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New regression model for predicting horizontal forces of single tines using a dummy variable and tine geometric parameters

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This paper discusses three different equations of a regression model to predict the horizontal force for single tines. Four standard single chisel plow tines were used (heavy duty, double heart, double heart with wings and duck-foot). The first model is based on the effect of the operational conditions speed and depth for each tine, the second model is employing a statistic dummy variable, also representing each tine. The geometry of tines is base for the third model. A stepwise selection with a multi-linear regression at significance level 5% was used to evaluate these regression models. Experiments were carried out in a sandy loam soil at soil moisture content of 10.3% ± 0.8 (based on dry matter) and soil bulk density of 1.38 g/cm³ ± 0.01 under controlled soil bin conditions featuring varying speeds between 1.1 and 3.6 m/s and varying depth from 5 to 20 cm. Field testing was done in order to validate the regression model obtained from the soil bin. The results show that the horizontal force increases linearly with the speed-depth interaction term and quadratically with the depth for each tine in all regression models. The depth is effecting the force more significantly in comparison to speed ($p < 0.05$). Eventually it can be stated that there is a good general accordance of observed and predicted values of the horizontal force for all tines by using the dummy and the geometric regression models.

Keywords
Standard single tines, horizontal tine force, soil bin

For the purpose of reducing the energy required to process tillage, it is important to know typical draft force (horizontal force) requirements and their range of variation in any given condition and machine configuration. Many analytical models for predicting draft forces on tillage tools have been developed. The analytical models are mainly focused on the soil failure zone ahead of tines, which is described in Terzaghi's passive earth pressure theory (Terzaghi 1943) for a two-dimensional soil failure for wide blade tools, which was further developed by Hettiaratchi et. al. (1966) later. A three dimensional soil failure model was initially proposed for a narrow blade by Payne (1956) and later specified and improved by many other researches (Hettiaratchi and Reece 1967, Godwin and Spoor 1977, McKyes and Ali 1977, Perumpral et al. 1983).

Wheeler and Godwin (1996) have proven that a speed below $\sqrt{5gW}$ was not significant on draft force for single and multiple tines and speed becomes critical at $\sqrt{5g(W+0.6d)}$, where g is the gravitational acceleration, w the tine width, and d the working depth. Many researches were finding a linear or second order polynomial, parabolic or exponential relationship between the draft force and the speed (Rowe and Barnes 1961, Siemens et al. 1965, Godwin et al. 1984, McKyes 1985, Swick and Perumpral 1988, Gupta et al. 1989). It can be seen that dynamic models for predicting draft force rely on

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adding the velocity component to the static models for both two-dimensional and three-dimensional models (Rowe and Barnes 1961, Gupta et al. 1989, Zeng and Yao 1992). All these static and dynamic models mentioned above used a flat blade with known rake angle, i. e. angle between the horizontal soil surface and bottom surface of the blade, neglecting standard tine shapes, which are curved or with wings. Therefore, these models have limitations in evaluating tillage tines.

Empirical models for predicting draft force using statistical regression equations based on data collected from field experiments for various tillage tools at various soil and operating conditions were developed (Upadhyaya et al. 1984, Grisso et al. 1996, Onwualu and Watts 1998). However, those regression equations are limited to the tillage tools and soil conditions tested. New regression equations using reference tillage tools have been developed (Glancey and Upadhyaya 1995, Glancey et al. 1996, Desbiolles et al. 1997, Ehrhardt et al. 2001, Sahu and Raheman 2006). All these regression models calculate the draft force as a ratio between the test sample and reference model without considering effects of the tool's geometry on draft force.

The main purpose of this paper is to develop and discuss regression equations relating to the horizontal force Fh of the various standard chisel plow tines and its dependency on the main operating conditions (speed, depth).

Material and methods

The evaluation was carried out at the Department of Agricultural Systems and Technology at Technische Universitaet Dresden, Germany, under controlled soil bin conditions. The soil bin is 28.6 m long, 2.5 m wide and 1.0 m deep. It is filled with a sandy loam soil (60.9% sand, 30.1% silt, 9% clay). The carrier is powered by an electric-hydraulic drive train with a maximum speed of 4.7 m/s delivering maximum traction of 13 kN. During the tests, soil moisture content was 10.3% ± 0.83 dry-based. Soil bulk density was 1.38 g/cm³ ± 0.01. Four standard chisel plow tines were used in the experiment: T1 Heavy duty, T2 Double heart, T3 Double heart with wings and T4 Duck Foot (Figure 1).

