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An investigation into the design of cultivation systems for inter- and intra-row weed control

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Abstract

The aim of this study was to investigate the factors that influence the design of soil engaging systems to mechanically control weeds between plants within the crop row in widely spaced field vegetables. A mass flow soil dynamics model based on particle dynamics was developed to aid designers in determining the lateral and forward displacement of soil as it is undercut by shallow working wide blades. The model was validated in soil bin laboratory experiments and used to design a novel mechanical inter- and intra-row weeding system.

The field performance of existing inter-row hoes was undertaken to ascertain the error associated with lateral positioning on a variety of guidance systems to identify the area left untreated during mechanical weed control operations. Overall lateral positioning error could be reduced to ± 30 mm with guidance systems, therefore, on a typical row width spacing of 0.5 m 81% of the area can be treated compared to 74% for a non-guided hoe.

To maximise the treated area through soil displacement, laboratory experiments were undertaken to identify and quantify the factors influencing forward and lateral displacement. Investigations into the effect of blade rake and sweep angle over a range of velocities from 1 to 10 km/h were undertaken in a sandy loam soil at densities of 1300 kg/m^3 and 1500 kg/m^3. The results showed that changes in soil density, velocity and rake angle significantly affected forward displacement, however only density and rake angle affected the lateral displacement.

The results enabled validation of the mass flow soil dynamics model which predicted the forward displacement of soil over blades with a 45^0 rake angle in loose and dense soil throughout the range of blade velocities within 20%. For blades with 20^0 rake angles prediction is less accurate, predicting within 15 mm in 90% of all cases in dense soil. In general terms the model predicts forward soil displacement within 25% for over 80% of the data. For lateral displacement prediction was less accurate, but predictions were all within the same order of magnitude. In the context of this project forward displacement is more critical than lateral movement as the design used a

swept blade to undercut in the intra-row, and utilised forward soil displacement to bury weeds close to the crop.

A novel inter- and intra-row mechanical weeder was designed, constructed and evaluated, which has the ability to operate within the commercial variations in transplanter intra-row spacing at speeds of 1.2 m/s. It is possible to operate at speeds of 2.2 m/s, although the blade tip entered the crop root zone 17% of the time.

At 1.2 m/s a 4 m machine has an effective work rate of 1.3 ha/hr, costing the operator £50/ha (covering a maximum area of 126 ha in 20 workable days), which is 20% of the cost of hand hoeing (£250-300/ha), and 60% of the cost of inter-row and hand hoeing (£84/ha) over the same area. It is also 71% of the cost of conventional spraying (£70/ha) over 126 ha.

With a market potential of circa 10,000 machines for Europe and the USA there is potential for manufacturers to take sufficient interest in building a commercial machine that will provide an economically viable mechanical weed control system.

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"If you want to walk on water,

you've got to get out of the boat"

Ortberg (2001)

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Nomenclature

w	= Width of blade	(m)
d_1	= Blade working depth	(m)
d_2	= Soil depth on blade	(m)
l	= Blade sliding length	(m)
l'	= Effective blade sliding length in the direction of motion	(m)
AB	= Blade base length	(m)
Z_o	= Rear blade height	(m)
α	= Blade rake angle	(deg)
δ	= Effective rake angle in the direction of motion	(deg)
ψ	= Blade sweep angle	(deg)
φ	= Angle of internal shearing friction	(deg)
β	= Angle of rupture/shearing made to the horizontal soil surface	(deg)
ε	= Divergence angle of soil in the horizontal plane	(deg)
e	= Factor representing soil deflection in the horizontal plane	
t	= Time	(s)
S_L	= Soil leakage factor	
V_b	= Blade Velocity	(m/s)
Vs_x'	= Horizontal velocity of soil relative to the ground perpendicular to the direction of travel	(m/s)
V_y	= Horizontal velocity of soil relative to the ground in the direction of travel	(m/s)
V_z	= Vertical velocity of soil relative to the ground	(m/s)
V_s	= Velocity of soil relative to and parallel over the blade	(m/s)
V_2	= Horizontal projection of V_s in the plane of the blade	(m/s)
ρ_1	= Initial oil density	(kg/m^3)
ρ_2	= Disturbed soil density	(kg/m^3)
ρ_f	= Soil flight density	(kg/m^3)
FT_b	= Forward Translocation due to the blade	(m)
FT_p	= Forward Translocation due to trajectory motion	(m)
FT_t	= Total Forward Translocation	(m)

LT_b	= Lateral Translocation due to the blade	(m)
LT_p	= Lateral Translocation due to trajectory motion	(m)
LT_t	= Total Lateral Translocation	(m)
Fp	= Forward projection	(m)
m_1	= Mass flow on blade	(kg/s)
m_2	= Mass flow off the blade	(kg/s)
m_y	= Mass flow off blade in the direction of travel	(kg/s)
m_x	= Mass flow off the blade perpendicular to the direction of travel	(kg/s)
tf	= Time in flight	(s)

1 Introduction

The problem of weed infestation in crops over the past 50 years has been mainly combated by the use of herbicides, although society has concern over these methods as they are perceived to cause environmental damage and may be a risk to human and animal health (Kurstjens, 2002; Duffy, 1998; Jones & Blair, 1995; Parish, 1990). In addition, economic pressures on farming could be reduced with reductions in herbicide usage as it forms a significant part of crop establishment and growing costs. Mechanical weed control offers a viable and cost effective alternative.

Up until half a century ago, weed control was carried out by hand and animal drawn implements. In mechanised agriculture mechanical weed control was largely replaced by chemical weed control, (Kouwenhoven, 1992). In recent times there has been a market demand for organic farming due to the belief that it results in a healthier lifestyle and less risk to health. This has caused a trend towards the physical removal of weeds between the crop, whether undertaken by hand or by mechanical hoes, in a highly mechanised agricultural sector. Pullen (1994) states that pressure to reduce costs and adapt techniques that are environmentally friendly have revived interest in non-chemical weed control methods.

Weeds compete directly with the crop, utilising vital nutrients, light and water, (Bond, 1997; Lockhart & Wiseman, 1988; Gwynne & Murray, 1987; Stephens, 1982; Russell, 1945) so they are removed to ensure the crop develops to deliver the highest potential yield and quality. The presence of weed seeds in a crop could cause its total rejection, or acceptance at a reduced price, (Stephens, 1982).

Pre-emergence weed control such as field rotations, stale seed beds, planting date, seeding rate, and other cultural methods can be effective at reducing weed populations, but provide limited benefit once weeds are established within the crop. Weed control can be broadly classified as chemical, combined and non-chemical techniques. These can be subdivided and split into relevant weed control options as shown in Figure 1-1.

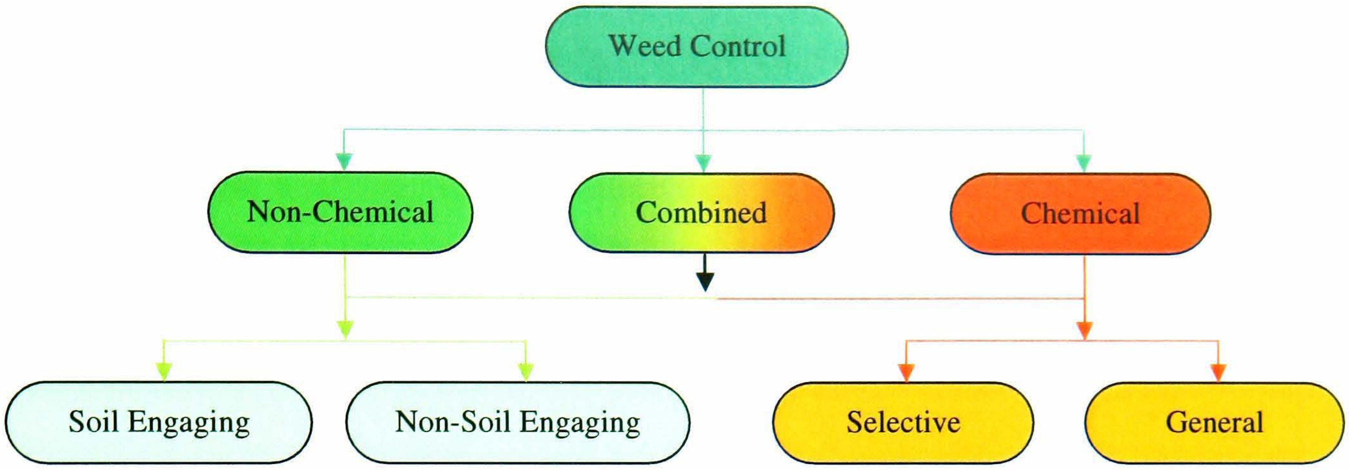


Figure 1-1 Weed control options

Agricultural field sprayers were in use prior to 1890, however, changes that took place in 1945 revolutionised not only weed spraying but the entire spraying programme (Anderson, 1952). Chemical control is a successful method of killing weeds within the crop. Spraying can be undertaken considerably more quickly than mechanical weed control techniques and typically covers 12 m to 24 m in one pass. Spraying is the only practical option for controlling weeds on conventional arable crops that are drilled on a spacing of approximately 125 mm or broadcast. It is not practical to cultivate between such random or narrow crop rows. Although herbicides provide a solution to weed control, many persistent soil acting herbicides are already being phased out, due to legislation and commercial pressures. Substantial research and design costs result in there being less substitute herbicides available, and those facing redundancy are not replaced. With reduced chemical availability herbicide resistance may increase. In recent times blackgrass has been a troublesome weed to control throughout the country. Jones (2000) stated that unless farmers are continually changing herbicide brands and are prepared to pay more for higher quality herbicides then it will be extremely difficult to control black grass successfully. Additionally, herbicides are expensive and with increasing public environmental awareness on the effects that chemicals may be having on public health and flora and fauna, result in an ever-increasing social cost.

Increasing environmental pressures have focused attention on improved targeting of applications. Band sprayers for example have been used, but the work rate of this type of equipment is less than that of overall boom spraying (Miller *et al.*, 1997). Palmer & May (1986) reported that a 50%-60% reduction in chemical usage could be achieved by band spraying and inter-row cultivations. Methods of achieving selective weed control i.e. spot spraying as means of reducing agricultural inputs were investigated by Hague *et al.* (2000), who found that chemical application could be reduced by up to 90% by precise targeting. Industry acceptance of these techniques is slow, but with increasing pressure from major purchasers (i.e. supermarkets) minimum chemical usage over time may be forced on some sectors of the industry, particularly in horticulture.

It appears that farming practice could revert back to earlier weeding techniques in an attempt to viably provide produce with reductions in establishment cost by reducing the level of herbicides applied to the crop. However to achieve that goal the cost and efficacy of non-chemical weed control techniques will need to be improved.

In these days of near universal availability of chemicals it is possible to lose sight of the value of non-chemical means of weed control and the part they play in minimising weed problems. Most cultivation techniques achieve some measure of weed control, and some have been designed specifically for this purpose (Gwynne & Murray, 1987). With new government legislation on herbicide usage and the link between subsidies and environmentally friendly farming, non-chemical control is becoming of paramount importance and is of primary concern within this research project. There are two main categories of non-chemical control, soil engaging and non-soil engaging. Both categories are capable of controlling weeds in and along the row. This research has considered non-soil engaging techniques but is principally concerned with soil engaging modes of weed control.

Kurstjens (2002) reports "mechanical methods control weeds by physical damage, such as cutting leaves and roots, bruising stems and leaves, covering plants by soil or by uprooting them". Weeds have been a problem consuming time and energy to ensure good crop yields ever since man has farmed the land (Stephens, 1982). Man has become very skilled in the removal of weeds by hand, but as available labour decreases, combined with an increasing labour cost per hour, hand hoeing has become too expensive, and is often a desperate but essential option to control weeds in organic farming systems. Tillage is an appropriate means of effective weed control, as the weeds can be cut and buried, as well as the additional benefits of mixing nutrients into the soil and breaking capped surface layers, allowing air and water to percolate through.

There are two types of weed position that pose a threat and they are referred to as inter-row and intra-row weeds, i.e. weeds between the rows and along the row respectively. Mechanical hoes are employed to control the inter-row weeds, travelling between the rows to cut and bury them. Accurate guidance is essential to avoid crop damage. Intra-row weed control methods are less advanced, usually requiring high levels of hand labour. Weeds growing between crop plants along the rows are the ones that cause the most problems for removal, (Kouwenhoven, 1992; Klooster, 1982). Melander & Rasmussen (2000) report that mechanical intra-row weed control is practically impossible.

The traditional inter-row hoe blade is effective at controlling weeds between the row at speeds of up to 5 km/h, but beyond this speed soil throw becomes a problem. The design of such blades has remained the same since being drawn behind the horse operating at much lower speeds. With national farm size increasing, combined with the possibility of the number of workable days in a year reducing due to climatic conditions, timelines of operation is crucial to ensure the area can be covered in the time available. A high-speed hoe blade combined with a guidance system that would facilitate accurate lateral positioning between crop rows would enable an increased area to be cultivated in the same cultivation window. A re-design of traditional hoe blades may be required to reduce the amount of soil movement. Knowledge of soil translocation would facilitate this.

Increased speed would significantly increase the work rate, and combined with accurate guidance and knowledge of soil translocation would result in hoe blade width being optimised for a given row spacing. Thus obtaining high levels of weed kill efficacy and leaving a small number of weeds within the row. The remaining intra-row weeds although reduced, still pose a threat to the crop. A suitable mechanism requires development; building upon the pre-mentioned. Accurate guidance and precise control of soil translocation would enable a mechanism to extend into the intra-row area, thus cutting and/or burying these weeds.

1.1 Aim

To investigate the factors that influence the design of soil engaging systems to mechanically control weeds between plants within the crop row.

1.2 Objectives

i) To determine the efficacy of existing mechanical inter-row weed control systems, from which the area of untreated soil can be determined.

ii) To quantify the soil dynamics of shallow working blades and to develop a prediction model for both the forward and lateral translocation of soil. This would allow the determination of improved cutting and burial weed control techniques.

iii) Identify and compare the true cost of alternative weed control techniques.

iv) To develop an experimental system to evaluate new concepts for intra-row weed control and evaluate those with potential economic advantages.

v) To investigate the market potential for an inter- and intra-row mechanical weeding system to work in widely spaced crops.

1.3 Outline methodology

This research programme can be categorised into 5 key elements, which when collated enable delivery of a mass flow soil dynamics model for predicting soil displacement and an experimental mechanical weed control system.

i) To undertake a review of historical, commercial and novel techniques for mechanical weed control in both organic and conventional crops. Identifying areas of further research, and techniques that should be considered in development of a mechanical weed control system.

ii) To conduct field investigations into the lateral positioning of commercial and research implements to quantify the levels of accuracy achieved during mechanical weed control operations. The area identified as untreated becomes the target area of this research programme for intra-row weed control.

iii) To conduct soil bin laboratory investigations to understand and quantify the processes involved in soil displacement from shallow working wide blades. Following this a soil translocation model will be developed to enable the geometry of blade design to be optimised to improve mechanical weed control.

iv) To identify the potential market for mechanical weed control systems, by reviewing appropriate databases and establishing the market need through conversation with large-scale growers; together with an economic analysis to determine the true cost of alternative systems.

v) To evaluate a novel mechanical intra-row weed control system developed by the author based upon the results of the above studies in both laboratory and field conditions. The weed control system will be evaluated on traditional plant spacing and current commercial hoeing speeds.

2 Literature review

Commercially available and traditional methods of weed control are investigated and examined for their practical use in controlling weeds in and along the row. Although this project focuses upon widely spaced field vegetables, some of the techniques are common to arable systems, therefore a broad range of weed control methods are reviewed. Investigations into weed control treatments and the advantages and disadvantages of soil tillage are discussed.

2.1 The importance of weed control in commercial farming

"Ever since the first cultivation systems were developed for food production, farmers of all generations and areas have been faced with the problems of non-crop plants (weeds) growing amongst the crops" (Parish, 1990). Weeds compete with crops for moisture, light, nutrients and space, both during establishment and in the established crop (Bond, 1997; Lockhart & Wiseman, 1988; Gwynne & Murray, 1987; Stephens 1982). Research by Russell (1945) found that weeds naturally depress crop yields and established that the weeds competed directly with the crops for water and nitrogen. Experiments undertaken between the years of 1937 – 1939 showed a mean decrease in potato yield of 1.8 tons/acre (0.66 tonnes/ha), compared to a weed free crop. Bond (1997) states "a relatively low number of weeds in vegetable crops will show a reduction in yield". In addition to potential yield reduction, Gwynne & Murray (1987) report that weeds interfere with harvesting operations, handling and quality, and that they also act as hosts for pests and diseases giving shelter to vermin, or diverting pollinating insects.

Weeding is not only critical to ensure good crop yield by eliminating competition, but it ensures high quality produce. Stephens (1982) reports that quality may be impaired by the presence of weeds, often reducing the economic value more than the reduced weight of crop would indicate; for example growers may be penalised for offering vegetables containing weed seeds.

There are many weed control techniques currently available to farmers these include crop rotation, cultural practices, mechanical or physical control and the use of biological or chemical herbicides (Eterson, 1983). Although all of these techniques are available to farmers, they cannot all be used in every cropping system. In organic systems, chemical control is not permitted and organic farmers often have to resort to weed control methods that have generally higher labour costs and relatively low work rates. These might include either hand weeding or existing mechanical weeding devices that the conventional farmer would not consider. This results in the organic farmer facing higher establishment costs and often-reduced yield. However, conventional growers are under pressure from their customers to reduce herbicide use and are also facing legislation changes that restrict the usage of herbicides. This process is changing the field vegetable and outdoor salad industry, increasing the importance of mechanical methods for commercial growers.

A control system is necessary to allow efficient crop production that controls weed infestations and allows the crop to achieve maximum yield potential. The problem of weed infestation in crops, have, since the 1950's been combated by the use of agro-chemicals. Post (1993) notes that weed control had for a long time been non-chemical. It was after World War II when agriculture was intensified that deeper cultivation, earlier sowing and many more major changes, along with the development of herbicides to control weeds occurred. The development of these chemicals now leads to new problems such as herbicide resistant weed species and environmental damage through leaching and drift of sprays. Cavan & Moss (1997) state "the emergence of herbicide resistance in Black–grass (*Alopecurus myosuroides*) and wild oats (*Avena ssp.*) threatens cereal production in north west Europe."

If herbicide resistant weeds continue to increase then implementation of mechanical weed control systems may become desirable.

There are many weed control techniques as outlined by Eterson (1993); the important aspect to consider is how these techniques can be adapted to suit farming systems. This section examines these alternatives and the optimum way to control inter- and intra-row weeds.

2.1.1 Classification of weeds into inter- and intra-row

A weed is often referred to as a plant out of place, and as mentioned is undesirable in the growing crop. For the purposes of this thesis there are two classifications for weeds amongst a growing crop; inter-row and intra-row weed. Inter-row weeds grow between crop rows, whilst the intra-row weeds grow between crop plants along the row. Figure 2-1 shows an illustration of inter-row and intra-row weeds.

Kouwenhoven (1992) states that with inter-row weed control 60-70% of the surface is treated. He notes that intra-row weed control is difficult and weeds closely surrounding the crop are almost impossible to control using existing intra-row weeding techniques such as ridging or brushing. Klooster (1982) stated that there is an increased interest in mechanical weed control, and that the weeds in the row are the biggest problem. Mechanical intra-row weeding is the removal of weeds between the crop along the row as shown in Figure 2-1.

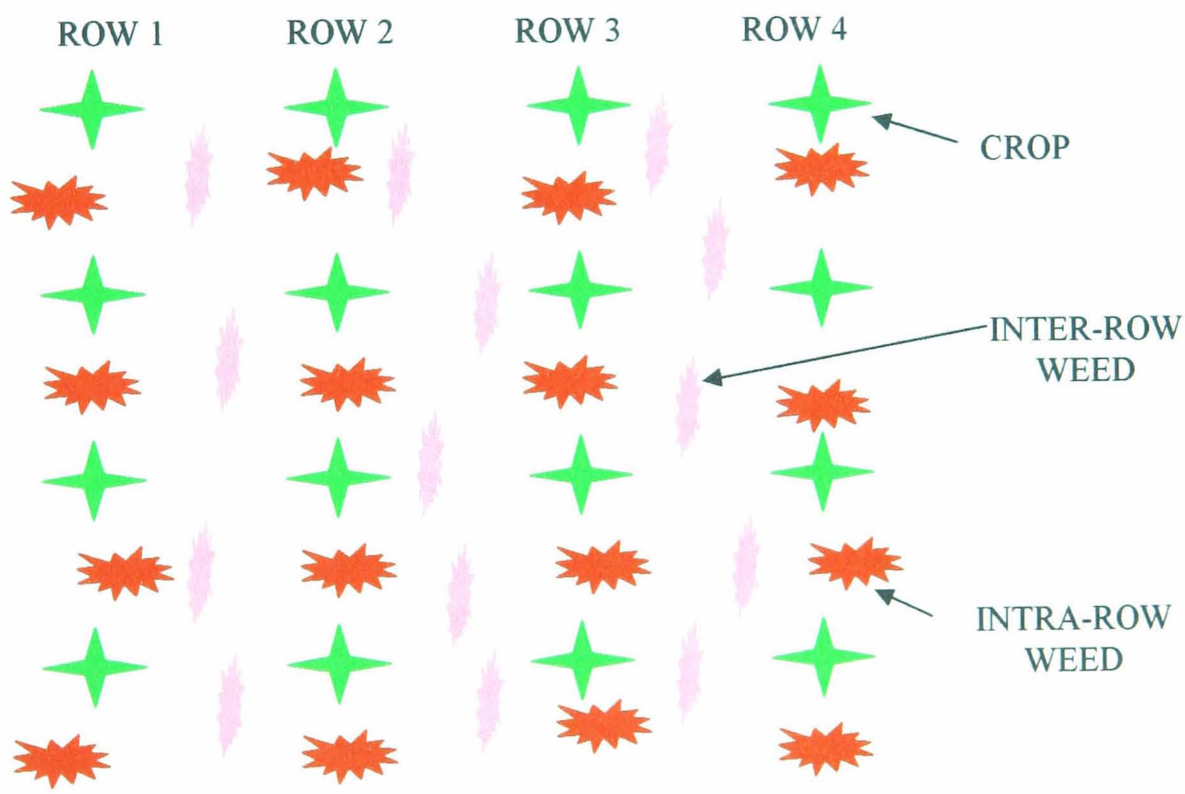


Figure 2-1 Inter-row and intra-row weed location

Weeding is not a new concept and there are many types of mechanical weeder commercially available to control weeds, however, available weeders concentrate mainly on the control of inter-row weeds.

2.2 Cultural weed management

Cultural weed control is the management of the crop to make it more competitive against weeds. "Cultural methods were once the only means to prevent pests, diseases and weeds" (Zadoks, 1993). It involves optimising planting date, seeding rate, row spacing, fertility, irrigation and adapted seed varieties so the crops grow vigorously. The plant that emerges first has the advantage that it can close the canopy to others below it. Other improvements such as keeping the land fallow between crop cycles can prevent build up of specific weeds and may restore natural fertility along with the help of correct crop rotation. (Integrated Weed Management, 2000). Crop rotation can form an important part in reducing weed numbers, by changing the varieties grown, for example one cleaning crop (ability to hoe between the rows) with two cereal crops will provide ample opportunities for weed suppression (Watson & More, 1962). Bastard and bare fallowing may also provide opportunities to reduce weed populations.

Zadoks (1993) reports "as farming output strives to be more productive by increasing field size, habitat is lost through the removal of hedges. The loss of birds due to these changes means that the weed seeds are not consumed, thus the spread of weed seed continues". There are now incentives offered to farmers to replant hedges and a new proposal is for a 10 m strip of land to be set-aside around the edge of the field known as the countryside stewardship scheme, which attracts and offers a home for wildlife. This is a new incentive and the benefits of such a system will need to be monitored.

Inter-cropping can be undertaken, by planting crops between the rows. Lee & Lopez-Ridaura (2002) report that intercropping has the potential to reduce weed populations and should be explored further. Experiments undertaken by Lee & Lopez-Ridaura (2002) drew tentative conclusions that weed biomass may have been reduced as the inter-crop was competing for light, soil moisture and possibly non-measured factors. It may be possible to sow nitrate fixing plants as done in Agro-forestry situations so that the intercrop is a benefit to the main crop. An alternative to planting crops in the inter-row may be the use of mulches in between the rows. Mulching controls weeds and may also promote crop growth, however it is crucial to ensure that mulches are weed free.

Integrated weed management relies on good farm management, starting from the inputs of the farming system through to harvesting. Weeds can enter through manure spread on the land, weed seeds blown from hedges, through harvesting and many other sources. Weeds need to be controlled and monitored at every stage to ensure minimal weed seed spread and germination. Integrated weed management is an option to farmers as they can reduce the risk of weed infestation, but nonetheless an alternative plan needs to be in place if the crops become infested, as weeds need to be removed as soon as they appear. In today's farming systems there is a big movement towards minimum tillage or direct drilling of crops, but this means little or no ploughing of the land. Ploughing has proven to be an excellent method of controlling weeds through burial often down to 250 mm. The percentage of weeds covered by ploughing was 95%, after disc-harrowing 48% and after tined cultivating 5% (Kouwenhoven, 1992). Adoption of minimum tillage practices are appealing to many growers to reduce establishment costs but the reduced establishment cost may be adversely affected by the increase in weed populations on the fields that require control. Post (1993) concludes by stating "more tools are needed to determine economically justified weed control, which can then be integrated into weed management systems for sustainable integrated forms of agriculture".

Welsh (1998) investigated the effects of night-time cultivation on weed emergence and crop establishment. He found that although night cultivation reduced weed density by up to 70% compared to plots drilled in the daylight, the reductions were transitory and did not improve crop yield. In terms of a weed control strategy, night-time cultivation and drilling was unsuccessful in isolation.

2.3 Soil engaging

This section describes shallow cultivation techniques for inter- and intra-row weed control, which are discussed as they relate to cultivation tool design.

The long history of mechanical weed control coupled with regional differences has resulted in a nomenclature that is confusing and often contradictory. The terminology therefore has been defined for this review. A number of mechanical weeding tools are reviewed, stating their mode of action, typical operating speeds and commenting on their limitations. A summary table allows comparisons to be made.

2.3.1 Hoe blade definitions

Generally the soil-engaging component of the hoe is referred to as the blade, but this covers a wide range of designs. Reviewing literature has enabled various names for different types of blade to be drawn together into categories. Figure 2-2 identifies the important design features for blade classification.

There are two important variables that define a blade, that of rake and sweep angle. Rake angle (α) is the angle that the hoe blade makes with the horizontal in a vertical plane parallel to the direction of motion. A low rake angle will cause the blade to cut cleanly, with minimal soil disturbance. Increased rake angle generates more soil movement and mixing of the soil whilst maintaining its cutting action. The sweep angle (ψ) is the angle of the cutting face or edge to a line perpendicular to the direction of motion, when projected onto a horizontal plane. Increased sweep angles give excellent self cleaning as the trash flows to the edge of the blade. However, increased sweep angles reduce the cutting efficacy as the weeds are pushed to one side rather than cut. A compromise is needed between self cleaning, effective cutting and draught force.

In general terms a blade with a sweep angle of 30-50 degrees with a low rake angle (< 10 degrees) can be classified as a sweep, (Clark *et al.*, 1981; Kotov, 1983). Sweeps are often referred to as 'L' blades or 'A' blades. Figure 2-2 shows an 'L' blade, illustrating the sweep angle and leg mounting. If two 'L' blades are placed back to back, to form an A shape then the A blade is formed, resulting in a low rake angle blade with a swept cutting face on either side of the leg.

A variation of the 'A' blade comes in the form of the 'Ducksfoot' blade. The difference is an increased rake angle, resulting in increased lift at the leg mounting/shank region of the blade which increases lateral and forward displacement of soil.

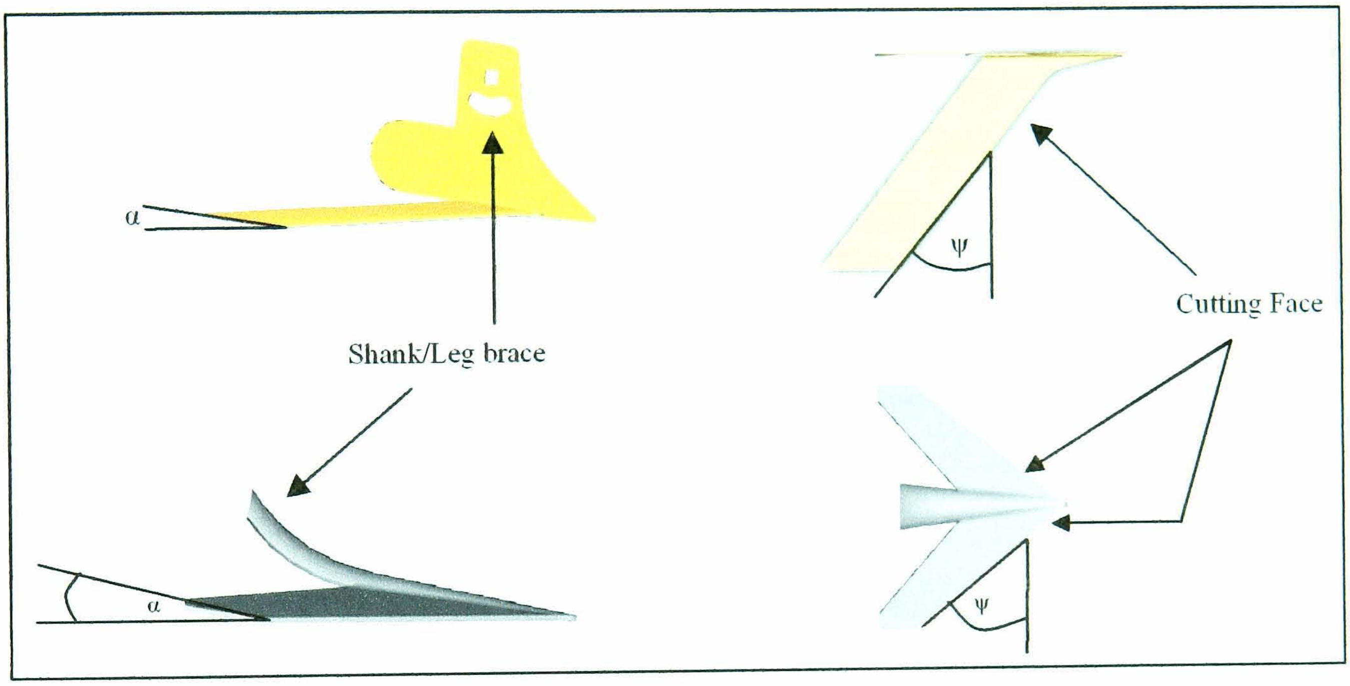


Figure 2-2 Hoe blade classification

2.3.2 Mode of weed control

Weed species can be broken down into two key groups, the grass weed and the broadleaf weed. The grass weed has a fibrous root structure and the broadleaf often has a main taproot. Servi-Tech Review (1999) state "the competitiveness of the broadleaf weed and the grass weed change depending upon which crop is surrounding them. As a general rule depending upon the plant density, broadleaf weeds are more competitive with broadleaf crops and grass species are more competitive with grass crops. Weeds of the same species as the crop must be the main target to reduce competition".

The differing root structure means that the effectiveness of mechanical weed control will vary depending upon the type of weed, whether broadleaf or grass. There are several modes of mechanical weed control, two typical methods being sub surface cutting and burial.

Each tillage operation influences and often controls weed population by covering, cutting and uprooting (Kouwenhoven, 1982). The differing root structure and growth habit of weeds means that the effectiveness of mechanical weed control will vary depending upon the type and size of weed. Jones *et al.* (1996) conducted pot experiments to investigate the effectiveness of these three modes of weed kill on grass and broad-leaf weeds. Four species of weed were chosen for their different root and growth habits, *Stellaria media (L.) Vill.* (a fibrous rooting prostrate broad-leaf weed), Pavpaver rhoeas L. (a tap rooted broad-leaved rosette forming weed), *Poa annua L.* (a postrate annual grass) and *Poa trivialis L.* (an upright grass). Each treatment was conducted with soil based compost under dry and wet conditions. Cutting was done 10 mm above the surface, at the surface and 10 mm below ground. There was also a treatment in which all leaves were removed and stems left intact. Burial was complete to a depth of 10 mm or partially. Uprooting was done with the roots laid on the surface and with reburial after uprooting. Results showed for broad-leaved weeds that uprooting leaving the roots on the surface and cutting at or below ground level were the most effective treatments giving approximately 90% reductions in dry weight. The efficacy of these treatments was improved in dry conditions. Uprooting and reburial was also effective in dry conditions but poor (65% reduction) in the wet indicating the importance of ground conditions at, or immediately after, treatments. Relatively poor results (35%-70% reduction) from cutting above ground and stripping indicate the importance of cultivation as opposed to a mowing operation in controlling these weeds. The results obtained by Jones *et al.* (1996) in grass weeds were broadly similar to those in broad-leaved weeds. One exception was that complete burial was always more effective (100%-98% reduction) irrespective of moisture. Uprooting grass on the other hand was even more sensitive to moisture than in broad-leaved weeds. Typically reductions were 55% for uprooting in wet conditions and 100% in the dry.

Sub-surface cutting is more successful at controlling broadleaf weeds, and burial is more effective at controlling grass weeds (Jones *et al.,* 1996). Cutting broadleaf weeds at the correct depth will cut through the taproot thus destroying it. However, cutting at the same depth with grass weeds may not cut all the roots and the grass weed may survive. Burial, to a depth of 10 mm or greater, will kill most grass weeds. Recovery, if any, will be slow and re-emergence minimal; the broadleaf, however, being more robust, is likely to re-emerge through the soil (Jones *et al.* 1996).

Terpstra & Kouwenhoven (1981) investigated depth of soil coverage necessary to kill weeds. They found 15 mm was lethal for small weeds and 20 mm for larger weeds. Their studies showed that increasing working depth from 25 mm to 40 mm gave only an 8% increase in weed kill. Their experiments were conducted under laboratory conditions using only garden cress (Lepidium sativum L.) as a weed.

Taken together these results show the potential for improved weed control by selecting an appropriate tool to treat specific types of weed at particular moisture levels. For example a tool that primarily has a subsurface cutting action may be appropriate to control broad-leaved weeds in dry conditions, but grass weeds in the wet may favour a tool that will result in a higher proportion of burial. However some caution is needed in the interpretation of these laboratory results conducted with a limited number of species.

2.3.3 Hand hoe

The simplest form of hoeing must be the hand. Up to half a century ago, inter-row weed control was carried out by hand and/or animal drawn implements (Kouwenhoven, 1992). The hoe is probably the most widely used tillage implement in the world. It can be used to clear large areas of weeds, in a scything action or to turn soil over to bury the smaller weeds (McRobie, 1990). Although not widely used, some horticultural growers still use hand weeding as a system of controlling the weeds in and along the rows. This is time consuming and expensive, yet very effective and accurate. Bond & Grundy (1998) state that hand-weeding may be combined with mechanical inter-row weed control to deal with weeds left in the row. Hand hoeing has been claimed to be the most consuming and exhausting human occupation in Agriculture (Stephens, 1982). Hand hoeing although historically an effective method of weed control, is with scarcity of labour and increasing wage costs often no longer viable. Hand hoeing also has low rates of work making it unattractive to the large-scale farmer. A major advantage of hand weeding is that of selectivity between the crop and the weed, which comes at no extra expense. Hand hoeing work rates and cost/ha are discussed in Section 6.4.

2.3.4 Harrows

The harrow acts uniformly over the entire area controlling both the inter-row and intra-row weeds. Despite the limitations outlined below, its relative simplicity has made it one of the most commonly used weed control tools. There are two common forms of harrow, the spring tine harrow and the chain harrow.

The spring tine harrow is known by many different names; flexi-tine, harrowcomb, and sometimes, incorrectly, named a finger weeder. Figure 2-3 shows a spring-tine harrow weeder, consisting of multiple gangs of tines mounted onto a tool bar, which are dragged across the field by the tractor. The tine diameter can be changed to increase or decrease aggressiveness in the soil; the tines may be either rigidly fixed or spring loaded.

Figure 2-3 Floating spring-tine harrow weeder.

The chain harrow illustrated in Figure 2-4 consists of a chain mesh supported from the steel frame of the implement with much smaller tines or spiked teeth. It is often considered to be more aggressive to the crop and weed. In both forms of harrow the tines engage in the soil and destroy the weeds by loosening and uprooting them for desiccation and burial.

Figure 2-4 Flexible chain harrow

Good weed control, which avoids damaging the crop, depends upon careful timing of the weeding operation to coincide with large differences in the growth stage of the crop and weeds (Pullen & Cowell, 1997). Harrows can be used pre-emergence and this is referred to as 'blind harrowing'.

A study undertaken by Kouwenhoven (1997) reported that harrows have a working width of 6 - 24 m and a working speed of approximately 6 km/h – 8 km/h and hence a large area capacity at relatively low capital cost. This has to be balanced against a high tine wear rate in stony soils and a need to make multiple passes in some cases. Bowman (1997) reported that harrows work well in loose or lightly crusted soil with no long stemmed residue, and that depth of operation was dependent upon the diameter of the harrow tine. A more aggressive spring tine harrowing action can be achieved by reducing the tine inclination to the vertical although harrows are not able to penetrate harder surfaces such as dried clay soils or silty soil that tend to cap.

Weed kill from spring tine harrowing has been investigated by Kurstjens *et al.* (2000). They found that harrowing uprooted an average of 51% of emerging plants and 21% of seedling plants; 70% of all uprooted plants were completely covered in soil. The report indicated that uprooting was promoted by higher soil moisture contents and increased working speed. Bond & Grundy (1998) reported that harrowing is ineffective against perennial and established deep-rooted weeds, and the chain harrow tended to bury weeds instead of uprooting, unlike the spring-tine harrow.

2.3.5 Tractor mounted hoe (toolbar)

The tractor hoe is a generic name given to a tractor and toolbar mounted weeding mechanism for inter-row cultivation shown in Figure 2-5.

Figure 2-5 Tractor mounted hoe for inter-row cultivation

The tractor hoe operates between the row crops achieving selectivity by geometry. An important aspect of the tractor hoe is the weeding device itself, the soil engaging part of the hoe. Many different types of blades can be fitted to the hoe and the next sub-section gives an overview of the common types.

Hoe blades are fitted in a variety of ways; the simplest and now uncommon system is direct mounting of the blade to a fixed leg attached to the toolbar. The leg is often attached with a shear bolt, to prevent bending if large obstacles are contacted. This system provides no ground contour following across its width, so may result in deep penetration one side and minimal penetration on the other if the ground undulates. The tool bar frame may be supported by position control within the cab, or by depth wheels mounted on the tool bar.

More often, the soil-engaging blade is attached to the toolbar via a spring tine, which allows the blade to move independently of the toolbar when obstacles are contacted in the ground (Figure 2-6). In order to accommodate transverse changes in soil level, hoe blades are often attached via a parallel linkage system whose height is controlled by a depth wheel. A number of these devices are fitted across the width of the tool frame.

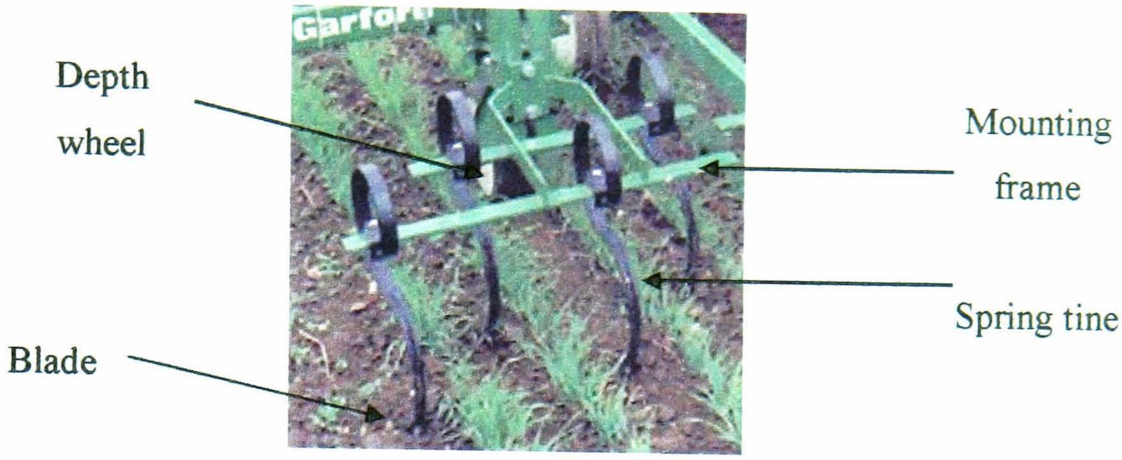


Figure 2-6 Spring tine mounted blade

2.3.6 Sweep

The blade shown in Figure 2-7 is an example of a sweep, generically called an L blade due to its plan view form. Clark *et al.* (1981) reported that an optimum swept angle for minimum draft occurred at approximately 40^0. For the same cutting length a 20^0 increase from this swept angle resulted in a 9% increase in draft whilst a 10^0 decrease in swept angle resulted in an increase of draft of 4%.

Figure 2-7 Sweep (L blade)

Kotov (1977) studied the parameters of sweep design and showed that sweeps clean themselves best in heavy conditions with a swept angle of approximately 57^0; and the condition of the cutting edge is the major factor in the accumulation of plant material on the sweep. Further studies showed that soil tended to pile up in front of the shank increasing soil movement problems.

Although a large swept angle is optimum for self-cleaning, it is not necessarily the ideal in terms of weed kill. An increase in sweep angle results in a longer blade to control the same width, and weeds can deflect around the cutting edge. In sweep design a compromise between draught, effective cutting and self-cleaning properties has to be reached. From research reviewed above detailed on self-cleaning and draft a sweep angle between 40^0 and 57^0 should be adopted. Rake angles are often less than 5^0 along the sliding face but have an increased cutting rake angle of approximately 20^0.

The main mode of action for killing weeds is subsurface cutting with some burial. The designs cause minimal disturbance to the soil, thus minimising new weed propagation. Minimal burial occurs even at high speed. A major advantage of the sweep is that it can travel close to the crop, cutting the weeds without throwing soil into the row, which could damage small crop plants. The sweep's inherent design ensures that trash does not build up on the blade. However, trash does sometimes accumulate on the vertical part of the blade connecting it to the leg. It is possible to design this vertical plate with a downward facing leading edge such that trash is forced down and cut rather than rising and wrapping around the leg. This can however increase crop damage if the vertical plate runs close to a crop with a prostrate habit. This should not be a problem in cereals but may be significant in some pulse and vegetable crops.

2.3.6.1 Ducksfoot (goose foot)

The Ducksfoot blade shown in Figure 2-8 differs from a sweep in that it has a raised profile where the shank is attached. Its main modes of action include burial and mixing as well as subsurface cutting. This raised profile projects the soil, causing a mixing effect. The swept edges of the blade cut the soil, then lift and displace some soil laterally. The Ducksfoot is effective against both grasses and broad-leaved weeds but lateral soil movement can cause crop damage through burial.

Figure 2-8 Ducksfoot

2.3.6.2 Hoe-ridger

Hoe-ridgers are used to control the intra-row weeds by burial whilst also controlling the inter-row weeds through burial and sub surface cutting. The hoe design shown in Figure 2-9 forces the soil to move outward from the row and placement of soil is between the crops due to its extreme rake angle. Problems arise when too much soil movement occurs, as there is a risk of crop burial.

Inter- and intra-row weed control studies undertaken by Terpstra & Kouwenhoven (1981) found that, in the path of a hoe-ridger, 57% of the inter-row weeds were killed by covering with soil and 33% by uprooting and drying at the soil surface. Intra-row weeds alongside the path of the hoe resulted in 45% being killed by a soil cover of 15 - 20 mm, being lethal for both small (30 mm) and larger (80 mm) weeds, in a band 50 - 100 mm aside of the path of the hoe. The influencing factors were soil type, plant height, working depth, tool position and the weather after cultivation. It also stated that the width of the rows must be 50% wider than the working width of the hoe blade for successful inter- or intra-row weed control. Shallow working depth and steep rake angle (55^0) of the hoe blade gave optimum results at a typical hoe working depth of 25 mm – 40 mm and forward speed of 7 km/h.

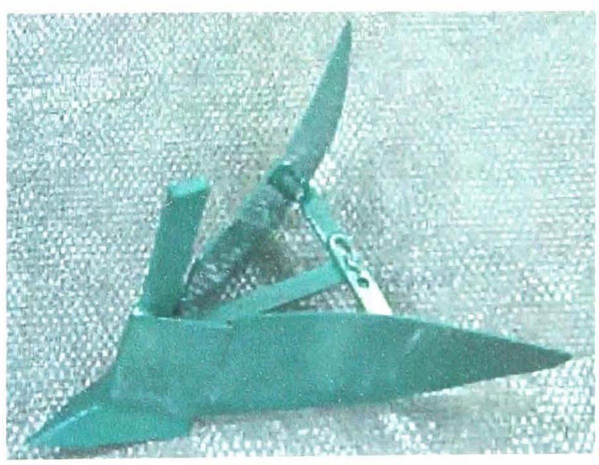


Figure 2-9 Hoe ridger

2.3.6.3 Subsurface tiller

Chase (1942) reported that ideal subsurface tillage consists of severing a layer of soil from the surface of the field, leaving no ruts or trenches. Chase (1942) developed a blade that cut the roots of weeds and gave a minimal disturbance to the soil profile. This design ensured that emerged weeds had their roots cut, and new seeds did not germinate, as the soil remained undisturbed at the surface. Chase (1942) showed that the subsurface tiller worked well in high trash conditions and in a variety of soil types. working at a depth of approximately 100 mm.

Subsurface tiller application may be limited to deep rooted perennial weeds, where it is able to cut through the tap root, thus destroying the broadleaf weed, and ensuring propagation of new weed seeds is minimal. It is fair to assume that small weeds, especially in the top layer of soil, will continue to grow as these are not targeted with this device. In wet conditions weed kill may be less effective as the sweep is cutting layers of soils that are not mixed or inverted, so weed re-growth is likely.

The sub-surface tiller works well on high trash surfaces, leaving trash or surface residue on the surface, thus retaining moisture, reducing the risk of erosion, and may be able to leave cover crops, such as clover that may be growing between the rows, relatively unaffected. It is still used today (mainly in the USA), but is often referred to as a subsurface sweep since that is the type of blade attached to the leg. It is commonly used where moisture retention and erosion prevention are critical. The traditional design remains unchanged and operates at around 8 km/h.

Chase (1942) notes that the shanks, which propel the sweeps, are very important, and that a shank should be designed to make the narrowest possible trench and gather the least amount of roots, consistent with enough material to pull or push the sweep.

2.3.6.4 Basket/Cage weeder

The Basket weeder, sometimes referred to as the Cage weeder, is an example of a non-powered rotary cultivator. Figure 2-10 shows that there are two horizontal axes upon which the baskets are mounted. The two axes are connected via a chain and sprocket arrangement providing a difference in speed between them. As they are dragged across the ground, the baskets have a "scuffing" action on the soil. The bars that scrub the soil are either parallel to the rotary axis, or are skewed for different levels of aggressiveness. It works only with small weeds in friable soil in the top 25 mm without moving soil into the crop row and it cannot deal with long stemmed residue

(Bowman, 1997). The weeder is often used in conjunction with a Sweep or Ducksfoot to loosen the soil, and provide a tilth in which the weeder works well.

Figure 2-10 Basket/Cage weeder

2.3.6.5 Finger weeder

The Finger weeder shown in operation in Figure 2-11 is a non-powered ground driven weeder, designed primarily to control weeds within vegetable rows. It would normally be used in conjunction with another inter-row cultivation blade. Steel cone wheels, rotated by ground-driven spike tines, push rubber 'fingers' just below the soil surface, reaching into the row. A difference in rolling radius between the spiked tines and rubber fingers results in a scuffing action within the row.

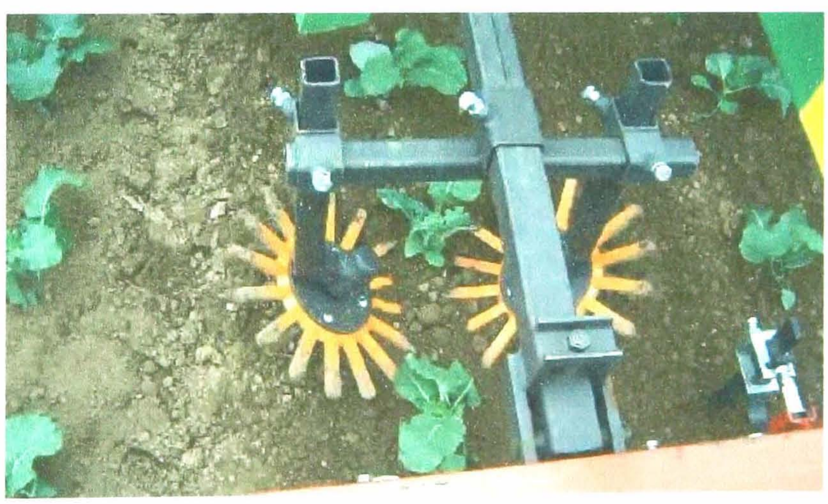


Figure 2-11 Finger weeder

Small weeds up to 25 mm are dislodged and the fingers operate at a depth of 12.5 – 19 mm (Bowman, 1997). The timing of the weeding operation is important, as the crop needs to be more robust than the weed to ensure good weed control without crop damage.

Finger weeders can work within row crops and on heavy soils with some crust on top of the soil. They work best at high speeds of approximately 10 km/h (Kouwenhoven, 1998) although Grubinger (1992) reports that wet clay soils can stick to fingers and require frequent removal. The effectiveness of this device in cereals has not, to the authors knowledge, been tested. It is likely to be most effective when the crop is sufficiently established to withstand the disturbance.

2.3.6.6 Torsion weeder

The Torsion weeder is another device for controlling weeds within vegetable rows often used in conjunction with another inter-row cultivation blade. It comprises two sprung steel tines that straddle the crop row and press into the base of the growing crop as shown in Figure 2-12. The tines control the intra-row weeds and a secondary hoe is required to control the inter-row weeds. This weeder is relatively inexpensive and simple in design.

In order to make the torsion weeder more aggressive the diameter of the steel tines can be increased, which results in more force required to splay them away from the crop. This method employs uprooting and soil-covering methods to achieve weed kill and results in undercutting of small weeds.

Figure 2-12 Torsion weeder

The University of Connecticut (1999) state that "the torsion weeder was found to be excellent at intra-row weed control, which is achieved with a simple low maintenance tool and is an economical addition to an existing cultivator. Crop damage can occur if the crop growth stage is similar to that of the weed. Forward speed is limited by the accompanying inter-row device and operation is at a depth of less than 25 mm".

2.3.6.7 Split hoe

The split hoe shown in Figure 2-13 is a non-powered rotary weeder consisting of a number of spring tines radially mounted on steel discs that are mounted on a common horizontal shaft that is free to rotate. Forward tractor movement results in the tines rotating and engaging in the soil. Weed kill from the split hoe is attributed to uprooting with some soil burial and stripping, although this has not been quantified.

Figure 2-13 Split hoe

Tei *et al.* (2002) found that operating the split hoe at a depth of 50 mm and at a forward speed of 3 km/h gave optimum results. A further study by Meyer *et al.* (2002) found that the split hoe could achieve better results than the standard spring-tine harrow. It was reported that it worked especially well in wet/crusted soils with large weeds and also gave high efficacy on lighter well-structured soils, controlling weeds up to 600 mm high.

2.3.6.8 Rotary hoe

The Rotary hoe, or rolling hoe as it is occasionally referred to, is another non-powered rotary weeder with 'star' or 'spider' rotors placed between rows. The rotors are set at a small angular offset to the direction of travel such that there is a scuffing action that moves soil away from, or towards the row. The latter action causes ridging of soil up the crop to bury small inter-row weeds (Bond & Grundy, 1998).

A comparison of six mechanical weeders by Pullen & Cowell (1997) reported that the rotary hoe works well on light stone free soil and produced the highest kill rate. The mode of action for weed kill was by cutting and mixing of the weeds in the soil at early growth stages, but when the weeds approached the true 5 leaf stage the weeder was not as effective.

Figure 2-14 shows a simple rotary hoe in combination with a sweep with rotors set to move soil onto the row.

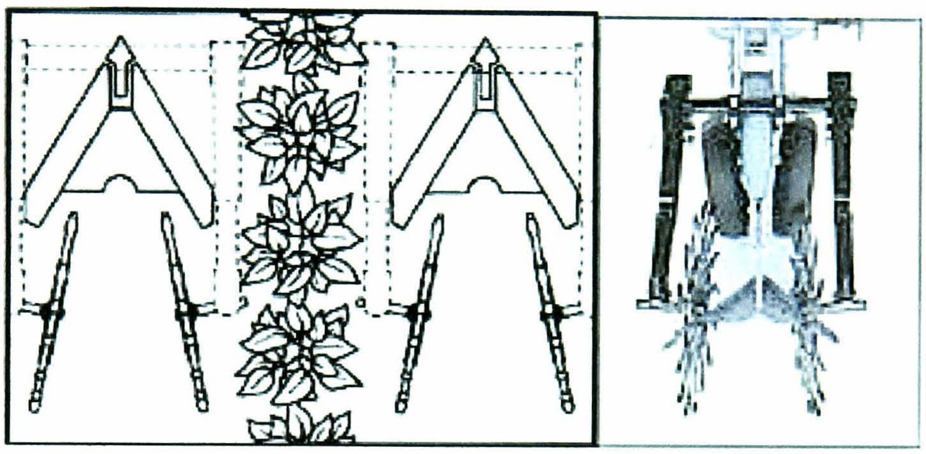


Figure 2-14 Rotary hoe

Yahia *et al.* (1999) undertook an extensive study of the rotary hoe and investigated the soil throw that can be achieved onto the row by changing depth, angle of rotor and forward speed. A regression model was also developed based on these variables, to predict the thickness of the layer of soil projected onto the row for the soil conditions in their experiments. The conclusions drawn stated that the use of higher speeds up to 9 km/h resulted in a more uniform projected soil profile and larger hills of soil over the rows. Thickness of soil projected onto the rows increased linearly with working depth. In field conditions with high residue the rotors are staggered so that they are not face-to-face and this allows the residue/trash to flow through. Faster speeds increase aggressiveness but decrease penetration (Bowman, 1997).

2.3.6.9 Brush weeder

Brush weeders can be divided into two types; those with a horizontal axis and those with a vertical axis. The first type is only suitable for inter-row weed control, whereas the second type can be used for both inter- and intra-row. Both types work in the soil to a depth of 20 - 30 mm and are designed to uproot small weeds (Kouwenhoven, 1997). Examples of both types of weeder are shown in Figures 2-15 and 2-16.

Kouwenhoven (1997) discusses the operational requirements of the brush weeder and states that rotational speed for the brushes range from 120 - 360 rev/min with low forward speeds 2 km/h – 3 km/h. Most effective weed control is obtained by brushing weeds in the earliest growth stage and, in order to achieve selectivity, the crop should be at an advanced growth stage.

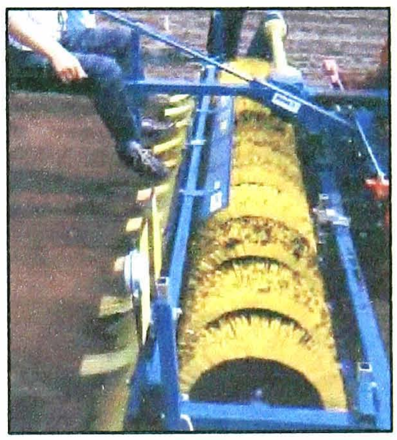


Figure 2-15 Horizontal brush weeder

The horizontal brush weeder is typically powered by the tractor mechanical power take off (PTO), and the vertical brush weeder is normally driven via hydraulic motors. It consists of flexible polypropylene brush discs assembled into units of the desired width and spacing for the crop. The brushes can be set to work at a depth of up to 50 mm and the crop rows can be protected by tunnels typically 600 - 800 mm long. The effect of the brushing action is to lift the weeds out of the soil, strip leaves, break stems and expose roots leaving them vulnerable to desiccation (Parish, 1990).

Pullen & Cowell (1997), in their mechanical weeder review, stated that dust was a major problem in dry conditions and reported that Pederson (1990) found forward speed could only be raised with accompanying increased rotor speed. Control of large weeds also required faster brush rotation, and concluded that in dry conditions a conventional hoe was better.

An advantage of the vertical brush weeder is that it provides some intra-row weed control by covering or uprooting, which in general cannot be achieved by unguided inter-row hoes. Although providing limited intra-row weed control, timelines of operation is critical to ensure individual crop plants are not uprooted with the weeds.

Soil height, rotor speed, direction and tractor forward speed were examined by Fogelberg & Kritz (1999) in an attempt to optimise vertical brush weeder performance. They found that direction of rotation was a major influencing factor for in-row soil height, as the soil was either thrown into the intra-row, or the inter-row. Increasing brush depth increased the intra-row soil height. Changes in forward speed had little effect on soil height and optimum speed was less than 3.5 km/h.

Figure 2-16 Vertical brush weeder

Reversing the direction of the vertical brush weeder can be beneficial if the previous operation tended to ridge the soil against the crop. The brushing action removes the ridged soil, thus killing the weeds and throwing soil into the inter-row, burying the inter-row weeds.

The disadvantages of both types of brush weeder are the costs and complexity needed to cope with a large number of rows. It is perhaps for this reason that Fogelberg & Kritz (1999) were not aware of any trials using the technique in cereals. It is also a major reason why this study investigates the potential of soil translocation and subsurface cutting as a technique to control intra-row weeds using a hoe blade.

Brush weeders have an advantage over the mechanical hoe as they can operate in soil conditions with increased soil moisture levels (Parish, 1990; Bond & Grundy, 1998; Bowman, 1990). However weed infestations in late growth stages of the crop could also present a problem as the radius of horizontal brushes would need to be large in order for the drive shaft to clear the crop.

2.3.6.10 'Rapid-O' hoe

In 1947 the 'Rapid-O' hoe, Figure 2-17 was launched and seen as a unique tractor approach to what usually had been considered a hand operation demanding discrimination and the individual treatment of each plant, (NIAE, 1947[a]). Its operation although simple, has been the closest any implement has approached the control of the intra-row weeds mechanically by cutting along the row. Individual operators, who not only steered the hoe, but also operated the mechanism, achieved selectivity.

The machine was designed to hoe not only between the rows, up to 203 mm on each side of the plants, but also between individual plants in the row, and therefore eliminated the need to cross hoe (NIAE, 1947[b]).

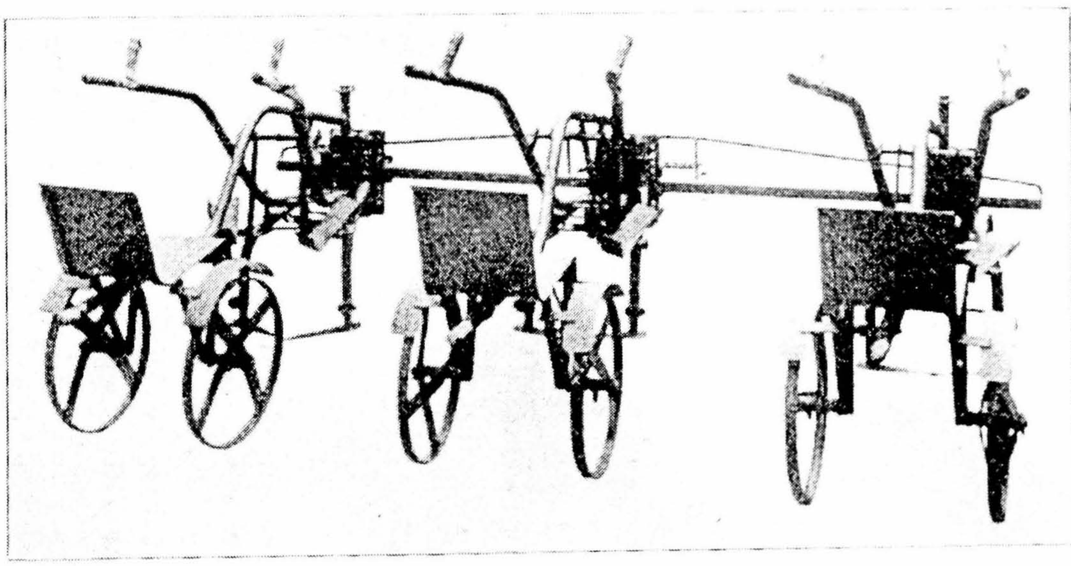


Figure 2-17 Rapid-O-Hoe

NIAE (1947[b]) stated the peculiarly human faculties of hand hoeing are still retained with the tractor equipment. A main frame carries two or three hoeing units each independently steered by a seated operator, who can open "V" hoeing blades at will by depressing a foot pedal, and thus hoe between the plants while avoiding damage to them.

It is reported in NIAE (1947[b]) that a speed of 1.28 mile/h (0.57m/s) was maintained, and the rate of work per man, including the tractor driver with the other operators, was estimated as four times the rate when hoeing by hand. The minimum intra-row plant spacing was considered to be 18 inch (457 mm). The minimum row width required to fit the implement between them was 26 inch (660 mm). Based on the pre-mentioned spacing a three row standard machine had a spot work rate of approximately 0.41

ha/hr. The report found that although it was not possible to cut the weeds quite so near to the plant stalk as with the hand hoe, the machine had the advantage of keeping the soil up to the plants.

No further information is available on the Rapid-o-Hoe, with NIAE (1947[a]) stating that the manufacturers Messer's M.B. Wild & Co would take on the recommendations made. Although the Rapid-o-Hoe still required operators for each row it did provide selective intra-row weed control, and was the first to offer an alternative to hand weeding.

2.3.6.11 Powered rotary cultivators

Figure 2-18 shows a PTO powered rotary cultivator, with and without guards. These cultivators operate between the crop rows and control the inter-row weeds. The weeds are killed through cutting, uprooting and burial as the cultivators rotate so mixing the soil.

Figure 2-18 Powered rotary inter-row weeder

The powered rotary cultivator is fitted with L-shaped blades on a horizontal axle. The width of the rotor can be adjusted to different row widths. It gives more intensive cultivation of the soil and can deal with larger weeds (Bond & Grundy, 1998). It is probably the most aggressive weeder, leaving a smooth soil tilth after operation, incorporating weeds and mixing soil to a depth of approximately 120 mm.

The energy input of such vigorous cultivation may also prove to be significant over arable production areas. The radius of the cultivator will, like the brush weeder, become a problem if used in certain crops that are at an advanced growth stage.

2.3.7 Summary of commercial equipment

Table 2-1 presents summary information on the weeders discussed in the review to enable comparisons between weeding alternatives, it makes no attempt to assess the potential crop damage that may occur by the various techniques. Melander & Rasmussen (2000) report direct control methods conducted post-emergence with an intra-row component, such as weed harrowing, vertical brush weeding, torsion weeding, ridging and finger weeding, have been shown to operate with relatively low selectivity, meaning that high weed control might be associated with unacceptable crop damage.

Table 2-1 Summary of commercial equipment

Hoe Device	Av. Speed (km/h)	Depth (mm)	Weed Control	Mode of action	Weed size (mm)
Harrow	7	20-30	Inter/Intra-row	Uprooting/burial	< 50
Brush weeder	< 3.5	15-45	Inter/Intra-row	Uprooting/burial	< 25
Split hoe	3	50	Inter-row	Uprooting/burial	< 50
Finger weeder	10	12-19	Intra-row	Uprooting	< 25
Torsion weeder	<10	25	Intra-row	Uprooting/burial	< 25
Hoe ridger	7	25–40	Inter/Intra-row	Burial/cutting/uprooting	Large
Subsurface tiller	8	100	Inter-row	Cutting	Large
Powered rotary	6	120	Inter-row	Cutting/burial/uprooting	<150
Rotary cultivator	10	20-50	Inter-row	Cutting/mixing	< 25
Basket weeder	8	25	Inter-row	Scrubbing, uprooting	< 20
Sweep	6	20-40	Inter-row	Cutting/burial/uprooting	Large
Ducks foot	6	20-40	Inter-row	Cutting/burial/uprooting	Large

2.4 Non soil-engaging, non-chemical

Non soil-engaging, non-chemical devices have been available for many years, but are not as readily used as soil engaging implements. They often have a higher operator risk attached to using them along with reduced rate of work (Parish, 1990; Stephens, 1982).

