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Forces on a Model 'Spot Plough'

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Abstract

The draught and the side force exerted on each working component of the model spot plough are discussed. The 150 mm wide model was composed of, principally, the share, main mouldboard, tilted disc coulter, and sub-mouldboard arranged in sequence. The vertical beams supporting each component were equipped with strain gauges and calibrated as force transducers. Soil bin experiments were conducted in wet plastic, dry compact, and dry loose soils at speeds of 0.2-1.3 m/s and at working depths of 50-70 mm. The force exerted on the share was the largest in the dry compact soil and significantly increased with speed. The effect of speed on the force on the main mouldboard and tilted disc coulter was mostly insignificant, suggesting the adaptability of the spot plough to high speed applications. The side force was mostly compensated for between the main mouldboard and tilted disc coulter in wet plastic and dry compact soils, but the redesign of the share or relocation of the tilted disc coulter was suggested for completely balancing the side forces. The force on the sub-mouldboard was negligible as to imply its exclusion from the design.

1. Introduction

'Spot ploughing' is a method of inverting a soil slice within its own furrow. It potentially decreases labour and energy input and facilitates invertible tillage for effective management of residues and weeds in desired paths (precise strip tillage), so that part of the land may be left untilled for enhanced protection of the soil from erosion and compaction. It is therefore designed to overcome shortcomings of conventional mouldboard ploughing while retaining its advantages. Of several designations given to ploughs of similar functions, the term ‘spot plough’ is used here to emphasise the concept of inverting the soil without lateral displacement, with the prospect of limiting the tillage practice to specific spots. The final objective is a practical prototype of the spot plough of as little complexity as possible.

This paper is supplementary to a previous report (Shoji, 2001), where a 150 mm wide model for soil bin experiments is described. The model (*Fig. 1*) is composed essentially of a share, a main mouldboard, a tilted disc coulter, and a sub-mouldboard, of which the tilted disc coulter and the sub-mouldboard are particular to the spot plough. The mouldboards have been fabricated of a plate of polyvinyl chloride, whereas other working components of steel. The degree of inversion, or transfer rate, and the average lateral and forward displacements have been evaluated as indices of the quality of operation; however, the applied force has not yet been reported.

The main purpose of this study, therefore, is to measure the force exerted on each working component, to specify the function and to suggest further improvement of particular working components, so as to facilitate the design of a prototype and to predict the maneuverability of the tractor-implement system. The longitudinal and lateral components of the force, hereinafter called ‘draught’ and ‘side force’, respectively, are discussed with regard to: (1) effect of speed and depth as operating variables, and (2) balance of side force indicating the stable single-unit operation without support of a landside; (3) implications for more simplified structure.

2. Literature review

Some draught measurements of prototypes of spot ploughs have been described, although the number of reports on ploughs of such specific function is small. McKibben (1966) has compared the draught required for his 'strip plough' with that for a conventional mouldboard plough of the equivalent width, demonstrating that the draught requirement for the former is relatively insensitive to the operating speed, and is smaller than that for the latter at speeds higher than 2.2 m/s; however, neither the detailed configuration of the plough bodies nor the experimental procedures have been described. Kawamura *et al.* (1986), measuring the draught of their prototype in a drained paddy field of clay loam, have shown that the total draught at speeds of 0.36-0.76 m/s does not change significantly, but with an increase in speed, the draught increases at the oscillating share and decreases at the rear mouldboards. Sakun *et al.* (1991) and Lobachevsky (1996) have a number of times emphasised the advantage of their 'frontal plough' in terms of the draught or power reduction by 20-30%.

Some measurements of multi-component of the force exerted on a plough have been made. Wang and Kamide (1993) have measured the force on symmetric model spot plough as a whole in a soil bin of sandy clay, where the draught increases slightly at speeds of 0.2-0.5 m/s, the side force is practically cancelled by the symmetry, and the vertical component is less than 20% of the draught. Shoji (1997) has applied the same method of measurement to each individual working component of his model spot plough in a soil bin of sandy clay loam, showing that the major part of the draught is generated at the beginning: at the share, the vertical knife coulter, and the front sub-mouldboards. At speeds of 0.05-0.6 m/s, a slight increase of the total draught is observed, and the total lateral and vertical components are less than 20% of the draught. The speeds set for the both of these studies, however, are still lower than the corresponding operating speed of the prototype achievable with a typical small four-wheel tractor, even if the law of similitude is taken into account.

