Prediction of Soil Forces Acting on Mouldboard Ploughs

C. Saunders, R.J. Godwin, M.J. O'Dogherty

Cranfield University, Silsoe, Bedfordshire MK45 4DT. c.saunders@cranfield.ac.uk

Abstract

The prediction model was developed to predict the horizontal (draught) forces acting upon mouldboard ploughs based on Mohr-coulomb soil properties and inertia effects. The purpose of the model, once validated with experimental results was to optimise the effects of working width, depth, forward speed and number of furrows in terms of time and energy to reduce the cost of tillage operations. The model attempts to calculate the cutting, turning and landside drag forces exerted on a mouldboard assembly. The draught force predictions are compared to mured mouldboard plough forces obtained experimental under known soil conditions, for two widths, two depths and two speeds. The predicted values of draught show a good representation of the measured values ranging from 23% below to 28% above with the overall average of 1%.

1 Introduction

The mouldboard plough is one of the oldest primary tillage implements and remains the only tillage operation with the advantage of total soil inversion, leaving a trash free surface and the burial of any weed seeds. Ploughing accounts for more traction energy than any other field operation (Kepner *et al.*, 1978), for this reason understanding the forces involved with the cutting and the moving of soil by mouldboard ploughs has always been important. Under the current state of the agricultural economy, tillage implements have to be efficient and highly productive.

Understanding the forces, which act upon a mouldboard plough when working at different settings, should assist in enabling the correct configuration of width, depth, speed and number of furrows to be selected to optimise productivity. The objectives of this paper are to develop and evaluate a mathematical model to predict the effects of those variables on the draught force of mouldboard ploughs using basic Mohr-Coulomb soil mechanics properties.

2 Previous work

Much work has been conducted on both measuring the draught forces of ploughs of different shapes and different settings (Rogers and Hawkins, 1956). There have also been several different methods of predicting the forces acting on mouldboard ploughs. Prediction models from (O'Callaghan and McCoy, 1965) and (Gyachev, 1985) used mathematical theory to determine the force of the soil slice on the mouldboard plough, with the former reliant upon a computer algorithm to handle the large number of calculations.

The draught force of mouldboard ploughs was predicted by Seig (1982), adopting the general soil mechanics equations modified by Hettiaratchi *et al.*, (1966) for blades and Godwin and Spoor (1977) for tines. This forms the basis of the prediction model presented in this paper, taking it further to develop the force acting on the mouldboard using the theory of inertia and momentum (Gyachev, 1985) and suggested mouldboard shapes and acceleration forces (Sohne, 1959).

Goryachkin (1968) pioneered studies on the forces acting on the body of a plough; and derived the general formula of resistance to traction and a concept of its components. Oskoui and Witney (1982) adapted the equation by Goryachkin (1968), using cone index data as a measure of soil strength and the effect of the mouldboard tail angle to predict the forces. A quick method of predicting forces was adopted by Desbiolles *et al.*, (1999) that used either cone penetrometer data or a simple narrow tine to predict the draught of tillage implements, including mouldboard ploughs. All these prediction models are compared with varying amounts of experimental data. They are however of insufficient resolution to solve the issues referred to in the objectives of this paper.

3 Development of Force Prediction Model

The prediction of the horizontal forces acting on the mouldboard plough Figure 1 were based on the principle that the total horizontal force acting upon a mouldboard plough body results from 1) cutting and 2) turning a section of soil. In addition to these there is 3) a force resulting from the drag effect on the landside, that results from a friction effect of the side force generated by 1) and 2) as shown in Figure 2. This figure also shows the sub-components and the underlying principles used for their estimation.