2.4.1 Thermal techniques

Parish (1990) states "thermal techniques, often called flame weeding, generally use liquefied petroleum gas (LPG), propane or oil burners; and have now become an established part of the organic growers machinery compliment". There are generally two basic designs of flame weeder available, flame contact and infra-red. A flame contact weeder is shown in operation in Figures 2-19 and 2-20.

Figure 2-19 Side view of the flamer

Figure 2-20 Flamers in action

Flame weeding kills by an intense wave of heat that ruptures plant cells. For best effects flaming requires a level soil surface and selectivity is achieved only by pre-emergence flaming. Its advantage is that there is no soil disturbance to stimulate a further flush of seedlings and they can also be used in soils that are too wet for mechanical weed control (Bond & Grundy, 1998; Parish, 1990). Flame weeders are used either before drilling or pre-emergence and are powerful enough to destroy seedlings that are just below the soil surface (Kirchoff, 1999). They are also used post emergence, as certain crop plants i.e. onion or maize can tolerate flaming (Parish, 1990; Ascard, 1990).

The infra-red flamer is fundamentally different from the contact flamer, covering a more closely defined area as heat is radiated towards the target plants by heating ceramic and metal surfaces. Infra-red weeders have the disadvantages of needing time to heat up; and the panels are sensitive to mechanical damage, less effective as operate at reduced temperature compared to the flamer, and are more expensive than flame weeders (Bond & Grundy, 1998; Parish, 1990; Ascard, 1990; Lampkin, 1990).

High energy requirements, the need for a level surface and the slow work rates make these machines unattractive to the large scale farmer (Stephens, 1982). Flaming by some is considered to be the wrong approach as the major objective of organic production is to reduce the amount of fossil fuels used (IFOAM, 1981). Between 8 to 36 kg/ha of gas was used according to trials undertaken on carrots by Vester (1984). Lague & Khelifi (2001) report that flaming is seven more times energy consuming when compared to mechanical hoeing.

2.4.2 Electrocution

Electrocution of weeds has never successfully entered the market and there is less literature supporting such methods. Diprose & Benson (1984) investigated two types of weed kill: spark discharges and continuous contact. The former uses high-voltage, short duration pulses for weed control, for plant thinning and acceleration of ripening. Blasco *et al.* (2002) have developed a weed control mechanism that incorporates a probe which has an electrode powered by batteries that is capable of producing a 15000 V electrical discharge to kill the weeds. The device has been demonstrated in lettuce crops in Spain reports Blasco *et al.* (2002), but figures on work rates and weeding efficacy were not detailed.

The second method uses an electrode connected to a high voltage source and as it touches the plants, current flows for the duration of the contact time. Some commercial contact machines are available in the USA, but for economic reasons it is unlikely that electrical weed control machines will be used in the UK. Diprose & Benson (1984) state that the system needs to be employed on farms larger than 900 ha for there to be an advantage over chemical methods. There are very serious safety issues, as the current required to kill a plant is many times higher than that needed to kill a human with their sensitive nervous system. Parish (1990) states "the high voltage required for these machines pose a hazard, which may be less of a problem if lower voltages were used to generate heat to expose them to infra-red radiation."

2.4.3 Additional non soil engaging weeding devices

There are many options available that could be used for weed control; Bond & Grundy (1998) discuss the advantages and disadvantages of the following methods: Cutting/mowing, freezing, steaming, solarisation, microwave radiation, water cutting, band heating and lasers. None of these methods are widely used amongst growers, due to cost, potential hazards and low rates of work. Future technological developments may cause a shift in current thinking as more research effort is spent on alternatives.

The project has focused on soil engaging devices, as weed kill can be very successful through subsurface cutting and burial. Acceptance in the industry should be relatively simple as tillage has been an important aspect in farming for centuries. It is also a low cost option with low levels of energy inputs. It has the added advantage of breaking capped ground, and mixing of nutrients in the soil.

2.5 Removal of weeds along the row

Historically hand hoeing has been the best adopted practice to reduce the number of weeds growing between and along the row. This operation was sometimes conducted at the same time as thinning, though the adoption of transplanting and mono-germ seed has resulted in a decline in this practice.

Weed control in the row was investigated by Liljedahl *et al.* (1956), they reported that hand hoeing sugar beet could take up to 32 man hours per acre, with reductions of 40% if mechanical thinners were used. Now almost fifty years on mechanical control of weeds along the row has still to be addressed. Further information on hand hoeing work-rates are discussed in Section 6.4.

2.5.1 Thinning

The objective of thinning is to reduce the initially high plant population to a final stand having a population and distribution that is optimum for a given crop (Miller *et al.* 1972). Two types of thinner were commercially used in intensive systems, the blind thinner (non-selective) and the selective thinner. The blind thinner was set up to leave a pre-determined plant stand down the row.

Robertson (1974) identifies the two main mechanisms of thinning as: L blades fitted to a bar that oscillates horizontally or in pendulum fashion across the row, knocking at the seedlings. The second mechanism is the rotary head thinner consisting of a cut away disc, which is angled to the direction of travel of the machine. As the disc passes along the row of seedlings, the gaps within the disc allow seedlings to remain, whist the solid portion of the disc removes the plants.

The severity of treatment depends upon the size of the gaps in the disc and the speed at which it revolves in relation to its forward speed. The mechanisms were either driven from a land wheel or tractor power take off (PTO). Thinning spaces can be adjusted by the speed of rotation/oscillation, or the length of the blade, as well as forward speed if PTO driven. Additional weeding by hand was required in conjunction with the blind thinner, but with the selective thinner it was often unnecessary as the crop could be selectively thinned more than once, (Robertson, 1974).

Selective thinning takes account of plant positions in the initial stand when removing plants to form the final stand, (Miller, 1973) and was therefore a more sophisticated system. Blades thinned out the crop until the minimum plant spacing distance had been covered, following this the mechanism was activated and the blades tripped out of work ensuring the next plant sensed was left. The system was then re-started and cutting re-commenced. In this way the machine takes care of any gaps there may be in the crop, by only starting to measure each new plant spacing gap from the previous actual plant position, which is the essential difference between selective and blind thinners, (Robertson 1974).

The selective down the row thinner was the closest automated mechanical method of achieving what we class today as intra-row weed control (excluding the hand hoe) and achieved good results. Miller *et al.* (1972) reviewed a wide variety of thinners and found that they operated at forward speeds between 0.9 - 4.8 km/h achieving work rates of between 0.2 ha/h and 1 ha/h dependant upon how many rows were covered and the forward speed. Weed kill efficacy was not detailed.

Sophisticated machinery was being developed in the late 1970's but with the introduction of mono-germ seed in the 1980's for use in sugar beet, and with improvements in precision drills the thinner was seldom used in farming practice.

2.5.2 Planting on the square across an entire field

Inter-row weed control could become intra-row weed control if plants were planted or drilled in squares. Mechanical hoeing of crops that have been drilled or planted on the square should enable 85-90% of the surface to be treated (Kouwenhoven, 1992).

Unfortunately planting on the square is not a practical solution as more issues are raised. Firstly, drill accuracy is not yet at a stage where it can accurately drill equi-spaced plants consistently. Secondly drill bout matching synchronisation between each bout would be of paramount importance to avoid crop damage. Also there would be junction problems within the field, and obstacles such as trees or telegraph poles would pose additional problems along with the field boundaries.

In 1974, Robertson reports on a system called "Cross blocking" reporting that this rough and ready form of thinning is rarely used in intensive growing, but can give results comparable to mechanical gapping with the added attraction of simple equipment. Cross blocking consists of hoeing across the rows of the crop, using a tool bar and standard A or L blade, set to give the desired centre to centre measurement (Robertson, 1974). Cross blocking is similar to that of planting on the square, but it requires additional seedlings across the field, which is an extra cost to establishment.

2.5.3 Intra–row weeding machines

Commercial intra-row weeding devices are used in forestry and vineyard applications. These are large robust pieces of equipment and operate on a contact basis (electro mechanical) for selectivity. There is often a metre between each tree or vine, and the weeding device, be it a mower for cutting or disc for cultivation has the following action. The weeding mechanism is mounted to a swing bar from the rear three-point linkage off-set to one side of a tractor. The swing bar mechanism retracts behind the tractor when an obstacle (tree or vine) is detected. Detection is via a mechanical switch activated from a feeler rod, which usually powers a hydraulic motor. After passing the obstacle the swing bar extends into the intra-row to control the weeds, until the next obstacle is sensed. Scaling down of the idea may be a possibility for the development of an intra-row weeding mechanism for row crops. Further research of intra-row weeding mechanisms with the potential for field scale weeding is reviewed in Chapter 6.

2.5.4 Plant identification along the row

Human vision is still the best technique for distinguishing between the individual plant and the weed as used in hand hoeing. The problems however, as previously discussed are those of work rates and labour cost.

Non-human techniques were tried in the 1960's - 1970's and applied to the selective thinner. Miller *at al.* (1972) report that there were three main types of detection unit:-

1) Contact resistance - A conductive element at right angles to the plant row and an electrical potential is applied. When the plant is contacted, earth is established and an output signal is generated.

2) Optical – Photo-electric cells detect presence of a light beam at right angles to the plant row, when the light beam is interrupted an electrical signal is obtained.

3) Electro-mechanical - A 'U' shaped rod was mounted at right angles to the plant row. When a plant was contacted, the rod moves backwards and actuates an electronic switch to produce an output. Resistance of rod movement was adjustable to suit plant size and type.

With the demise of the thinner over the last thirty years, development ceased on these ideas, as rapid growth in drill technology and chemical control became the main focus. The ability to recognise individual plants was not seen as important, when the mono germ seed and equi-spaced drilling were introduced. Today however, the cycle has now almost gone full circle as chemicals are seen as potentially harmful to health, and consumer demand for organic produce has increased.

Sensing techniques described in this section are seldom used, apart from the electro-mechanical system, used for inter row guidance, or for intra-row weed control in forest nurseries. Vision guidance systems are being developed to detect the individual plant position along the row. Section 2.6 investigates vision guidance in more detail, and how it can be used for accurate guidance between and along the row.

2.6 Guidance and positioning review

In order to maximise weed kill by inter-row cultivation it is important to increase the cultivated area. Melander & Hartvig (1997) reported that if crop damage is to be avoided precise lateral control is needed. "Automatic guidance of agricultural equipment can reduce stress on the operator due to the demands of steering. This permits the operator to focus on the functioning of the equipment and improving performance" Kocher *et al.* (2000[b]).

A number of guidance systems have been proposed for agricultural use (Tillett, 1991; Hague *et al.*, 2000). However, for inter-row cultivation only the very highest levels of accuracy are acceptable. The most appropriate guidance techniques are those that either sense the crop directly or operate from a marker (furrow or soil slot) laid down at drilling time. The most common of these techniques is manual guidance, either by very accurate tractor steering, or through the input of a second operator seated on the hoe. Both tasks demand high levels of concentration.

2.6.1 Tractor steering accuracy

In 1978 a survey was conducted investigating the lateral steering accuracy required for a range of agricultural operations (Bottoms, 1978). The experiments aimed to establish optimum and average variation limits for agricultural operations. Optimum and average lateral variations were defined respectively as "that within which a first class driver (i.e. the best 5%) will work" and "that within which the average driver will work" (Bottoms, 1978). Unfortunately the data collected was skewed with relatively small samples and therefore median values of each operation were stated. The field operations were broken down into five groups, and the group of paramount interest is group 1, in which field hoeing lies. The optimum median value of the lateral variation was 38 mm and the average median value was 75 mm (Bottoms, 1978).

Although this data is not directly comparable with experiments undertaken in Chapter 3, it can be seen that there is approximately a 2:1 difference between the best and average drivers. To cope with high variations in lateral positioning the tool operating between the rows often tends to be much narrower than the row so that crop damage does not occur. Although the crop survives without damage, the area of cultivated land between the rows is substantially reduced.

Kocher *et al.* (2000[a]) investigated an articulated implement guidance systems in conjunction with an automatic steering device (Agtronics, Electronic Steering Pilot). The device had a field feature sensor that could be used to follow a marker furrow. A laboratory experiment was undertaken to evaluate the performance of the mechanism and it was assumed that the operator was mainly concerned about how much time an implement guidance controller could keep the implement inside a ± 30 mm or 50 mm error band. The results show that the tractor guidance system kept at least 70% of the tractor positional errors within ± 30 mm when travelling a straight line and widened to ± 50 mm when following a curve; the tractor guidance system controller maintained this 94% of the time. The mean standard deviation for the above work is 55 mm, which is substantially higher than other guidance systems reviewed in Table 2-2. This is however the tractor's positional error when following the row, via a guidance system. Kocher *et al* (2000[b]) went on to investigate implement positional errors within ± 50 mm, and found that this could be achieved for 80% of the time. For comparison, the standard deviation is 39 mm. This is less than the tractor's lateral position, however some three times greater than measured performance indicated in Chapter 3 by manual steerage systems. Kocher *et al.* (2000[b]) mentioned that the side-shift system is more accurate than the disc-steer system except when following curves.

2.6.2 Candidate guidance technologies

"There are many candidate guidance technologies available, some very primitive and relying on crop sensing for positioning but at the other extreme some are very complex like satellite navigation systems. However, none of them are 100% accurate", Tillett (1991). Tillett (1991) investigated many guidance technologies available and assessed them in accordance to their ability to accurately follow the row. He reported that mechanical guidance systems that utilise existing features are generally cheapest as the costs are restricted to the sensing and control devices. Lateral positioning accuracy is of paramount importance, and as there is a need to improve on that for non-guided implements, a guidance system that reduces the error will reduce the number of weeds in the inter-row.

Tillett (1991) lists several technologies that improve lateral positioning. However it must be noted that even ± 50 mm still leaves a wide gap as the hoe blade would have to be a minimum of 100 mm narrower than the row spacing. On a typical row spacing of 250 mm (organic cereals), 40 % of the soil would remain untilled, allowing weeds to compete with the crop.

Increased accuracy is needed, and the review undertaken by Tillett (1991) identifies the following suitable technologies presented in Table 2-2, with additions by the author.

Table 2-2 Summary of automatic guidance techniques

Guidance type	Accuracy
Steel rails or concrete tracks	± 10 mm
Sensing stretched or buried cables	± 20 mm
Laser (fixed beam or plane)	± 1 mm
Laser (rotating beam)	± 5 mm ± 150 mm
Vision guidance	± 10 mm (1 sd)
Ultrasonic	99% over range 0.1-10 m
Leader cable	± 5 mm up to 50 mm outdoors
Furrow following	< 28 mm
John Deere GPS	± 100 mm (50 mm in 2003/4)

Table based on Tillett 1991 with additions by the author

Steel rails or concrete tracks clearly have their use in the agricultural sector, enabling high accuracy to be achieved, and the benefits of low rolling resistance. However for field use they are somewhat limited as they would need to be permanently placed within the field. They could, however, be incorporated into the guidance of wide span gantry systems, which have yet to be commercially successful in Europe. Sensing stretched or buried cables again could be used with gantry systems where they could be permanently placed on dedicated tramlines. In conventional systems, however, the risk of damage through successive field operations is high. Accurate placement of the cables would be essential for precision guidance.

Leader cables have been employed in guidance for many years reports Tillett (1991). The most popular use is in factory and warehouse areas, although they are sometimes used in agriculture to guide specialist applications such as multi-truss irrigation gantries. Unlike steel tracks or concrete roads, they can be buried up to 0.5m deep to avoid damage from tillage operations (Finn-Kelcey & Owen, 1967).

The lack of agricultural acceptance for the pre-mentioned guidance technologies appears to be the lack of dedicated tramlines, which results in the tramlines moving across the field each year and the accuracy and expense inlaying the system. Farmers have been reluctant in adopting permanent tramline systems, even with the additional benefits of controlled traffic, thus less soil damage and potentially higher yield. As the costs of field operations increase due to rising fuel, labour and machinery costs combined with crop price reductions perhaps its acceptance will come as the cost of breaking up compacted ground will become even more significant.

Zuydam & Sonneveld (1994) investigated the accuracy of a laser guidance system to guide a hoe. The guidance system was mounted on a 12 m wide gantry vehicle incorporating a side shift unit. The transmitter was positioned at the end of the field and aligned with the aid of a second operator with a hand held receiver. A lateral error signal was generated to activate the hydraulic cylinder via an electro-hydraulic valve to move towards the appropriate side. For a field length of 417 m one change of the laser transmitter was required per hectare at the chosen working width of 12 m. The maximum distance the chosen laser could work over was a length of 500 m. They achieved an average steering accuracy of ± 6 mm (one standard deviation) over a distance of 250 m. The maximum deviation (worst case) did not exceed 19 mm, Zuydam & Sonneveld (1994). This performance might have been adequate for inter-row cultivation but employing it on the narrower span of a conventional tractor would reduce efficiency, and with the additional operator exclude it from being a viable system. In recent times major advances in image analysis techniques have been made, and are now incorporated into certain implement vision guidance systems.

Keicher & Seufert (2000) report that an accuracy of ± 45 mm can be achieved at a speed of 2 km/h, using the vision system of Astrand & Baerveldt (1999) developed in 1999. Tillett *et al.* (1999) report an accuracy of ± 13 mm (one standard deviation) with speeds up to 6 km/h with the Silsoe Research Institute vision guidance system. Astrand & Baerveldt (2002) report a vision guidance system that can control a field robot within ± 20 mm at a speed of 0.2 m/s. This system also provides identification of the individual plant within the row, differentiating between the weed and the plant.

High accuracy can be obtained from ultrasonic guidance and Tillett (1991) reports that their accuracy is 99% of the distance to target in a range of 100 mm to 10 m. It is also reported that problems are encountered with stray foliage as distance is calculated from the time taken for an ultrasonic signal to reach and be reflected back from the target, thus the reflected signal may bounce back from a weed rather than the crop.

2.6.3 Furrow following

Furrow following is an alternative technique providing guidance at increased speeds whilst improving accuracy between the row; soil engaging sensing arms follow a furrow or slot specifically made for this purpose (Grovum & Zoerb, 1970; Lawson, 1978; Roberts, 1982; Pullen, 1995). The principle of furrow following is detailed by Roberts (1982) whom notes that the initial furrow must be installed during drilling of the rows, where a channel usually 125-155 mm deep is made. In subsequent hoeing operations a fin/follower is placed in the furrow, which follows the furrow causing the hoe blades to follow between crop rows. It is reported that this guidance system works well in most soils apart from those that are rocky, or loose which would not hold the furrow, throughout the season.

Further work on furrow following was undertaken by Pullen (1995), whom investigated the use a high-speed automatically guided mechanical inter-row weeder for arable crops. The guidance technique employed was that of furrow following, where the creation of a stable guidance mark, follower shape and mounting were all investigated. Pullen (1995) achieved successful hoeing results up to speeds of 14 km/h. The simplicity of this system makes it potentially a cheaper alternative to guidance than many other systems.

Non- contact furrow following systems are commercially available i.e. ECO-DAN guided hoe. ECO-DAN (2003) state "A marker, mounted on the drill, forms a V-shaped furrow, running parallel to the plant rows. During hoeing a laser beam projected at a given angle with respect to the centreline of the camera; the furrow is seen as a V-shaped deflection, which can be recognised by the camera even after long exposure to the weather". The implement is steered though a hydraulic side shifting mechanism.

An alternative non-contact furrow following system has been developed by Andersen (2003). A laser light source projects a line over the soil furrow, and a light detector, mounted vertically above the projected line captures the view, which is analysed to determine extreme value points i.e. furrow bottom. The implement is then steered to provide the correct lateral positioning; levels of accuracy are not quoted. Furrow following technologies have the potential for pre-emergence hoeing as well as drill bout matching by following the previous furrow.

2.6.4 Global positioning systems

A Global Positioning System (GPS) is a worldwide radio-navigation system formed from a constellation of 24 satellites and their ground stations. GPS uses these satellites as reference points to calculate positions accurate to within metres (Trimble, 2003). Differential GPS (DGPS) uses a stationary receiver (base station); this ties all the satellite measurements to a known reference position. From this reference it is possible to calculate corrections for errors due to local atmospheric effects etc. These corrections can then be transmitted to mobile GPS receivers in the area and used to refine the basic position estimate. Systems are now available that use a network of reference stations to calculate correction signals that are broadcast over a wide area, thus avoiding the need for a local base station. Real Time Kinematic (RTK) GPS is a refined variety of DGPS. In addition to differential corrections from a local reference station the phase relationship of the carrier signal from satellites is resolved, further increasing accuracy (Keicher & Seufert, 2000).

Zuydam (1999) investigated the use of Real Time Kinematics (RTK) DGPS (Differential Global Positioning System) as a means of guiding an implement along a pre-stored electronic map. The digital electronic map contains co-ordinates to describe the intended path of the implement. Non-field based investigations were undertaken and the results show that the true path of the implement deviated from a straight line by less than ± 20 mm, Zuydam (1999). The use of satellite navigation had the great advantage of not requiring individual fields to be set up with buried cables or corner reflectors for example (Zuydam, 1999). However, the system did require a local differential base station to achieve the desired accuracy. For best results this base station should be close to the mobile unit, which may be inconvenient for farms covering broad areas. The implement was guided by GPS using a side-shift mechanism to control lateral position. The paper concludes by remarking that further tests on soil are needed to prove the universal applications of the system. It must be noted that all tests were conducted in open spaces and that there were no obstacles within 150 m, and, therefore, had a 360 degree field of vision to the sky. However in field situations, especially on the headland, hedges may cause the error to increase.

The cost of RTK DGPS had made this technology economically non-viable, but lower cost DGPS are being introduced by tractor manufacturers. Most of these systems are based on broadcast differential correction signals which whilst very convenient in not requiring a local base station are not as accurate. Henry (2003) reported that the John Deere GPS navigation system known as Starfire2 will provide an accuracy of ± 50 mm in real time, at an approximate cost of £14,000 and an annual license fee of £1100/annum. Starfire2 will automatically steer the tractor parallel to the next bout, all the operator need do is turn at headlands, thus offering improved lateral positioning giving the driver more time to optimise implement operation.

2.6.5 Self steer agricultural vehicles

The self steer tractor concept throughout this study of research has developed rapidly with major manufacturers such as John Deere, Agco group, Caterpillar, CNH group and Renault all now offering a self steering tractor, based on GPS guidance technology.

Farm Contractor & Large Scale Farmer, (October, 2000) reported that Renault Agriculture was in the development stage of the self-steer tractor. The guidance system can be used to steer the tractor in the field, leaving the driver free to concentrate on operating the implement. This was achieved by driving around the field to mark its boundary, entering the width of the implement and the desired headland width. Using this information, the system steers the tractor up the field before turning at the appropriate headland mark and beginning the next bout. They report an accuracy of up to ± 50 mm between each bout. Renault plans to bring the system to the market in 2003.

Unfortunately for Renault it seems that the other major manufacturers have beaten them to the market place, with the most widely sold unit being that of John Deere. Accuracies being claimed for the steerage system are within ± 50 mm when out in open clear spaces. Although not accurate enough to guide a hoe blade between crop rows it has the potential to improve drill bout matching.

Complete Driverless tractors such as those detailed by Fitzpatrick *et al.* (1997) who evaluated the first unmanned windrower (Demeter project) in conjunction with New Holland and the autonomous vehicle detailed by Hague & Tillett (1996), were both successful in field evaluations. However these technologies are unlikely to be adopted in the UK with increasing health and safety legislation. Therefore, although not removing the operator, self-steer systems are the next best available option for increasing productivity, reducing driver positioning concentration and enabling implement performance to be maximised. The lateral positioning claimed in these systems however is not yet accurate enough to provide precision guidance for hoeing operations.

2.6.6 Summary

New technologies offer new guidance opportunities that may change the way in which implements are guided and controlled, but as the review of literature has shown relatively little is known about the level of lateral positioning accuracy already achieved in mechanical weed control. In order to establish current levels of tractor lateral position, experiments were undertaken to provide quantitative data and are discussed in Chapter 3. This data will enable hoe blades to be optimised to increase the weeding efficacy between widely spaced crops, and indicate the industry standard for lateral positioning.

2.7 Soil displacement following disturbance from hoe blades

This review has concentrated on ways in which inter-row and intra-row weeds can be destroyed by mechanical methods. Section 2.3.2 detailed weed kill experiments undertaken by Jones & Blair (1996) who found that subsurface cutting and burial were the most effective means of weed control. This section reviews available literature to improve the level of understanding in soil displacement with a view to improving hoe blade design. It also identifies areas where additional research is required.

As a result of improved guidance, hoe blade width can be optimised so the tip of the blade travels closer to the row (detailed in Chapter 3). This reduced distance between the crop and the blade tip combined with increased forward speeds, potentially in excess of 10 km/h can result in excessive lateral soil translocation that may result in crop damage through burial. Lateral soil displacement in commercial systems is sometimes controlled by fitting side guards, either side of the hoe blade, shown in Figure 2-21.

Figure 2-21 Side guards to prevent lateral soil translocation

Projected soil leaving the blade impacts the guard preventing it from covering the row. Side guards increase capital cost and weight, cause leaf damage at advanced crop growth stages, and increase forces on the equipment. However with many current designs of hoe blade they are essential to provide soil control. With research and correct design of hoe blades it may be possible to remove side guards if soil displacement off the blade could be precisely controlled.

Soil translocation if controlled effectively can be desirable. The lateral and forward translocation of soil can be utilised to bury the weeds close to the crop row, or individual plant, therefore avoiding cutting, which may prune the plant roots, thus reducing yield. Cutting the majority of weeds along the row, and burying the weeds close to the individual plant, could control intra-row weeds.

Hanna *et al.* (1993[b]) state that "information on effects of tillage sweep geometry, operation and soil conditions including soil surface elevation, is needed for effective design, selection, and use of sweeps for row crop cultivation and ridge construction". Unfortunately there has been very little research undertaken in understanding the translocation of soil from shallow working blades and prediction of soil translocation appears to have received little attention, Rahman *et al.* (2002). Those few researchers who have studied soil flow paths and movement report tool geometry, operating speed and soil physical parameters as important factors in influencing soil displacement, (Sharifat & Kushwaha, 2000; Hanna *et al.,* 1993[a]).

Mech & Free (1942) have investigated soil movement on slopes where it was recognised that appreciable movement occurs following tillage operations. Although useful in identifying soil displacement their work is not relevant to this study as hill slope is not thought to be a major factor during mechanical weeding.

2.7.1 Velocity and trajectory of soil

In 1942 Chase undertook a study to investigate the behaviour and operation of soil as it was disturbed with a subsurface tiller blade. It was observed that a flat blade (low rake angle) would slip through the soil with minimal disturbance. Increasing blade rake angle resulted in increased soil mixing and disturbance, which resulted in increased force to pull the blade through the soil. Chase (1942) also noticed the distinction between the leg (shank) and the blade main body, which many authors have subsequently over looked. He states that the shanks that propel the blades through the soil are very important, and should be designed to give minimal soil disturbance.

Vasilkovskii & Harris (1970) investigated the trajectory and velocity of soil particles by using the Pigulevskii method of placing marker blocks in the soil. He reported that they only gave final position of soil movement, whereas the path and velocity of motion of the soil particles cannot even be approximated. Vaslikovskii (1970) adopted a different and rather more complex approach using magnets to trace soil movement. Magnets were placed in the soil surface, and induction coils mounted next to a series of holes drilled through the sweep blades. As the magnets passed over the holes in the blades, their position was recorded via an oscilloscope and thus soil movement above the induction coils was obtained. Experiments at speeds of 3, 6 and 12 km/h were undertaken in an ordinary clay loam with a moisture content of 25-27% at a working depth of 70-80 mm. He concluded by stating that the relationship between tine speed and soil velocity at various forward speeds varies little, and that the velocity of particle motion over the blade surface is always lower than the forward speed. No prediction work was undertaken.

In 1977, Kotov investigated the effects that swept blades had on soil movement and the interaction between the leg and the blade. He reported that if the blades were designed correctly then soil could be moved away from the leg, thus reducing the undesirable soil scatter due to leg thickness. In order to observe the effects of soil movement, thus reducing the risk of soil scatter from the leg, soil flow over the blade was monitored. Soil angle was measured on the blade face by attaching threads to the wing just above the cutting edge. The other ends of the threads were not attached but were the correct length to ensure they did not become entrapped under the soil leaving the blade. At the end of the run, the blade entered free space outside of the soil bin and came to a sudden stop in free space, where the angle of the strings was measured.

The blade investigated had a 20^0 rake angle with a 35^0 sweep angle, and had a sliding face length of 0.087 m. It was pulled through a medium loam black soil, and the effects of density and speed were investigated to see the effects of soil flow angle. The density ranged from 819 kg/m^3 to 1230 kg/m^3 at approximately 18% - 20% moisture content. The influence of speed was monitored at four values: 1.78, 2.5, 3.47 and 4.33 m/s. Soil depth was also recorded above the blade at heights of 0.03 m and 0.06 m above the surface, using vanes connected to potentiometers.

Kotov (1977[a]) found that soil actually moved towards the centre of the leg, rather than to the ends of the blade when sweep angle was introduced. This is contrary to research undertaken in Chapter 4. His result may have been due to deficiencies in the string angle technique he employed to measure the soil angle over the blades. However, based on these results an equation to predict the soil divergence angle (ε) over the blade was developed. The equation includes the following parameters: soil friction over the blade and between the soil, blade width, rake angle, sweep angle and the velocity of the soil and blade. The predicted values do not correlate with observations in this study neither with those reported by Hanna *et al.* (1993[a]). It is also possible due to the complexity of the formulae that an error may have occurred in translating the transcript as symbols have had to be assumed where they were unclear or omitted.

Another approach to determine the trajectory of soil over a sliding surface was undertaken by Suministrado *et al.* (1990). The effects of soil passing over a mould board plough body were investigated by tracing over the scratch lines soil had left on the metal surface with a marker pen to obtain representative trajectory lines. This reported to be a successful method of obtaining the actual soil flow path over the blade. A similar methodology could be adopted for investigating the trajectory of soil over shallow working wide blades. It appears to be a more reliable technique than that employed by Kotov (1977[a]).

Russian tillage theorist Goryachkin (1968) developed three theories to explain soil trajectory over a plane inclined at two angles, one to the horizontal plane that the cutting edge makes with the direction of travel (sweep) and another in a vertical plane perpendicular to the tool's cutting edge (rake), (Hanna *et al.*, 1993[a]). The three theories describe soil deformation: crushing, lifting and shearing, using a trihedral wedge to describe soil trajectory over a surface resembling the wing of a sweep. The theories predict the relative velocity of the soil to the tool in the travel direction, to be less than tool speed, which is in agreement with Vasilkovskii & Harris (1970). The prediction of soil velocity over the blade decreases with decreasing sweep angle and for blades with no sweep angle predicts a component of zero velocity. A situation that does not occur in practice.

Hanna *et al.* (1993[a]) conducted experiments to compare Goryachkin theory with actual soil trajectory over a swept blade as they could find no experimental data to support this work. They believed that if crushing or lifting theories were able to predict soil trajectory, they would be useful in designing sweeps to change soil micro-topography. Blades with a range of sweep rake angles from 13.5^0, 16^0 and 44^0 were investigated at three speeds of 5, 7 and 9 km/h, at depths of 50 and 100 mm. Soil trajectory or divergence was determined from scratch marks on the painted sweep surface. Most of the tool influence seemed to be in lifting soil. They conclude by reporting that the Goryachkin trihedral wedge model correctly predicted greater variation in vertical flow than in lateral. It correctly identified rake angle as influencing the soil flow path but indicated that changing speed and depth had no influence. The models, although useful in predicting soil trajectory over the blade do not attempt to predict overall soil displacement and fail to take account of soil parameters. Hanna *et al.* (1993[a]) make no recommendations on how the model could be used to predict soil displacement in actual field conditions.

2.7.2 Soil translocation distance

Further work by Hanna *et al.* (1993[b]) investigated the effects of rake angle, speed and depth on changes in soil micro-topography. Three pairs of sweeps were operated each with different geometry, operated at three speeds 5, 7 and 9 km/h and at two depths 50 and 100 mm to form ridges in field experiments. Three dependent variables were chosen to evaluate changes in soil micro-topography following action by the sweep. These changes included: physical movement of soil (soil shift), potential change in agronomic environment (ridge height) and loosening of the soil (change in surface height).

Soil trajectory was recorded using a similar scratch line technique as previously described. Soil displacement was measured using 10 mm square blocks of wood on the soil surface and soil aggregate velocity was measured using the direction and magnitude of the marker blocks during a finite time interval between frames on a video tape.

Hanna *et al.* (1993[b]) report that soil shift was significantly affected by rake angle and speed, agreeing with previous work (Chase, 1942; Dowell *et al.*, 1988). It was also observed that lateral soil displacement proportionally increased with tool speed. Ridge height was also significantly affected by tool rake angle and speed, whilst depth effects were not statistically significant. Steeper rake angles resulted in higher ridges, but caution must be taken when examining the results as the three tools had varying crowns widths, (the area that leads to the leg/shank), which may have contributed to the increased soil movement. The change in surface height indicated soil loosening by tillage rather than mass re-arrangement of soil aggregates into a ridge; possibly indicating a change in soil failure mechanisms at different speeds.

The investigations into changing blade rake angle by Hanna *et al.* (1993[b]) identified some of the key factors affecting soil displacement, with general statements on the cause of soil movement. No attempt was made to state which operating conditions suited which soil type and no model on prediction of soil translocation was developed. Changes in sweep angle and location of the leg were not investigated in these experiments, but were thought to affect soil displacement. They state the influence the shank has on the soil displacement after leaving the blade may be attributed to the overall soil movement, but was not analysed separately.

Sharifat & Kushwaha (1997) undertook soil bin experiments to investigate soil translocation by two tillage tools, a knife opener and sweep. The tools were 14 mm wide and 300 mm wide respectively. The frontal area of the sweep and knife opener were measured to be 12600 mm^2 and 956 mm^2 respectively, thus giving a ratio of 13.2:1, therefore frontal area of sweep is 13 times that of the knife. They were operated at speeds of 5 and 8 km/h with moisture contents of 10 - 11% and 15 - 16% and two levels of soil compaction. The authors do not state the variation in soil compaction neither do they state operating depth. The movement of soil was determined by the measurement of plastic blocks that were inserted into the soil in a line perpendicular to the direction of travel. The blocks were 15 x 15 x 11 mm with a density of 1.2 Mg/m^3 (reported to have a similar density to the soil), placed in five layers to a depth of 75 mm, spanning 315 mm across the soil bin, with all blocks touching each other. Different colours and numbers were used to specify row and column position. It was assumed that block movement was equal to that of soil movement, following each test the blocks new x,y,z position was measured. Block positions were measured using a purpose built device that consisted of three potentiometers and one pointer. The pointer was placed at each block, and the position recorded.

Results from Sharifat & Kushwaha (1997), state that the soil moved per unit of frontal area is less on the sweep than the knife opener for different moisture contents and compaction levels. However data indicates that the sweep had more soil movement under all test conditions. The movement recorded by the blocks was inversely proportional to the depth of block layer with surface blocks moving further. In addition soil movement was inversely proportional to distance from the centreline of the tool in the direction of travel. It is presumed that the shank/leg caused the particles to travel further {this would be in agreement with Chase (1942) and Hanna *et al.* (1993[a])}. It was also discovered that a particle with a longer flow path over the surface of the tool needs more time to travel along its flow path, and consequently will be dragged over a larger distance. However, increasing speed by a factor of 1.6 did not change the soil trajectory although typically increased soil displacement between 1.3-1.7 times for the sweep. They state that variations in compaction did not have a significant effect. However they failed to give the range of compaction levels used in their soil bin experiments.

In 1998, Sharifat & Kushwaha revisited their soil movement results and developed a regression model to predict the forward movement of soil in front of tillage tools, solved numerically using MATLAB® software. It was assumed that there is a dynamic influence zone (shown in Figure 2-22) moving in front of the tillage tool. This influence zone is considered to be of circular shape and attached to the tillage tool in the travel direction. The forward travel of a tool forces the soil in front of the tool to fail or move, dependent upon the soil conditions. Some of the movement was in the direction of the tool travel and some in the direction perpendicular to tool travel. At the same time soil moves forward and to the sides until it exits the influence of the tillage tool, coming to rest when the tillage tool has passed, (Sharifat & Kushwaha, 1998; Sharifat & Kushwaha, 2000). Figure 2-22 illustrates their theory of the pattern of soil movement in front of a tillage tool.

The model does not predict soil movement directly in front of the tillage tool as Sharifat & Kushwaha (1998) state soil particles that come in contact with the tool theoretically should travel with the tool, in the forward direction, however the sliding action prevents this from happening in practice, and the model does not account for this.

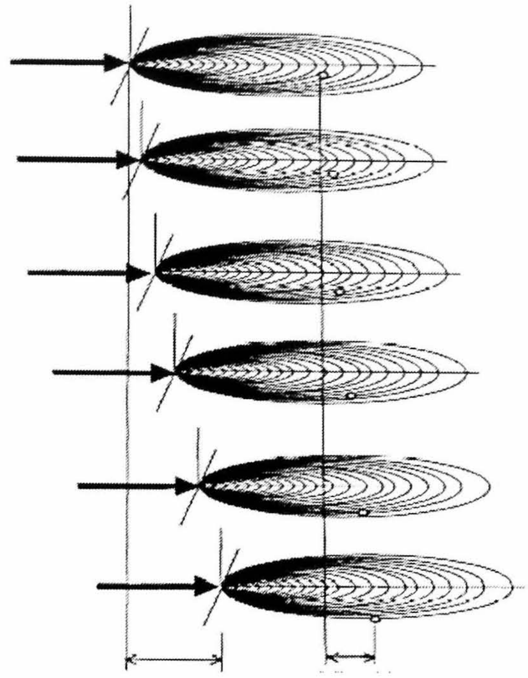


Figure 2-22 Soil movement in front of a tillage tool (taken from Sharifat & Kushwaha, 1998)

The regression model shown in Equation 2-1 was verified against experimental data obtained in 1997, with the blocks directly in front of the tool removed.

$$SM = c_1 + c_2 C + c_3 M + c_4 SMP \quad \{2\text{-}1\}$$

Where:

SM	= Soil movement (m)
C	= Soil Compaction (Cone Index, kPa)
M	= Gravimetric soil moisture content (%)
SMP	= Soil movement predicted by the "Speed soil movement model" (resolved using MATLAB® software)
c_1, c_2, c_3, c_4	= Regression coefficients

Sharifat & Kushwaha (2000) report that the SM model predicted soil movement well when compared to data from high speed experiments undertaken in 1998 with a maximum error of 20%. An error of 7% was achieved when compared to experimentally measured movement for the knife opener in 1997. They conclude by stating "considering soil non-uniformity and the difficulties associated with obtaining accurate measurements of soil parameters, the results from the modelling are promising. Soil movement with speed of operation of tillage tools can be modelled by considering a circular influence zone in front of tillage tools by describing the motion of the particles by differential equations."

The soil movement model (SM) can only be undertaken computationally, and relies on the solution of the SMP component, which predicts soil movement and velocity based on the influence zone. MATLAB is required to numerically solve differential equations expressing movement and velocity vectors. The SM regression model only applies to the soil conditions during experimentation in their soil bin. Unfortunately a generic model to factor in tool geometry, speed, and soil conditions to calculate soil movement was not undertaken.

The movement of soil by sweep injection tools under soil bin conditions was investigated by Rahman *et al.* (2002). Three commercially available sweeps were studied, classified as large, medium and small at widths of 225, 255 and 330 mm with rake angles of 16^0, 17.5^0 and 19^0 respectively. For consistency a constant bulk density of 1.2 Mg/m^3 was used for all experiments, two operating speeds (0.6 and 1.4 m/s), two moisture contents (14% and 18%) and three depths (50, 100 and 150 mm). Soil translocation was undertaken using tracers that were placed into the soil at 30 mm intervals along the width of the bin in the direction of travel, and down the bin at depth intervals of 25 mm to a maximum depth of 150 mm. After each pass the tracers were excavated by hand and the position recorded, (tracer details were not stated in the paper). The effects of the leg were not separated from the sweep blade, and the results were analysed all together for overall soil displacement.

Rahman *et al.* (2002) conclude that increased depth and forward speed resulted in a significant increase in forward translocation of soil (in the direction of travel); yet changing moisture content had no overall effect. Changing tool speed from 0.6 to 1.4 m/s resulted in a 2.7 times increase in lateral soil movement for the large sweep, with similar trends for the medium and small sweep widths. Changes in sweep width along with increasing forward speed gave no statistically different results for vertical translocation, but increasing depth and moisture content increased vertical translocation. The experiment provides a useful insight in the effects of depth, speed, moisture content and geometry, yet the analysis includes the effects of the leg, which may have influenced the overall translocation data. They report that considerably larger translocation was observed from the tracers located on the centreline of the blade due to the width of the stem (80 mm). It is further concluded that tracers located on and around the leg had the largest vertical translocation, while tracers located near the edge had the least. The probable cause seems to be leg disturbance.

The paper by Rahman *et al.* (2002) along with others reviewed all indicate the need for further research to be undertaken on soil translocation, specifically investigating the blade characteristics. It is also apparent that there is no general equation that can be used to enter factors such as blade geometry, speed, depth, soil conditions to predict soil translocation. The development of such a model would enable the accurate prediction of soil displacement after tillage operations, and thus soil could be controlled to provide weed kill through targeted burial.

2.8 Soil deformation

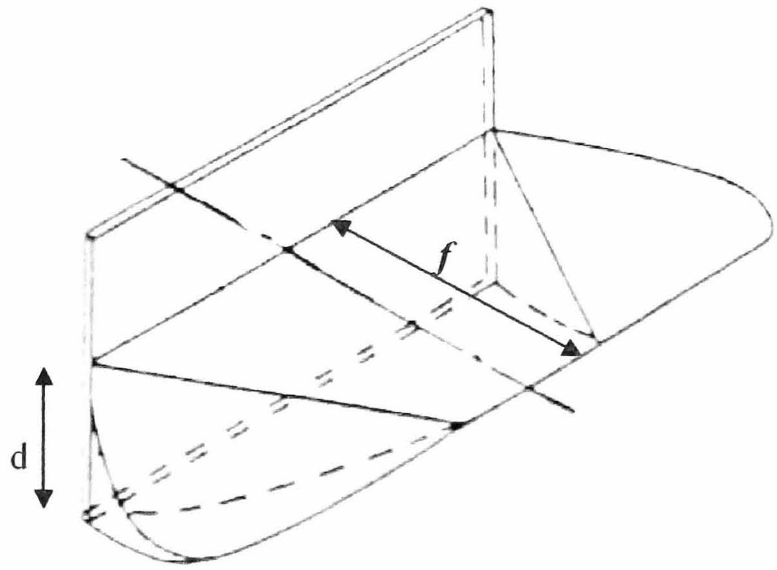
2.8.1 Introduction

O'Callaghan & Farrelly (1964), state that "as a tine is advanced through the ground, the soil in and adjacent to its path is subjected to a compressive stress that causes shearing of the soil as it is displaced by the tine". This review aims to identify the type of shearing and soil flow that occurs over wide blades at shallow working depths. Section 2.7 identified that amongst the limited research undertaken on soil displacement no generic model was available for predicting soil displacement from shallow working blades. The following sub sections investigate the possible theories of soil deformation to aid in development of a soil displacement model. Many workers have investigated the forces associated with soil engaging implements and during their work have identified/developed theories to predict soil deformation ahead of the blade, at the start of the displacement process.

2.8.2 Crescent failure and rupture distance

Work undertaken by Sharifat & Kushwaha (1998) identified an influence zone in front of the blade. This concept was first detailed by Payne (1956) whom investigated the relationship between the mechanical properties of soil and the performance of simple cultivation implements. Payne reports that "it is assumed in soil mechanics theory that when subjected to compressive or tensile stresses, soil fails along definite surfaces of slip whose inclinations to the principal stresses are defined by the soils own properties". Based on this assumption the theory of crescent failure (shown in Figure 2-23), also observed by Sohne (1956) was developed.

Crescent failure forms when a blade is pulled through the soil, distinct failure cracks can be seen in front of the blade tip, causing the surface to deform. Payne (1956) further reported that additional forward movement after the crescent had formed resulted in a wedge of soil moving slowly up the face of the blade, only being broken by obstacles or collapsing under its own weight. It always maintained crescent failure cracking in front of the tip. Payne (1956) reports failure occurs every 3 - 6 mm of forward movement, therefore the distance from the tip of the tine to the crescent (*f*) is approximately constant.



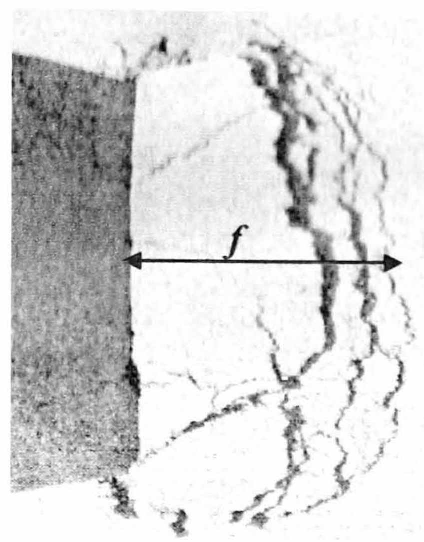


Figure 2-23 Crescent failure (after Payne 1956)

Payne (1956) stated "Soil is initially in a state of elastic equilibrium, i.e. a small increase in strain would be accompanied by a proportional increase in stress. As an implement moves forwards a zone of soil immediately in front of it is gradually transformed into a state of plastic equilibrium, thus meaning a further increase in strain would not affect the stress conditions, but rather cause the soil to flow, i.e. fail." Plastic equilibrium (as defined by Terzaghi & Peck, 1967) is when every part of a body of soil is on the verge of failure". Sohne (1956) reports that it is not easy to identify plastic flow either experimentally or theoretically, as elastic and plastic flow over lap. Sohne (1956) indicates that plastic flow occurs readily in soils with high moisture contents and rarely occurs in dense soil with normal moisture content. Elastic soil deformation is readily observed in dense hard dry soil conditions where the soil returns to its original state after the load is removed.

As blades are pulled through the soil, it changes from elastic equilibrium to plastic equilibrium, which creates soil flow from initial rupturing and deformation (Payne, 1956; Terzaghi & Peck, 1967). This concept was investigated by Payne & Tanner (1959); where experiments were undertaken with rectangular plate tines covering a range of rake angles from 20^0 to 160^0 and a selection of depth width ratios from 1.5:1 to 6:1. They state that "the distance in the direction of travel from the line of emergence of the tine, to the limit of the crescent increased more rapidly as the rake angle became more acute". Relationships between the bottom of the tine and the leading edge of the crescent failure were established and plotted, shown in Figure 2-24; depth width ratios less than 1.5:1 were not investigated.

The rupture distance in front of the tine face at the soil surface was continued by Hettiaratchi *et al.* (1966), Godwin & Spoor (1977). Rupture distance ratios were developed from empirical data, and an experimental relationship was obtained between rupture distance ratio (m) and tine rake angle (α), where $m = f/d$. f is forward distance of soil breakout from the tine at the surface, and d is the depth as illustrated in Figure 2-23. Godwin & Spoor (1977), undertook further experiments on rupture distance and combined the work of Hettiaratchi and Reece (1967), Payne (1956) and Payne & Tanner (1959) and found the results of different studies to be in close agreement, all concluding that increasing rake angle results in decreased rupture distance. The relationship applies for narrow tines pulled through soils with appreciable friction and density in addition to some cohesion.

Figure 2-24 illustrates the experimental relationship obtained by Godwin & Spoor (1977), Payne (1956), Payne & Tanner (1959) and Hettiaratchi and Reece (1967) reproduced from Godwin & Spoor (1977).

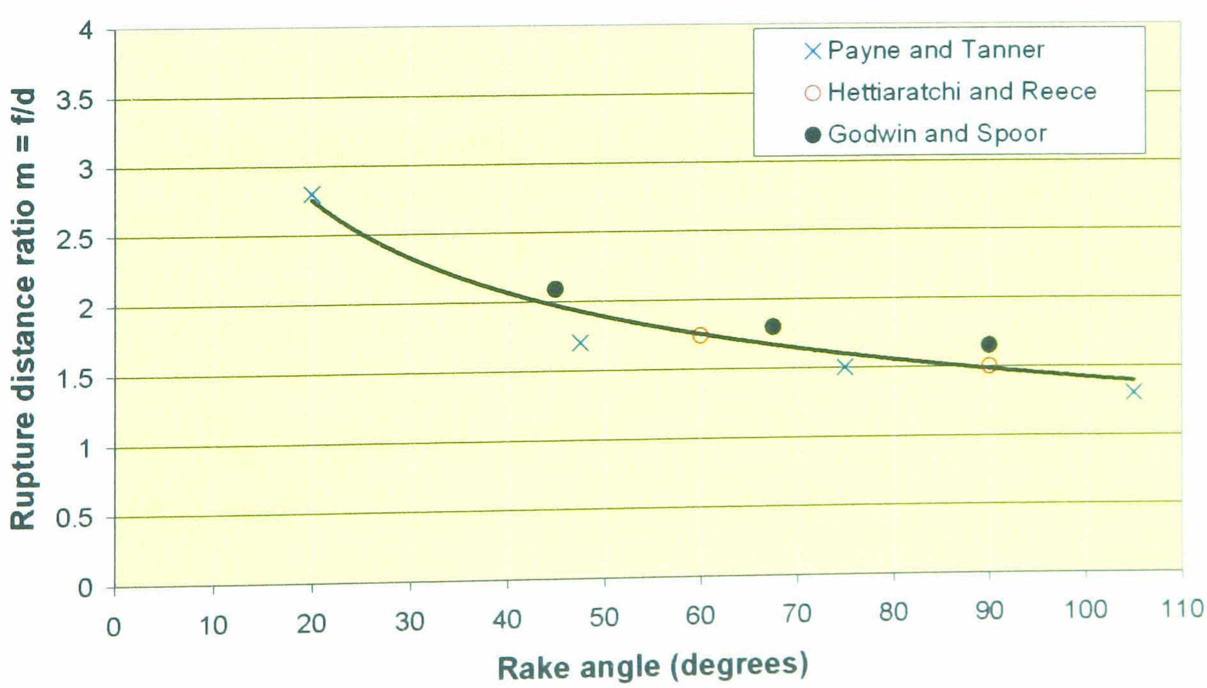


Figure 2-24 Experimental relationship between rupture distance and blade rake angle (reproduced from Godwin & Spoor 1977)

2.8.3 Rupture angle

The previous approach outlined for rupture distance calculation is supported by Kawamura (1952 & 1953) who believed that rake angle, and forward rupture distance from the tip of the tine were important parameters to be characterised as they lead to the angle at which soil fails, relative to the horizontal. Experiments involved measurement of soil block position when separated away from the main soil mass as shown in Figure 2-25.

Gill & Vanden Berg (1968), reports that Kawamura (1952 & 1953) noted that as the tine moved forward the soil rose linearly, until a critical range was reached, where further forward movement resulted in rapid increases in soil height. Kawamura used the transition stage between soil blocks leaving the main mass of soil and the block being completely separated, as the shear surface point from which to predict, the soil rupture angle (β) by a geometric relationship using Equation 2-2.

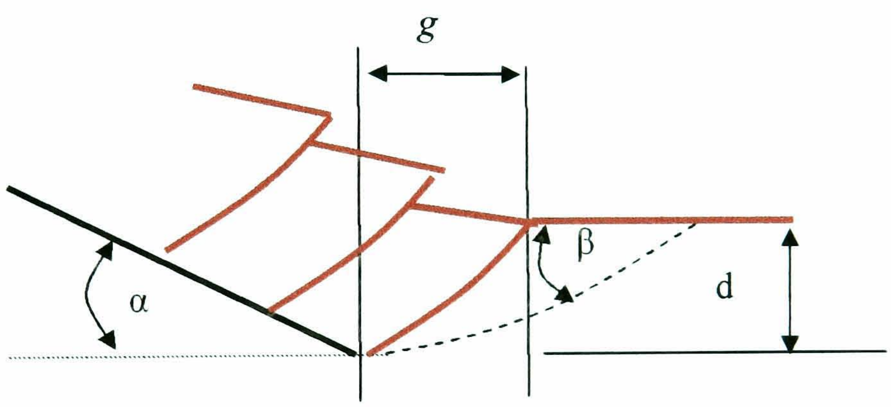


Figure 2-25 Kawamura prediction of shear surface angle

$$\tan\beta = \frac{d}{g} \qquad \textbf{\{2-2\}}$$

The studies by Kawamura (1952 & 1953) were undertaken at very low blade velocities, unfortunately not detailed; however Gill & Vanden Berg (1968) report they were less than 1m/s, at depths of 30 mm and 60 mm, covering blade rake angles of 10^0 to 45^0 degrees. Data extrapolated from Kawamura (1952 & 1953) is plotted in Figure 2-26 illustrating the values of β for changing blade angle at 30 mm depth, no soil data was presented with his results.

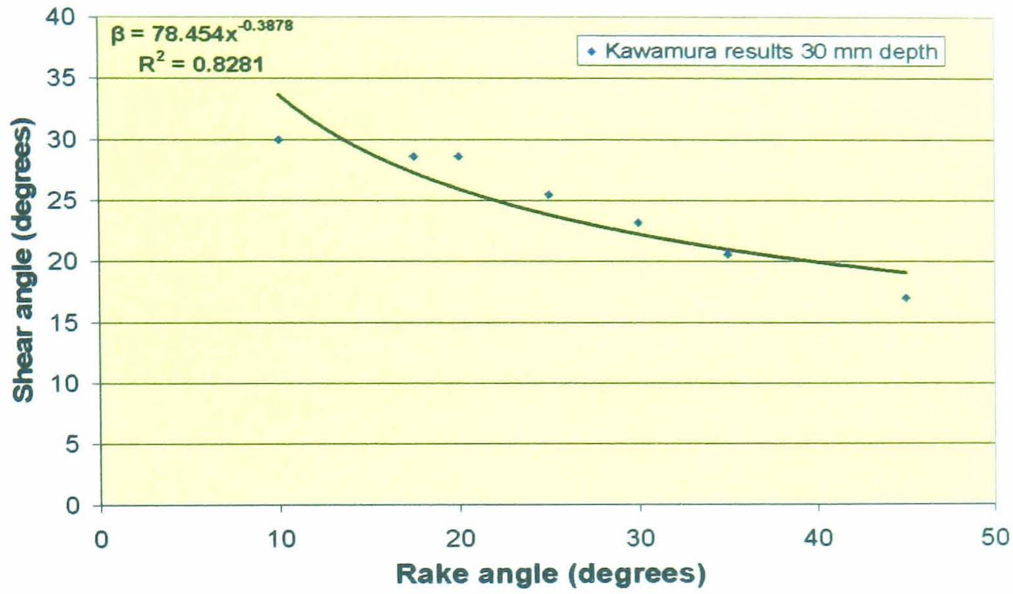


Figure 2-26 Relationship between Rake angel (α) and shear angle (β)

Comparison of the techniques for determining the shear plane angle (β) and crescent formation ahead of the blade is undertaken in Chapter 4, to predict the height of soil as it flows over a shallow working blade.

The shear plane angle (β) and relationship $m=f/d$ all provide essential information on how soil fails ahead of the blade and can help prediction in soil height over the blade. Additional theories available to express β are derived for predicting forces on passive tillage tools where approximations were adequate. Hettiaratchi & O'Callaghan (1980), state "classical soil mechanics depend upon the identification of a rupture boundary and this is helpful in the estimation of volume of soil disturbed by soil working implements". Considerations into soil displacement after rupture were not often considered in experimentation investigating blade forces. However, traditional earth pressure reviews provide us with an insight into rupture/shear plane failure.

Wide tine or blade failure is of primary importance, classified as such when its working width is much greater than its operational depth. Blades used in this research and commonly used commercially fall within this criteria and are treated as having wide tine or blade failure characteristics. Many workers have concentrated on calculating forces on two dimensional soil failure associated with wide tine failure, based on Mohr-Coulomb soil mechanics. The aim of this review is to extrapolate from the force prediction models the fundamental soil deformation that is being assumed, to provide a basis for developing a value of rupture angle β as illustrated in Figure 2-27.

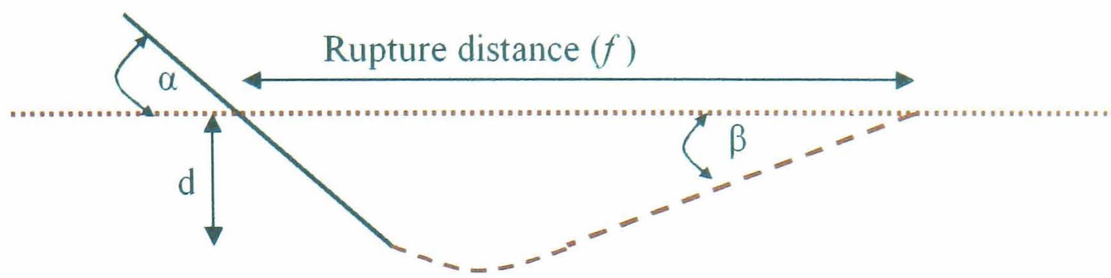


Figure 2-27 Wide tine/ blade soil failure

2.8.3.1 Coulomb (1776)

Hettiaratchi (1968) states that "historically all earth pressure calculations were based on Coulomb who was responsible for the basic concepts of soil strength" as expressed in Equation 2-3.

$$\tau = c + \sigma \tan \varphi \qquad \text{\{2-3\}}$$

where: τ = shear stress

σ = total compressive stress

c = apparent cohesion

φ = angle of internal soil friction

A blade passing through soil exerts pressure, Terzaghi & Peck (1967) state that pressure in the broadest sense indicates the resistance of a mass of soil against displacement.

Coulomb (1776) assumed that applying pressure to soil would result in a failure plane rising to the soil horizontal surface. The angle at which the failure plane intersects the horizontal soil surface is known as the shear plane or rupture angle, assigned the symbol β. The derived expression by Coulomb (1776) for calculating the angle β is expressed in Equation 2-4, taken from Kawamura (1952).

$$\tan \beta = \frac{-\sin \varphi \sqrt{\sin \alpha \sin(\varphi + \varphi')} + \sin \alpha \sqrt{\sin \phi \sin(\alpha + \varphi')}}{\cos \varphi \sqrt{\sin \alpha \sin(\varphi + \varphi')} - \cos \alpha \sqrt{\sin \phi \sin(\alpha + \varphi)}} \qquad \text{\{2-4\}}$$

The Coulomb equation predicts values for β with varying blade geometry and values of φ (loose) and φ' (dense), taking into account the range of soil shearing angle.

An alternative procedure for predicting rupture angle (β) investigated the use of the Coulomb trial wedge to predict passive earth pressure, a technique described by Smith (1981). This technique is laborious requiring many iterations and β is obtained when the minimum value of earth pressure is determined.

2.8.3.2 Rankine (1857)

Rankine theory (1857) is probably the most widely used approach for predicting β in force prediction models. This approach takes into account the differences in failure planes that occur from loose and dense soils by including φ (the soil friction angle). The angle at which the soil fails to the horizontal according to Rankine is expressed in Equation 2-5 and shown in Figure 2-28.

$$\beta = 45 - \frac{\phi}{2} \qquad \{2\text{-}5\}$$

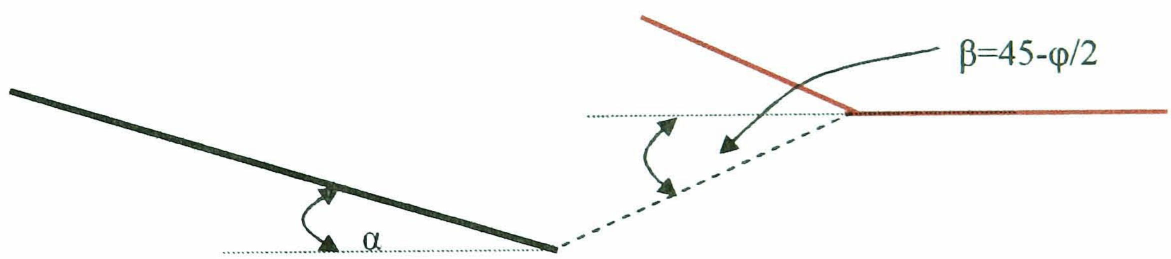


Figure 2-28 Rankine Theory

2.8.3.3 Ohde (1938)

Advanced theoretical analysis and experiments undertaken by Ohde (1938) show that the sliding surface of shear consists of a curved lower portion and a straight upper portion as shown in Figure 2-29. Ohde's logarithmic spiral approach for predicting β will have identical values with Rankine theory as section abc (Figure 2-29) has an identical shear pattern. However, the rupture distance *f* (the interface between the soil and tine face) will be greater as the failure plane occurs in front of the tip. The logarithmic spiral technique was simplified by the equation derived by Ohde, in 1932, expressed in Equation 2-5, however, Smith *et al.* (1989) state that the logarithmic spiral technique requires a number of lengthy trial solutions.

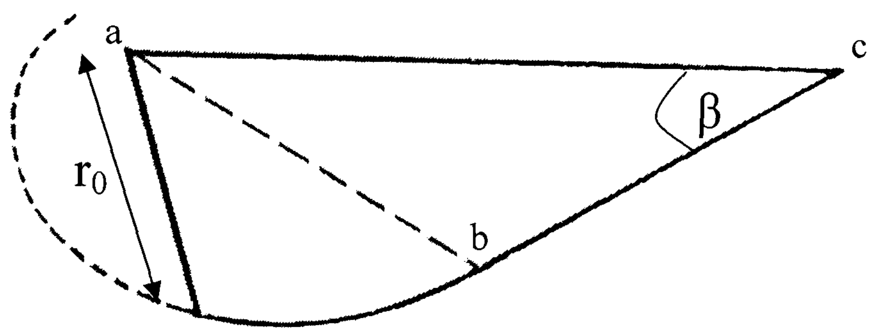


Figure 2-29 Ohdes approach for Beta

$$r = r_o\, e^{\theta \tan \varphi} \qquad \textbf{\{2-5\}}$$

Where: r = radius

r_0 = length of face

θ = angle rotation from origin

φ = angle of internal soil friction

It can be seen that by not assuming tip failure, and including the logarithmic spiral that breakout occurs further forward from the blade tip, which would increase the overall height of soil flowing over the blade.

2.8.4 Soil flow over the blade

An additional area to complement the prediction of shear plane or rupture failure already undertaken within this section, is that of soil flow over the blade. It was previously discussed that at slow speeds, the rupture distance increases, and in loose soil there appears to be an apparent link between rupture distance and blade velocity, which is further reviewed.

Tanner (1960) developed the work by Payne (1956) by examining soil flow as well as crescent failure, again at depth/width ratios in excess of 1.5:1. To record soil flow, pieces of wet paper tissue were placed in soil in a glass sided tank at regular intervals parallel to the soil surface from 31.25 mm to 108 mm. Soil was pushed past a stationary tine at speeds of 0.0067 m/s and 0.22 m/s, with blade rake angles between

34^0 and 90^0. It was discovered that in dense soils at rake angles of 48^0 and 34^0, that soil followed crescent failure and flowed over the blade. Further investigations were undertaken by Elijah & Weber (1971) who measured soil flow over simple cutting blades with a 45^0 rake angle. Soil deformation was recorded by painting a grid pattern of white paint on the side of excavated soil and recording the deformation as the blade was pulled through. They classified soil deformation into four alternative modes of failure, a) shear plane, b) flow, c) bending and d) tensile. It is thought for this review that shear plane and flow are the two most relevant for the soil bin studies detailed in Chapter 4.

Distinct planes of failure were observed in shear plane failure and soil thickness on the blade was greater than the cutting depth, (Elijah & Weber, 1971) also observed by Sohne (1956). It is also assumed that failure to the surface follows the classic Rankine theory of 45- $\varphi/2$. In flow theory no distinct planes of failure were observed, with shear and normal strain occurring ahead of the blade, again the soil is greater than the depth of cut. In loose granular material Elijah & Weber (1971) report that flow failure occurred at all speeds. Oslon & Weber (1966) reports that increasing speed can cause the transition from shear plane to flow. This theory of shear plane transition to flow is also supported by Sprinkle *et al.* (1970), who recorded that shear plane deformation occurred at speeds of 0.22 m/s but at speeds of 1.1 m/s flow-type failure occurred.

