer and a fifth wheel. The towed linkage load cell used to measure implement draft force was calibrated prior to the experiments using a specially built calibration rig. A performance test program was developed and documented for the data logger to scan the transducers every second during field operation. Therefore, the number of readings made in each treatment depended on the operation speed of the tractor.

Table 1: Results of draft force measurement (three replications) at soil moisture contents of 16.1 and 25.4% used for determining two-variable regression models

Soil moisture content (%)	Tillage depth (cm)	Operation speed (km/h)	Draft force of moldboard plow (kgf)		
			R_1	R_2	R_3
16.1	7	1.95	418	424	427
		2.69	439	444	455
		3.80	467	472	492
		4.50	510	527	532
	14	1.95	471	474	483
		2.69	507	512	526
		3.80	551	556	570
		4.50	571	575	594
	19	1.95	546	547	560
		2.69	605	612	625
		3.80	682	689	705
		4.50	752	760	762
	23	1.95	672	678	693
		2.69	761	774	787
		3.80	885	891	903
		4.50	998	1006	1020
25.4	7	1.95	373	389	390
		2.69	397	399	422
		3.80	434	439	447
		4.50	479	481	489
	14	1.95	425	427	432
		2.69	461	464	470
		3.80	491	505	528
		4.50	521	525	538
	19	1.95	500	506	521
		2.69	561	565	575
		3.80	635	639	652
		4.50	691	702	719
	23	1.95	625	628	640
		2.69	716	724	738
		3.80	829	832	847
		4.50	928	938	960

Table 2: Results of draft force measurement (three replications) at soil moisture content of 22.0% used for verifying selected two-variable regression model

Soil moisture content (%)	Tillage depth (cm)	Operation speed (km/h)	Draft force of moldboard plow (kgf)		
			R_1	R_2	R_3
22.0	7	1.95	395	399	412
		2.69	419	428	440
		3.80	451	458	465
		4.50	490	499	505
	14	1.95	436	440	467
		2.69	481	485	501
		3.80	513	519	528
		4.50	549	558	570
	19	1.95	523	528	536
		2.69	576	580	590
		3.80	663	669	678
		4.50	731	736	744
	23	1.95	649	654	665
		2.69	757	761	771
		3.80	865	870	878
		4.50	989	995	1007

To begin the field tests, the depth wheels lever was adjusted to lower the implement corresponding to the tillage depth. Then the tractor was accelerated to the required operation speed with a known gear range before entering the first test block. Data acquisition was activated by pressing the push button switch on the activity unit as the tractor passed the flag marking the beginning of the first test block. Data acquisition continued until the end of the test block. After finishing the first test block, the tractor was again driven straight toward the second test block with a different operation speed and the process was repeated. Similar procedure was repeated for other treatments. Results of draft force measurement at soil moisture contents of 16.1 and 25.4% (Table 1) were utilized to determine two-variable regression models and results of draft force measurement at soil moisture content of 22.0% (Table 2) were used to verify selected model.

Regression Model: A typical two-variable regression model is shown in equation 1:

$$Y = C_0 + C_1X_1^r + C_2X_2^s \quad (1)$$

Where:
Y = Dependent variable, for example draft force (DF) of moldboard plow
X_1, X_2 = Independent variables, for example tillage depth (TD) and operation speed (OS) of the implement, respectively
r, s = Power of the independent variables
C_0, C_1, C_2 = Regression coefficients

In order to predict draft force of moldboard plow from tillage depth and operation speed of the implement, four regression models were suggested and all the data were subjected to regression analysis using the Microsoft Excel 2007. Two-variable regression models and their relations are shown in Table 3.

Statistical Analysis: A paired samples t-test and the mean difference confidence interval approach were used to compare the draft force values predicted by selected model with the draft force values measured by field tests. The Bland-Altman approach [21] was also used to plot the agreement between the draft force values measured by field tests with the draft force values predicted by selected model. The statistical analyses were also performed using the Microsoft Excel 2007.

RESULTS AND DISCUSSION

The p-value of independent variables and coefficient of determination (R^2) for the two-variable regression models are shown in Table 4. Among the four models, model No. 3 had the highest R^2 value (0.904). Moreover, this model totally had the lowest p-value of independent variables among the four models. Based on the statistical results model No. 3 was selected as the best model, which is given by equation 2:

$$DF = 160.0 + 0.760\ TD^2 + 69.02\ OS \quad (2)$$

Table 3: Two-variable regression models and their relations

Model No.	Model	Relation
1	$DF = C_0 + C_1\ TD + C_2\ OS$	$DF = 31.17 + 21.88\ TD + 69.02\ OS$
2	$DF = C_0 + C_1\ TD + C_2\ OS^2$	$DF = 133.0 + 21.88\ TD + 10.62\ OS^2$
3	$DF = C_0 + C_1\ TD^2 + C_2\ OS$	$DF = 160.0 + 0.760\ TD^2 + 69.02\ OS$
4	$DF = C_0 + C_1\ TD^2 + C_2\ OS^2$	$DF = 261.9 + 0.760\ TD^2 + 10.62\ OS^2$

