An experimental investigation of the characteristics of and conditions for brittle fracture in two-dimensional soil cutting

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Received 11 August 1999; received in revised form 30 May 2000; accepted 29 August 2000

Abstract

Although the occurrence of different soil failure mechanisms during soil cutting operations is well attested to in the literature, not all have been successfully characterised and modelled. Such quantitative and qualitative models are essential for improving the design, selection and use of soil cutting implements, in different field soils under different field soil conditions. This paper describes an experimental investigation of the failure characteristics of, and conditions for brittle fracture in two-dimensional soil cutting. Comprehensive tests were carried out on sandy loam, clay loam and cemented sand soils using a glass-sided box apparatus and five model plane blades of rake angles 25°, 40°, 55°, 70° and 90°, respectively. Cutting forces were measured and soil deformation patterns were studied using a bead tracer technique. The failure characteristics of brittle fracture are shown to be quite different from those of shear failure. Whilst shear failure is characterised by extensive shear distortion, compaction and the regular formation of distinct slip planes, brittle fracture is characterised by crack propagation and negligible deformation within separated soil clods. This indicates the possibility of using fracture mechanics methods to model the mechanism of brittle fracture. The results further show that transitions between these two modes of failure do occur and are governed by certain soil and implement factors, namely blade rake angle, soil strength and soil–blade interface condition. For example, for three different levels of soil strength of the sandy loam at 176.0 g kg⁻¹ soil moisture content, the mean transition rake angle from brittle fracture to shear failure increased from 32.5° in S1 (c = 11.20 kN m⁻², φ = 29°) to 47.5° in S2 (c = 16.00 kN m⁻², φ = 35°) and to 62.5° in S3 (c = 23.93 kN m⁻², φ = 49°). These factors should provide a basis for the reliable prediction of the failure type, and hence the quality of soil tilth expected in two-dimensional soil cutting operations. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Soil cutting; Soil failure mechanisms; Brittle fracture; Soil deformation characteristics; Soil strength

1. Introduction

Cultivation operations are performed to create a desired tilth for plant growth. Improvements in the design and use of tillage and traction equipment in cultivation operations have been brought about by fundamental research work. For example, research studies of soil cultivation have been used to improve the design and performance of tines and sub-soiling implements (Spoor and Godwin, 1978) and agricultural discs (Godwin et al., 1985). The aim of these studies has been to acquire sufficient information for the design, selection and use of suitable tillage equipment in various soil conditions. Success in achieving this aim is still limited because not all the different

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mechanisms of soil failure that occur during cultivation operations are fully understood.

Previous investigations of soil cutting have led to the identification of some basic types of soil failure: shear failure, plastic flow, crescent failure, lateral failure and tensile failure. In shear failure, the soil is loaded by predominantly compressive stresses (passive pressures) as the cutting blade advances. Failure occurs when the applied load becomes sufficient to overcome the shearing strength of the soil. A block of soil, having a logarithmic spiral shape, is separated and slides forwards and upwards over the undisturbed soil and the blade surface. With further movement of the blade, the process is repeated until another block of soil is sheared off. Fig. 1(a) shows typical shear failure as observed in front of cutting blades. In the figure, the blade working depth is denoted by \( z \). Shear failure in front of a cutting blade is very well known and has often been reported (Payne, 1956; Sohne, 1956; Siemens et al., 1965). Olson and Weber (1966), Elijah and Weber (1968) and Stafford (1981) reported changes from “shear” failure to “flow” failure corresponding to increase in implement speed. In flow failure, no distinct planes of shear are evident but there is general strain of the entire soil mass. Kosrotsyn (1956), O’Callaghan and Farrely (1964) and Godwin and Spoor (1977) reported changes in the nature of the soil disturbance and mode of failure corresponding to changes in the soil conditions, tine rake angle and aspect ratio (working depth/blade width). It was shown that below certain working depths, termed critical depths, soil movement changes from a predominantly forward and upward form, crescent failure, to a mainly forward and sideways one, lateral failure. This is schematically illustrated in Fig. 1(b). Lateral failure is characterised by large plastic soil deformation and is a particularly useful mode of failure in the establishment of mole channels (see Spoor and Godwin, 1978; Spoor and Fry, 1983). In tensile failure, the soil splits ahead of the cutting edge of the blade and a crack is propagated. The crack rapidly extends until it intersects the soil surface thus separating a clod. Fig. 1(c) is a schematic illustration of typical tensile failure for an inclined cutting blade. This type of failure has been reported by a number of research workers (Drees, 1956; Selig and Nelson, 1964; Elijah and Weber, 1968; Koolen, 1972, 1973).