Soil flow characteristics following disturbance from shallow working blades are identified in Chapter 4, where a description of the deformation process is given, in order that development of a soil displacement model can be undertaken.

2.9 Summary

Much of the research on inter-row cultivation techniques for weed control as reviewed has been in the form of field tests of one system against another. Whilst providing some valuable practical indications of efficacy and limitations they can only draw definite conclusions about the specific circumstances of the trial related to the weeds present, crop type and weather conditions, for example. Such studies do little to further the scientific understanding of the detailed interactions that build up to provide the overall system result. There is a need to improve detailed knowledge of the mode of operation of each component of different systems. This would allow more analytical techniques to be used in designing weed control systems and in providing advice on how and when they should be used. Areas of interest might include mechanisms of weed kill, influence of cultivation on the crop, improved understanding of the precision achieved in inter- and intra-row systems and soil/blade interaction as it relates to soil displacement. Reducing draught force and designing to avoid blockages formed by weed or stones will also merit consideration as implements become larger and work rates higher.

The review has shown that there are currently no commercial techniques available to viably control intra-row weeds and there have been no significant advances in inter-row cultivation apart from the introduction of guidance systems to improve their overall lateral positioning accuracy.

The literature has also found that subsurface cutting and/or burial are the most effective means of controlling weeds within the crop. Most conventional inter-row hoe blades are designed primarily to cut weeds rather than bury them by soil translocation. Lateral displacement of soil is obtained from blades such as the hoe ridger and ducksfoot, yet these are seen more as problematic due to excessive soil translocation rather than a benefit in terms of intra-row weed control. It has been indicated that the leg causes excessive soil movement, yet results on soil translocation include the leg effects in the overall placement of soil. Further investigations are required that isolate the blade effects from those of the leg, as it is the blade that travels close to the crop, causing potential damage through burial. The problem the industry encounters with crop burial through soil displacement needs re-addressing so that burial is seen as an effective way of controlling intra-row weeds.

A fundamental understanding into the physical parameters that lead to soil translocation is required. If the level of scientific understanding in mechanical weed control could be raised to a level closer to that already achieved in chemical control, improvements could be made in technology available to organic growers and mechanical weeding could be more attractive to conventional farmers as part of an integrated strategy. The development of a soil translocation prediction model would allow designers/manufacturers to choose operating speed, blade geometry and soil conditions to be factored into any hoeing operation to maximise weed kill.

Although little work has been conducted on mechanical intra-row weed control the review has highlighted that it is an important aspect that needs to be investigated. Melander & Rasmussen (1999) report weeds growing between the crop plants in the rows are the ones that cause the most problems, not those growing between the rows. Intra-row weed control is more difficult than inter-row weed control and control of weeds closely surrounding crop plants practically impossible (Kouwenhoven, 1992). Kouwenhoven (1992) concludes by reporting present options for intra-row weed control are not yet ready for application in practice, and more attention should be given to the control of weeds closely surrounding crop plants.

The review has clearly identified the need for a selective intra-row mechanical weeder, combined with an understanding of soil translocation from hoe blades; weeds close to the crop could be buried, thus avoiding the risk of cutting the roots.

3 Lateral Positioning Experiments

3.1 Introduction

The aim of the lateral positioning experiments were to provide quantitative results of the accuracy of tractor mounted hoes whilst operating in field conditions. The results provided benchmark data that will enable the development of an intra-row weeder as detailed in Chapters 6 and 7. The results indicate how close to the row a mechanism can safely travel without causing crop damage, and how far soil would have to travel to bury the weeds within the row.

This experimental study compares some of the manual and automatic guidance techniques available for inter-row cultivation and establishes performance data in terms of lateral accuracy for best practice. A discussion is given on how this information is essential to optimise implement configuration and how this might aid developments in intra-row weed control. The benefits that automatic guidance can offer are also discussed.

The experiments and experimental apparatus detailed in this section were designed to record the true hoe path of mechanical inter-row hoes whilst operating under actual field conditions. To ascertain the lateral positioning of six hoeing systems an adaptable evaluation system is developed. Evaluation consisted of leaving a trace of dye on the ground to record the path taken by the hoe blades in normal operation. The position of that dye trace relative to the crop rows could then be measured manually.

Material for this chapter has been drawn from papers published for the Brighton Crop Protection Conference - Weeds, (Home *et al.*, 2001) and the European Weed Research Society Conference, Italy, (Home *et al.*, 2002).

3.2 Hoe path tracer apparatus

In order to establish the true hoe path a tracer needed to be placed behind the hoe blade that could be measured after the hoeing operation. The lateral positioning studies were to be undertaken on commercial farms in high value crops, therefore a vegetable dye was chosen to ensure no harmful residues were left in the soil, or on the crop. The vegetable dye needed to be visible on the soil after the hoe had passed through the crop.

Before true hoe path position could be recorded, an adaptable evaluation system was required that could be fitted onto any commercial hoe simply and quickly, thus avoiding down time when arriving on farm.

The jetting nozzle and solenoid valve are mounted on an adjustable frame as shown in Figure 3-1. The adjustable frame provided lateral and vertical adjustment so that the desired location behind the hoe blade could be achieved, with varying implement geometry and soil conditions.

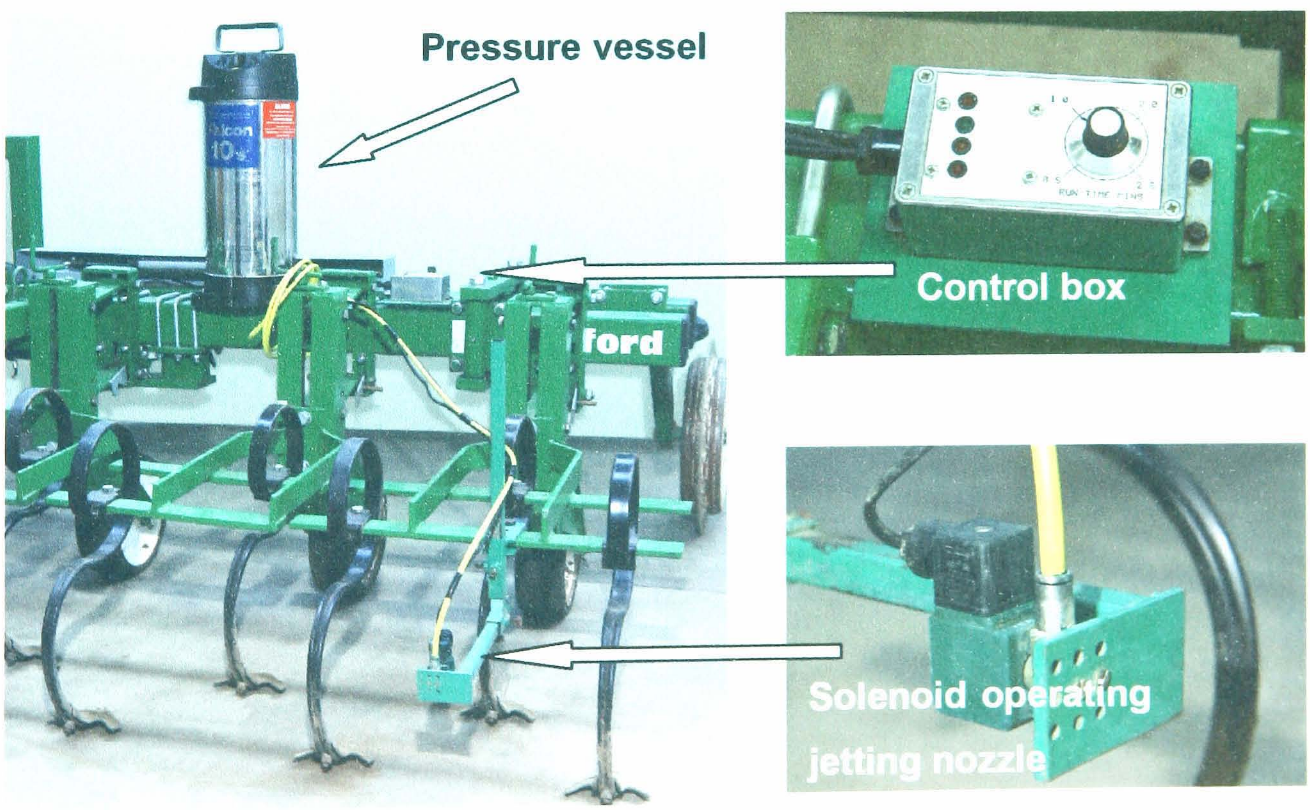


Figure 3-1 Lateral position monitoring system fitted to an inter-row hoe

The apparatus to deliver the dye trace is shown in Figure 3-1 mounted on a 4 m inter-row hoe. The main components of the system are the pressure vessel containing vegetable dye, a solenoid valve and control circuit.

Activation of the electronic circuit is via a radio link, to ensure the driver is unaware when monitoring is being undertaken, thus reducing the effect of unsustainable increases in concentration. The circuit consisting of an in-built oscillator controls the pulsing of the solenoid valve, and an external potentiometer allows the run time to be adjusted, providing a run time between 0.5 to 2.5 minutes, dependent upon length of run across the field. The circuitry is shown in Appendix A1-1.

The initial technique development was undertaken at Cranfield University, Silsoe soil bin laboratory (detailed in Section 4.2). A speed of 7 km/h (1.94 m/s) was chosen as this reflected the maximum working speed of commercial hoes. The study assessed the feasibility of applying the dye to the soil, and the visibility of dye after the hoe had passed through the soil. The dye is jetted onto the soil surface via a pressure vessel with a solenoid controlling the outlet of the dye as shown in Figure 3-1.

The variables were -

- Nozzle diameter
- Nozzle height above ground
- System operating pressure
- Soil compaction

The initial study, being purely qualitative, is dependent upon how clear the dye is on the soil. It became obvious that the dye was clear on rolled soil, but on a rough tilth, nozzle diameter and outlet pressure influenced dye appearance.

Figures 3-2 and 3-3 show the dye after it has been jetted onto a dense and loose soil surface respectively.

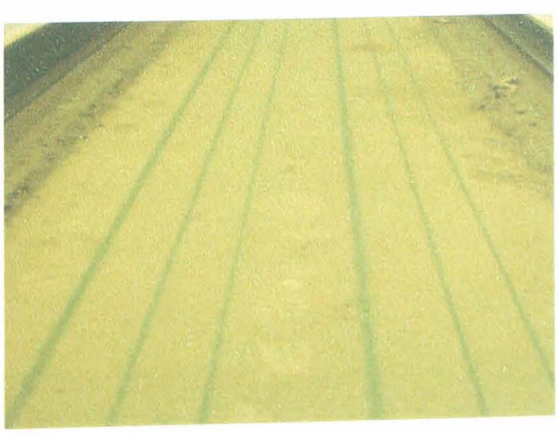


Figure 3-2 Dye on smooth surface

Figure 3-3 Dye on rough soil

Variations in the height of jet above soil surface and changing operating pressure between 1.5 and 2.5 bar had little effect. The main effect is caused by nozzle diameter. A nozzle diameter of 0.7 mm and a pressure of 2 bar were chosen as it gave the most distinctive line with the dye jetting out of the nozzle with minimal splatter and some penetration into the soil surface.

Simple calculations were undertaken to select a suitable pressure vessel for the dye before constructing the evaluation unit. The pressure vessel would be initially primed, with a compressed air dye mix. The volume of compressed air needed to be sufficient to maintain adequate pressure as the dye volume decreased. In order to save on dye volume jetted onto the ground the solenoid would be pulsed, saving dye, and allowing the forward speed to be calculated, as the pulse time is known. The volume of dye required per 100 metre run was calculated at 0.316 litres if travelling at a forward speed of 1 m/s, based on a pressure of 2.4 bar (35 PSI), nozzle flow rate of 0.0063 litres/s and a 50% valve on time.

3.2.1 Objectives

To establish the level of accuracy achieved by inter-row hoeing with guided and unguided hoes by measuring their performance in the field, thus providing information on the area to be treated by an intra-row mechanism.

3.2.2 Procedure

During field operations the solenoid and jetting nozzle were mounted 200 mm directly behind a hoe tine and 60 mm above the soil surface. The distance behind the hoe tine allows soil to settle after being hoed, thus leaving a visible dye trace on the surface. The dye is delivered to the nozzle at a pressure of 2 bar via the solenoid valve from the hand primed pressure vessel. The circuit is designed to pulse the solenoid on for 0.5 seconds per second upon activation from the radio link. The dye pulses enable true forward speed to be calculated by measuring the length of dye trace on the ground. The true hoe path is recorded by measuring the dye trace in relation to a number of crop rows using a template marked with the row crop spacing. a technique detailed by Tillett *et al.* (1999).

Table 3-1 summarises the evaluations. In each case hoes were mounted to a traditional three-point linkage arrangement on the tractor. The 3 m fixed hoe (Run A) is the only hoe to be front mounted; all the others were mounted at the rear. All hoes except the 4 m fixed hoe used in Run C and identified with an asterix in Table 1 had tight check chains to ensure the lower link arms did not move independently of the tractor, thus ensuring the hoe frame closely followed tractor position.

Table 3-1 Mechanical hoes under evaluation

Run	Hoe type	Steerage System	Operator (s)	Mounting	Crop Type
A	5.5 m fixed hoe	Tractor driver	Professional	Front	Wheat
B	9 m steerage hoe	Second operator	Professionals	Rear	Sugar beet
C	4 m fixed hoe*	Tractor driver	Professional	Rear	Wheat
D	4 m steerage hoe	Vision guidance	Non-professional	Rear	Wheat
E	4 m fixed hoe	Tractor driver	Non-professional	Rear	Wheat
F	4 m steerage hoe	Vision guidance	Non-professional	Rear	Wheat

** Hoe mounted with slack check chains*

All experiments measuring the performance of commercial hoes were undertaken with optimum drivers because the errors between optimum and average drivers may be misleading in comparing the hoes' lateral positioning as reported by Bottoms (1978). Three of the six systems evaluated relied on the driver alone to guide the hoe accurately between crop rows. The other three trials were steerage hoes that used a hydraulically operated lateral side shifting mechanism to make fine adjustments between a fixed frame on the tractor and a moving frame to which the hoe blades were attached.

One of the steerage hoes, a 9 m sugar beet steerage hoe (Run B) shown in Figure 3-4 was guided by a second operator, located at one side of the hoe in a purpose built cabin, mounted onto the moving frame of the hoe. This second operator had a clear view of the crop rows ahead and controlled a hydraulic orbital control valve. The control valve operated two hydraulic linear actuators that facilitated lateral movement between the fixed head stock and rear frame. A pointer mounted directly in front of the additional cab aids alignment with the crop rows. The tractor driver still had responsibility for aligning the tractor within the row, and the additional driver corrected/dampened any driver error resulting in hoe misalignment.

Figure 3-4 9 m steerage hoe in sugar beet

The other two steerage hoes (Runs D and E) used a vision guidance system developed at Silsoe Research Institute and now sold by Garford Farm Machinery under the name "Robocrop". The hoe evaluated in this study used a pre-commercial system, as shown in Figure 3-5, but is very similar to the commercially available version. It consisted of two frames; the front frame is connected to the tractor via the 3-point linkage with check chains tight. Two flanged wheels mounted on the fixed frame provided further resistance to lateral movement. The rear frame is linked, via a parallel linkage, to the front frame allowing it ± 150 mm of sideways movement controlled by hydraulic actuators. Single mounted spring tines with 130 mm wide A-blades were arranged to cultivate in between the winter wheat cereal rows at 220 mm spacing along the moving frame. A video camera is mounted on the moving frame inclined down at 45° such that it viewed five crop rows to one side of the tractor as illustrated in Figure 3-6. Images were passed at 25 Hz to a 200 MHz Pentium PC and analysed to extract the lateral offset and heading angle of the camera with respect to all five crop rows. The analysis techniques employed (Tillett & Hague, 1999; Hague & Tillett, 2001) were relatively insensitive to moderate levels of missing crop and weed growth.

Figure 3-5 Experimental vision guided cereal hoe

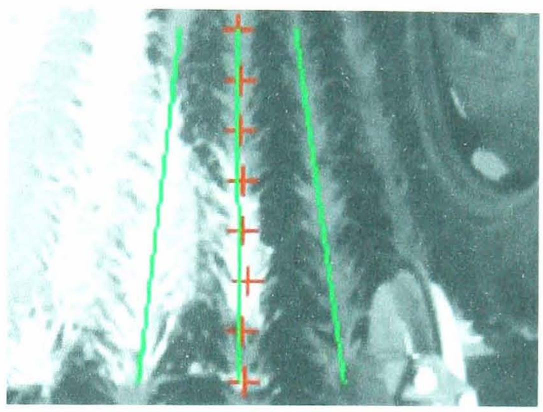


Figure 3-6 View from vision guided hoe camera showing correctly located crop rows

With one exception all experimental runs were conducted at speeds regarded as appropriate for the crop and soil conditions present at the time of the trial. The exception is the vision guided run (Run F) conducted at 11 km/h. This trial was conducted specifically to test previous experience suggesting vision guidance could perform without loss of accuracy at speeds in excess of normal cultivation limits or those that could be sustained manually for extended periods. The wheat crop chosen for this trial was hoed when the flag leaf is just visible [decimal code growth stage 37, (Tottman & Broad, 1987)] and is sufficiently robust to withstand the amount of soil movement created at this elevated speed.

During each run a minimum sample size of 30 spot measurements of the dye trace were recorded to ensure a representative measure of the lateral positioning. This is repeated several times across and throughout the field, to ensure the samples were random. All of the individual data sets from each run were collated, from which the standard deviation and bias were calculated.

3.2.3 Results

A summary of the results are presented graphically in Figure 3-7. For statistical purposes the data is regarded as normally distributed. Additional data is presented in Appendix A1-2, whilst Table 3-2 characterises error distributions measured from each trial in terms of their means and standard deviations.

Table 3-2 Lateral positing accuracy results

Run	Guidance	Speed (km/h)	Bias (mm)	Standard deviation (sd)	Guidance error 95.4% (2 sd)
A	Tractor driver (front mounted)	4.5	9	22 mm	44 mm
B	Second operator	4.8	-2	10 mm	20 mm
C	Tractor driver	5.1	7	11 mm	22 mm
D*	Vision guidance	6.5	-7	9 mm	18 mm
E*	Tractor driver	6.5	-17	14 mm	28 mm
F*	Vision guidance	11.0	-8	10 mm	20 mm

* Non–professional driver (average)

Automatic vision guidance (Run D) provided the most accurate control with a standard deviation of 9 mm and a bias of –7 mm operating at a speed 6.5 km/h. The results also confirmed that vision guided performance is not greatly effected by speed as Run F at 11 km/h achieved very similar performance figures. A direct comparison of Runs D and E (manual and vision guided 4 m hoe at 6.5 km/h) were undertaken with the same tractor, hoe and (non-professional) driver to ascertain differing lateral accuracy. The guidance system is locked centrally for the tractor driver guided run. Results show that vision guidance brought the standard deviation down from 14 mm to 9 mm and bias down from –17 mm to –7 mm.

Comparisons between professional and non-professional drivers under manual guidance indicates, as might be expected, that the former out-performed the latter although performance is not as good as the vision guidance system, and is achieved at slower speeds. The front mounted hoe had the worst performance with a standard deviation of 22 mm. However, it would be unreasonable to assume from one series of results that front mounted hoes have the worst lateral positioning. Further analysis of front mounted hoes would be required before further conclusions could be made.

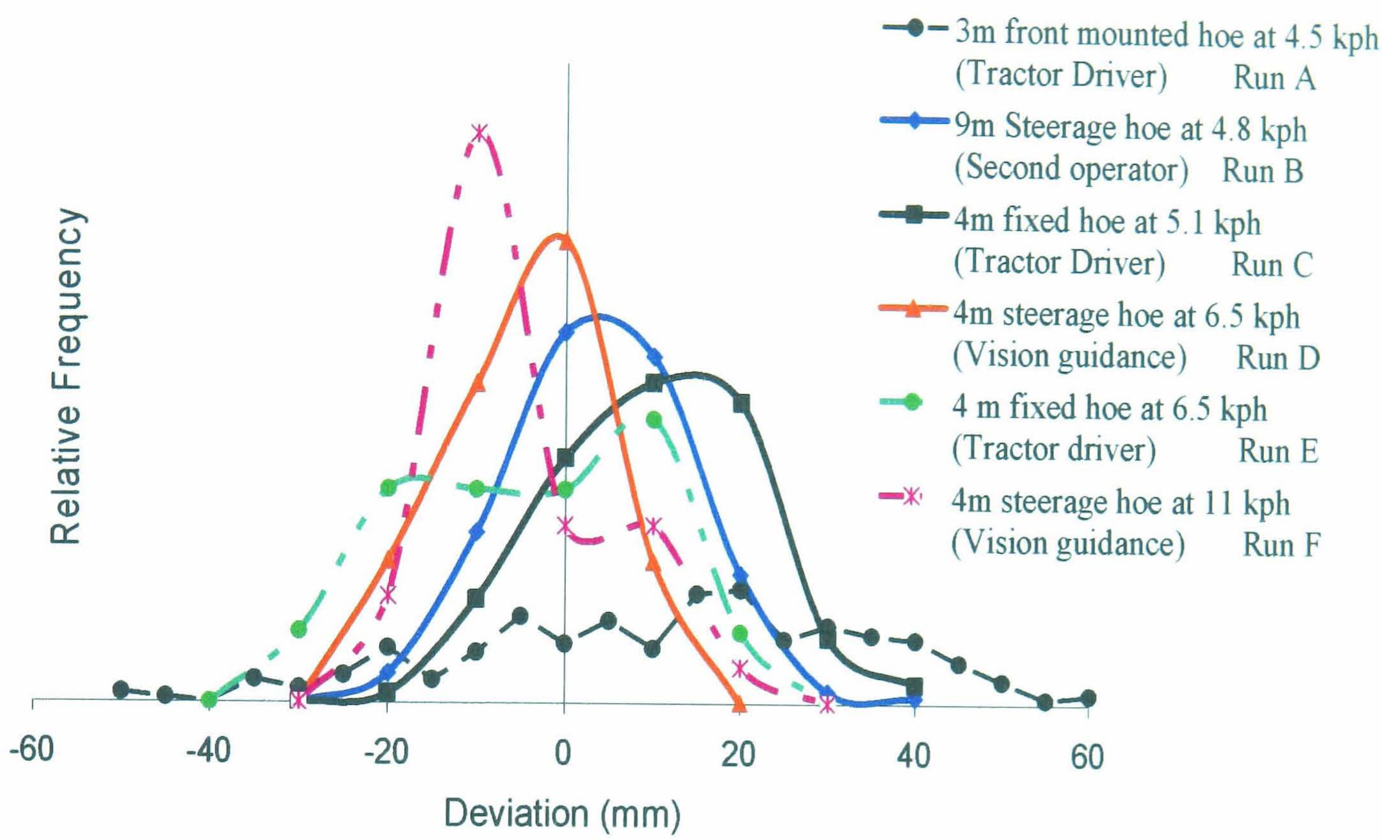


Figure 3-7 Lateral positioning accuracy of mechanical inter-row hoes

3.2.4 Discussion

The operator's reported hoeing speed was found to be slower than true measured hoeing speed. Each operator was asked to drive in their usual manner, but there is no way of judging whether they tried to excel by increasing concentration, or under performed due to the increased pressure they may have felt from being monitored. Remote monitoring via the radio link meant drivers were unaware exactly when they were being monitored and so it is hoped that performance was representative of normal hoeing conditions. Drivers were asked if they would feel comfortable operating at higher speeds and their replies were all the same in that increased speed would be to the detriment of the crop.

The vision guided hoe (Run F) enabled high speed hoeing (11 km/h) to take place without loss of accuracy. One reason for this may have been that it was noticeable that there were fewer driving steerage corrections made at higher speeds. Such corrections are not measured by the control system and therefore represent a performance degrading disturbance. A reduction in these operator induced disturbances may balance negative factors such as the increased significance of control time delays as speed increases.

Paarlberg *et al.* (1998) reported that higher speed cultivation could improve the odds of timely completion of needed cultivation, and that faster speed did not impede weed control or yield in corn. Increasing the forward speed of a 4 m hoe from 6.5 km/h to 11 km/h changes the work-rate of the hoe from 1.95 ha/h to 3.3 ha/h, respectively, accounting for a field efficiency of 75%. Over an eight-hour day the high speed hoe would cover an extra 10.8 hectares, thus substantially lowering the cost of that operation.

One of the major uncertainties relating to mechanical weed control is the number of workable days available. With timeliness of operation being critical, high speed hoeing may be advantageous. In recent years the number of available workable days in the UK has reduced due to the wetter climate in autumn and spring; if this climatic change continues then high speed hoeing may well be a solution.

These results complement the review undertaken by Tillett (1991) and provide quantitative data on image analysis in real time situations. It also enables the advantages between non-guided and guided hoes to be compared, which previously had not been undertaken.

Many of the candidate guidance technologies reviewed in Section 2.6 were unsuitable for direct use in agriculture, and unless there are changes in the way fields are planned, many will never be employed. If permanent tramline systems were adopted, together with gantry vehicles to complement the system, it is possible that leader cable, rails or concrete tracks could provide accurate guidance at relatively low cost. However farmers still require further persuasion to adopt a permanent tramline farming system and one suspects that its take up will be limited.

Image analysis and machine vision offers a solution to this problem. In recent years systems have become reliable, accurate and affordable. Vision guidance is also accurate with high travel speeds, enabling the work-rate of a traditionally slow operation to be increased. It also has other major advantages over all of the other systems, in that it not only identifies the row, but can also identify the crops along the row, which can be utilised for intra-row weeding.

Melander and Hartvig in 1997 reported that inaccurate steering becomes much more important the closer the shares get to the crop, i.e. hoeing close to the crop requires accurate and reliable steering of the hoe. The six evaluations undertaken have highlighted the variability in lateral hoe position and inherent positioning bias in the hoeing operation. It is important that these results are used in ways to help improve the efficacy of the weeding operation in and/or along the row.

3.3 Improved weed control

The following section investigates the effect of guidance accuracy on the effective area hoed, utilising the results from the lateral positioning experiments reviewed in Section 3.2, based on a cereal spacing of 220 cm for mechanical weed control.

Improving lateral positioning accuracy enables the hoe blade width to be increased, so maximising weed kill by increasing cultivated area within the row, whilst keeping crop damage levels low.

The factors affecting blade optimisation illustrated in Figure 3-8, are crop zone clearance, guidance error and positioning bias. These three factors are critical when attempting to optimise hoe blade width. The crop zone is left un-hoed to ensure minimal root damage occurs, which could result in reduced yield. Guidance error made up of bias and variability (represented in terms of standard deviation) result in a need for a buffer width between the crop and blade. Therefore comparisons of different guidance techniques can be made, by investigating the percentage increase in cultivated area between the crop rows by having improved lateral positioning of the hoe.

The equation below calculates the percentage hoed area accounting for the above variables. Hoe blade width has been calculated on the basis that variability in hoe blade position over the long term bias is equal to twice the standard deviation. This ensures that 95.4% of the time no crop damage occurs.

$$HW = RW - [B + CZ + (2 \times V)]$$

$$\%\text{Hoed area} = \frac{HW}{RW - CZ} \times 100$$

It should be noted that a direct comparison of the percentage hoed area can only be made if comparing two systems on the same crop spacing. An example of the advantages that improved lateral positioning has on hoed area follows.

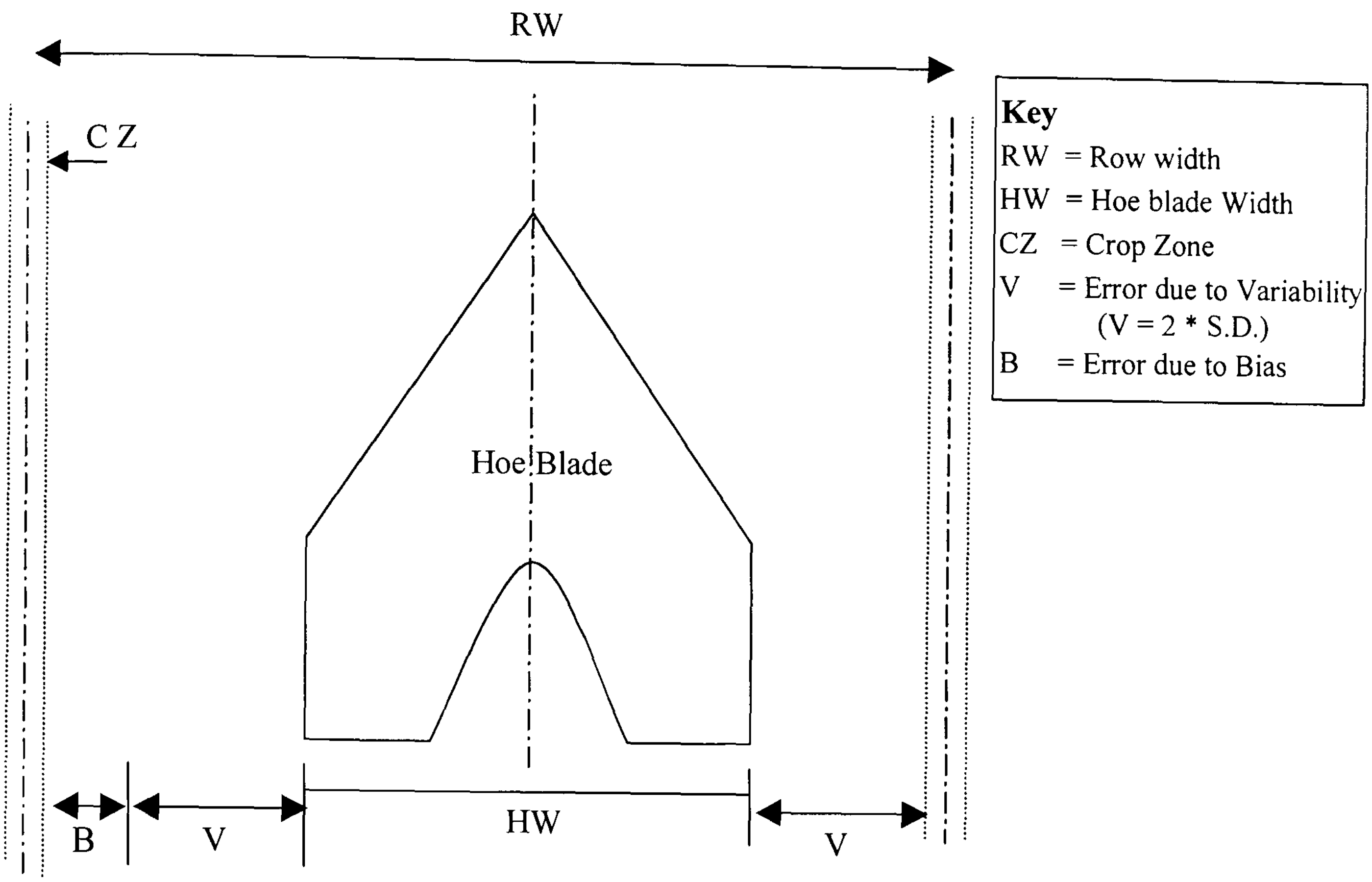


Figure 3-8 Hoe blade optimisation

Runs D and E are compared as all the variables were the same apart from the guidance of the hoe, run D having vision guidance and run E having no guidance.

Table 3-3 Blade width optimisation

Factors	Run D Vision guidance	Run E No guidance
Row spacing	220 mm	220 mm
Crop zone	20 mm	20 mm
Error due to bias	7 mm	17 mm
Error due to variability	18 mm	28 mm

The optimised hoe width for Runs D and E using the hoe width formula follow: -

Run D = $HW = 220 - [7 + 20 + (2 \times 18)] = 157mm$

Run E = $HW = 220 - [17 + 20 + (2 \times 28)] = 127mm$

Run D $$\% \, Hoed\, area = \frac{157}{220-20} \times 100 = 78.5\%$$

Run E $$\% \, Hoed\, area = \frac{127}{220-20} \times 100 = 63.5\%$$

Kouwenhoven (1992) states that with inter-row weed control 60-70% of the surface is treated, and also states that with guidance this may be about 80%. The above calculations support this view.

Hoe width optimisation by utilising machine vision is an appropriate method of achieving greater weed control and increases weed kill. The result above shows that a 15% increase in cultivated area can be achieved. Jones & Blair (1996) indicate that cutting and burial will approximately kill 85% of the weeds, therefore it can be assumed that a 13% increase in weed kill per unit area could be achieved by optimising blade width.

By having a guidance system fitted to a mechanical inter-row hoe, the lateral performance of the hoe will be improved. The assurance of knowing that the hoe is being guided by an additional system other than the driver alone will reduce the pressure on the operator and enable hoeing at higher speeds. The operator can also concentrate more on checking that the hoe is cultivating correctly and examine the crop throughout the field.

Lateral positioning data is essential in the design of inter-row cultivation systems for weed control between crop rows as outlined above. However, the data is also of great benefit in designing systems to deal with weeds in-the-row.

3.4 Conclusions

- Guidance systems for inter-row hoes, whether using computer vision or an additional operator, enabled improved accuracy compared to unguided hoes. They also offer increased consistency of performance over long periods without operator fatigue, whilst maintaining high levels of accuracy. The adoption of vision guidance could remove the need for a skilled driver, thus an economic saving could be made by employing unskilled labour.

- Speeds up to 11 km/h were achievable with vision guidance in the crops investigated whilst still providing excellent lateral positioning which other wise was unachievable

- Knowledge of achieved accuracy enables blade width to be optimised, increasing weed kill by an extra 13% in wheat crops on a 0.22 m spacing as the hoe can be safely guided closer to the crop.

- Lateral positioning experiments and data provide the essential information for the future development of an intra-row weeder, as the guidance error is now known to be 27 mm for 99.7% of the time, using vision guidance.

4 Experimental investigation into soil dynamics of shallow working blades

4.1 Introduction

This chapter details experiments undertaken to investigate lateral and forward translocation of soil resulting by undercutting from shallow working wide blades. Wide blades are classified as such when their working width is much greater than their operational depth. Payne (1956) defines blades as implements with a depth width ratio of < 0.5. In this study the depth width ratio is 0.0625. The experiments were designed to obtain a further understanding of soil displacement, in order that blade design could be modified to control soil exiting the blade. The experimental data and observations will be used to derive a model to predict lateral and forward translocation of soil from a blade with known geometry as detailed in Chapter 5.

The controlled soil can be used to target weeds, thus burying as well as cutting. Alternatively where crop plants are vulnerable to burial soil movement can be minimised to enable close working to the crop. The results from the experimental studies combined with the information on lateral positioning detailed in Chapter 3, enabled the development of an accurate weed control mechanism reported in Chapter 7.

Following initial trials in the soil bin it was apparent that there were several factors influencing soil displacement. The predominant factors could be categorised into soil conditions, and blade geometry. Soil conditions are detailed in Section 4.2, where compaction, moisture content and repeatability are presented. Initial investigations found that blade geometry and speed had a significant effect on soil displacement. Leg width, overlooked by many previous authors also seemed to be having an effect on soil displacement. It was therefore decided to design the experiments around two main aspects, one investigating leg width and the other blade geometry. The experiments were specifically designed to monitor and record as much of the soil displacement process as practically possible, as detailed in Sections 4.3 onwards.

4.2 Soil preparation and parameters

4.2.1 Apparatus

All of the indoor soil experimentation was undertaken at Cranfield University, Silsoe, in the purpose built soil bin laboratory. The indoor soil bin is 20 m long, 1.7 m wide and 1 metre deep sunk within the floor of a heated building. The soil processor is powered from a 75 kW 6-cylinder diesel engine and is pulled the length of the soil bin by a variable speed hydraulic winch. Figure 4-1 shows the layout of the soil bin processor.

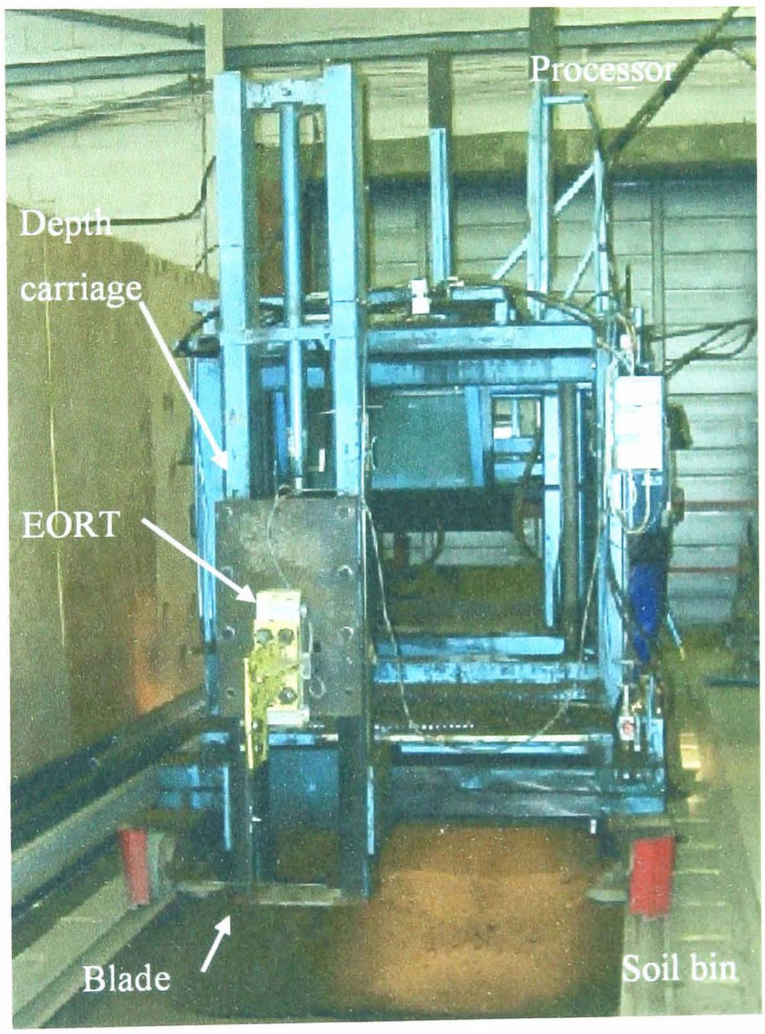


Figure 4-1 Cranfield University, Silsoe, soil bin processor

The processor ensures that the sandy loam, stone free soil is uniform between each replication, thus minimising the risk of soil variation. It has the ability to excavate, lift and carry the soil along the whole length of the bin, and has a heavy flat roll and a spiked roll to provide the desired level of soil compaction.

Implement height adjustment is via a separate hydraulic frame fitted to the rear which is controlled via manual spools at the side of the processor. At the rear of the processor (as shown in Figure 4-1) the blade is attached to an Extended Octagonal Ring Transducer (EORT). The EORT is a machined aluminium block to which strain gauge bridges are attached. During each run the strain gauge bridge output voltages are relayed and recorded in the control room for further analysis. Details of EORT design and operation are reported by Godwin (1975). The EORT provides information on the vertical and horizontal forces applied to the blade from calibration curves enabling the draught force of the blade to be calculated.

4.2.2 Procedure

To enable a further understanding of soil flow characteristics, it was essential that the soil was prepared in a repeatable manner. It was decided that two differing soil densities would be investigated, with target densities of 1300 kg/m^3 and 1500 kg/m^3 to represent loose and dense soil conditions respectively. The loose soil condition represents the soil in a tilled state, and the dense soil represents a soil that has suffered compaction, weathering or a capped soil layer. Two levels of density were investigated to determine if density change was an important factor in soil displacement. Changes in soil moisture content were not investigated.

The soil bin processor provided repeatable soil preparation. Soil layers were prepared in 50 mm intervals to ensure the working depth of the blade at 25 mm did not enter the interface between two preparation layers. The dense preparation received 6 heavy rolls, whilst the loose condition was poured, and scraped to the desired surface height.

Two main soil parameters were monitored and recorded to ensure consistency between treatments and replications; these were bulk density and moisture content. Soil bulk density was obtained using soil density rings. A density ring consists of a brass ring of known volume that is pressed into the soil, then excavated and the soil is carefully removed, just leaving a full ring of soil. The soil is then emptied into a suitable container, weighed and placed in an oven for 24 hours; the dry weight of soil is then weighed. With known soil weight and volume an accurate measurement of soil bulk density can be obtained. Density measurements were undertaken before and after each blade pass at three locations along the soil bin, thus providing replicate information on initial and disturbed density as well as soil bin variation.

Soil moisture content at three bead locations along the bin were also recorded to provide data on consistency of replications. A graph of soil moisture content and tables presenting soil bulk density can be found in Appendix A2-1. The mean soil moisture content was 8.1% with a standard deviation of 0.5%. The initial mean bulk density in dense conditions was 1490 kg/m^3 with a standard deviation of 36 kg/m^3, and for loose conditions it was 1300 kg/m^3 with a standard deviation of 44 kg/m^3. In disturbed conditions the values for dense and loose soils were 1300 kg/m^3 and 1250 kg/m^3 with standard deviations of 49 kg/m^3 and 49 kg/m^3, respectively. In loose conditions it is believed that that an accurate measurement of density was achieved with the steel rings. However, in dense conditions there were many voids in the soil due to the surface breaking up into plates. This resulted in the density samples being taken within the plates, which inevitably gave a high reading in disturbed dense conditions. Section 4.7 discusses the alternative measurement of disturbed density using profile gauges.

4.3 Influence of leg width

4.3.1 Objectives

To investigate whether the width of the leg supporting the blade influences soil displacement in either the forward or lateral direction. Chase (1942) indicated that the leg caused excessive soil disturbance, but work on leg design of shallow working blades was limited. The experiment set out to investigate the following hypothesis –

- Increasing leg width increases overall soil movement

4.3.2 Experimental design

The investigations into the effects of changing leg width were conducted in a randomised block design. The experiment was blocked in terms of leg width whilst speed and soil density were randomised, with three sub samples of each taken during each soil bin preparation. The parameters investigated are presented in Table 4-1.

Table 4-1 Leg width and target parameters

Leg Width (mm)	Speed (km/h)	Compaction (kg/m^3)
6	1	1500 (dense)
20	5	1300 (loose)
40	9	

It was considered that effects of speed would be the most difficult to keep constant, therefore replicates were conducted along the length of the soil bin, as this was more effective. This reduced the speed variability, and it was considered acceptable as although the soil bin should provide overall uniform conditions of density, there are some variations along its length.

Blade velocity and compaction levels in Table 4-1 are target conditions, but when analysis is undertaken recorded values are used.

Each blade had a cutting width of 400 mm. This is wider than most inter-row cultivation blades but was chosen to reduce the end effects. The leg was set 100 mm behind the rear edge of the blade as shown in Figure 4-2.

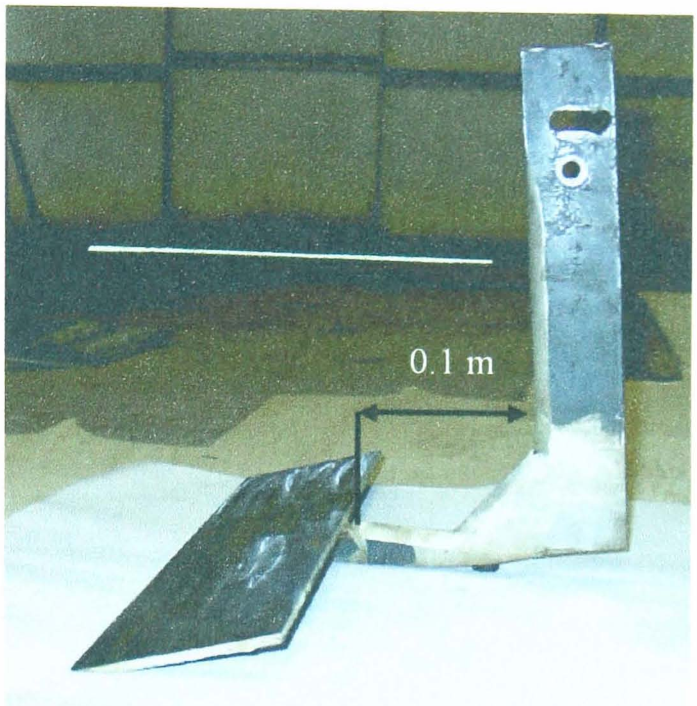


Figure 4-2 Wide blade with 6 mm leg

A fixed depth of 25 mm was chosen for the experimentation as this is commercial practice and deep enough to cut through weed roots. Roberts (1982) reports that most seedling weeds arise from seeds in the top 50 mm of arable soil, and are strong enough to emerge often without tillage, therefore hoeing in this depth range should not cause additional weed stimulation.

The target speeds chosen for the experiments of 1, 5 and 9 km/h were selected for the following reasons. 1 km/h is seen as the quasi-static state, where analysis can be undertaken to develop prediction models. 5 km/h was the typical commercial hoeing speed as mentioned in Chapter 2, and 9 km/hr is the speed at which operators would like to travel if excessive soil throw could be avoided.

4.3.3 Apparatus and procedure

In order to determine the effects of leg width and blade geometry, it was necessary to record soil displacement. Previous workers (Vasilkovskii & Harris, 1970;Kotov, 1977) described methods recording soil displacement detailed in Section 2.7, but the most promising seems that of placing markers in the soil (Hanna *et al.*, 1993[a]; Sharifat & Kushwaha, 1997). For the soil bin experiments undertaken throughout this study, plastic beads were used to represent soil displacement. A series of plastic beads pressed into the soil surface were used to determine the movement of soil after the blade had been pulled through by the soil bin processor. Beads were placed in the blade path, in a line perpendicular to the direction of travel.

Each bead had a weight of 0.14 grams and a nominal diameter of 6.2 mm, giving a density of 1122 kg/m^3. Although this density is less than the starting conditions of the loose and dense soil, it is a compromise between the density of soil at rest, and the density of soil whilst in flight.

Coloured beads were used for ease of identification following disturbance. In order to obtain replication, three sets of beads were placed laterally across the soil bin, thus giving three sub samples per run.

It was essential that bead displacement represented soil displacement as the majority of analysis is based on bead movement data, therefore pilot experiments were conducted to ensure representation. This simple method involved pressing the beads into the soil, and covering an area of soil around the beads with white lime. After the blade had been pulled through the soil the disturbed beads were found to be in the same region as the lime coloured soil. As the beads reacted in the same manner as the soil it could be inferred that it was a repeatable way of establishing soil movement. A repeatable method of placing and recording the beads was established, as described below.

Each bead was placed in the soil using a location device as shown in Figure 4-3 as it was essential that the beads were perpendicular to the direction of blade travel. The location apparatus spans the width of the soil bin, so as not to disturb the soil surface and eliminates the risk of changing the soil density and surface height. The apparatus is then set perpendicular to the processor track. A bead position template (consisting of a wide strip of aluminium with holes at regular intervals) was then placed on the soil surface, and two datum holes in the template were aligned with those made by the location apparatus. Once the template was correctly located, the coloured beads are placed into the corresponding template holes. Each bead was pressed so that the top of the bead was level with that of the soil surface. When the blade was pulled through the soil the beads were disturbed. Measurement of the beads resting position provides information on overall bead displacement.

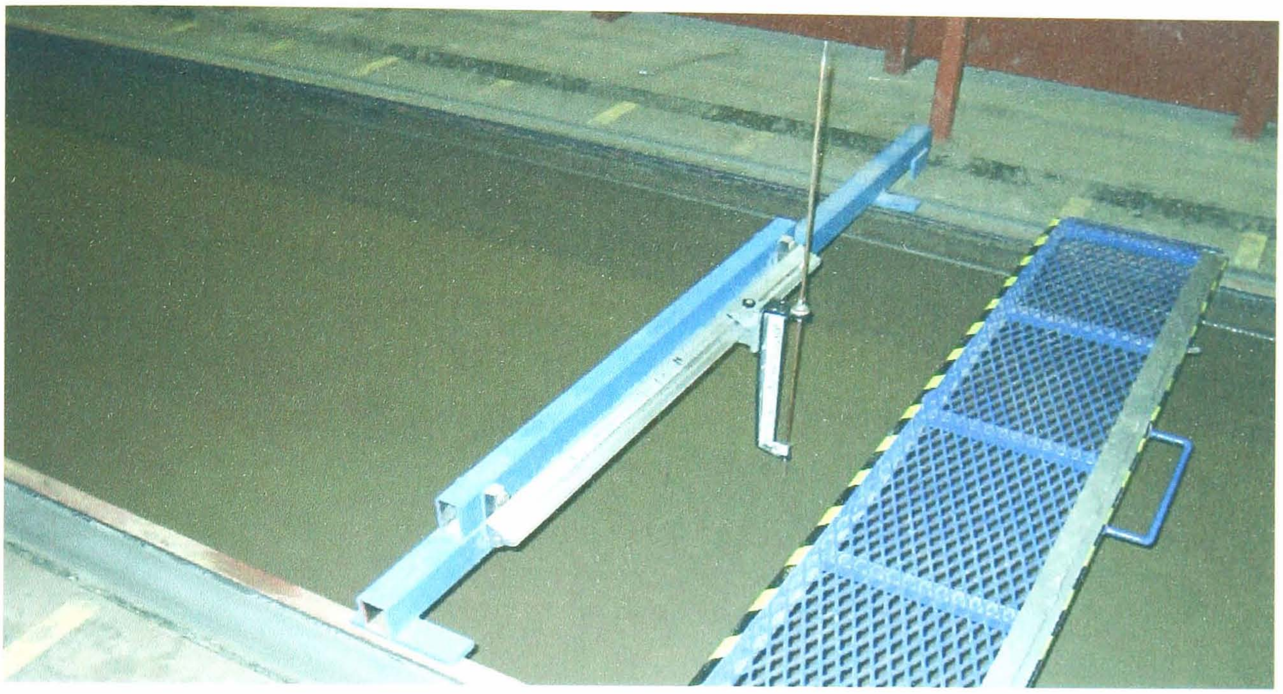


Figure 4-3 Bead location apparatus

Figure 4-4 shows an example of beads placed in the soil before disturbance and their resting position after the blade has been pulled through. In this case blade sweep was 0^0 with a 20^0 rake angle and a 6 mm leg operating at 5 km/h in dense soil conditions.

Measurement of overall bead movement was initially undertaken using a three-dimensional co-ordinate system as detailed by Eatough (2002). A pointer was connected to three draw string potentiometers, and when the pointer was placed directly on a bead, the voltage readings were recorded from the potentiometers, and stored via a strawberry tree data logger, and down loaded to a PC.

Analysis of the data enabled bead position to be determined and referenced back to each beads' starting location, thus providing overall bead movement and hence soil displacement.

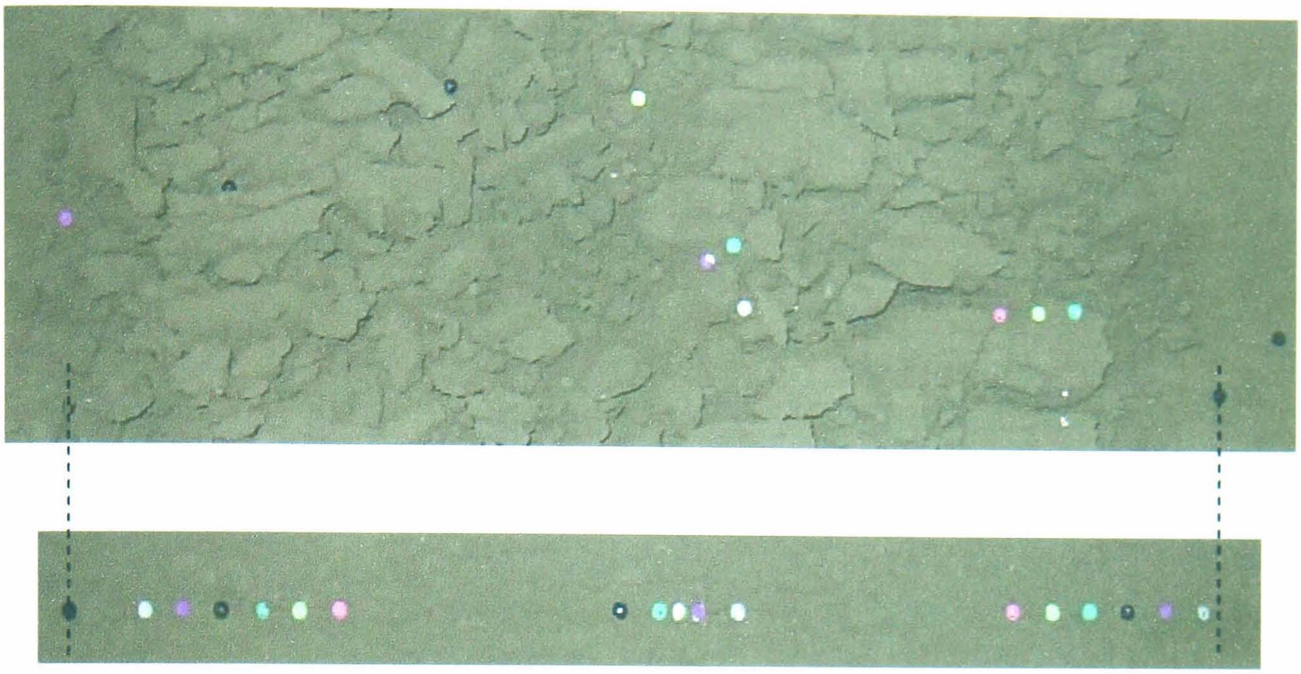


Figure 4-4 Start and rest of beads located in the soil surface

4.3.4 Results

The results from the experiments investigating leg width are presented in Tables 4-2 and 4-3 for forward and lateral displacement respectively, additional data is provided in Appendix A2-2. Graphical representations of bead displacement are shown in Figure 4-5, where actual bead position from start and rest has been plotted. Analysis was undertaken to examine the effects of increasing leg width with changes in soil density and blade velocity.

4.3.4.1 Forward displacement

Analysis of variance (ANOVA) indicated that velocity, density and leg width all had significant effects (5% level) on forward displacement of soil each with $F<0.001$. However at target blade velocities of 1 km/h for the 6 mm and 20 mm leg higher displacements were observed than at target speeds 5 km/h. This is likely to be due to the wide variability within the data set, indicated by the high coefficient of variances (CV) obtained for the displacement data. More variability was observed in dense soil conditions than loose; for the 6 mm leg all CV were greater than 37%, the 20 mm leg greater than 53% and for the 40 mm leg at blade velocities of 5 and 9 km/h the CV was in excess of 53% (as shown in Appendix A2-2).

Table 4-2 Mean forward displacement by varying leg width

Velocity-density (km/h) / Leg	1 Loose (m)	5 Loose (m)	9 Loose (m)	1 Dense (m)	5 Dense (m)	9 Dense (m)
6 mm	0.236	0.104	0.158	0.046	0.071	0.267
20 mm	0.297	0.194	0.447	0.034	0.603	1.303
40 mm	0.267	0.357	0.406	0.341	0.272	1.281

4.3.4.2 Lateral displacement

ANOVA on the lateral displacement provided similar results to that of forward displacement with density, blade velocity and leg width all significant ($F<0.001$) at the 5% level. It is therefore likely that there is insufficient evidence to reject the null hypothesis that soil displacement increases with increasing leg width. This is in agreement with Rahman *et al.* (2002) whom state that low speeds and narrow shank widths could be used to minimize lateral soil translocation.

Although significantly different from each other, it can be seen in Table 4-3 that 40 mm leg in dense soil conditions has less lateral displacement than with the 20 mm leg. Again this is possible due to the wide spread of data represented by the coefficient of variance exceeding in the range of 54%-63% for the 40 mm leg, 49% - 63% for the 20 mm leg and 48% - 116% for the 6 mm leg in dense soil conditions.

Table 4-3 Mean lateral displacement by varying leg width

Velocity-density (km/h) / Leg	1 Loose (m)	5 Loose (m)	9 Loose (m)	1 Dense (m)	5 Dense (m)	9 Dense (m)
6 mm	0.006	0.013	0.033	0.013	0.014	0.150
20 mm	0.027	0.018	0.076	0.062	0.224	0.441
40 mm	0.023	0.028	0.096	0.219	0.121	0.278

Figure 4-5 presents bead displacement that occurred from a 6 mm leg and 0-20 blade in loose and dense soil conditions. It can be seen that even with a minimal leg width the soil is disturbed more by the leg. Two blade velocities are shown in Figure 4-5 to illustrate the effects velocity has on overall bead displacement.

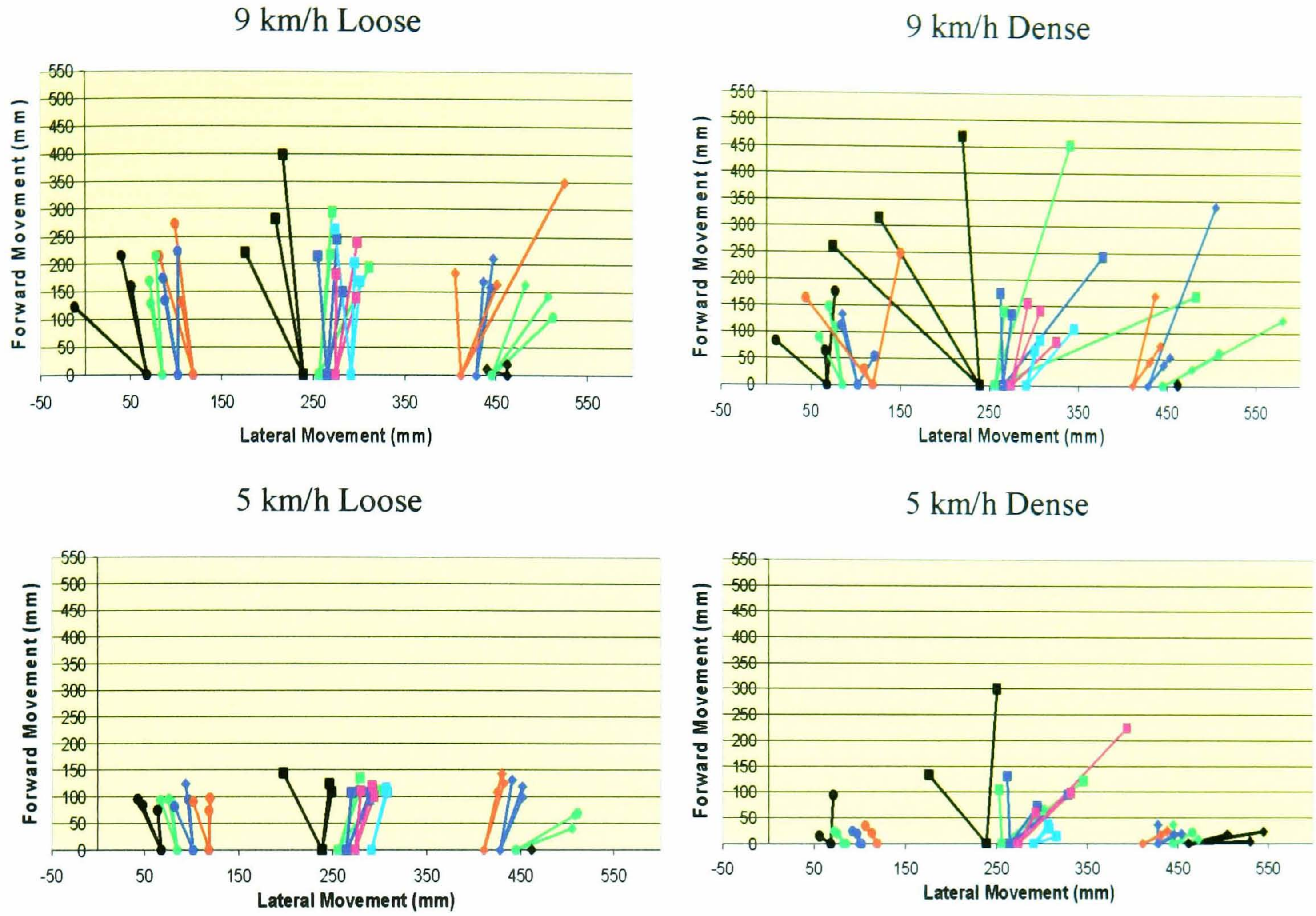


Figure 4-5 Bead displacement from 0-20 blade with 6 mm leg

As leg width was found to significantly increase soil displacement it was decided a 6 mm leg would be used for experiments examining soil displacement over blades, and that no beads would be placed in the path of the leg to avoid the leg effects.

4.4 Soil methodology based on bead displacement due to the blade

4.4.1 Objectives

Blade geometry experiments were undertaken to ascertain the differences in soil displacement that occurs from changes in blade rake angle (α) and blade sweep angle (ψ), at different blade velocities and soil densities.

The results will provide a basis for development of a model to predict the lateral and forward displacement of soil as it is undercut by shallow working wide blades.

4.4.2 Experimental design

Four blades with varying geometry and narrow legs were studied as presented in Table 4-4, and shown in Figure 4-6. All blades were fitted with a nominal leg width of 6 mm as this thickness provides adequate support to the blade, and minimises soil disturbance as reported in Section 4.3. No beads were placed in the path of the leg to ensure only effects of the blade were investigated. Each blade had an effective cutting width of 400 mm with a sliding face length of 100 mm. Rake angle (α) and sweep angle (ψ) were varied to determine the effects of soil movement. Each blade was pulled through the soil at target velocities of 0.278 m/s (1 km/h), 1.39 m/s (5 km/hr) and 2.5 m/s (9 km/hr) and operated at a cutting depth of 25 mm.

Table 4-4 Blade geometry combinations

Blade	Sweep angle (γ)	Rake angle (α)	Effective rake (δ)
1	0^0	20^0	20^0
2	0^0	45^0	45^0
3	45^0	20^0	14.4^0
4	45^0	45^0	35.3^0

The introduction of sweep angle onto the blade results in an effective rake angle being calculated which is discussed in Chapter 5 and included in Table 4-4 for completeness.

The same target parameters of density of 1500 kg/m^3 and 1300 kg/m^3 were used for the four variations of blade geometry. Blades are described here in after according to their sweep and rake angle i.e. a blade with 45^0 sweep and 20^0 rake will be referred to as 45-20, also their target conditions i.e. 5 km/h in loose conditions is referred to as 5 Loose, but their actual velocities are plotted for graphical and analysis purposes.