3. Materials and methods

3.1. *Experimental setup and conditions*

The model spot plough was tested in the soil bin, where the bin was anchored and the plough was mounted on a moving trolley pulled by chains along rails. Three soils (Table 1) were prepared by changing the moisture content and the order of the tillage; the soil was rotary-tilled above the plastic limit and pressed with a roller (wet plastic) and then naturally dried (dry compact), or tilled below the plastic limit and simply pressed (dry loose). In limiting the width-to-depth ratio (Shoji, 2001), the actual depth, or working depth (Section 3.3), was obtained at 50-70 mm. This tentative procedure is based on the experience that the working depth is always greater than the set depth (Section 3.3) and is not completely controllable in wet plastic and dry compact soils (Shoji, 2001). The plough was operated at speeds of 0.2, 0.8, and 1.3 m/s, with the highest speed corresponding to the maximum operating speed of a 360 mm wide field-scale plough pulled by a small four-wheel tractor (about 7-9 km/h, inclusive of slippage), according to the requirements for dimensional analysis (Murphy, 1950). The experimental variables (Table 2) except for the soil conditions were randomised. A few instances of apparent soil blockage were excluded from the observation.

3.2. *Measurement of force and speed*

The draught and the side force of the share, main mouldboard, tilted disc coulter, and sub-mouldboard were measured. The vertical component was not measured because of its relative unimportance; the smaller magnitude of the vertical component is reported (Wang & Kamide, 1993; Shoji, 1997), and the vertical component is affected rather by the sharpness of the share (Nichols *et al.*, 1958), which in practice can be compensated for by minor adjustment of gauge wheel or sliding heel within the hitch system. The individual side force, in contrast, is an important indicator of the inversion of the soil in spot ploughing, since the torsion or rotation of the soil cannot be established unless a couple of forces is applied from several working components of the plough. The sum of the individual side forces also indicates the feasibility of the single unit operation for small-scale equipment, although the location of a line of traction should, strictly speaking, also be considered.

The vertical supporting beam for each working component was converted into a force transducer (*Fig. 1*). Other methods, such as extended octagonal rings, were not considered because of the particularly limited space available for the transducers. The share and the main mouldboard were separated and attached to individual beams, but their clearance was covered with a thin plastic sheet fixed to the share, which overlapped approximately 8 mm with the front edge of the main mouldboard, to prevent the ingress of fine soil particles. This is a compromise procedure with the knowledge that some mutual interference is involved in the sensed forces.

The force was measured by subtracting the bending moments of the beam at two sections from each other. Two pairs of strain gauges were affixed at the front and back of the beam, and a complete bridge circuitry of four gauges was made to detect one component of the force; a total of eight strain gauges were installed on the four vertical surfaces to detect the draught and the side force. The transducers were calibrated with various intensities of the load applied to at least two different points. The coefficients of determination were more than 0.999 at any circuitry, and the calibrated sensitivities are summerised in Table 3. The interference, or output of the other component of the force with respect to that of the principle component, which is attributed mainly to the precision of the strain gauge alignment and to the asymmetric shape of the section of the beam, was not more than 6%.

A 15-revolution rotary potentiometer was installed on one of the axes of the wheels of the trolley to measure its location and to calculate the average speed. All the signals were recorded into a memory-card based signal recorder (TEAC DR-C1) equipped with signal conditioners and amplifiers. The sampling rate was varied so that the signals were recorded at the distance of every 3-4 mm; 50, 200 and 500 Hz were selected from the possible settings provided by the recorder for the speeds of 0.2, 0.8, and 1.3 m/s, respectively. The data of the force were averaged from 600 mm of travel when the speed was steady and all the working components were fully engaged with the soil.