Of the basic types of soil failure identified above, both crescent failure and lateral failure below the critical depth are peculiar to three-dimensional soil cutting by narrow implements. Soil cutting with a narrow blade above the critical depth is quite different from soil cutting with a wide blade. In the former case, the soil cut is crescent shaped, extending sideways on both sides of the cutting blade. In contrast, in two-dimensional soil cutting with relatively wide blades, the width of soil cut corresponds almost entirely to the width of the cutting tool. The proportion of the cut soil beyond the width of the cutting tool is normally considered negligible. Thus, in comparison, a greater amount of soil is moved per unit of tool width in three-dimensional soil cutting than in two-dimensional soil cutting. Furthermore, whilst two-dimensional shear failure involves predominantly compressive stresses, lateral soil tensile stresses are common during the sideways expansion of the cut soil crescent in three-dimensional soil cutting.

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Fig. 1. A schematic illustration of typical failure patterns in soil cutting: (a) shear failure; (b) crescent failure and lateral failure; (c) tensile failure. \( z \): blade working depth; \( d_c \): critical depth.
The foregoing differences between two- and three-dimensional soil cutting not withstanding, the mechanism of shear failure has received considerable attention and the shear parameters, cohesion \( c \) and angle of internal shearing resistance \( \phi \) have been used to model shear failure (Sohne, 1956; Siemens et al., 1965; Hettiaratchi and Reece, 1974, 1975), flow failure (Stafford, 1984), crescent failure (Godwin and Spoor, 1977; McKyes and Ali, 1977) and lateral failure below the critical depth (O’Callaghan and Farrely, 1964; Godwin and Spoor, 1977). It has, however, been pointed out that the pulverisation of soil and formation of a good tilth often relies on brittle fracture by the propagation of tensile cracks (Chandler, 1984; Hatibu, 1987).

In the field of soil physics, it has been recognised that brittle fracture is important in soil processes pertinent to the development and management of soil structure (Dexter, 1975; Braunack et al., 1979; Snyder and Miller, 1989; Mullins et al., 1990). The soil pores are regarded as flaws or microcracks inherent within the soil matrix. Braunack et al. (1979) reported a progressive development of failure by the propagation of these microcracks at soil water potentials less than \(-100 \text{ kPa}\). Miller (1978) proposed that the initiation of ice lenses in frozen soil (secondary frost heave) is a physical analogue of tensile failure (brittle fracture) in unfrozen, unsaturated soils. The occurrence of brittle fracture is particularly common in hardsetting soils, especially during rapid and intense drying of these soils in hot dry regions. It has been pointed out that the timing of cultivation operations in these soils is crucial and it is often difficult to produce a seedbed that is neither too cloddy nor too dusty (Mullins et al., 1990).

As pointed out earlier, much of the previous work on soil cutting has been focussed on soils failing according to the Mohr–Coulomb rigid–plastic model of shear failure. Considering the importance of brittle fracture in different soil processes that are vital to agricultural production, it is surprising that brittle fracture in soil cutting has largely been neglected. Moreover, not much is known about soil deformation prior to failure, particularly when this type of failure occurs. Knowledge of the soil deformation characteristics, used in conjunction with observed failure patterns, is very important in the choice of appropriate mechanical properties to characterise the failure mechanism. This study was carried out to acquire a more comprehensive understanding of two-dimensional soil cutting operations, particular attention being given to the mechanism of brittle fracture. Detailed experiments were carried out to study soil deformation characteristics in soil cutting and to analyse soil and implement conditions in which brittle fracture will occur.

2. Experimental procedure

2.1. Soils and equipment

In order to investigate the different soil and implement factors influencing brittle fracture unambiguously, the experimental work has been carried out using model plane cutting blades and a glass-sided box in the laboratory. Three soil types, described in Table 1, have been used under different conditions of soil strength as shown. Soil shear strength properties and soil–blade interface properties were determined from triaxial tests and sliding friction tests, respectively. Each blade had a width of 98 mm. The blades, each designed to ensure a constant working depth of 70 mm, had rake angles of 25°, 40°, 55°, 70° and 90°, respectively. Polished (angle of soil–blade interface friction, \( d = 16° \) or 17°) and rough (\( d = 42° \) or 47°) soil–blade interface conditions were considered to cover the two extremes of interface conditions that occur in soil cutting operations. Rough soil–tool interface conditions may arise, either due to the material from which the tool is made, or due to the adherence of a layer or “body” of soil to the surface of the tool during soil cutting. In instances where the latter obtains, the layer becomes “fixed” to the tool altering the soil–tool interface properties. Whereas polished soil–blade interface conditions were obtained by machining blade surfaces, rough soil–blade interface conditions were obtained by bonding a coarse grained builders’ sand (all particles <2 mm, 25% of particles finer than 1 mm) onto the blade surfaces using a thin film of Araldite adhesive. The internal dimensions of the glass-sided box consist of a length of 800 mm, a width of 100 mm and a depth of 250 mm.

