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Shoji, Koichi

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Design of a Model 'Spot Plough' for Inversion of Soil Slice within the Furrow

Koichi Shoji

Faculty of Agriculture, Kobe University, Kobe, 657-8501, Japan; e-mail: shoji@eng.ans.kobe-u.ac.jp

Abstract

A model spot plough to invert soil slice within its own furrow was designed and tested in soil bin, with a view to overcome disadvantages of conventional tillage systems for mouldboard plough. The model was especially designed to avoid soil clogging, whilst the basic structure was not altered from what had been surveyed from previous research. Followed by share and main mouldboard at the beginning of the inversion, tilted disc coulter (TDC) was located on the other side of the main mouldboard to assist the spot inversion and to reduce relative motion to the soil. Toward the end, the tilted disc coulter was replaced by sub mouldboard. Optimum width to depth ratio and width of the mouldboards were also considered. The mouldboards were expressed as helicoidal surfaces, and were fabricated of a plate of polyvinyl chloride. A series of experiments showed that the model spot plough performed well in wet-plastic soil, acceptably in dry-powdery soil at higher speed, and somewhat less steadily in dry-solid soil conditions. In any soil condition, the function of the rotating tilted disc coulter was found to be essential for stabile operation.

Notation

A, B, C	areas defined in the cross section of the soil slice and furrow
b	working width, mm
e	supplementary depth of the tilted disc coulter, mm
h	maximum working depth used for design, mm
h_a	actual working depth used for adjustment, mm
k	rate of inversion, mm^{-1}
l	effective length of contact with the soil slice and tilted disc coulter, mm
R	radius of the tilted disc coulter, mm

x, y, z global coordinates, mm

x', y' local coordinates fixed to the soil slice, mm

x_0, y_0 global coordinates of the trajectory of the soil slice, mm

α angle defined by width-to-depth ratio of the soil slice, –

ϕ angle of inversion, –

ϕ_s statically stabile angle of inversion, –

γ tilt angle of the tilted disc coulter, –

1. Introduction

Historically, one of the main functions of mouldboard plough has been to turn over the soil. The plough buries residues and weeds to create clean seedbed suitable for germination and growth of the plant, and functions as one of the effective methods of weed control. It also contributes to aeration of the soil; for example, in wet paddy fields in East Asia, ploughing after the growth period provides enough oxygen to decompose organic materials left in the field.

However, side effects of the ploughing have become more focused in last couple of decades, and the mouldboard plough has become less and less popular in most of developed countries. The first concern is vulnerability of the ploughed ground to erosion, especially in upland cultivation. Complete mouldboard ploughing not only exposes the soil aggregates to wind flux and rain drops, but also forms a compacted soil layer which impedes water infiltration and crop root growth. Secondly, the ploughing operation should be followed by secondary tillage to form flat and smooth seedbeds. In addition to soil displacement caused by ploughing, the structural difficulty of combining with other implements results in more labour and energy input. Therefore, reduced or minimum tillage packages have been adopted in many Western developed countries, and rotary tillers are predominantly used in paddy fields in Japan.

On one hand, the development and extensive use of chemical materials such as fertilisers, pesticides, and herbicides have supported these trends. In the reduced tillage packages, several varieties of herbicide are used to control perennial weeds. In both upland and paddy fields where sufficient chemical fertilisers and herbicides are provided, farmers only have to loosen the surface of the topsoil by chisel ploughs or rotary tillers without concerns for weed control or incorporation of organic materials. However, recent policies discourage usage of those chemical materials for environmental protection, and more consumers are inclined to buy organically grown products. It is commonly accepted nowadays that alternative approaches are necessary for sustainable crop production.

Recently came out some reevaluation and suggestion about the use of the plough to answer this counter-demand. For example, Sakai *et al*. (1998) proposed a theoretical analysis that weeds could be effectively controlled by altering the ploughing depth every year. Perdok and Kouwenhoven (1998) admitted necessity of ploughing especially for organic farming, and sought a less environmentally intrusive method than conventional ploughing. If the plough is required to be protective to the environment and less labour-demanding for the operators to use, however, the shortcomings have to overcome: the vulnerability of the totally ploughed ground to erosion and displacement of the ploughed soil.

As one of the solutions, it is worth considering a plough to invert the soil slices within their own furrows. The plough would immediately eliminate the inconveniences associated with the lateral soil displacement, and would facilely implement invertible ‘strip tillage’ or ‘zone tillage,’ in which only necessary portion is tilled and the rest is remained undisturbed for soil conservation (Pierce & Burpee, 1995). Currently however, tillage tools used for this method are mainly limited to non-invertible implements such as chisel plough or rotary tiller.

2. Literature review

There are already several names for the ploughs satisfying the above function, depending on the characteristics to emphasise. ‘Front(al) plough’ (Shmelev, 1985; Sakun *et al*., 1991;

Lobachevsky, 1996) is attributed to the feature that the plough could mount additional equipment behind, and 'strip plough' (McKibben, 1966) to a peculiar cultural practice. 'Inverting plough' (Kaufman & Totten, 1972) and 'new concept plough to invert furrow slice at the same position' (Kawamura *et al*., 1986; Kawamura & Takakita, 1988; Shoji *et al*., 1993; Kamide & Wang, 1993; Wang & Kamide, 1993 and 1995; Lee *et al*., 1997) intend to express the concept of inversion and no lateral displacement. However, the former lacks one of the keywords and the latter seems to be too long. The author has simply named it 'spot plough' (Shoji, 1996 and 1997), and also may as well use it hereafter. The terms refer not only to the function of ploughing the soil within the furrow, namely on the 'spot,' but also to the prospective tillage practices focused specifically on the necessary 'spot.'

Prospective benefits of the spot plough, from an engineering point of view, are structure of the implement and manoeuverability of the tractor-implement system (Sakun *et al*., 1991; Lobachevsky, 1996). Staggered alignment of multiple units will be readily eliminated and there will be potential for combining with other working implements such as fertiliser applicator or drill (McKibben, 1966). Symmetric alignment of the units is also possible to cancel out side forces applied to them. Therefore, not only steering of the tractor will become easier, but also frictional force associated with landsides could be minimised to reduce the draught.

The spot plough usually contains additional components, so that the soil is not laterally displaced during the tillage. The following examples represent some of the basic designs, in which one more mouldboard is added. Kaufman and Totten (1972) developed a unit of prototype for field use, shown in *Fig. 1*, in which the 'trailing surface' seems to be equivalent to the additional mouldboard. Farm Line (unknown) obtained a Japanese Patent (1987) with similar designs, and had several prototypes on product catalogues. Kamide and Wang (1993) developed a symmetric soil bin model composed of main and small sub mouldboards, with inward inversion of each soil slice. Lobachevsky (1996) presented a structure similar to that of Kamide and Wang (1993), and stated that the research group had already designed several prototypes for various field applications. However, the researchers or designers noticed some difficulties of operating the spot plough. A typical problem was that the ploughs easily piled up the soil and made it impossible to continue operating, and this was especially observed when handling brittle or powdery soils.

As a solution, auxiliary powered components were usually added to discharge the soil behind and to generate supplementary traction. Kaufman and Totten (1972) attempted to hydraulically drive the transverse coulter, but no significant improvement was observed. Shmelev (1985) designed augers to attach between the main mouldboards placed symmetrically facing with each other. Takakita (1987) once catalogued a six-row spot plough for small tractors, and rotary tines were attached on each row to rake out the soil behind. Kawamura *et al*. (1986 and 1988) and Shoji *et al*. (1993) developed and tested a prototype similar to that of the Takakita (1987) equipped with oscillated shares but the tines. These active components, however, made the structure of the spot ploughs far more complicated than that of conventional mouldboard ploughs.