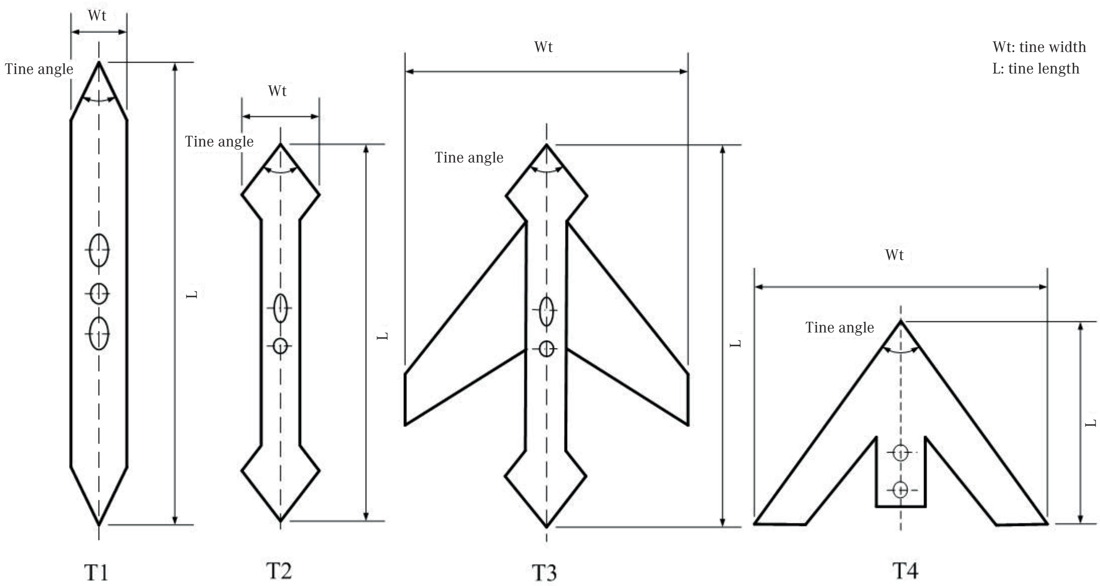

Fig. 1: Tine shape and dimension

Table 1 summarizes the characteristic tine parameters.

Table 1: Tine parameters

Tines	Length in cm	Width in cm	Thickness in cm	Radius in cm	Tine angle	Weight in g
Heavy duty	47	6.5	2	30	60°	3,400
Double heart	44	13.5	2	30	65°	3,200
Double heart with wings	32	45.0	2	30	65°	4,200[1)]
Duck foot	30	40.0	1	30	85°	2,900

[1)] Wings only.

Tines were operated at speeds 1.1, 1.9, 2.8, and 3.6 m/s for T1 and T2, and 1.1, 2.4 and 3.6 m/s for T3 and T4 with varying depths of 5, 10, 15 and 20 cm for T1 and T2 and 10, 15 and 20 cm for T3. The depth of 5 cm was excluded for T3 because it is below the minimum operational depth of the tine. T4 was run at 5, 12.5 and 20 cm depth. All tests were done with three replicates.

The horizontal force *Fh* was measured by using two load cell sensors, similar to measurements from Reich (1977). Sensor type was S9 (HBM GmbH) with a maximum load of 50 kN. Speed was measured by using a radar ground speed sensor with a velocity range of 0.15 to 29.7 m/s at an accuracy of ± 5%.

Regression model

Three different equations of a regression model to predict *Fh* for a single tine were used. The first model bases on the relationship between speed and depth (operating conditions) and is presented by Equation 1 (Glancey and Upadhyaya 1995), where S is speed in m/s, D is depth in cm and C_0, C_1, C_2, C_3, C_4 and C_5 are the regression coefficients.

$$Fh = C_0 + C_1S + C_2D + C_3SD + C_4S^2 + C_5D^2 \quad \text{(Eq. 1)}$$

The second model is employing the statistic dummy variable K (Equation 2). This variable is capable of representing each tine regardless of its shape and geometry.

$$Fh = K + C_0 + C_1S + C_2D + C_3SD + C_4S^2 + C_5D^2 \quad \text{(Eq. 2)}$$

The geometry of tines is base for the third model (Equation 3).

$$Fh = G_1W_t + G_2L_t + G_3\theta_t + C_0 + C_1S + C_2D + C_3SD + C_4S^2 + C_5D^2 \quad \text{(Eq. 3)}$$

W_t is tine width in cm, L_t is tine length in cm, θ_t is tine angle in degree and G_1, G_2 and G_3 are tine geometric coefficients. Note that identical geometric parameters were excluded.

