BIOSYSTEMS ENGINEERING 171 (2018) 52–62

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

A draught force estimator for disc harrow using the laws of classical soil mechanics

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ARTICLE INFO

Article history:
Received 28 December 2017
Received in revised form
6 March 2018
Accepted 16 April 2018

Keywords:
Disc harrow
Draught force
Rolling resistance
Clod break up
Analytical models

The disc harrow is a tillage implement that can be used to perform both the conventional and conservation tillage practices; therefore, it is important to have an accurate understanding of draught force and power requirements of it. The main objective of this study was to develop and validate a theoretical equation for the estimation of draught force of a disc harrow in a range of tillage practices and configurations. The model considers soil cutting, clod break up, soil displacement, and disc blade rolling resistance processes. According to the results of this study, in all cases of operation of a tandem and an offset disc harrow, the output values of the estimator were within the acceptable range obtained from the ASAE standard. In addition, the error of the estimator in predicting experimental data obtained from various published sources was lower than 20%. Finally, measured draught forces of a 28-blade tandem disc harrow on a silty clay loam soil varied in the range of 14 kN to 42 kN for primary, and 15 kN to 20 kN for secondary disc harrowing. In addition, errors of the estimator to predict the experimental data obtained in this study for primary and secondary disc harrowing were lower than 8%, and 6%, respectively. Therefore, the overall conclusion of the present study is that the developed estimator will be able to predict the draught force requirements of a disc harrow.

1. Introduction

A disc harrow consists of one, two or four gangs of disc blades. All of the blades of a disc gang are installed on a common shaft with a spacer spool separating them from each other (Fig. 1). Although the working elements of both disc harrow and plough are disc blades, each blade of a disc plough has its own supporting bearing; while, as just mentioned, the supporting element of the blades of a disc gang is their common shaft. Therefore, blade angles of a disc plough can be adjusted independently while it is not the case for the blades of a disc harrow.

Disc harrows can be used for conducting conventional tillage practices (Kheiralla, Yahya, Zohadie, & Ishak, 2004), as well as conservation and reduced tillage operations (Kepner, Bainer, & Barger, 1982). Therefore, it is important to have an accurate view about the draught force and power requirements of them. In this regard, the majority of previous studies was based on the measurement of the draught force of disc harrows, which were either performed in a field (Kheiralla et al., 2004; Kogut, Sergiel, & Zurek, 2016), or were carried out in a soil bin using a single disc blade (Nalavade, Salokhe, Niyamapa, & Soni, 2010; Sahu & Raheman, 2006). Moreover, the analytical methods for draught prediction attracted the

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https://doi.org/10.1016/j.biosystemseng.2018.04.008

Nomenclature

c	Soil cohesion (kPa)
cc	Clod cohesion (kPa)
CP	Clod coverage percentage (%)
dA	Area of the elemental failure plane (mm^2)
db	Width of the elemental soil wedge (mm)
dF	Normal force exerted on the elemental failure plane (N)
DP	Drawbar power (kW)
dR	Shearing resistance of the elemental failure plane (N)
dW	Weight of the elemental soil wedge (N)
F_{cb}	Draught force due to clod break up process (N)
F_{rr}	Draught force due to rolling resistance (N)
F_{sc}	Draught force due to soil cutting (N)
F_{sdx}	X-component of force due to soil displacement (N)
F_{sdy}	Y-component of force due to soil displacement (N)
M	Mass of a disc + frame (kg)
Nb	Number of disc blades per gang
OP	Overlap percentage of blades (width ways) (%)
Pu	Total draught force (N)
R	Radius of a disc blade (mm)
v	Forward velocity (km h^{-1})
ξ	An angle formed between the reference radius and the rotating radius for calculating F_{sc} using a single integration (rad)
z	Depth of the elemental soil wedge (mm)
z_m	Maximum working depth of a disc blade (mm)
α	Rake angle (rad)
η	Angle of soil displacement in horizontal plane (rad)
ρ_{soil}	Soil bulk density (kg m^{-3})
θ_d	Disc angle (rad)
θ_g	Disc gang angle (rad)
φ	Angle of soil internal friction (rad)

attention of some other researchers (Ahmadi, 2016; Godwin & O'Dogherty, 2007; Swick & Perumpral, 1988). The analytical equations developed in these theoretical studies were based on the consideration of a single disc blade; moreover, the primary concern of these equations was the prediction of the draught force of a disc plough instead of a disc harrow.

The aim of this study is to develop an equation for the estimation of draught force requirement of a disc harrow based on the hypothesised processes considered for its operation. Furthermore, this equation will cover the draught force needs of a range of arrangements of disc gangs of the machine (i.e. tandem, single acting, offset, and one-way arrangements). Validation of the draught equation was undertaken against the ASAE standard formula as well as past field tests by earlier researchers. In addition, an experimental test was conducted in this study and the obtained results were compared with the outputs of the estimator.

2. Development of draught force estimator

2.1. *Factors affecting the draught force of a disc blade*

2.1.1. *Soil cutting process*

Soil cutting refers to the separation of the machine-affected soil from the bulk soil in the operation performed by the primary tillage implements. Because there is a partial resemblance between the blades of a disc plough and a disc harrow, the same procedure as reported by Ahmadi (2016) is used here in order to compute the draught force of a disc blade due to the soil cutting process (F_{sc}). Therefore, the considered procedure is discussed here briefly. To estimate the draught force due to the soil cutting process, the blade-soil contact area is divided into a series of elemental areas, which vary in depth (Fig. 2a). It is hypothesised that the shape of the cut soil in front of each elemental area is a slender soil wedge called an elemental soil wedge. Furthermore, it is assumed that each elemental soil wedge is positioned in the direction of the harrow forward motion, i.e. the base of each elemental soil wedge forms an angle equal to the disc angle (θ_d) with its corresponding elemental area. By integrating the force used to cut the elemental soil wedge (dF_{sc}), the draught force due to the soil cutting process (F_{sc}) will be calculated. On the other hand, since the soil failure by a disc blade is the passive soil failure, the angle of the failure plane with the horizontal plane equals to ($\pi/4 - \varphi/2$) (McKyes, 1985). To estimate the elemental cutting force of a blade using the force equilibrium of the elemental soil wedge (Fig. 2b), Eq. (1) should be satisfied:

$$dF_{sc}\cos\left(\frac{\pi}{4}-\frac{\varphi}{2}\right) - dW\sin\left(\frac{\pi}{4}-\frac{\varphi}{2}\right) = dR \quad (1)$$

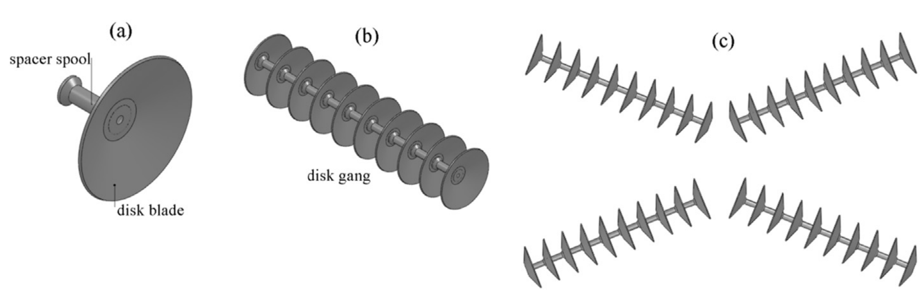

Fig. 1 – Components of a disc harrow a) a disc blade and a spacer spool b) a disc gang, c) top view of a complete tandem disc harrow.