Rather than installing additional powered components, Shoji (1997) arranged a free-rotating wheel at the end of inversion, shown in *Fig. 2*, to partly avoid relative motion to the soil. However, the soil still accumulated at the beginning of the plough in dry and brittle soil conditions. The force exerted on the wheel was relatively small, and even when it was substituted with a rear sub mouldboard, the force was not significantly different. Conversely, the largest force was observed to apply on the front sub mouldboards at the beginning of the inversion.

Whilst the spot ploughing refers to handling the soil slice within single furrow, there is an approach, in broader definition, to permit temporal displacement of the soil while operating. Domsch (1991) presented an elaborated design that the lower soil layer was temporarily retained and transported by belt conveyers while symmetrically located mouldboards inverted and re-inverted the upper layer. Ung Jin (1993) catalogued ‘ridge plough,’ which consisted of several diagonally arranged simple mouldboards and one mouldboard facing with the others. Shoji (1996) proposed a similar design that consisted of a pair of symmetric mouldboards, but complete inversion of each soil slice was not achieved. Most of these ideas above entail several mouldboards as a unit, to complete overall inverted zone tillage within the width of the implement.

It is concluded from the survey that:

(1) basic designs of the spot plough have already been proposed;

(2) soil clogging sometimes may occur, and the remedies have usually resulted in complicated designs; and

(3) if definition of the spot ploughing is extended, there are already tools developed for zone tillage to accomplish inversion without overall soil displacement.

Whilst maintaining the same basic design, the objective of this study is to overcome the problem of soil clogging without the complexity of the mechanism equipped with more working components.

3. Structural considerations

3.1. *Overview*

Figure 3 shows an overview of the model spot plough designed for soil bin testing. It consists of vertical disc coulter, share, main mouldboard, tilted disc coulter (TDC), and sub mouldboard. The working width is 150 mm and the maximum working depth is 75 mm. Unlike most of conventional ploughs, direction of the inversion is counterclockwise facing to the forward direction, to facilitate observation under given laboratory environment.

It is supposed that the cross section of the soil slice retains as much its original shape as possible without pulverisation, and that the slice behaves somewhat like a plastic body, such as a sod of pasture or a slice of drained wet paddy soil. The shape of the mouldboard thus can be characterized as ‘helicoidal’ surface (Kaufman & Totten, 1972), or a more generalised shape of helix (Barrett, 1967). However, the plough itself is applicable to loose or solid soil conditions, although perfect inversion is not an important objective.

3.2. *Width-to-depth ratio*

The nature of the spot ploughing brings some unfavourable constraints such that:

(1) edges of the soil slice interfere with the adjacent undisturbed wall; and

(2) the allowable area within which the surface residue is buried would be restricted.

These properties are not relevant when inverting the soil slice toward the adjacent open space, shown in *Fig. 4 (a)*, with a conventional plough. With the proposed spot plough in *Fig. 4 (b)*, at the left hand side where the tilted vertical cutting of the lower edge and compression of the upper edge may occur, the side is conveniently regarded as an arc of a circle whose diameter is equal to the working width. Conversely, the right lower edge of the slice may disturb the adjacent untilled wall, and the disturbed portion may be displaced somewhere else. By accepting the above assumptions, such design with a purpose of strictly avoiding the interference of the edges, as Kamide & Wang (1993) proposed, will not be considered here.

The width-to-depth ratio geometrically relates to the extent of the interference and to allowance for residue burial, from which feasibility of the spot inversion can be estimated. They are calculated and expressed as ratios to the working cross-sectional area in Table 1 for examination, with auxiliary notations in *Fig. 4 (c)*. Compared to the theoretical minimum width-to-depth ratio of 1.27 allowed for conventional ploughs to maintain the static stability of the inverted soil slices (Bernacki & Hanman, 1972), allowable ratio for the spot plough is relatively large. As suggested by Kaufman & Totten (1972), a width-to-depth ratio of 2.0 or larger would be acceptable in view of the above constraints.

The maximum working depth is therefore 75 mm for the working width of 150 mm. It will be also used to design the components, because at least two sides of the cross section, as shown in *Fig. 3 (b)*, are restrained to accomplish the spot ploughing. Smaller working depth may be justified to the extent that may not result in pulverization of the soil slice hence in unstable operation, but alignment of some components should be adjusted according to the working depth to complete as exact spot inversion as possible, to be discussed in Section 3.6.

3.3. *Tilted disc coulter and sub mouldboard*

Additional devices are necessary for the spot plough to place the soil slice eventually within its own furrow. With conventional ploughs, the slice has two consecutive edges as stationary pivots in *Fig. 4 (a)*, around which the slice is inverted. This is one of the largest contributions to the stabile inversion. With the spot plough on the other hand, there is not any apparently stationary pivot in *Fig. 4 (b)*. Therefore, as the plough proceeds, the pivot must be shifted aside by installing an auxiliary component such as a sub mouldboard. However, the slice may easily collapse if too much force is exerted, with the pivot being moved against the contact with the ground. Some of the unexpected previous experimental results could have been attributed to little consideration of the intensity of the interactions, specifically frictional force, between the soil and the auxiliary component.

A rotating component can be thus installed at the beginning of the inversion, as the Shoji's trial (1997) implied, to avoid as much relative motion as possible to the soil slice and therefore to reduce the friction. The tilted disc coulter (TDC) is introduced on the other side of the main mouldboard, with small tilt angle γ against the forward direction. It is not only a substitute for the front sub mouldboard to shift aside the pivot of the slice at the beginning, but also has the function as an effective vertical cutting device. Subsequently, it is smoothly replaced by the sub mouldboard to complete the inversion. The diameter of the TDC is 300 mm, namely 4 times as much as the maximum working depth, so that the rotating disc could adequately avoid the relative motion to the slice. The TDC is located deeper than the share edge with supplementary depth e to securely rotate itself. The appearance consequently looks similar to the design by Kaufman and Totten (1972), yet their ‘transverse coulter’ appears to have been relatively too small to reduce the relative motion. The tilt angle γ and position of the TDC are specified hereafter in Section 3.5, in accordance with equations of the mouldboards.

3.4. *Width of the Mouldboards*

In the cross section of *Fig. 3 (b)*, the width of the mouldboards is defined as the length of the straight-lines adjoining the soil slice. It could be extended as wide as the working width, but this setting may cause several problems. If there comes unexpectedly thick portion of the slice or there is too much residue left on the surface, the slice might be completely 'sandwiched' or blocked between the mouldboards. Further more, from a structural point of view, the share can not be completely adjusted and connected to the main mouldboard across the full working width.

It is obvious from the figure that only a portion of the width is necessary to apply sufficient moment for deformation and inversion of the slice. To avoid the soil blocking, one of the criteria is that the sum of the width of the main and sub mouldboards should be less than that of the soil slice (Shoji *et al*., 1993; Shoji, 1997). Too much reduction, however, would cause unnecessary deformation or pulverisation of the slice, which may hinder complete soil inversion. As a compromise, 40% of the working width, namely 60 mm, is taken for each mouldboard.

3.5. *Shape of mouldboards and alignment of tilted disc coulter*

According to the definition of the helicoidal surface, the mouldboard surface can be readily defined by compiling the cross-sectional straight-lines in the *Fig. 3 (b)*, as 'surface generators' along the longitudinal direction. It is expressed by parallel and rotational transformation of the cross section: (1) the trajectory of the centre of the cross section; and (2) rotation of the cross section around the centre. As discussed in Section 3.2., the maximum working depth of 75 mm will be used for the design.

Practically, the trajectory is supposed to be almost parallel to the ground, and therefore the rotation is solely expressed by the angle of inversion ϕ in *Fig. 5 (b)*. This assumption is acceptable if the curvature of the trajectory is moderate, namely if the inversion of the soil slice gradually takes place as the plough proceeds, and if temporary deviation of the trajectory in lateral direction is small. For a more theoretical analysis of the surface, however, complete expression of the rotation, such as Euler's transformation, would be preferable.