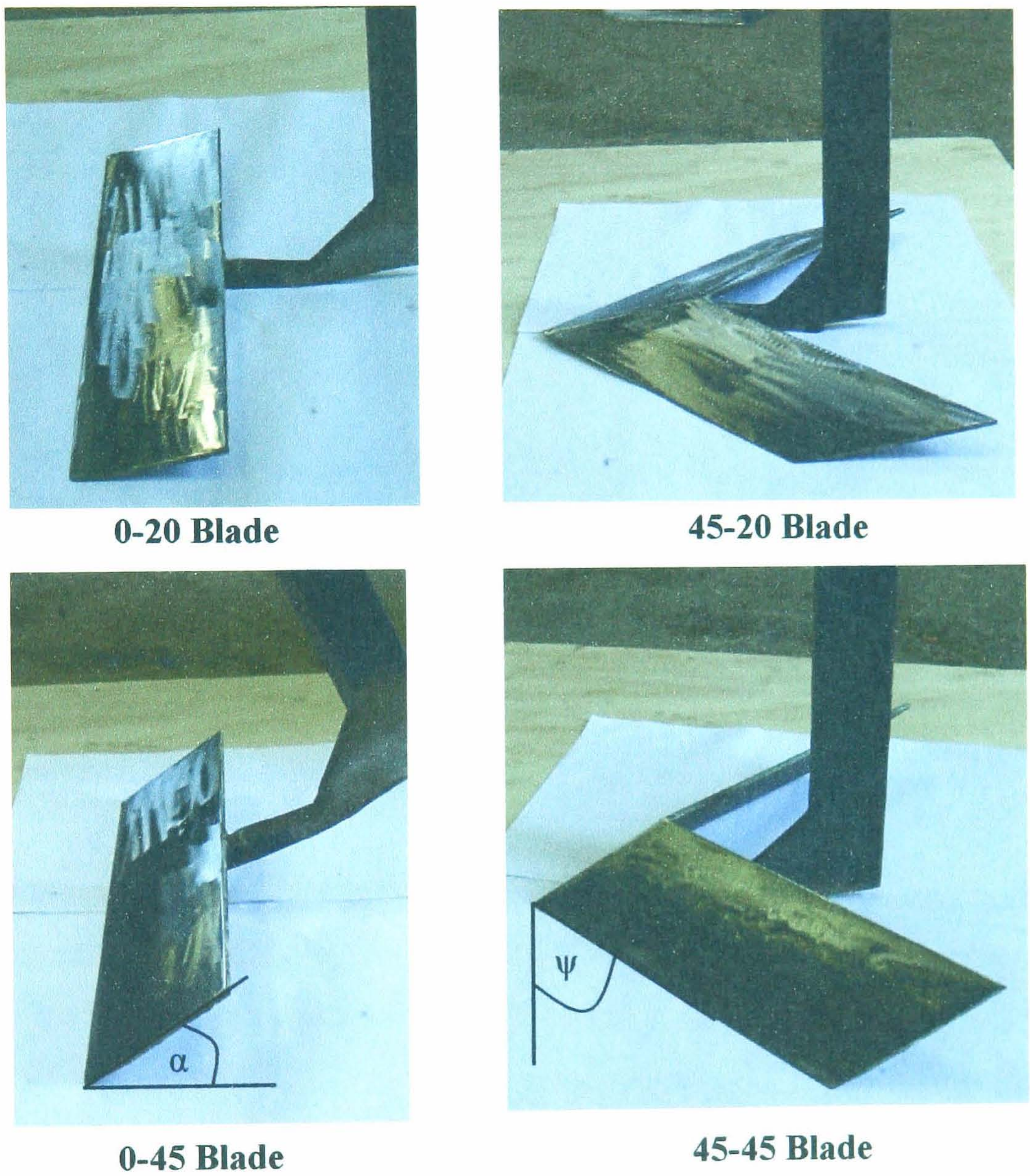


Figure 4-6 Four blades with different geometry

Following analysis of the first set of experiments (in 2001) it was apparent that soil failure was different at the quasi-static speed of 0.278 m/s (1 km/h), therefore it was decided to undertake additional experiments (in 2002) with the same blades and parameters, at target blade velocities of 1.1 m/s, 1.94 m/s and 2.78 m/s (4 km/h, 7 km/h and 10 km/h respectively) thus complementing the data set. Tables 4-5 and 4-6 present target velocities with actual velocities in loose and dense soil bin investigations. All graphical representations of blade velocity are based on measured rather than target velocities in m/s, and displacement recorded in metres.

Table 4-5 Actual blade velocities in loose soil conditions (1307 kg/m^3)

Velocity-density (km/hr)	1 Loose	4 Loose	5 Loose	7 Loose	9 Loose	10 Loose
Target Velocities / Sweep-rake	**0.28** (m/s)	**1.11** (m/s)	**1.39** (m/s)	**1.94** (m/s)	**2.50** (m/s)	**2.78** (m/s)
0-20	0.36	1.32	1.48	2.18	3.04	2.96
0-45*	-	1.90	-	2.30	-	2.92
45-20	0.28	1.38	1.39	2.13	2.50	3.16
45-45	0.28	1.41	1.43	2.34	2.90	3.14

* No experimental data for 0-45 blade at target velocities of 1 km/h, 5 km/h and 9 km/h.

Table 4-6 Actual blade velocities in dense soil conditions (1494 kg/m^3)

Velocity-density (km/hr)	1 Loose	4 Loose	5 Loose	7 Loose	9 Loose	10 Loose
Target Velocities / Sweep-rake	**0.28** (m/s)	**1.11** (m/s)	**1.39** (m/s)	**1.94** (m/s)	**2.50** (m/s)	**2.78** (m/s)
0-20	0.41	1.30	1.69	2.03	2.89	2.58
0-45*	-	1.26	-	2.20	-	3.03
45-20	0.28	1.34	1.39	2.21	2.50	3.05
45-45	0.41	1.35	1.67	2.24	2.86	3.00

* No experimental data for 0-45 blade at target velocities of 1 km/h, 5 km/h and 9 km/h.

To improve efficiency three sub samples were undertaken along each run with 10 beads placed at three locations along the bin which were placed to avoid end and leg effects. This was considered an acceptable technique as variation along the length of the bin would be similar to that of replicate bin preparations. In addition, blade velocity was considered to be an important factor in determining soil displacement and a repeatable method of setting blade velocity would have been extremely difficult as processor speed is set from analogue engine revs. Therefore individual replication by new soil bin preparations would not aid in the conclusions as more variability may have been encountered with variations in replicating blade velocity.

4.4.3 Measurement procedure

Section 4.3.3 detailed the use of a three dimensional co-ordinate system to measure overall bead location, from start to rest. Although this was accurate to within ± 3 mm, (Eatough, 2002) data extrapolation was extremely time consuming, not only in recording bead position, but it required extensive analysis of co-ordinate data after the initial data collection. A simple and less time consuming method was developed and adopted for all subsequent experiments and is detailed as follows.

Following bead location in the soil, as described in Section 4.3.3 two additional datum pegs were located on either side of the blade path. Following disturbance the pegs provided location for a 25 mm x 25 mm steel mesh grid as shown in Figure 4-7. The grid when aligned with pegs allowed simple measurements to be taken from the bead start and rest positions. Measurements were initially taken to the nearest 25 mm and then measured within each square, to the nearest 1 mm. This method proved to be a simple, repeatable and accurate method of obtaining overall bead displacement

Mesh

Displaced beads

Template

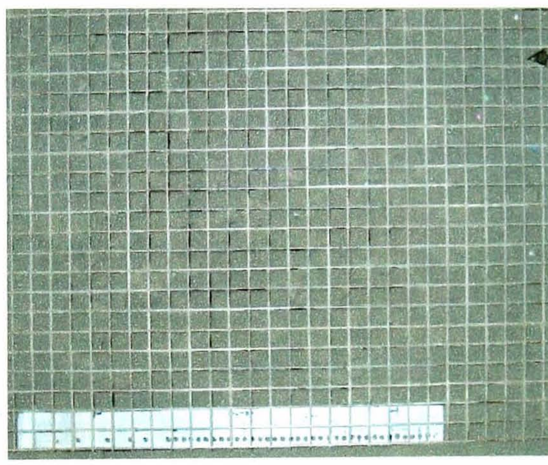
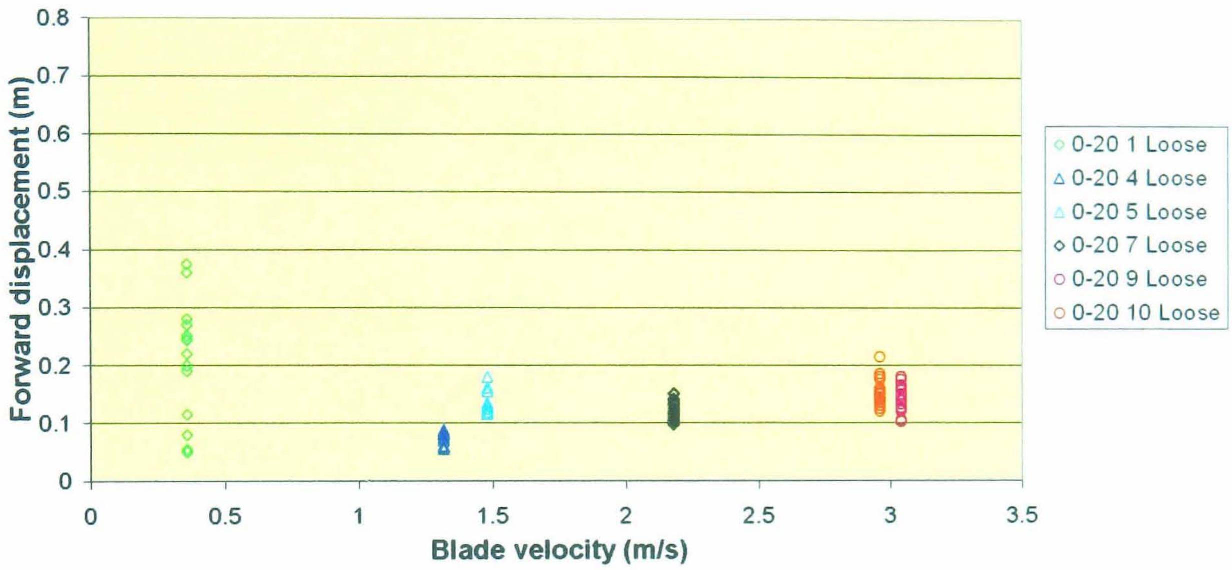


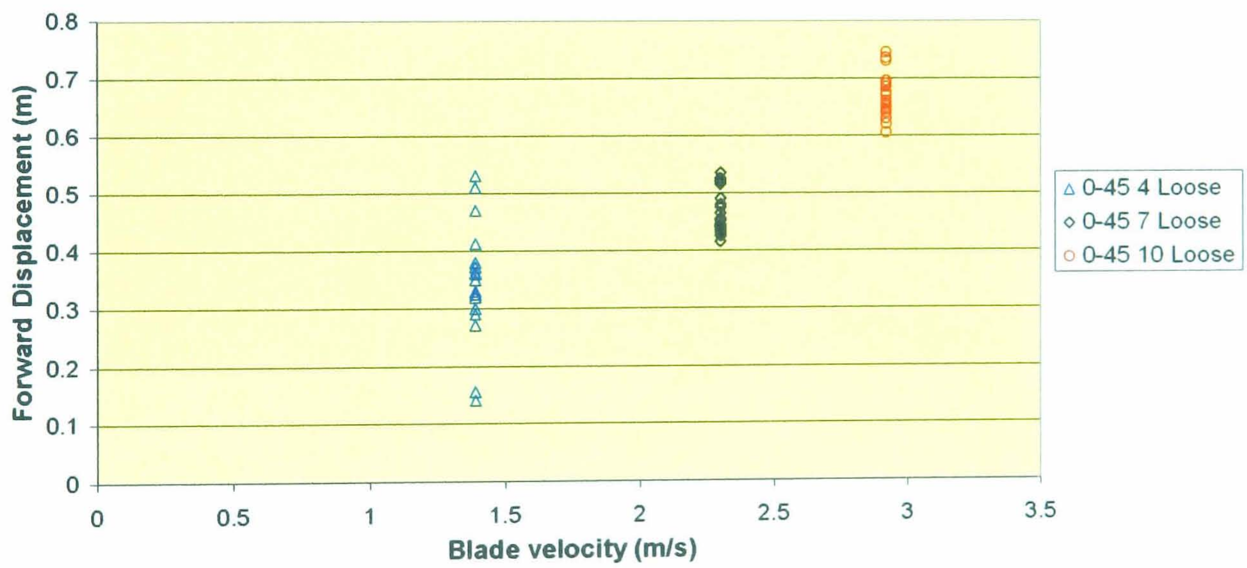
Figure 4-7 Grid technique for recording bead displacement

4.4.4 Forward displacement results

Observed values of forward displacement are shown graphically in Figures 4-8 to 4-11 and the means are tabulated in Table 4-7 with additional data tabulated in Appendix A2-3. Each point on the graphs represents individual bead position, and therefore the variability of displacement can be seen.

To ensure the results between the first set of experiments at blade velocities of 1, 5 and 9 km/h could be directly compared to velocities of 4, 7 and 10 km/h an ANOVA test was undertaken investigating the factors of blade geometry and density as well as the variants of velocity and date of experiments. Date was found to be insignificant (5% level) in affecting the results with a probability of F= 0.829, which allows the comparison of different experiments to be compared as there is insufficient evidence to suggest that the date of experiments did not influence the forward displacement. The effects of velocity, blade geometry and density were significant (5% level) with F<0.05. Therefore it is likely that velocity, blade geometry and density influence soil displacement.





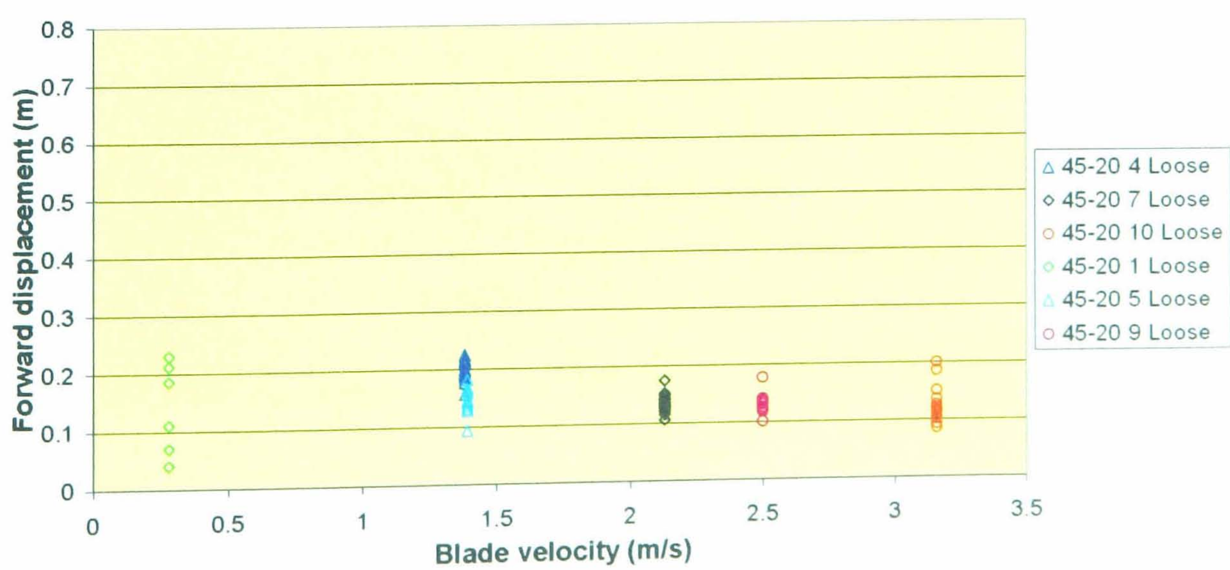


Figure 4-8 Observed forward bead displacement loose conditions

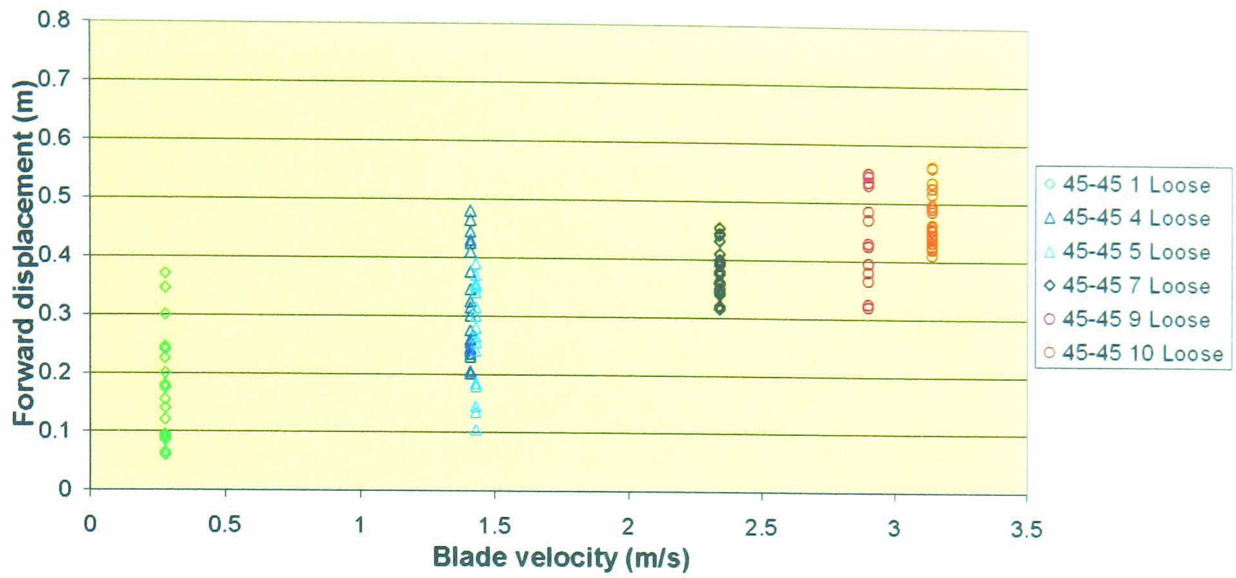
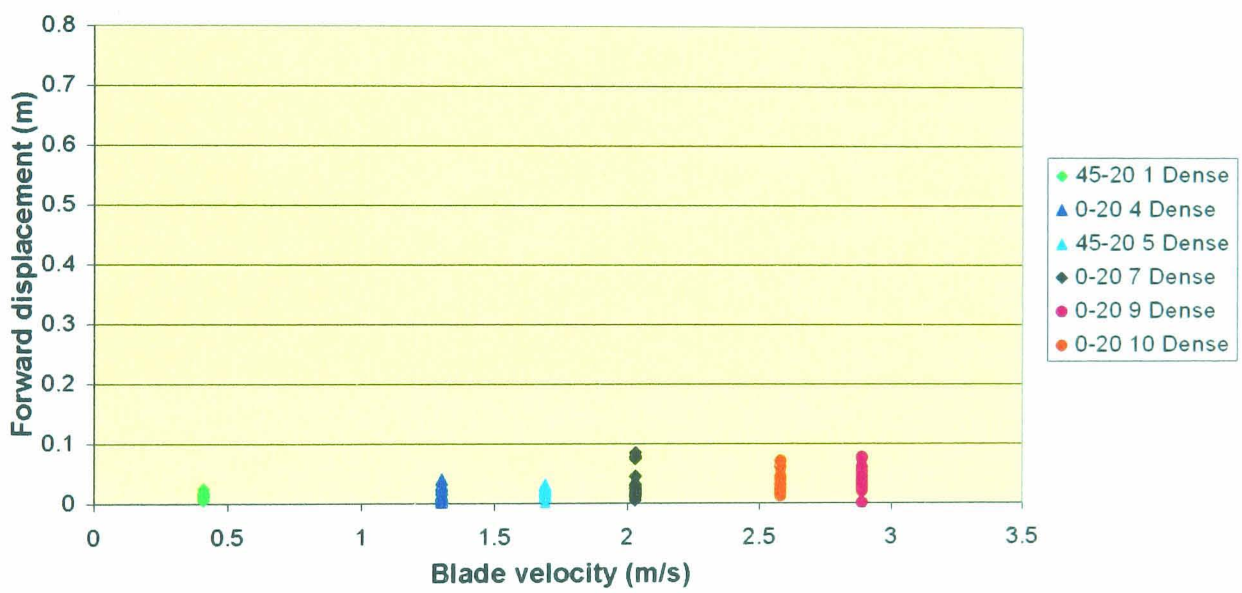


Figure 4-9 Observed bead forward displacement loose conditions continued



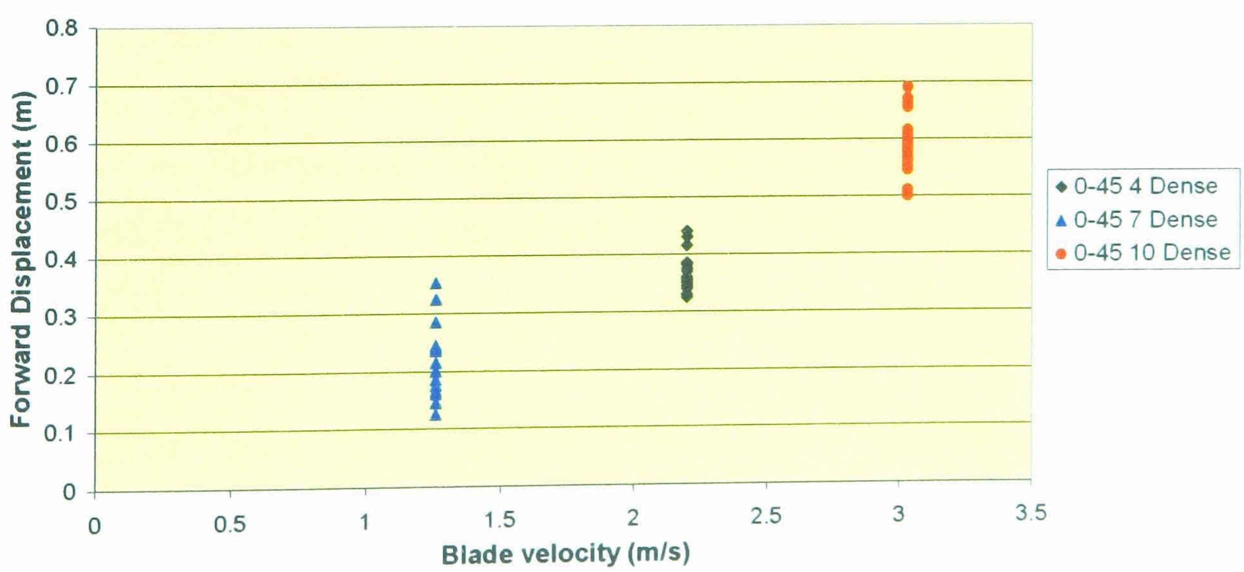
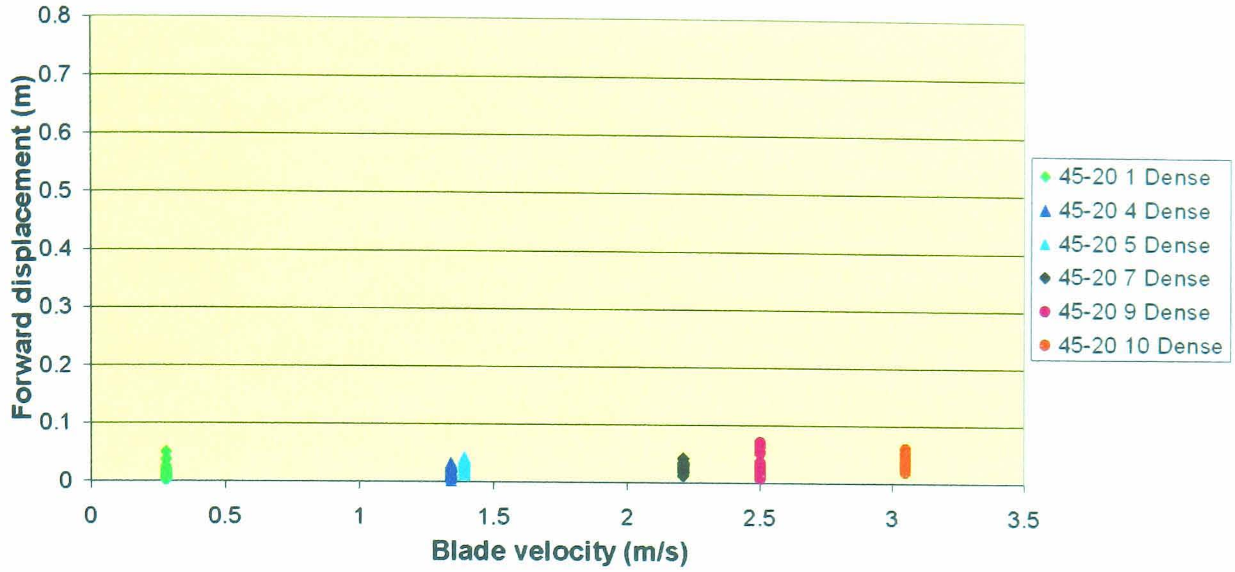


Figure 4-10 Observed bead forward displacement dense soil conditions



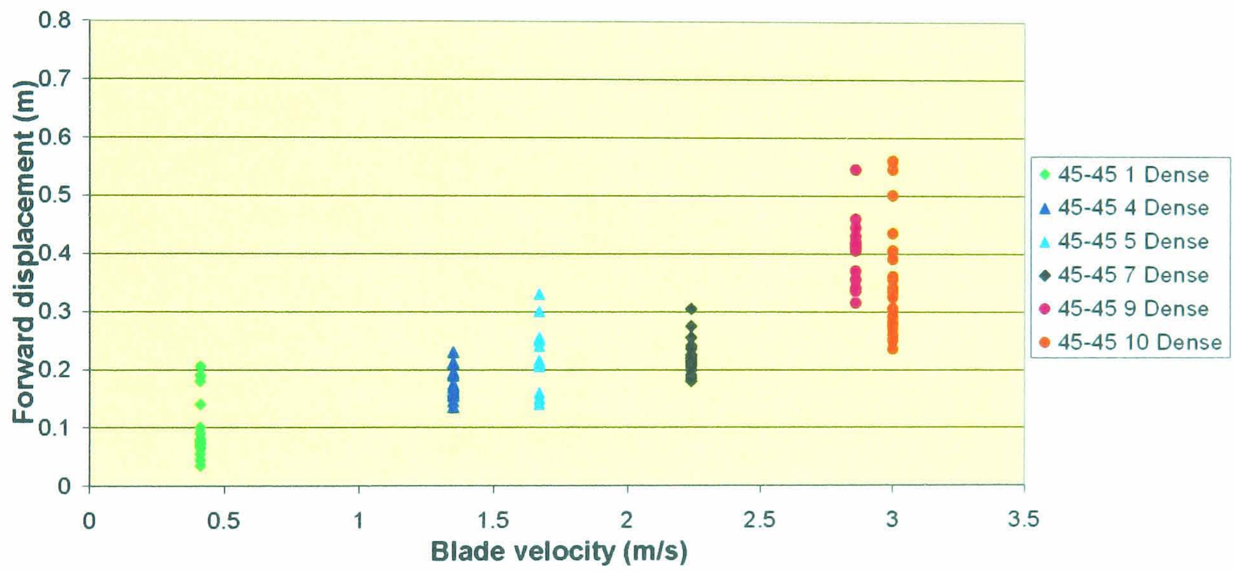


Figure 4-11 Overall forward bead displacement in dense soil conditions

The graphs indicate that bead forward position has a relatively wide range of data points (presented in Appendix A2-3) indicating that soil displacement had considerable variation. This can occur as the soil hitting the blade can react in a ballistic nature. There is more displacement in loose soil conditions as the beads may get mixed within the soil on the blade and some bulldozing occurs, amplified at low blade velocity.

In order to investigate the importance of the variables within the experiment an analysis of variance (ANOVA) test was undertaken which examines the variations of individual components. The results showed that at the 5% level rake, sweep, density, and velocity were all highly significant with $F < 0.001$. Therefore it is likely that if changes occur in any of the components listed above that soil displacement will be significantly different. ANOVA also provides an overall least significant difference (l.s.d.) for the data set of 0.047 m for the interaction between rake, sweep, density, and velocity. and an overall CV of 12.5 %.

Table 4-7 Bead forward displacement

Sweep-rake angle	0-20		0-45		45-20		45-45	
Speed-density* (km/h)	Mean (m)	CV %	Mean (m)	CV %	Mean (m)	CV %	Mean (m)	CV %
1 – Loose	0.210	49.2	-	-	0.141	55.9	0.182	52.5
4 – Loose	0.076	12.8	0.205	6.2	0.199	9.0	0.327	28.2
5 – Loose	0.134	16.1	-	-	0.148	15.8	0.263	33.3
7 – Loose	0.127	13.6	0.371	7.4	0.131	10.4	0.374	2.1
9 – Loose	0.142	15.2	-	-	0.129	12.4	0.443	18.4
10 – Loose	0.148	11.8	0.584	5.6	0.123	21.7	0.465	2.0
1 – Dense	0.012	40.8	-	-	0.013	89.0	0.097	54.5
4 – Dense	0.018	67.2	0.346	28.3	0.017	51.4	0.174	15.0
5 – Dense	0.019	51.0	-	-	0.029	27.8	0.221	25
7 – Dense	0.027	78.0	0.461	9.3	0.244	31.4	0.222	14.8
9 – Dense	0.038	56.4	-	-	0.029	58.9	0.398	15.5
10 – Dense	0.038	36.0	0.666	7.9	0.036	26.3	0.344	27.3

* Loose – 1307 kg/m^3 Dense 1494 kg/m^3

Table 4-7 presents the mean value observed as well as the coefficient of variation (CV) which is a measure of relative dispersion. In general at low blade velocities in loose and dense soil conditions the coefficient of variance was always greater than 40 %, whilst at increased blade velocities, in loose conditions the CV was less than 22% and less than 36% in dense soil conditions. Therefore it can be concluded soil displacement is more variable at low blade velocities, mainly due to partial bulldozing rather than direct soil flow.

4.4.5 Lateral displacement results

Observed mean lateral bead displacement is presented graphically in Figures 4-12 through to Figure 4-15, and the mean observations are presented in Table 4-8, with additional data in Appendix A2-3.

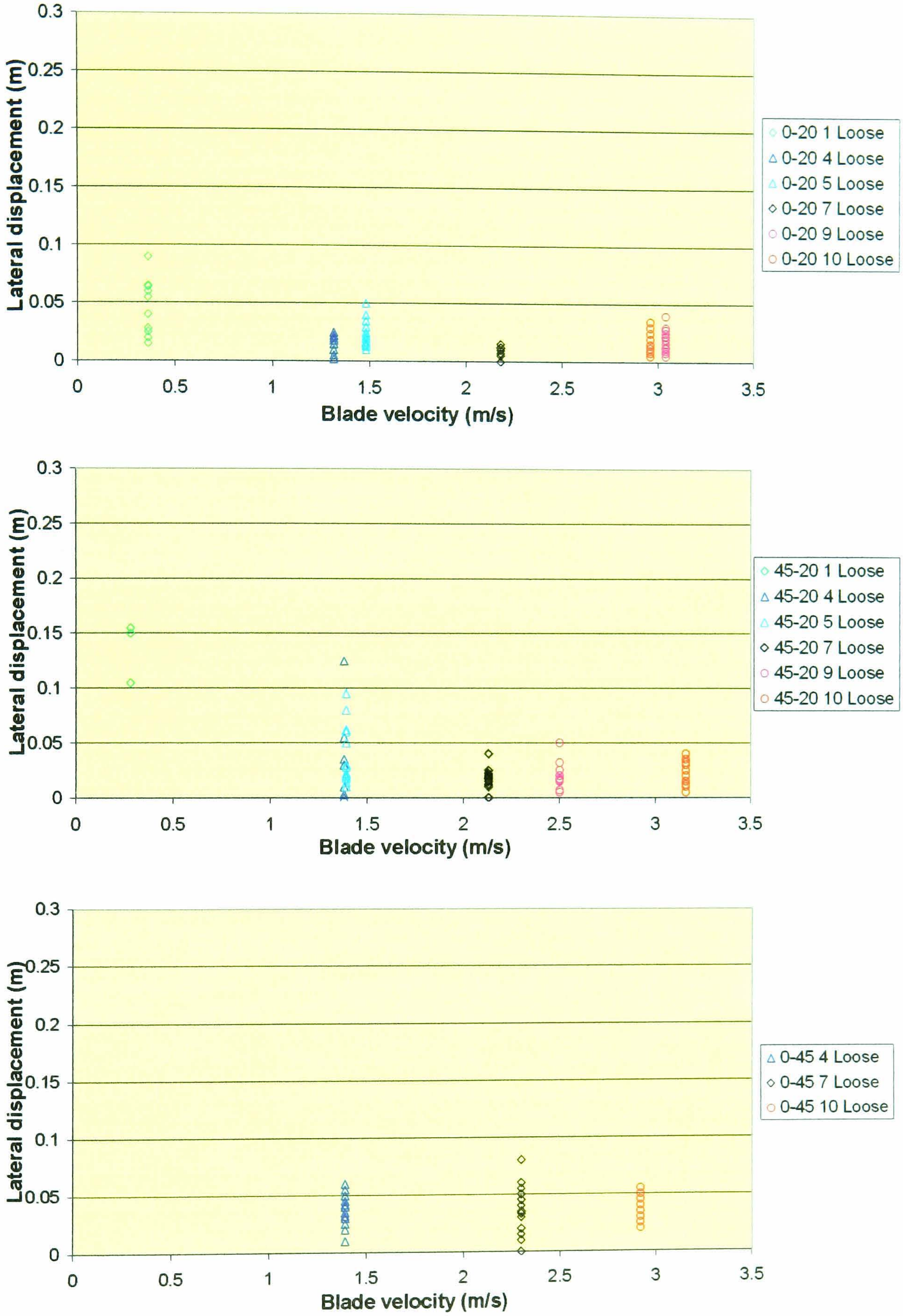


Figure 4-12 Observed bead lateral displacement in loose soil conditions

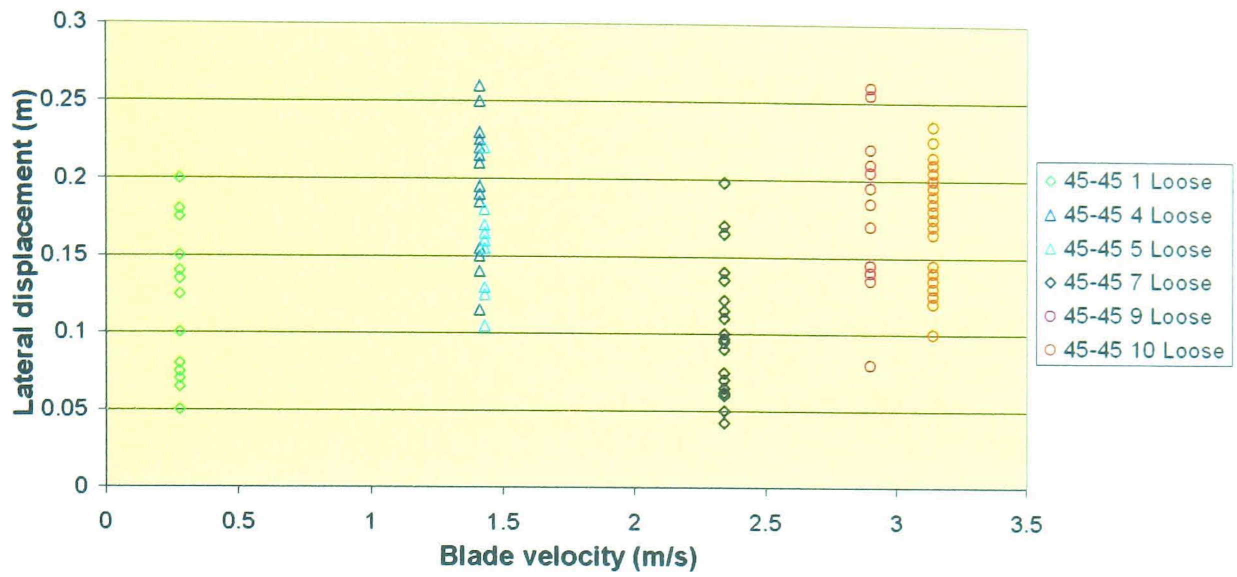


Figure 4-13 Observed bead lateral displacement in loose conditions continued

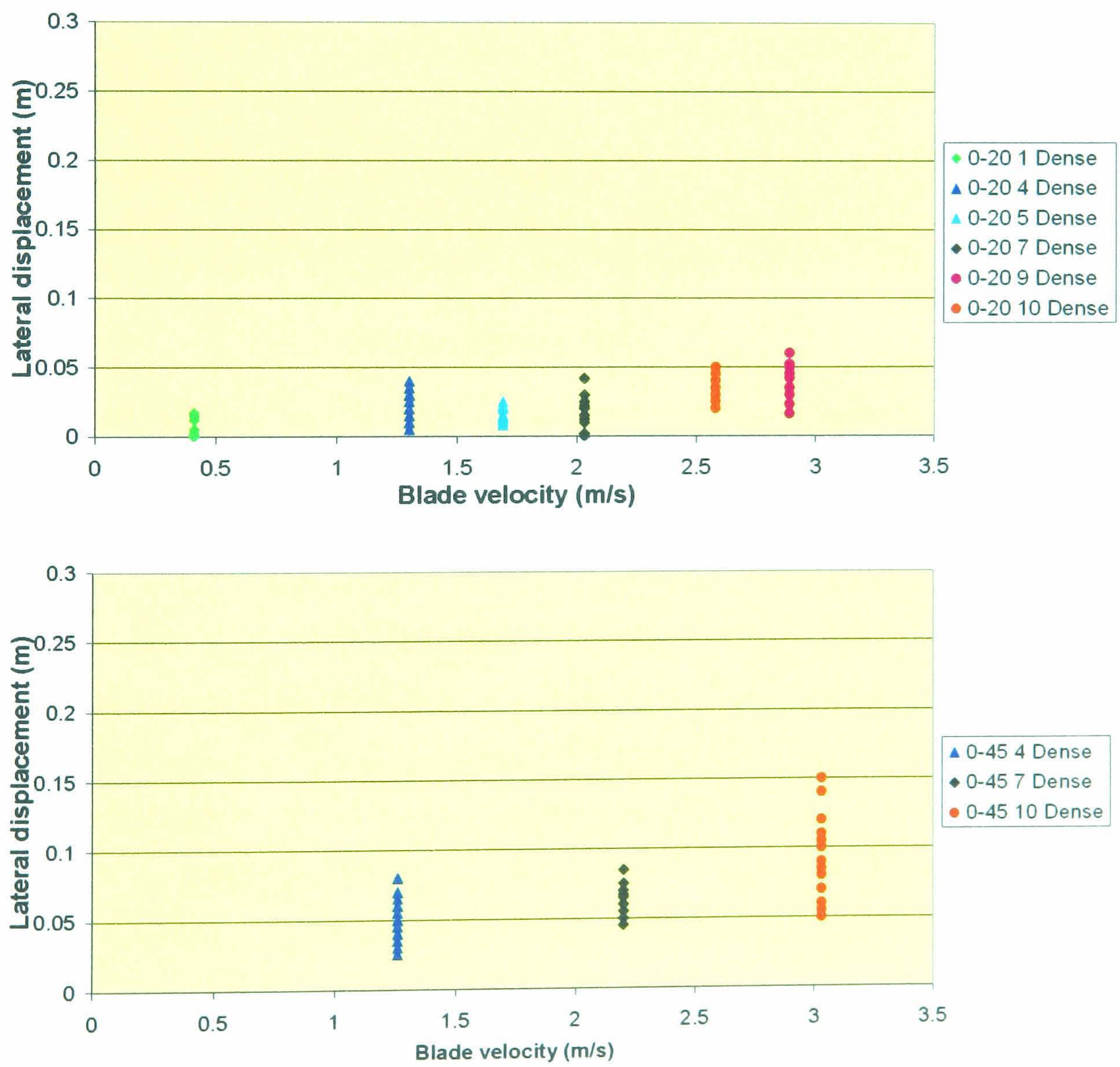
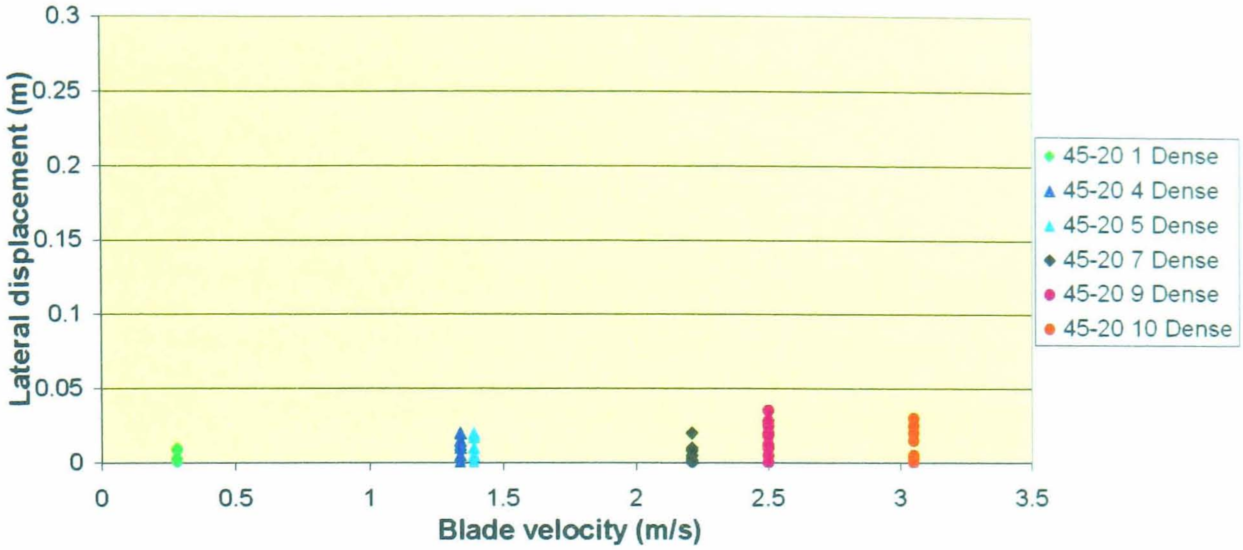


Figure 4-14 Overall lateral displacement in dense soil conditions



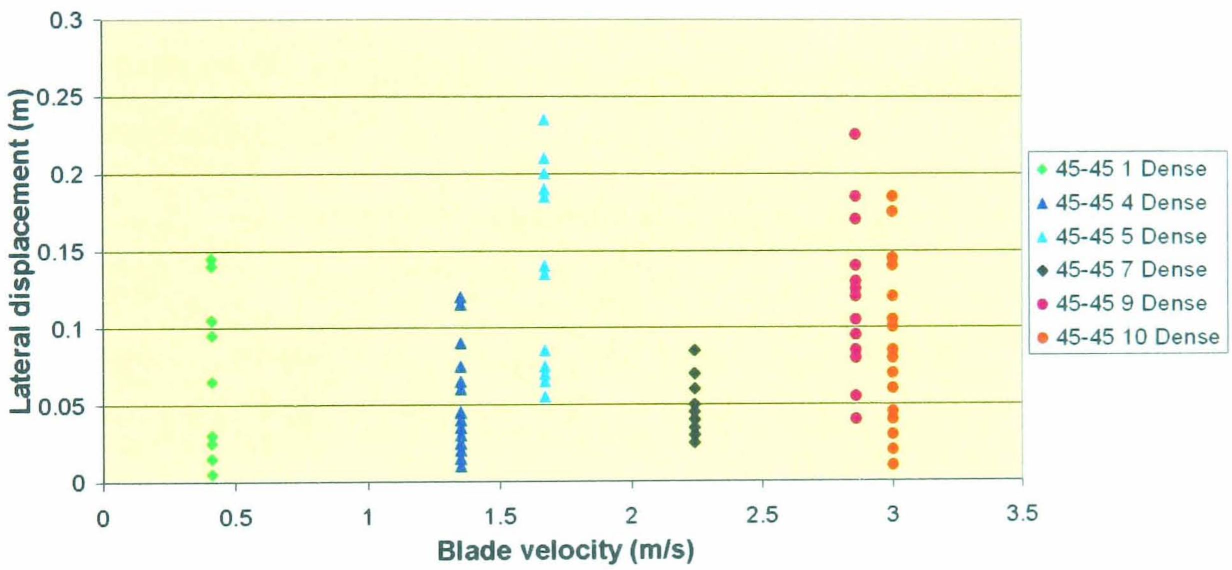


Figure 4-15 Overall lateral displacement in dense soil conditions

Analysis of variation for lateral bead data indicated that rake and density had a significant affect (5% level) on lateral bead displacement with F <0.001, whilst velocity was insignificant with F =0.103. Therefore, there is insufficient evidence to suggest that increasing lateral displacement occurs from increasing blade velocity between the range of 0.28 m/s to 3.16 m/s considered in this research programme. The least significant difference (lsd) at the 5% level for the data set was 0.03214 m for the interaction between rake, density, and velocity and an overall CV of 40.6 %.

The variability in the lateral displacement is greater than three times the variability observed in forward bead displacement by comparison of the coefficients of variance. The observed range of data collected as illustrated in Figure 4-13 and particular Figure 4-15 shows that the range of observed data points was large. On blades with steep rake angles i.e. 0-45 and 45-45 there was more variability in the data than with shallower rake angles. However examination of the coefficients of variance in Table 4-8, suggest that the 0-20 and 45-20 have increased CV%. This occurs as the mean displacement is relatively low, compared to blades with 45^0 rake angles.

Any lateral displacement occurring on blades with zero sweep angle can effectively be classified as leakage over the edge of the blade. It should also be remembered that shallow working wide blades have their lateral displacement restricted by the adjacent soil surface. As rake angle increases so more of the sliding face is exposed to free space, thus allowing greater lateral displacement.

Table 4-8 presents the mean of the observed values for lateral displacement as well as the coefficient of variation.

Table 4-8 Mean lateral displacement and CV

Sweep–rake angle	0-20		0-45		45-20		45-45	
Speed-density* (km/h)	Mean (m)	CV %	Mean (m)	CV %	Mean (m)	CV %	Mean (m)	CV %
1 – Loose	0.042	55.9	-	-	0.014	16.8	0.122	39.9
4 – Loose	0.015	43.9	0.037	37.7	0.236	131.8	0.196	19.8
5 – Loose	0.022	50.2	-	-	0.037	74.1	0.155	17.8
7 – Loose	0.010	47.1	0.035	46.5	0.017	41.4	0.099	42.8
9 – Loose	0.019	47.8	-	-	0.020	48.8	0.199	29.2
10 – Loose	0.016	51.5	0.036	25.4	0.020	51.2	0.174	22.9
1 – Dense	0.005	137.5	-	-	0.007	57.1	0.064	81.8
4 – Dense	0.018	58.2	0.051	26.9	0.009	81.0	0.018	64.4
5 – Dense	0.018	27.9	-	-	0.007	112.6	0.136	47.9
7 – Dense	0.018	47.2	0.060	19.2	0.007	93.6	0.046	37.6
9 – Dense	0.038	32.9	-	-	0.013	77.5	0.115	43.6
10 – Dense	0.033	21.3	0.095	29.6	0.013	89.7	0.082	62.8

* Loose – 1307 kg/m^3 Dense 1494 kg/m^3

4.5 Measurement of soil flow over the blade

Vasilkovskii & Harris (1970) states that bead movement techniques, although useful in providing overall displacement does not assist in understanding the detailed process of soil movement over the blade. In order to develop a model to predict soil movement it is necessary to understand how the soil flows over the blade, and the level of soil displacement occurring at this stage.

There are two distinct stages of bead movement – (a) movement over the blade, and (b) movement after the soil leaves the blade. In this section an attempt is made to measure the former.

4.5.1 Objectives

To develop a procedure to record the flow of soil in real time over shallow working wide blades by non-invasive methods.

4.5.2 Design

The experimental procedure was undertaken during the overall bead displacement data gathering, therefore the design is identical to that detailed in Section 4.4.2

4.5.3 Apparatus and procedure

Manual analysis of video images proved to be the best way of investigating soil deformation and trajectory, as it was non-invasive. Traditional video cameras proved inadequate with recording rates of 25 frames per second (fps), because at speeds of 10 km/h (2.78m/s), this equates to 0.111 m movement per frame, which was insufficient as the blade sliding length was only 0.1 m. It was, therefore, necessary to employ the use of a high-speed video camera.

The high-speed digital video camera selected was on loan from the EPSRC instrumentation pool. This was an Ektapro system, Kodak EM (Electronic Memory). It records directly to solid state memory and will record up to 1000 frames per second (fps) with a full height image definition of 240 pixels horizontal x 200 vertical x 625 grey levels. An advantage of this high speed camera over many others was its relatively long recording duration of 20 seconds, which ensured that all three sub samples were recorded.

All recording was undertaken at 500 fps as lower light intensities could be used whilst obtaining high clarity of image. At a recording rate of 500 fps at 2.78 m/s each frame represented 5.56 mm movement per frame. The movement per frame for varying blade velocities is presented in Table 4.9 and the camera and auxiliaries are shown in Figure 4-16.

Table 4-9 Soil movement per frame at 500 fps

Blade velocity km/h (m/s)	**Movement /frame** mm/frame
1 (0.28)	0.56
4 (1.11)	2.22
5 (1.39)	2.78
7 (1.94)	3.89
9 (2.50)	5.00
10 (2.78)	5.56

The camera or imager (1) is connected to the digital recorder (2) and relayed to a black and white monitor (3) so the view can be seen, ensuring correct location of imager. Lights (4) were used to illuminate the soil surface to ensure the imager received enough light to enable high speed filming, providing good image clarity.

The frame rate, imager set up and record trigger were controlled by the Kodak remote control unit (5). After capturing the image, the video footage was replayed at 1 fps for further analysis and recorded onto a standard VHS tape (6). Pictures could be printed off via the video printer (7), which were used for reference purposes.

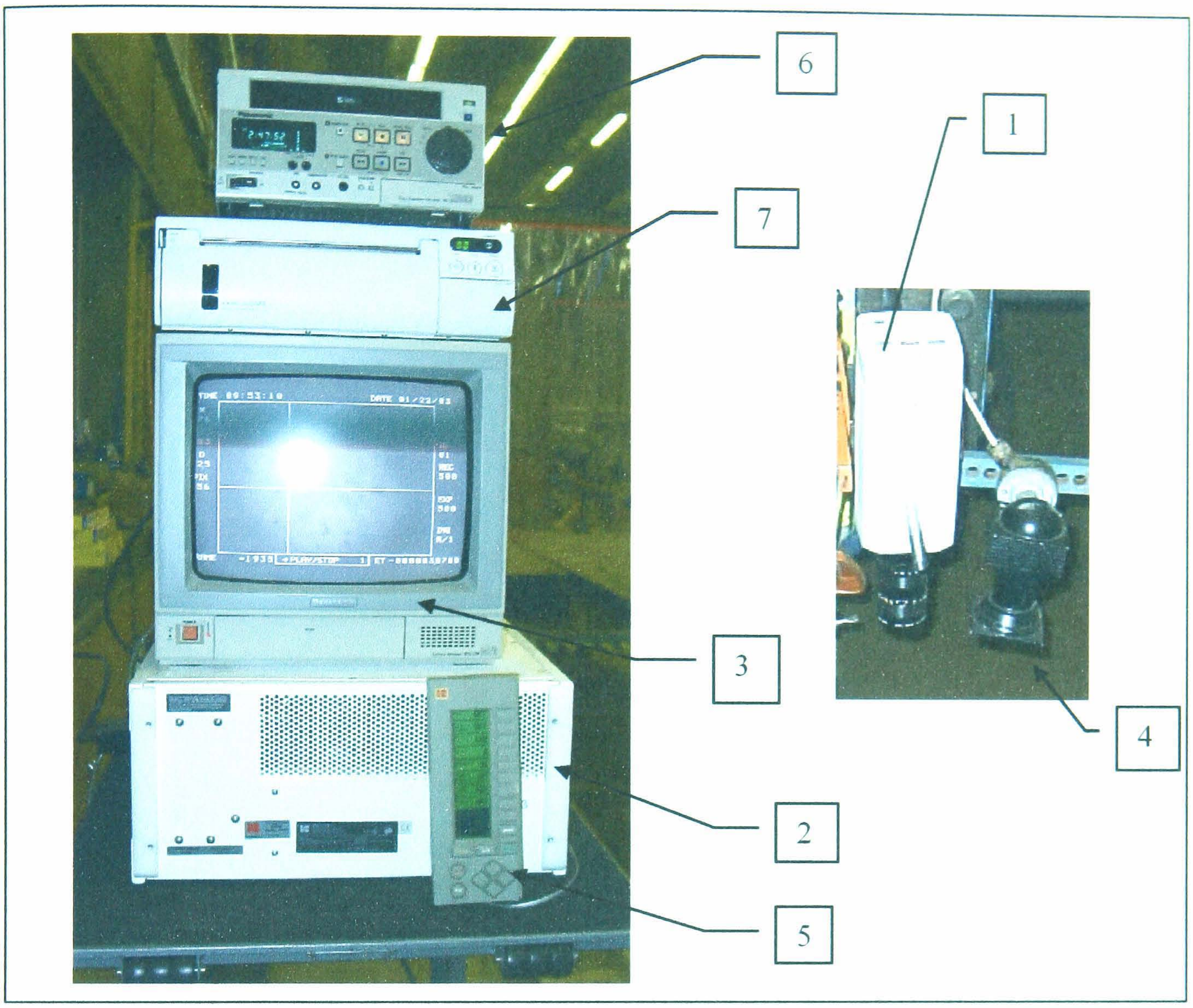


Figure 4-16 Kodak high-speed video Camera

High speed video recording of the soil alone was not enough, as the camera needs to pick up on points to enable further analysis of soil movement. Therefore to obtain representative information on soil flow white markers were placed into the soil surface as shown in Figure 4-17. The markers had a very thin steel pin leg fixed to the head, and were inserted approximately 10 mm into the soil.

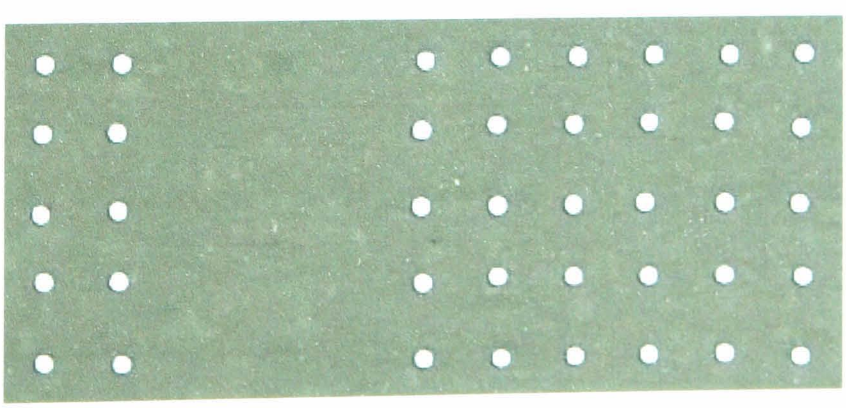


Figure 4-17 Pin markers in soil

The markers were located in a regular grid pattern, so the effects of soil and pin displacement could be monitored simultaneously. The paired line of pins on the far left of the image are datum points outside the path of the blade allowing pin movement to be related to this datum.

To determine pin movement manual analysis was undertaken by projecting the recorded video onto a large white board. The pins could be clearly seen on the board and were traced by plotting their position frame by frame using a marker pen as they flowed over the blade as illustrated in Figure 4-18. Each row of appearing pins were effectively replications of soil displacement, this technique was undertaken three times along the bin length and the mean of the plotted points in Figure 4-18 was taken to provide forward and lateral displacement over the blade, presented in Table 4-10 and Table 4-11 respectively.

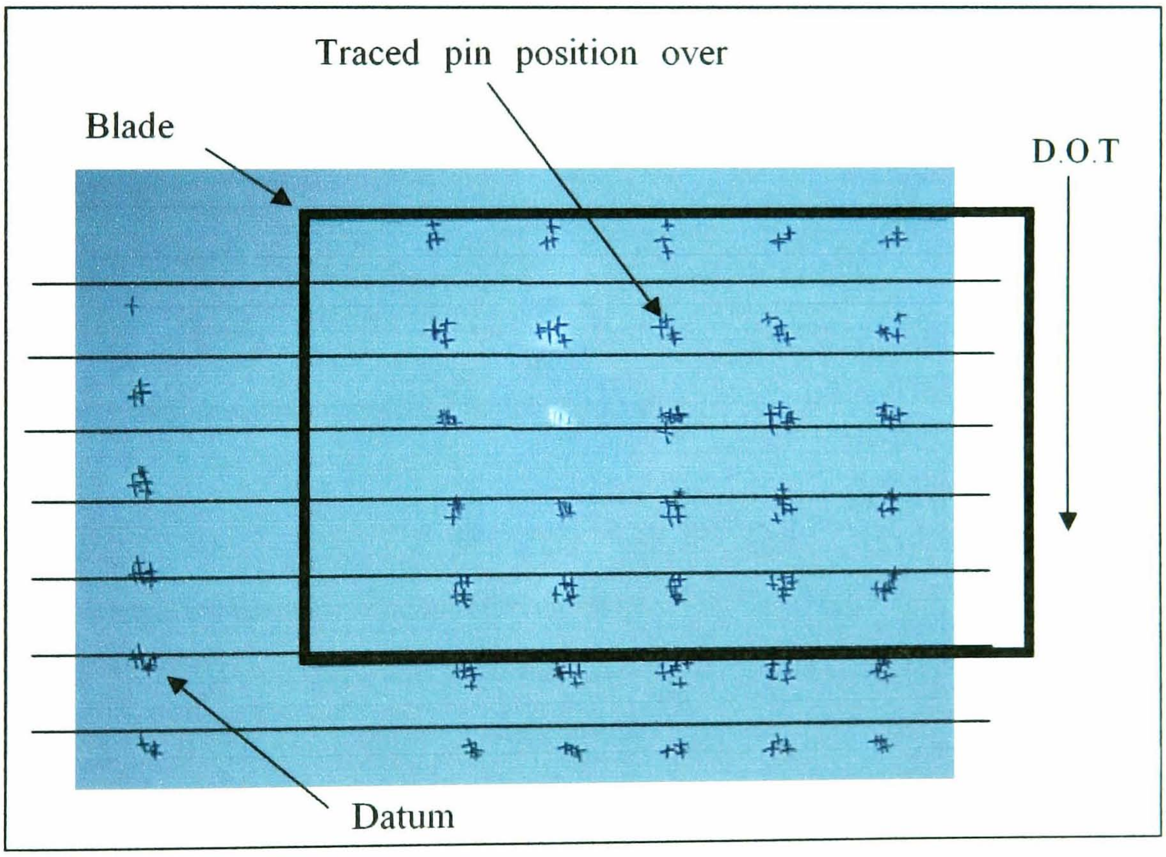


Figure 4-18 Recording technique for soil displacement over the blade

The projected image was distorted due to the camera lens and, therefore, calibration was required to convert the projected image into true pin position. Figure 4-19 presents a 0-20 blade covered with a 20 mm x 20 mm grid formation over the blade surface. Measurements of line distortion were recorded; and projected pin position was calibrated against grid distortion to obtain true pin displacement. This technique was undertaken for each blade examined within this study.

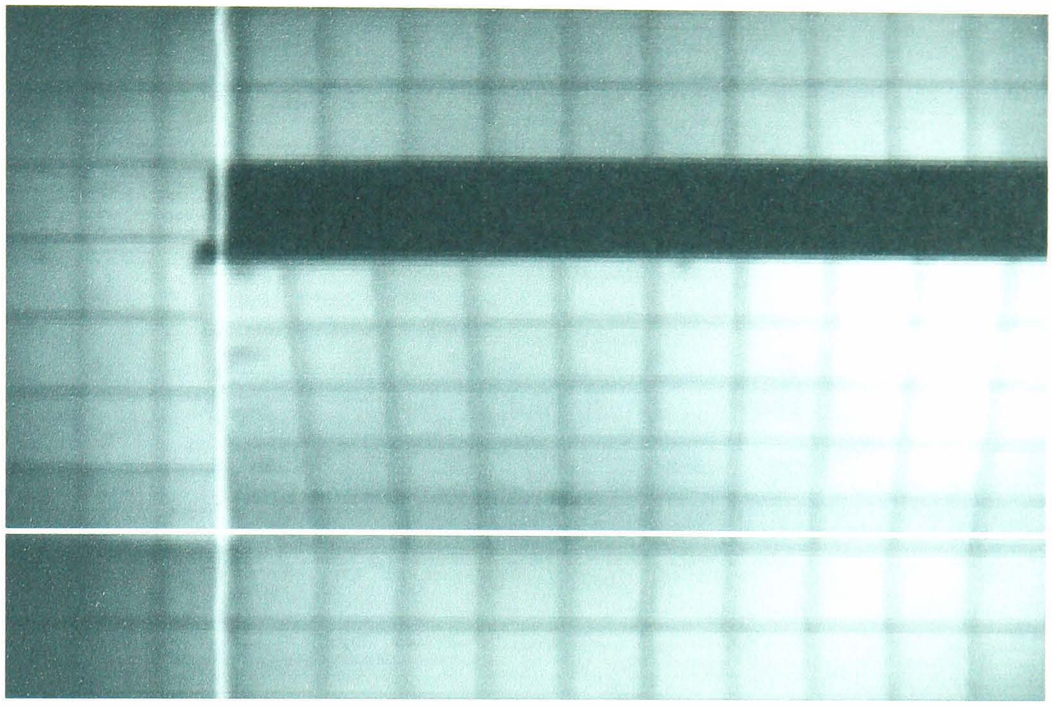


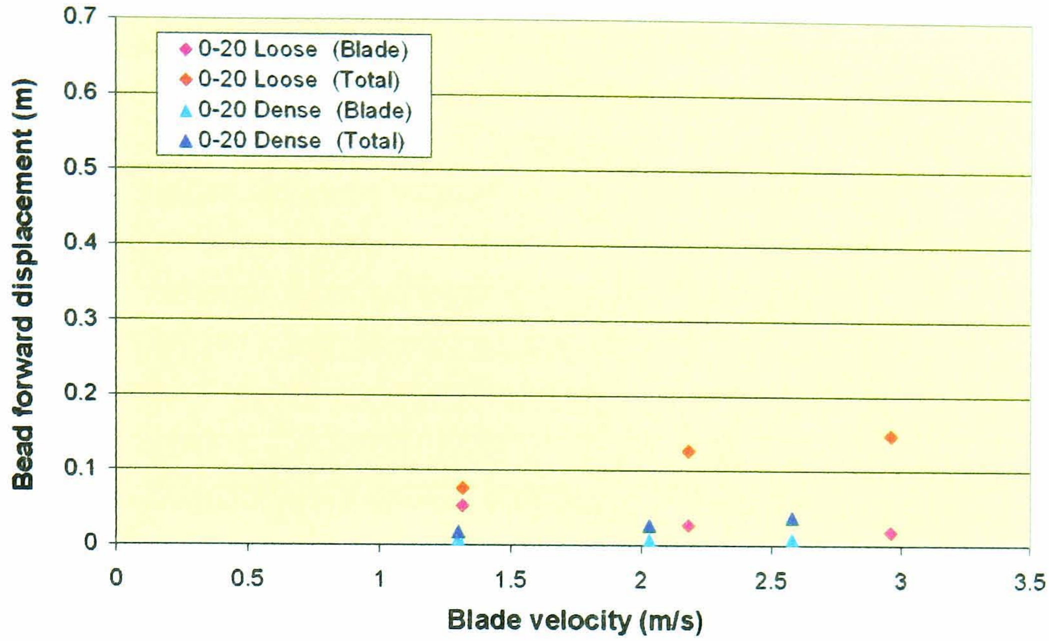
Figure 4-19 High speed camera lens distortion

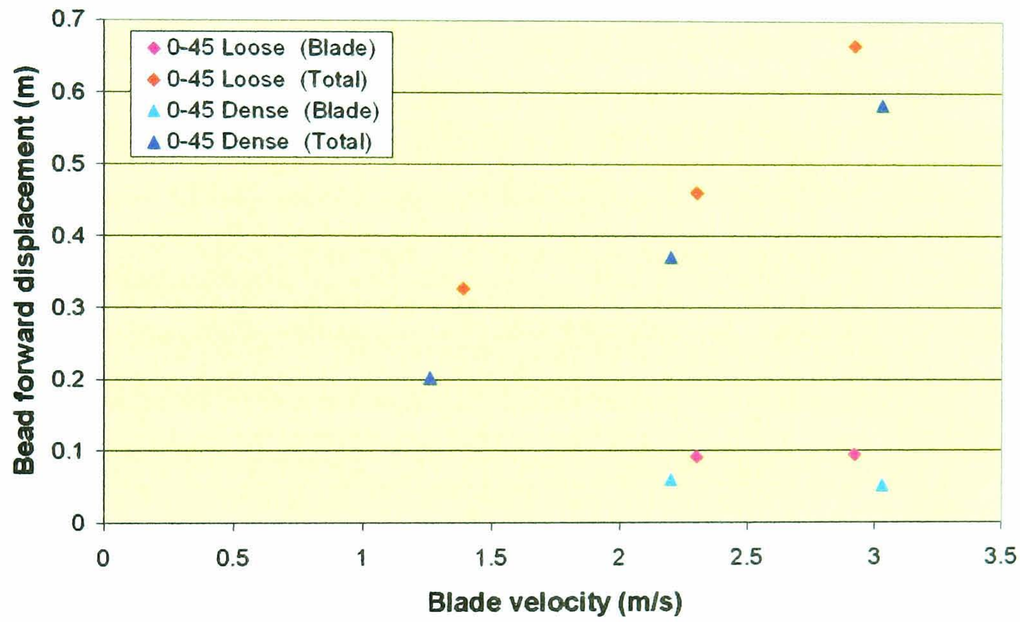
Figure 4-19 shows that lens distortion is exaggerated as the blade is closer to the lens at the top of the screen. The grid lines, therefore, at the top of the blade diverge from the centre of the line. Calibration corrected lens distortion.