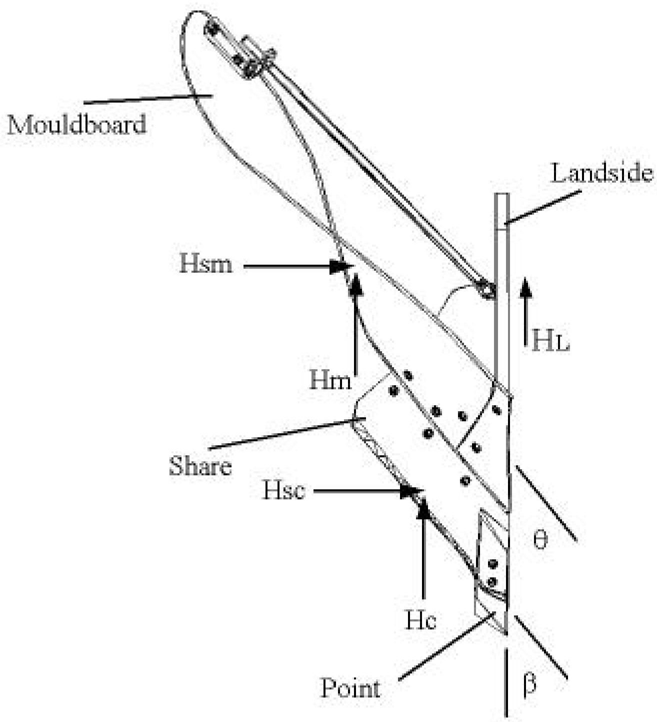

Figure 1. Diagram of the mouldboard forces.

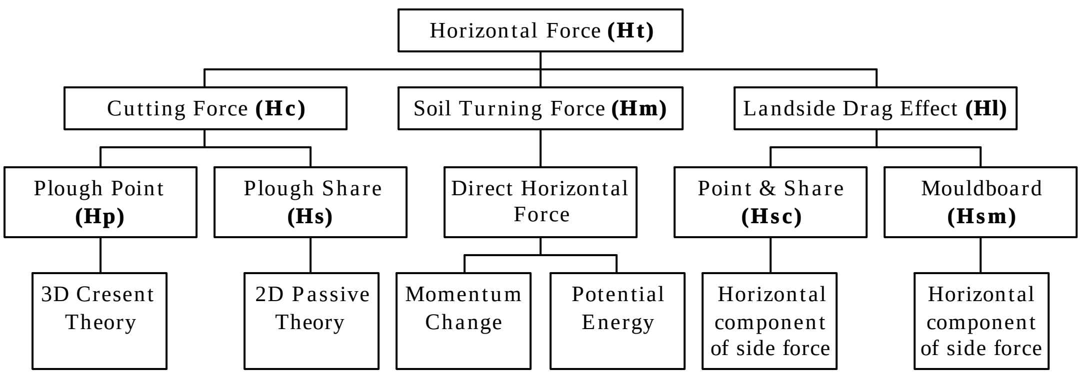

Figure 2. Force components acting on a mouldboard plough.

The cutting, turning and landside drag components can be considered as follows.

3.1 Cutting Force. The prediction methodology for the cutting section was based on the theoretical force prediction models of Godwin *et al.*, (1984) split into the point and the share. This assumes a generated by a 3-dimensional crescent failure about the point and a force from a 2-dimensional passive failure occurring from the share as used by Seig, (1982). A velocity factor was added, based upon the work of McKyes, (1985) as used by Wheeler and Godwin, (1996). The formula used to predict the soil cutting effect of the plough point takes the form.

$$Hp=\left\{\left(\left[gd_P^2N_{gP}+cd_PN_{cP}\right]\left[w_P+d_P\left(m-\frac{1}{3}(m-1)\right)\right]\right)+\left(\left[\frac{gv^2N_a d_P}{g}\right]\left[w_P+0.6d_P\right]\right)\right\}\sin\left(a_P+d\right) \quad \text{……. 1}$$

The formula used to predict the share force is added to complete the cutting section

$$Hs=\left\{\left(\left[gd_W^2N_{gW}+cd_WN_{cW}\right]+\left[\frac{gv^2N_a d_W}{g}\right]\right)w_W\right\}\sin\left(a_W+d\right) \quad \text{……..………………. 2}$$

3.2 Turning and lifting Force. The soil turning can be separated into the energy required to lift, accelerate and move the soil over the shape of the mouldboard, changing its rate of momentum. This can be expressed as potential energy, which is independent of velocity. In addition, the momentum change effect of the soil flowing over the mouldboard is dependent on the velocity; there is also the frictional and adhesive effects of the soil moving over the mouldboard. The angle of the mouldboard θ was considered constant at an angle equivalent to the angle through the centre line of the mouldboard, as shown in Figure 1. The formula for the momentum component of horizontal force acting on the mouldboard is given Equation 3.

$$Hm=\left(\frac{g}{g}\right)\left(\left(w_w+w_p\right)d_p\right)v^2\left((1-\cos q)+\tan d\sin q\cos q^2\right) \quad \text{……………………...… 3}$$

For the purpose of potential energy it is assumed that the soil is lifted half the height of the soil slice depth. This is then dependent on the depth of work of the mouldboard assembly.

$$He=g\left(\left(w_w+w_p\right)d_p\right)\left(0.5d_p\right) \quad \text{……..………………...………………….. 4}$$

3.3 Landside Drag Force. This can be separated into point/share and mouldboard, considering the horizontal force occurring from the frictional component of the side force applied by each of these parts of the plough. The point and the share produce a side force during the cutting of the soil slice, which is transmitted as force through the landside. Additionally, as the mouldboard is turning the soil slice there is a side force involved due to the approach angle of the mouldboard, this is also transmitted to the landside. The combination of these forces creates a frictional resistance due to the interface friction between the plough landside and the soil.