The x coordinate of the trajectory, x_0, is simply expressed in terms of the angle of inversion ϕ:

$$x_0 = \begin{cases} \frac{1}{2} b \sin(\phi + \alpha) & (0 \le \phi \le \frac{1}{2}\pi - \alpha) \\ \frac{1}{2} b & (\frac{1}{2}\pi - \alpha \le \phi \le \frac{1}{2}\pi + \alpha) \\ \frac{1}{2} b \sin(\phi - \alpha) & (\frac{1}{2}\pi + \alpha \le \phi \le \frac{3}{4}\pi) \end{cases} \tag{1}$$

where, b is the working width, and α is an angle in the cross section defined as:

$$\sin \alpha = \frac{h}{b} \tag{2}$$

and where h is the maximum working depth used for the design.

In the above expressions, the left side of the cross section of the slice in *Fig. 5 (b)* is regarded as a fraction of an arc, as assumed in Section 3.2. This assumption, unlike a rectangular cross section, consequently averts apparent ‘notch,’ or undifferentiable point of the trajectory at ϕ of 90°.

The angle of inversion ϕ is tentatively defined as a linear function of the z coordinate:

$$\phi = k z \tag{3}$$

where k is constant rate of inversion,

although there is plenty of room for further optimisation of the mouldboard surface. The value of k should be that the soil slice is already rotated to the statically stabile angle of inversion ϕ_s of:

$$\phi_s = \frac{1}{2}\pi - \alpha \tag{4}$$

when it is released from the TDC. By releasing the slice before ϕ of 90°, a slice whose thickness accidentally exceeds the maximum working depth may not be easily blocked between the main mouldboard and the TDC.   With reference to the *Fig. 5 (a)*, the interaction of the TDC with the slice terminates at:

$$z = l\cos\gamma \tag{5}$$

with which k is calculated as:

$$k = \frac{\phi_s}{l\cos\gamma} \tag{6}$$

where l is the effective length of contact with the slice and the TDC, approximately given by:

$$l = \sqrt{R^2 - \{R-(e+h)\}^2} + \sqrt{R^2 - \{R-(e+h\cos\phi_s)\}^2} \tag{7}$$

and where: R is the radius of the TDC; e is supplementary depth of the TDC.

For the values for b and h of 150 mm and 75 mm, respectively, the slice is released at the stabile angle of inversion ϕ_s of 60°, according to Eqn (2) and (4). R and e could be arbitrarily determined, and the values selected here are 150 mm and 10 mm, respectively. Substituting these values for the Eqn (7), l is calculated as 245 mm.   For the small tilt angle, $\cos\gamma$ is nearly 1, and therefore k is finally determined from the Eqn (6) as 0.00427 rad/mm. The angle of inversion ϕ is defined up to 135°, after which the slice would be automatically inverted by the gravity.

The y coordinate of the trajectory y_0 is defined as below:

$$y_0 = \begin{cases} -z\tan\gamma & (0 \le \phi \le \alpha) \\ \frac{1}{2}b\{1-\cos(\phi-\alpha)\} - z\tan\gamma & (\alpha \le \phi \le \frac{1}{2}\pi - \alpha) \\ 0 & (\frac{1}{2}\pi - \alpha \le \phi) \end{cases} \tag{8}$$

The first equation is geometrically derived from the contact of the TDC with the arc of the slice, whilst the second, with the edge of the slice.   The third follows the strict definition of spot ploughing while the slice is not handled by the TDC.

Accordingly, the tilt angle γ of the TDC is calculated so that the y coordinate of the trajectory is zero when the slice is released from the TDC, namely at the statically stabile angle of inversion ϕ_s.   This is to avoid discrepancy of the trajectory expressed by the second and the third equations of the Eqn (8). Substituting values of the second equation for ϕ, α, z, and y_0 of 60°, 30°, 245 mm, and 0 mm respectively, γ is calculated as 2.4°.

The calculated coordinates of the trajectory are plotted in *Fig. 6*, with which shows that the trajectory is almost parallel to the ground and that the lateral deviation is minimal as assumed. Global coordinates of the surface (x, y) are finally expressed by adding the rotation ϕ of the given local coordinates of the cross section (x', y') to the trajectory (x_0, y_0):

$$\begin{Bmatrix} x \\ y \end{Bmatrix} = \begin{Bmatrix} x_0 \\ y_0 \end{Bmatrix} + \begin{bmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{bmatrix} \begin{Bmatrix} x' \\ y' \end{Bmatrix} \tag{9}$$

Equation (9) thus becomes a function of the z coordinate by substituting the Eqn (1) to (3). Reminding in the *Fig. 3 (b)* that the mouldboards adjoin the surface and bottom of the soil slice, and that their lengths are 40% of that of the working width, the following local coordinates:

$$\left.\begin{array}{r} x' = -0.5h \\ -0.5b \le y' \le -0.1b \end{array}\right\} \tag{10}$$

give the surface for the main mouldboard; and:

$$\left.\begin{array}{r} x' = 0.5h \\ 0.1b \le y' \le 0.5b \end{array}\right\} \tag{11}$$

for the sub mouldboard.

Note that the above geometrical expressions of the mouldboards do not always represent the trajectory of the soil slice induced by real ploughing operations. In the future, it may be considered together with mechanical properties of the slice and with optimisation of the components.

3.6. *Fabrication and adjustment*

The main and sub mouldboards were fabricated from a 5-mm thick hardened polyvinyl chloride plate. It is not only efficiently trimmed into a desired shape, but also its softening point is conveniently around 100°C. It allows certain amount of torsion and bending when moderately heated, and restores enough solidity for ploughing when cooled down. Its durability and coefficient of friction may not be satisfactory for practical applications, but the author takes advantage of convenience of fabrication at this experimental stage.

In the strict sense, the helicoidal shape of the mouldboards can not be fabricated by simple bending, and therefore is not developable into a plane plate. However, it was defined in the previous section that the shape consisted of a series of the straight-line as the surface generator. Along the longitudinal direction, the three-dimensional helicoidal shape thus can be divided into successive thin triangles, and it can be 'pseudo-developed' into a plane without practical problems. As shown in *Fig.* 7, the trimmed plate was then heated in an oven at 105°C, and was shaped along a mould representing selected points of the shapes defined by Eqns (9) to (11).

The main mouldboard was then connected to a 50-mm wide share, whose approach and lift angles were 45° and 24°, respectively. These angles were selected to maintain similitude with a commercially available mouldboard plough unit for development in the future. The share wing was notched as shown in *Fig. 3 (a)*, so that the soil slice would overpass the wing as closely as defined without being unnecessarily lifted. The leading portion of the main mouldboard was cut off and slightly adjusted to connect to the share. Finally, the outer edge of the main mouldboard in *Fig. 3 (a)*, which had already exceeded beyond the range of the working depth according to the expression by Eqn (9) and (10), was slightly trimmed to avoid agitation of the adjacent untilled wall of the soil.

Theoretically, the TDC and both the mouldboards generally need to be adjusted for smaller working depth, to place the inverted soil slice exactly at desired position. The amount that each component should be shifted in either lateral direction is approximately evaluated by:

$$\tfrac{1}{2}(h - h_a)\,|\sin\phi\,| \qquad (12)$$

where h_a is actual working depth.

For example, at the working depth of 50 mm, both the mouldboards should be shifted by 12.5 mm each at the angle of inversion ϕ of 90° to compensate half the difference of the working depth, and at the tail of the sub mouldboard where ϕ is 135°, by 8.8 mm. Accordingly, the tilt angle γ of the TDC is adjusted to follow the adjustment of the sub mouldboard.

In reality, only the tail of the sub mouldboard was adjusted according to the working depth to minimise the lateral displacement. The clearance between the main mouldboard and the TDC was retained as designed, to bear unexpected increase of the thickness of the soil slice or clods, and to avoid their retardation that would potentially result in the blocking.