3.3. *Measurement and definition of depth*

The profiles of the soil surface were measured before and after the operation with a laser-beam range finder mounted on an electro-magnetic linear scale (Shoji, 2001). The range finder continuously scanned perpendicular to the traveling direction at the intervals of 100 mm. The ‘set depth’ was taken as the distance between the untilled surface and the edge of the share, whereas the ‘working depth’, or actual depth, was between the untilled surface and the bottom of the furrow.

4. Results and discussion

4.1. *Fluctuation of the draught*

The force exerted on each working component changed constantly as the plough proceeded (*Fig. 2*), even though the signals were recorded after the initial transitional period without any blockage of the soil in the plough. In the wet plastic soil (*Fig. 2a*), the period of the fluctuation was inconsistent or unnoticeable for each working component. The stable draught of the main mouldboard in particular reflected the continuous deformation, inversion, and release of a slice of the soil (Shoji, 2001).

In dry compact soil (*Fig. 2b*), a characteristic period of the draught appeared at the share and the tilted disc coulter. The period corresponded approximately to the length of each soil block of about 100-200 mm formed through one operation. A similar tendency was observed in dry loose soil (*Fig. 2c*); however, the magnitude and the period of the draught were smaller, which was attributed to the loose cohesion between the small soil aggregates. In these dry soils, the draught evidently fluctuated with the share and the tilted disc coulter functioning as a soil cutting device, whereas it was relatively stable at the main mouldboard and the sub-mouldboard, where the main function was to invert the soil blocks or to mix the aggregates already detached or loosened from the ground.

4.2. *Effect of speed and working depth*

Simple multivariate linear regressions were applied to speed and working depth as independent variables and the draught and the side force as individual dependent variables for each soil (Table 4). In dry loose soil, the set depth was used for analysis instead, since the bottom of the furrow, where the working depth was measured and defined, was not distinguishable after the operation.

In wet plastic soil, the increase in the working depth directly affected the force exerted on the inverting devices, the main mouldboard and the tilted disc coulter. As indicated in *Fig. 3a*, however, the depth actually had a negative effect, although not statistically significant, on the force on the share (partial regression coefficients of -2.65 N/mm and -0.82 N/mm for the draught and side force, respectively at the significance level of less than 15%, not shown in Table 4). This can be explained by the increase in the thickness of the soil slice, the enhanced resistance against bending, particularly in that the main mouldboard was instrumental in the separation and the deformation of the soil slice by partly bypassing the function of the share. Some effect of the speed was also observed on the soil cutting devices, the share and the tilted disc coulter. On the other hand, the force on the sub-mouldboard was not significantly influenced by speed and depth because of the small magnitude on the average (*Fig. 3a*).

In dry compact soil, speed greatly influenced the force on the share and consequently to a lesser extent on the main mouldboard (Table 4), possibly because the length of each soil block separated from a continuous solid slice of soil tended to increase with speed, as indicated by the characteristic period of the force discussed in Section 4.1. Instead of a length of less than 200 mm at a speed of 0.2 m/s, the most observable length was over 300 mm at 1.3 m/s, indicating that greater force was needed to separate a soil slice to form each block at a higher speed. The longer soil block was also problematic in its passage through the clearance between the main mouldboard and the tilted disc coulter or sub-mouldboard, and in completion of inversion (Shoji, 2001). A positive effect of speed on the draught of the sub-mouldboard shown in Table 4, therefore, can be attributed partly to a greater tendency of soil blockage in front of the sub-mouldboard, although the instances of apparent soil blockage were excluded from the analysis. The effect of the working depth was only observable where the vertical cutting of the soil was involved at the tilted disc coulter.

In dry loose soil, the increase in depth affected the force on the main mouldboard and tilted disc coulter, as in wet plastic soil. The coefficients were smaller, however, because the adhesion of the soil to the working components or resistance against cutting and deformation of the soil does not have to be taken into consideration. The depth also had a positive effect on the force exerted on the share, unlike in wet plastic soil, indicating that the friction on the surface of the share simply increased with the depth. Conversely, a negative effect of speed was observed on the force on the sub-mouldboard. Clearly, the force was practically negligible at the speed of 1.3 m/s (*Fig. 3c*), implying that the vertically accelerated and thrown soil aggregates landed on the ground with the least interaction with the sub-mouldboard.