2.2. Soil movement and deformation studies

Soil preparation in the glass-sided box entailed compacting the soil to a pre-determined density which
was also used in the determination of strength parameters. The soil was compacted in 15 mm layers. A variant of the bead tracer technique used by Spoor and Fry (1983) was developed and used to record soil deformation and movement patterns relative to blade movement. The technique involves the placement of beads in a rectangular grid within the soil. The grid is made up of smaller squares of beads each of which can be regarded as a small unit volume element. The beads were placed right up against the front glass to facilitate measurements.

Spherical beads having a diameter of 4 mm were sliced in half to give them a flat surface for contact with the glass sheet. The centre of the surface of each one was marked with a dot. The trajectories of these dots (points) were recorded during experiments. Beads of four different colours were used to ensure that beads of successive rows were not mistaken for one another during soil deformation and failure. Bead spacing along rows and columns was approximately 15 mm. Fig. 2(a) is a schematic illustration of the blade position and grid arrangement at the beginning of an experiment. Fig. 2(a) shows the nomenclature adopted for reference to each unit element within the entire grid. For example, the element marked with × in its centre will be referred to as unit element 4C.

At the beginning of each experiment, the initial position of each bead within the grid and the position of the blade, prior to soil disturbance in the vicinity of the beads, was recorded. This was done on a fresh sheet of acetate and was marked “Sheet 1” for each experiment. In this way, actual initial bead positions which might have been slightly altered due to the compaction process were accounted for. For subsequent regular horizontal displacements of the cutting blade, bead and blade positions, as well as observed crack profiles and shear planes, were recorded on fresh sheets of acetate. The bead positions were recorded to an accuracy of $1.0 \text{ mm}$ in each coordinate axis (i.e., $X$ and $Y$). For each sheet, strains and volume changes were quantified with reference to “Sheet 1” using a procedure similar to that of Spoor and Fry (1983). Fig. 2(b) shows the initial and final positions of a unit element of the grid due to deformation. The points $a$, $b$, $c$, $d$ represent initial bead positions and the points $a'$, $b'$, $c'$, $d'$ represent the final bead positions. For each unit element, the volume change in $a'b'c'd'$, denoted by $\Delta V$, was determined as a percentage of the initial volume $abcd$. Thus, a negative value ($-\Delta V$) indicates net compaction and a positive value ($\Delta V$) indicates net dilation of the unit element.

Further extraction and processing of data from the acetate sheet recordings was achieved using a computer-controlled digitiser and an $X$–$Y$ plotter. Thus, successive soil deformation diagrams could be plotted and the associated volume changes computed. Fig. 2(c) shows the initial and final configurations of a unit element of soil which have been severely deformed. In such cases, shear failure occurred with large plastic deformations and distortion of the bead configuration. As a result of this distortion, the calculations for percentage volume change in such cases produce

| Soil type       | Soil series’ code | Moisture content (g kg$^{-1}$)$^a$ | Density (Mg m$^{-3}$) | Shear strength parameters $c$ (kN m$^{-2}$) $\phi$ (°) | Soil–blade interface properties
<table>
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<td></td>
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<td></td>
<td>Polished $a$ (kN m$^{-2}$) $\delta$ (°)</td>
</tr>
<tr>
<td>Sandy loamb$^b$</td>
<td>S1 176.0</td>
<td>1.26</td>
<td>11.20</td>
<td>29</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>S2 176.0</td>
<td>1.33</td>
<td>16.00</td>
<td>35</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>S3 176.0</td>
<td>1.52</td>
<td>23.93</td>
<td>49</td>
<td>0.000</td>
</tr>
<tr>
<td>Clay loam$^c$</td>
<td>CS1 234.7</td>
<td>1.16</td>
<td>9.69</td>
<td>24.5</td>
<td>0.0593</td>
</tr>
<tr>
<td></td>
<td>CS2 234.7</td>
<td>1.40</td>
<td>18.38</td>
<td>40</td>
<td>0.0765</td>
</tr>
<tr>
<td>Cemented sand$^d$</td>
<td>SC2 64.1</td>
<td>1.49</td>
<td>29.90</td>
<td>55</td>
<td>0.000</td>
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$^a$ All soil moisture contents were determined by the gravimetric method.

