Soil & Tillage Research 161 (2016) 129–134

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Development and evaluation of a draft force calculator for moldboard plow using the laws of classical mechanics

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ARTICLE INFO

Article history:
Received 10 February 2016
Received in revised form 3 April 2016
Accepted 4 April 2016

Keywords:
Soil cutting
Soil displacement
Soil-metal friction
Draft force prediction
Classical mechanics laws

ABSTRACT

The moldboard plow is the most common primary tillage implement in the world; therefore, it is valuable to consider this plow from an engineering viewpoint. Since the required draft force and power are among the most important engineering specifications of a moldboard plow, in this paper, a model was developed to calculate them. In this model, the effect of soil cutting, soil displacement, and soil-metal friction on the plow specific draft was considered. Soil parameters, plow parameters, and working condition parameters were considered as the model inputs. To simplify the required calculations, the derived equations were entered in the Excel software, and the finalized spreadsheet was utilized as the moldboard plow draft force and power calculator. To verify the model, comparison of the model outputs with the corresponding results of other studies was carried out. Furthermore, the output of the model and the measured draft force of plowing on a silty clay loam soil was compared. According to the results of this study, the developed model produced acceptable specific draft forces that were within the overall range of the moldboard plow specific draft. Furthermore, draft force and power requirements of a three-bottom moldboard plow working on a silty clay loam soil with the forward velocity of 7 km h^{-1} were 17.9 kN, and 34.8 kW, respectively, that were about 8% higher than the results obtained by the developed model (16.64 kN, and 32.28 kW). Therefore, the developed model can be used to calculate the draft force and power of the moldboard plow with reasonable accuracy.

1. Introduction

In many parts of the world, farmers apply conventional tillage practices to prepare soil for planting, and moldboard plow is the most common primary tillage tool in order to conduct these practices (McKyes, 1985; Srivastava et al., 2006). Therefore, it is valuable to consider this plow from an engineering viewpoint. On the other hand, draft force and power requirements of a machine are important engineering specifications; therefore, researchers have been trying to develop techniques for measuring, predicting, or calculating the draft force and power of a moldboard plow (Hettiaratchi et al., 1966; Karmakar and Kushwaha, 2006; Bentaher et al., 2008; Shmulevich, 2010; Okayasu et al., 2012).

Fabrication of drawbar and three-point-hitch dynamometers has been the response of researchers to increasing demands for measuring the plow draft force and power (Zoerb et al., 1983; Godwin et al., 1993; Chen et al., 2007; Formato et al., 2005; Reid et al., 1985; Chaplin et al., 1987; Al-Jalil et al., 2001; Kasisira and du Plessis, 2006). Furthermore, development of the empirical equations to predict the draft force and power of a moldboard plow was examined in some studies (Askari and Khalifahamzeh-ghasem, 2013; Rashidi et al., 2013; Ranjbar et al., 2013). The outputs of these equations are an estimation of the required force and power, therefore, these equations mostly utilized by farmers. Finally, some researchers focused on the calculation of the draft force and power of a plow. In this discipline they utilized different methods such as artificial neural networks (ANNs) (Saleh and Aly, 2013), finite element method (FEM) (Bentaher et al., 2013), or development of classical models based on the laws of pure mechanics (Hettiaratchi and Reece, 1967; Godwin and Spoor, 1977; Grisso et al., 1980). One of the advantages of model development for the calculation of the required draft force and power of a plow is that the developed models could be used for both research and academic purposes.

In this paper, a model was developed to calculate the moldboard plow specific draft force. In this model, the effect of soil cutting, soil displacement, and soil-metal friction on the plow specific draft was considered. Soil parameters, plow parameters, and working condition parameters were considered as the model inputs. To simplify the required calculations, the derived equations were entered in Excel software, and the finalized spreadsheet was

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http://dx.doi.org/10.1016/j.still.2016.04.003
0167-1987/

Nomenclature

$(\pi/4-\varphi/2)$	Angle of soil failure plane with horizon (rad)
b	Working width of a plow bottom (m)
c	Soil cohesion (Pa)
d	Working depth of a plow bottom (m)
DP	Required power of a plow bottom (kW)
DPR	Power requirement of the plow (kW)
M	Mass of a plow bottom (kg)
N	Number of plow bottoms
P	Draft force of the moldboard plow (kN)
P_c	Draft force due to the soil cutting (N)
P_{dx}	X-component of force due to the soil displacement (N)
P_{dy}	Y-component of force due to the soil displacement (N)
P_f	Draft force due to the soil-metal friction (N)
P_s	Specific draft of the moldboard plow (N/cm^2)
P_u	Draft force of a plow bottom (N)
v	Forward velocity (m/s)
W	Weight of the soil wedge (N)
δ	Angle of soil-metal friction (rad)
θ	Moldboard tail angle (rad)
$\mu=\tan(\delta)$	Coefficient of soil-metal friction
ρ	Soil bulk density (kg/m^3)
φ	Angle of soil internal friction (rad)

utilized as the moldboard plow draft force and power calculator. To verify the model, comparison of the model outputs with the corresponding results of the ASAE Standard D497.4, as well as the results of Srivastava et al. (2006) and Hendrick (1988) was carried out. Furthermore, the output of the model and the measured draft force of plowing a silty clay loam soil was compared.