In all the soils, the overall effect of speed on the forces was relatively insignificant, specifically at the soil inverting devices; the mouldboard, the tilted disc coulter, and the sub-mouldboard. Being similar to the speed-draught relationship presented by McKibben (1966), the current design and configuration of this spot plough may be suited to significantly high-speed applications as far as the kinetic energy of the soil slice or blocks is concerned, since acceleration of the soil in the lateral direction is practically negligible. Nevertheless, a comparative study with models or prototypes in the same soil at high speeds is needed to confirm this expectation.

4.3. *Portion of draught and side force*

The greatest draught was observed at the share and then at the tilted disc coulter, where the cutting of the soil occurred (*Fig. 3*, upper panel). In wet plastic soil, the main mouldboard also required considerable portion of the draught, indicating that it executed the crucial function of deforming the soil slice for inversion. In dry compact soil, the smaller draught at the main mouldboard indicated less adhesion of the soil to its surface and practically no deformation of the soil that had already been partially pulverised into soil blocks at the share. In dry loose soil, the role of the main mouldboard was negligible, as indicated by the insignificant magnitude of the force exerted on it; the vertical acceleration of the soil aggregates took place mostly at the share at a higher speed, and most of the aggregates were temporarily retained at the clearance between the main mouldboard and the tilted disc coulter at a lower speed.

The side forces (*Fig. 3*, lower panel) appear to be balanced as a whole. For detailed analysis, the null hypothesis of the sum of the side forces was examined (Table 5). The balance was achieved, or the null hypothesis was accepted, without the side force of the share in wet plastic and dry compact soils (Table 5, last column). In dry loose soil, on the other hand, the total balance of the side force was attained (Table 5, third column), taking into consideration that the function of the main mouldboard was relatively insignificant as discussed above. Therefore, if the objective is to balance the side forces of the spot plough in a wet plastic or dry compact field, which is often a practical case, the approach angle of the share (currently 45° with respect to the travelling direction) may be increased, as one of the choices, within a range that would not affect the horizontal cutting of the soil. Another possibility is to place the tilted disc coulter (*Fig. 1*, upper panel) slightly in forward direction to assist the cutting of soil for reducing the force exerted on the share, and to generate greater magnitude of the force on itself that potentially intensify its lateral component *i.e.* the side force. These alternations, however, should be carefully made as they might change the motion of the soil slice or blocks that leads to incomplete inversion of the soil.

The side force of the sub-mouldboard was negligible in all the soils (*Fig. 3*, lower panel). This is explained by the observation that the soil was already separated from the ground and either pulverised or deformed before reaching the sub-mouldboard. Notably, in dry compact soil, the sub-mouldboard still required a certain magnitude of draught (*Fig. 3b*; Section 4.2), despite its reduced contribution to the inversion of the soil as indicated by the minimal magnitude of the side force; this reflects the tendency of the forward displacement of the soil that occasionally leads to the soil blockage interfering with continuous operation (Shoji, 2001). It is therefore suggested that although the sub-mouldboard plays an important role in maintaining the lateral displacement of the soil at a minimal level, a design of the spot plough without the sub-mouldboard, as by utilising the inertia of the soil slice or blocks to rotate itself (Shoji, 2000; Shoji, 2003), may be worth examining for practical application.

5. Conclusions

The draught and the side force, the longitudinal and lateral components of the force, exerted on each working component of the model spot plough were measured.

(1) The force on the main mouldboard was steady in all the soils, whereas that to the cutting devices, the share and the tilted disc coulter, fluctuated in dry soils.

(2) The draught at the share was predominant in all the soils. It increased particularly with

speed in dry compact soil, as longer soil blocks were formed.