The vertical disc coulter, which had not been of importance during the design, was also relocated along the longitudinal direction, depending on the soil conditions to be described in Section 4.1. In the wet-plastic and dry-solid conditions, the centre was placed 100 mm ahead of the share point, to avoid the slice or clods from being blocked between the TDC and itself. In the dry-powdery condition, it was placed right above the share point to function as a retaining wall, so that a mass of the soil aggregates did not collapse away from the outer edge of the main mouldboard. Note that this inconvenience is attributed to the property of the spot plough that, unlike conventional mouldboard ploughs, the soil must be intentionally shifted toward the outer edge of the main mouldboard.

4. Experimental details

4.1. *Experimental design*

The assembled model spot plough was operated on a soil bin, which was 3600-mm long by 800-mm wide by 400-mm deep. The soil type used was ‘sandy clay loam,’ whose plastic and liquid limits were 17.0% and 25.6% in dry base, respectively. Three soil conditions were provided according to soil moisture content and method of preparation:

(1) wet-plastic – tilled slightly above the plastic limit, then pressed with a roller;

(2) dry-solid – processed as above, then naturally dried down below the plastic limit; and

(3) dry-powdery – tilled and crushed below the plastic limit, then pressed with a roller.

Moisture contents for each condition were 18.2±0.5%, 14.3±1.3%, and 12.3±0.5%, respectively. The last two conditions were not in fact contemplated at the design. However, for practical applications, it is worth observing the performance regardless of the completeness of the inversion.

Other experimental variables and levels are summerised in Table 2. The free rotation and disablement of the TDC was to verify the emphasis of this particular design. At least two levels were set for the rest of the variables. In the wet-plastic and the dry-solid soil conditions, the depth was taken as the principle variable, whilst in the dry-powdery soil condition, the speed. The levels of the variables were mostly randomised except those of the soil condition.

4.2. *Method of evaluation*

Performance of the plough was evaluated by measuring displacement of the soil caused by the operation. Three pieces of tracer, 10 mm in diameter and 10 mm in length, were equally spaced and buried in two vertical layers in each cross section as shown in *Fig. 8 (a)*. They were made of acrylic plastic pipe filled with an aluminum bar so that their bulk density was approximately adjusted to 1500 kg/m^3, which was close to that of the dry-powdery soil, to minimise the effect of gravitational screening of the tracers. In the dry-solid condition, the tracers were buried while the soil was still wet and plastic before the soil was naturally dried. Three cross sections at intervals of 200 mm were prepared as replicates, thus 18 pieces were buried in total for each operation.

Vertical profiles of the untilled and tilled surfaces were acquired at intervals of 50 mm, with an instrument consisted of a laser beam range finder (KEYENCE, LB-1200) mounted on an electro-magnetic linear scale (MTB, Temposonics® LP-SKVM1500). If the furrow formed by the share and coulters was observable, specifically in the wet-plastic and dry-solid soil conditions, the profiles of the furrow bottom were also acquired after the soil slice and clods were completely removed. The working depth was then calculated by subtracting the level of the furrow bottom from that of the untilled surface. In the dry-powdery condition where the furrow was not left obvious, the level of the leading edge of the share was used instead of the furrow bottom; the actual working depth was considered to be identical to the set depth. Some profiles in the neighbourhood of the scattered tracers were averaged, and were finally superposed into such projected views of the tracers as *Fig. 8 (b)* and *(c)*.

Transfer rate, an index to represent completeness of the inversion, is defined by ratio of the tracers transferred from one layer to the other. The concept is essentially close to the one defined by Araya *et al*. (1996), but the method here is even simpler. However, it should be noted that the replicates are essential to smooth variability of events occurred to each tracer, and to increase the resolution of the index. The boundary of the layers after the operation is defined as the middle line between the averaged profile of the tilled surface and that of the furrow bottom. Tracers located less than 5 mm away from the boundary are counted to be the half, considering the size of the tracers and the error of the measurement. For example, the transfer rates are calculated as:

$$(2.5 + 2.5) / 6 = 0.83 \tag{13}$$

and:

$$(1.5 + 1) / 6 = 0.42 \tag{14}$$

for *Fig. 8 (b)* and *(c)*, respectively. If the soil slice is inverted and laid flat exactly within its own furrow, the transfer rate becomes 1.

Average lateral displacement was calculated, when all the six pieces of the tracer were discovered without disturbance at each replicate, as an index to verify weather the spot ploughing was accomplished. This method was found to be more suitable to express the lateral soil displacement than calculating the centroid of the tilled profile, especially when the soil slice leaned against the untilled wall to form an empty space thereunder. Similarly, average forward displacement was calculated as an index for the retardation of the soil, thus potential for the compete blocking.

5. Results and discussion

5.1. *Observations*

In the wet-plastic soil condition, as anticipated, a continuous soil slice such as shown in *Fig. 9 (a)* and *(b)* was formed. Unless complete blocking occurred, the inversion was stabile. However, exact inversion within the furrow, namely to lay the slice flat, was not obtained no matter how the tail of the sub mouldboard was adjusted; the slice eventually leaned against the untilled wall after it was released. Generally, cracks tended to propagate deeper than the edge of the share, as shown on the right side of the *Fig 9. (b)*, and the rough interface of the horizontal cutting was observed on the inverted surface of the soil slice, shown in the left portion of the *Fig 9. (b)*. This resulted in more actual working depth than the set depth, to be discussed in detail in Section 5.3. The blocking still occurred in the clearance between the main mouldboard and the TDC when an unexpectedly thick soil slice entered, although some measures had already been taken at the design.

In the dry-solid soil condition, shown in *Fig. 10 (b)*, neither bending nor torsion of the soil slice was permitted, but the slice was torn into 150 to 200 mm-long soil clods inconsistently distributed within the furrow. Correspondingly, the vertical profiles varied at section by section, and the tracers sometimes came off from the clods and stayed on the furrow bottom. Therefore, a limitation should be considered on the use of the transfer rate and average lateral displacement. There was also a periodically fluctuated interface of the horizontal cutting left on the furrow with intervals of 150 to 200 mm, which corresponded to the length of the clods. Complete blocking of the clods between the main mouldboard and TDC frequently occurred when the TDC was disabled at the higher speeds. It occurred even at a working depth, namely the thickness of the clods, of 55 mm, where there supposed to be enough clearance to pass through. Like in the *Fig. 10 (a)*, shear failure developed diagonally to the horizontal surface when each clod was separated, and the clods readily accumulated on each other to finally cause the blocking at a working depth less than the maximum. The rotating TDC is thus thought to have functioned as an effective ejector to avoid the accumulation and blocking in severe operational settings.

Some structural revision is worth considering for the above wet-plastic and dry-solid soil conditions, whilst maintaining the advantage of the free rotation of the TDC. For example, the radius R of the TDC could be smaller and its supplemental depth e be even negative to avoid the same amount of the relative motion to the soil, as long as the passive rotation of the TDC is guaranteed in these soil conditions. This modification consequently allows more clearance between the main mouldboard and TDC, with a view to deal with a thick slice or clods and to reduce the accumulation and retardation, and therefore to widen the range of the prospective application.

In the dry-powdery soil condition in *Fig. 11 (a)*, neither the slice nor clods of the soil were formed. The soil aggregates were slightly gathered forward and some temporal retardation was observed in *Fig. 11 (b)*, but they were steadily released behind the plough without any serious event of complete blocking. The tilled surface, as the result, became almost flat as shown in *Fig. 8 (c)*, when the retardation was minimal. However, it was not clear by visual observation to judge to what extent they were inverted or displaced forward. When the TDC was disabled at the greater depth at higher speeds, the mass of the soil aggregates was continually bulldozed forward and sometimes too much accumulated, though not exactly blocked, to continue the operations.