4.5.4 Forward displacement results over the blade

The results of forward soil displacement over the blade are shown graphically in Figures 4-20 and 4-21 and the mean displacement is presented in Table 4-10. It was not always possible to obtain soil displacement data as the pins became engulfed in the soil flowing over the blade, making observations impossible.

The graphical representations of soil displacement over the blade are plotted with the overall bead displacement data obtained in Section 4.4 for comparison purposes.





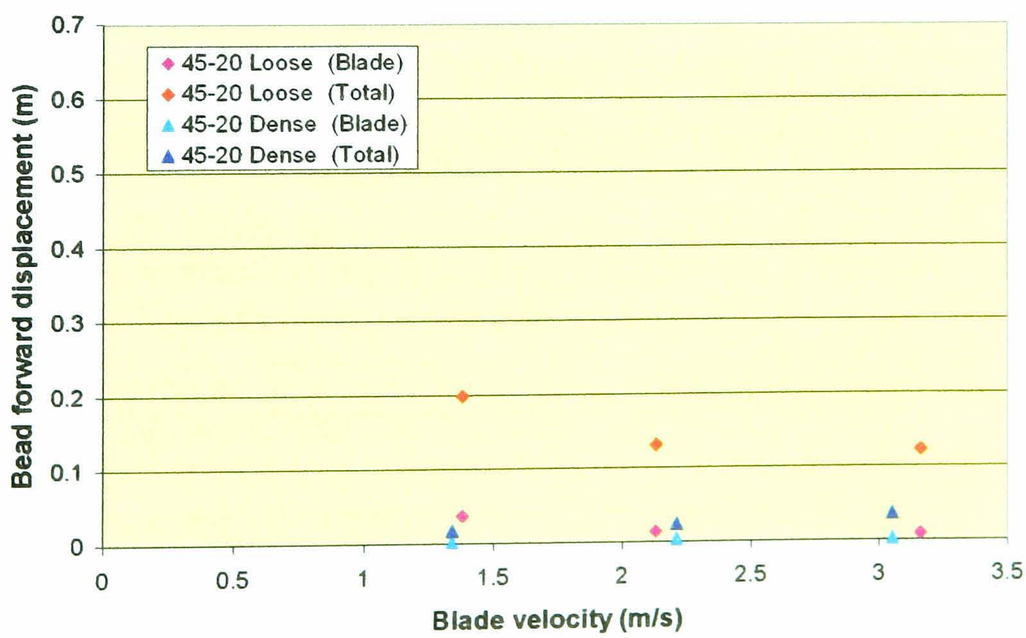


Figure 4-20 Forward displacement, and displacement over the blade

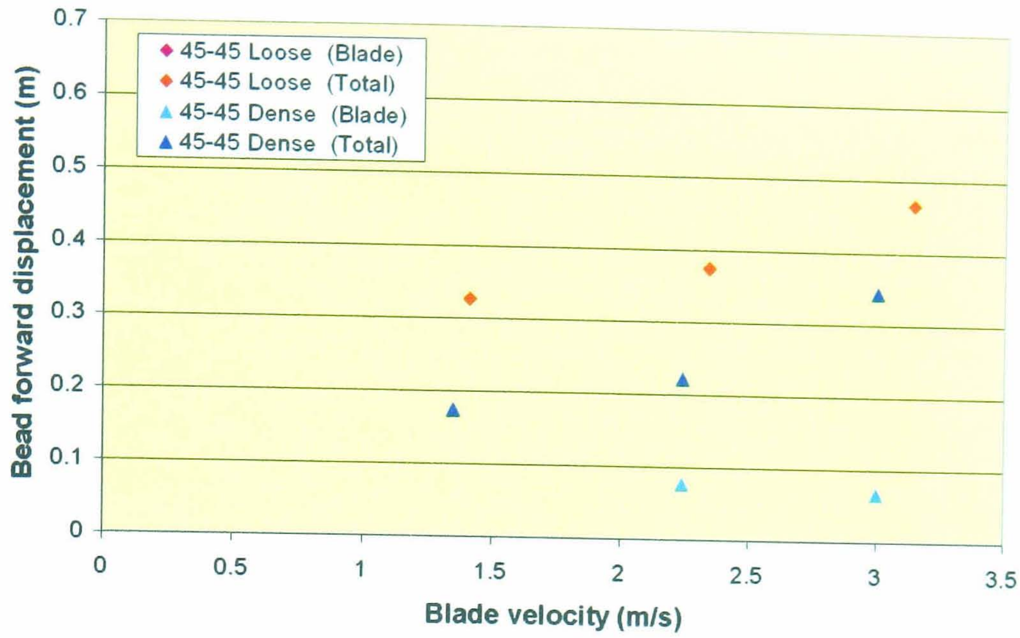


Figure 4-21 Forward displacement, and displacement over the blade continued

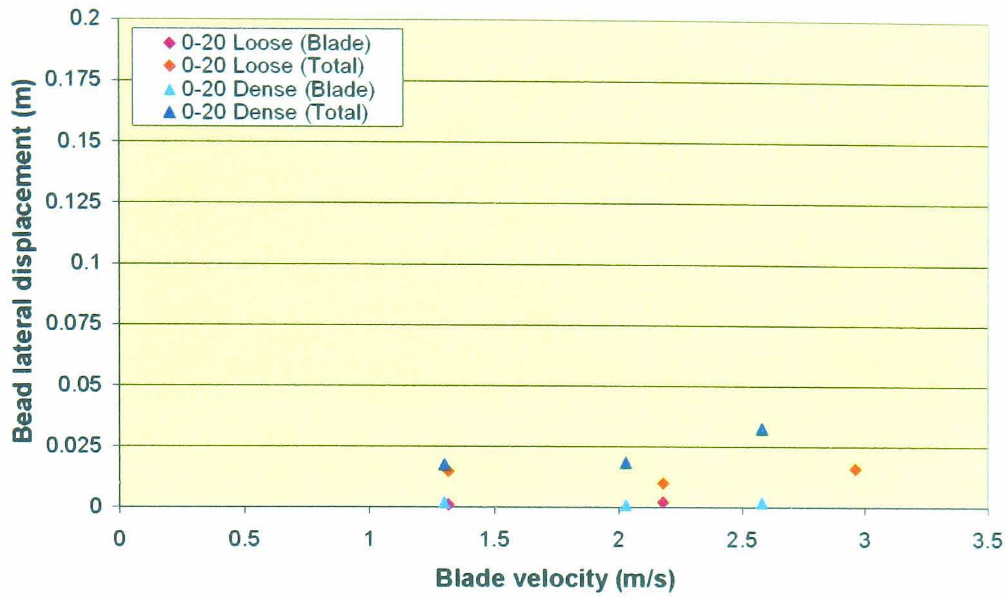
Figure 4-20 and 4-21 indicate that soil displacement due to the blade in comparison to overall displacement is relatively low, i.e. approximately < 25%. It is clear from Table 4-10 that increasing rake angle, increases the forward displacement of the beads over the blade, which accounts for a part of the increase in overall bead displacement. Blade velocity does not seem to be a major influence in movement over the blade in either loose or dense conditions. Introducing sweep angle seemed to increase the displacement for a 45^0 rake, which could be due to the increase in effective sliding face length as detailed in Chapter 5. When sweep was introduced on the 20^0 rake the displacement was reduced, mainly due to the effective rake being reduced to 14.4^0.

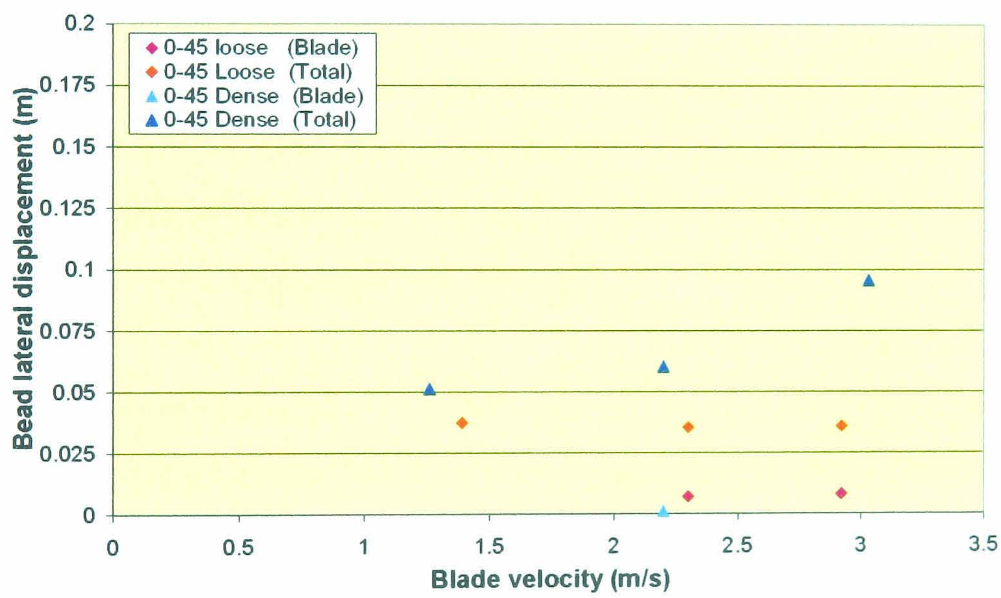
Table 4-10 Forward displacement over the blade measured using high speed video

Velocity-density (km/h) / Sweep-rake	4 Loose (m)	4 Dense (m)	7 Loose (m)	7 Dense (m)	10 Loose (m)	10 Dense (m)
0-20	0.053	0.008	0.027	0.007	0.018	0.009
0-45	--	--	0.092	0.060	0.095	0.052
45-20	0.037	0.002	0.014	0.004	0.009	0.002
45-45	--	--	--	0.076	--	0.066

-- Data unattainable

4.5.5 Lateral displacement results over the blade





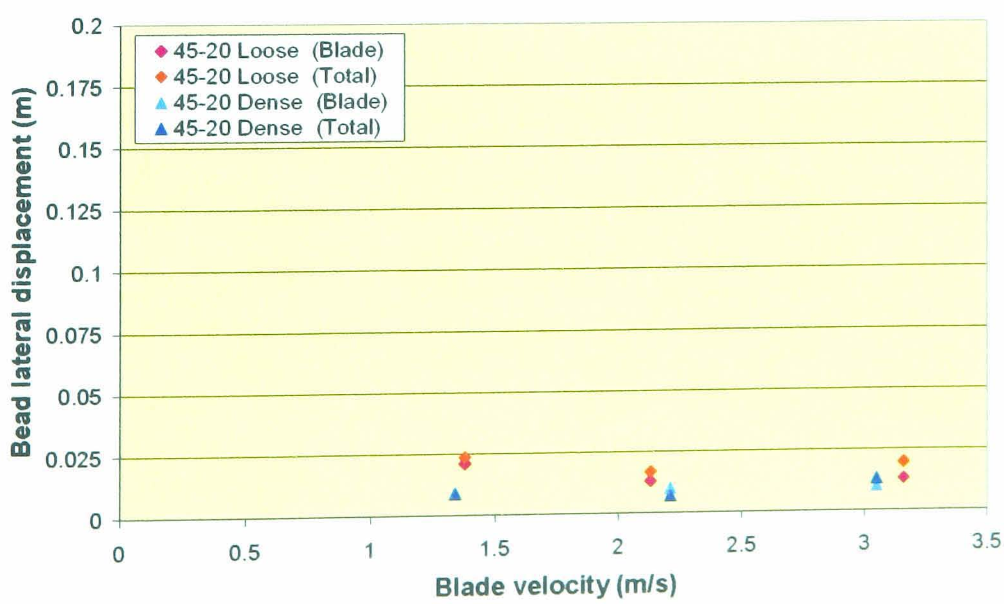


Figure 4-22 Lateral displacement, and displacement over the blade

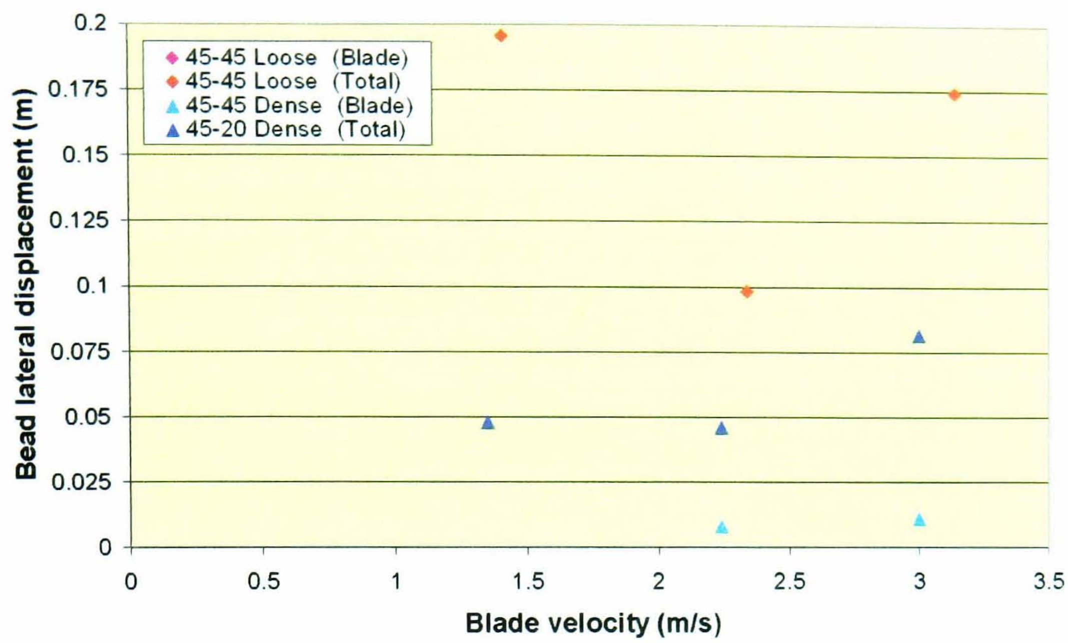


Figure 4-23 Lateral displacement, and displacement over the blade continued

Figures 4-22 and 4-23 show that lateral soil displacement is considerably less than forward displacement. The mean recorded lateral displacements are presented in Table 4-11. In general, displacement due to the blade is considerably less than overall displacement in all blades examined.

Table 4-11 shows that blade velocity does not have a significant affect on lateral displacement as a 3 mm increase is observed with a 30% increase in velocity in dense soil conditions, where no increase in lateral displacement occurred with a 30% increase in blade velocity in loose soil conditions.

Table 4-11 Mean lateral displacement over the blade measured using high speed video

Velocity-density (km/h) / Sweep-rake	4 Loose (m)	4 Dense (m)	7 Loose (m)	7 Dense (m)	10 Loose (m)	10 Dense (m)
0-20	0.001	0.002	0.002	0.001	--	0.002
0-45	--	--	0.007	0.001	0.008	--
45-20	0.021	0.009	0.013	0.010	0.013	0.010
45-45	--	--	--	0.008	--	0.011

-- Data unattainable

The introduction of sweep angle onto the blade increases lateral displacement by approximately 10 mm, but as with blades without sweep, blade velocity does significantly effect lateral displacement.

4.5.5.1 Divergence angle over the blade

Measurement of the lateral and forward displacement of the pins over the blade enables the soil divergence angle at the surface to be calculated, the results are presented in Table 4-12.

Table 4-12 Soil divergence angle over the blade by pin analysis

Velocity-density (km/h) / Sweep-rake	4-Loose (^{0})	4-Dense (^{0})	7-Loose (^{0})	7-Dense (^{0})	10-Loose (^{0})	10-Dense (^{0})
0-20	0.6	1.1	1.1	0.6	--	1.1
45-20	11.9	5.1	7.4	5.7	7.4	5.7
0-45	--	--	4.0	0.6	4.6	--
45-45	--	--	--	4.6	--	6.3

-- Data unattainable

The results in Table 4-12 show that with increases in rake angle from 20^0 to 45^0 the divergence angle increased. It can also be seen that increasing blade velocity from a target of 4 km/h to 10 km/h did not result in a significant change of divergence angle, therefore it can be assumed that divergence angle is not proportional to blade velocity.

4.5.5.2 Soil velocities

As mentioned when obtaining pin displacement across the blade, it was possible for the soil velocity to be obtained by knowing the time between frames and the movement of each pin. The same difficulties were encountered in recording the data as outlined in Section 4.5.4, but the results provide a guide that can be used in the prediction model. In all scenarios apart from 4 km/h in dense soil conditions with the 45-20 blade, soil velocity was less than blade velocity, as expected. This anomaly can be explained by the soil deformation process, as the plates break apart, they can expand. A proportion of that expansion may provide an increase in velocity, as well as possible measurement error.

Table 4-13 presents the observed soil velocities (V_{soil}) over the blade, and compares them against blade velocity (V_{blade})

Table 4-13 Observed velocity of soil over the blade

Velcoity-density (km/h) sweep-rake	Velocity	4 -loose (m/s)	7 -Loose (m/s)	10 - Loose (m/s)	4 - Dense (m/s)	7 - Dense (m/s)	10 – Dense (m/s)
0-20	V_{blade}	1.35	2.18	2.96	1.30	2.03	2.58
	V_{soil}	1.29	2.04	2.71	1.28	1.87	2.32
0-45	V_{blade}	1.39	2.3	2.92	1.26	2.20	3.03
	V_{soil}	-	2.00	2.67	-	2.00	2.98
45-20	V_{blade}	1.38	2.13	3.16	1.34	2.21	3.05
	V_{soil}	1.27	1.98	2.95	1.38	2.09	3.02
45-45	V_{blade}	1.41	2.34	3.14	1.35	2.24	3.00
	V_{soil}	-	-	-	-	2.04	2.86

4.6 Soil height measurement on the blade using projected laser line

Soil height in-transit is a fundamental requirement in understanding soil deformation and soil flow characteristics whilst being undercut by a blade. Harrsion (1988) developed a system of measuring the in-transit height of soil using a profile meter mounted above the blade, having twelve potentiometers mounted onto it, which recorded displacement. Fingers were attached to the potentiometers, which followed the soil flow path; however problems were encountered as the fingers were interacting with each other and the mass of the fingers resulted in erroneous readings. Heavy fingers penetrated the soil whilst it was reported that light fingers bounced excessively at speeds of 7 km/h. Due to inherent problems reported by Harrison (1988) a non-contact system was developed to measure the in-transit height of soil as it passed over a series of blades.

4.6.1 Objectives

To investigate the in-transit height of soil as it flows over the blade throughout the length of the soil bin, by a non-invasive approach, at the same time as other soil observations are being recorded.

4.6.2 Experimental design

The measurement of soil height over the blade was conducted during the bead displacement experiments; therefore the experimental design is the same as detailed in Section 4.4.2.

It is well known that soil breaks out in front of the tip or cutting edge of the blade. A measure of soil height some distance in front of the blade would help in determining the point of rupture to the surface. Soil height at the tip of the blade is also an important factor, as this presumably is a key factor determining the height of soil travelling on the blade. Measurement of soil height at the rear of the blade can be compared to soil height at the tip to determine if soil height on the blade is uniform along the blades sliding face. The final parameter records maximum lift height, as this provides information on soil flow after leaving the rear of the blade. The parameters to be recorded are listed below and shown graphically in Figure 4-24.

A) Blade depth
B) Commencement of soil lift in front of cutting edge
C) Soil height at blade cutting edge
D) Height of soil at rear of blade
E) Maximum recorded lift height

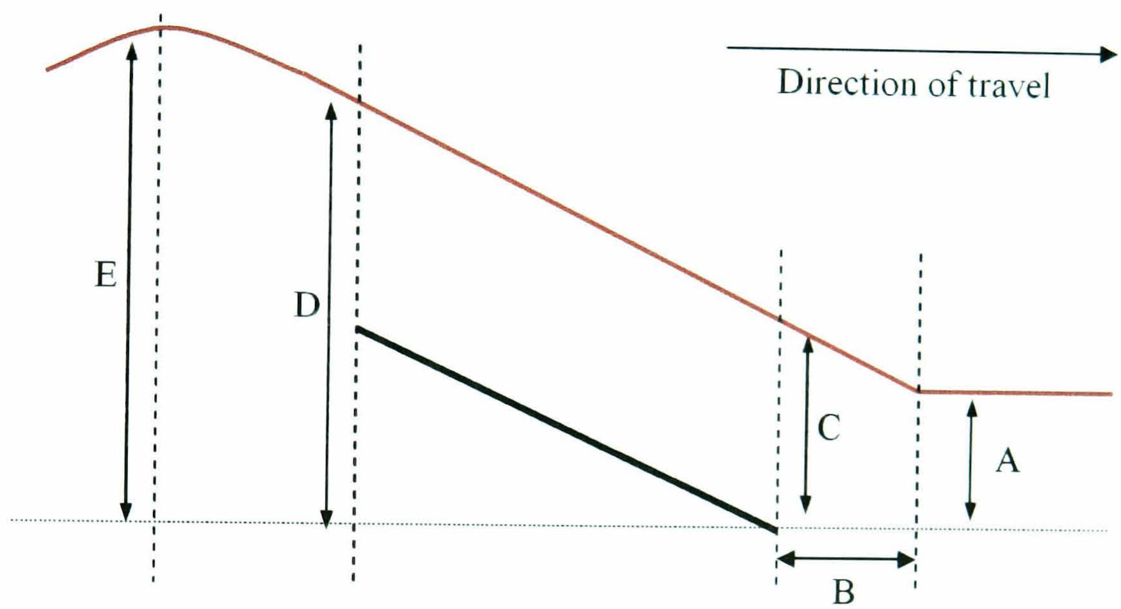


Figure 4-24 Pictorial cross-sectional representation of soil in-transit height

4.6.3 Apparatus and procedure

A line generating laser beam was selected to record the soil in-transit height. A 5mW-red/infrared laser (eye safe) with a 90^0 lens was used to generate a straight line; the laser was attached to an adjustable frame mounted to one side of the blade as shown in Figure 4-25.

The line generating laser required careful positioning to ensure the line generated on the soil surface was parallel to the direction of blade travel and was at an angle of 45^0 to the soil surface. Keeping the laser at a constant angle of 45^0 to the horizontal enabled changes in soil height to equate to changes in lateral shift of the generated laser line when viewed from above.

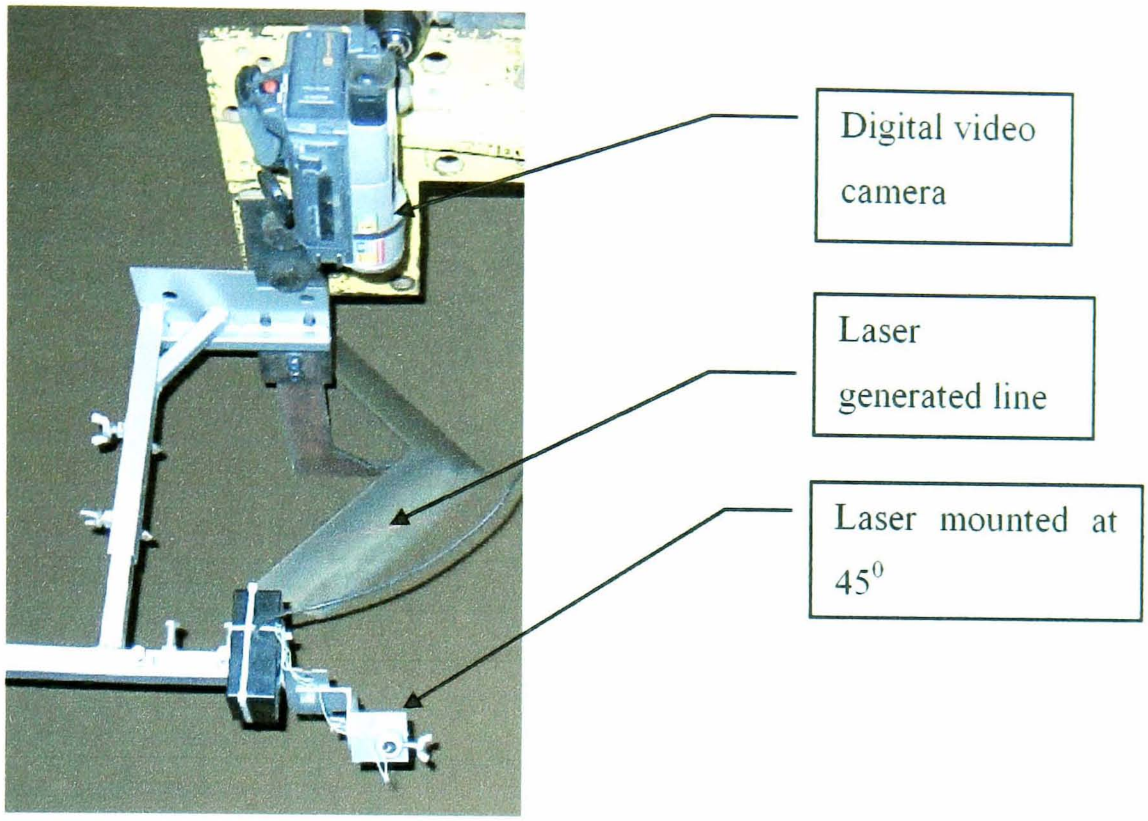


Figure 4-25 Laser beam to determine in transit height of soil

A digital video camera, was mounted directly above the generated line over the blade and soil surface, this recorded lateral deviations of the line, due to increased soil height, whilst the blade was pulled through the soil.

Image calibration was undertaken before each run using a selection of steel blocks with known height and width, all which were placed directly beneath the cameras' field of view. These were then measured to obtain the correct ratio of lateral and vertical movement as shown in Figure 4-26 along with the clear presentation of the laser line over the blade showing lateral shift with increasing blade height.

The procedure for measuring the lateral deviation of the laser line was conducted in a similar manner to that described in Section 4.5.3. The video was projected on to a large white board, and the steel blocks were then measured to obtain the lateral and vertical calibration factors. Video footage was then replayed frame by frame and the in-transit laser generated line was traced onto the board. At the end of the run the mean of the traced lines was drawn, and lateral movement of the generated line measured and recorded. The recorded results were multiplied by the calibration factor to obtain actual lift height of soil over the blade.

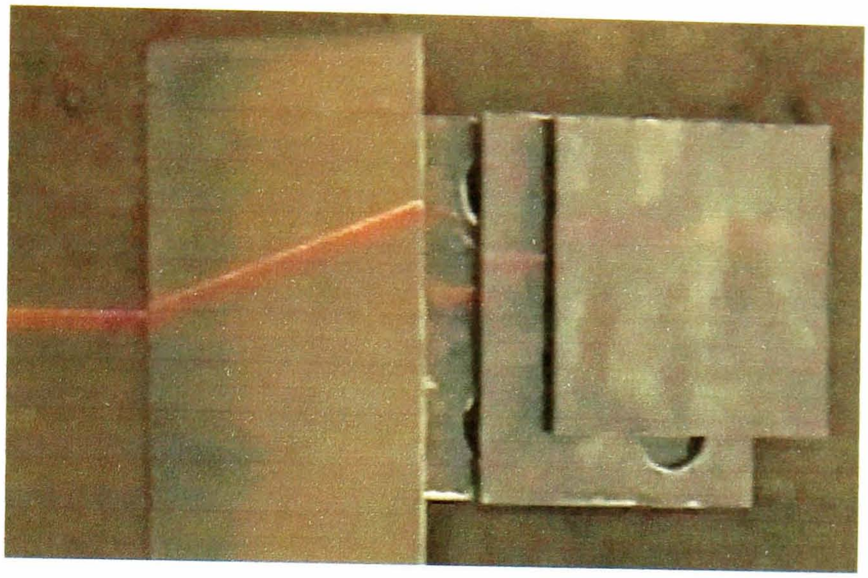


Figure 4-26 Projected laser line calibration for a 0-20 blade

Figure 4-27 shows the projected laser line on loose soil flowing over a 0-20 blade at 1 km/h.

Figure 4-27 Projected laser showing in-transit height of loose soil over a 0-20 blade

Figure 4-28 shows the projected laser line on dense soil flowing over the same 0-20 blade at 1 km/h. The soil deformation can be seen, which made height recording more variable, therefore, mean heights were taken over the blade, there was more noise in the mean height in dense soil conditions than in loose.

Figure 4-28 Projected laser showing in-transit height of dense soil over a 0-20 blade

4.6.4 Results

Table 4-14 presents the mean results of soil depth over the four blades with variations in velocity and geometry.

Table 4-14 Depth of soil flow over blades using projected laser technique

Sweep – rake angle / Velocity – density (km/h)	0-20 (m)	0-45 (m)	45-20 (m)	45-45 (m)
4 – Loose	0.045	0.067	0.050	0.061
7 – Loose	0.048	0.071	0.050	0.045
10 – Loose	0.036	0.060	0.050	0.048
4 – Dense	0.039	0.055	0.044	0.042
7 – Dense	0.039	0.061	0.049	0.041
10 - Dense	0.038	0.054	0.046	0.037

Observations of the soil height in-transit as well as recorded in-transit heights by the projected laser suggest that soil flow over the blade can be approximated to that of parallel flow with the blade surface. Observations also show that in loose soil conditions at relatively low blade velocities the soil height increased over the blade, especially at the tip. This is due to a different failure characteristic occurring. Observation of soil flow shows that the soil is pushed forward ahead of the blade, then collects and builds up on the blade and then eventually with further forward movement flows over the top. This was only observed at blade velocities of 1 km/h. At velocities greater than 1 km/h investigated in this study, no noticeable bulldozing occurred; soil flowed over the blade. In general terms the affects of velocity on soil height over the blade tend to be inconsistent suggesting that increasing the blade velocity will not have a significant effect on soil height.

The values of soil in-transit height presented in Table 4-14 are the best available and will be used as a guide in the development of a soil displacement model. It is worth noting at this point that there was appreciable error in setting the depth of the blade. Blade height was zeroed when on the soil surface and then lowered 25 mm for the cutting depth. However depth was recorded by a ruler attached to the processor, and the depth carriage lowered by a manually operated hydraulic spool valve. It is, therefore, likely that blade cutting depth could be in error by 2-3 mm approximately 10 % or more, at this shallow working depth. When used at increased depths then this tolerance is more than adequate. It is for this reason that blade velocity is assumed to have an insignificant effect on soil height as the cutting depths may have varied by ± 2.5 mm, which is approximately the difference observed between different blade velocities. There was also noise present as vibration occurred on the laser mounting although firmly mounted to the processor, which became worse at increased speeds, accounting for approximately 2-5 mm of variation

It can be concluded that although velocity is unlikely to have a significant effect on soil height over the blade, increasing density and rake angle result in increased soil height.

4.6.5 In-transit height of soil over the blade

Section 2.8 investigated the work previously undertaken on soil deformation and flow over soil engaging blades. It resulted in identifying several workers who have developed theories for predicting soil rupture angle (β). Assuming soil flow is parallel to the blade surface as indicated by observations of video footage and laser measurements the breakout rupture angle can be calculated. Therefore, the depth of soil flowing over the blade (d_2) can be calculated, by adoption of a geometric approach detailed in Figure 4-29 and using the Equation expressed in Equation 4-1.

Depth of soil over the blade (d_2) $= \left[\dfrac{d_1}{\sin\beta}\right].\sin[\alpha+\beta]$ **{4-1}**

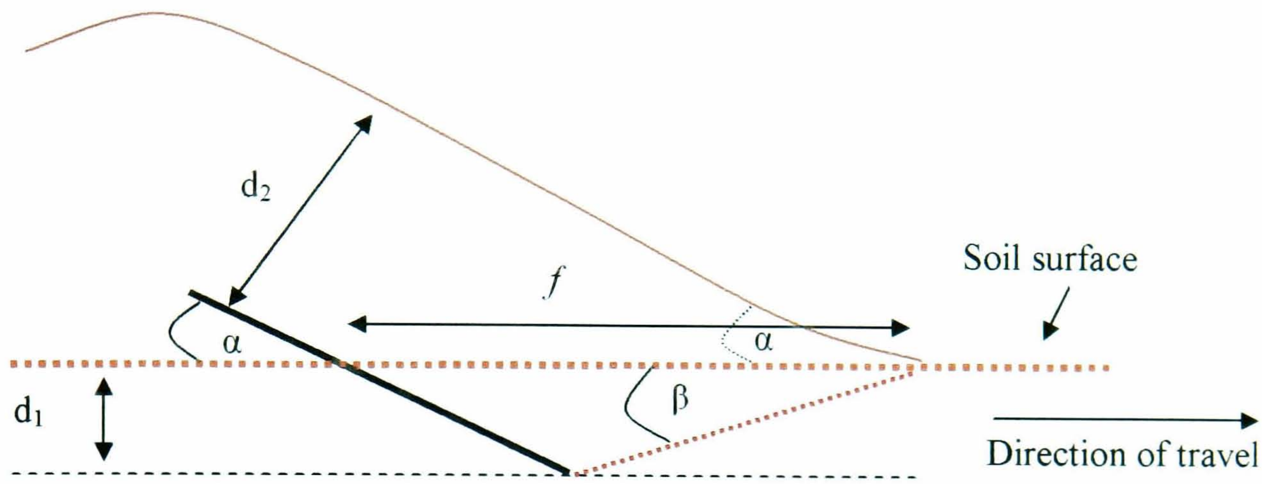


Figure 4-29 Soil depth over the blade

Crescent failure theory, could based on Equation 4-1 be used to predict the height over the blade, therefore results recorded during this study are compared to those of previous workers (Godwin & Spoor, 1977; Payne & Tanner, 1959; Hettaratchi & Reece, 1967), and the results are presented in Figure 4-30.

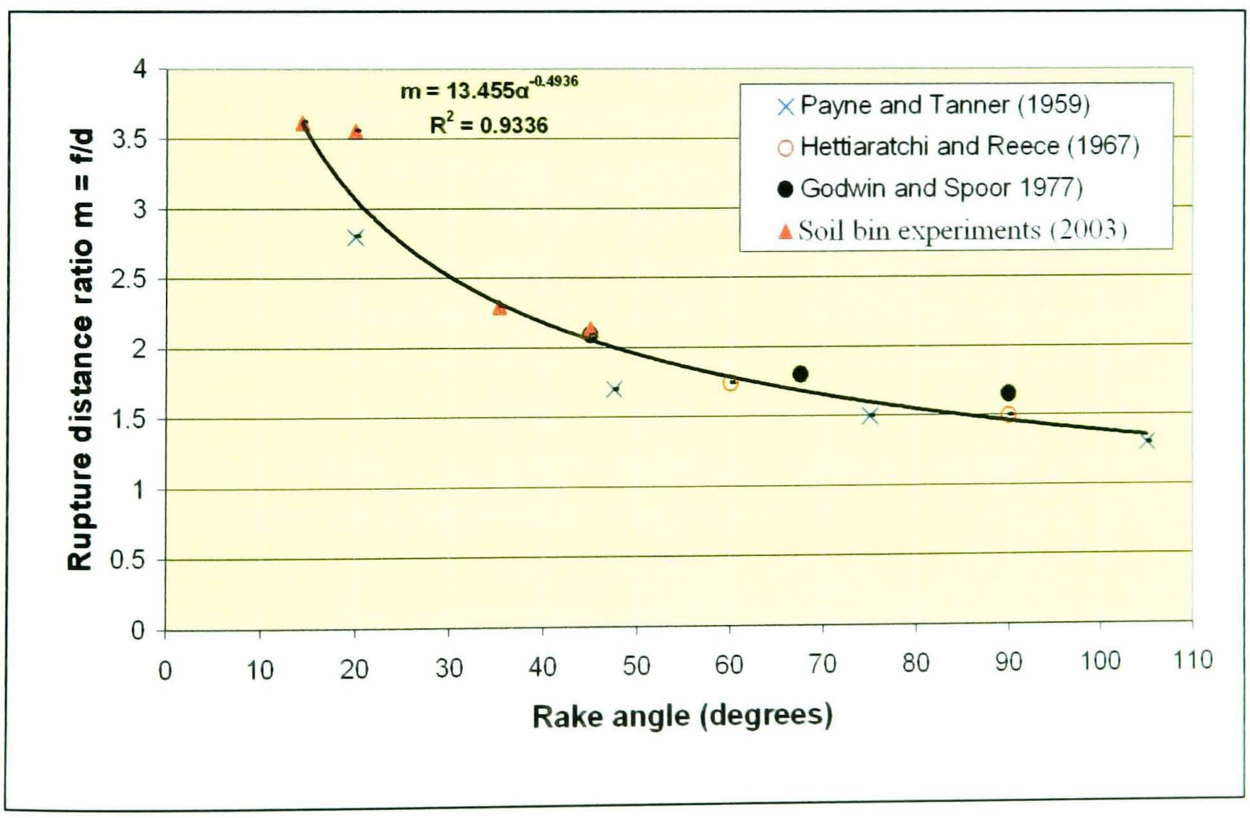


Figure 4-30 Experimental relationship between rupture distance and blade rake angle

It can be seen that results of crescent failure from this study are in agreement with previous work undertaken with narrow blades, indicating that this technique is robust for a variety of soil engaging blades. As rake angle decreases so rupture distance was found to increase, which is in agreement with Payne & Tanner (1959).

A power relationship has been fitted to the combined data set, to provide a prediction of the rupture distance ratio *m*, for a given rake angle (α). With a known rupture distance, and operating depth, the rupture angle can be calculated, and thus calculation of soil depth over the blade.

As reported, soil depth over the blade seemed to be independent of blade velocity, therefore, theories will be compared against mean recorded heights presented in Table 4-15.

Table 4-15 Mean recorded laser height for 0-20 and 0-45 blades in loose and dense soil

Sweep-rake / Density	**0-20** (m)	**0-45** (m)
Loose	0.043	0.066
Dense	0.039	0.057

Table 4-16 compares theories undertaken by previous authors reviewed in Section 2.8 presenting the values for rupture angle (β) and soil depth over the blade (d_2) based on the soil parameters in this study.

Table 4-16 Comparison theories of rupture angle and soil height

Workers	**Density**	**φ** (^{0})	**β when $\alpha = 20^0$** (^{0})	**Depth at $\alpha = 20^0$** (mm)	**β when $\alpha = 45^0$** (^{0})	**Depth at $\alpha = 45^0$** (mm)
Coulomb	General	33 - 37	28.3	39.4	24.2	57.0
Coulomb wedge	Dense	37	35.0	35.7	37.5	40.7
	Loose	33	35.0	35.7	40.0	38.8
Rankine	Dense	37	26.5	40.6	26.5	53.1
	Loose	33	28.5	39.2	28.5	50.2
Ohde	Dense	37	26.5	41.9	26.5	55.5
	Loose	33	28.5	39.2	28.5	50.2
Crescent failure	Dense	37	18.4	49.2	26.5	56.1
Kawamura	Dense	37	16.7	47.0	28.6	91.2

When comparing theoretical predictions of soil height in Table 4-16 the Coulomb equation has excellent correlation with recorded values in dense conditions. However the Coulomb equation predicts β for a general soil condition, rather than for loose or dense, but is the only theory that accounts for changing rake angle.

The crescent failure technique predicts well with a 45^0 rake angle but over predicts with a 20^0 rake angle. There is also no data available to develop a relationship in loose soil conditions as it would be extremely difficult to measure rupture failure. Kawamura's technique over predicts at both the 20^0 and 45^0 rake.

Ohde's approach has limits on its working range, which state that this technique will not work at rake angles less than $45\text{-}\varphi/2$, which have been used in this study.

Following analysis it is concluded that the most appropriate technique for predicting rupture angle and soil height above the blade is the approach adopted by Rankine. Reasonable correlation between recorded and predicted soil height was obtained and this simple approach makes it attractive to use in the prediction model.

4.7 Static soil profiling after blade disturbance

Profile analysis is important for a number of factors. It enables working depth to be checked in dense conditions, which can be cross referenced with the laser work detailed in Section 4.6 It enables density prediction in dense soil to be undertaken as the surface profile and excavated profiles are known providing a total disturbed area. Disturbed soil density in loose conditions can also be undertaken assuming a nominal working depth. Disturbed soil density is of major interest within the scope of the project as the only available technique so far has been that of the density rings described in Section 4.2.

There are several methods available to measure the static level of the soil surface following disturbance, ranging from manual to automatic laser measurement. In a review of current practice it was clear that laser profiling was the preferred method but at a relatively high cost, and would rely on a gantry system for the laser to track across the soil bin. This would involve substantial investment of time and money and, therefore, an alternative method was sought.

Current practice for soil profile measurement at Cranfield University, Silsoe was undertaken using an aluminium profile gauge but the resolution was too coarse for precise measurement, and extrapolation from the gauge was obtained through tracing and measurement of the traced profile.

4.7.1 Objectives

To develop a semi automated process, with low cost technology to enable accurate recording of soil profiles following disturbance by shallow working wide blades.

4.7.2 Experimental design

The profile recording was undertaken following the bead displacement experiments therefore experimental design is the same as detailed in Section 4.4.2.

4.7.3 Apparatus and procedure

The new procedure for recording profiles employs the use of a wooden dowel profile gauge, a digital camera, and computer software.

The profile gauge, as shown in Figure 4-31 is of conventional design, consisting of a series of dowels each with a nominal diameter of 9 mm. The dowels are located between two vertical supports and are clamped by spring pressure either end of the gauge. The springs act upon an aluminium cross member, which presses a 15 mm thick strip of foam between the aluminium and the dowel. The foam is required to prevent the dowels from moving whilst being clamped, which takes account of any deviations in dowel diameter and aluminium cross member thickness.

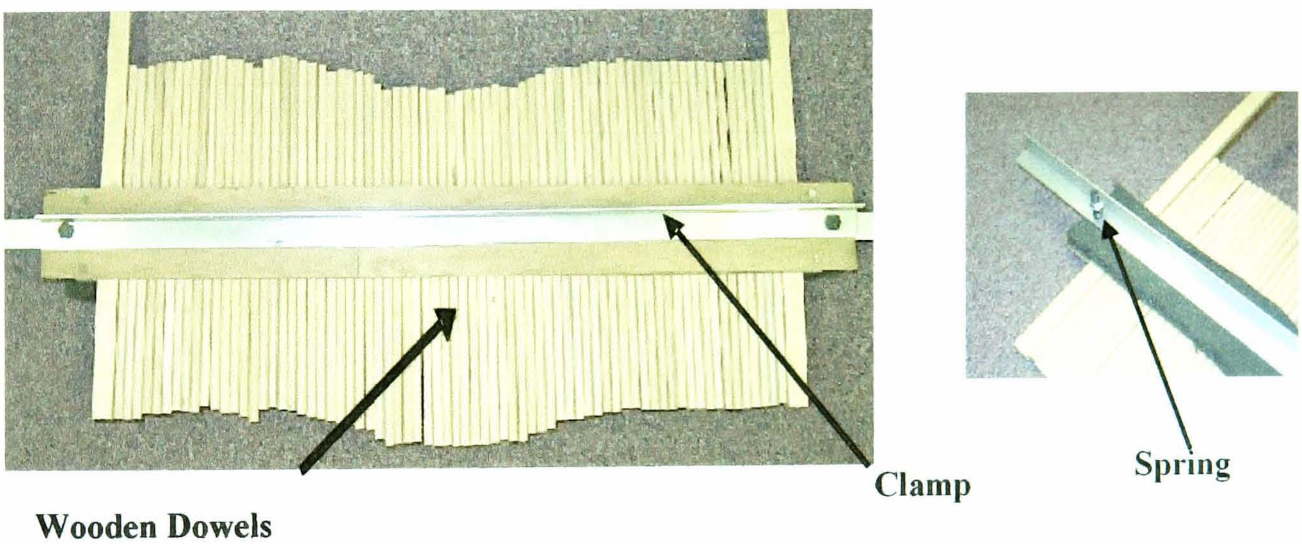


Figure 4-31 Dowel profile gauge

The profile gauge is held above the soil profile and the spring clamps are depressed. Upon depression the dowels are released thus tracing the surface profile. Once the dowels are all in contact with the profile the clamps are released and the profile gauge is removed. The gauge is then placed in a set location directly below a digital camera where an image of the profile gauge is taken against a contrasting background.

After the photos are downloaded, they are manipulated in Adobe Photoshop. A threshold is applied to each image to obtain a black and white profile. The adjusted image is then cropped and saved. Using Software from the image analysis toolbox in Matlab® the images are split into vertical columns and the height of each column calculated providing a series of data points representing the profile. These data points are transferred to Excel where a macro produces a graphical representation of the profile and conducts some analysis. The process is shown illustratively in Figure 4-32.

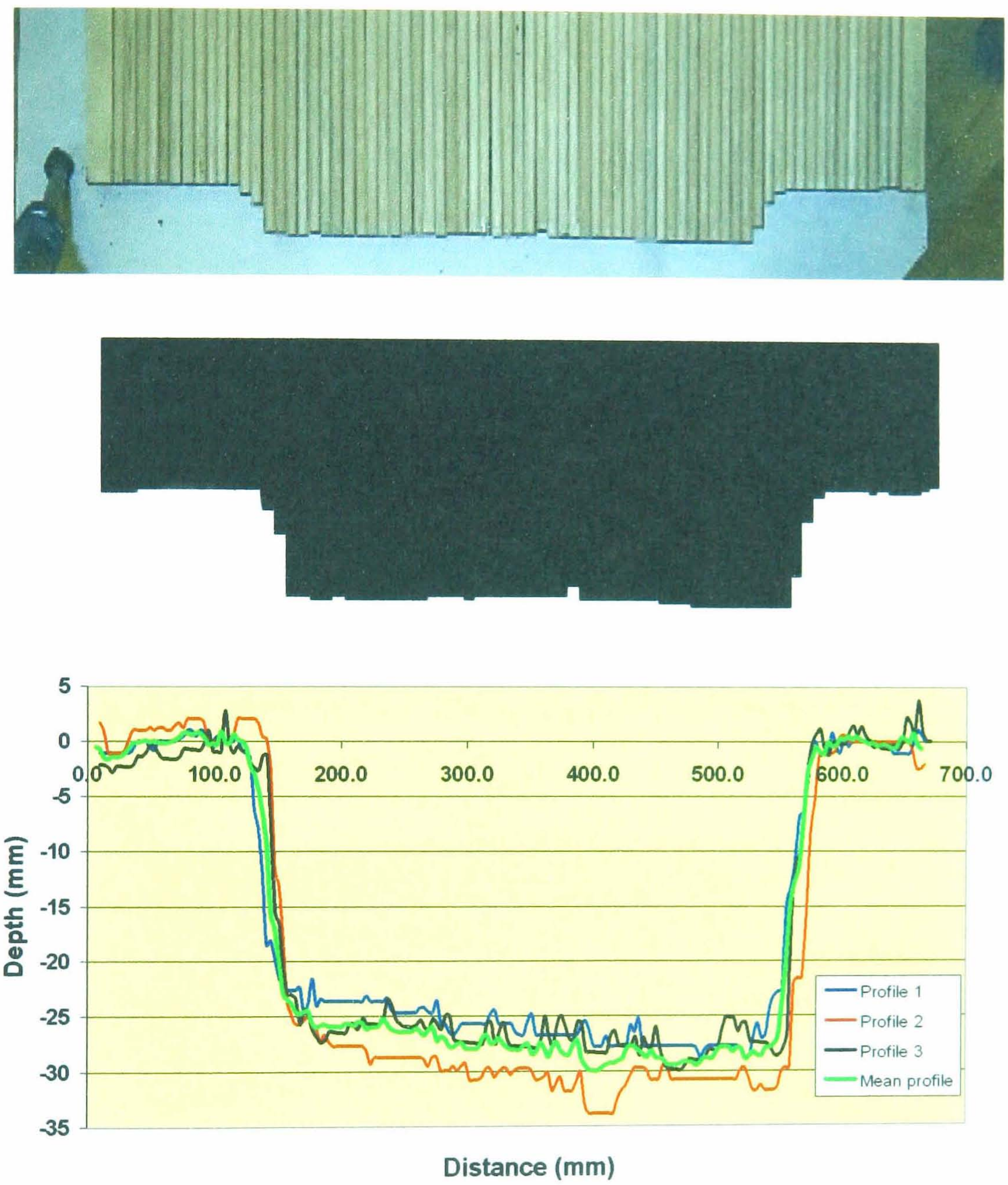


Figure 4-32 Profile analysis from gauge to Excel based on 45^0- 45^0 blade at 1.35 m/s

From soil profile to Excel takes less than five minutes for each image. The Excel macro was developed to manipulate the data to correct for any camera skew when taking the photo to ensure the profile is horizontal. Once the data has been plotted, a visual check of the profiles can be undertaken, Figure 4-32 represents the excavated profiles for a 45^0- 45^0 blade operating in dense soil conditions at a speed of 1.35 m/s.

The top soil profile is taken after each run, as well as the excavated soil profile, to establish the volume of soil moved, which is later used for density and leakage calculations.

4.7.4 Results

A summary of the mean profiles in dense soil are presented in Figures 4-33 and 4-34.

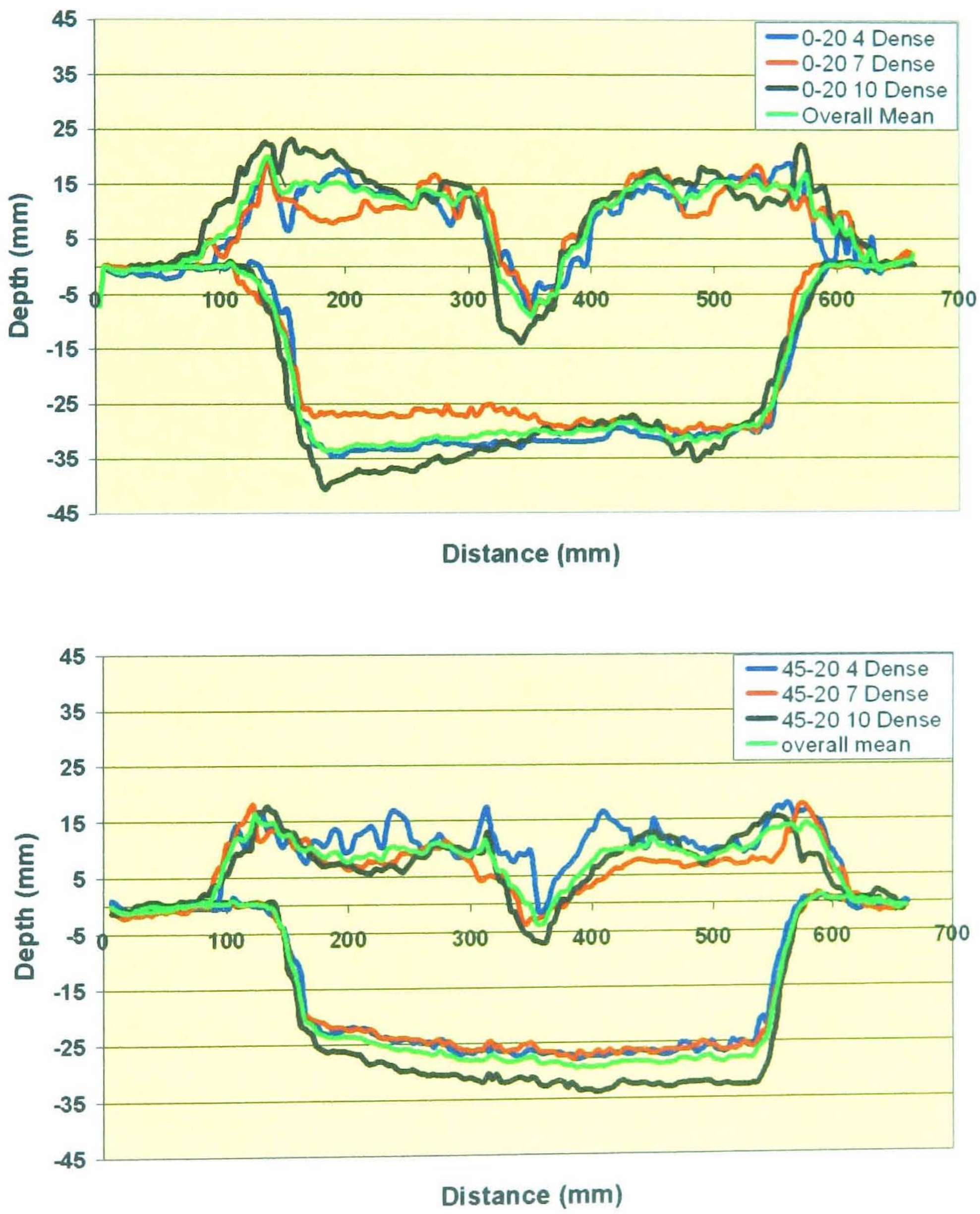
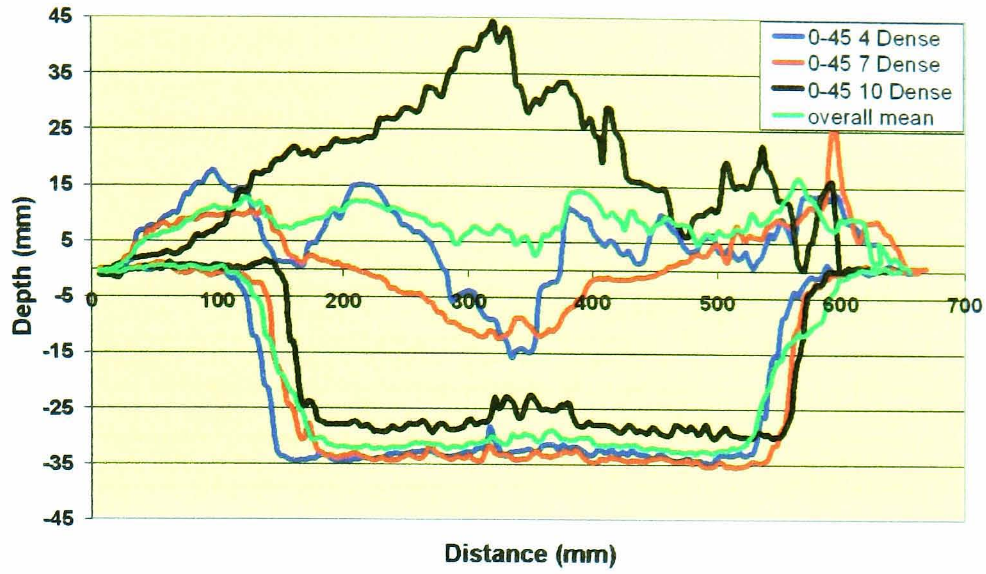


Figure 4-33 Static surface and excavated profiles in dense soil conditions (20^0 rake)



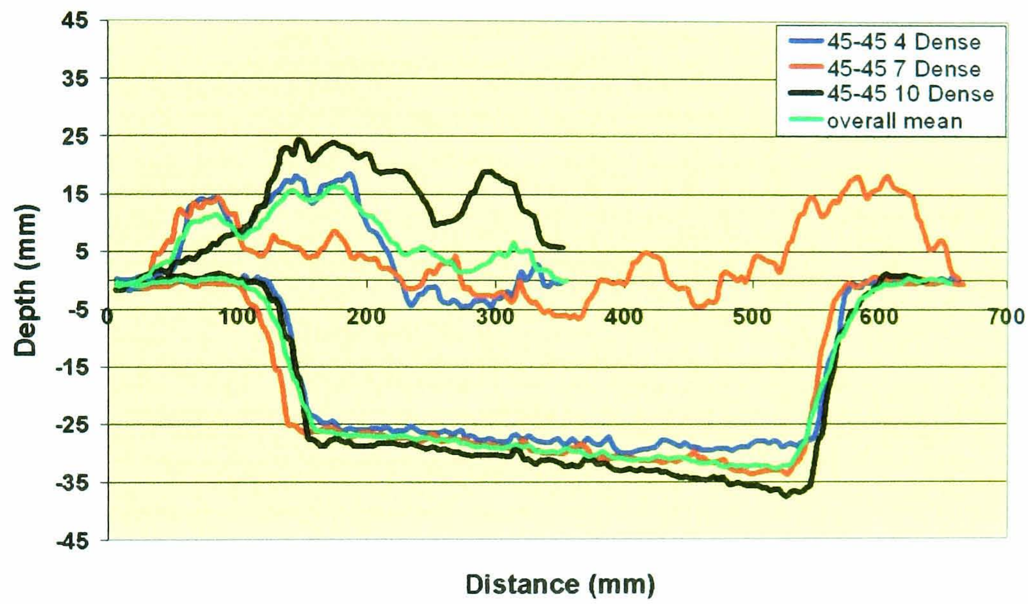


Figure 4-34 Static surface and excavated profiles in dense soil conditions (45^0 rake)

From the figures above it can be seen that the excavated profile depth is often in excess of the target depth of 25 mm. This error was due to the process of setting depth as reported in Section 4.6.4. The excavated base profile is also not horizontal, thus suggesting that the blade was not parallel to the soil surface, this may partially be due to blade deflection as well as misalignment in the processor depth carriage.

In loose conditions the disturbed soil could not be excavated, as it was impossible to determine the interface between undisturbed and disturbed soil. Therefore Figures 4-35 and 4-36 present surface profiles only.

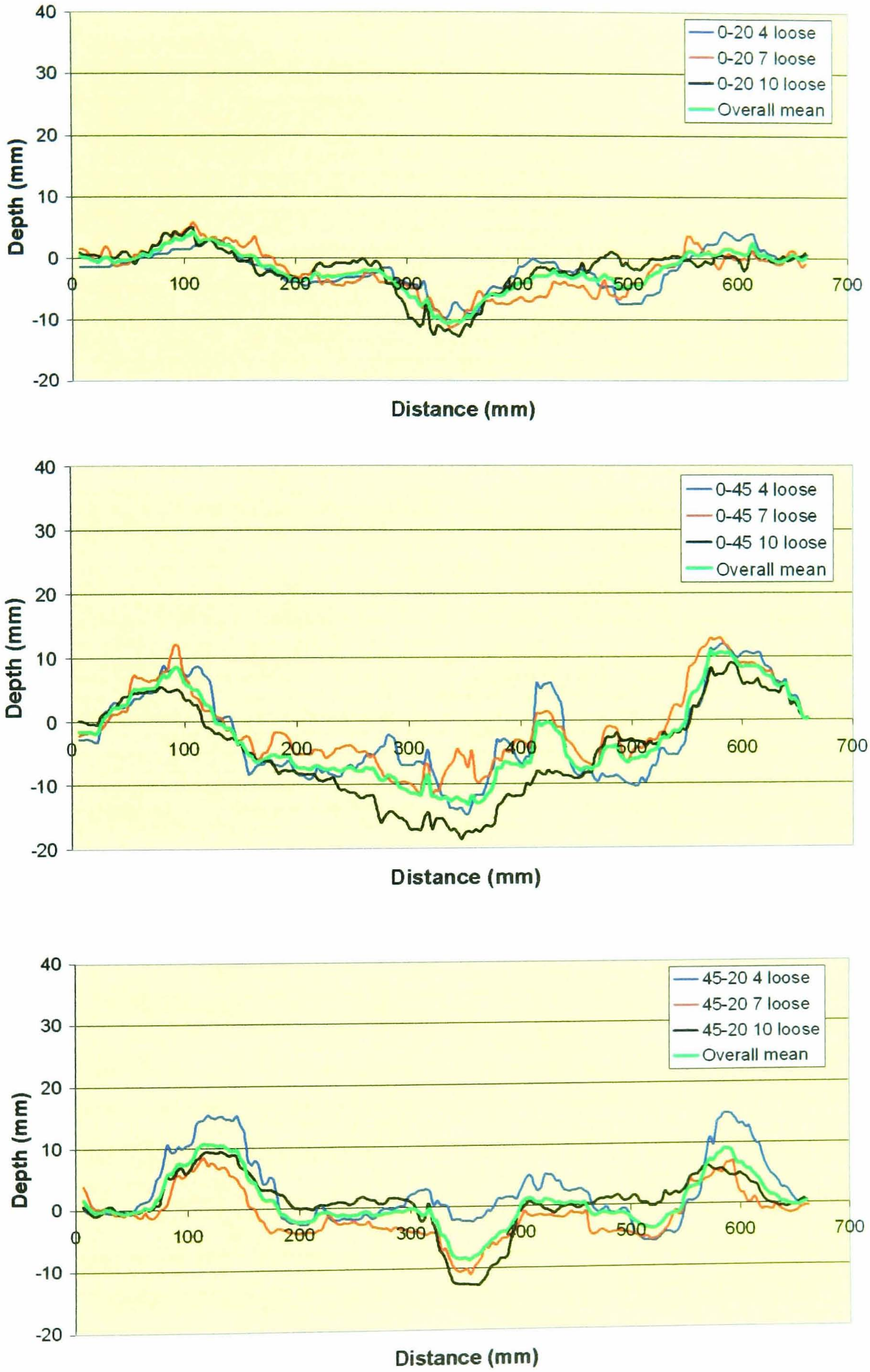


Figure 4-35 Static surface profiles in loose soil conditions

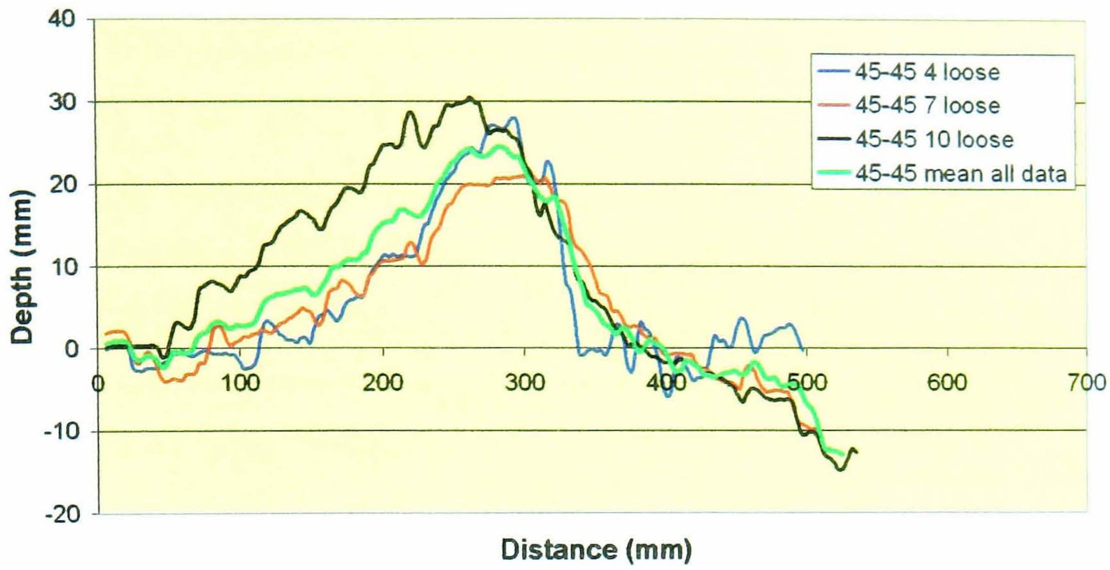


Figure 4-36 Static surface profiles in loose soil conditions continued

Only half of the surface profile for the 45-45 blade was recorded as displacement was too great to measure the overall profile, it was therefore assumed to be symmetrical about the centre line.

The profile analysis has shown that blade velocity in the range investigated throughout the experiments in loose and dense soil has no significant effect on the soil profile following disturbance. This can be seen in figures above, as the blue, red and black lines represent changing blade velocity and the green line is the mean profile over the velocity range considered.

It was apparent that a change in soil density occurred as the disturbed surface height in dense soil conditions was significantly different to the undisturbed height, which is not purely due to soil mass re-arrangement. The surface height change is mainly through the loosening of the soil following tillage, a view supported by Hanna *et al.* 1993[a]. Table 4-17 details the change in density following disturbance from the four blades. It can be seen that in dense soil the mean density decreases by 58% across all blades, with disturbed densities being similar, independent of blade geometry. In loose soils, it can be seen that there is a very slight increase in density, but it can be assumed that density with initial loose conditions remains unchanged. These findings are contrary to those discussed in Section 4.2.2 where the density ring technique resulted in final densities of 0.87 x initial dense and 0.95 x initial loose, the readings obtained in disturbed soil were erroneous due to the technique employed. When entering the density ring into disturbed soil the exact location of the density ring will vary the result. Soil break up in dense soil often occurs in plates, if the density ring is pressed in the centre of the plates it would be possible to get the same density as initial conditions. In loose soil conditions the technique is more reliable as the soil is uniform, however pressure applied to the soil during the sampling process could increase the density. It is therefore concluded that this popular technique gives an accurate prediction of soil before disturbance, but profiling is a more accurate way of predicting the disturbed densities.

