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Draft forces prediction model for standard single tines by using principles of soil mechanics and soil profile evaluation

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This paper explains a model to predict the draft force acting on varying standard single tines by using principles of soil mechanics and soil profile evaluation. Draft force (F_d) measurements were made with four standard single tines comprising Heavy Duty, Double Heart, Double Heart with Wings and Duck Foot. Tine widths were 6.5, 13.5, 45 and 40 cm, respectively. The test was conducted in a soil bin with sandy loam soil. The effects of forward speeds and working depths on draft forces were investigated under controlled lab conditions. Results were evaluated based on a prediction model. A good correlation between measured and predicted F_d values for all tines with an average absolute variation less than 15 % was found.

Keywords
Draft force, prediction model, standard single tines, soil bin

From the point of designing and manufacturing, it is very important to know the amount of draft force acting on tillage tools. Numerous two-dimensional and three-dimensional analytical models have been developed based on the results from empirical work and Terzaghi's passive earth pressure theory (Terzaghi 1943). Later dynamic models for predicting draft force rely on adding the velocity component to the static models (Payne 1956), (Rowe and Barnes, 1961), (Hettiaratchi et al. 1966), (Hettiaratchi and Reece 1967), (Godwin and Spoor 1977), (McKyes and Ali 1977), (Perumpral et al. 1983), (Gupta et al. 1989), (Zeng and Yao 1992). All these static and dynamic models mentioned above used a simplified 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 for various tillage tools for different soil and operating conditions were developed based on the data collected from field experiments (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 have been developed using reference tillage tools (Glancey and Upadhyaya 1995) (Glanceyet 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 any effects of the tool's geometry on draft force.

(Al-Neama and Herlitzius 2016) developed regression models based on (Glancey and Upadhyaya 1995) by adding new terms related to the tine geometric parameters or a dummy term variable for a standard single tine under soil bin condition. These regression models predict the draft force without considering the effect of the soils mechanical properties.

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The main purpose of this paper is to explain and discuss a prediction model relating to the draft force of various standard single tines and its dependency on the principles of soil mechanics and soil profile.

Material and methods

The experiment was carried out at the Chair of Agricultural Systems and Technology at the Technical University Dresden, Germany, under controlled soil bin conditions. The soil bin was 28.6 m long, 2.5 m wide and 1.0 m deep. It was filled with a sandy loam soil, which had the physical properties given in Table 1.

Table 1: Physical properties of the soil bin soil ± standard error

Parameters	Units and abbreviations	Values
Soil texture		sandy loam
Clay content	%	9.0
Silt content	%	30.1
Sand content	%	60.9
Wet bulk density	ρ_w in g/cm³	1.55 ± 0.02
Moisture content dry base	Mc in %	10.4 ± 0.88
Internal friction angle	ϕ in °	42.0
External friction angle	δ in °	22.5
Cohesion	C in kN/m²	5.6
Con index	N	74.8 ± 9

The tine carrier was powered by an electric-hydraulic drive train with a maximum speed of 4.7 m/s delivering a maximum traction of 13 kN, and it was equipped with a radar sensor for measuring the ground speed (velocity range 0.15 to 29.7 m/s ± 5 %). A hydrostatic drive was used to attach the tools.

Four standard single tines comprising T1 (Heavy Duty), T2 (Double Heart), T3 (Double Heart with Wings) and T4 (Duck Foot) were used (Figure 1). The tine widths were 6.5, 13.5, 45 and 40 cm, respectively.

Figure 1: Standard single tines used in the experiment (© A. Al-Neama)

The tines were operated at speeds of 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 from T3 because it was 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 measurements were done in two parts. Measurement part one was related to the force measurements: draft force F_d was measured by using six load cell sensors, two for horizontal force F_h, one for vertical force F_v and three for lateral force F_L, similar to measurements from (Reich and Hohenheim 1977). Sensor types were S9 and U9B (HBM GmbH) with a maximum load of 50 kN and 20 kN, respectively with an accuracy ± 5 %. Measurement part two was related to a 2-D soil profile measurement using a laser spot sensor for the vertical coordinates and a draw-wire position sensor for the horizontal coordinates (Figure 2).