A stepwise selection with a multi-linear regression at significance level of 5% was used to determine these regression models by using IBM SPSS program version 22.

Field test

The regression models obtained from the soil bin were validated in field by testing the four tines at three speed levels 1.1, 3.3 and 5.6 m/s and three depths 5, 10 and 20 cm. Tests were done with three replicates. The field soil type was similar to the soil bin sandy loam. Soil moisture and soil bulk density were measured during the test at 10.4% ± 1.1 dry base and 1.42 g/cm³ ± 0.1 respectively.

Results and discussion

Regression models and coefficients for prediction of the horizontal force

Three regression models were used to predict Fh at soil bin conditions by using multi-linear regression models with a stepwise selection to exclude the insignificant coefficients (under 5% level) of regression. Results are presented in Table 2. From this table it can be seen that Fh increased linearly with the speed-depth interaction term and quadratically with the depth for each tine and for all regression models (positive values of C_3 and C_5). It is obvious that all coefficients except C_5 increase with increasing width of tines in the operating condition model at a high coefficient of determination $R^2 > 90\%$.

Table 2 also shows that the coefficient of interaction between speed-depth and the coefficient of depth square C_3 and C_5 have the same value of 0.020 and 0.002 respectively in the dummy and geometric model and are similar to the values in operating conditions. The similarity can be attributed to the stable test environment done in specific soil type and conditions.

The coefficient K for the dummy regression model is equal to zero for T1 because of its setting as tine reference (Table 2). It increases with increasing width of tines at a high R^2 of 0.957.

As expected from previous regression models only the coefficient of width G_1 had appeared in the geometric regression model with a high value of 0.019 at high R^2 of 0.952.

Table 2: Regression models and coefficients

Regression model	Tines	Regression coefficient						
		C_0	C_1	C_2	C_3	C_4	C_5	R^2
Operating condition	T1	-0.038	n.s.	n.s.	0.018	n.s.	0.002	0.974
	T2	-0.076	n.s.	n.s.	0.022	n.s.	0.002	0.964
	T3	0.318	n.s.	n.s.	0.023	n.s.	0.003	0.954
	T4	0.209	n.s.	n.s.	0.020	n.s.	0.004	0.968

Regression model	Tines	K	C_0	C_1	C_2	C_3	C_4	C_5	R^2
Dummy variable	T1	0.000	-0.166	n.s.	n.s.	0.020	n.s.	0.002	0.957
	T2	0.008							
	T3	0.707							
	T4	0.574							

Regression model	Tines	G_1	G_2	G_3	C_0	C_1	C_2	C_3	C_4	C_5	R^2
Geometric variable	T	0.019	n.s.	n.s.	-0.350	n.s.	n.s.	0.020	n.s.	0.002	0.952

n.s.: not significant

Validation of horizontal force

The observed (field) and the predicted (regression) values of Fh for all tines are plotted in Figure 2. It can be seen that the field test had recorded higher values of Fh than predicted for all tines, which is due to the field conditions being different to the soil bin in regard to existence of stones, roots of the previous crop and weeds that caused higher soil resistance.

The comparison in Figure 2 illustrates a general accordance between observed and predicted values of Fh for T1 with a slope of 0.744, 0.720, and 0.701 and with higher R^2 of 0.959, 0.960, and 0.954 for the dummy, geometric and operating condition regression respectively. The variation between observed and predicted values of Fh is 24% for the dummy, 25% for the geometric and 29% for the operating condition regression.