5.2. *Transfer rate and average lateral displacement*

The stabile spot inversion in the wet-plastic soil condition contributes to high transfer rate and minimal amount of the average lateral displacement. In *Fig. 12*, the transfer rate is stably between 0.7 and 0.8. The slight tendency that it decreases with the working depth is attributed to the definition of the transfer rate. Analogising form the *Fig. 8 (b)*, the thicker the slice, the less final angle of inversion, and therefore the fewer tracers likely to be counted as one transferred between the layers. The average lateral displacement is less than 17 mm, although at the greater working depths, it would be unrealistic to make it close to zero despite the adjustment of the sub mouldboard. The edge of the thicker soil slice had the more interference with an untilled wall when inverted, and the slice leaned on the other wall with the more lateral displacement. However, a notable fact that both the indices are independent of the speed implies prospective adaptability of the spot plough for high-speed operation.

The less stabile inversion in the dry-solid soil condition is expressed by both the indices, even though the limitations on the definition and measurement should be taken into account. The transfer rate in *Fig. 13* is correspondingly as low as 37% on the pooled average, and the effect of the disablement of the TDC is not statistically significant. The average lateral displacement distributes within a range of 40 mm across the zero, which explains the unstable operations from a different point of view. Nonetheless, the absolute value of the average lateral displacement is still within an acceptable range, which still shows the feasibility of the spot ploughing in this soil condition as long as the complete blocking does not take place.

The result is somewhat acceptable in the dry-solid soil condition. As shown by the average lateral displacement in *Fig. 14*, the soil was slightly displaced to the side of the main mouldboard, especially when the rotation of the TDC was disabled. Namely, the soil retarded to pile up to some height around the TDC, and tended to slide down toward the main mouldboard when released. The effect of neither the speed nor depth is apparently observed. On the other hand, the transfer rate increases with the speed. In the quasi-static operations at the speed of 60 or 200 mm/s, the mass of the soil lifted by the share and main mouldboard 'avalanched' or flowed toward the TDC, and therefore little inversion occurred. At higher speeds, however, certain inversion occurred to the originally middle and right portions, denoted by the circles and rectangles in *Fig. 8 (a)*, by being thrown up in the air. At the fastest operation, the transfer rate reached the maximum of 0.67. The least displaced tracers were the ones denoted by triangles in *Fig. 8 (c)*, probably because enough vertical acceleration was not obtained from the notched share to increase the likelihood of inverted landing. However, this mode of inversion was not intended at the design, thus an optimised design could be pursued for such a brittle condition as this dry-powdery soil.

5.3. *Effect of tilted disc coulter*

In addition to the advantages of the free rotation of the TDC already observed by first hand in the dry-solid and dry-powdery soil conditions, especially at greater depth at higher speed, there is also an effect in the wet-plastic condition. It is observed, in *Fig. 15*, in terms of the actual working depth *versus* the set depth. The working depth is, on the average, 9 mm greater than the set depth when rotating, and 19 mm greater when disabled, whilst the effect of the speed is relatively insignificant. The average forward displacement shown in *Fig. 16* also supports this effect. The fact that the disablement results in more forward displacement implies that the more forward component of the force may have been applied to the soil slice. The actual working depth therefore became far greater than the set depth, by creating the deeper cracks beneath the leading edge of the share, as already discussed with *Fig. 9 (b)*.

In this regard, less soil blocking is likely to occur with the rotating TDC at the same set depth. For example, with reference to the plots quoted by parentheses in *Fig. 15* and *16*, when the TDC was disabled, the complete blocking occurred at the set and working depths of 60 and 88 mm. On the other hand, with the coulter rotating, the blocking did not occur until the set and working depths of 68 and 74 mm, respectively. It could be thus concluded that the free rotation of the TDC reduces the likelihood of clogging, namely retardation hence blocking of the soil slice, in the wet-plastic condition.

On the other hand, the effect of the disablement was not always evident in the dry-solid soil condition in terms of the depth augmentation. On the average, the working depth was 9 mm greater than the set depth when rotating, and 11 mm greater when disabled, and no statistically significant difference was confirmed. Considering the mode of cutting that formed the soil clods, some phenomena, such as shearing, tearing, or cracking might have more predominantly appeared around the leading edge of the share rather than around the TDC. For more stabile spot ploughing in the dry-solid condition, more observation in detail and modification thereupon would be necessary.

6. Conclusions

(1) Based upon the survey, a model spot plough was proposed to operate at the working width of 150 mm, with a view to cause less soil clogging. It consisted of vertical disc coulter, share, main mouldboard, tilted disc coulter (TDC), and sub mouldboard. The maximum working depth was determined as 75 mm. The width of both the mouldboards was 40% of that of the working width, and the diameter of the TDC was 300 mm for the design.

(2) Shape of the mouldboards was defined as a helicoidal surface to treat the soil slice as a plastic and continuous body. The surface was generated by combination of parallel and rotational transformation of the cross section of the slice. The contact of the slice with the tilted disc coulter and with the furrow bottom was considered to determine the trajectory of the slice. The mouldboards were fabricated from a polyvinyl chloride plate heated and shape along the mould.

(3) In the wet-plastic soil condition, a continuous soil slice was formed, and the minimal average lateral displacement and consistently high transfer rate of the soil slice confirmed the intended performance of the spot plough. The effect of the rotation of the TDC appeared in terms of the less increase of the working depth to the set depth, the less average forward displacement, and therefore of the less likelihood of soil clogging.

(4) In the dry-solid and dry-powdery soil conditions, the average lateral displacement was still small, but the transfer rate was lower than in the wet-plastic condition. The advantage of the free rotation of the TDC was obvious at high-speed settings with the working depth close to the maximum. However, structural improvement or another approach for design

is necessary for more optimised spot ploughing in these soil conditions.

Acknowledgements

Useful literatures were personally and favourably provided from several institutions all over the world. The soil bin facility was constructed with components donated by several Faculty Members of Agriculture in Kobe University. This work was financially supported by the Grant-in-Aid for Scientific Research (1997-1998) from Ministry of Education, Japan, and by a special research fund for young researchers (1998) from Kobe University.

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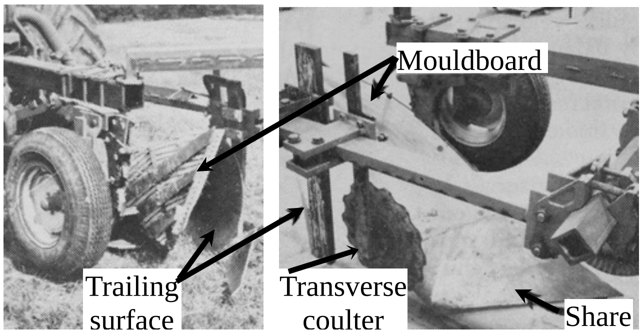
Table 1
Calculated ratios of areas defined in *Fig. 4 (c)* in terms of width-to-depth ratio:
***A*, original rectangular cross-sectional area of the soil slice; *B*, interfering area;**
***C*, allowable space for residue burial;**

Width-to-depth ratio	*Areal ratios*	
	B/A, %	*C/A*, %
4.0	1.1	107.6
3.0	1.9	68.8
2.0	4.3	30.7
*1.5	8.0	12.9
*1.27	11.6	5.7

* not considered to be suitable for design

Table 2
Experimental variables and levels

Variable	*Level*		
tilted disc coulter	rotating		disabled
soil condition	wet-plastic	dry-solid	dry-powdery
set depth, mm	30 to 70		50 70
speed, m/s	0.2 1.3		0.06 to 1.9



(a) *(b)*

Fig. 1. Prototype of 20-inch 'inverting plough' proposed by Kaufman & Totten (1972): (a) rear view; (b) front view

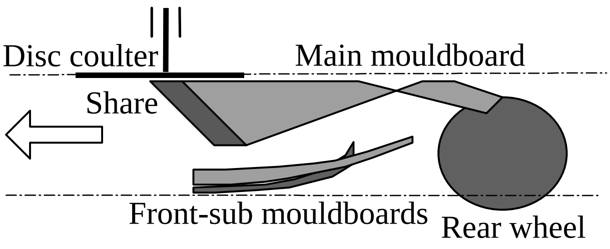


Fig. 2. Model 'spot plough' equipped with rear wheel proposed by Shoji (1997)