The horizontal force resulting from the landside drag due to the side force generated by the cutting action of the wing is as follows.

$$Hcs=\left[\left\{\left(\left[gd_W^2N_{gW}+cd_WN_{cW}\right]+\left[\frac{gv^2N_a d_W}{g}\right]\right)w_W\right\}\sin\left(a_W+d\right)\right]\left(\cos b\right) \quad \text{……….. 5}$$

Likewise, the horizontal force due to the side force generated from the soil flowing over the mouldboard is given by.

$$Hms = \left(\frac{\gamma}{g}\right)\left(\left(w_w + w_p\right)d_p\right)v^2 \sin \theta \quad \text{……..……..……………..……….. 6}$$

These forces act upon the landside, from which the resistance to direction of travel is generated as a result of the soil/metal friction (δ), this produces the horizontal landside force.

$$Hl = \left(Hcs + Hms\right)\tan \delta \quad \text{…….……..…………………………. 7}$$

3.4 Total Draught Force. The total predicted horizontal force (Ht) is the vector sum of all the individual components as given in equations 1 – 7.

$$Ht = Hp + Hs + Hm + He + Hl \quad \text{………..………………………. 8}$$

The predicted forces from the model were compared to the results of preliminary laboratory studies where the effect of width, depth and speed on the horizontal (draught) forces of a general purpose mouldboard assembly were recorded in controlled soil conditions of known Mohr-Coulomb properties.

Notation

Ht	=	Total Horizontal Force	β	=	Share approach angle
Hp	=	Horizontal Point Force	θ	=	Mouldboard angle
Hs	=	Horizontal Share Force	γ	=	Bulk unit weight
Hm	=	Horizontal Mouldboard Force	c	=	Cohesion
He	=	Force due to Potential Energy	δ	=	Angle of soil/metal friction
Hcs	=	Horizontal Cutting Side Force	ϕ	=	Angle of internal shearing resistance
Hms	=	Horizontal Mouldboard Side Force	m	=	Rupture distance ratio
Hl	=	Horizontal Landside Force	v	=	Velocity
D_p	=	Depth of point	N	=	Dimensionless number *Suffixes*
W_p	=	Width of point			γ = Gravitational
d_W	=	Depth of wing			ca = Cohesive and Adhesive
w_W	=	Width of wing			a = Inertial
α	=	Rake angle			q = Surcharge

4 Experimental Procedure & Equipment

Soil bin studies were conducted to determine the forces acting on a modern general-purpose/semi-digger mouldboard assembly for the width depth and speed combinations shown in Table 1. The assembly consisted of the plough point, a share, a landside and the mouldboard. The tests were carried out under controlled laboratory conditions, in a sandy loam soil of known properties, using the indoor soil bin facility at Cranfield University, Silsoe similar to that reported by (Godwin, *et al.*, 1984). A particle analysis giving 68.1% sand, 22.1% silt and 9.8% clay; this soil can be prepared to a controlled moisture and density to give a repeatable test environment. The plough assembly was fitted to the processor unit via a 2-dimensional extended octagonal ring transducer (Godwin, 1975) used to measure the horizontal force, the vertical force and the resulting moment of the total mouldboard assembly.

Table 1. Width, depth and speed combinations used in the laboratory study.

Width (mm)	Depth (mm)	Speed (km/h)
508	125	4.5
508	225	4.5
508	125	10
508	225	10
355	125	4.5
355	225	4.5
355	125	10
355	225	10

A second and smaller 2-dimensional extended octagonal ring transducer was attached to the back of the mouldboard to measure the horizontal and lateral forces. The lateral mouldboard force was selected because it was expected to have a more significant effect on the landside force as the depth of work increased (Girma, 1989). The mouldboard was held slightly above is normal mounting position so that all its forces were transmitted through the octagonal ring. To enable this to be achieved a mounting bracket was made up to hold the small octagonal ring transducer independently on the plough leg and enable the mouldboard to be located in the correct position. Spacers were added to the other components of the assembly to ensure that all sections lined up and the soil flow was not disturbed. The force transducers were linked to a signal conditioning and data logging unit via strain gauge amplifiers and the forces were recorded at 103 Hz to avoid aliasing errors.