(3) The forces on the main mouldboard and the tilted disc coulter, which functioned as a inverting device, increased with the working depth in wet plastic soil, whereas it was not the case in the dry soils. The effect of speed was mostly insignificant in all the soils, suggesting the possibility of application in high-speed ploughing.

(4) The balance of the side force was established in dry loose soil, whereas such was the case without the share in wet plastic and dry compact soils, suggesting scope for the altering the approach angle of the share in practical applications.

(5) The magnitude of the force, especially that of the side force, exerted on the sub-mouldboard was negligible, and its omission is indicated in future designs.

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Figure captions

Fig. 1. Working components (upper case letters) and vertical force-sensing beams (lower case letters) of the model spot plough: (A)(a) share; (B)(b) main mouldboard; (C)(c) tilted disc coulter; (D)(d) sub-mouldboard

Fig. 2. Change in draught with the advance of the plough, measured at the working depth of 50-56 mm and the operating speed of 0.2 m/s, in: (a) wet plastic; (b) dry compact; (c) dry loose soils, exerted on: ▬, share; ━, main mouldboard; —, tilted disc coulter; —, sub-mouldboard

Fig. 3. Average draught and side force at minimum (thin line) and maximum (boxed bold line) working depths observed (see Table 2) and operating speed of 1.3 m/s in: (a) wet plastic; (b) dry compact; (c) dry loose soils, exerted on: □ , share; ■ , main mouldboard; ■ , tilted disc coulter; ■ , sub-mouldboard

Table 1

Properties of soils [a]

Designation	*Moisture content, %* [b]	*Cone penetration resistance, MPa*	*Wet bulk density, Mg/m^3*	*Tensile strength, kPa*	*Internal friction angle, deg*	*Cohesive strength, kPa*	*Soil-PVC* [d] *friction angle, deg*	*Soil-steel friction angle, deg*	*Secant modulus* [e], *MPa*	*Hysteresis modulus* [f], *MPa*
Wet plastic	17.7±0.8	0.29±0.01	2.39±0.03	11.8±6.7	8.4±1.1	16.1±0.6	10.2±0.3	9.8±0.7	0.15±0.00	1.48±0.29
Dry compact	14.2±0.8	1.70±0.10	2.04±0.02	15.0±7.7	N/S [c]	117±7	11.5±0.8	12.0±0.9	7.74±0.10	24.1±4.3
Dry loose	12.3±0.5	0.35±0.03	1.35±0.06	N/A	21.5±0.9	N/S [c]	12.2±0.3	13.2±0.1	N/A	N/A

[a] Prepared from a soil having the texture of 21% clay, 20% silt, and 59% sand (sandy clay loam). Plastic and liquid limits were 17.0% and 25.6%, respectively.
[b] Dry basis
[c] The slope or the intercept in the shearing-normal stress plot from the direct-shear tests was not statistically significant *i.e.* regarded as zero.
[d] Polyvinyl chloride
[e] Average slope of the stress-strain curve for the range in stress between zero and 50% the unconfined compressive strength (Terzahgi and Peck,1948)
[f] Average slope of the stress-strain curve during unloading and reloading in unconfined compression tests (Terzahgi and Peck,1948)

Table 2

Experimental variables and levels

Soil	*Speed, m/s*	*Set depth, mm*	*Working depth, mm*	*Observations* [a]
Wet plastic	0.2	38-60	50-70	5
	0.8	37-51	53-65	5
	1.3	40-61	51-73	6
Dry compact	0.2	39-55	42-62	3
	0.8	46-56	52-63	4
	1.3	42-54	51-62	4
Dry loose	0.2	Approx. 50 and 70	N/A	2
	0.8			2
	1.3			2

[a] Total number of observations at each speed

Table 3

Parameters of force transducers for draught and side force

Working component	*Section size* [a], *mm*	*Section spacing* [b], *mm*	*Transducer*	*Output sensitivity* [c], $\mu V\,N^{-1}V^{-1}$
Share	22×16	60	Draught	0.232
			Side force	0.322
Main mouldboard	16×10	60	Draught	0.754
			Side force	1.216
Tilted disc coulter	25× 9	60	Draught	0.314
			Side force	0.866
Sub-mouldboard	16×16	100	Draught	0.749
			Side force	0.746