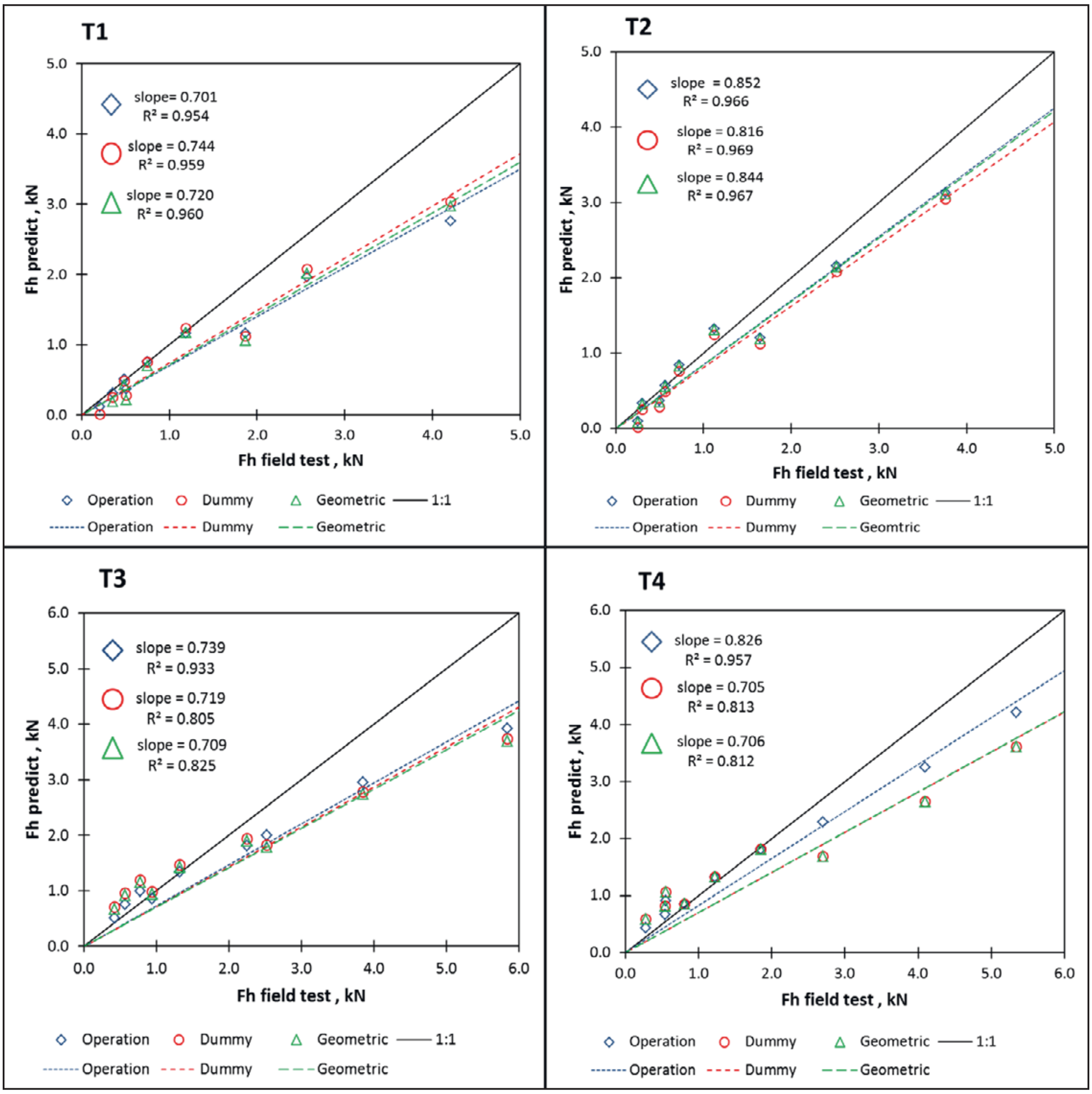

Fig. 2: Comparison of the observed and predicted Fh for all tines

A good general accordance of the observed and the predicted values is found for Fh of T2 with a slope of 0.852, 0.844, and 0.816 and higher R^2 of 0.966, 0.967, and 0.969 for the operating condition, geometric and dummy regression respectively (Figure 2). The variation between observed and predicted values of Fh is calculated to be 13% for both the operating condition and the geometric and 19% for the dummy regression.

Correlation between observed and predicted values exists for Fh for T3 in Figure 2 with a slope of 0.739, 0.719, and 0.709 and higher R^2 of 0.933, 0.805, and 0.825 for the operating condition, dummy and geometric regression respectively. The variation between observed and predicted values of Fh is found to be 18% for the operating condition, 16% for the dummy and 17% for the geometric regression.

Tine T4 shows a general accordance between observed and predicted values of Fh (Figure 2). From this graph, it can be seen a slope with 0.826 for operation condition, 0.706 for geometric and 0.705 for the dummy regression with higher R^2 of 0.957, 0.813, and 0.812 respectively. The regression equation model predicted the Fh of the operating condition, geometric and dummy regression with a variation of 9, 17 and 17% respectively.

Conclusions

Empirical regression models for prediction of the horizontal force acting on tines were developed by adding new coefficients related to tine geometry and by using a dummy variable. With these models it is possible to calculate horizontal forces for a wide range of tine shapes using parameters of tool geometry, working depth and speed in a sandy loam soil under controlled soil bin conditions. The different regression models are creating very similar predictions at acceptable coefficients of determination with an absolute variation less than 25%. The dummy coefficient K increased with increasing tine width. Only the coefficient of tine width G_1 appeared in the geometric regression model with high significance ($p < 0.05$).

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