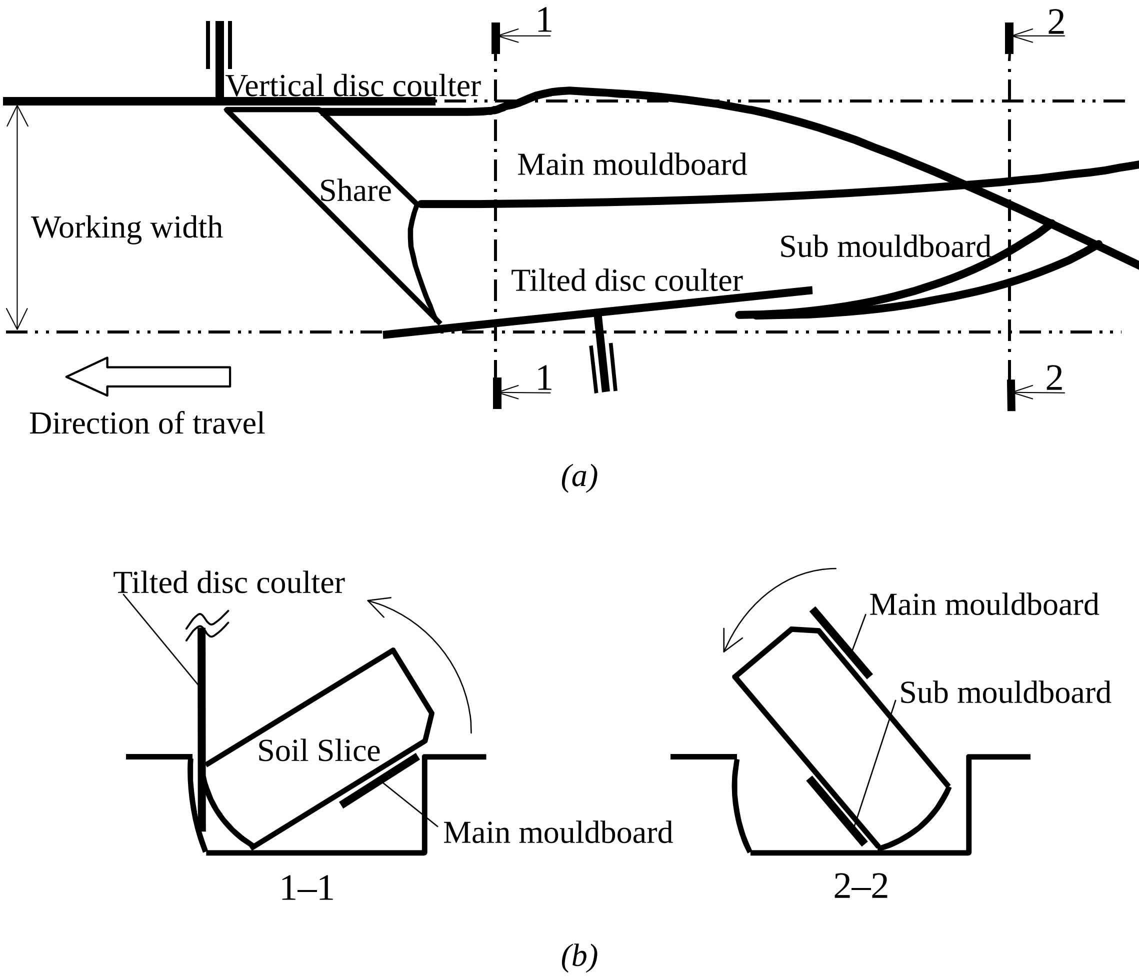
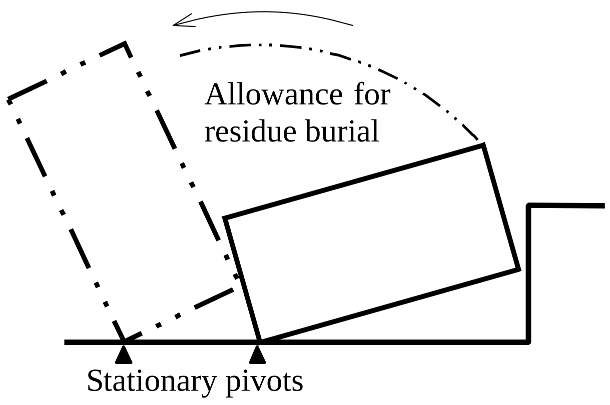
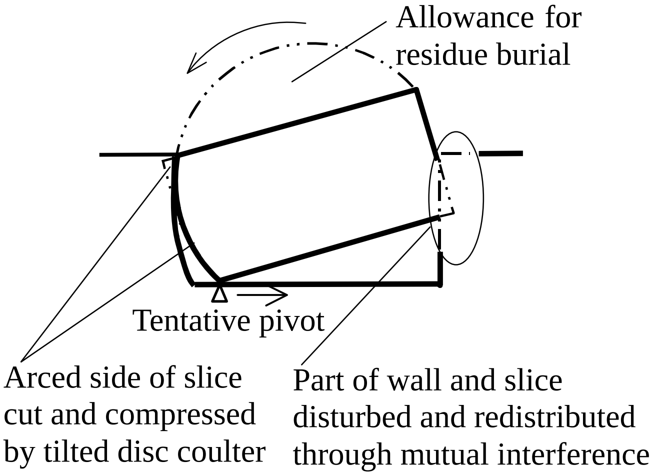


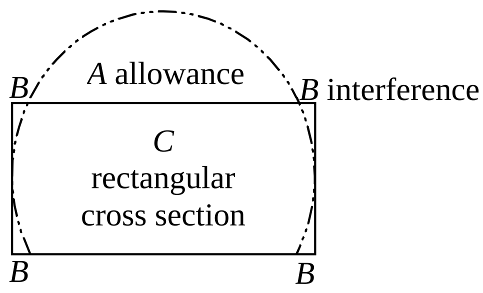
Fig. 3. Scheme of the model spot plough:
(a) plan; (b) cross sections of the components and soil slice



(a)



(b)



(c)

Fig. 4. Mode of inversion:
(a) conventional plough; (b) spot plough;
(c) notations for Table 1