[a] Section size of the vertical supporting beam for each working component

[b] Distance between two pairs of strain gauges on the beam that constitute a complete bridge circuit to detect each component of the force

[c] Output voltage per unit force applied, normalised by the input voltage of the bridge circuitry

Table 4

Effect of speed and working depth on draught and side force expressed by partial regression coefficients and their significance level

Working component	*Force*	*Wet plastic soil*		*Dry compact soil*		*Dry loose soil*	
		Speed effect, N s/m	*Depth^{+} effect, N/mm*	*Speed effect, N s/m*	*Depth^{+} effect, N/mm*	*Speed effect, N s/m*	*Depth^{+} effect, N/mm*
Share	Draught	$42^{\#}$		110^{**}		12^{*}	2.4^{*}
	Side force	17^{*}		32^{**}			0.72^{*}
Main mouldboard	Draught		2.7^{**}	$27^{\#}$			0.72^{***}
	Side force		2.4^{***}	$13^{\#}$	$0.9^{\#}$		0.62^{**}
Tilted disc coulter	Draught	$15^{\#}$	2.6^{***}		1.9^{*}	9.8^{*}	0.89^{*}
	Side force		2.6^{*}				$0.88^{\#}$
Sub-mouldboard	Draught					$-8.3^{\#}$	
	Side force			$12^{\#}$		$-3.1^{\#}$	

$^{\#}$, *, **, ***: Two-sided significance levels below 10%, 5%, 1%, and 0.1%, respectively

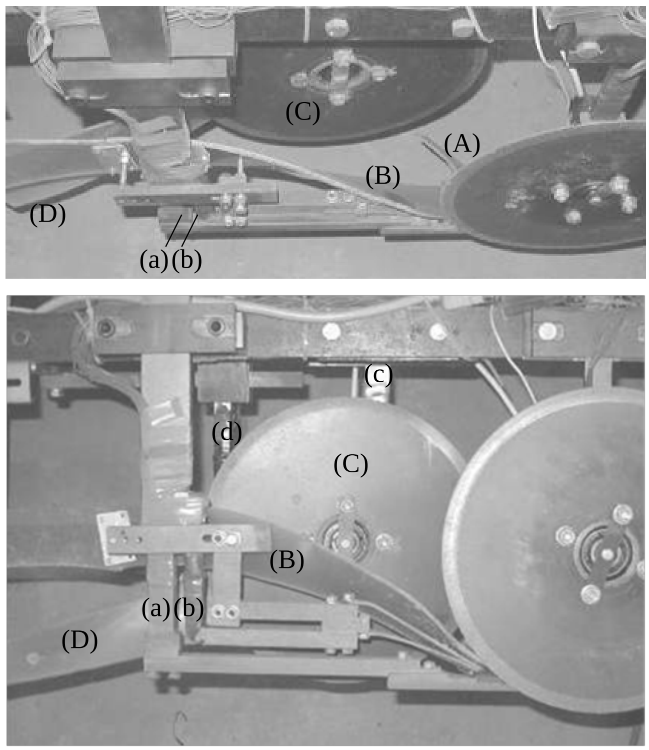
$^{+}$ Working depth in wet plastic and dry compact soils and set depth in dry loose soil

Table 5

Balance of side force

Soil	*Observations*	*Case* [a]	*Total side force, N*	*Significance level* [b]
Wet plastic	16	1	66±40	0.12
		2	-28±8	0.77
Dry compact	11	1	89±32	0.02
		2	-9±15	0.58
Dry loose	6	1	15±15	0.34
		2	-24±9	0.05

[a] 1: share, main mouldboard, tilted disc coulter, and sub-mouldboard;
2: main mouldboard, tilted disc coulter, and sub-mouldboard only
[b] Two-sided t-test