$^b$ 640 g sand kg$^{-1}$, 190 g silt kg$^{-1}$, 170 g clay kg$^{-1}$, 17 g organic matter kg$^{-1}$ (FAO classification: Luvisol).

$^c$ 485 g sand kg$^{-1}$, 261 g silt kg$^{-1}$, 254 g clay kg$^{-1}$, 21 g organic matter kg$^{-1}$ (FAO classification: Planosol).

$^d$ Builders’ sand, all particles <2 mm, 25% of particles finer than 1 mm, mixed with 91 g ordinary Portland cement per kilogram.
spurious values, e.g., $\Delta V = -134\%$. Since it is impossible to have more than 100% compaction, it is clear that such values result from distortion of the unit element and represent extensive shear failure.

2.3. Investigation of soil and implement variables

In the investigation of soil and implement variables influencing brittle fracture, two sets of experiments were carried out in which the forces on cutting blades were measured. The first set was carried out in the glass-sided box whilst the second was carried out using a modified glass-sided box apparatus, having the same internal dimensions as the former. Soil preparation for both sets of experiments was similar to that described above except that beads were not placed within the soil. For the modified glass-sided box experiments, however, after soil preparation, the glass sheets on both sides of the soil block were carefully removed and replaced with shallower glass sheets and side trays (see Aluko, 1988). This modification provided firm support for soil well below blade working depth whilst eliminating extraneous side forces (due to soil–glass interaction) on soil within, and just below the working depth. To record observations of rupture blocks, a succession of still photographs at different blade displacements with the camera fixed relative to the blade was taken during each experiment. A graduated 10 cm scale was placed against the front glass side to facilitate reliable measurements of rupture distances from prints and slide projections. Horizontal and vertical cutting force components were measured using an extended octagonal ring transducer in conjunction with a signal amplifier and an $X$–$Y$ recorder. The soil and implement variables considered were rake angle, soil strength and soil–blade interface condition. The influence of the confining glass sides was also investigated for the sandy loam soil (S1, S2, S3). In all cutting experiments, the tool was held in a fixed position whilst the soil box was moved horizontally at a constant speed of 5 mm/s. Statistical analyses, namely $t$-test and analysis of variance, were carried out on rupture distance data and cutting force data, respectively, using SAS software (SAS Institute, 1987).

3. Results

3.1. Soil deformation results

In the presentation that follows, micro deformation refers to the compression, dilation or shearing of a unit...
element. Macro deformation, on the other hand, refers to the overall distortion of separated soil clods relative to their initial configurations within the original grid. A soil clod comprises a number of unit elements.

Fig. 3 shows typical examples of soil deformation in shear failure (a, b) and brittle fracture (c, d). Fig. 3(a) and (b) shows stages of soil deformation occurring in a sandy loam S2 during cutting with a polished vertical blade. The initial undisturbed soil grid is shown prior to blade movement ($x = 0$). At a forward blade displacement of 175 mm, a portion of the grid now falls within the zone of disturbed soil. Distinct slip planes occurred as shown in Fig. 3(b). The lower slip plane demarcates relatively undisturbed soil from disturbed soil and the percentage volume change $\Delta V$ of some unit elements from both these zones were examined. Referring to the grid nomenclature shown in Fig. 2(a), values of $\Delta V$ for elements 1A, 3A, 4A, 1B and 2B within the disturbed zone of soil were $-80$, $-111$, $-80$, $-89$ and $-84$, respectively. For elements 6A, 5B, 4C and 3D within the undisturbed portion of the soil grid, $\Delta V$ was found to be $1$, $-5$, $-5$ and $7$, respectively. An experimental error of approximately $\pm 5\%$ may arise in the $\Delta V$ values due to errors in the recorded coordinates. This would be more obvious in the $\Delta V$ values within the relatively undisturbed portion of soil. However, it can be seen that extensive shear distortion and some compaction had taken place within the disturbed zone of soil. Elements 1E–9E showed little or no compaction or dilation indicating that no significant soil disturbance occurred below the working depth of the blade. In general, in shear failure, large micro and macro deformation occur due to the compressive and shear stresses imposed on the soil. Soil disturbance decreased with increasing distance from the blade.