Table 4-17 Change in density with changing blade geometry in dense and loose soil.

Sweep-rake	Dense	Sweep-rake	Loose
0-20	0.558	0-20	1.13
0-45	0.582	0-45	1.17
45-20	0.573	45-20	0.96
45-45	0.595	45-45	0.91
Mean	**0.577**	**Mean**	**1.04**

It was apparent from observation of the static profile graphs that soil leakage or lateral movement occurred in dense and loose conditions represented by an increase in surface height at the extremities of blade. The amount of soil displacement over the edge of the blade was determined by calculating the volume of soil above the initial soil surface, outside the 400 mm wide cutting zone. The results presented in Table 4-18 suggest that increases in both rake and sweep angle, increase lateral soil movement.

Table 4-18 Leakage factors

Sweep - rake	Dense	Loose
0-20	6.0%	3.0%
0-45	6.8%	12.7%
45-20	8.1%	10.3%
45-45	10.2%	16.7%

The profiles provide an additional use in that actual cutting depth can be measured by comparing excavated depth. The target depth was 25 mm but it was apparent following excavation that this was not achieved all of the time. Section 4.6.4 discusses the problems associated with accurate depth setting and the data in Table 4-19 shows the difference in target depth of 25 mm compared to measured cutting depth by the laser line and measured cutting depth by the profiles.

For consistency the profile depth measurement given in Table 4-19 was taken at the same location where the laser was located to provide like for like comparisons. This could only be undertaken in dense soil conditions where excavation of the profile was possible.

Table 4-19 Comparison of blade depth using profile gauge and laser techniques

Sweep -rake	Target velocity (km/h)	Profile (mm)	Laser (mm)	Difference (mm)
0-20	4	33	20	13
0-20	7	27	19	8
0-20	10	33	25	8
45-20	4	25	21	4
45-20	7	24	26	-2
45-20	10	30	30	0
0-45	4	33	28	5
0-45	7	34	26	8
0-45	10	28	27	1
45-45	4	27	23	4
45-45	7	28	24	4
45-45	10	30	26	4

Generally the laser under predicted depth by approximately 5 mm, but it is known that there was considerable noise in the data collection of the laser. Noise came from several sources, but in particular the vibration of the laser mounting to the processor which resulted in +/- 5 mm variations, which increased with speed. The soil surface also had variations along the length of the bin of approximately 2-3 mm, this combined with measurement and calibration error could account for over 5 mm of error.

4.8 Scratch lines to identify soil trajectory over the blade at the soil blade interface

All of the experimental measurement techniques have concentrated on measuring surface flow and displacement. It was decided that the flow of soil over the blade at the blade soil interface should also be recorded to ensure that flow at both levels acted in a similar manner.

4.8.1 Objectives

To record the soil flow at the soil blade interface, and evaluate if there is any difference between flow at this interface and surface flow.

4.8.2 Experimental design

The same four blades as detailed in Section 4.4.2 were investigated in target loose and dense soil conditions of 1300 kg/m^3 and 1500 kg/m^3 respectively. The blades were operated at target velocities of 4 km/h and 10 km/h.

4.8.3 Procedure

The procedure for recording the trajectory of soil over the soil blade interface following reviews in Chapter 2, resulted in a similar technique employed by previous workers (Sohne, 1956; Suministrado *et al*, 1990). Scratch lines were recorded by painting the blade surface and measuring the angle of the scratches in the paint, as soil scratches on the blade were not clear enough for accurate measurement.

The technique employed during this study involved coating the blade in a copper sulphate (Cu SO_4) solution to enhance the scratch lines made by the soil. The blade surfaces were polished with a medium grade wet and dry paper, ensuring polishing was perpendicular to the blade travel, so that polish lines would not be confused with marks left from the soil. After the surface was cleaned and dried, the copper sulphate (Cu SO_4) solution was liberally applied to the blade surface, and allowed to dry. This left the blade surface with a thin coating of copper as shown in Figure 4-37.

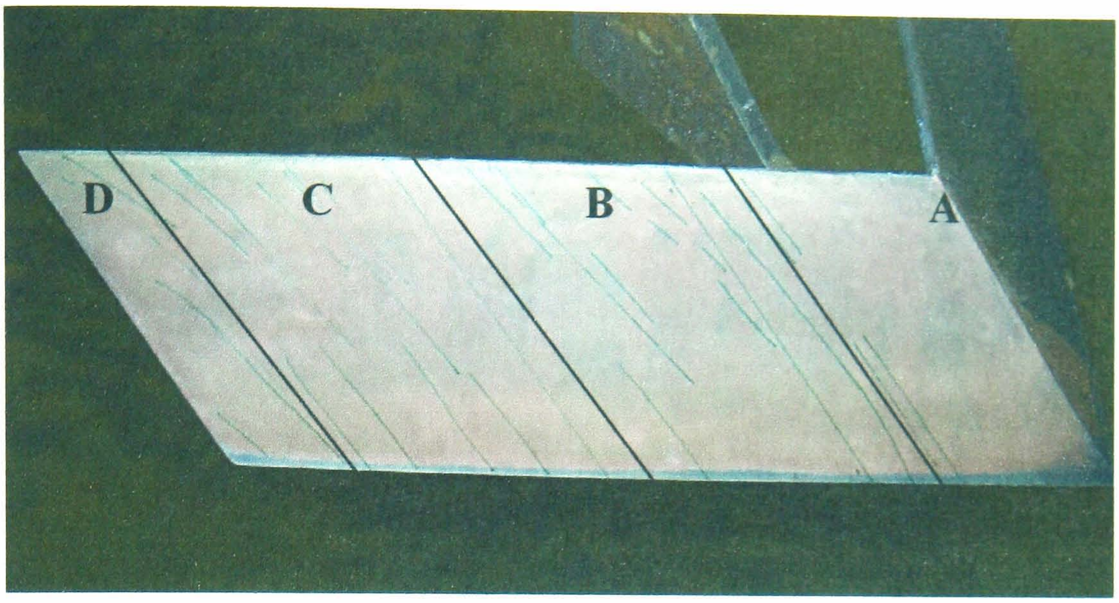


Figure 4-37 Scratch lines over a 45^0 sweep and 45^0 rake

The blade was split into four sections, A through to D to examine the effects along the blade. The scratch angles in section D, were noticeably increased when compared to the other sections due to the end effects of the blade, and were therefore not grouped with the data in the other sections. The mean angles of the enhanced scratch lines (traced with ink for clarity) were measured and are presented in Table 4-20.

4.8.4 Results

It is clear from the results presented in Table 4-20 that for a blade of shallow rake angle, blades 0-20 and 45-20, the scratch lines are in the direction of travel. Therefore the soil was lifted and simply flowed straight over the blade. Increasing the rake angle from 20^0 to 45^0 increased the mean divergence angle and the introduction of sweep further increased the soil divergence angle.

Table 4-20 Soil divergence angle over the blade by scratch identification

Velocity-density / Sweep-rake	4-Loose (^{0})	4-Dense (^{0})	10-Loose (^{0})	10-Dense (^{0})
0-20	0-1	0-1	0-1	0-1
45-20	0-1	0-1	0-1	0-1
0-45	0-7^0	5-10^0	5-7^0	0-10^0
45-45	5-15^0	10-20^0	9-15^0	4-15^0

Blades with 20^0 rake angles would have less lateral flow as the adjacent soil surface would act as a wall to the soil preventing it from flowing to the side. When rake angle was increased to 45^0, then more of the sliding face was above the soil surface so the soil could freely travel off the blade. This is supported by the observations in the scratch technique as the first third of the blade scratch lines were in the direction of travel, then divergence of soil occurred. It was also observed that increasing blade velocity, did not alter divergence of soil over the blade which is supported by Sharifat & Kushwaha (1997) which reported increasing speed did not result in a change of lateral soil flow path on the blade.

Section 4.5 investigated the displacement of soil whilst flowing over the blade, by recording the displacement of pins. The angle of trajectory across the blade was calculated and presented in Table 4-12. For comparison purposes the scratch data presented in Table 4-12 combined with Table 4-20 is compared in Figure 4.21.

Table 4-21 Comparison of soil divergence angle over the blade

Velocity - density	**4 – Loose**		**4 – Dense**		**10 – Loose**		**10 - Dense**	
Sweep – rake	scratch	pin	scratch	pin	scratch	pin	scratch	pin
0/20	$0\text{-}1^0$	0.6^0	$0\text{-}1^0$	1.1^0	$0\text{-}1^0$	--	$0\text{-}1^0$	1.1^0
45/20	$0\text{-}1^0$	11.9^0	$0\text{-}1^0$	5.1^0	$0\text{-}1^0$	7.4^0	$0\text{-}1^0$	5.7^0
0/45	$0\text{-}7^0$	--	$5\text{-}10^0$	--	$5\text{-}7^0$	4.6^0	$0\text{-}10^0$	--
45/45	$5\text{-}15^0$	--	$10\text{-}20^0$	--	$9\text{-}15^0$	--	$4\text{-}15^0$	6.3^0

-- data unattainable

Although some data was unattainable due soil covering, comparisons can be made. The scratch and pin analysis both indicate that velocity does not significantly affect the divergence angle of soil over the blade, and increased rake angle, results in increased divergence angle, away from the blade centre line. Further support of the data is provided by Hanna *et al.* (1993[a]) whom concluded that a typical soil divergence angle over a swept blade is in the region of $0\text{-}5^0$.

The combination of pin movement over the blade from high speed analysis and scratch line recording each give a contribution to the trajectory of the soil as it passes over the blade. Although the information presented in Table 4-21 are obtained by two differing techniques they are mainly in agreement with each other except for the 45-20 blade where the pin data has larger values. However they provide a guide of soil divergence angle for the development of the prediction model detailed in Chapter 5. It can be concluded that for shallow working depths of 25 mm soil flow at the soil blade interface behaves in a similar manner to that of surface flow.

4.9 Conclusions

- Soil translocation over shallow working wide blades, was monitored and quantitatively and qualitatively assessed during soil bin experiments. The experiments were designed to record the physical parameters that result in soil displacement. The techniques employed had varying success, but when analysed in totality provides accurate data on the soil displacement process, which can be used to validate a prediction model.

- Bead displacement techniques provided an accurate and repeatable method of measuring overall soil displacement in the forward and lateral direction with reasonable confidence. The results showed that changes in soil density, velocity and rake angle significantly affected overall forward displacement, however only density and rake angle affected overall lateral displacement

- Further displacement information was obtained through the high speed video analysis. This technique was beneficial for several reasons: it enabled the velocity of soil to be obtained whilst flowing over the blade in real time, provided lateral and forward displacement of soil during the time on the blade and enabled the soil divergence angle to be measured. The results obtained indicated, soil velocity was always less than blade velocity and speed had no significant effect on soil displacement over the blade.

- The laser technique provided useful results into the in-transit soil height over the blade. The technique worked well at all blade velocities and changing soil conditions, although noise on the data increased in dense soil and at increased blade velocities. The measurement technique employed, although relatively time consuming provided useful results. Clarity of the laser line would have been improved if the high speed filming was not undertaken at the same time, as excessive light was required to ensure clarity of high speed camera images. However a compromise was required as it was important that both the high speed filming, and laser work were undertaken in conjunction.

- Soil profiling enabled the cutting depth in dense soil conditions to be obtained, as well as providing information to calculate the amount of lateral displacement and reductions in soil density. The technique was simple, effective and efficient, providing repeatable results. It also highlighted that profiling techniques provide much more accurate ways of obtaining density than that of the density rings. The results obtained by static soil profiling enabled an additional calibration to the laser work, where it highlighted that on average the laser measurements were under predicting by 5 mm.

5 Modelling soil translocation

Research throughout this project has indicated a lack of knowledge regarding soil translocation following disturbance by shallow working blades. Research into blade design and operation has primarily investigated the forces associated with different blades. Working depths, speed and geometry with regard to forces have received extensive reviews throughout the last century (Payne, 1956; Sohne, 1956; Payne & Tanner, 1959; O'Callaghan & Farrelly, 1964; Hettiaratchi *et al.*, 1966; Godwin & Spoor, 1977; McKyes, 1985; Wheeler & Godwin, 1996 to name but a few). However a greater understanding of soil translocation will enable shallow working blades to be designed and operated to control soil displacement.

This Chapter investigates the development of a mass flow soil dynamics model that can be used to predict the forward and lateral translocation of soil after disturbance from shallow working wide blades. The predictive model could be used to optimise a blade for a given row spacing. Geometry and blade velocity can be changed to either avoid crop damage by minimising soil displacement, or to achieve burial of weeds close to the crop by increasing soil displacement.

Throughout this Chapter the width of the leg has been minimised and effects due to the leg have been removed so that the blade is assumed to be of semi-infinite width. The importance of leg width and its effects on soil displacement are detailed in Section 4.3.

5.1 Modelling approach synopsis

The following summarises the approach taken in deriving the mass flow soil dynamics model. The model consists of two components, displacement over the blade and displacement through projection after soil leaves the blade. Figure 5-1 should be referred to for information on terminology.

Forward translocation: Soil flows in a quasi-static way up the blade sliding face (l), whilst decreasing in bulk density. At the top of the blade (point C), the soil has moved forward a small amount in the direction of travel (y direction). This is due to density change and the blade geometry as the sliding length of the blade is greater than the base length ($l/\cos\alpha$), leading to derivation of the first displacement component, that due to the blade.

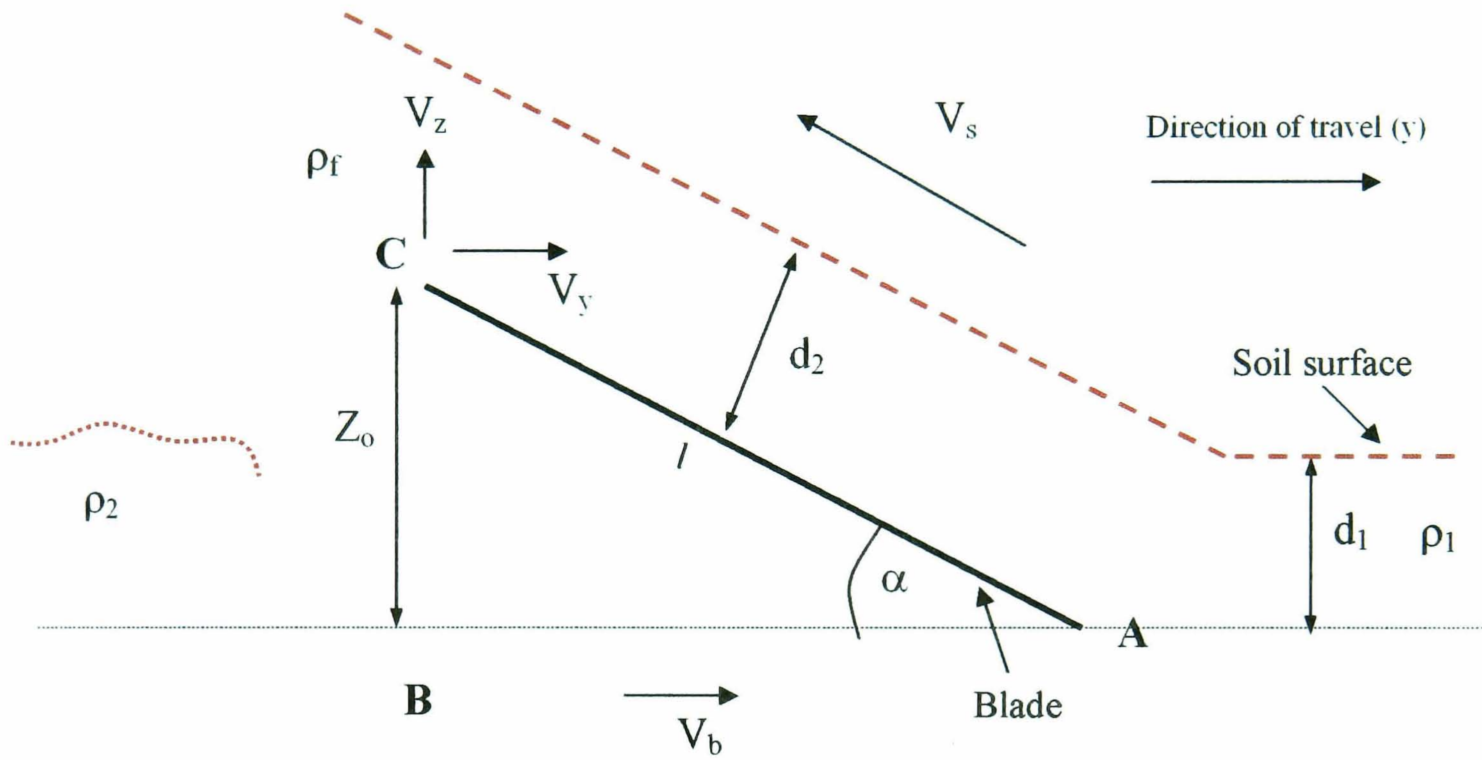


Figure 5-1 Blade nomenclature

At the rear edge of the blade (point C) the soil departs the blade with a vertical velocity (V_z) and a horizontal velocity in the direction of travel (V_y). The time in-flight is calculated by free fall with V_z and Z_o as initial conditions. The second component that of projection after leaving the blade, is calculated from the time in flight, and assumes V_y is constant during this time. It is also assumed that the soil comes to rest the moment it contacts the ground.

The Lateral Translocation Model is based on the previous model description and assumptions. Soil displacement occurring on the blade is accounted for by considering the soil divergence angle over the blade (ε) to predict the first component. Projected lateral displacement uses the same time in-flight calculated by free fall with V_z and Z_o as initial conditions but uses V_{sx} as the velocity of soil perpendicular to the direction of blade travel.

5.2 Model development

Soil displacement occurred in the direction of blade travel (y) and laterally perpendicular to the direction of travel, (x). Analysis of the high speed video footage indicated there were four main stages to the process as the soil passed over the blade.

1) Soil rupture, determining the height of soil as it flowed over the blade,
2) Change in soil conditions,
3) Flow path over the blade,
4) Projection through the imparting of blade speed to the soil.

An illustration of soil displacement is given in Figure 5-2 for simple blade conditions, (zero sweep angle).

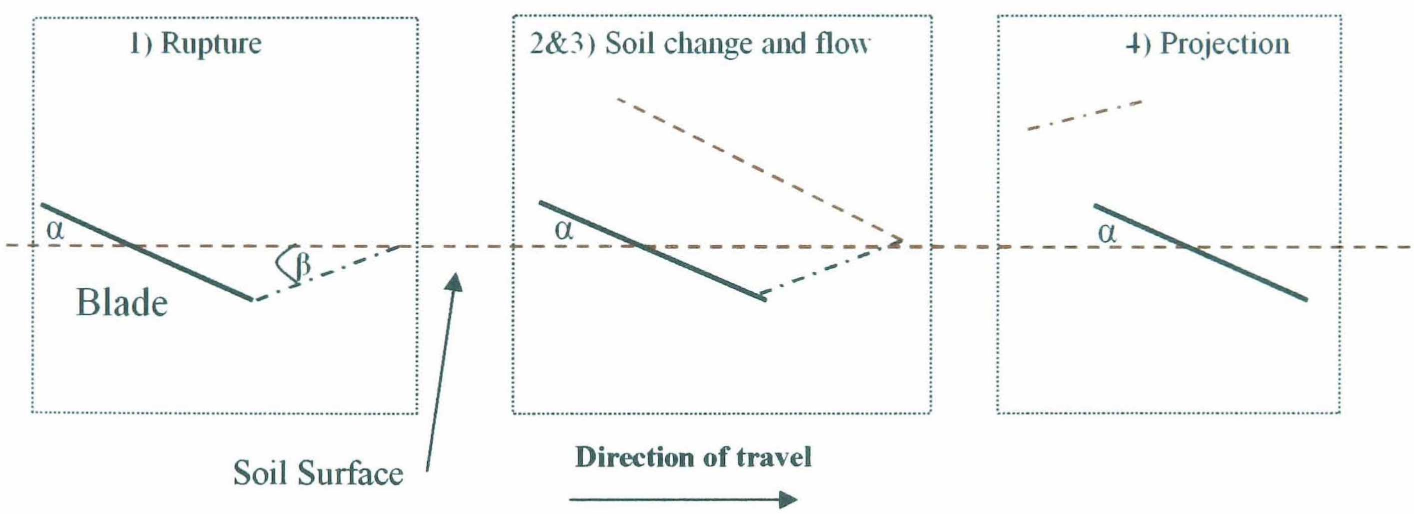


Figure 5-2 Modes of soil displacement and deformation

Initial soil conditions are forced to change as the blade passes through the soil, resulting in soil displacement. There is a zone of soil in front of the blade tip that is affected by the approaching blade, referred to as crescent failure zone (Payne, 1956) or the influence zone (Sharifat & Kushwaha, 1998). As the blade attempts to compress the soil in front of the blade it takes the path of least resistance, causing the soil to rupture (1) up from the tip of the blade to the soil surface at an angle beta (β).

The rupturing of the soil is then a catalyst to further soil displacement. As the soil ruptures, its volume increases (2) thus reducing its initial density (ρ_1). Soil then continues to travel over the blade and is lifted up at its new in-flight density (ρ_f) over the sliding face of the blade. The lifted soil now has a further distance to travel (3), as it has to go up and over the blade which in addition to blade velocity being imparted to the soil in the direction of travel accounts for an amount of soil translocation on the blade. Experimental data in Section 4.5 showed that the velocity of soil over the blade was less than the velocity of the blade, which is in agreement with conclusions made by Vasilkovskii (1970). The final mode of soil displacement is that of trajectory motion (4), as soil departs the blade.

For development of a mass flow soil dynamics model, analysis of soil displacement has been separated into two aspects, primarily the model is developed for simple blades, those without sweep angle, and secondly for complex blades, where sweep angle is introduced, which provides both forwards and lateral soil translocation.

5.3 Soil translocation over simple blades

Simple blades in the context of prediction are classified as blades without sweep angle, i.e. the cutting edge of the blade is perpendicular to the direction of travel. The sliding face is assumed to be linear with the only geometric change occurring through rake angle.

In order to develop a generic prediction model based on fundamental soil principles the modes of soil displacement as described in previous sections needed to be understood and expressed in terms of equations.

Nomenclature used throughout the model derivation can be found on Page xv. Figure 5-1 also illustrates the nomenclature for a blade with zero sweep angle.

5.3.1 Forward translocation over simple blades (FT_b)

It is known that a small proportion of forward soil displacement occurs as the soil is passing over the blade and two factors have been identified for the resultant displacement. Primarily, the soil has to travel a greater distance, as it travels over the face of the blade, and secondly the soil velocity will be different to that of the blade velocity, and therefore, it will take longer to travel up the sliding face of the blade. These two factors are expressed as follows:-

Time for a soil particle to travel the blade sliding face (l) $= \dfrac{l}{V_s}$

(V_s is the velocity of soil relative to and parallel to the blade)

Time for the blade to travel the blade base length (AB) $= \dfrac{l \cos\alpha}{V_b}$

(V_b is the velocity of the blade)

The difference in time (Δt) is: $$\Delta t = \frac{l}{V_s} - \frac{l\cos\alpha}{V_b}$$

Re-arranging: $$\Delta t = l\left(\frac{1}{V_s} - \frac{\cos\alpha}{V_b}\right)$$

The amount of soil forward translocation on the blade (FT_b) $= \Delta t \,.\, V_b$

Therefore: $$FT_b = l\left(\frac{V_b}{V_s} - \cos\alpha\right) \qquad \textbf{\{5-1\}}$$

The unknown in Equation 5-1 is that of soil velocity relative to the blade (V_s), which can be predicted by adopting a continuity of mass flow approach.

Mass flow on the blade ($\dot{m}_1$) = Mass flow off the blade ($\dot{m}_2$)

$$\dot{m}_1 = V_b.d_1.\rho_1.w$$

$$\dot{m}_2 = m_y + m_x \qquad \textbf{\{5-2\}}$$

Where m_y = Soil flow off the blade in the direction of motion
m_x = Soil flow perpendicular to the direction of blade motion
w = Blade width

m_x, represents lateral flow and for blades with zero sweep is referred to as leakage. Section 4.7 details the level of leakage observed with varying blade geometry and soil density.

$m_x = m_y.S_L$ Where S_L = Soil leakage factor

$$m_y = V_s.d_2.\rho_f.w$$

Substituting for m_l, m_y and m_x into Equation 5-2

Where:

$$V_b.d_1.\rho_1.w = V_s(d_2\rho_f w) + S_L V_s(d_2\rho_f w)$$

$$V_b.d_1.\rho_1.w = (1+S_L)V_s d_2\rho_f w$$

re-arranging $$V_s = \frac{V_b d_1 \rho_1}{d_2\rho_f(1+S_L)}$$ **{5-3}**

Where ρ_f is the density of soil over the blade.

The best estimate of in-flight density (ρf) over the blade is assumed to be that of disturbed density from the profile measurements detailed in Section 4.7. The volume increase from initial dense soil conditions of 1494 kg/m^3 was found to be approximately 58%, resulting in a disturbed density of 866 kg/m^3. Studies by Negi *et al.* (1976) investigating blades to inject liquid wastes into agricultural soils of density 1400.6 kg/m^3 found that disturbed soil increased in volume by 57.8 % at 101.6 mm and 59% at 152.4 mm depth. Therefore, for, development of a prediction model a factor of 0.58 times initial dense and a factor of 1 times for initial loose will be used to provide the values of disturbed density.

For initially dense soil, ρ_f dense = Initial soil density x 0.58

For initially loose soil, ρ_f loose = Initial soil density

The remaining unknown in Equation 5-3 is that of the depth of soil flowing over the blade (d_2). To calculate d_2 based on fundamental soil principles it is assumed that soil flows parallel to the blade surface; this assumption is supported by video observations of soil flow, and previous investigations undertaken by Elijah & Weber (1971). Therefore, based on the assumption of parallel soil flow, d_2 can be calculated using a geometric relationship based on cutting depth, (d_1), blade rake angle, (α) and soil shear plane angle, (β), expressed in Equation 5-4, and shown illustratively in Figure 5-3. β is reviewed in Chapter 2 and compared with experimental results in Section 4.6.5 where it was found to be best represented by Rankine's assumption:

$$d_2 = \left[\frac{d_1}{\sin\beta}\right].\sin[\alpha+\beta] \qquad \textbf{\{5-4\}}$$

where $\beta = 45 - \frac{\varphi}{2}$

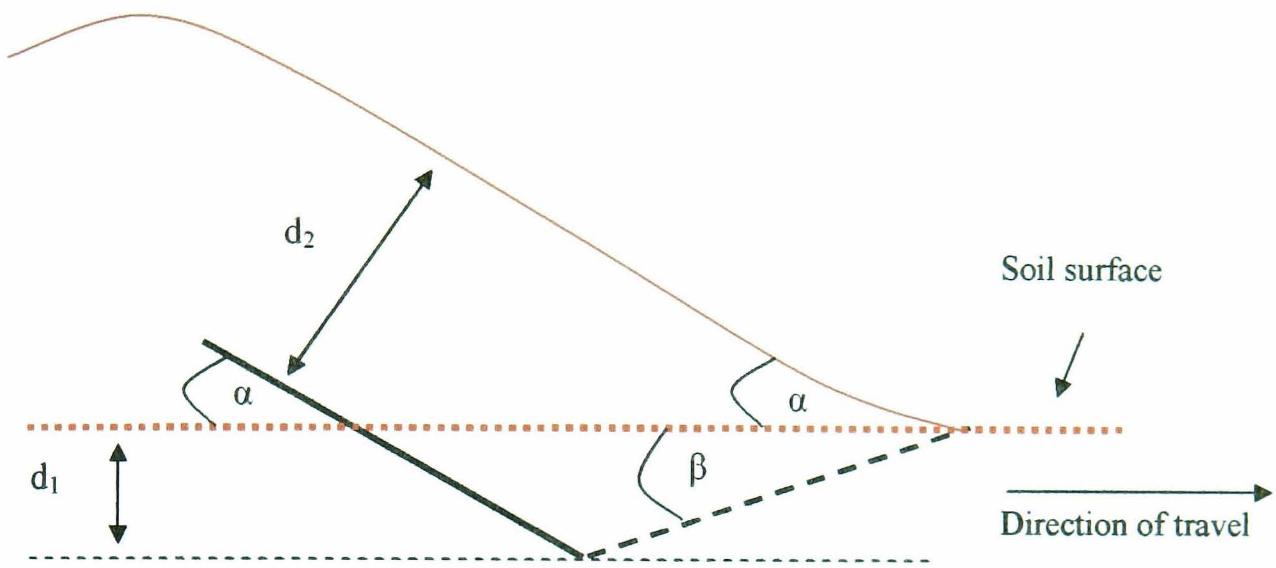


Figure 5-3 An illustration of in-transit height calculation

Substituting d_2 in Equation 5-3, enables the prediction of V_s (velocity of soil over the blade) to be undertaken. Figure 5-4 shows the relationship between predicted V_s and observed V_s in both loose and dense soil conditions. In dense soil the correlation is always within 20%, however, in loose soil, V_s under-predicts by up to 50%. The observed values for V_s were obtained by recording pin movement captured on video as described in Section 4.5. As discussed in Chapter 4, it was difficult to see the pin movement in loose soil conditions; therefore, there is considerable uncertainty in the observed values in loose soil. It was apparent that in loose soil the flow characteristics were different to that of dense soil. Soil tended to bulldoze in loose soil, building a mass in front of the blade, slowly moving and mixing towards the blade, until sufficient volume where it then flowed over the blade surface at increased velocity.

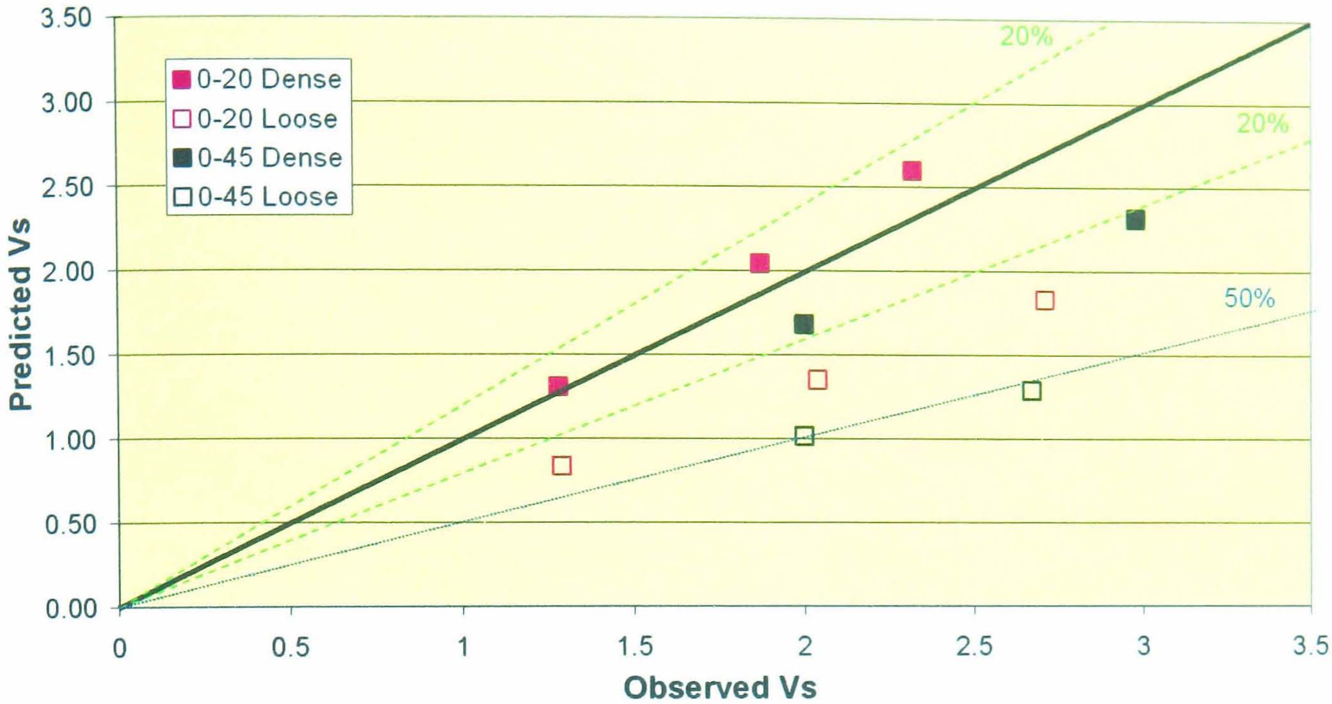


Figure 5-4 Predicted v observed V_s over simple blades.

5.3.2 Forward translocation due to projection (FTp)

Forward translocation due to projection is a function of V_y (horizontal velocity of soil relative to the ground, in the direction of blade travel) and the time of flight (t_f) of the soil particles, expressed in Equation 5-5.

$$FT_p = t_f . V_y \tag{5-5}$$

Time in flight is a function of the starting height (rear edge of the blade) and vertical velocity.

At time t the height of a soil particle Z (t) will be:

$$Z_{(t)} = Z_0 + V_z t - \int_0^t g dt \tag{5-6}$$

Where V_z is the vertical velocity of the soil relative to the ground as the soil leaves the blade.

$V_z = V_s \sin\alpha$

When a soil particle has just returned to the ground; $t = t_f$ and $Z_{(t)} = 0$

$$0 = Z_0 + V_Z t_f - \frac{g t_f^{\,2}}{2}$$

Re-arranging and solving the quadratic

$$0 = \frac{g t_f^{\,2}}{2} - V_z t_f - Z_o \qquad \{5\text{-}7\}$$

Using the formula for the solution of a quadratic equation: $ax^2+bx+c=0$

$$\text{i.e.: } x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \qquad \{5\text{-}8\}$$

Then for Equation 5-7 we have where $a = g/2$, $b = -V_z$ and $c = -Z_o$ the expression for predicting the time in flight of soil is expressed in Equation 5-9.

$$t_f = \frac{V_Z \pm \sqrt{V_Z^{\,2} + 2gZ_o}}{g} \qquad \{5\text{-}9\}$$

If the time in flight is known then the projected displacement can be calculated by multiplying the time in flight by the velocity of soil relative to the ground.

The velocity of soil relative to the ground in the direction of travel (V_y) is expressed in Equation 5-10.

$$V_y = V_b - V_s \cos\alpha \qquad \{5\text{-}10\}$$

Therefore translocation due to projection can be calculated by substituting Equations 5-9 and 5-10 into Equation 5-5.

$$FT_p = \left(\frac{V_Z \pm \sqrt{V_Z^{\ 2} + 2gZ_o}}{g} \right) V_b \text{ - } V_s \cos\alpha \qquad \textbf{\{5-11\}}$$

Therefore total forward translocation (FT_t) is a combination of forward translocation due to the blade combined with translocation due to projection as expressed in Equation 5-11. Combining Equations 5-1 and 5-11 we obtain:

$$FT_t = \left[\left(\frac{V_b}{V_s} - \cos\alpha \right) l \right] + \left[\left(\frac{V_Z + \sqrt{V_Z^{\ 2} + 2gZ_o}}{g} \right) V_y \right] \qquad \textbf{\{5-12\}}$$

Where:-

$$V_s = \frac{V_b . d_1 . \rho_1}{d_2 . \rho_f . (1 + S_L)}$$

$$d_2 = \left[\frac{d_1}{\sin\beta} \right] . \sin\left[\alpha + \beta\right]$$

$$\beta = 45 - \frac{\phi}{2}$$

$$V_y = V_b - V_s \cos\alpha$$

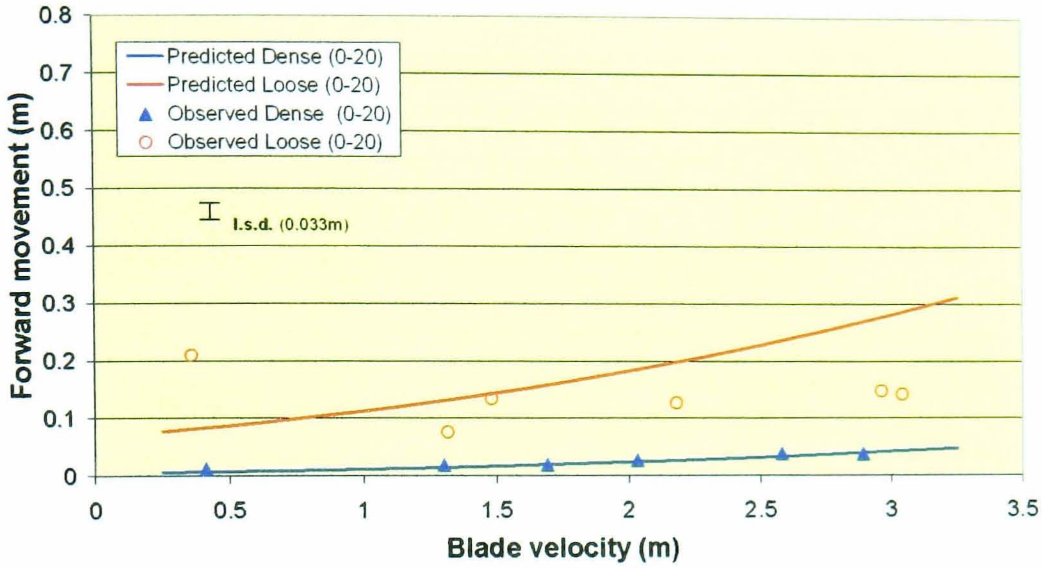
$$V_z = V_2 \sin\alpha$$

ρ_f loose = ρ_1 loose

ρ_f dense = ρ_1 . 0.58 dense

Figure 5-5 presents the predicted forward displacement of soil over a simple blade with that of observed values during experimentation, based on Equation 5-12.

5.3.2.1 Predicted forward displacement



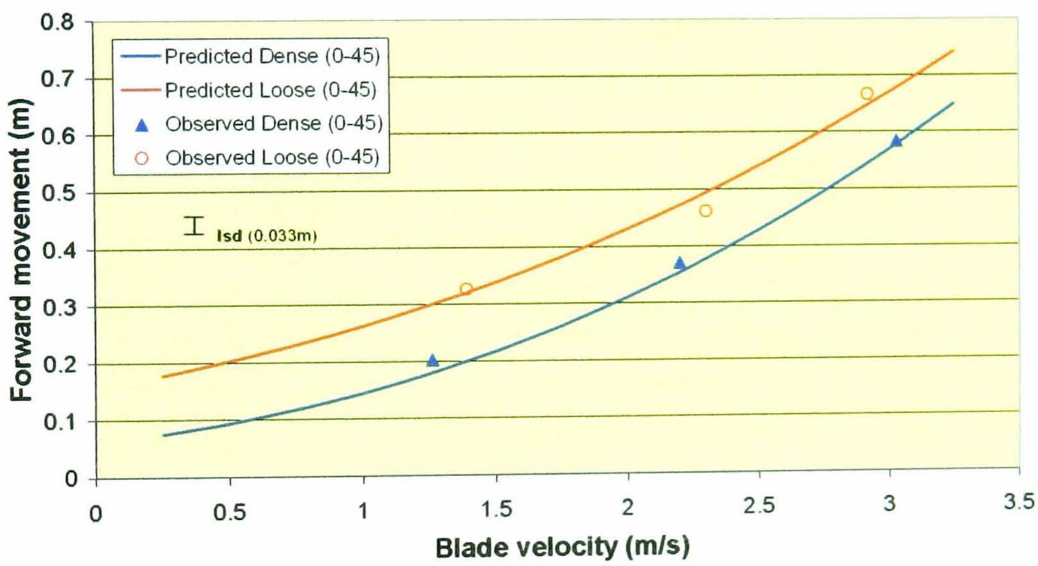


Figure 5-5 Forward displacement over simple blades predicted v observed

Figure 5-5 presents the forward displacement of soil over shallow working simple blades for 20^0 and 45^0 rake angles in dense and loose soil conditions. It can be seen that at the 45^0 rake angle the prediction model has excellent correlation with observed values. At 20^0 rake angle the model shows good correlation in dense soil but correlation is not as good in loose soil conditions. This can be explained by the flow characteristics in loose soil; the soil tended to bulldoze ahead of the blade, which would explain the high value at low blade velocities.

It can also be seen that for a 20^0 rake angle blade that blade velocity shows no significant effect with increasing forward displacement, but density has a significant effect. At a rake angle of 45^0 both density and velocity significantly increased forward displacement.

Figure 5-6 shows the overall correlation between predicted and observed soil displacement with variations in blade velocity, rake angle and soil density. The model predicts within 10% for the 45^0 rake angle blades in both dense and loose soils. With a rake angle of 20^0 the model predicts within 20% for dense soils but prediction error increases to 50% in loose conditions. The model over predicts the forward displacement occurring in loose soil conditions with the 20^0 rake angle. At low blade velocities of 0.36 m/s and 0.41 m/s under prediction occurs for the 0-20 blade in loose and dense conditions.

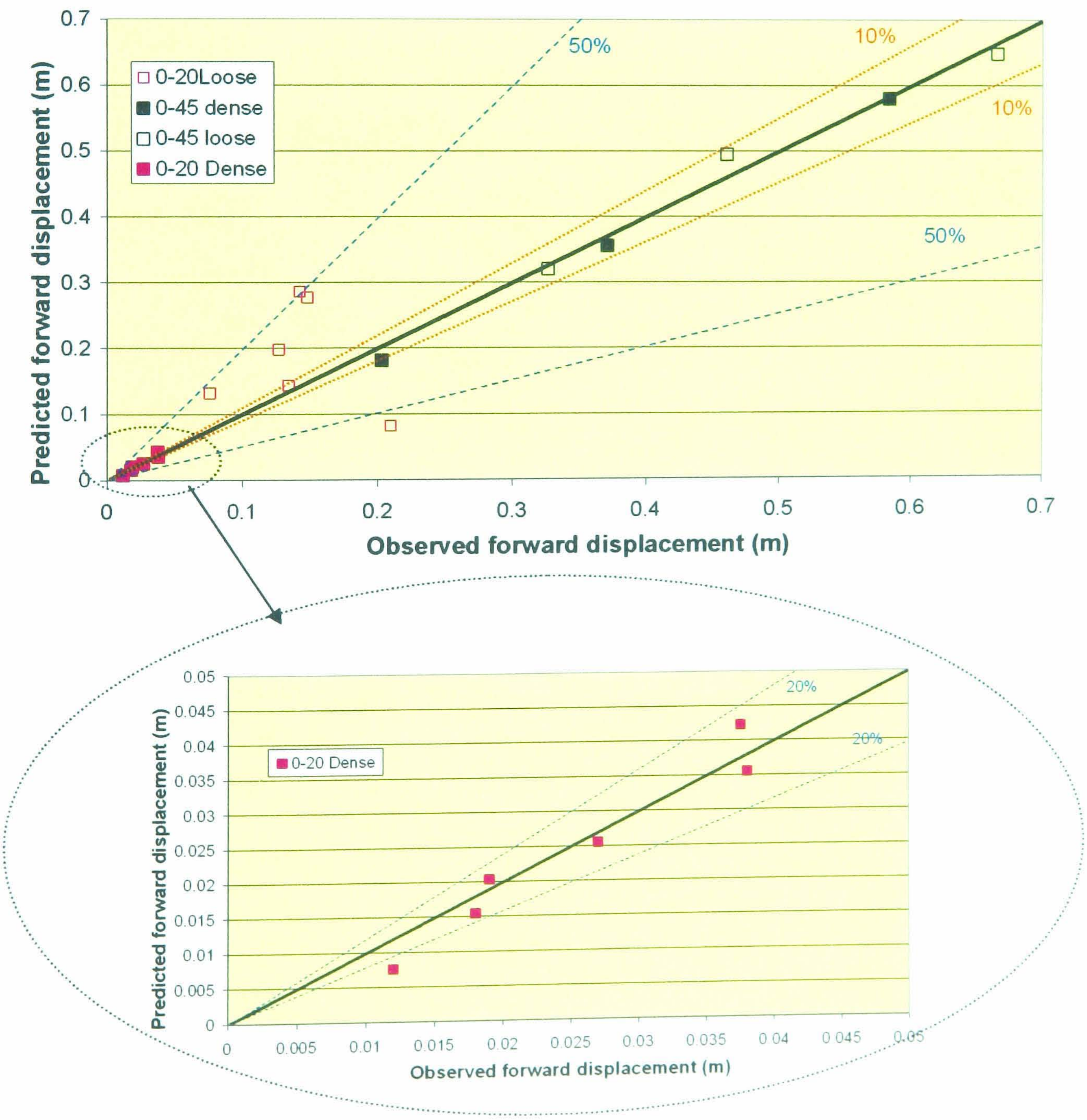


Figure 5-6 Predicted V observed forward displacement over simple blades

5.4 Soil translocation from complex blades (introduction of sweep)

Rake angle (α) in Equation 5-1 refers to the blade rake angle in the direction of motion. However when sweep angle (ψ) is introduced the blade has an effective rake angle (δ) and effective sliding face length (l') in the direction of motion due to changes in geometry. Therefore the true rake angle and sliding length taking account of sweep angle should be used as derived:

The following approach has been taken to find the effective rake angle (δ) and effective sliding face length (l') of a swept blade.

Consider three orthogonal axes O_x, O_y and O_z which are intersected by the upper blade face at points A, B and C, respectively, as illustrated in Figure 5-7.

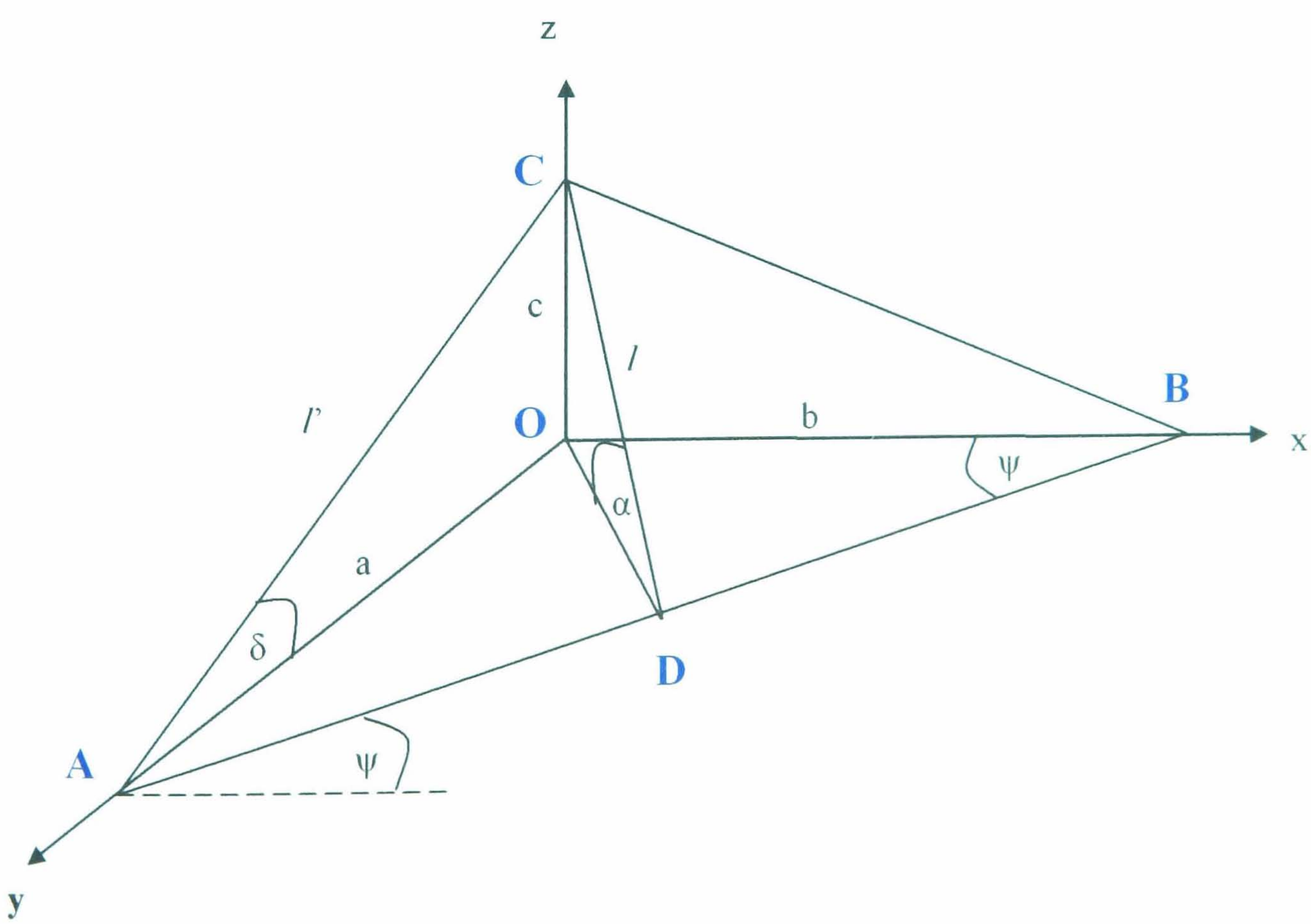


Figure 5-7 Effective rake angle (δ) and sliding length (l') of a swept blade

Let OA = a, OB = b and OC = c and let the effective rake angle $O\hat{A}C = \delta$. If a line OD is drawn in the Oxy plane perpendicular to the line AC, then the true blade rake angle, α, is the angle $O\hat{D}C$. the sweep angle, ψ, is the angle made by the line AB with the axes O_y, i.e. It is the angle $O\hat{B}A$.

To find the angle δ

1) from Δ OAB : $\frac{a}{b} = \tan\psi$ i.e. $a = b\tan\psi$

2) from Δ OAC : $\frac{c}{a} = \tan\delta$ i.e. $c = a\tan\delta$

3) from Δ OCD : $\frac{c}{OD} = \tan\alpha$ i.e. $OD = \frac{c}{\tan\alpha}$

4) from Δ OBD : $\frac{OD}{b} = \tan\psi$ i.e. $OD = b\sin\psi$

5) from (3) and (4) $\frac{c}{\tan\alpha} = b\sin\psi$

Therefore: $c = b\sin\psi\tan\alpha$

from (2) $\tan\delta = \frac{c}{a}$

and from (1) and (5): $\tan\delta = \frac{b\sin\psi\tan\alpha}{b\tan\psi}$

Rearranging: $\tan\delta = \cos\psi\ \tan\alpha$ **{5-13}**

The effective sliding length (l') with the effective rake angle is derived as follows:

$$c = l \sin \alpha$$

$$\frac{c}{l'} = \sin \delta$$

$$\frac{l \sin \alpha}{l'} = \sin \delta$$

re-arranging
$$l' = \frac{l \sin \alpha}{\sin \delta} \qquad \text{\{5-14\}}$$

5.4.1 Translocation occurring from complex blades

Equation 5-1 for soil translocation over a simple blade has now been modified to cater for complex blades with the introduction of sweep as expressed in Equation 5-15

$$FT_b = l'\left(\frac{V_b}{V_s'} - \cos \delta\right) \qquad \text{\{5-15\}}$$

Where V_s' is the velocity of soil relative to and parallel to the blade in the direction of motion, over a swept blade.

The following derivation continues in a similar approach to that for simple blades, but equations are modified to cater for effective rake and sliding length.

Mass flow on the blade ($\dot{m}_1$) = Mass flow off the blade ($\dot{m}'_2$) **{5-16}**

$$\dot{m}_1 = V_b.d_1.\rho_1.w$$

$$\dot{m}'_2 = \dot{m}'_y + \dot{m}'_x \qquad \text{\{5-17\}}$$

Where w = distance between the blade centre line and tip perpendicular to the direction of travel.

N.B. m'_x, is now classified as lateral displacement of soil, rather than soil leakage.

The component of velocity in the horizontal direction V_{sx} is assumed to vary with V_s', the sin of the sweep angle (ψ) and a factor (e) representing soil deflection in the horizontal direction.

$$V_{sx} = e\, V'_s \sin\psi \qquad \textbf{\{5-18\}}$$

Soil velocities on the blade resolved parallel to the direction of motion and horizontally are depicted below:

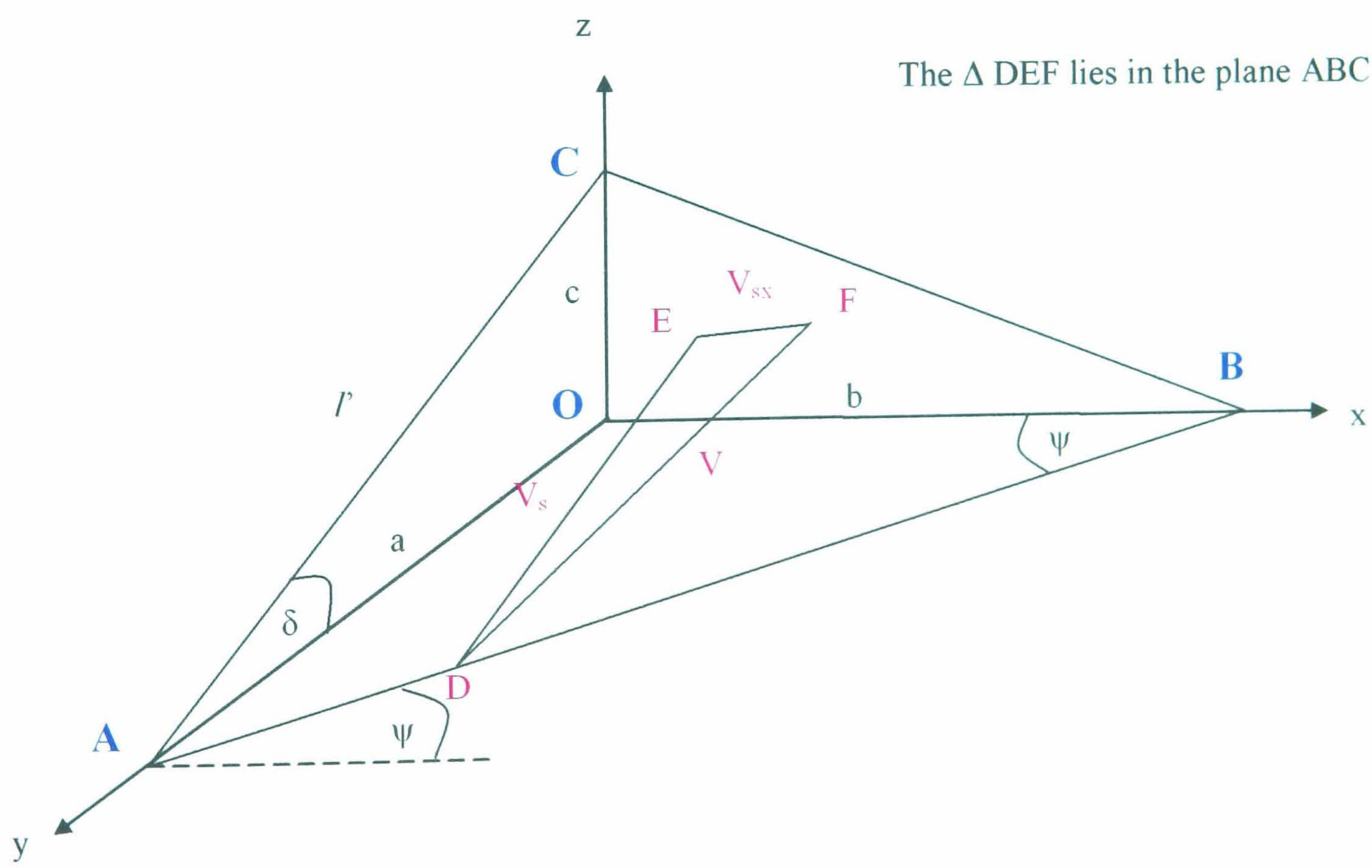


Figure 5-8 Soil velocities over a swept blade

The components for $\dot{m}'_2$ (mass flow off the blade) expressed in Equation 5-17 and restated below are detailed as follows:

$$\dot{m}'_2 = \dot{m}'_y + \dot{m}'_x \qquad \textbf{\{5-17\}}$$

$$\dot{m}'_x = e\, V'_s\ d_2\, \rho_f\, l' \sin\psi$$

$$\dot{m}'_y = V'_s\ d_2\, \rho_f\ w$$

Substituting for m_1, m_y and m_x into Equation 5-15

$$V_b\, d_1\, \rho_1\, w = V'_s\, d_2\, \rho_2\, w + e\, V'_s\ d_2\, \rho_f\, l' \sin\psi$$

therefore

$$V_b\, d_1\, \rho_1\, w = V'_s\, (d_2\, \rho_2)\, (w + e\, l' \sin\ \psi)$$

re-arranging

$$V'_s = \frac{V_b\, d_1\, \rho_1}{d'_2\ \rho_f\ (1 + e\ \frac{l'}{w} \sin\ \psi)} \qquad \textbf{\{5-19\}}$$

Equation 5-4 gave the expression for calculating the depth of soil over the blade d_2. With the introduction of sweep the formula has been revised to take account of the effective rake angle (δ) and is expressed in Equation 5-20.

$$d'_2 = \left[\frac{d_1}{\sin\beta}\right] . \sin[\delta + \beta] \qquad \textbf{\{5-20\}}$$

As before time on blade:

$$\Delta t = \frac{l'}{V'_s} - \frac{l' \cos\ \delta}{V_b}$$

$$\Delta t = l'\left(\frac{1}{V'_s} - \frac{\cos\ \delta}{V_b}\right) \qquad \{5\text{-}21\}$$

The amount of soil translocation on the blade (FT_b) $= \Delta t \,.\, V_b$

Therefore: $$FT_b = l'\left(\frac{V_b}{V'_s} - \cos\delta\right) \qquad \{5\text{-}22\}$$

Horizontal translocation can be derived in similar a manner to forward displacement as Δt remains the same, but is multiplied by the velocity in the horizontal direction as follows:

$$HT_b = \Delta t\, eV'_s \sin\psi \qquad \{5\text{-}23\}$$

Inserting equation 5-21 into 5-23 we obtain

$$HT_b = l'\left(\frac{1}{V_s} - \frac{\cos\delta}{V_b}\right) e\, V'_s\ \sin\ \psi$$

Re-arranging

$$HT_b = l'\left(1 - \frac{V'_s\ \cos\ \delta}{V_b}\right) e\ \sin\ \psi \qquad \{5\text{-}24\}$$

5.4.2 Translocation due to projection from complex blades (T_p)

In the same way translocation due to projection was derived for simple blades a similar approach has been adopted taking into account effective rake angle and sliding length. As sweep angle is introduced onto the blade, two components of translocation occur. These are projections in the direction of travel, V_y and lateral projection V_{sx}.

Where forward translocation due to projection: FT_p'

$$FT_p' = t_f.V_y \qquad \text{\{5-25\}}$$

Where Horizontal translocation due to projection: HT_p'

$$HT_p' = t_f.\ V_{sx} \qquad \text{\{5-26\}}$$

The Equation for predicting time in flight as expressed in Equation 5-9 has been modified to represent the new component V_z' for complex blades.

$$t'_f = \frac{V'_Z \pm \sqrt{V'_Z{}^2 + 2gZ_o}}{g} \qquad \text{\{5-27}$$

where:

$$V_z' = V'_s \sin \delta$$

Velocity in the direction of motion (V_y')

$$V_y' = V_b\text{-}V_s' \cos \delta \qquad \text{\{5-28\}}$$

Velocity perpendicular to the motion direction, (V_{sx}')

$$V_{sx}' = e\ V_s' \sin \psi \qquad \text{\{5-29\}}$$

Therefore translocation due to projection in the direction of motion can be obtained by substituting Equations 5-27 and 5-28 into Equation 5-25

$$FT'_p = \left[\left(\frac{V'_Z + \sqrt{V'_Z{}^2 + 2gZ_o}}{g}\right)(V_b - V'_s \cos \delta)\right] \qquad \text{\{5-30\}}$$

Similarly translocation due to projection perpendicular to the direction of motion can be obtained by substituting Equation 5-29 and 5-27 into 5-26.

$$HT'_p = \left[\left(\frac{V'_Z + \sqrt{V'^2_Z + 2gZ_o}}{g}\right)(eV'_s \sin\psi)\right] \qquad \textbf{\{5-31\}}$$

Now combining translocation over the blade (Equations 5-22 and 5-23) with translocation due to projection (Equations 5-30 and 5-31) we obtain total translocation in the direction of travel (FT_t') and perpendicular to the direction of travel (HT_t'):

$$FT'_t = \left[\left(\frac{V_b}{V'_s} - \cos\delta\right)l'\right] + \left[\left(\frac{V'_Z + \sqrt{V'^2_Z + 2gZ_o}}{g}\right)V'_y\right] \qquad \textbf{\{5-32\}}$$

$$HT'_t = \left[l'\left(1 - \frac{V'_s \cos\delta}{V_b}\right)e \sin\psi\right] + \left[\left(\frac{V'_Z + \sqrt{V'^2_Z + 2gZ_o}}{g}\right)V'_x\right] \qquad \textbf{\{5-33\}}$$

where,

$$V'_s = \frac{V_b\, d_1\, \rho_1}{d'_2\, \rho_f\, (1 + e\,\frac{l'}{w}\sin\psi)}$$

$$d_2 = \left[\frac{d_l}{\sin\beta}\right]\sin[\delta + \beta]$$

$$l' = \frac{l\sin\alpha}{\sin\delta}$$

$$\delta = \tan^{-1}(\cos\psi . \tan\alpha)$$

$$\beta = 45 - \frac{\phi}{2}$$

$$V_z' = V'_s \sin \delta$$

$$V_y' = V_b - V_s' \cos \delta$$

$$V_{sx}' = e\, V_s' \sin \psi$$

$$\rho_f \text{ loose} = \rho_l \text{ loose}$$

$$\rho_f \text{ dense} = 0.58\, \rho_l \text{ dense}$$

A worked example based on Equation 5-32 is shown in Appendix A.3.1.

5.4.3 Divergence angle (ε)

The formulas expressed in Equations 5-32 and 5-33 both rely on the empirical value e, the factor representing soil deflection.

Figure 5-8 illustratively presents the velocity in the horizontal direction (V_{sx}') and as expressed in Equation 5-18 and restated below.

$$V_{sx}' = e\, V_s \sin \psi \qquad \textbf{\{5-18\}}$$

Inspection of the geometry in Figure 5-8 shows that the divergence angle of soil in a horizontal plane, (ε), is directly related to V_{sx}' and therefore e. Whilst it was not possible to experimentally measure e directly it has been possible to measure ε (soil divergence angle) as described in Chapter 4. Thus it has been necessary to express e in terms of ε.

