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Modeling of Double Action Disc Harrow Draft Force Based on Tillage Depth and Forward Speed

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Abstract: Tillage depth and forward speed of the implement have the greatest influence on the draft requirement for tillage with the most common tillage tools. Therefore, this study was conducted to predict draft force (DF) of a double action disc harrow (pull-type) based on tillage depth (TD) and forward speed (FS) of the implement. For this purpose, DF of the double action disc harrow was measured at three levels of soil moisture content (11.27, 17.04 and 22.87%), four levels of TD (4, 8, 12 and 16 cm) and four levels of FS (3.05, 4.30, 5.89 and 7.15 km/h). Results of DF measurement at soil moisture contents of 11.27 and 22.87% were utilized to determine two-variable regression models and results of DF measurement at soil moisture content of 17.04% 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 double action disc harrow based on tillage depth and forward speed of the implement, the two-variable regression model $DF = 315.8 + 6.977\ TD + 2.447\ FS^2$ with $R^2 = 0.678$ can be strongly suggested.

Key words: Draft force · Double action disc harrow · Tillage depth · Forward 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 forward 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 forward 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].

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As tillage depth and forward 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 double action disc harrow (pull-type) based on tillage depth (TD) and forward speed (FS) of the implement.

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: One commercial double action disc harrow (pull-type) with width of 255 cm was used in this study (Fig. 1).

This implement was representative of the standard secondary tillage implement most commonly used for seedbed preparation in Iran. It consisted of four groups with 28 discs, each 36 cm in diameter.

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 forward speed (FS) of the implement on draft force of double action disc harrow (pull-type). Draft force measurement at three soil moisture contents (11.27, 17.04 and 22.87%), four levels of TD (4, 8, 12 and 16 cm) and four levels of FS (3.05, 4.30, 5.89 and 7.15 km/h) were used in a combination resulting in a total of 48 treatments. The treatments were randomly distributed in the field tests.

Fig. 1: Double action disc harrow (pull-type) used in this study

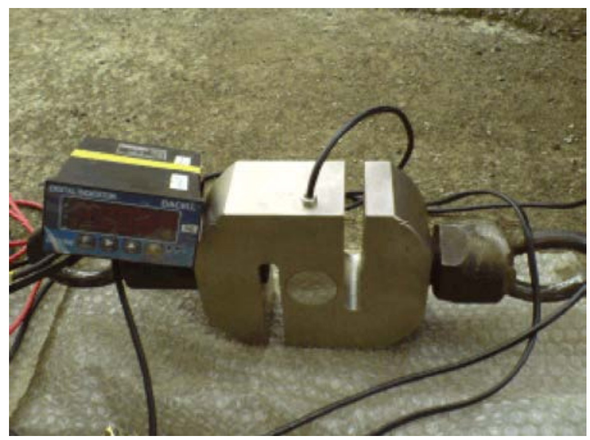

Fig. 2: Towed linkage load cell used in this study

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 forward 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 forward 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 forward speed during field operations were measured and recorded by an onboard data logger in the tractor cab.

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

Table 1: Results of draft force measurement (three replications) at soil moisture contents of 11.27 and 22.87% used for determining two-variable regression models

			Draft force of double action disc harrow (kgf)		
Soil moisture content (%)	Tillage depth (cm)	Forward speed (km/h)	R_1	R_2	R_3
11.27	4	3.05	381	387	387
		4.30	412	413	414
		5.89	425	429	431
		7.15	466	466	472
	8	3.05	410	414	415
		4.30	458	463	465
		5.89	466	482	483
		7.15	570	575	586
	12	3.05	418	418	421
		4.30	463	467	474
		5.89	479	483	487
		7.15	579	583	590
	16	3.05	503	504	505
		4.30	533	533	534
		5.89	545	456	553
		7.15	588	589	591
22.87	4	3.05	353	354	359
		4.30	376	385	386
		5.89	394	395	400
		7.15	431	436	438
	8	3.05	370	372	377
		4.30	407	409	414
		5.89	423	424	426
		7.15	492	493	494
	12	3.05	376	379	382
		4.30	415	416	418
		5.89	430	430	431
		7.15	498	500	503
	16	3.05	423	424	426
		4.30	450	451	453
		5.89	465	465	466
		7.15	503	504	508

Table 2: Results of draft force measurement (three replications) at soil moisture content of 17.04% used for verifying selected two-variable regression model

			Draft force of double action disc harrow (kgf)		
Soil moisture content (%)	Tillage depth (cm)	Forward speed (km/h)	R_1	R_2	R_3
17.04	4	3.05	363	367	380
		4.30	389	398	410
		5.89	403	410	426
		7.15	448	451	460
	8	3.05	388	392	399
		4.30	431	435	442
		5.89	440	444	454
		7.15	511	518	528
	12	3.05	391	398	408
		4.30	431	438	445
		5.89	449	455	464
		7.15	519	525	534
	16	3.05	458	463	471
		4.30	485	491	503
		5.89	501	507	519
		7.15	541	545	555

Table 3: Two-variable regression models and their relations

Model No.	Model	Relation
1	$DF = C_0 + C_1\ TD + C_2\ FS$	$DF = 259.3 + 6.977\ TD + 24.72\ FS$
2	$DF = C_0 + C_1\ TD + C_2\ FS^2$	$DF = 315.8 + 6.977\ TD + 2.447\ FS^2$
3	$DF = C_0 + C_1\ TD^2 + C_2\ FS$	$DF = 288.9 + 0.335\ TD^2 + 24.72\ FS$
4	$DF = C_0 + C_1\ TD^2 + C_2\ FS^2$	$DF = 345.5 + 0.335\ TD^2 + 2.447\ FS^2$

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 forward speed of the tractor. 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 forward 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 forward speed and the process was repeated. Similar procedure was repeated for other treatments. Results of draft force measurement at soil moisture contents of 11.27 and 22.87% (Table 1) were utilized to determine two-variable regression models and results of draft force measurement at soil moisture content of 17.04% (Table 2) were used to verify selected model.