Fig. 3(c) and (d) shows stages of soil deformation occurring in the same sandy loam S2 during cutting with a polished 25° raked blade. Fig. 3(c) shows the initial undisturbed soil grid at the beginning of the experiment. Fig. 3(d) shows the soil deformation at a forward blade displacement of 175 mm. The leading edge of the blade has penetrated the soil grid and two cracks have developed across the grid as shown. The $\Delta V$ values for unit elements 2A, 3A, 4A, 3C, 5B and 7A, within the soil clods bounded by the crack profiles, were $11$, $-3$, $15$, $-1$, $2$ and $-1$, respectively. Thus, very little deformation occurred within the soil clods bounded by the crack profiles. In Fig. 3(d), the second crack started to propagate before the first one was fully formed (i.e., before the first clod was separated). One possible explanation for
this is that the influence of the glass sides may have had a stifling effect on crack growth. This will subsequently be discussed in the light of further experimental investigations, in which this constraint was eliminated. In general, in brittle fracture (tensile failure), little or no micro or macro deformation takes place as the blade progressively cuts into the soil. In this type of failure, soil clods may be lifted, separated (torn off) and reoriented. Bits of soil may fall off due to the fracture process but the basic macro structure experiences little or no shear or compaction.

3.2. Rupture block analysis

Typical examples of brittle fracture are presented in Fig. 4. The figure shows different stages of soil cutting in a sandy loam soil S3, using a rough blade with a rake angle of 25°. In Fig. 4(a), cutting has been initiated by the penetration of the blade tip into the soil. It can be seen that whilst only the tip of the blade had penetrated the soil, the crack had propagated rapidly and had curved towards the soil surface. Thus, crack propagation occurred at a much faster rate than tool speed. The crack direction was initially slightly inclined below the horizontal. It subsequently became inclined above the horizontal and finally sloped more steeply as the crack approached the soil surface. With additional blade movement the crack opened further and the soil clod, almost fully formed, began to move up the blade surface (Fig. 4(b)). As the clod moved up the blade surface, a localised “abrasive” action took place at the clod–blade contact interface. This was due to the high interface friction (see Table 1) as well as some adhesion. A thin layer of soil, immediately adjacent, adhered to the blade surface but the clod retained its basic shape as it moved further up the blade surface (Fig. 4(c)). Prior to further cracking and formation of a new soil clod, bits of soil were chipped off as the blade progressed. With further blade movement, cutting was again initiated as shown in Fig. 4(d). This time, the crack direction was inclined above the horizontal. As the blade continued to advance, the crack opened and propagated further, heading straight for the soil surface (Fig. 4(e)). Simultaneously, the new clod began to move up the blade surface. The appearance of some soil–soil sliding in Fig. 4(d) and

![Fig. 4. Brittle fracture in a dense sandy loam soil (S3: \( c = 23.93 \text{kN m}^{-2}, \phi = 49^\circ \)) with a rough 25° raked blade. Blade working depth \( z = 70 \text{ mm} \). \( \alpha \): blade rake angle; \( x \): forward horizontal blade displacement.](image-url)
was due to the effect of interface friction on clod travel over the blade surface. However, this sliding was minimal and had no effect on the actual failure mechanism. In Fig. 4(f), the first clod had fallen off the blade, the second clod had travelled up the blade surface and some crumbs of soil had been chipped by the blade tip.

Experimental clod sizes, where brittle fracture occurred, were measured and compared with the corresponding theoretical predictions assuming shear failure (see Hettiaratchi and Reece, 1974, 1975). A rupture distance \( f \) has been defined as the forward horizontal extent of the soil clod, taken from the blade tip. Rupture distances thus determined, covering the range of rake angles \( (20–60°) \) where brittle fracture frequently occurred, have been plotted in non-dimensional form \( f/z \) (Fig. 5(a)–(f)). For each experiment, the theoretical calculation of the rupture distance was based on the actual values of internal and surface friction angles, measured for the particular soil and soil–blade interface conditions, respectively (see Table 1). In general, both the experimental and theoretical rupture distances increased with rake angle. However, it can be seen that the experimental values were considerably larger than the theoretical values. Indeed, the results of the \( t \)-test showed that the experimental non-dimensional rupture distances were significantly higher than the theoretical values at 5% probability level.