The dry base soil moisture content and bulk unit weight were measured for each laboratory test and the Mohr-Coulomb properties were measured using triaxial apparatus to determine the angle of soil internal shearing resistance (ϕ) and cohesion (c). A sliding frictional plate was used to determine the angle of soil/metal friction (δ) and adhesion (ca). These are summarised in Table 2.

Table 2. Soil physical properties.

Moisture Content (mc)	9.25 %
Bulk Unit Weight (γ)	1.56 kN/m^3
Cohesion (c)	10.54 kN/m^2
Soil internal shearing resistance (ϕ)	30.75°
Soil/metal friction (δ)	24°
Adhesion (ca)	Negligible

5 Discussion of Results

The combinations of width, depth and speed used in the experiments are given in Table 1, the results of the work are presented in Figure 3a, b and c together with predicted values. The least significant difference (l.s.d) at 95% confidence level is also shown for the complete measured data set (0.38kN) for which the coefficient of variation was 7.4%.

Figure 3a, shows the increase in draught force for the total assembly and the mouldboard individually with the increase in working depth. As was expected the draught force increased with the depth of work. This was true for both the measured and the predicted values, with the measured draught increasing by 65% and 95% for the wide-fast and narrow-fast configurations respectively. Depth had the greatest effect overall on the total draught force.

Figure 3b, shows the effect of speed on the draught force of a mouldboard assembly; the draught force increase due to speed had the smallest effect with as little as 7% increase for the narrow-shallow setting, and 26% increase for the wide-shallow configuration.

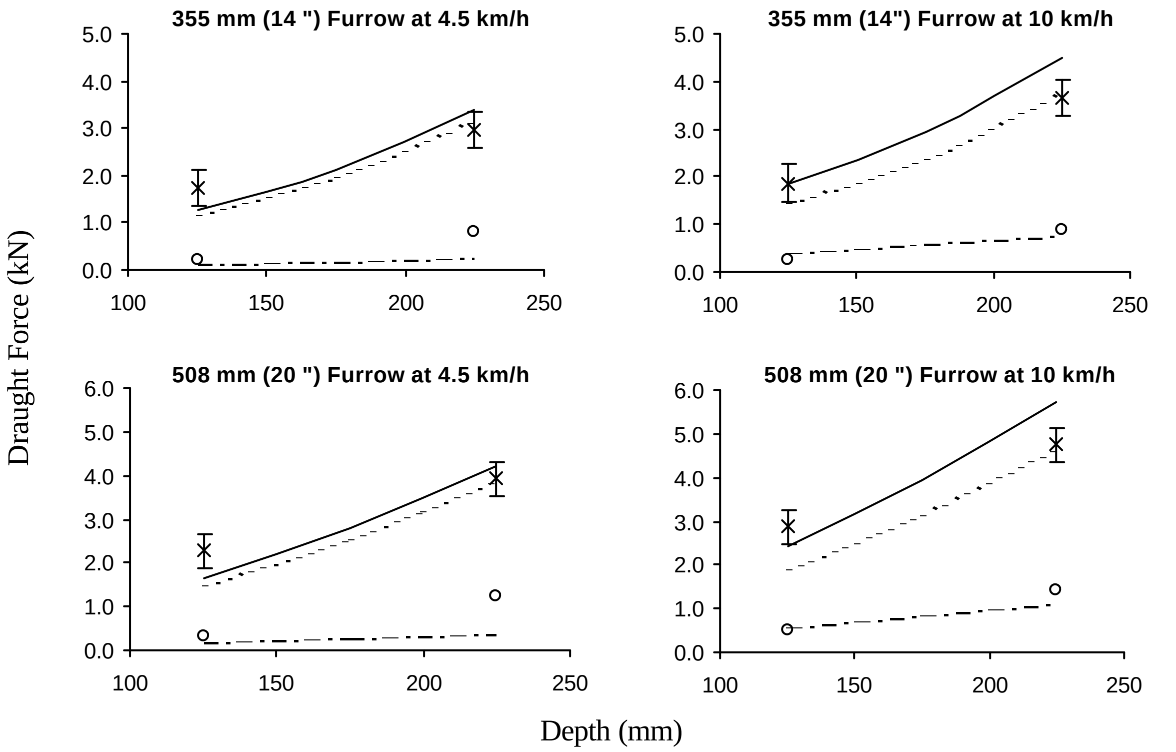

Figure 3a. Comparison of predicted and experimental forces showing the effect of depth for 355mm (14") and 508mm (20") furrow widths.

