The relationship between draft force and horizontal force acting on passive tillage tool in term of soil-tool interaction. A review

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Abstract
This paper presents a review of the relationship between draft force and horizontal force acting on passive tillage tool in term of soil-tool interaction. Scientifically, the horizontal force is one of the draft force components, but sometimes in the literature refers to the horizontal as the draft force. This difference needs clarifying.

Keywords: Draft force; horizontal force; passive tillage tool; soil-tool interaction

Nomenclature

| Symbol | Description |
|--------|-------------|
| c      | Soil cohesion |
| c_a    | Soil adhesion |
| d      | Depth |
| d_c    | Critical depth |
| F_d    | Draft force |
| F_f    | Friction force |
| F_f_h  | Horizontal component of friction force |
| F_f_v  | Vertical component of friction force |
| F_h    | Horizontal force |
| F_l    | Lateral force |
| F_n    | Normal force |
| F_n_h  | Horizontal component of normal force |
| F_n_v  | Vertical component of normal force |
| F_v    | Vertical force |
| F_t    | Total force |
| g      | Acceleration of gravity |
| kN     | Kilo newton |
| N_a    | Dimensionless factor denote the soil inertia |
| N_c    | Dimensionless factor denote the cohesiveness |
| N_d    | Dimensionless factor denote the adhesiveness |
| N_d_d  | Dimensionless factor denote the surcharge pressure |
| q      | Surcharge pressure |
| s      | Second |
| w      | Width of tine |
| w_c    | Critical width |
| v      | Speed |
| α      | Rake angle |
| α_c    | Critical rake angle |
| ρ      | Soil bulk density |
| δ      | Soil-metal friction angle |
| δ      | Degree (angle) |

1. Introduction

Tillage operations are always described by finding the best compromise between effort and result by matching of mechanical interaction with the soil with fuel consumption and greenhouse gas emissions. As a result, numerous technique for reducing and predicting the amount of the draft force have been applied such as: Dimensional analysis [1-3], Analytical models [4-11], regression technique [12-16], and numerical model for instance finite element method (FEM) or distinct element method (DEM) [17-20].

Sometimes in the literature refers to the horizontal force ($F_h$) as the draft force ($F_d$) (see table 1). From this table, it can be seen that the other literature refers to $F_d$ as the total force ($F_t$).

The main aim of this paper is to provide a comprehensive understanding of the relationship between draft force and horizontal force acting on tillage tine in term of soil-tool interaction, as well as the standardization of terminology used in the field of agricultural engineering.
Table 1. References vary in which force terms they include. Where: $F_h$ is the horizontal force, $F_v$ is the vertical force, $F_d$ is the draft force and $F_t$ is the total force.

| Reference | $F_h$ | $F_v$ | $F_h$ as $F_d$ | $F_d$ as $F_t$ |
|-----------|-------|-------|----------------|----------------|
| [21]      | ✓     | ✓     | ✓              | ✓              |
| [22]      | ✓     | ✓     | ✓              | ✓              |
| [23]      | ✓     | ✓     | ✓              | ✓              |
| [24]      | ✓     | ✓     | ✓              | ✓              |
| [25]      | ✓     | ✓     | ✓              | ✓              |
| [26]      | ✓     | ✓     | ✓              | ✓              |
| [27]      | ✓     | ✓     | ✓              | ✓              |
| [28]      | ✓     | ✓     | ✓              | ✓              |
| [7]       | ✓     | ✓     | ✓              | ✓              |
| [29]      | ✓     | ✓     | ✓              | ✓              |
| [30]      | ✓     | ✓     | ✓              | ✓              |
| [6]       | ✓     | ✓     | ✓              | ✓              |
| [31]      | ✓     | ✓     | ✓              | ✓              |
| [32]      | ✓     | ✓     | ✓              | ✓              |
| [33]      | ✓     | ✓     | ✓              | ✓              |
| [34]      | ✓     | ✓     | ✓              | ✓              |
| [35]      | ✓     | ✓     | ✓              | ✓              |
| [9]       | ✓     | ✓     | ✓              | ✓              |
| [36]      | ✓     | ✓     | ✓              | ✓              |
| [16]      | ✓     | ✓     | ✓              | ✓              |
| [37]      | ✓     | ✓     | ✓              | ✓              |
| [38]      | ✓     | ✓     | ✓              | ✓              |
| [39]      | ✓     | ✓     | ✓              | ✓              |
| [40]      | ✓     | ✓     | ✓              | ✓              |
| [41]      | ✓     | ✓     | ✓              | ✓              |
| [42]      | ✓     | ✓     | ✓              | ✓              |
| [43]      | ✓     | ✓     | ✓              | ✓              |
| [10]      | ✓     | ✓     | ✓              | ✓              |
| [44]      | ✓     | ✓     | ✓              | ✓              |
| [45]      | ✓     | ✓     | ✓              | ✓              |
| [46]      | ✓     | ✓     | ✓              | ✓              |