3.3. Cutting forces and failure mechanisms

In general, over the full range of experiments carried out, changes in the failure mechanism from...
brittle fracture to shear failure (or vice versa) were often observed. A typical example of the change from brittle fracture to shear failure, with rake angle, is shown in Fig. 6. Fig. 6(a)–(d) shows different stages of brittle fracture in a clay loam soil CS1, using a polished 25° raked blade. These figures show crack initiation (Fig. 6(c)) and subsequent crack opening (Fig. 6(d)), rather than soil–soil sliding and the intermittent formation of distinct shear planes. The first crack, which had already been initiated prior to Fig. 6(a), is seen opening further in Fig. 6(a) and (b) as the first clod travels over the blade surface. At an increased rake angle of 40° in the same soil, the failure mechanism changes to shear. Soil–soil sliding as well as distinct slip planes, which separate successive rupture blocks of soil, can now be seen clearly in Fig. 6(f)–(h). The effects of changes in the experimental variables, on failure patterns and associated cutting forces, were studied. These may be distinguished as follows.

### 3.3.1. Effect of soil strength

The forces on polished cutting blades in the sandy loam soil at different strengths (S1, S2, S3) were plotted as a function of blade rake angle \( \alpha \) in Fig. 7. Only the modified glass-sided box experiments were considered here. As expected, both draft and vertical forces on a particular blade increased with increasing soil strength. In general, the draft force for each soil strength increased gradually over the range of rake angles from 25° to 70°. Thereafter, the draft increased at a more rapid rate between 70° and 90°. The analysis of variance showed that changes in both blade rake angle and soil strength significantly \((P = 0.01)\) affected the draft force \( V/H \), as well as the resultant force \( V/H \). The general trend of the curves shown in Fig. 7 agrees with previous reports by research workers (Payne and Tanner, 1959; Dransfield et al., 1964; Osman, 1964; Siemens et al., 1965). Thus, a rake angle of 25° would seem to be an optimum rake angle in the minimisation of draft forces on cultivation blades.

It is interesting to note in Fig. 7 that though the general trend of draft force agrees with previous research work, there was an important difference in the failure mechanism at low rake angles (25° < \( \alpha \) < 55°). It can be seen that in general, at higher rake angles, shear failure occurred. However, as the rake angle was decreased from the vertical to the lower rake angles, a point was reached where there was a transition in failure type from shear to brittle fracture. In Fig. 8, the mean transition rake angle \( \alpha_t \), from brittle fracture to shear failure, was plotted against selected soil strength parameters, namely cohesion \( c \) (Fig. 8(a)) and angle of internal shearing resistance \( \phi \) (Fig. 8(b)), for the sandy loam and clay loam soils. For the sandy loam soil, \( \alpha_t \) increased from 32.5° at a cohesion of 11.20 kN m\(^{-2}\) to 47.5° at a cohesion of 16.00 kN m\(^{-2}\) and to 62.5° at a cohesion of 23.93 kN m\(^{-2}\). For the clay loam soil, \( \alpha_t \) increased from 32.5° at a cohesion of 9.69 kN m\(^{-2}\) to 55° at a cohesion of 18.38 kN m\(^{-2}\). For both soils, similar increases in \( \alpha_t \) were obtained when plotted against the angle of internal shearing resistance \( \phi \) (Fig. 8(b)).

Although the present results, particularly for the sandy loam soil, suggest that the relationship between \( \alpha_t \) and \( c \) (or \( \alpha_t \) and \( \phi \)) might not be a linear one, further investigation, involving more data points, is required to establish the precise trend of this relationship. In general, however, it was evident that as the soil strength increased, the rake angle at which there was a transition from brittle fracture to shear failure gradually increased. Similar results were obtained for the cemented sand soil at different strengths (Aluko, 1988). Considering Fig. 8(a), it appears that, for the same value of cohesion \( c \), the mean transition rake angle for the clay loam was slightly higher than the corresponding value for the sandy loam. This observation also requires further investigation with the acquisition of more data points.

### 3.3.2. Effect of interface condition

A typical example of the effect of the soil–blade interface condition on the cutting forces is shown in Fig. 9. Here also, only the modified glass-sided box experiments were considered. It can be seen that, for this sandy loam soil S3, a change in interface condition from polished (\( \delta = 17° \)) to rough (\( \delta = 42° \)) led to an increase in the draft force on a particular blade. However, it appears that the main effect of increasing interface roughness was to decrease, or reverse, the magnitude and direction of the vertical force component on a blade. This altered the direction of the resultant force on the blade (or the ratio \( V/H \) of the cutting force components) considerably. The analysis of variance showed that the change in interface
Fig. 6. Change in failure mechanism with rake angle in clay loam soil CS1 ($c = 9.69 \text{ kN m}^{-2}, \phi = 24.5^\circ$). Blade working depth $z$ was 70 mm. 
\(\alpha\): blade rake angle; \(x\): forward horizontal blade displacement.
condition significantly \( (P = 0.01) \) affected the vertical force \( V \), as well as the resultant force \( V/H \).