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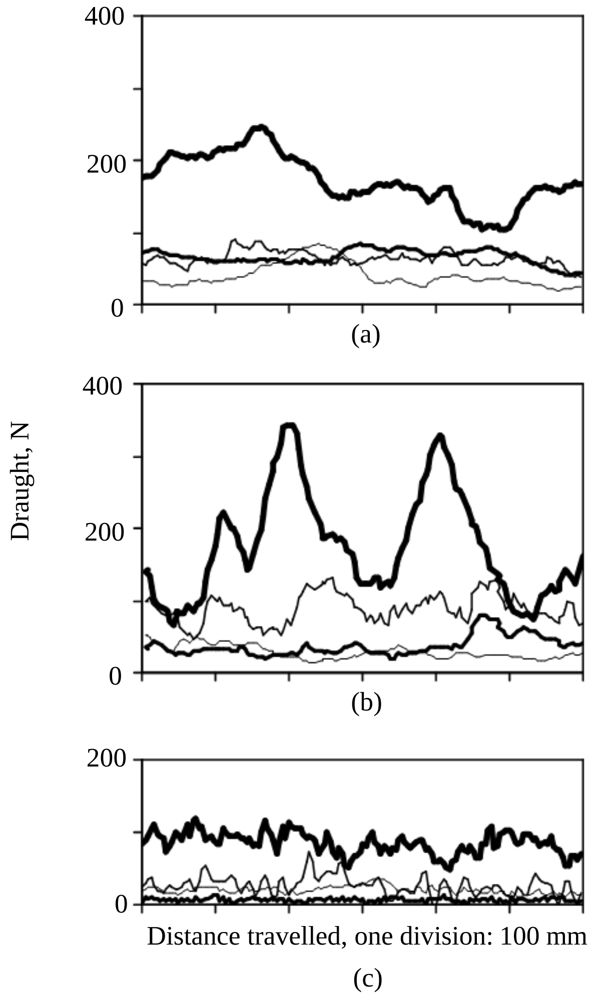

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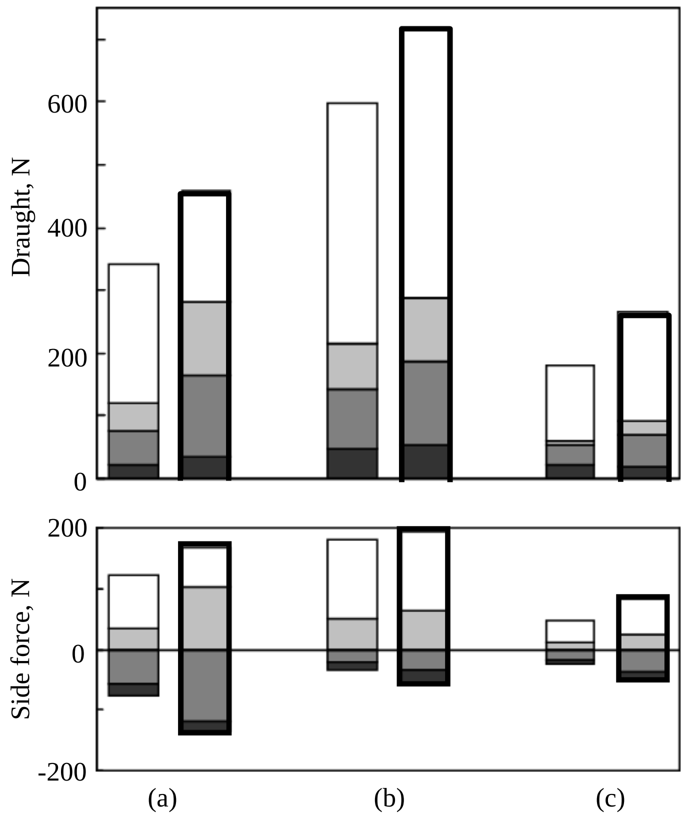

Fig. 3. Average draught and side force at minimum (thin line) and maximum (boxed bold line) working depths observed (see Table 2) and operating speed of 1.3 m/s in: (a) wet plastic; (b) dry compact; (c) dry loose soils, exerted on: ☐ , share; ☐ , main mouldboard; ☐ , tilted disc coulter; ☐ , sub-mouldboard