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

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

where:

Y = Dependent variable, for example draft force (DF) of double action disc harrow
X_1, X_2 = Independent variables, for example tillage depth (TD) and forward speed (FS) 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 double action disc harrow from tillage depth and forward 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. 2 had the highest R^2 value (0.678). Moreover, this model totally had the lowest p-value of independent variables among the four models. Based on the statistical results model No. 2 was selected as the best model, which is given by equation 2:

$$DF = 315.8 + 6.977\ TD + 2.447\ FS^2 \qquad (2)$$

Draft force of the double action disc harrow was then predicted for SMC of 17.04% at four levels of TD (4, 8, 12 and 16 cm) and four levels of FS (3.05, 4.30, 5.89 and 7.15 km/h) using the two-variable regression model No. 2. The draft force values predicted by model No. 2 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. 2 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. 2 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 1.30 kgf (95% confidence intervals for the difference in means: -6.95 kgf and 9.55 kgf; P = 0.7433). The standard deviation of the draft force difference was 15.5 kgf (Table 6).

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	FS	FS^2	R^2
1	4.58E-05	---	2.12E-06	---	0.665
2	3.52E-05	---	---	1.18E-06	0.678
3	---	8.32E-05	2.89E-06	---	0.652
4	---	6.46E-05	---	1.65E-06	0.665

Table 5: Tillage depth, forward speed and draft force of double action disc harrow used in evaluating model No. 2

		Draft force of double action disc harrow (kgf)			
Tillage depth (cm)	Forward speed (km/h)	Measured by field tests	Predicted by model No. 2	Average of measured and predicted draft force (kgf)	Difference of measured and predicted draft force (kgf)
4	3.05	370	367	368	3
	4.30	399	389	394	10
	5.89	413	429	421	-16
	7.15	453	469	461	-16
8	3.05	393	394	394	-1
	4.30	436	417	426	19
	5.89	446	457	451	-11
	7.15	519	497	508	22
12	3.05	399	422	411	-23
	4.30	438	445	441	-7
	5.89	456	484	470	-28
	7.15	526	525	525	1
16	3.05	464	450	457	14
	4.30	493	473	483	20
	5.89	509	512	511	-3
	7.15	547	553	550	-6

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. 2	1.30	15.5	0.7433	-6.95, 9.55

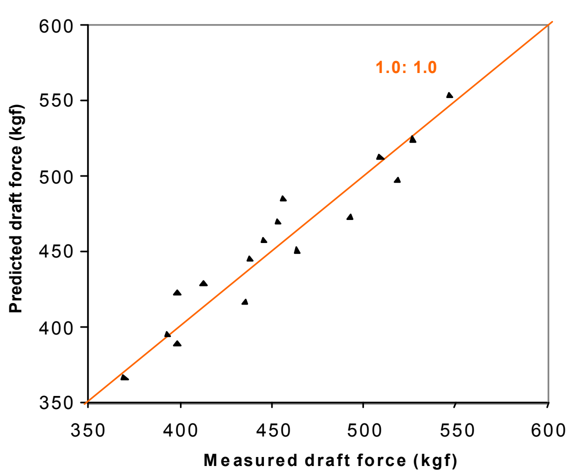

Fig. 3: Measured draft force by field tests and predicted draft force by model No. 2 with the line of equality (1.0: 1.0)

The paired samples t-test results showed that the draft force values predicted by model No. 2 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. 2 was calculated at -29.1 kgf and 31.7 kgf (Fig. 4).

Therefore, the draft force values predicted by model No. 2 may be 29.1 kgf lower or 31.7 kgf higher than the draft force values measured by field tests. The average percentage difference for the draft force values predicted by model No. 2 and measured by field tests was 2.8%.

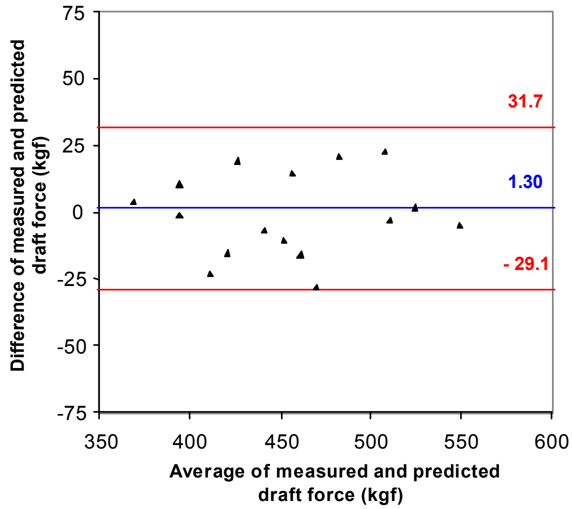

Fig. 4: Bland-Altman plot for the comparison of measured draft force by field tests and predicted draft force by model No. 2; the outer lines indicate the 95% limits of agreement (-29.1, 31.7) and the center line shows the average difference (1.30)

CONCLUSION

It can be concluded that the two-variable regression model DF = 315.8 + 6.977 TD + 2.447 FS^2 with $R^2 = 0.678$ can be strongly recommended to predict draft force (DF) of double action disc harrow (pull-type) based on tillage depth (TD) and forward speed (FS) of the implement [26-28].

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