In addition to changing the direction of the resultant force on a particular blade, an increase in interface roughness promoted a transition in failure mechanism from brittle fracture to shear failure. In soil S3 (Fig. 9), the failure transition rake angle occurred between 55° and 70° for polished blades and between 25° and 40° for rough blades. Therefore, brittle fracture occurred using the polished 40° blade whereas the same blade, when given a rough surface, induced shear failure.

3.3.3. Effect of glass sides

Typical examples of the influence of glass sides on cutting forces and failure mechanisms are shown in Fig. 10. The figure shows two sets of measured forces on polished cutting blades in the sandy loam soils S2 and S3. One set of forces corresponds to experiments in the glass-sided box whereas the other set corresponds to experiments in the modified glass-sided box (i.e., with shallower glass sheets and side trays). The figure clearly shows that in general, both the draft and vertical forces on any blade were considerably higher for experiments with the glass sides. This observation applies to the different soil types and soil strengths. In the sandy loam S2, there was a percentage increase of 141.2% in the value of the draft force on a 25° raked blade due to the influence of the glass sides. At a larger rake angle of 55°, the percentage increase in draft force had increased to 315.9% and for a vertical blade, the percentage increase in draft force was found to be 228%. In soil S3, the percentage increase in the draft
forces for 25° and 55° raked blades were 162.4 and 260.9%, respectively. The analysis of variance showed that the influence of the glass sides significantly affected both draft and vertical forces. Similar results were obtained for the cemented sand SC2 (Aluko, 1988).

These results show that in general, the percentage increase in draft force due to the influence of the glass sides, increased with increasing rake angle. This indicates that the effect of the glass sides was twofold: the soil being cut was subjected to soil–glass interface friction as well as extraneous side forces which were normal to the plane of cutting. Had the effect of the glass sides been purely frictional, the increase in draft force would be expected to be constant regardless of blade rake angle. However, an increase in the normal side forces as the rake angle increased was believed to account for the observed trends in the percentage increase of draft force due to the glass sides.

Probably, a more important observation was the effect of the glass sides on the ensuing failure mechanism. Fig. 10 shows that the influence of the glass sides promoted a transition from brittle fracture to shear failure for a particular blade. In soil S2, the failure transition rake angle occurred between 40° and 55° for experiments without the influence of the glass sides. However, with the glass sides, the failure transition rake angle occurred between 25° and 40°. Also in soil S3, the failure transition rake angle occurred between 55° and 40° for experiments with the glass sides. Similar changes in the failure mechanism occurred in soils S1 and SC2 (Aluko, 1988). These results contradict the observations of previous research workers (Siemens, 1963; Godwin and Spoor, 1977). Siemens (1963) reported that the glass sides did not appear to affect the development of the slip surfaces and the soil movement. Godwin and Spoor (1977) also reported that soil–glass friction had not significantly affected the failure pattern. However, in the present investigation, changes in the failure mechanism as

![Fig. 9. Effect of interface condition on cutting forces and failure mechanisms in a dense sandy loam soil, S3 (c = 23.93 kN m⁻², φ = 49°).](image)

![Fig. 10. Influence of glass sides on cutting forces and failure mechanisms with polished blades.](image)
well as the retardation of crack growth occurred due to the influence of the glass sides.

4. Discussion

The deformation diagrams presented in Fig. 3(a) and (b) show that shear failure was characterised by extensive shear distortion, compaction and the formation of distinct shear planes. In conjunction with Figs. 4 and 6(a)–(d), Fig. 3(c) and (d), on the other hand, shows that brittle fracture was characterised by crack propagation and within the separated clod, there was negligible deformation. The soil mechanical properties of cohesion $c$, angle of internal shearing resistance $\phi$ and the soil–tool properties of adhesion $a$ and angle of soil–metal friction $\delta$, adequately characterised the mechanism of shear failure. Whilst these mechanical properties do not suffice for brittle fracture, the present observations of its deformation characteristics indicate that within limits, the behaviour of brittle agricultural soils in this failure mechanism can be macroscopically considered to be elastic. This leads to the important conclusion that the mechanism of brittle fracture can be modelled using fracture mechanics methods for elastic–brittle materials.