2. Material and methods

2.1. Development of a model to calculate the moldboard plow draft force

To develop a draft force calculating model, it is hypothesized that three processes are involved to create the plow draft, namely, soil cutting, soil displacement, and soil-metal friction.

2.1.1. Draft force due to the soil cutting (P_c)

To produce this part of the model, the soil failure plane is considered as a flat plate located precisely in front of the plow. On the other hand, since the process of soil failure due to the motion of a plow is a passive soil failure process, the angle of the failure plane with the horizontal plane equals to $(\frac{\pi}{4}-\frac{\varphi}{2})$, where φ is the angle of soil internal friction (McKyes, 1985). Furthermore, the volume of the cut soil is the volume of a wedge located above the soil failure plane, and with the same width and depth as the working width (b) and depth (d) of the plow (Fig. 1a). Three forces are involved in the process of soil cutting, namely, draft force due to the soil cutting (P_c), the weight of the soil wedge (W), and shearing resistance of the soil (R) (Fig. 1b). Soil fails when algebraic sum of the components of P_c and W which are parallel to the failure plane (i.e. $P_c\cos(\frac{\pi}{4}-\frac{\varphi}{2})$and $W\sin(\frac{\pi}{4}-\frac{\varphi}{2})$) equals to the soil shearing resistance R (Fig. 1c). In mathematical terms, at the instant of soil failure, the following equation must be satisfied:

$$P_c\cos\left(\frac{\pi}{4}-\frac{\varphi}{2}\right)-W\sin\left(\frac{\pi}{4}-\frac{\varphi}{2}\right)=R \quad (1)$$

On the other hand, mathematical formulas to calculate the weight of the soil wedge (W), and the soil shearing resistance (R) are as follows:

$$W=\rho g V_{\text{wedge}}=\rho g b A_{\text{triangle}}=\rho g b\frac{d^2}{2\tan(\frac{\pi}{4}-\frac{\varphi}{2})} \quad (2)$$

$$R=cA+F\tan\varphi \quad (3)$$

where c is the soil cohesion, A is the area of the soil failure plane, and F is the algebraic sum of the components of P_c and W which are perpendicular to the soil failure plane (i.e. $P_c\sin(\frac{\pi}{4}-\frac{\varphi}{2})$ and

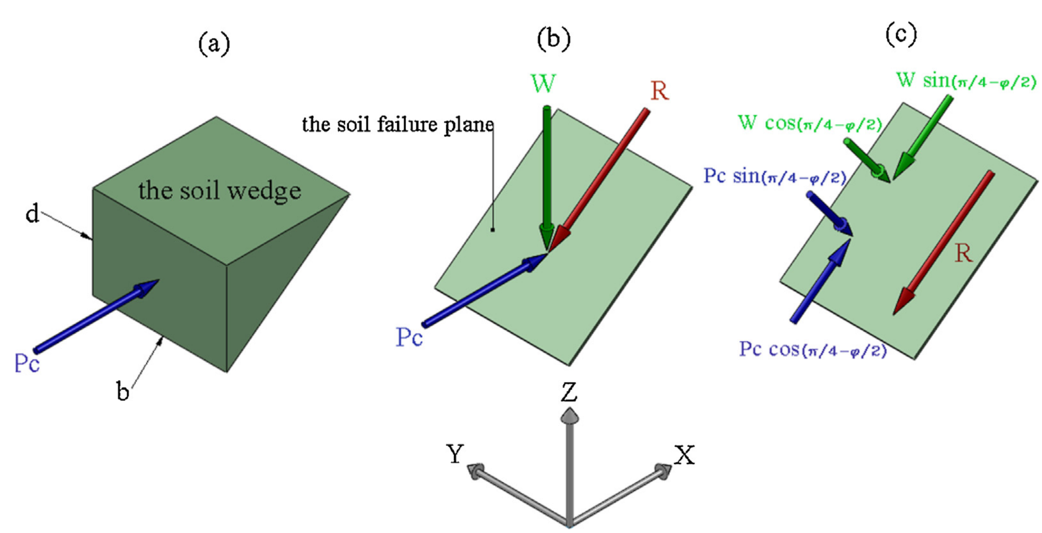

Fig. 1. (a) 3D representation of the soil wedge located above the inclined soil failure plane and subjected to the draft force due to the soil cutting (the blue-colored arrow P_c), (b) three forces applied to the soil wedge, i.e. draft force due to the soil cutting (the blue-colored arrow P_c), the weight of the soil wedge (the green-colored arrow W), and shearing resistance of the soil, (the red-colored arrow R) (c) the same figure as Fig. 1b, where forces P_c and W were resolved into components which are parallel and perpendicular to the failure plane (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).