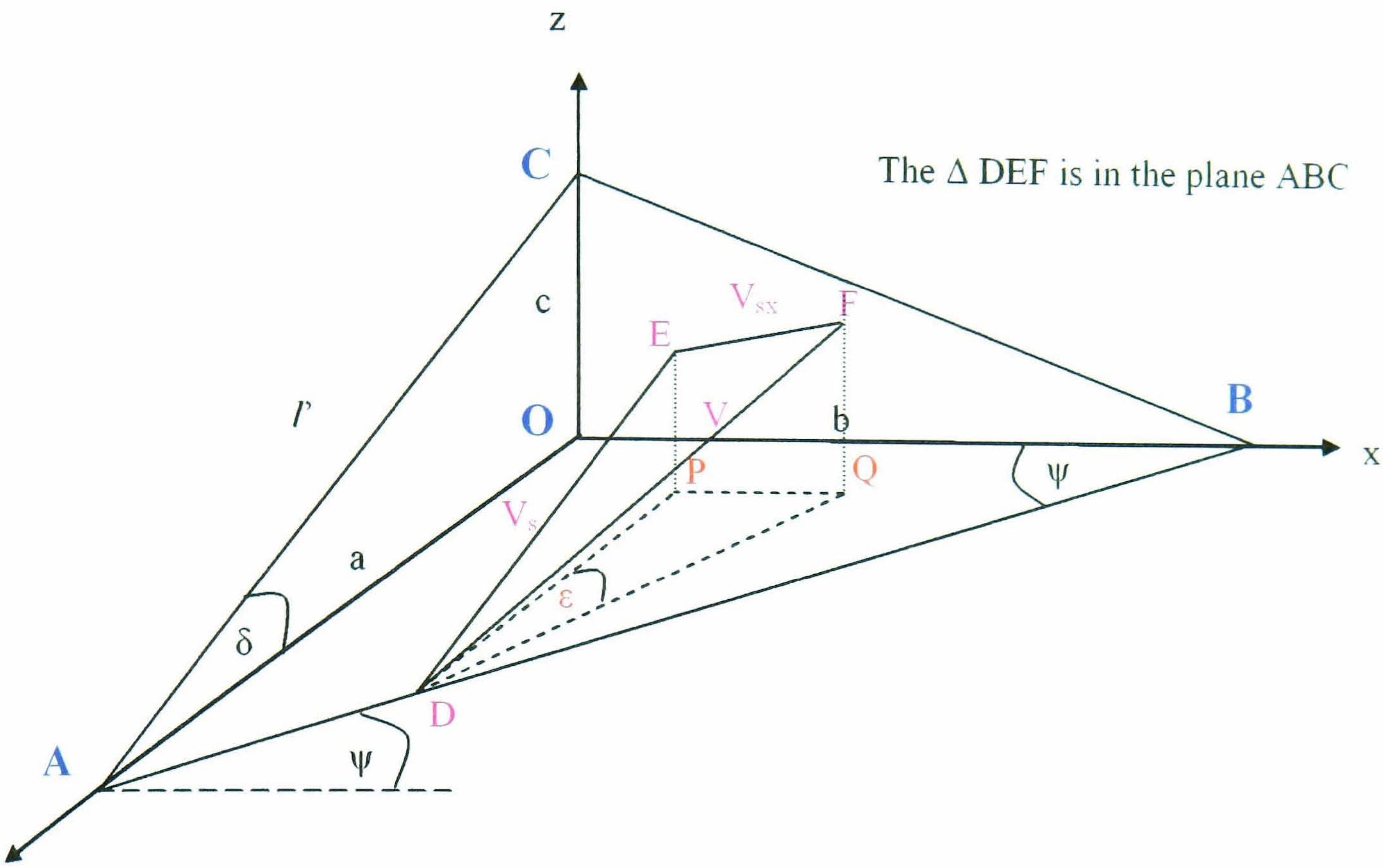


Figure 5-9 Introduction of divergence angle (ε)

Projection of Δ DEF on to the horizontal plane OAB results in Δ DPQ and the introduction of V_2, which is the horizontal projection of V_s the velocity of soil in the plane of the blade.

Projection of Δ DEF on to the horizontal plane is shown in Figure 5-10 (PQ = EF)

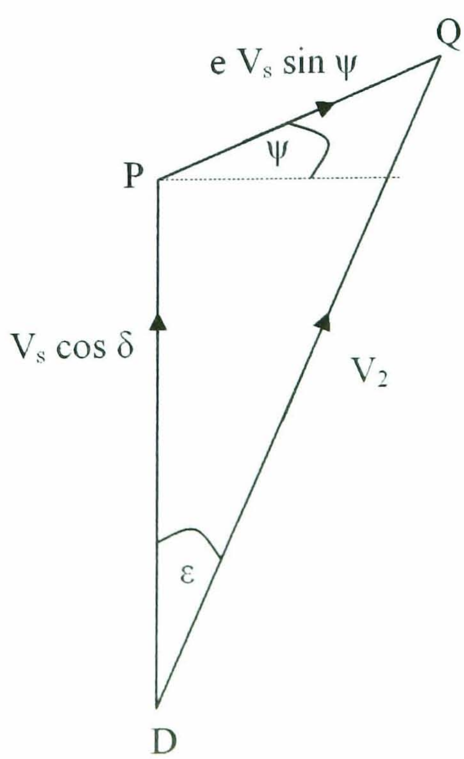


Figure 5-10 Horizontal projection of velocity vectors

Using the cosine formula for Δ DPQ we have:

$$a^2 = b^2 + c^2 - 2bc\cos A$$

$$V_2^2 = V_s^2\cos^2\delta + e^2V_s^2\sin^2\psi - 2eV_s^2\cos\delta\sin\psi\cos(90^0+\psi)$$

re-arranging

$$V_2^2 = V_s^2(\cos^2\delta + e^2\sin^2\psi + 2e\cos\delta\sin\psi\sin\psi)$$

re-arranging

$$V_2 = V_s(\cos^2\delta + e^2\sin^2\psi + 2e\cos\delta\sin^2\psi)^{\frac{1}{2}}$$

Using the sine formula for Δ DPQ we have:

$$\frac{a}{\text{SinA}} = \frac{b}{\text{SinB}}$$

$$\frac{V_2}{\sin(90^0+\psi)} = \frac{eV_s\sin\psi}{\sin\varepsilon}$$

re-arranging
$$\sin\varepsilon = \frac{eV_s\sin\psi\cos\psi}{V_2}$$

Combining formulae derived from sine and cosine rules we obtain:

$$\sin\varepsilon = \frac{e\sin\psi\cos\psi}{(\cos^2\delta + e^2\sin^2\psi + 2e\cos\delta\sin^2\psi)^{\frac{1}{2}}} \qquad \textbf{\{5-34\}}$$

Hence the divergence angle, ε, can be expressed in terms of sweep angle, ψ, effective rake angle, δ, and e. It is therefore possible to measure ε experimentally and derive a value for e. The results from the scratch line study reported in Chapter 4 give the best approximation of ε as soil travels over the blade. The following divergence angles were recorded over the blade by measuring the scratch lines, and the value e was obtained by a graphical procedure shown in Figure 5-11.

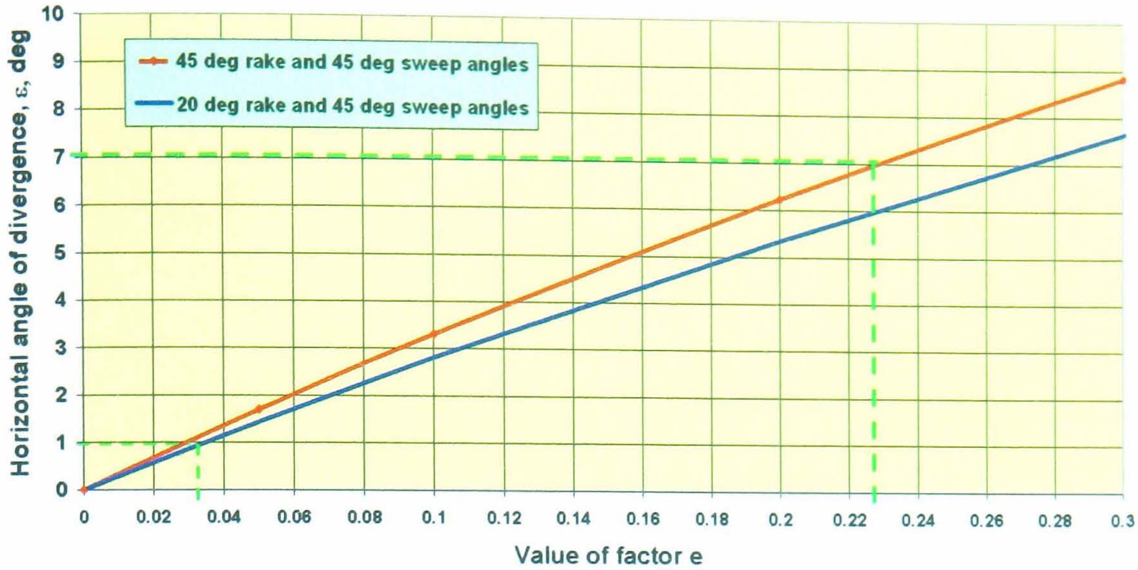


Figure 5-11 Divergence angle (ε) v factor (e)

Divergence angle for a 45-20 blade was observed as 1^0 therefore e = 0.032, and the divergence angle for a 45-45 blade was observed as 7^0 therefore e = 0.225. These same angles are used in the prediction of lateral soil displacement.

The observed results are similar to those reported by Hanna *et al.* (1993[a]) who found that the divergence angle of soil over a blade was at acute angles between 0^0 and 5^0. Hanna *et al.* (1993[a]) compared their results to Goryachkin lifting theory (1968) for determining soil divergence angle, and found it to predict similar low values of divergence. When comparing observed results in this study with that of Goryachkin lifting theory (expressed below); Lifting theory is in close agreement to observed values of soil divergence.

$$\tan\varepsilon = \frac{\sin\psi\cos\psi(1-\cos\delta)}{\sin^2\psi\cos\delta + \cos^2\psi} \qquad \text{Goryachkin Lifting Theory}$$

The following values were predicted on blade geometry used in this study.

45-20 = 0.91^0

45-45 = 6.18^0

Goryachkin Lifting theory could be of value in determining the divergence angle as it has shown to predict the divergence angle with reasonable accuracy. It could, therefore, be used in blade design with some confidence.

5.4.4 Forward translocation comparison

In Figure 5-12 it can be seen that for the 45-20 blade in loose and dense soils that velocity does not significantly increase the forward displacement; however the prediction model is responsive to changes in blade velocity. Soil displacement significantly increased with density reductions. It can be seen that increasing effective rake angle from 14.4^0 to 35.4^0 resulted in a significant increase of forward displacement with increasing velocity. The forward displacement is greater for loose soil than dense soil for both blades. In general the model has good agreement with observed values.

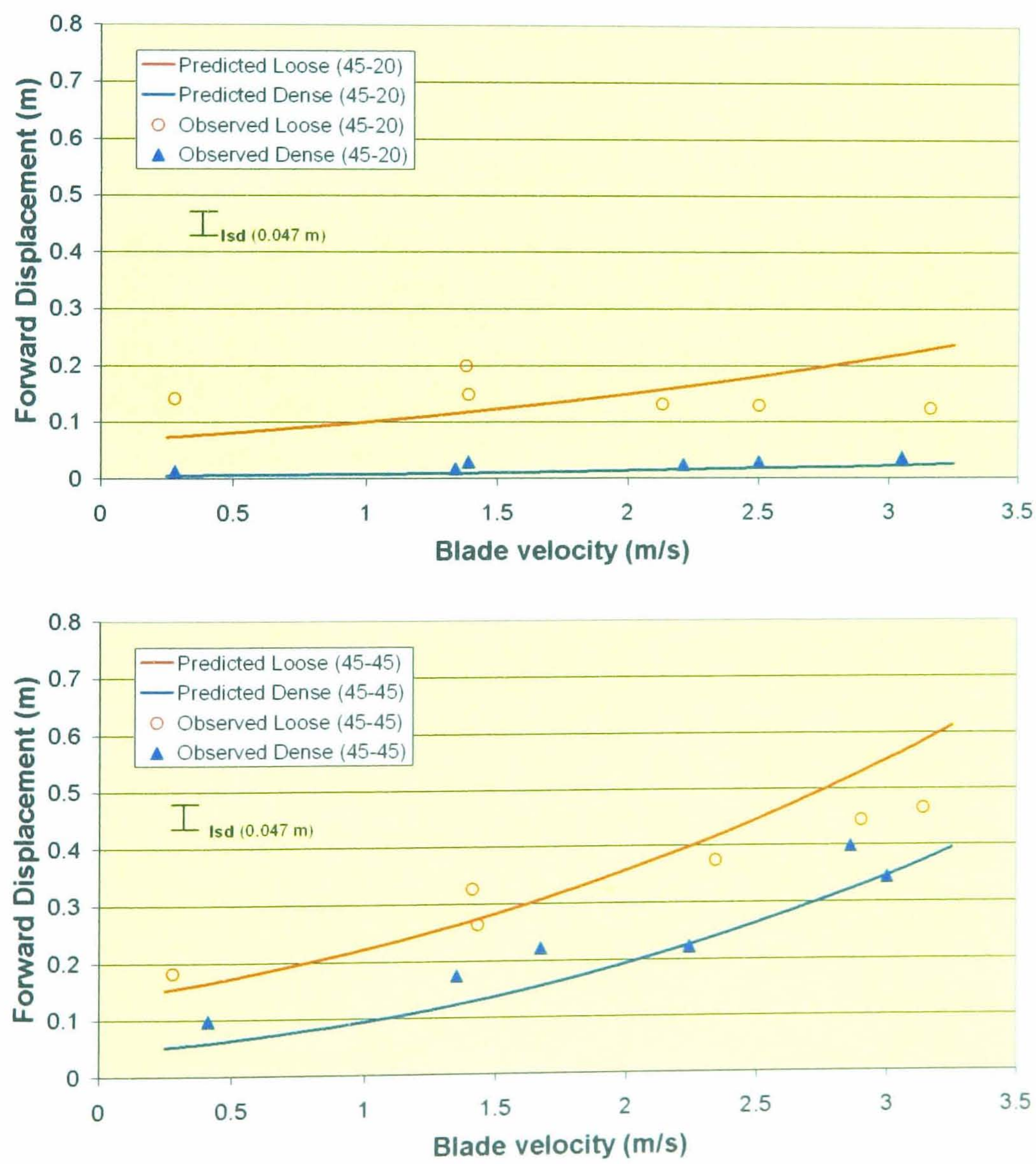
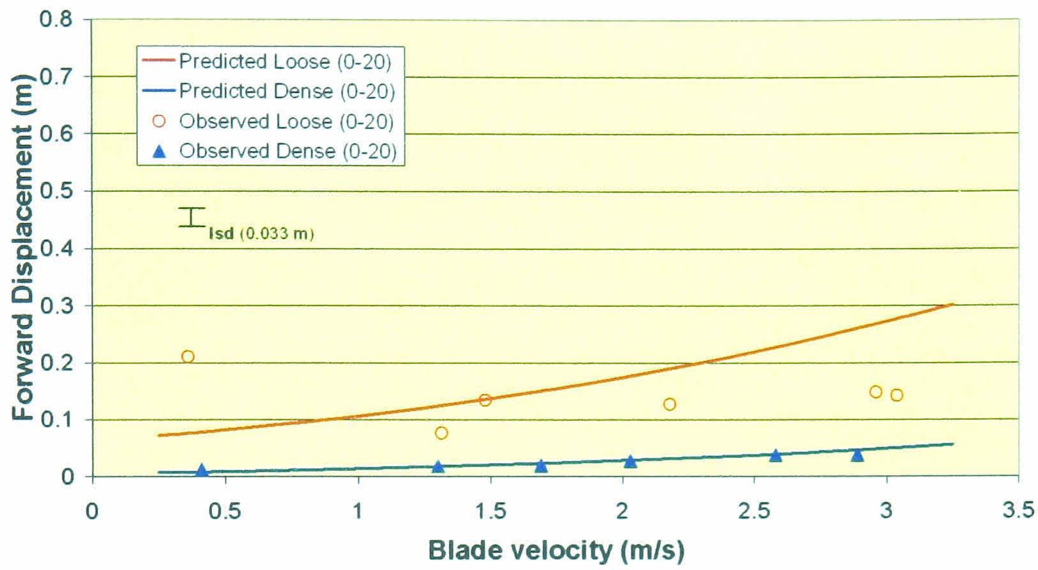


Figure 5-12 Forward displacement (complex blades)

For completeness the model for complex blades (5-32) has been used on blades without sweep to justify it as a general purpose model in predicting forward displacement as shown in Figure 5-13. The values of e are not important as when sweep angle is 0^0 that aspect of the equation equates to zero.



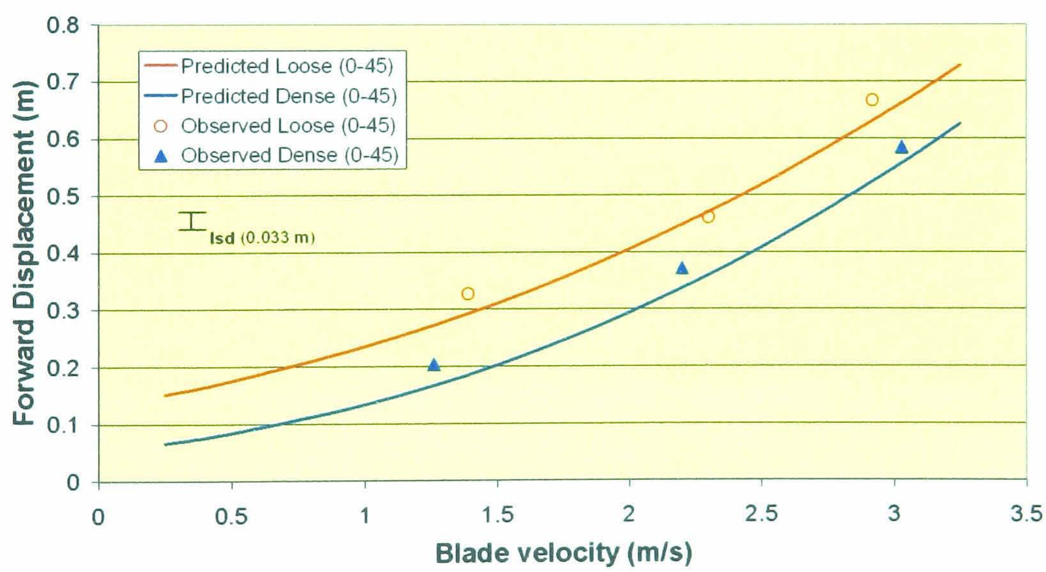


Figure 5-13 Forward displacement of blades without sweep using Equation 5-32

The model including sweep angle when applied to blades with no sweep provides good prediction of forward displacement, thus Equation 5-32 can be used as a general equation for all blades. Figure 5-14 presents the overall observed forward displacements plotted against predicted values for all blades examined in this research programme.

It can be seen that the model predicts within 15% for the 0-45 blade in loose and dense soil conditions. The model also predicts within 15% for the 45-45 blade in dense conditions extending to 20% in loose conditions. Prediction for the 0-20 blade in dense conditions is within 20% of the observed values throughout the velocity range, but in loose conditions the model does not predict well with a maximum prediction error of 94%. When sweep is introduced on the 20^0 rake angle blade with an effective rake of 14.4^0 the model predicts within 55% in loose soil except at very low blade velocities, whilst in dense soil the prediction error increases to 71% although it must be remembered that large percentage errors are obtained due to the relatively low displacements at the 20^0 rake angle; i.e. a 71% error for a 45-20 in dense conditions equates to only 12 mm.

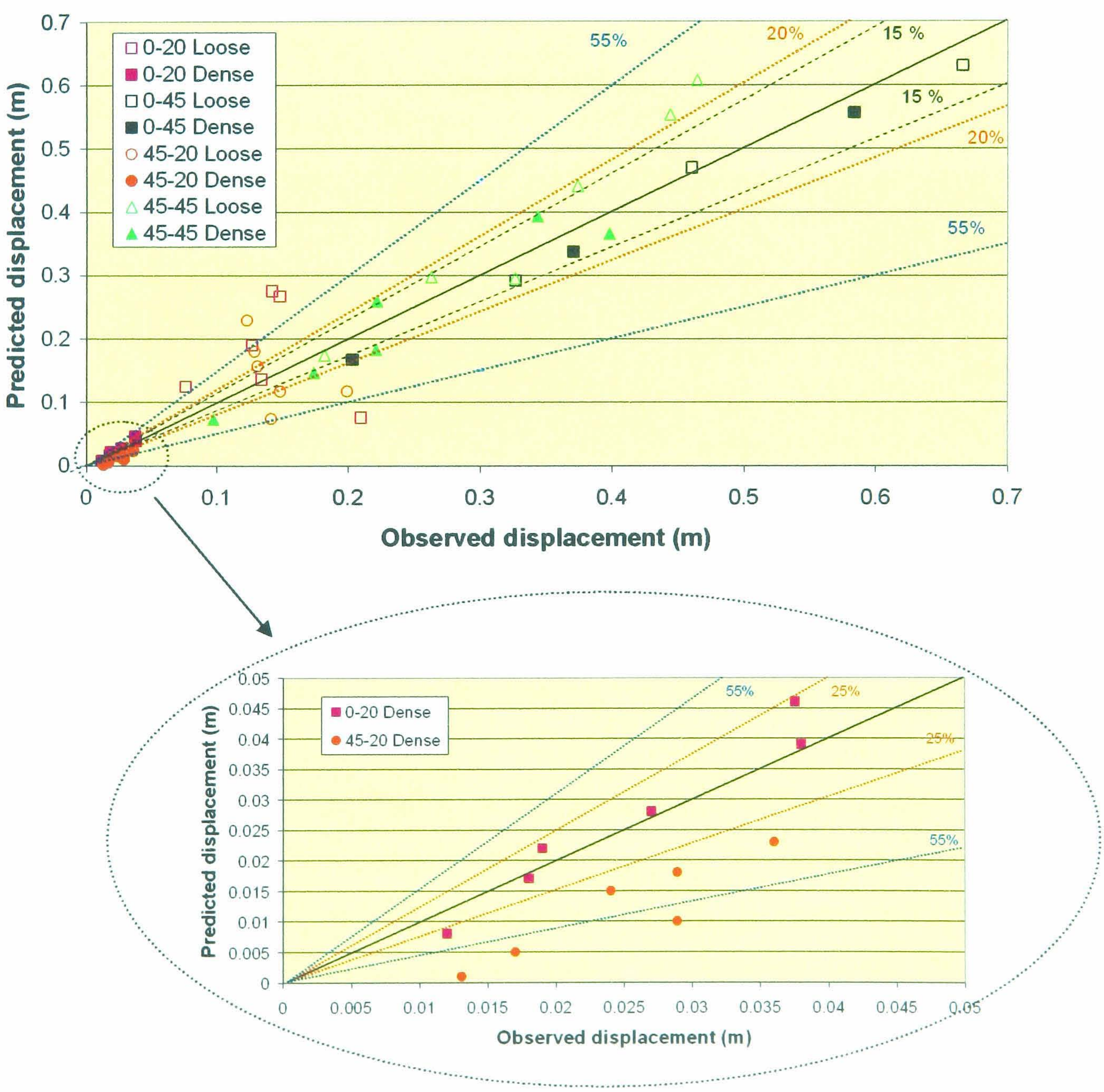
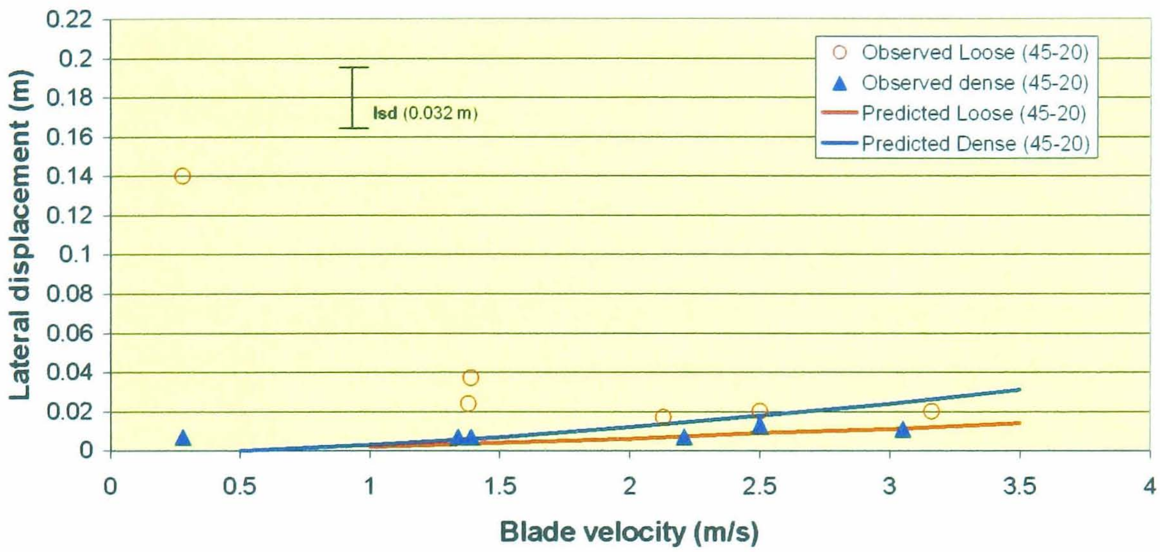


Figure 5-14 Observed V predicted forward displacement (complex blade model)

5.4.5 Lateral displacement

Lateral displacements using Equation 5-33 for blades with a sweep angle under loose and dense soil conditions are illustrated in Figure 5-15, with the same values of divergence angle as used to predict forward displacement.



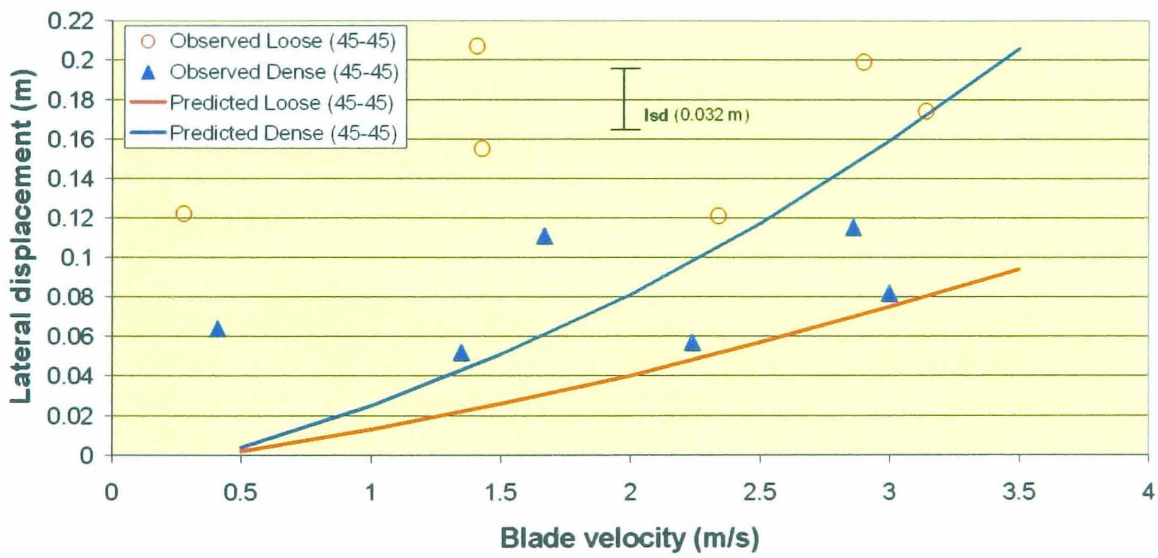


Figure 5-15 Lateral displacement (complex blades)

Figure 5-15 shows lateral displacements for blades with a 45^0 sweep angle in dense and loose soil conditions with varying blade velocity. It can be seen by visual inspection that the model predicts an increase in lateral displacement with increases in blade velocity but the observed data for lateral displacement is not significantly affected by changes in velocity. However, the model predicts values of lateral displacement of the right order of magnitude. For the 45-20 blade lateral soil displacement was not significantly effected by density or speed.

For the 45-45 blade the model predicts lateral displacements of the right order of magnitude for dense soil although correlation is relatively poor because of the inherent variability in the observed data. In loose soil the model predicts values of lateral displacement which are considerably less than observed values. If the lsd of the data points is considered in relation to the predicted values then for the 45-20 blade the model accounts for all observed values except those with low velocities in loose soil conditions. For the 45-45 blade, the model would be in the range for all observed values in dense soil conditions except extremely low velocities. In loose conditions it would still predict less than the observed values.

Lateral displacement is difficult to predict as the range of observed values as discussed in Chapter 4 were very high. It was reported that certain blade velocities resulted in coefficients of variance generally in excess of 30% with some greater than 100%, with an average coefficient of variance of 40.6 %.

Figure 5-16 presents the observed values against predicted values and shows that the model has a prediction error up to 90%. However the 60% limits result in accounting for the majority of the data points. The inherent variability associated with the soil failure characteristics make prediction of lateral displacement difficult.

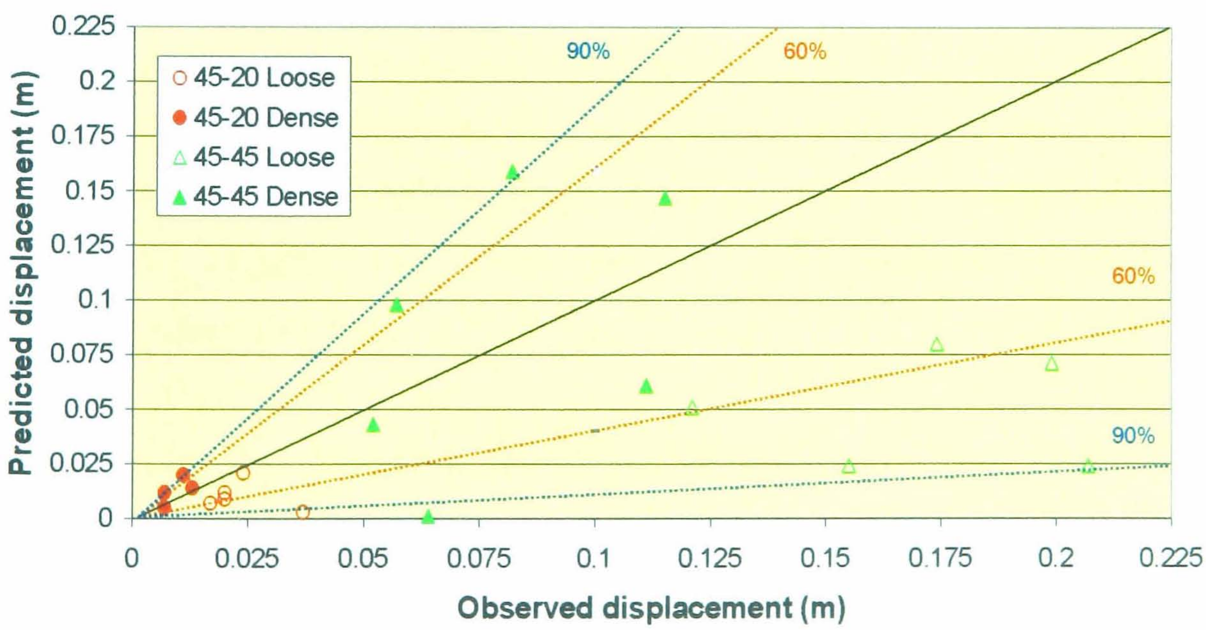


Figure 5-16 Observed V predicted lateral displacement

5.5 Experimental data comparison

As reviewed in previous chapters Sharifat & Kushwaha (2000) and Rahman *et al.* (2002) investigated soil displacement by sweep blades. Neither attempted to fit a model to their data sets, but plotted the effects of speed which have enabled comparisons to be made between their studies and the predictive model. Unfortunately the influence of the leg, although noticed as significant by Rahman *et al.* (2002) was not removed from the mean forward soil displacement. Therefore soil displacement values from sweep blades have been extrapolated from submitted graphs.

Rahman *et al.* (2002) investigated soil displacement in a soil with a density not dissimilar to the loose conditions investigated in this project of 1200 kg/m^3 at speeds of 0.6 m/s and 1.4 m/s. The blade had a sweep angle of 67^0 and a rake of 19^0. The results for comparison were undertaken at 0.05 m depth. Based on these conditions, when entered into the translocation model, a forward soil displacement of 53 mm was predicted. Rahman *et al.* (2000) had results ranging between 45-60 mm. Therefore it would suggest that the model predicts with reasonable confidence against actual values those of Rahman *et al.* (2002)

Rahman *et al.* (2002) state that forward displacement from the leg (i.e. rake = 90^0) was approximately 360 mm. When changing rake angle in the model to 90^0 and removing sweep angle, with all other variables the same the model predicts 343 mm displacement. Therefore the model predicts with reasonable confidence the displacement due to the leg.

Observed results from Sharifat & Kushwaha (2000), have also been compared against the prediction model. Sweep blades were investigated at 1.39 m/s and 2.2 m/s in soil with a density of 1200 kg/m^3. Results compared are for the cutting range up to 15 mm depth. From an illustration in the paper the sweep angle has assumed to be 50^0 and the rake 12^0.

The results in a similar manner to those of Rahman *et al.* (2002) were not distinguished from the leg; therefore extrapolation of soil displacement occurring across the blade was undertaken. At 1.39 m/s, soil displacement ranged from 25-100 mm with the model predicting 71 mm, whilst at increased speeds of 2.2 m/s, soil displacement was in the range of 50-150 mm and the model predicted 94 mm. Although the range of observed values is high, the model predicts well within the range for each blade velocity.

For an analysis of soil displacement from the leg, with all variables kept the same, but rake assumed to be 90^0. Sharifat & Kushwaha (2000), observed approximately a 1m displacement at 2.2 m/s whilst the model predicts 0.86 m. At 1.39 m/s, a range of 0.4 to 0.7 m was observed whilst the model predicts 0.533 m

The prediction model, therefore, correlates well with that of earlier experiments and when predicting for the displacement from the leg, it still predicts with reasonable accuracy.

The soils in the two above studies both had higher moisture contents in the order of 14-18% and operated at different depths yet the model seems to predict well. This can possibly be explained by experiments undertaken by Sharifat & Kushwaha (2000), who found that depth of tool cutting had little effect on forward displacement within the range investigated from 15 mm and 75 mm, but increasing depth beyond 75 mm reduced forward displacement. Effects of changing soil moisture content from 15% to 18% were found to be insignificant on soil displacement. However Rahman *et al.* (2002) although in agreement that moisture content within the range of 14-18% did not have a significant effect on forward displacement of soil, believed cutting depth to be significant in the range considered of 50 to 150 mm. The conflicting statement regarding depth of operation may simply be due to the range over which the depths were considered. If Sharifat & Kushwaha (2000) had increased depth further, the same results may have been found.

5.6 Conclusions

- The mass flow soil dynamics model based on particle dynamics has been successful in predicting soil displacement in the mass flow situation. A general model has been developed from first principles that predicts lateral and forward displacement of soil as it is undercut by shallow working wide blades. The model accounts for blade geometry (face length, rake angle and sweep angle) soil density, soil internal angle of friction and blade velocity.

- The forward translocation model tends to under predict at very low blade velocities as soil flow tends to bulk at the front of the blade and then continues in flow failure. The model predicts within 25% for blades with steep rake angles in loose and dense soil conditions, with and without sweep. For blades with 20^0 rake angles prediction is less accurate, predicting within 15 mm in 90% of all cases in dense soil. The model is generally more reliable in dense soil conditions than loose.

- Lateral displacement predictions are typically less accurate with a maximum error of 15 mm on a nominal displacement of 10 mm for 20^0 rake angle blades and 25 mm error on a nominal lateral displacement of 110 mm for 45^0 rake angle blades in dense soil conditions.

- Blades with low rake angles cause limits to be set in the model when predicted velocity of soil is greater than blade velocity. When this occurs then soil velocity should be replaced with blade velocity to obtain meaningful results.

6 Business and Commercial

6.1 Introduction

The following chapter investigates the viability of intra-row weeding, focusing upon UK conventional and organic sectors that could benefit from improved mechanical inter-row weed control and adoption of an intra-row weed control mechanism.

Skilled labour is now becoming scarce and with rising labour prices, alternatives to hand weeding are required to ensure growing high value crops in the UK is economically viable in the long term, when subsides and premium prices may be a thing of the past.

Unlike a century ago, agriculture is no longer the backbone of Great Britain, the workforce is moving from the primary sector into the tertiary and service sectors. With less than 1% of the population of Great Britain actively engaged in agriculture and its importance and the farmers 'power' seems to be diminishing.

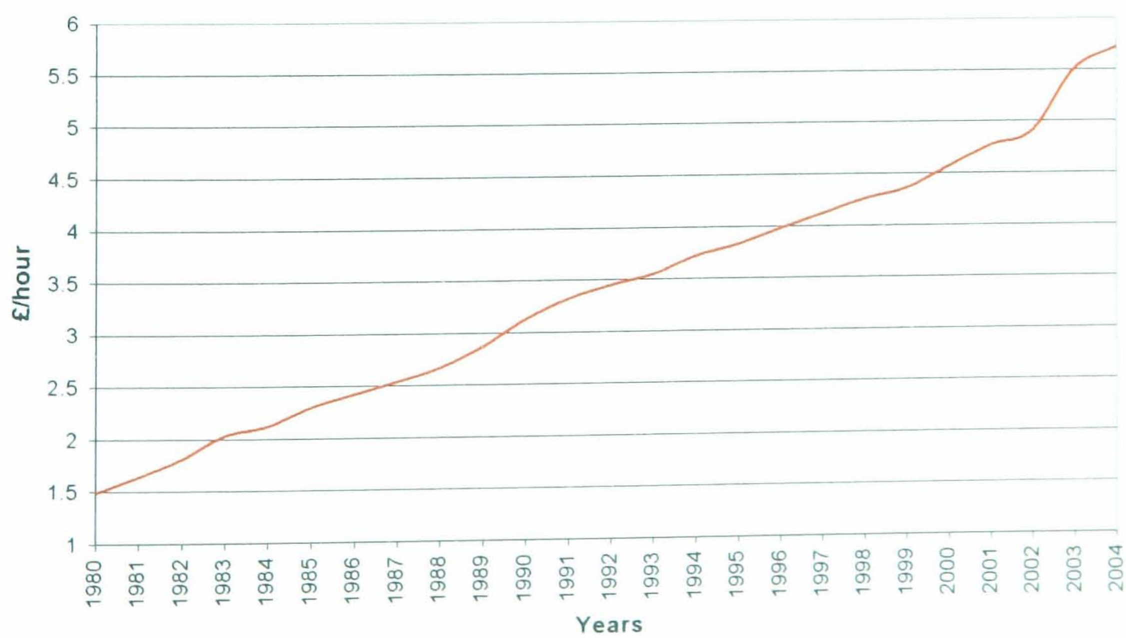
It is possible that UK farming had reached a low point in the last century, following foot and mouth outbreaks and low crop prices. As a sector it has less appeal to the next generation of farmers, as pay scales are low and the level of effort required is enormous, however it may be that it can still be a profitable sector with the correct mechanisation to suit our changing society. The introduction of new technology within the sector may also make it more attractive to the younger generation.

6.1.1 Workforce

"The population census of 1851 recorded two million persons as being engaged in agriculture in Great Britain. By 1951 this figure had fallen to 1.1 million, and by 1986 to 0.6 million" quoted by Marks, 1989. By the end of December 2002 there were only 409,000 people engaged in agriculture (including fishing), UK National Statistics office (2003). This clearly depicts the workforce decline in UK agriculture since 1900.

Marks, (1989) reports that mechanisation has been the prime cause of the decline, mainly due to the introduction of the tractor, which by the 1960's had largely replaced horses on farms. Therefore, there was no need to retain men to work the horses, and labour was cut back and only hired in for the seasonal demand. Although true to a certain extent, post war attitudes of the workforce changed; as their standard of living and expectations rose, people moved out of the farming sector, into those offering career progression and increased salaries. This reduction in workforce meant that mechanisation was even more important to meet the populations' food demand at an affordable price. More recently rising labour costs, low (5.2%) unemployment, UK National Statistics Office, (2003) and a qualified labour force that find agricultural unappealing, have made mechanisation essential for stability and growth in terms of quality and output.

The labour price for a standard agricultural worker has been steadily rising from 1980 to 2003 as shown in Figure 6-1 (non-inflated for cost of living index). An increase of £4.02/hr over this time, over a 39 hour week for 48 weeks of the year equates to an extra cost of £7525/annum with further increases likely to continue. These prices reflect the minimum wage agriculture workers over 18 years of age on the standard grade will get paid, but often the pay rate is higher. In many cases these workers are employed full time and therefore, the cost to the farmer is much higher with other contributions such as holiday entitlement and employer's contribution.



Source – DEFRA[a], DEFRA[b] (2003)

Figure 6-1 Minimum standard agricultural wages for England and Wales

Further advances in mechanisation are probably the only option to make mechanical weed control viable in the long term, especially if government farm support continues to decline. The organic sector struggles to command premium prices as more farmers enter the market, and the conventional grower strives to reduce the growing costs, which are largely chemical based. Mechanisation has also enabled individual farmers to take on more land, thus increasing the size of their holdings. This enables them to spread the cost of new machinery required to increase productivity, which has only been possible by spreading the cost over a greater area. Mechanisation for weed control is now of paramount importance to ensure the whole crop is weeded in the available time over the increased size of holding.

6.1.2 Policy

Changes in agricultural policy and European guidelines may result in mechanical weeding operations being the only option available for farmers to control weeds due to the perceived risk of chemicals.

Goodchild (1998) reports "Increasing pressure, from both government and environmental groups concerning the effects of agricultural chemicals on the environment are making farming practices less acceptable". Goodchild is referring to the pressure applied to agriculture concerning chemical application. This currently passes as acceptable, but there may be a time in the near future where farming practice has to change, reverting back to pure mechanical weed control.

Government officials have already proposed that agricultural subsidies be reviewed, or that the level of subsidy reflects how environmentally conscious the grower is. Hence minimal use of chemicals, results in high levels of subsidy and vice versa.

In recent times the Common Agricultural Policy (CAP) reform has been accepted and Defra (2003[c]) state "Main subsidies are linked to compliance with European standards covering the environment, public and animal health and welfare. Farmers also have to maintain land in good agricultural and environmental conditions."

This will make the demand for mechanical alternatives even more popular. Thus the future of farming due to decreases in labour availability rising labour costs, combined with government reviews will lead towards that of a minimal chemical allowance making mechanised weed control the only viable option.

6.1.3 Summary

Farm outputs and long term economic viability of farming was achieved through post war mechanisation and increased chemical usage, which combined with a change in workforce attitude and expectations saw hundreds of thousands of employers migrate from the UK agriculture sector. Now as chemical usage is perceived as unfriendly, and alternatives are sought to control weeds and the UK labour force can not be afforded, nor is available to continue traditional methods; mechanisation is needed to overcome weed control in the number of available days within the season.

6.2 UK high value crop sector

Crops included within this section are those that are currently weeded by hand labour, or are designated suitable for weeding by mechanical means. These crops are all widely spaced in the inter-row and intra-row having a relatively high harvest value. Chapter 2 investigated many of the ways in which weed control can be undertaken and reported on the slow rates of work of hand weeding, but until a viable alternative is available this old tradition continues as the best available option at present. Table 6-1 is based on information taken from Soffe (1996) and presents the spacing in and along the row for high value crops that could potentially be mechanically weeded along the row.

Table 6-1 Plant variety and seasonal crop spacing

Crop	Inter-row spacing	Intra-row spacing
Brussels Sprouts	500-900 mm	450-600 mm
Calabrese	400-500 mm	230-300 mm
Cabbage - Spring	300-450 mm	350-500 mm
Cabbage – Summer/Autumn	300-600 mm	400-500 mm
Cauliflower – Spring/Summer	600 mm	450-550 mm
Cauliflower –Summer/Autumn	600 mm	600 mm
Cauliflower – Late Autumn	600 mm	700 mm
Cauliflower - Winter	650-750 mm	600-750 mm
Lettuce	700 mm	250-450 mm
Sugar Beet*	<500 mm	160-180 mm

*Potentially too narrow for intra-row weeding device.

Sugar beet is often hoed in the inter-row yet the intra row space is seen as too close for a selective intra-row weeder at this stage and has therefore been omitted for further analysis. The five remaining crops presented in Table 6-2, have the corresponding UK cropped area in hectares. Information presented and discussed has been obtained from DEFRA (2002).

From the data presented in Table 6-2 the mean annual area of suitable crops grown over the years 2000 to 2003 is 35,366 hectares (87,391 acres). It can therefore be assumed that this area is suitable for mechanical intra-row weed control in the UK, which accounts for 20% of the UK horticultural sector, data source DEFRA (2003[d]).

Table 6-2 Available area to mechanically weed by crop type

	2000/1 (ha)	2001/2 (ha)	2002/3 (ha)	Mean (ha)
Brussels	5656	3604	4431	4564
Calabrese	7543	4691	6116	6117
Cabbage	9485	7968	8711	8721
Cauliflower	11968	8860	10462	10430
Lettuce	6068	5081	5453	5534
Total	**40720**	**30204**	**35173**	**35366**

Cauliflower and Cabbage have the largest mean cropped areas in this sector, covering 10,430 ha and 8,721 ha, respectively, a total of 19,151 ha (47,323 acres). With spring cabbage having the closest intra-row spacing of 300 mm (11.81 in). Therefore, a suitable mechanism needs to be designed to operate on the closest intra-row spacing possible to cope with seasonal and crop variations.

Figure 6-2 illustrates the mean annual area of the crops presented in Table 6-2 and also presents the area of crops that are grown organically. It can be seen from Figure 6-2 that organic produce levels are very low. Table 6-3 shows that only 915 ha (2261 acres) of suitable organic crops are grown which amounts to 2.6% of the total area (HDRA, 2003). The main difference between conventional and organic is that conventional growers can use a pre-emergence spray. However following emergence all the crops have to be mechanically weeded, as the current herbicides scorch the crops and buyers, i.e. the supermarkets stipulate no use of chemicals. Another problem is the number of suitable chemicals available, and those allowed to control weeds are now becoming fewer, making pre-emergence weed control difficult.

Due to potential changes in the sector it is, therefore, decided that the market of a mechanical intra-row weed mechanism will be aimed at the conventional high value produce farmer. It will incorporate the organic farmers rather than a dedicated organic approach as an economically viable weeder will benefit the whole sector.

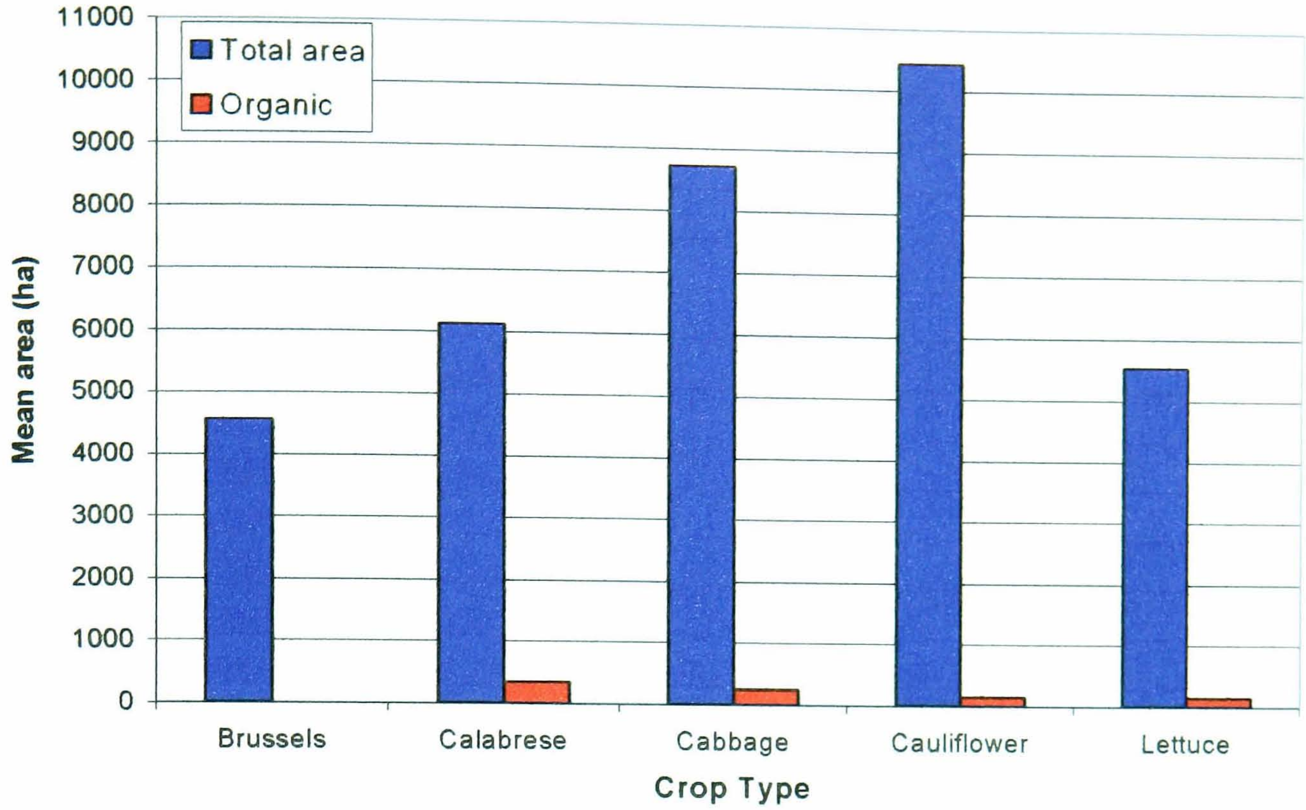


Figure 6-2 Available UK crop in hectares

Table 6-3 Organic area by crop type

Organic Crops UK	Area (ha)
Calabrese	351
Cabbage	255
Cauliflower	155
Lettuce	154
Total Organic	**915**

(Source HDRA, 2003).

The Soil Association (2003) reported that 3 out of 4 households in the UK are buying organic produce, and although the level of organically grown produce is low, demand may encourage premium prices and thus more farmers may enter the totally organic market. It is likely that these entrants will come from the conventional sectors.

6.2.1 Size of UK market sector

Section 6-2 reported the mean horticultural area that can be mechanically weeded in the UK as 35,366 ha/annum, accounting for 20% of the total horticultural sector in the UK. Data of horticultural holdings is not broken down by crop type and therefore to approximate the number of holdings that could benefit from an intra-row weeding mechanism a figure of 20% of horticultural holdings has been used. Due to the unavailability of UK information on holding size, Table 6-4 details the total number and the 20% ratio of horticultural holdings in England and Wales in June 1999.

Data presented in Table 6-4 shows the approximate number of holdings and holding area that grow crops which could be weeded mechanically. Section 7.8 Investigates at which level of holding a new mechanical weeding mechanism may be a viable option compared to existing weeding techniques.

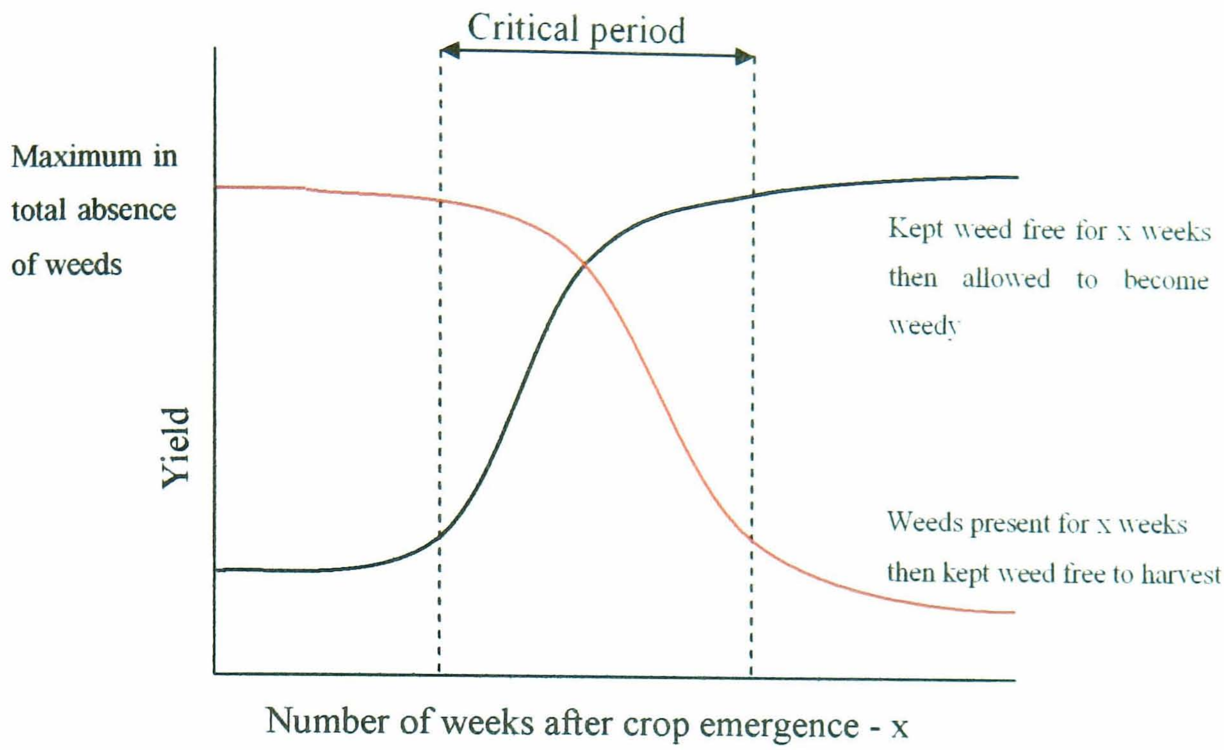
Table 6-4 Horticultural holdings and area in England & Wales 1999

100 %	**0:<1 ha**	**1:<2 ha**	**2:<5 ha**	**5<20 ha**	**>20 ha**	**Total ha**
Holdings	5967	2113	2704	3393	2141	16318
Area (ha)	2272	2881	8458	36184	111097	160891
20 %	**0:<1 ha**	**1:<2 ha**	**2:<5 ha**	**5<20 ha**	**>20 ha**	**Total ha**
Holdings	1193	423	541	679	428	3264
Area (ha)	454	576	1692	7237	22219	32178

Source June Census 1999, DEFRA (2003[d])

6.2.2 Work rate requirements

In order to develop a target work-rate for an economically viable weeding system the following assumptions have been made. Table 6-2 showed that a mean area of 35,366 ha of crops grown per annum were suitable for mechanical weed control along the row. Although the growing season for many of the varieties stated in Table 6-2 take about 4 months between planting and harvest, it is fair to assume that there are only probably 20 days available for mechanical weed control through a typical growing season, due to the crop growth stage, and climatic conditions. Figure 6-3 illustrates the importance of weeding as the crop is subjected to weed competition.



After Stephens (1982)

Figure 6-3 Critical period of weed competition

Stephens (1982) details the importance of maintaining a weed free crop, in the critical period. Initially when both the plant and weed are small, there will be negligible effect on yield as they are not directly competing for nutrients and light. As they grow they directly compete and it is in this stage that weeds must be controlled. Controlling weeds after competition with the plant does not benefit yield as the damage has already occurred as shown by the red line. This is why the number of days available to mechanically control weeds is reduced, due to the critical period of weeding.

It should also be remembered that the majority of conventional growers use a pre-transplant spray, which are persistent soil acting herbicides, these control the weeds very well within the first two weeks after planting, leaving approximately 2-3 weeks before the leaves meet in the row. However some of these herbicides are being reviewed and phased out, their alternatives although, allegedly friendlier to the environment, come at a price.

The following assumptions have been made to determine a suitable work rate to ensure the crops are weeded within the critical period, based on an area to be hoed of 35,366 ha (Table 6-2), and 20 workable days:-

8 hour days	- 160 hours
Field efficiency	- 75 %
Typical width	- 4 m
Target speed	- 1 m/s

1 m/s = 3.6 km/h	= 3600 m/hr
3600 x 4	= 14,400 m^2/hr
14,440 / 10,000	= **1.44 ha/hr** (spot work rate)
1.44 x 0.75	= **1.08 ha/hr** (effective work rate)
35,366/160/1.08	= **204.6 machines**

Based on the above assumptions 205 machines would be needed to hoe 35,366 ha based on an effective work rate of 1.08 ha/hr. In practice it is likely that two hoeing operations would be required, thus doubling the number of machines to 410. This would be the minimum number required as weather constraints and breakdowns have yet to be factored in, it also assumes that hoeing operations are undertaken by a co-operative organisation rather than individual farmers.

An alternative way of estimating the market potential investigates the number of holdings as presented in Table 6-4. From Table 6-4 it was assumed there were 428 holdings in England and Wales farming 22,219 ha that had an area greater than 20 ha, equating to an average area within that band of 52 ha/holding. If each of these holdings required the ability to hoe twice a year, then the following can be assumed:–

52 ha x 2/1.08 ha/hr = 96.3 hours, / 8 hrs in a day = 12 days

This allows 40 % spare capacity allowing them to cope with climatic conditions, contract out some work and also have capacity in case of break down.

The next holding band lies between 5-20 ha, assuming only 10 % purchase a hoe then an additional 68 machines would be required, having a spare capacity of approximately 88 % allowing them to contract out the machinery to other users. On the assumptions made on holding numbers and potential users it is fair to assume that the market potential (England & Wales) for mechanical weeders could be circ 500 machines.

6.2.3 Market potential across the European Union

Charlier (2000) reports that across the 15 member EU states in 2000, that 126,797,000 ha were in agricultural food production, accounting for 6,769,000 holdings. Based on the market potential for the UK in Section 6.2.2 the same assumptions have been applied for EU holdings.

Horticultural production accounts for 3% of land use, and assuming 20% of the horticultural sector was suitable for intra-row weed control then the market potential for weeding machines is:

Number of holdings greater than 20 ha	= 1,286,110
Assumed 3% of holdings to be engaged in horticulture	= 38,583
Assuming 20% suitable for mechanical intra-row weeding	= 7717

Therefore it can be assumed that there are 7717 holdings actively engaged in horticultural production in the EU. If as assumed before 10% of holdings between 5 and 20 ha would require a weeding machine the market potential is as follows:

Number of holdings greater than 20 ha but less than 50 ha	= 1,556,870
Assumed 3 % of holdings to be engaged in horticulture	= 47,706
Assumed 20% suitable for mechanical intra-row weeding	= 9341
Assumed 10% within sector require a weeding machine	= 934

Therefore, there is a potential European market based on figures by Charlier (2000) of:

$$7717 + 934 = 8651 \text{ machines}$$

With a requirement of approximately 8651 machines, there should be sufficient commercial interest to manufacture the product throughout Europe.

6.2.4 Market potential across the United States of America

Statistical information on the number of holdings and holding size for the USA was not readily available. However, the area of widely spaced crops identified as UK potential, in Section 6.2 for the USA is shown in Table 6.5.

Table 6-5 Potential area to mechanically weed by crop type in the USA 2002

Crop	(ha)
Brussels	1,052
Calabrese	53,823
Cabbage	31,764
Cauliflower	17,669
Lettuce	120,152
Total	**224,460**

The area of widely spaced crops in the USA is 6.35 times greater than the area grown in the UK. As USA holding size is not stated, the potential market size has been based on the available area and the potential work-rate of 1.08 ha/hr detailed in Section 6.2.2.

Therefore,

$$224{,}460/160/1.08 = 1299 \text{ machines.}$$

It is likely that this is a conservative estimate but is the best approximation that can be made with the data available.

6.2.5 Summary

It can, therefore, be concluded that across Europe and the USA there is a potential market of 9950 machines. The market on a world wide scale is obviously much greater, but for Europe and the USA alone sufficient interest should warrant manufacturers to enter the market of intra-row weeding.

6.3 Current drilling/transplanter practice

Many of the crops discussed in Section 6.2 are transplanted or precision drilled, therefore within the drill bout there should be a regular planting pattern. Small-scale producers and the occasional large scale co-operative still plant by hand, where variability is considered to be greater along the row and within the planted bed. Many of these producers use an inter-row hoe and mechanical intra-row weed control is mainly undertaken with hand labour with some using the finger weeder/ brush weeder with limited success.

6.3.1 Crop stand

If a crop stand has a uniform spacing along the row, whether planted on the square within the drill bout, or equi-spaced, it facilitates ease of mechanical actuation of a mechanism, as a cyclic operation can be employed. A uniform spacing pattern lends itself to vision guidance as the plant can be distinguished from the weed. The camera if desired can look at one row within the bed and all those drilled at the same time will be on the same pitch spacing regardless of wheel slip or skid.

If non-mechanised hand planting was employed then a guidance system for each row would be required and there could be no synchronisation across the drilled bed; this would add to the cost of the overall mechanism. If each row is random and not linked to the next then the intra-row weeder would have to sit above the row crop, and weed a single row at a time. If on a regular pattern then the weeder could be placed between two rows, and weed in the intra-row either side.

The following section investigates current technologies employed within the industry to develop a uniform crop stand, and those that may later be adopted to improve current practice.

6.3.2 Plants on the square across an entire field

The author has found no evidence to support or indicate that drilling on the square across a field is practical as detailed in Section 2.5.2. Within the drill bout it would seem feasible, as the coulters are set and move together, but it is the registration of adjacent bouts that causes problems. Drill bouts would need to be aligned at the start of every run, with negligible error. Synchronisation of bouts would be the primary problem, as previous seed placement is not obvious (they cannot be seen with the naked eye). Most drill metering devices are land driven via a wheel, so wheel skid or undulation will affect the spacing. Differential global positioning systems (DGPS) could be tried, but such systems are expensive and thought not to provide sufficient accuracy.

Using a transplanter to plant on the square seems more feasible as a transplanter has a much higher degree of accuracy compared to drilling. The transplanter has an advantage over the drill as it leaves behind a visible plant, which could be used for alignment. However, problems could occur through alignment error, which would result in the crop row being destroyed.

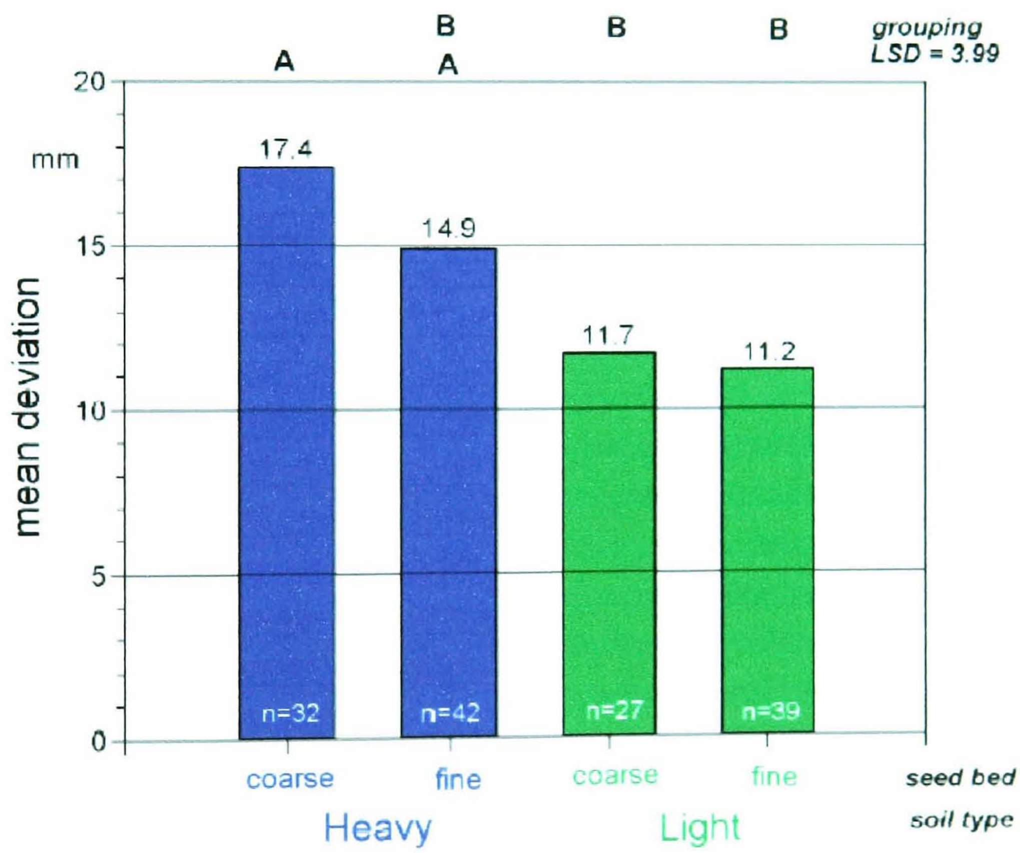
Drilling or transplanting on the square is not current convention, and would cause many problems in aligning drill bouts, it has, therefore, been dropped at this stage as a non-suitable approach to controlling weeds along the row by a cross-hoeing technique. Instead plants will be inter-row hoed, and intra-row hoed in the same pass, whilst travelling between the row.

6.3.3 Precision drill accuracy

Experiments on the Stanhay Singulaire Precision seed drill were undertaken by Maguire (2000) who investigated the along the row spacing consistency when drilling maize. Two experiments were undertaken, a theoretical study to check the seeding performance as seed was drilled onto a sticky belt in the laboratory and later field trials. The results from the sticky belt showed that at slow forward speeds of 3.2 km/h the drill was more accurate than at the tested higher speed of 4.8 km/h. It also showed that the drill became more accurate as plant population/m^2 increased. With a mean plant spacing of 100 mm along the row, the drill obtained a standard deviation of 18 mm.