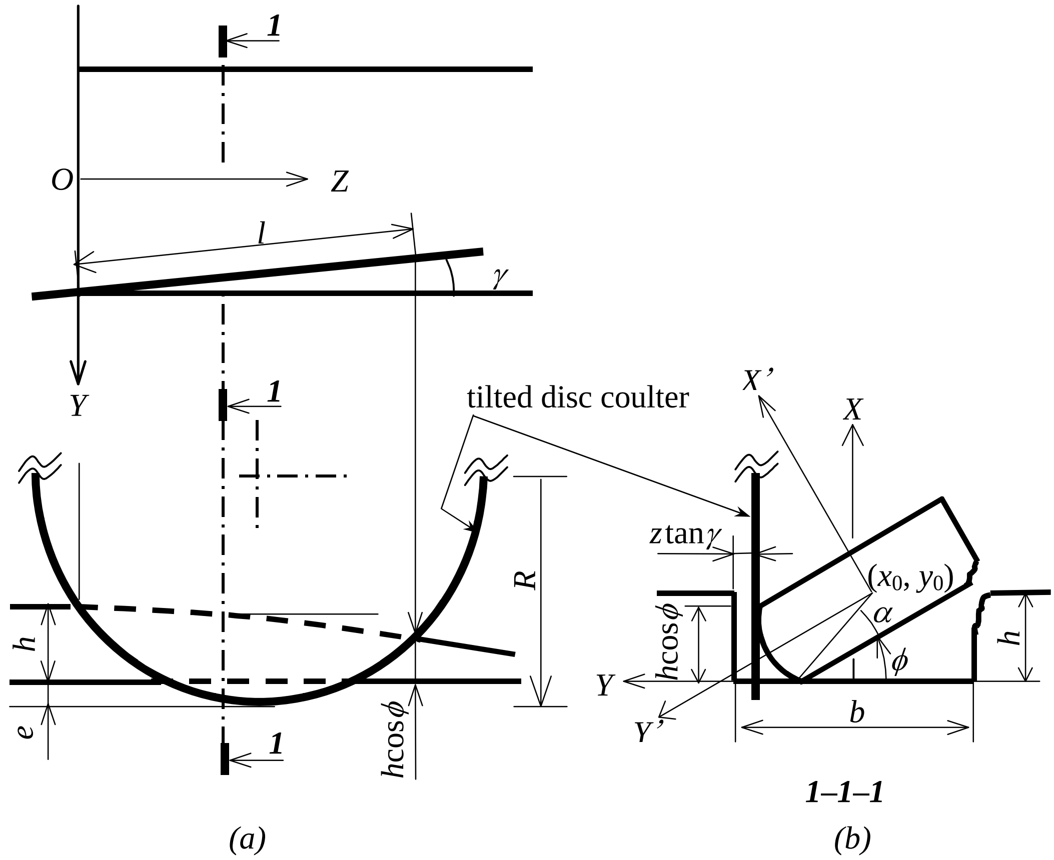


Fig. 5. Rotation of soil slice and alignment of tilted disc coulter:
(a) plan and side view; (b) cross section;
b, working width; e, supplementary depth of the tilted disc coulter; h, working depth;
l, effective length of contact with the soil slice and tilted disc coulter;
R, radius of the tilted disc coulter; (X, Y, Z), global axes;
(X', Y'), local axes fixed to the soil slice; (x_0, y_0), coordinates of the trajectory of the soil slice;
α, angle defined by width-to-depth ratio of the soil slice; γ, tilt angle of the tilted disc coulter;
ϕ, angle of inversion; ϕ_s, statically stabile angle of inversion

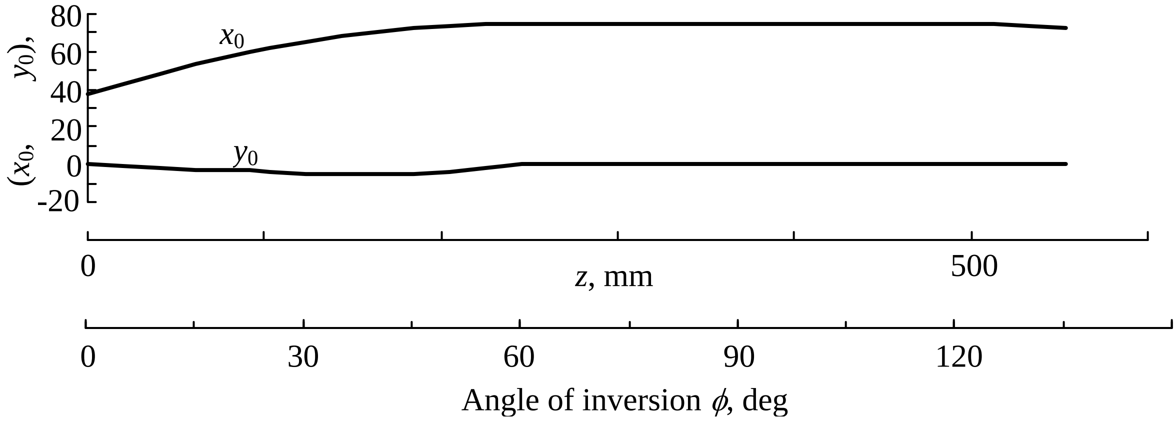


Fig. 6. Calculated trajectory of the soil slice (x_0, y_0) expressed in terms of angle of inversion ϕ and z coordinate

Fig. 7. A trimmed polyvinyl chloride plate heated and shaped into the main mouldboard along the discrete mould made of long bolts

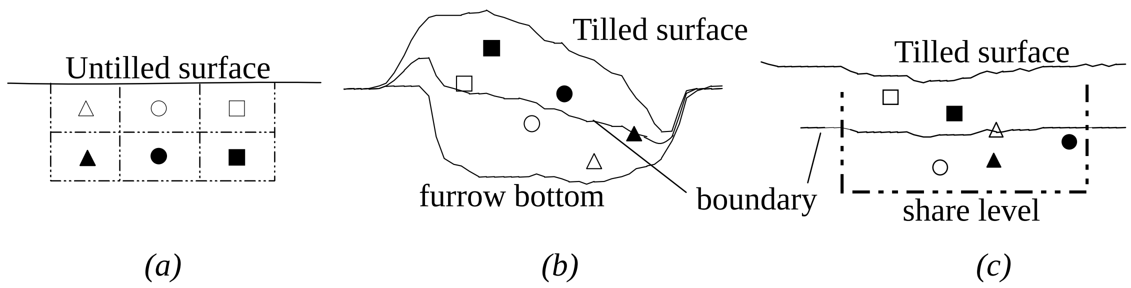
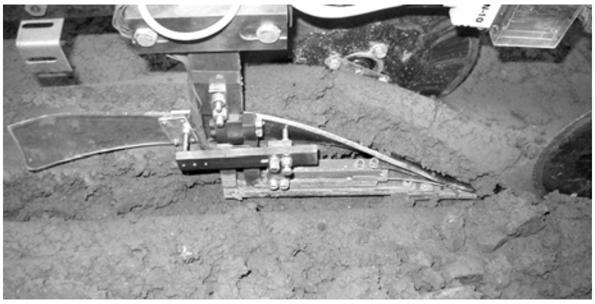


Fig. 8. Examples of cross-sectional view of tracers and surfaces:
(a) original alignment of the tracers;
(b) tilled surface and furrow bottom of wet-plastic soil, operated with tilted disc coulter rotating at the speed and depth of 1.3 m/s and 56 mm, respectively;
(c) tilled surface of dry-powdery soil, operated with tilted disc coulter rotating at the speed and depth of 1.3 m/s and 71 mm, respectively

(a)



(b)

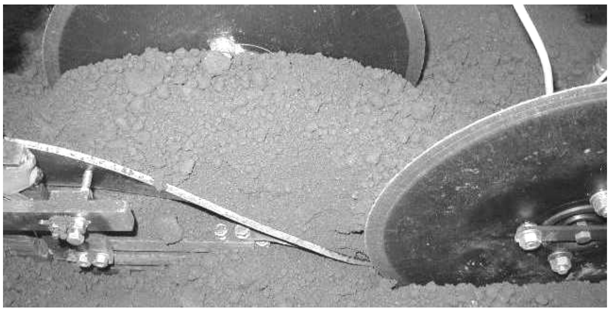
Fig. 9. Operation in wet-plastic soil, with tilted disc coulter rotating at the speed and depth of 1.3 m/s and 62 mm, respectively: (a) front view; (b) side view

(a)

(b)

Fig. 10. Operations in dry-solid soil, with tilted disc **coulter rotating***:*
(a) front view at the speed and depth of **1.3 m/s and 70 mm***, respectively;*
(b) rear view at the speed and depth of **0.2 m/s and 56 mm***, respectively*

(a)



(b)

Fig. 11. Operations in dry-powdery soil, with tilted disc coulter rotating at the speed and depth of 1.8 m/s and 71 mm, respectively: (a) front view; (b) side view