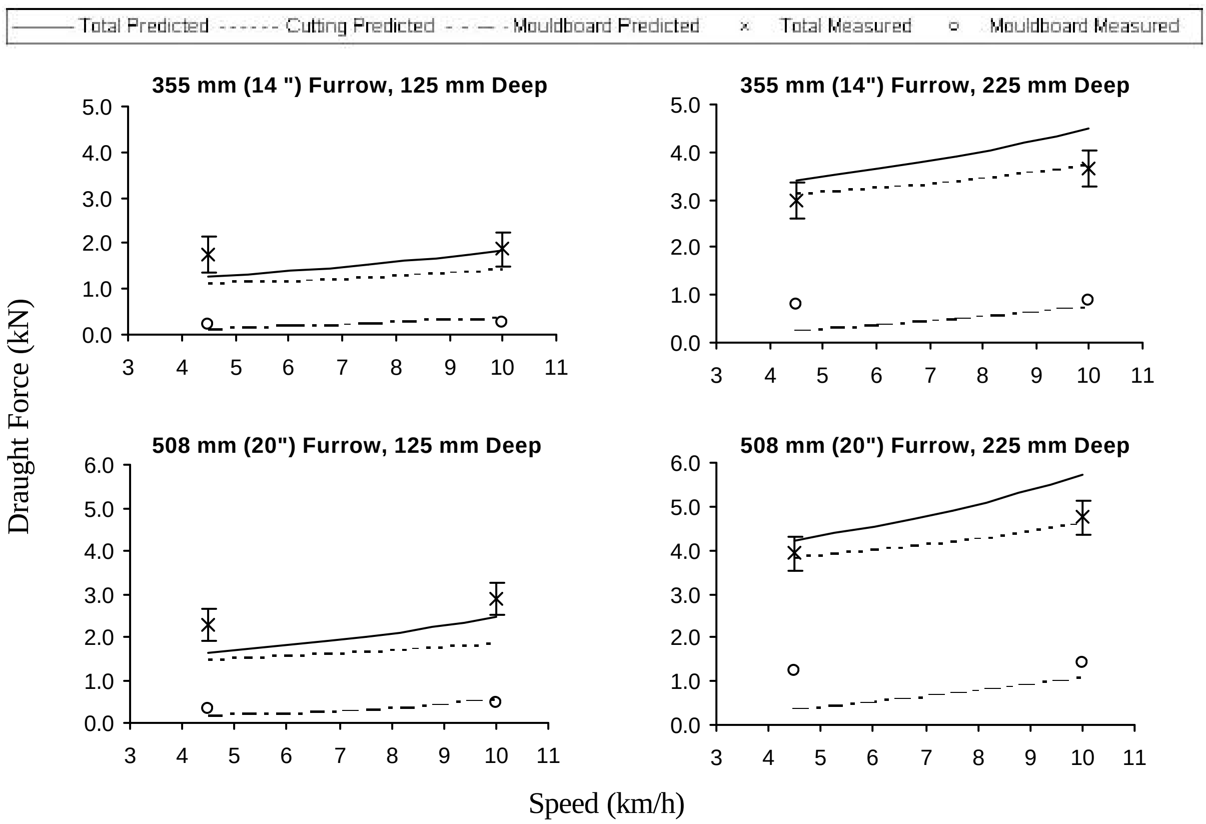

Figure 3b. Comparison of predicted and experimental forces showing the effect of speed for 355mm (14") and 508mm (20") furrow widths.

Figure 3c, shows the measured and predicted values of draught for the change in furrow width. The increase due to width ranged from 23% for the deep fast setting to 30% for the shallow slow configuration. The mouldboard forces ranged from 12% to 30% of the total draught force of the plough assembly.