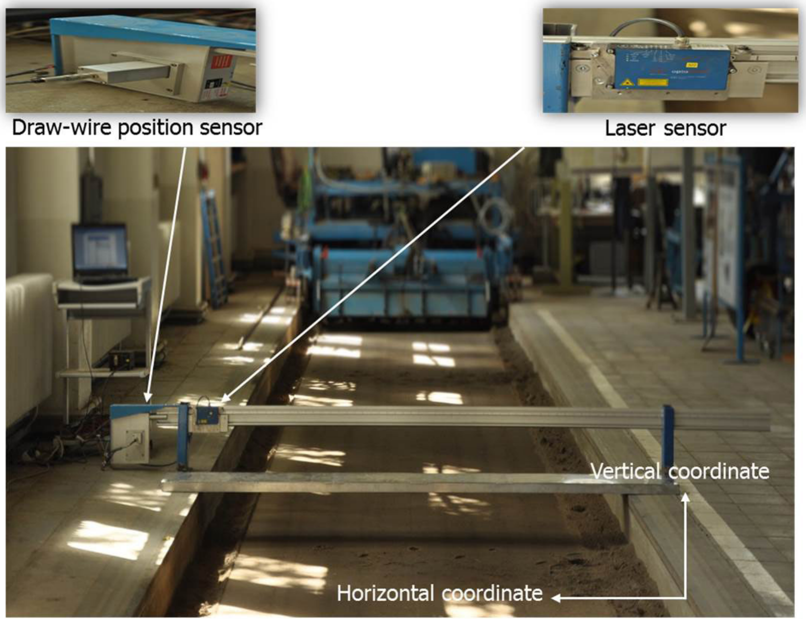

Figure 2: Laser scanner (© A. Al-Neama)

Draft force prediction approach for standard single tines

The analytical model for the prediction of soil force acting on the flat blade of the speed term is presented in Eq. 1.

$$F_r = (\rho_w\, g\, d^2\, N_\rho + C\, d\, N_c + C_a\, d\, N_{ca} + q\, d\, N_q + \rho\, S^2\, d\, N_a)\, w_t \qquad \text{(Eq. 1)}$$

where, F_r is the soil resistance force in kN, ρ_w is the wet soil bulk density in kg/m³, g is the acceleration of gravity in m/s², d is the operation depth in m, C is the soil cohesion in kN/m², C_a is the soil adhesion in kN/m², q is the soil surcharge pressure in kN/m², S is speed in m/s, w_t is the tine width in m and N_ρ, N_c, N_{ca}, N_q and N_a are dimensionless factors like soil friction cutting factor, soil cohesion cutting factor, soil adhesion cutting factor, soil overburden cutting factor and soil inertia cutting factor, respectively.

The main differences in all models is the determination of the N factors. A prediction model for a standard tine is presented in Eq. 2.

$$F_d = F_p + F_g + F_i + F_c \qquad \text{(Eq. 2)}$$

where, F_d is the draft force in kN, F_p is the penetration force in kN. It is measured by using a penetrometer. F_g is the gravitational force in kN presented in Eq. 3.

$$F_g = \rho_w\, g\, V \qquad \text{(Eq. 3)}$$

where, V is the soil volume cutting by tine in m³. Figure 3 specifies the shape of swept volume. For T1 and T2 the shape of the soil profile is equal to a triangle-based pyramid (Figure 3 A), while it is equal to a trapezoidal-based pyramid (Figure 3 B) for T3 and T4. Therefore, the swept volume is calculated by Eq. 4.

$$V = \tfrac{1}{3}\,(A_1 \times R) \qquad \text{(Eq. 4)}$$

A_1 is the area of the furrow; it is measured by laser scanner and calculated according to Eq. 5.

$$A_1 = \sum_{i=1}^{n} f(x_i)\ \Delta x \qquad \text{(Eq. 5)}$$

where, $\Delta x = (x_2 - x_1) / n$, with $x_1 \le x_i \le x_2$ is the interval and n is the subinterval. R is the rupture distance in m and calculated by using Eq. 6 as proposed by (McKyes and Ali 1977).

$$R = d \times (\cot \alpha + \cot \beta) \qquad \text{(Eq. 6)}$$

where, α is the rake angle in °, it is equal to 45° for the standard tine (Desbiolles et al. 1997). β is the angle of soil failure in °, which is obtained from passive earth pressure theory as given in Eq. 7.