Though crack propagation usually proceeds towards the free soil surface, the present results show that in general, the direction of cracking varied (Fig. 4). It was therefore not possible to associate a specific clod shape or size with a particular blade and soil condition as is done in the analysis of shear failure. However, the fissures of cracking were well defined and separated clods remained intact as they traversed the blade surface. The comparison of experimental and theoretical rupture distances (Fig. 5) clearly show that the soil clods produced in brittle fracture were significantly larger than those expected when shear failure was assumed to occur.

It has previously been considered that low rake angles and changes in interface conditions lead to stress discontinuities and soil wedge formation (Hettiaratchi and Reece, 1974, 1975). The results of the present work (Figs. 7–9) show that more often, in compact brittle soils, there was a change in failure mechanism from shear to brittle fracture as the rake angle was decreased from the vertical. Even when the interface is rough, brittle fracture can still occur at low rake angles (see Fig. 4). The results show that the transition between the different failure mechanisms was not marked by a drastic change in the patterns of the measured draft and vertical forces with rake angle. However, there was a significant change in the type of soil break-up and the size of clods produced. In general, brittle fracture produced large, relatively undeformed soil clods whereas the soil clods produced from shear failure were smaller and had undergone extensive deformation and compaction. This has interesting implications for soil cutting and loosening operations. For example, in the cultivation of brittle agricultural soils, the engineer must base his/her design or selection of an appropriate cutting implement on both the type of soil loosening desired and the resultant force requirement of the implement. It may therefore be necessary to settle for an optimum cutting force, rather than a minimum, if the minimum force corresponds to an unacceptable resultant tilth. Prediction of the expected failure mechanism is therefore as important as the prediction of the cutting forces. The present results show that changes in the rake angle, interface properties and soil strength often led to changes in the failure mechanism that occurred. Therefore, the criteria required for the reliable prediction of the failure type in a given situation, should take into consideration the effects of these soil and blade factors.

The effect of soil–glass interaction during cutting, on the ensuing failure mechanism, has interesting implications for cutting blades of varying aspect ratios (working depth/width). In general, for wide two-dimensional blades, side or end effects are considered negligible, whereas for narrow three-dimensional blades, they are not negligible. In the field, the firm surrounding soil exerts considerable confining stresses on the soil being cut by cutting blades in the latter category. The influence of the glass sides can be compared to the side effects (or confining stresses) on narrow blades having a large aspect ratio. This leads to the following hypothesis: for a fixed low rake angle ($20^\circ < \alpha < 55^\circ$) and working depth in a compact agricultural soil, a transition in failure mechanism from brittle fracture to shear failure will occur at some point as the aspect ratio (blade working depth/blade width) is increased.

Although further investigations of soil cutting, using blades having the same working depth and rake
angle but different widths, are required to examine the validity of the foregoing hypothesis, there is complementary evidence that decreasing confining pressure, during triaxial testing of cylindrical soil samples, increases soil brittleness and increasing confining pressure, increases ductility (Spoor and Godwin, 1979; Hettiaratchi and O’Callaghan, 1980; Hatibu, 1987).

5. Conclusions

Specific conclusions from this investigation may be summarised as follows:

1. Deformation characteristics of brittle fracture were significantly different from those of shear failure. Whilst shear failure was characterised by extensive shear distortion, compaction and the regular formation of distinct slip planes, brittle fracture was characterised by crack propagation and negligible deformation within separated soil clods. This shows that brittle fracture in soil cutting is principally an elastic problem and can be modelled using methods of fracture mechanics for elastic–brittle materials.

2. Experimental results showed that the rupture distances of the soil clods produced in brittle fracture were significantly larger than expected when shear failure was assumed to occur. However, it was not possible to associate a particular shape or size of clods with certain soil and blade conditions.

3. The cutting force, in brittle fracture, was essentially from the region of the blade tip. Passive pressures at the blade surface were negligible and the clods produced during cutting remained intact as they traversed the surface.

4. The experimental results showed that a change in either the soil strength, blade rake angle or soil–blade interface condition can lead to a change in the failure mechanism from brittle fracture to shear failure (or vice versa). In general, increasing rake angle, increasing soil–blade interface roughness and decreasing soil strength, led to shear failure rather than brittle fracture.

5. For fixed soil strength and soil–blade interface conditions, a change in failure mechanism did not alter the general trend of the resultant force with rake angle.

Acknowledgements

The authors are grateful to the European Economic Community (EEC) for its financial support during the initial stages of this investigation which forms part of the first author’s Ph.D. Thesis.

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