Table 4: The p-value of independent variables and coefficient of determination (R^2) for the two-variable regression models

	p-value				
Model No.	TD	TD^2	OS	OS^2	R^2
1	5.74E-12	---	3.00E-06	---	0.844
2	6.08E-12	---	---	3.22E-06	0.843
3	---	4.89E-15	4.24E-08	---	0.904
4	---	5.41E-15	---	4.75E-08	0.903

Table 5: Tillage depth, operation speed and draft force of moldboard plow used in evaluating model No. 3

Tillage depth (cm)	Operation speed (km/h)	Draft force of moldboard plow (kgf) Measured by field tests	Predicted by model No. 3	Average of measured and predicted draft force (kgf)	Difference of measured and predicted draft force (kgf)
7	1.95	402	332	367	70
	2.69	429	383	406	46
	3.80	458	460	459	-2
	4.50	498	508	503	-10
14	1.95	441	444	442	-3
	2.69	489	495	492	-6
	3.80	520	571	546	-51
	4.50	559	620	589	-61
19	1.95	529	569	549	-40
	2.69	582	620	601	-38
	3.80	670	697	683	-27
	4.50	737	745	741	-8
23	1.95	656	697	676	-41
	2.69	763	748	755	15
	3.80	871	824	848	47
	4.50	997	873	935	124

Table 6: Paired samples t-test analysis on comparing draft force determination methods

Determination methods	Average difference (kgf)	Standard deviation of difference (kgf)	p-value	95% confidence intervals for the difference in means (kgf)
Field tests vs. model No. 3	-0.95	49.5	0.9407	-27.3, 25.4

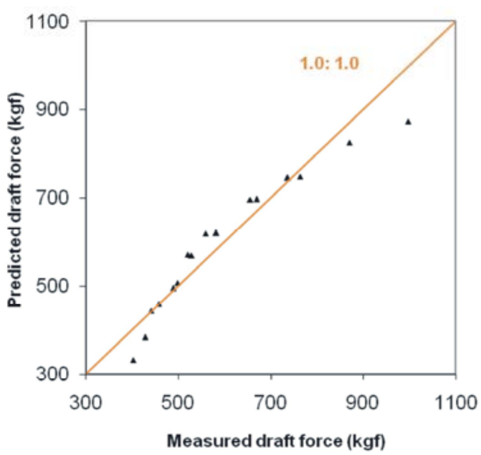

Fig. 3: Measured draft force by field tests and predicted draft force by model No. 3 with the line of equality (1.0: 1.0)

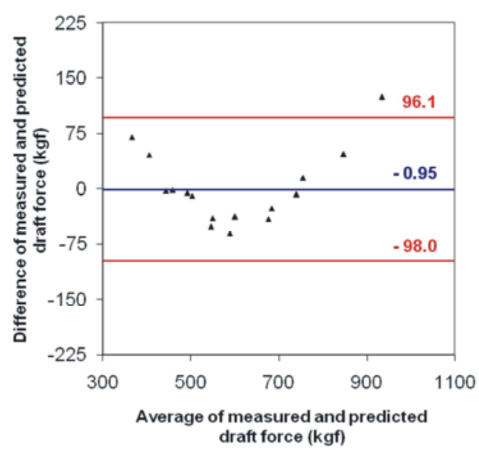

Fig. 4: Bland-Altman plot for the comparison of measured draft force by field tests and predicted draft force by model No. 3; the outer lines indicate the 95% limits of agreement (-98.0, 96.1) and the center line shows the average difference (-0.95)

Draft force of the moldboard plow was then predicted for SMC of 22.0% at four levels of TD (7, 14, 19 and 23 cm) and four levels of OS (1.95, 2.69, 3.80 and 4.50 km/h) using the two-variable regression model No. 3. The draft force values predicted by model No. 3 were compared with the draft force values measured by field tests and are shown in Table 5. A plot of the draft force values predicted by model No. 3 and the draft force values measured by field tests with the line of equality (1.0: 1.0) is shown in Fig. 3. Moreover, a paired samples t-test and the mean difference interval approach were used to compare the draft force values predicted by model No. 3 with the draft force values measured by field tests. The Bland-Altman approach [21] was also used to plot the agreement between the draft force values measured by field tests with the draft force values predicted by model No. 3. The average draft force difference between two methods was -0.95 kgf (95% confidence intervals for the difference in means: -27.3 kgf and 25.4 kgf; P = 0.9407). The standard deviation of the draft force difference was 49.5 kgf (Table 6). The paired samples t-test results showed that the draft force values predicted by model No. 3 were not significantly different than the draft force values measured by field tests. The draft force difference values between two methods were normally distributed and 95% of these differences were expected to lie between μ-1.96σ and μ+1.96σ, known as 95% limits of agreement [22-25]. The 95% limits of agreement for comparison of the draft force values determined by field tests and model No. 3 was calculated at -98.0 kgf and 96.1 kgf (Fig. 4). Therefore, the draft force values predicted by model No. 3 may be 98.0 kgf lower or 96.1 kgf higher than the draft force values measured by field tests. The average percentage difference for the draft force values predicted by model No. 3 and measured by field tests was 6.2%.

CONCLUSION

It can be concluded that the two-variable regression model $DF = 160.0 + 0.760\ TD^2 + 69.02\ OS$ with $R^2 = 0.904$ can be strongly recommended to predict draft force (DF) of moldboard plow (pull-type) based on tillage depth (TD) and operation speed (OS) of the implement [26-28].

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