$$\beta = 45 - (\phi / 2) \qquad \text{(Eq. 7)}$$

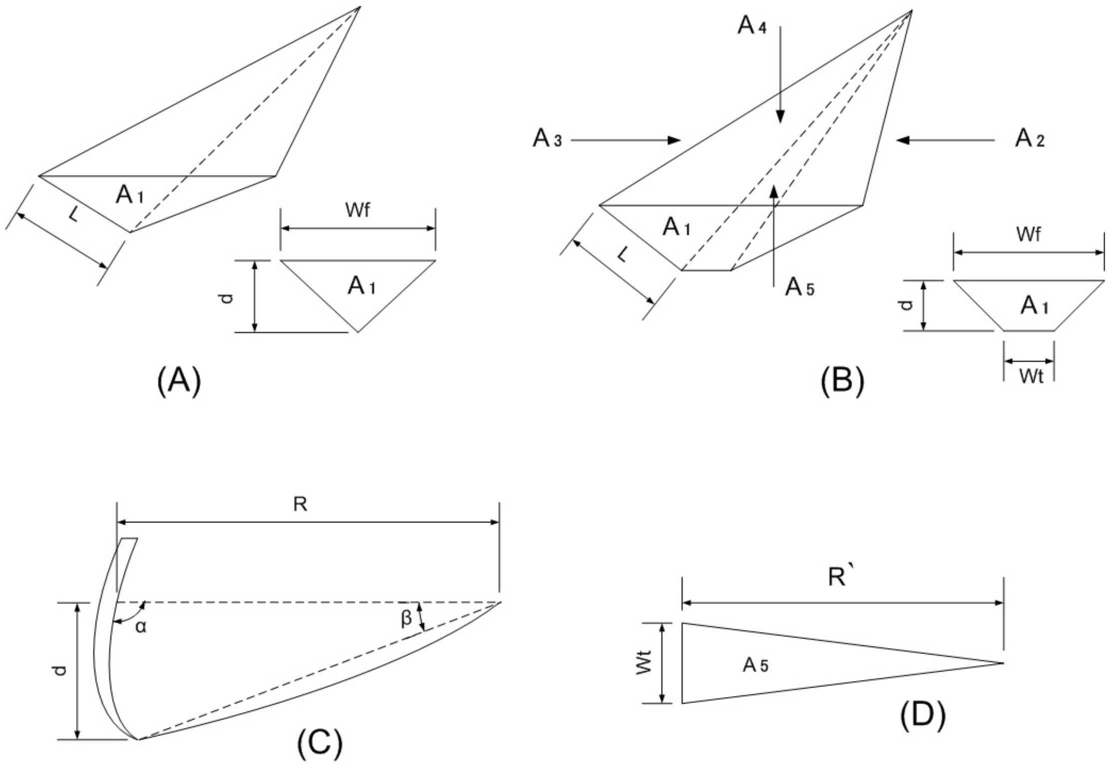

Figure 3: Cross section of soil profiles A) triangle-based pyramid B) trapezoidal-based pyramid C) side view D) the base of the trapezoidal-based pyramid: where, **R** is the rupture distance, $\mathbf{W_f}$ is the furrow width, $\mathbf{W_t}$ is the tine width, **d** is the working depth, **L** is the length of the side of the furrow, **R`** is the altitude of the based area, α is the rake angle, β is the soil failure angle, A_1 is the furrow area, A_2 and A_3 are the sides area of the soil profile, A_4 is the top area of the soil profile and A_5 is the base area of the soil profile (trapezoidal-based pyramid)

F_i is the inertial force in kN and calculated according to Eq. 8.

$$F_i = \rho_w S^2 A_1 \qquad \text{(Eq. 8)}$$

F_c is the cohesion force in kN and calculated according to Eq. 9 and 10 for T1, T2 and T3, T4, respectively.

$$F_c = C \times A_1 + 2 \times C \times A_2 \qquad \text{(Eq. 9)}$$

$$F_c = C \times A_1 + 2 \times C \times A_2 + C \times A_5 \qquad \text{(Eq. 10)}$$

where, A_2 is the side area of the soil profile (note $A_2 = A_3$) and equal to ½ ($L \times R$), L is equal to $\sqrt{d^2 + (\frac{wf}{2})^2}$ for T1 and T2, while it is equal to $\sqrt{d^2 + (\frac{wf - Wt}{2})^2}$ for T3 and T4. A_5 is the base area of the soil profile and equal to ½ ($w_t \times R`$), by $R`$ is equal to $\sqrt{R^2 + d^2}$ (Figure 3 D).

Results

In order to verify the validity of the model, the measured values of F_d at different speeds and depths obtained from the soil bin are plotted versus the predicted F_d values in Figure 4. As shown in Figure 4 there is a good correlation between the measured and predicted values of F_d for all tested tines. The slopes of the best fit line (linear regression with intercept = 0) were 0.99, 1.07, 1.12 and 1.13 for T1, T2, T4 and T3, respectively, with average absolute variations of 2.8 %, 10.4 %, 11.5 % and 13.8 % for T1, T2, T4 and T3, respectively.