2. Forces acting on tine tools

To specify the forces acting on simple tillage tools (tine), the analytical model gives the best clue of all forces acting on it, as shown in Eq. [47].

$$F_t = (\rho g d^2 N_r + c d N_c + c_s d N_{cs} + q d N_q + \rho v^2 d N_d) w$$  \hspace{1cm} (1)

Where: $F_t$ is the total force, $\rho$ is the soil bulk density, $g$ is the gravitational acceleration, $d$ is working depth, $c$ is soil cohesion, $c_s$ is soil adhesion at the soil-tool interface, $q$ is the surcharge pressure vertically acting on the soil surface, $v$ is operating speed, $w$ is tool width, and $N_r, N_c, N_{cs}, N_q,$ and $N_d$ are dimensionless factors denoting the gravitational, cohesive, adhesive, surcharge, and soil inertia component, respectively.

The total force $F_t$ (passive force, soil cutting force) is the sum of gravitational, cohesive, adhesive, surcharge forces and inertial forces. The $F_t$ is composed two components, which can simply be obtained by basic mathematics as given in Eq. (1) and (2) in the coordinate system.
\[ F_h = F_t \sin(\alpha + \delta) + c_d \Delta w \cot \alpha \]  
(2)

\[ F_v = F_t \cos(\alpha + \delta) - c_d \Delta w \]  
(3)

Where: \( F_v \) is the vertical force, \( \alpha \) is the rake angle, and \( \delta \) is the soil-metal friction angle. From a practical point of view, normal force \( F_n \) and friction force \( F_f \) are exerted with soil-tool interaction, perpendicularly and tangentially on the tine, respectively [48]. Logically both \( F_n \) and \( F_f \) are composed two parts; \( F_{n_h} \) and \( F_{f_h} \) are the horizontal coordinate components, \( F_{n_v} \) and \( F_{f_v} \) are the vertical coordinate components.

3. Exceptional cases

This section reviews exceptional cases that \( F_v \) magnitude can be neglected, leads to \( F_h \) is equal to \( F_d \) [49]. \( F_h \) is defined as a required force that need to push or to pull the tillage tool through the soil in the direction of travel, while \( F_v \) is defined as a required force that need to penetrate the tillage tool into the soil, meanwhile \( F_l \) is the lateral force (see Figure 1). But practically, needs to overcome all active forces to draw or to push the tool through the soil. According to \( F_h \) definition, it can be said that \( F_h \) equal to \( F_d \) in some of the literature reviews (see table 1).

\[ \alpha \] displayed the effect of rake angle on \( F_h \) (solid line) and \( F_v \) (broken line) , quoted from [50]. From this figure it can be see that the critical rake angle \( \alpha_c \) where the \( F_v \) magnitude changed its trend from upward to downward (\( \alpha_c = 67.5^\circ \)). Therefore, in this case it can be said that the \( F_h \) equal to the total force (\( F_t \)) or the draft force (\( F_d \)). However, at the \( \alpha_c \) the magnitude of \( F_h \) is higher than the \( \alpha \) equal to 22.5 (see Figure 2).

![Figure 1. Forces acting on the single tine in the Cartesian Coordinates.](image1)

In addition, when the magnitude of \( (\alpha + \delta) \) is equal to 90° (see Eq. ()), then \( F_v \) is equal to zero and \( F_h \) is equal to \( F_t \) (in an adhesion less soil).

[7] displayed the effect of rake angle on \( F_h \) (solid line) and \( F_v \) (broken line) , quoted from [50]. From this figure it can be see that the critical rake angle \( \alpha_c \) where the \( F_v \) magnitude changed its trend from upward to downward (\( \alpha_c = 67.5^\circ \)). Therefore, in this case it can be said that the \( F_h \) equal to the total force (\( F_t \)) or the draft force (\( F_d \)). However, at the \( \alpha_c \) the magnitude of \( F_h \) is higher than the \( \alpha \) equal to 22.5 (see Figure 2).

![Figure 2. Effect of tool rake angle on horizontal (solid) and vertical (broken) forces.](image2)
Numerous studies have been addressed the effect of speed, depth, and tine width on $F_h$ and $F_v$, but, are not specify the critical speed ($v_c$), critical depth ($d_c$), and the critical width ($w_c$) that leads to the $F_v$ magnitude can be neglected. Soil texture is one of the significant parameters highly effected not only on the soil physical properties such as soil water content and soil water infiltration [51], [52], but also on the $F_h$ and $F_v$ magnitude. However, few studies have addressed this issue. Scientifically, the tine can be easily penetrating in the light soil (sandy or silty with very little clay content) than the heavy soil. Therefore, $F_v$ magnitude is very small can be neglected at the light soil.

**Conclusions**

Scientifically, the horizontal force is equal to the draft force when the magnitude of the vertical force very small can be neglected or equal to the zero. This can only be achieved at a critical rake angle, when the $F_v$ magnitude changed its trend from upward to downward at the $\alpha_c = 67.5^\circ$. It needs to know the critical value of speed, depth and width, which leads to neglect the amount of vertical force.

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