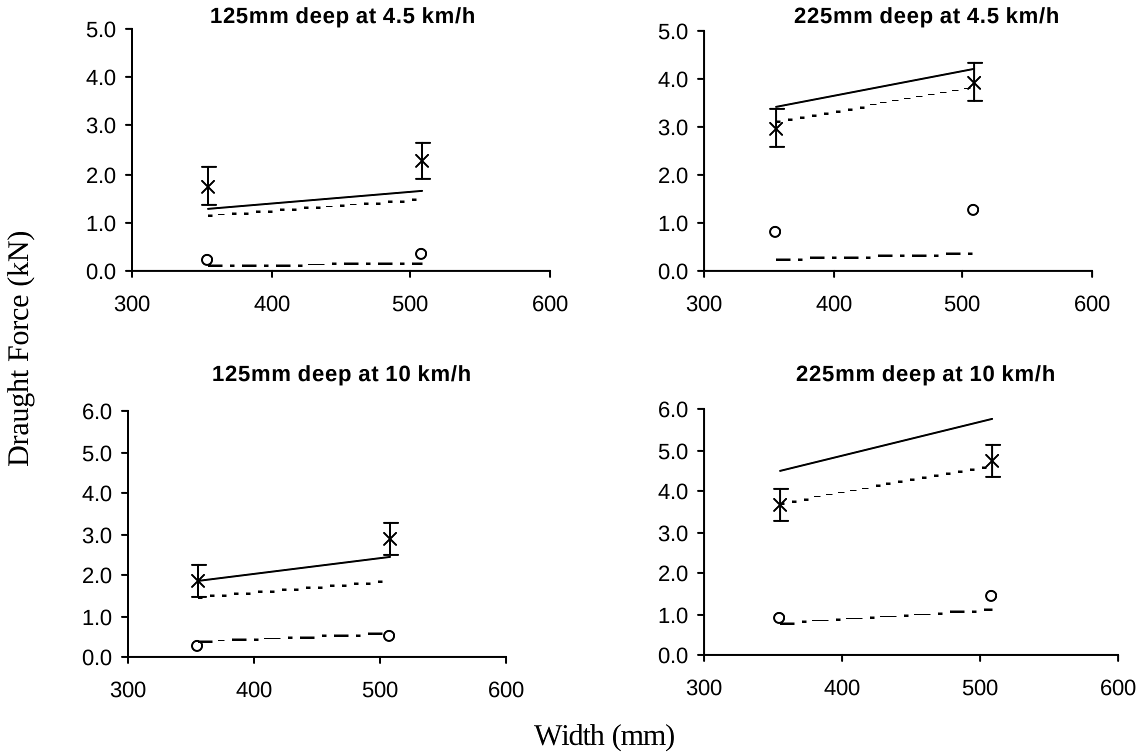

Figure 3c. Comparison of predicted and experimental forces showing the effect of width for two depths and speeds.

Total Predicted ------ Cutting Predicted - - — - Mouldboard Predicted × Total Measured o Mouldboard Measured

The magnitude of the predicted forces shown in Figure 3 reflect the changes in the measured force, with approximately half of the comparisons within the 95% l.s.d value (i.e. 0.38 kN) of the measured data, as shown in Figure 4. The average error of prediction in 1%, however, closer examination of the data shows an over and under prediction of 23% and 28%, for the deep-fast and shallow-slow combinations respectively.

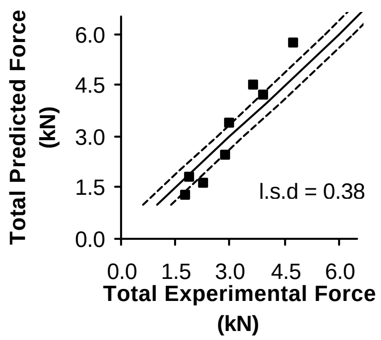

Figure 4. A comparison of experimental and predicted total draught forces.

Ideal relationship (predicted and experimental in agreement) —— ± l.s.d at 95% level

It is recognised that two measured points for each variable is not ideal for comparison and some model re-workings are required to improve accuracy.

6 Conclusion

1. The force prediction based upon Mohr-Coulomb soil theory and inertia effects was developed from the three main fundamental areas of cutting, turning and drag effects; to predict both the total and the mouldboard force acting upon a general-purpose mouldboard assembly.
2. When compared to experimental measurements for a range of working widths, depths and speeds the model predicts total draught force within the range of –28 % and +23 % with an average error of 1%. The model over-predicted values of horizontal force at higher speeds and larger depths, but under-predicted at the lower speeds and shallower depths.
3. Depth had the greatest effect overall on the measured total draught force, increasing by 65% to 95% over the range. The increase due to width was next biggest ranging from 23% to 30% and the draught force increase due to speed was the smallest effect with as little as 7% increase.

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