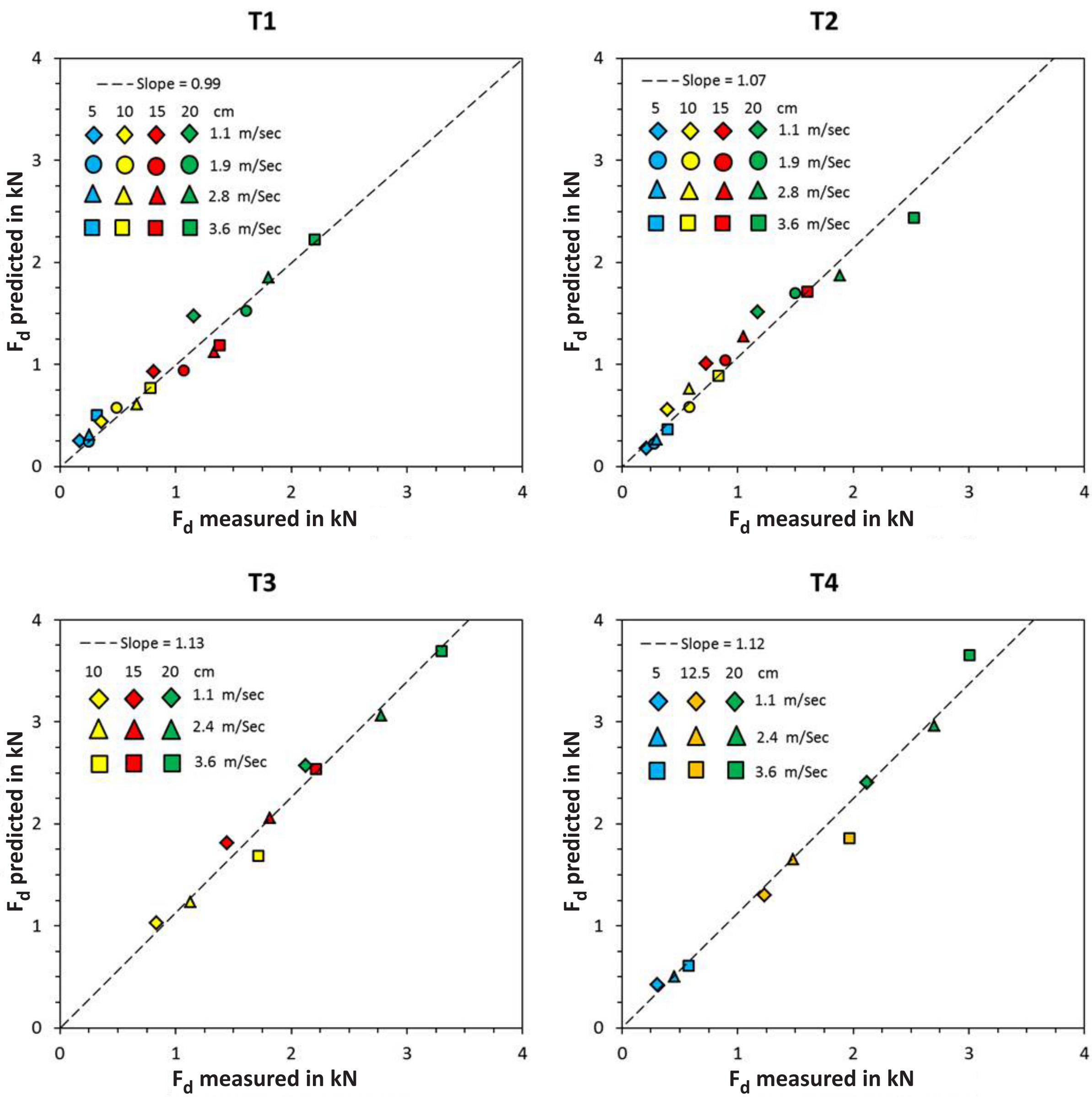

Figure 4: Correlation between measured F_d and predicted F_d for all measured tines in soil bin

Conclusions

The empirical model for prediction draft force acting on varying standard single tines based on principles of soil mechanics and soil profile evaluation was verified. An average absolute variation of less than 15% between measured and predicted F_d values of all measured tines tested in a soil bin filled with a sandy loam soil could be determined.

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