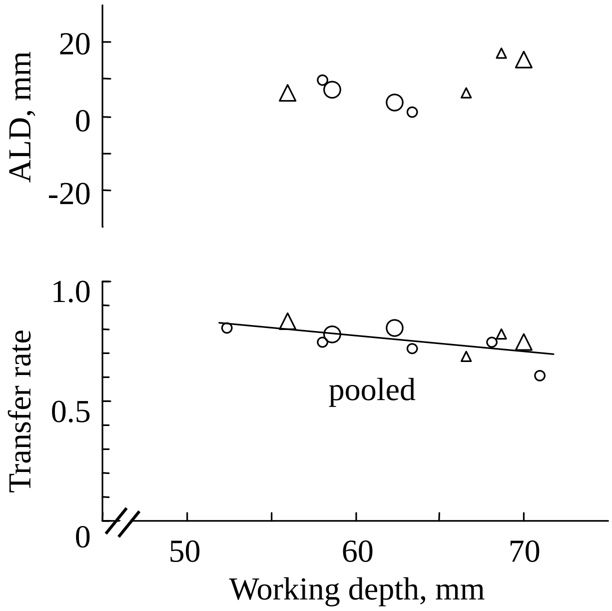


Fig. 12. Transfer rate and average lateral displacement (ALD) versus working depth, in wet-plastic soil condition with two status of tilted disc coulter at two speeds:
O, rotating; Δ, disabled;
small, 0.2 m/s; large, 1.3 m/s

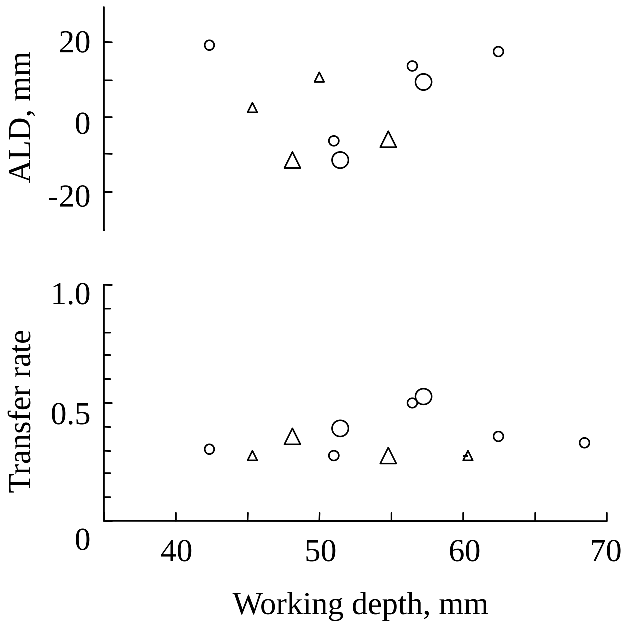


Fig. 13. Transfer rate and average lateral displacement (ALD) versus working depth, in dry-solid soil condition with two status of tilted disc coulter (TDC) at two speeds:
O, rotating; Δ, disabled;
small, 0.2 m/s; large, 1.3 m/s

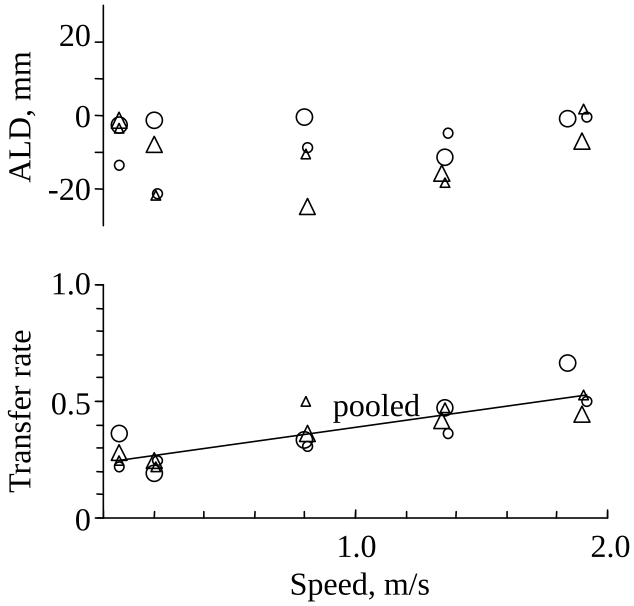


Fig. 14. Transfer rate and average lateral displacement (ALD) versus speed, in dry-powdery soil condition with two status of tilted disc coulter at two depths:
O, rotating; Δ, disabled;
small, 50 mm; large, 70 mm

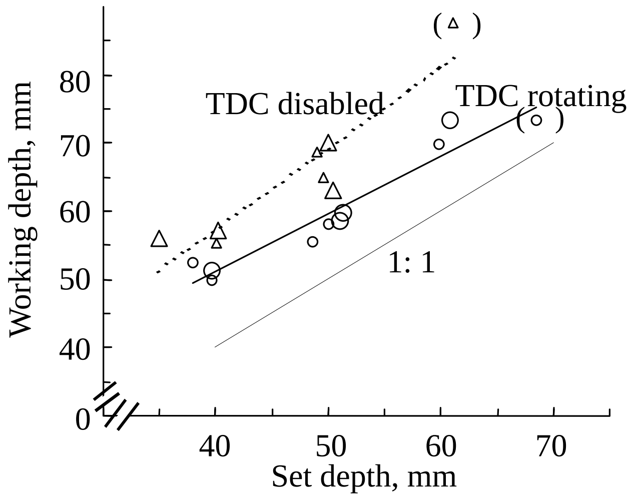


Fig. 15. Relation between set and working depth, in wet-plastic soil condition with two status of tilted disc coulter (TDC) at two speeds: O, rotating; Δ, disabled;
small, 0.2 m/s; large, 1.3 m/s;
( ), occurrence of complete blocking

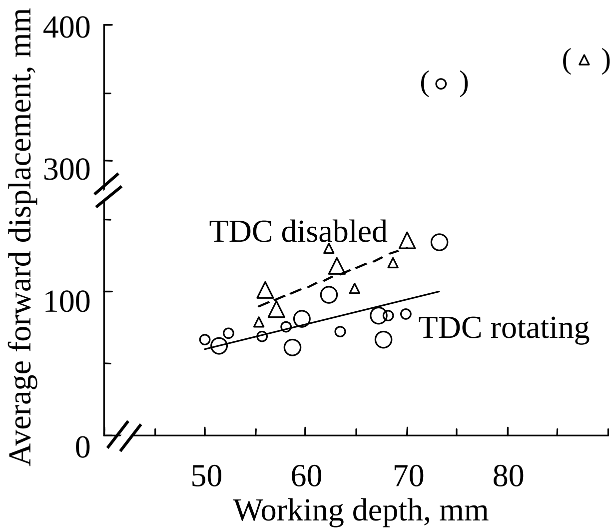


Fig. 16. Average forward displacement versus working depth, in wet-plastic soil condition with two status of tilted disc coulter at two speeds:
O, rotating; Δ, disabled;
small, 0.2 m/s; large, 1.3 m/s;
( ), occurrence of complete blocking

Fig. 1. *Prototype of 20-inch 'inverting plough' proposed by Kaufman & Totten (1972): (a) rear view; (b) front view*

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Fig. 6. *Calculated trajectory of the soil slice* (x_0, y_0) *expressed in terms of angle of inversion* ϕ *and z coordinate*

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Fig. 13. Transfer rate and average lateral displacement (ALD) versus working depth, in dry-solid soil condition with two status of tilted disc coulter (TDC) at two speeds: O, rotating; Δ, disabled; small, 0.2 m/s; large, 1.3 m/s

Fig. 14. Transfer rate and average lateral displacement (ALD) versus speed, in dry-powdery soil condition with two status of tilted disc coulter at two depths: O, rotating; Δ, disabled; small, 50 mm; large, 70 mm

Fig. 15. Relation between set and working depth, in wet-plastic soil condition with two status of tilted disc coulter (TDC) at two speeds: O, rotating; Δ, disabled; small, 0.2 m/s; large, 1.3 m/s; ( ), occurrence of complete blocking

Fig. 16. Average forward displacement versus working depth, in wet-plastic soil condition with two status of tilted disc coulter at two speeds: O, rotating; Δ, disabled; small, 0.2 m/s; large, 1.3 m/s; ( ), occurrence of complete blocking