Field investigations indicated similar results, but a higher standard deviation of 25 mm was recorded for a mean spacing of 100 mm. This was probably due to the movement of seed placement within soil due to clods and stones. If these units were all linked together, then it may be possible to use a precision seed drill, as a regular pattern is achieved.

Griepentrog & Norremark (2002) investigated the precision of the new Kverneland Accord Monopill precision seed drill. Set on a 202 mm spacing drilling sugar beet at 3.5 km/hr. The positions were recorded using RTK GPS (Real Time Kinematics Global Positioning System). Figure 6.4 shows the effects and accuracy of seed placement on varying soil types.



Source Griepentrog & Norremark, (2002)

Figure 6-4 Kverneland Accord Monopill precision drill accuracy

These results are similar to those obtained by Maguire (2000) but an additional factor that of variability through soil tilth is included, where it can be seen that better performance was obtained in light soil types. Any proposed weeding mechanism must be able to cope with variation that occurs in plant position along the row, through either changes in soil type or error associated with drilling.

6.3.4 SRI Dibber drill

The Silsoe Research Institute Dibber drill is an alternative to precision drills and a cheaper alternative to transplanting. Brown *et al.* (1994) report the cheapest way to establish a crop is by field sowing and that some commercial drills offer reasonably accurate spacing (standard deviation ± 15 mm) but the spacing of the plant stand is often degraded by erratic emergence.

The Dibber drill gently presses each seed into contact with the soil to provide precise seed placement and creates optimum growing conditions. The Dibber drill is capable of speeds up to 2 m/s (7.2 km/h) and can place seeds to an accuracy of ± 3 mm and also shows emergence improvements, (Silsoe Research Institute, 1996).

Although the Dibber drill appears to be a solution to the problems of planting on a regular pattern it has not been taken up commercially. Whether the development of an intra-row weeder will give new life to the Dibber drill concept will be a matter of time. However with a standard deviation of 3 mm it would be possible to use a less sophisticated recognition system.

6.3.5 Transplanter accuracy

Transplanters are popular and widely used in the high value vegetable growing sector. They provide excellent establishment and regular spacing of plants.

During August 2000 a measure of transplanted performance was undertaken in brussels sprouts on a 162 ha (400-acre) farm in Bedfordshire as part of this research programme. The transplanting method employed by this farm was more suited to the small-scale producer, as the transplants were put in by a semi-mechanised hand planting system. A toolbar the width of the tractor was pulled across the soil, and marks were made in the soil at a set spacing by a spiked wheel. The field workers followed behind, and placed transplant modules in the mark provided. The crop investigated was planted on a target intra row spacing of 550 mm. The results from the transplanted crop showed that a mean intra plant spacing of 550 mm could be achieved with a standard deviation of ± 54 mm, (9.8% error where affects of wheel slip and skid have been removed). One of the noticeable problems with the transplant marker was that of slip or skid that must have been experienced whilst placing the marks, so that occasionally two plants would be close to each other followed by a large gap. This could be overcome by altering the land wheel metering system, which causes many problems in drilling crops. Analysis of the data has shown over the 64 readings taken 4 were excessively out of place, therefore, typically 6.3 % of the plants were out of place.

On 17th July 2003 transplanter accuracy as part of this study was further investigated. The transplanter reviewed was a British built 7 row transplanter under the name of Pelican. Measurements were undertaken at Marshall Brothers, Butterwick, England who jointly farm approximately 4452 ha (11,000 acres) of high value crops per annum. Three crop varieties were selected, each with a different target intra-row field spacing. The along the row spacing for each variety was measured to obtain the variation that occurred along the row, and the frequency of slip or skid. Table 6-5 presents the actual mean row spacing and the percentage variation in intra-row spacing; additional information can be found in Appendix A4-1. As observed with the manual method of transplanting, slip/skid or operator error in transplant module loading occurred, which resulted in either plants being missed or closely spaced. For analysis purposes of transplanter precision, plants missed or closely spaced have been removed.

Table 6-6 Measured crops

Crop	**Spacing** mm/(inches)	**Actual spacing** (mm)	**Standard deviation** (mm)	**% of spacing**
Summer Cauliflower	610 x 457 (24x18)	479	42	8.7%
Calabrese	610 x 381 (24x15)	406	41	10.0%
Tundra Cabbage	500 x 330 (20x13)	333	29	8.7 %

It can be seen from Table 6-6 that the intra-row spacing (pitch) error is approximately 9 % of the spacing for the three varieties, indicating that the error is independent of pitch. A mechanical intra-row weeding device needs to be able to cope with a 10% variation in pitch to ensure it success on commercial farms.

Grouping of data from the three crop varieties has shown that over the 207 samples measured, 16 had large deviations through either having a missing plant or two closely spaced plants; the percentage of this occurring in the field would be 7.7% of the time. When compared to hand planting, the Pelican transplanter performed slightly worse in terms of missing plants or two closely spaced with 7.7% occurrence compared to hand planting with 6.3% occurrence. In terms of repeatability in intra-row spacing the results were similar with the average pitch spacing for the pelican having 9.1% variation and the hand planting system having 9.8% variation.

6.3.6 Crop zone clearance

Although variability in crop spacing is known through experimentation outlined in Section 6.3.5 the clearance for the crop root zone is also of great importance, as any weed control mechanism must avoid this area to prevent root damage. In early growth stages i.e. within a week of transplanting then the clearance zone can be small as the plant remains mainly in the module. A typical commercial module plug width is 30 mm, therefore a clearance of 15 mm either side would be acceptable. As the transplant grows then root zone clearance limits have to increase to avoid root damage. Personal communication with Marshall Brothers (2003) indicated that the available window of weeding was between 2 – 4 weeks after transplanting. In the first two weeks the pre-planting herbicide would control the weeds, and after 4 weeks the leaves would touch in the row, thus limiting intra-row weed growth. In July 2003 the root zone of cabbage 4 weeks after being transplanted was investigated; a typical example is shown in Figure 6-5, the important parameters are illustrated.

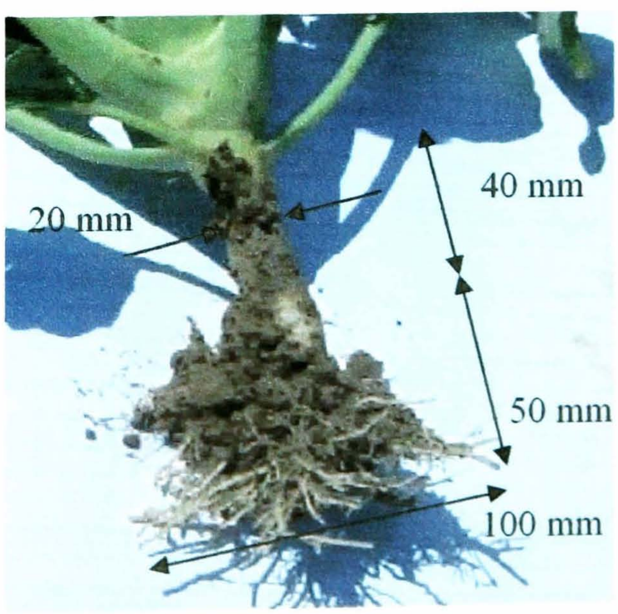
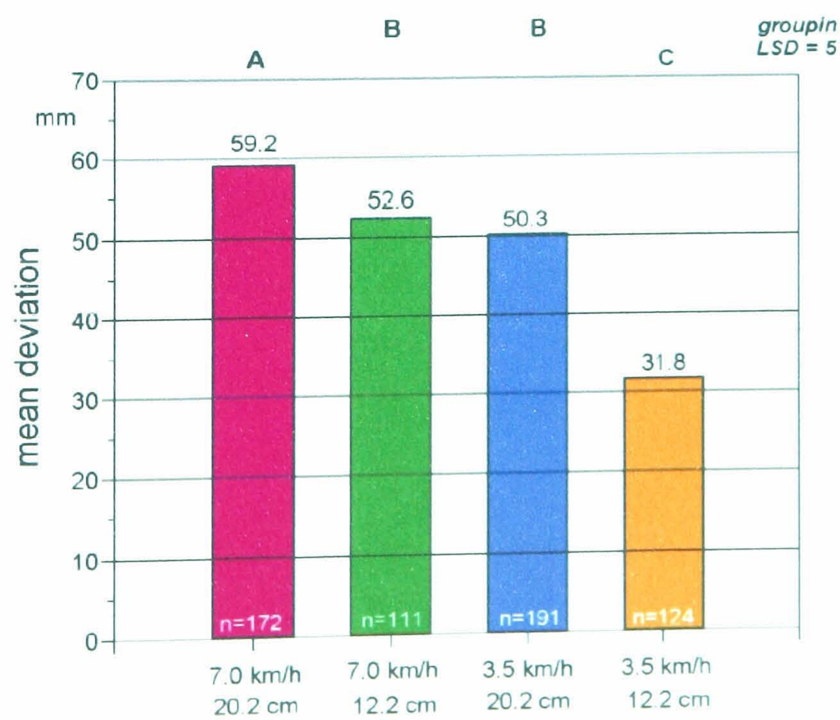


Figure 6-5 Cabbage root zone

The crop roots were generally fibrous, having no major tap root unless facing drought conditions, therefore the roots spread out laterally from the module. All of the transplanted crops were set in square peat modules with a nominal width of 30 mm. It can be seen from Figure 6-5 that the nominal stem width is 20 mm, of which approximately 40 mm of stem is below the soil surface before the root ball starts. The root zone extends nominally 50 mm below the base of the stem and extends to an approximate width of 100 mm. Any cutting mechanism must therefore allow clearance around the stem of the plant. Due to the depth of the root zone it is unlikely that the plant roots would be cut by a mechanism operating in the top 25 mm of the soil.

Another variable that should be considered is that of transplanted position and true plant position, as certain crops can grow along the ground, then grow vertically. Griepentrog & Norremark (2002) undertook experiments to determine the position between drilled location and final true plant stand in sugar beet. The results presented in graphical form in Figure 6-6 show that with the combined deviation through drilling and emergence, seed position has a mean deviation up to a maximum of approximately 59 mm, on a pitch of 202 mm, dependant upon pitch spacing and drilling speed. The drilling deviation was approximately a third of the total deviation, therefore the emergence accounted for about 40 mm error, and a crop zone clearance of 20 mm either side would be required to avoid cutting the main stem of the plant.



Source Griepentrog & Norremark, (2002)

Figure 6-6 Mean deviation between estimated position and true plant position

6.3.7 Summary

As planting on the square across an entire field is not yet possible, intra-row drill bout matching technology is currently unavailable, and cross hoeing is not feasible an intra row weeding device is necessary to control weeds along the row. Knowledge of along the row crop spacing variability will inevitably aid in the design of a mechanical intra-row weeding mechanism. The developed system must adapt to existing technology as massive investment costs of new transplanter technology cannot be justified to facilitate mechanical intra-row weed control. The recognition system and mechanical device employed must be able to cope with variations in intra-row spacing of 10% of the pitch and also cope with 8% of the plants being closely spaced or missed.

With a nominal root zone of 100 mm a 50 mm area either side of the plant would be necessary to avoid the roots completely. However as the root zone starts approximately 40 mm away from the soil surface it could be argued that only 10 mm either side of the plant centre need to be allowed to clear the stem. This however would increase the risk of damage. Therefore to allow a factor of safety when operating at 25 mm deep for weed control, a root zone clearance of 30 mm either side has been selected based on Griepentrog & Norremark (2002).

6.4 Current intra-row weed control

This chapter has so far reviewed the widely spaced field vegetables sector in Europe and the USA, reporting on current practice in terms of crop establishment, number of holdings and crop varieties that would suit a mechanical weeding device. Chapter 2 reviewed the many ways intra-row weeds can be controlled, classifying them into soil engaging and non-soil engaging approaches. This project has focused upon the soil engaging approach as detailed in Section 2.3. Research indicates that intra-row weed control needs to occur at an intra-row spacing minimum of 300 mm. Currently hand hoeing is seen as commercial best practice and therefore alternative systems are compared with that of hand hoeing.

6.4.1 Hand hoeing work rates

There is no doubt that hand hoeing is one of the few remaining tasks that has yet to be mechanised in agricultural, the work is arduous, yet necessary to achieve high crop yield. Watson & More (1949), stated that if a man is to make good work he can generally do no more than a quarter or fifth of an acre per day. Converted to metric results in 0.08 - 0.1 ha/day. Watson & More are referring to singling sugar beet, which is the removal of extra plants along the row, similar to that of intra-row weeding.

Miles (2000) of Marshall Brothers Ltd, Boston, discussed commercial hand weeding operations that are currently undertaken, reporting that typical intra-row hand weeding in brassica is 0.15 ha/day; thus suggesting there has only been slight advances in hand weeding work-rates over the last fifty years. The commercial intra-row hand weeding rates stated by Miles (2000) were achieved when following mechanical weeding in the inter-row.

If the work rate of 0.15 ha/day is taken over a standard eight hour day that equates to an intra-row hand weeding rate of 0.0193 ha/hr. This is not only expensive in terms of time but also very costly for labour. Figure 6-1 presented the minimum agricultural wages for England and Wales with the projected hourly rate of £5.72/hr for 2004. Based on Figure 6-1 a typical cost to hand intra-row hoe a hectare of ground by one man is £305 based on taking 52 hours to complete. It must be remembered that it is unlikely one man would be hoeing, often there are gangs of men to increase the rates of work as shown in Figure 6-7 where a gang of six men are intra-row hoeing a lettuce crop. This makes intra-row hand weeding a very expensive option, but occasionally a necessity that can only be justified due to the high value of the crops.

Picture shown by courtesy of Bedfordshire Growers (2003)

Figure 6-7 Intra–row hand hoeing in Bedfordshire

There are of course alternatives, as discussed in the review in Chapter 2. One way of reducing the burden of intra-row weeds is to maximise the inter-row weed area as mentioned in Chapter 3, by improved lateral positioning, thus increasing the width of the hoe blade. With this improved lateral positioning it is also possible to travel at higher speeds if the soil displacement can be controlled. Chapter 7 discusses soil displacement in further detail, and how hoe blade design can use soil displacement to control weeds close to the crop.

6.4.2 Mechanical hoeing

Unlike hand hoeing, mechanical inter-row weeding has made significant advances over the last 50 years and optimisation of the hoe blade width will reduce the number of intra row weeds that need to be targeted.

Watson & More, 1949 state that "traditionally, weeding operations were undertaken using horse and hand labour (Figure 6-8). The horse would drag the hoe blade through the soil, which was guided by the horseman. A work rate of about three man-hours per acre was achieved until later replaced by a two- horse cultivator with suitable shares as to deal with three rows. This reduced the labour cost to little more than one man-hour per acre". In today's terms that would be a work-rate of 0.4 ha/hr or 2.5 hr/ha.

Figure 6-8 Single row horse hoeing

Today with vision guided inter-row hoes the work rate on a standard 4 m hoe provides a spot work rate of 4 ha/hr, thus providing a ten fold increase in output with improved accuracy. Further details on inter-row weed control can be found in Section 2.3, where other types of soil engaging weed control implements are described detailing their efficacy and work rate.

6.4.3 Recent intra-row developments

There are currently two other dedicated mechanical intra-row weeding machines in the development stage that attempt to provide a solution to hand weeding. They are the 'rotating disk' from Wageningen University and the 'Cycloid Hoe' from Osnabrück. Cavalieri *et al.* (2001) report that "the rotating disk and the cycloid hoe are two newly developed intra-row weeders, which have to be guided by a real time system or a mapping system".

The rotating disk developed at Wageningen University, and shown in Figure 6-9 consists of a vertical rotating disk on which two knives are attached with springs, Bontsema *et al.* (1998).

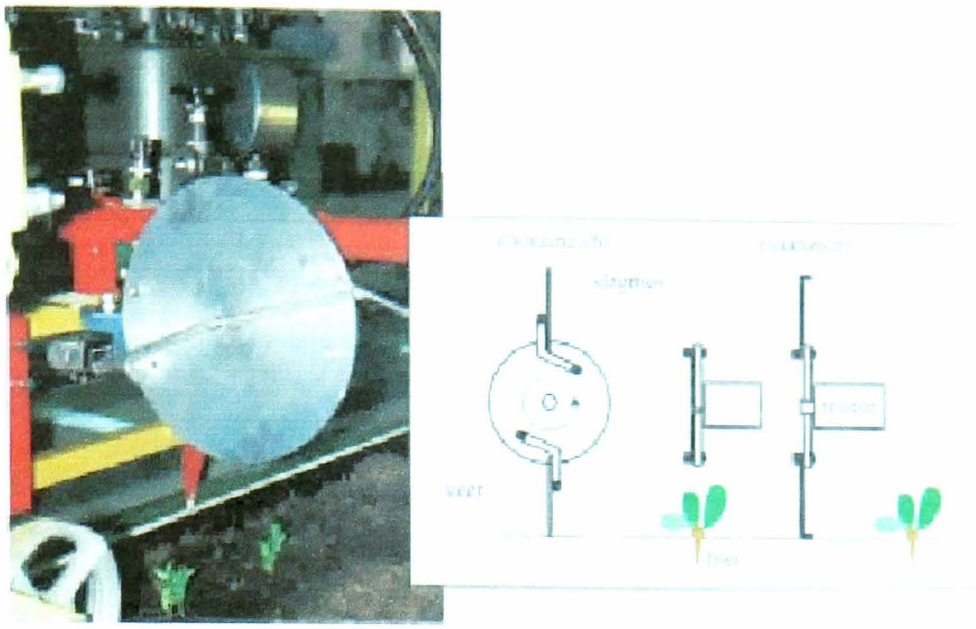


Figure 6-9 Rotating tine (Cavalieri 2001)

Bontsema *et al.* (1998) state "the disk is actuated by a hydraulic motor and the number of revolutions by the motor is controlled by a hydraulic controller. The motor is permanently rotating at 850 rev/min and the knives are folded out, due to the fact that the centrifugal force is larger than the spring force. If the detection system detects a beet plant, the number of revolutions is set to 700 rev/min and the knives almost immediately are folded in".

The design chosen ensures that it has a bi-stable operation, i.e. blades are either in or out. Bontsema *et al.* (1998) report measurements taken, showed that it takes less than 40 ms to go from one position to the other. This system is non-soil engaging and acts similar to a mower along the intra-row. If it were soil engaging, several factors such as excessive soil throw and force required, ensuring bi-stable operation may pose a problem. Plant detection consists of light sensors at three different heights of plant level. Week kill efficacy according to Jones & Blair (1995) will be reduced if cutting (above the surface) is the only mode of action.

More recently, Asselt (2002) found the device to be unsuccessful in the field, and has moved to investigate the practicalities of using CO_2 lasers to cut the weeds rather than the rotating knives. Current difficulties seem to be the high power requirement of 150 W for the laser beam to provide an adequate work rate. The same detection system is capable of working at 10 km/h and can distinguish between the crop and the weed as long as the along the row spacing is more or less constant. There is no information on the working speed, or working quality for the rotating disk, Cavalieri *et al.* (2001).

Osnabrück Applied University in collaboration with Amazone Werke have developed the cycloid hoe, (Cavalieri *et al.*, 2001). This hoe is designed to control both the inter-row and intra-row weeds in one pass. Inter-row weeding is undertaken using the traditional method of a 'goose foot' hoe blade. Figure 6-10 details the intra-row weeding mechanism mounted to an autonomous vehicle.

Two intra-row tools are attached to the implement bar to carry out the intra-row weeding control in each row, one tool on each side of the row. The tools are directly placed above the row, but to one side. Each tool consists of eight tines that are placed in a circle around an axis. The axis turns around as do the tines in a circular motion. The combination of the circular movement of the tines and the linear movement of the implement leads to a cycloidal path, (Cavalieri *et al.*, 2001). It is reported that the cycloid hoe can operate at 8.5 km/h with an around plant safety zone of 18 mm. The machine is complicated with many working parts, which leads to high maintenance and high purchase price. The system is still in prototype stage and has not been tested in the field. The cost of the system has been forecast (Cavalieri *et al.*, 2001) at £21,051 for a 6 row machine with an additional cost of £29,599 for RTK GPS, the principle of which is described in Section 2.6. These are budget costs but already it is an expensive piece of machinery and with an around the plant clearance of 18 mm, the mechanism could potentially damage the crop.

Source: - Christensen *et al.* (2001)

Figure 6-10 Cycloid hoe

6.4.4 Summary

In order for mechanisation of intra-row weeding to be accepted it must be economically and commercially viable. Rates of work must be superior to that of existing methods and the machine must be robust and accurate.

Although there are now two alternative approaches to control intra row weeds, field evaluation and weeding efficacy have yet to be quantified. The Cycloid hoe strongly relies on the use of real time kinematic GPS, which has yet to have the levels of accuracy for weeding at an affordable cost. The alternative approaches both have complex mechanisms and control systems that are not in a commercial form, and cost has not been a priority in the design. If a mechanism is to be successful on a commercial basis it must not only be effective but have simple operation, few moving parts, at a cost that reflects its work rate and is appealing to the industry. Neither of the systems used sub-surface cutting, and therefore weed kill efficacy according to Jones & Blair (1995) could be reduced.

It has already been proven that accurate guidance is essential to a successful weeding operation and therefore a vision guidance system will be harnessed to deliver the lateral positioning of the hoe because it is already commercially available, and its performance already quantified. The following sections detail the criteria for a proposed mechanism that will successfully control intra-row weeds, using cutting and burial as the main modes of weed kill; desiccation and up-rooting will be additional benefits to the system.

6.5 Design considerations

It is of paramount importance that all relevant design considerations are considered at this conceptual stage as if the mechanism is to be versatile and cost effective it needs to be designed correctly from the outset. It is known that it is difficult to reduce the cost after the initial design stage, therefore cost and crop versatility will be dominant factors throughout the design, as well as providing excellent weeding efficacy.

6.5.1 Target area

Section 3.3 details the design of an optimised hoe blade, stating that its width can be maximised to ensure maximum inter-row weed control, based on Equation 3-1 in Section 3.3. The parameters listed in Table 3-3 (Chapter 3) were for a cereal crop, and although the bias of 7 mm and guidance error of 28 mm for the SRI vision guidance system will remain the same, crop zone clearance has been increased to 30 mm either side of the plant. Table 6-7 details the width of an optimised hoe blade for each given row crop spacing.

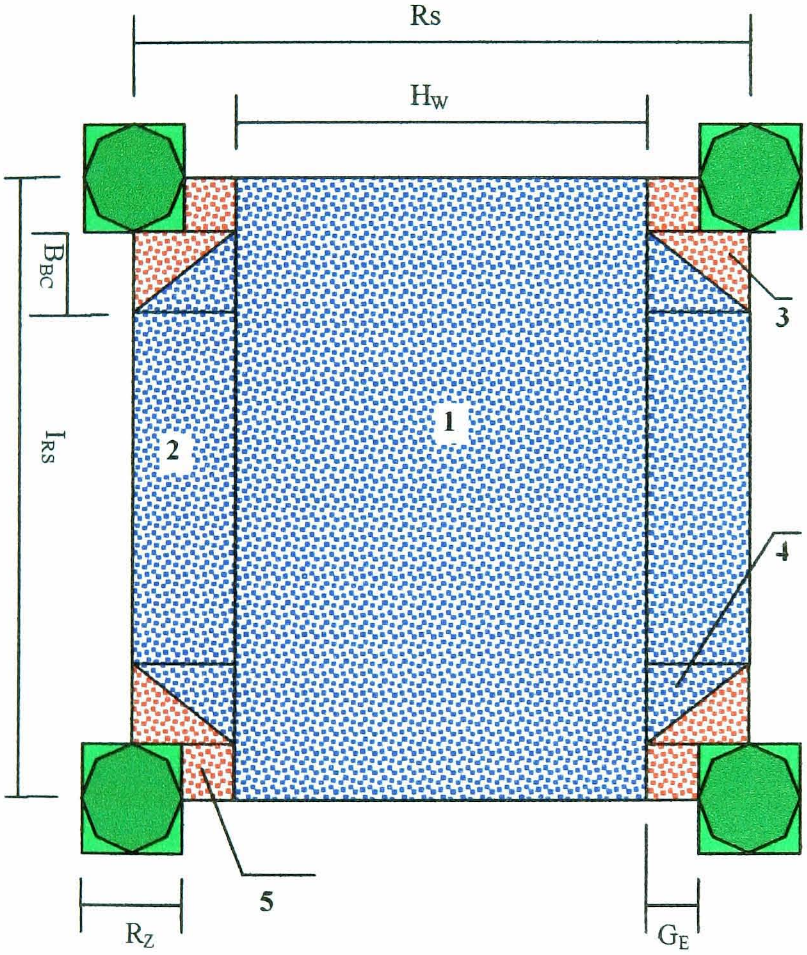
Table 6-7 Crop spacing

Crop	Inter-row spacing (mm)	Optimised inter-row blade width (mm)
Brussels Sprouts	500-900	387-787
Calabrese	400-500	287-387
Cabbage	300-600	187-487
Cauliflower	600-750	487-637
Lettuce	700	587

Table 6-7 shows that a combination of inter-row hoe blades would be required to provide optimised inter-row weed control. This is not desirable as many producers grow a variety of crops, and would therefore need to change the blades for each hoeing operation. Therefore an intra-row weeding mechanism will be designed to fit to a standard width hoe blade, and the intra-row device will provide adjustment for the designated plant variety.

Within the weed target area the two main effective modes of weed kill as stated in Section 2.3 are cutting and burial, each having their own level of efficacy based on experiments undertaken by Jones *et al.* (1996).

An idealistic pictorial representation of the efficacy of cutting and burial is shown in Figure 6-11 and an effective weed kill equation follows based on the efficacy of cutting and burial. Cutting is chosen as the main mode of weed control with a secondary mechanism of burial. Burial can be used close to the crop where cutting may damage the plant roots.



KEY		
H_W	=	Hoe blade width
R_S	=	Row spacing
I_{RS}	=	Intra-row spacing
R_Z	=	Root Zone
G_E	=	Guidance error
B_{BC}	=	Burial before cutting
E_C	=	Effective cutting (Blue zone)
E_B	=	Effective burial (Red zone)
EWK	=	Effective weed kill
EA	=	Effective area

Figure 6-11 Weed kill efficacy

Zone 1 Weeds controlled by optimised inter-row cutting

Zone 2 Weeds controlled by intra-row mechanism through cutting

Zone 3 Weeds controlled through burial by inter-row and intra-row mechanism

Zone 4 Weeds controlled through cutting by intra-row mechanism

Zone 5 Weeds controlled through burial by inter-row blade

The red shaded zones in Figure 6-11 illustrate where burial will be employed to control the weeds as any mechanism needs a proportion of time for lead in and lead out. The inter-row blade will be used to bury the weeds close to the crop in zone 5, and a combination of inter and intra mechanism burial to control the weeds in zones 3 and 4, where the mechanism will have lead in and out. The effective controlled area can be calculated, for any given crop spacing with the use of the control efficacy of burial and cutting. The equations below detail the effective weed control area, the effective area available to undertake weed control, thus providing a percentage weed kill by area, derivation can be found in Appendix A4-2.

$$\textbf{EA} = (IRS*RS)-RZ^2$$

$$\textbf{EWK} = \{(IRS*HW)+[(RS-HW)*BBC]+[(RS-HW)*(IRS-RZ-(2*BBC))]\}*EC)+$$
$$\{[RZ*(RS-RZ-HW)]+[(RS-HW)*BBC]\}*EB$$

$$\textbf{WK\%} = EWK/EA * 100$$

The following shows an example based on summer cauliflower spacing.

IRS	= 0.5 m	RZ	= 0.06 m
HW	= RS – Guidance error – RZ = .413 m	Ge	= 0.027 m
RS	= 0.6 m	E_c	= 0.945
B_{BC}	= 0.2 m	E_b	= 0.70

EA = 0.246 m^2
EWK = 0.228 m^2
WK % **= 92.6 %**

The calculation shows that with an area of 0.246 m^2 available for weed control, 0.228 m^2 can be mechanically weeded without risking damage to the crop based on the weeding efficacy for burial and cutting of the controlled area in Figure 6-11. If a weeding mechanism can cut and bury in the area illustrated in Figure 6-11; 92.6 % of the weeds in the available area will be controlled. Figure 6-11 illustrates an ideal situation, the mechanism must now be designed to closely match that to maximise cutting, whilst avoiding crop damage.

Although not offering a 100 % solution to weed control, it certainly provides improved performance over any other mechanical system. The weed kill can be broken down into two components of inter-row and intra-row weed kill, of which 79.2% and 13.4% of the area respectively account for total weed control of 92.6%

The new weeding mechanism needs to ensure cutting can be maximised, thus reducing the area that is buried, as burial is less effective at controlling weeds when compared to cutting. Actual weeding efficacy for the mechanical intra-row weeding device is detailed in Section 7.6.

6.5.2 Individual plant recognition

As it is appropriate to use vision guidance for lateral positioning the already commercial vision guidance system known as 'Robocrop' developed at Silsoe Research Institute will provide lateral positioning accuracy with individual plant identification made available, at minimal extra capital cost.

For a weeding machine to be implemented it must work within current practice, therefore cope with variations in pitch spacing caused through transplanter error, as well as wheel slip and skid along the row as discussed. The error associated with growth stages as the plant does not grow vertically may also be accounted for to a certain level. Transplanted crops are set on a regular grid pattern; therefore, a cyclic mode of weed control can be employed. A vision recognition system could therefore change the phase relationship between where plants should be on a grid formation to their actual location. The vision guidance system is based on techniques developed by Hague & Tillett (1996), Marchant *et al.* (1997), Hague *et al.* (2000) and Hague & Tillett (2001).

6.6 Conclusions

- Rising labour prices and labour scarcity in the agricultural sector, combined with policy change, require mechanisation to undertake mechanical weed control in and along the row.

- There are currently no commercial machines for mechanical control (sub-surface cutting and burial) of weeds in the inter- and intra-row of widely spaced field vegetables.

- There is a potential mechanical weeding market of circa 10,000 machines in Europe and the USA

- For a commercial machine to be successful it must be able to operate with an intra-row plant spacing ranging from 0.3 m to 0.6 m. It must also have the ability to operate with a 10% variation in mean intra-row spacing as well as cope with missing and closely spaced plants.

- An inter- and intra-row weeding system has the potential to treat 93% of the available area on a 0.5 m spacing through sub-surface cutting and burial. This is a 16% increase over inter-row hoeing alone which treats 79% of the area.

7 Intra-row weeding mechanism

7.1 Introduction

The literature review identified that there were no commercial techniques currently available to viably control intra-row weeds. There has also been no significant advance in inter-row cultivations apart from the introduction of guidance systems to improve their overall operational speed and accuracy. Rates of work remain similar to those achieved 50 years ago on unguided machines, and hoe blade design has remained the same.

In order to develop an intra-row weeding system it was important to quantify the lateral positioning accuracy of inter-row weeding operations, as maximisation of inter-row weed control reduces the weed area. Commercial blade width maximisation had not been previously undertaken due to the lack of accurate positioning information and, therefore, a sufficient buffer strip was required between the crop row and the hoe blade tip. The lateral positioning experiments addressed this problem by identifying that implements with a guidance system improved lateral positioning to within ± 30 mm. This error value is extremely important as it will allow designers and manufacturers of hoe blades to specify the correct blade for a given implement and guidance system. Farmers with a guidance system whether an additional operator or vision guidance have the existing benefit of reduced risk of crop damage, but should now be able to have increased weed control through correct blade selection.

The inter- and intra-row weeding system with known levels of positioning accuracy can be further developed, as the target area for intra-row weed control has been reduced though maximising hoe blade width. For successful weeding between crop row centres the mechanism with vision guidance will require a minimum swing distance of 60 mm. This will ensure weeds are controlled even if the implement is offset. If successful, a weeding module can be situated between every other row, thus reducing the number of components and the overall cost.

Following field investigations of inter-row hoeing it was apparent that excessive soil displacement was caused by the tillage operation. This was often controlled by the installation of side guards, but these can cause crop damage and add additional cost to the implement. Observation of various leg widths and mountings to the blade indicated that their parameters influenced soil displacement and was also identified as a potential contributory factor to soil displacement in the literature review. The solution to excessive soil displacement is blade and leg redesign. Although few authors have researched soil displacement and identified the parameters such as, speed, compaction, leg width, sweep angle and rake angle as influencing factors no further work in quantifying their effects had been undertaken. The problem of soil displacement was traditionally concerned with lateral displacement; however for a new inter- and intra-row weeding system control of forward displacement may be critical if a blade operates between plants along the row. If a blade operates in the intra-row area soil will be moved forward, which could potentially bury the crop plants. However, forward soil displacement can be a successful mode of weed control when cutting may be seen as dangerous, i.e. around the crop roots. Therefore, for development of the weeding system it was essential to understand the soil displacement process to enable design of potential intra-row weeding blades.

The fundamentals of soil deformation and influencing factors of soil displacement were quantified to aid blade re-design. This was possible with the use of the soil laboratory investigations under controlled conditions. The factors identified as influencing soil displacement were investigated i.e. blade velocity between 0.278 m/s to 2.78 m/s, effective rake angles of 14^0, 20^0, 35^0 and 45^0 and blades with a 45^0 sweep and blades without sweep, at two densities of 1306 kg/m^3 and 1493 kg/m^3. Leg widths of 6 mm, 20 mm and 40 mm were investigated separately to examine their effects of soil displacement, and how this could be incorporated into blade design.

To reduce the number of possible blade widths required to maximise inter-row weeding in widely spaced field vegetables it was decided that a standard blade could be designed, and the width maximised by the correct location of the intra-row blades. The inter-row blade could, therefore, be designed to cause significant mixing by having a steep rake angle as forward displacement would not damage the crop plants, and lateral displacement kept to reasonable limits i.e. less than 50 mm as the distance between the inter-row blade and crop plant would be relatively large, as the intra-row blades would travel close to the crop. For a typical row spacing of 0.5 m a 0.4 m wide inter-row blade could be designed as a general purpose blade.

Blade design is aided by the use of the soil translocation model, developed from first principles based on a mass flow approach. The model enables prediction of both forward and lateral soil translocation, and facilitates the manipulation of soil parameters, blade geometry and operating speed.

If analysis of potential designs finds cutting in the intra-row as the most effective means of controlling intra-row weeds, then the mass flow soil dynamics model will enable the correct design of an intra-row blade. Experimental field evaluations will establish the true blade path and thus determine the required distance of soil forward translocation.

With the ability to design the hoe blade to provide the correct amount of soil displacement, and employing vision guidance to enable the inter-row hoe blade width to be maximised, the operational speed and work rate remain to be addressed. The review of holding size (England & Wales) found that the average holding greater than 20 ha was 52 ha. Assuming the crop needed two treatments per year in an assumed available 20 workdays, with 75% field efficiency an effective work rate of 1.08 ha/hr would be required. Therefore, the new weeding system will have to operate at 1 m/s for a 4 m five module unit (10 rows at 0.5 m row spacing). This leaves approximately 40% spare capacity, for break downs, poor weather conditions, or possible contracting of the weeding machine.

In Europe and the USA it is proposed that there is a market potential of circa 10,000 machines, this should ensure that such a system would be of significant interest to potential manufacturers. It also has the ability if correctly priced to compete with chemical approaches to provide mechanical weed control in conventional systems. When a design has been selected and built, field evaluations will enable the work-rate to be calculated, as well as machine costs and, therefore, cost per hectare to be established. Comparisons can then be undertaken against alternative weeding systems, to determine if the proposed inter- and intra-row weeding machine is a viable approach to mechanical weed control.

Research throughout this study has identified the need for a mechanical weed control system. Obtaining lateral positioning data combined with development of a soil translocation model will enable blades to be designed for specific weeding operations. The market potential is large enough to generate sufficient interest from manufacturers; therefore, if the principle can be proved in laboratory and field evaluations there is every possibility that this research programme will have identified a viable alternative to existing weeding operations.

7.1.1 Design criteria for a proposed weeding system

The research and reviews detailed in this project have identified key aspects in mechanical weed control that when combined together lead to the criteria of a successful intra-row weeding mechanism as outlined below.

- Simple low maintenance soil engaging mechanism
- Economically viable compared to traditional alternatives
- One pass hoeing controlling inter- and intra-row weeds
- Weeding device to operate over an intra-row spacing of 0.3 m to 0.6 m
- One mechanism for a variety of row widths and intra-row spacing
- Weeding device to operate in real time with 10% variations in intra-row spacing
- Optimisation of inter-row cutting area
- Main mode of weed control – cutting and burial
- Soil displacement utilised to control weeds close to crop
- Target forward speed of 3 km/h
- Hydraulics as mechanism power source.
- Adaptability to existing drilling/transplanter establishment

A mechanical weeding device that controls both the inter and intra-row weeds in one pass will provide the sector with an effective economic alternative to hand labour and reduce the cost of crop establishment through reduced chemical usage. The new mechanism must be versatile to hoe plants that have been drilled/transplanted with traditional technology. The following sections select a suitable mechanism evaluate an experimental system in laboratory and field trials, in conjunction with an economic analysis of comparison weeding systems.

7.2 Conceptual design of an intra-row weeding mechanism

There are many ways in which mechanical weed control can be achieved using cutting and burial techniques. The evaluation chart in Table 7-1 lists proposed designs, with weighted criteria, enabling design comparison and evaluation. The solution with the highest rating in the evaluation table would appear to be the best design, but features from other designs should be considered as they could be incorporated into the final design. All mechanisms were considered to be vision guided to provide lateral positioning accuracy. Basic conceptual sketches of the top five mechanisms are shown in Figure 7-1 and presented below in ranking order

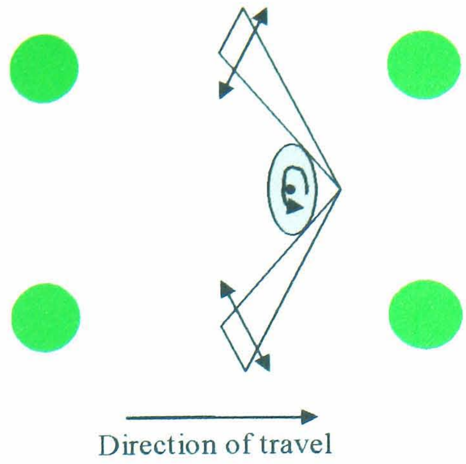
- Opening share (85)
- Moving arm (78)
- Soil movement (78)
- Side- shift (71)
- Extending spring (71)

The first two concepts shown illustratively in Figure 7-1 have similar principles, in that they both cut in the intra-row by swinging into the gap between the plants. Cutting is the main mode of weed control and some burial may occur from the blade if designed correctly. The parameter to investigate is that of the time available for the mechanism to enter into the intra-row, without risking crop damage. Although soil movement has less weed control efficacy than cutting, it is an attractive design feature as it eliminates the risk of root/crop damage. This combined with cutting in the intra-row may prove to be a successful means of weed control.

The side-shift approach controls both the inter- and intra-row weeds by cutting, but at narrow pitch spacing and relatively high forward speeds the response of moving two beams rapidly may be the limiting factor. The final concept shown is that of the extending spring. This would provide rapid entry into the intra-row, with cam rotation but supporting the extending mechanism may be more complex. The major problem with this design is that the extending blade would be a sliding mechanism which is prone to accelerated wear in soil.

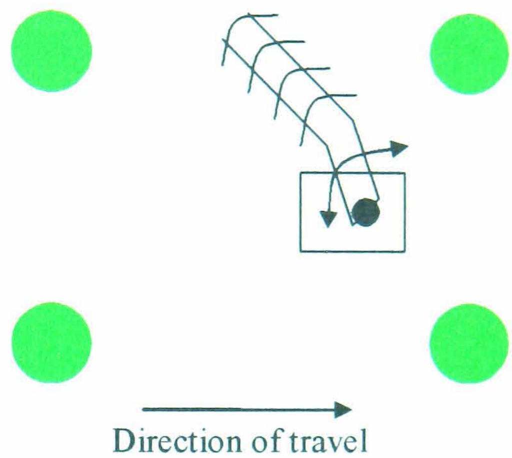
Table 7-1Evaluation chart of potential weeding mechanisms

	Adaptability			Main mode of weed control			Costs		Maintenance		Durability		Modular form		Weeding efficacy	Total
	Ability to work in transplanted/drilled crops	Ability to cope with variations in plant spacing	Ability to cope with variations in row spacing	Cutting	Burial	Cutting and burial	Low Capital	Low Running	Frequency	Ease of maintenance	General life expectancy	Wear	Modularisation	Ease of modularisation	Ability to control weeds	
	30			20			10		10		10		10		10	
Solutions	**10**	**10**	**10**	**10**	**4**	**6**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**10**	**100**
Cross hoeing	0	0	9	8	3	4	5	5	5	5	5	5	5	5	5	**69**
Moving arm	9	9	9	8	3	4	2	4	3	3	4	4	5	4	7	**78**
Soil movement	9	9	9	0	4	3	5	5	5	5	5	5	5	5	4	**78**
Opening share	9	9	9	9	3	5	3	5	3	4	6	4	5	5	8	**85**
Phased brush	6	3	8	1	3	1	2	3	4	4	3	1	5	4	3	**51**
Spinning chain	4	5	8	6	1	3	5	5	4	5	5	3	5	5	4	**69**
Side shift	8	7	8	8	1	4	3	4	3	4	5	4	3	2	7	71
Pendulum	9	9	7	4	2	2	3	3	3	4	4	2	4	3	6	**65**
Extending spring	10	10	5	7	2	3	4	5	4	5	3	2	5	5	5	71
Splayed brush	7	7	5	1	3	1	2	3	4	3	3	1	5	4	2	51



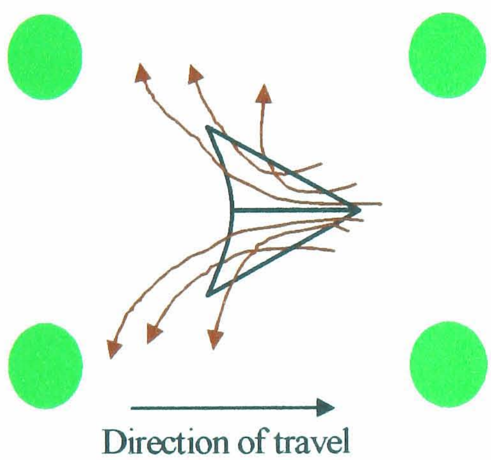
Opening share

As the cam rotates, two blades extend into the intra-row and cut the weeds, some burial may occur from the blade angle and bury weeds close to the crop.



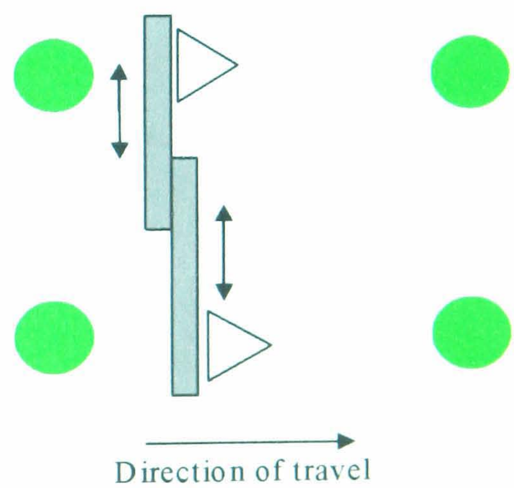
Moving arm

An arm consisting of several discs swings into the intra-row, controlling weeds through cutting.



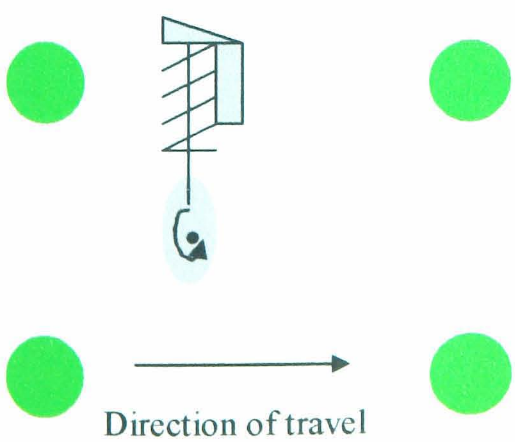
Soil movement

A steep rake angle blade is pulled through the soil, cutting in the inter-row and using soil to bury weeds in the intra-row.



Side shift

Two beams side-shift into the intra-row thus controlling the weeds by cutting, whilst also controlling the inter-row weeds.



Extending spring

As the cam rotates so a blade is released with the power of a spring to control intra-row weeds and further rotation pulls the spring back in.

Figure 7-1 Basic design concepts for intra-row weed control

7.3 Embodiment and analysis design

Following identification of three conceptual designs for further development the layout and form of suitable mechanisms were developed, along with technical and economic considerations. The proposed design is based on the opening share principle and soil movement concept, detailed in Figure 7-1. The opening blades extend out into the intra-row to cut the weeds, but weeds close to the plants are buried through appropriate design of the opening blade. The design of the intra-row cutting blade can be optimised by using the forward translocation model as soil displacement is critical in this direction to avoid crop plant burial. The inter-row weeds are controlled with an inter-row hoe blade, and the blade is optimised by correctly setting the extending blades retracted position. Before commencing mechanism design operating parameters were calculated to ensure the functionality of design as detailed in the following sections.

7.3.1 Response times required for mechanism actuation

With a lateral positioning error and root zone clearance, both of approximately 30 mm, the mechanism will need to extend a minimum of 60 mm into the intra-row to control the weeds. Table 7-2 details the time available to enter the intra-row for a range of forward speeds and row spacing. The time to enter the row has been calculated based upon the basic relationship that time is a function of distance over speed.

Table 7-2 Time available to enter the intra-row space

Forward	Row spacing			
Speed	0.3 m	0.4 m	0.5 m	0.6 m
(m/s)	(s)	(s)	(s)	(s)
0.50	0.48	0.80	1.00	1.20
0.75	0.32	0.45	0.59	0.72
1.00	0.24	0.34	0.44	0.54
1.25	0.19	0.27	0.35	0.43
1.50	0.16	0.23	0.29	0.36

As forward speed increases and/or intra-row space decreases then the available time to weed is significantly reduced.

7.3.2 Mechanism actuation

With hydraulics being selected as the power source, two methods were available for the mechanism, either hydraulic actuators or a motor and cam arrangement. A motor and cam arrangement was selected as it is a continuous mechanism, rather than the bang/bang approach by two hydraulic actuators. The continuous mechanism approach is less severe on the components, as the loadings are more constant and a rotary mechanism lends itself to a phase lock loop relationship between plant and mechanism position.

Assuming a hydraulic motor will be used to operate the mechanism then the rotational speed for the given intra-row spacing and forward speed can be calculated along with the torque required by the motor shown in Table 7-3 as well as illustrated in Figures 7-2.

Each cycle (one plant to the next) is completed every 180^0 of motor rotation, therefore, based on a forward speed of 1 m/s and an intra-row spacing of 0.5 m the following motor speeds are required.

½ rev per 0.5 sec = 1 rev/sec x 60 = 60 rpm

Table 7-3 Hydraulic motor revolutions (rev/min)

	Row spacing			
Forward speed (m/s)	**0.3 m** (rev/min)	**0.4 m** (rev/min)	**0.5 m** (rev/min)	**0.6 m** (rev/min)
0.50 m/s	50	37.5	30.0	25.0
0.75 m/s	75	56.5	45	37.5
1.00 m/s	100	75	60.0	50
1.25 m/s	125	93.75	75	62.5
1.50 m/s	150	112.5	90	75

Table 7-3 presents the range of the motor speed in revolutions/minute, given that 180^0 rotation will extend, and retract a mechanism within the intra-row plant space. Given the above working motor speeds a correct motor needed to be selected, which can operate through the range of calculated speeds and have sufficient torque to open the blades whilst cutting in the soil.

It was assumed for motor torque calculations that a maximum draught force of 0.761 kN (based on Wheeler & Godwin, 1996) could be subjected to a blade 550 mm wide operating at 35 mm deep at 3 m/s with a rake angle of 45^0. The motor specified was required for development and evaluation purposes and needed to be capable of delivering enough torque to cope with future demands. It was assumed that the maximum subjected force on each half of the blade is 0.761/2, with a cam diameter of 170 mm in a soil of density equal to 1494 kg/m^3. Draught force calculations are based on Wheeler & Godwin (1996) and presented in Appendix A.5-1. Figure 7-2 presents the forces on the blade.

Additional force due to acceleration of the blades as detailed in Appendix A.5-1 was found to be negligible and, therefore, has not been included in the torque requirement for the motor.

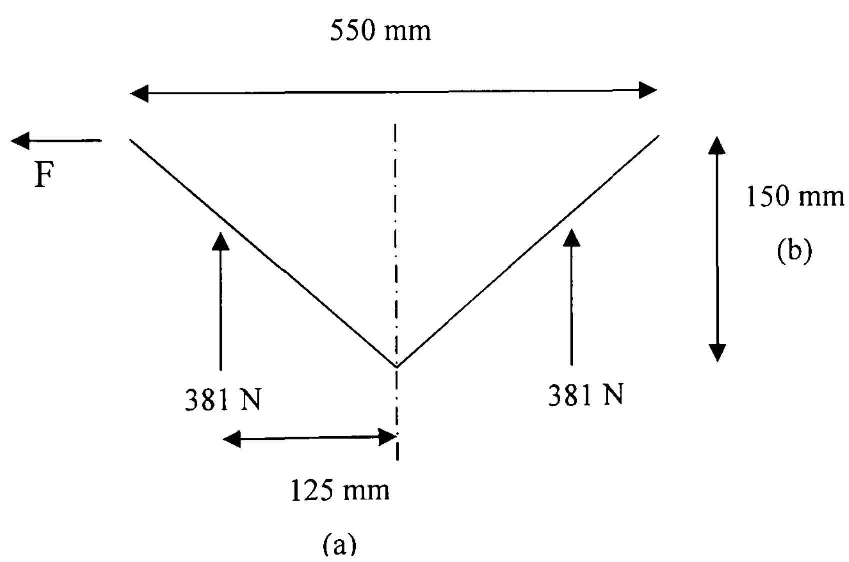


Figure 7-2 Potential forces on a new weeding blade

$$F \times b = 381 \times a$$

$$F \times 0.150 = 381 \times 0.125$$

$$F = (381 \times 0.125) / 0.150 = 317.5 \text{ N}$$

If a cam of 170 mm diameter was used to swing the wings out then the motor needs the following torque requirement.

Torque (T) = Force (F) x Distance (D)

Therefore:

$$T = 317.5 \times 0.085 = 27 \text{ Nm}$$

Therefore a motor generating a torque minimum of 27 Nm will be required to operate the experimental mechanism. The motor selected has the following torque:

Motor torque = [Motor displacement (cc) x Pump pressure (bar)]/[20 x 3.142]

= [31.6 x 160] / [62.832]

= 80.4 Nm torque from the motor.

Although the motor seems over specified by a factor of 3, it has the capacity to cope with modifications in design through the development phase as well as the torque to allow for field obstacles such as stones and trash.

7.3.3 Operating principles

As a continuous mechanism was decided through a cam arrangement the opening blades cycle at every 180^0. It is therefore essential that a phase lock loop between plant position and mechanism position is established. This phase relationship will provide the base for control of the system to cope with variations in intra-row spacing as it is known that there is approximately a 10 % error in plant spacing along the row. If plant spacing and typical forward speeds are known then motor speed can be set to ensure the motor revolutions coincide with plant position. If a plant is shorter than the mean spacing then the motor speed should increase to ensure the blades are retracted before damaging the plant. If the plant is on a greater spacing than the mean, then motor speed needs decreasing, to maximise cutting area.

7.4 Laboratory investigations of a weeding mechanism

Chapter 3 detailed the importance of lateral positioning to improve inter-row weed kill thus reducing the number of weeds within the row. The best commercial system available for this was found to be the vision guidance system developed at Silsoe Research Institute, and licensed to Garford Farm Machinery, commercially as 'Robocrop'. A swing distance of approximately 60 mm is required to control the intra-row weeds based on employing 'Robocrop' as detailed in Section 7.1.

7.4.1 Objectives

Based on a vision guided technique for lateral positioning develop and evaluate a mechanism and control principles for an automated intra-row weeding mechanism.

7.4.2 Mechanical Design

Laboratory investigations were undertaken during the design stage to examine the control aspects of a potential weeding system; in particular the harnessing of the guidance system to new hardware. Laboratory trials were undertaken with the use of an autonomous vehicle detailed by Hague & Tillett (1996), and shown in Figure 7-3. During 2002, Hague further developed the vision guidance system to identify each individual plant along the row, as well as track the row for lateral positioning. Additional hardware was required to link the vision guidance software with that of mechanism actuation as detailed in Section 7.5.3.

The autonomous vehicle is powered by a 6 kW petrol engine with a hydrostatic drive to each front wheel and used the previously developed Silsoe Research Institute vision guidance. Modifications made to the vehicle included the installation of a hydraulic Power Pak, to provide an auxiliary oil supply to the mechanism and a tool bar for mounting. The Power Pak, mounted directly behind the driver has its own 4 kW Honda petrol engine supplying rotary motion to a gear pump, delivering 7.5 litres/min with a maximum pressure of 160 bar, at 5 litres/min. This would then supply a motor with oil for mechanism actuation. A low speed high torque orbital motor was specified for providing actuation of the mechanism, based on calculations in Section 7-3. The motor as well as having high torque characteristics is designed to cope with high axial and radial loadings, which enable a cam to be supported and operated without the need for additional bearings.

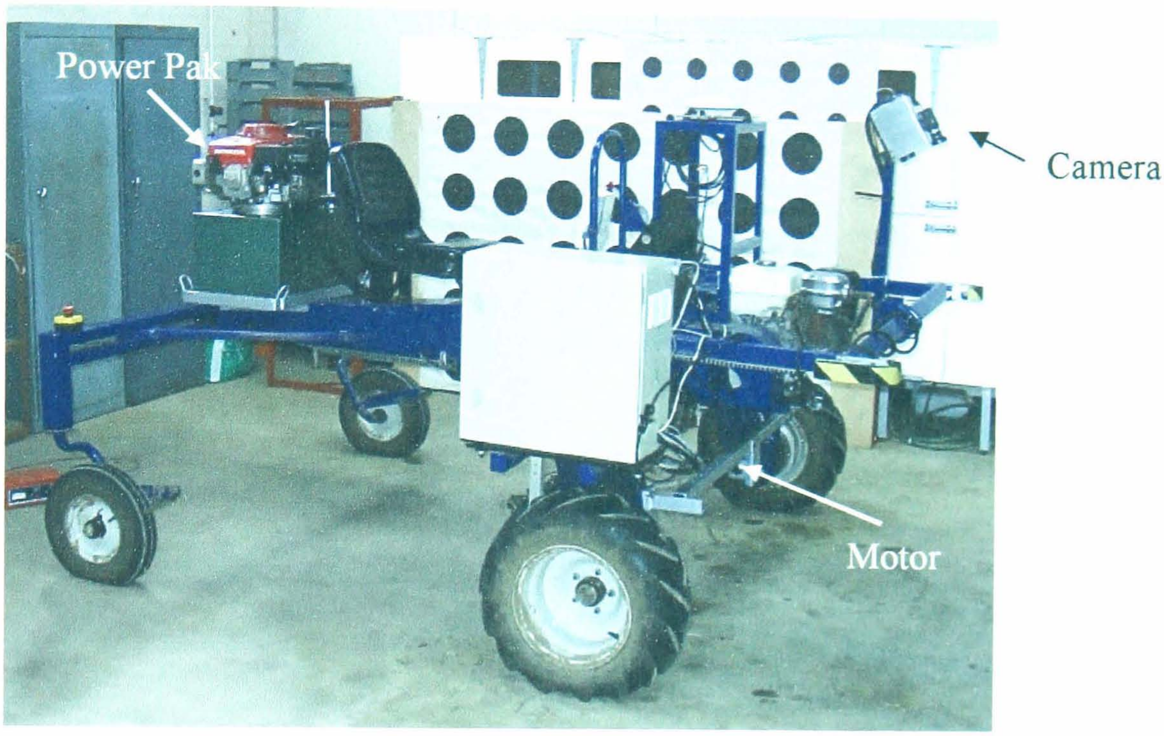


Figure 7-3 Autonomous vehicle

Initial investigations were undertaken by placing white polystyrene cups on the floor set on a 0.5 m spacing, in two rows stretching 20 m, which were used to represent a typical high value crop. The vehicle was driven at speeds up to 1 m/s and a pointer was fitted to the hydraulic motor to ensure it correctly pointed at each individual plant. The link between the software and hardware proved successful and a phase relationship was established between actual plant position and mechanism position.

Following success of initial investigations, a prototype mechanism was designed and evaluated to ensure the concept of opening blades would be suitable. Figure 7-4 shows the first mechanism developed for laboratory trials, which is referred to as mechanism A. Although simple, mechanism A represents the form of the selected mechanical prototype weeding mechanism, which provides a platform to investigate operating and control principles in the laboratory.

Although mechanism A was not designed for soil engaging operations a ducks foot blade has been fitted to represent the inter-row weeding component and L blades represented an intra-row weeding tool.

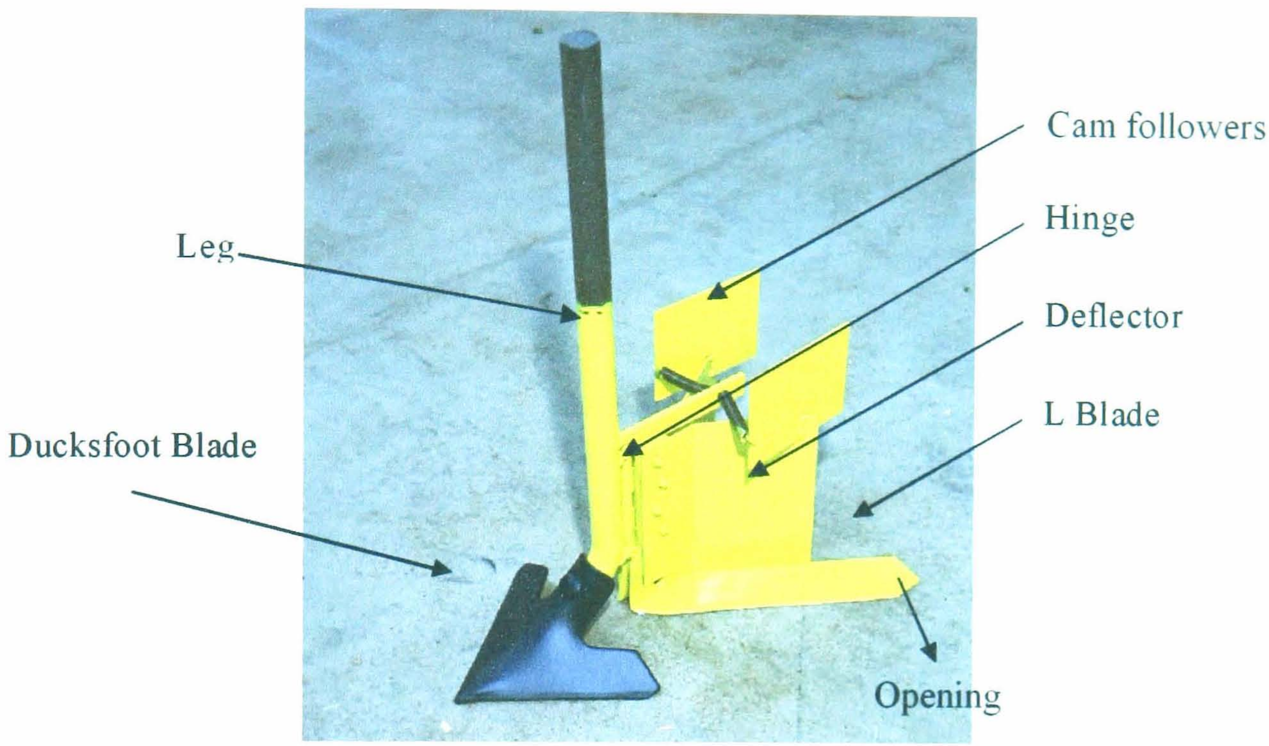


Figure 7-4 Mechanism A

The leg is central to mechanism A as it provides the main sub frame for the mechanism, including mounting to the vehicle. Welded to the rear of the leg is a hinge arrangement that supports the L blades allowing them to rotate outwards from the centre. Deflector plates are fitted above the L blades to demonstrate that soil displacement could be directed onto the row as an alternative to burial created from the blade alone. A central support bar mounted above the hinge on the rear of the leg has springs attached to ensure deflector plate retraction, and cam followers stay in contact with the cam. Control between the mechanism and software is similar to that previously described, but the pointer is now replaced with a cam to drive mechanism A as detailed further in Section 7.5.1. Figure 7-5 shows mechanism A with the cam fitted for actuation, and Figure 7-6 shows mechanism A mounted to the autonomous vehicle for laboratory investigations.

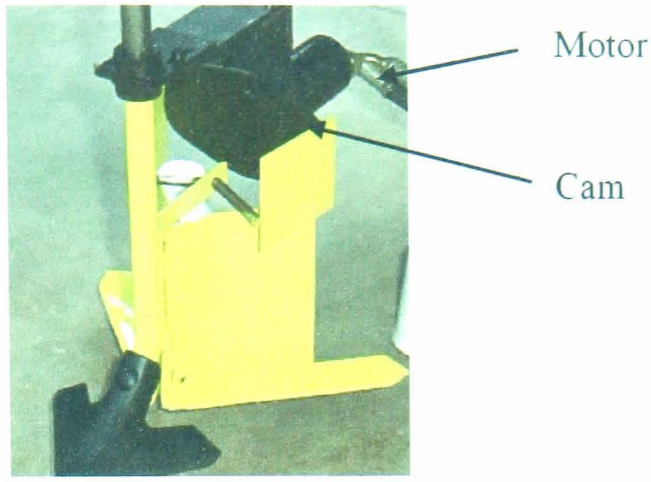


Figure 7-5 Mechanism A with motor attached

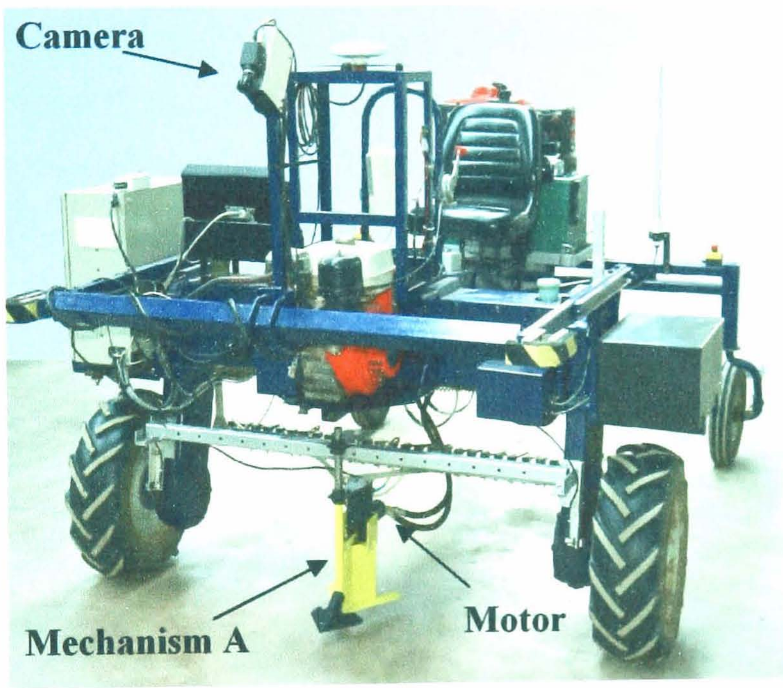


Figure 7-6 Autonomous vehicle with intra-row weeding mechanism

7.4.3 Mechanism control and design

The system will be described from the point of initialisation for ease of description.

As the vehicle is positioned at the start of the run, the computer, hydraulic power pack, and solenoid valve are activated. The vision system places a template across the plant spacing and identifies the start of the row. The vision system calculates the position from the first plant to the centre of the mechanism, as the inherent geometry is known, and the phase of the cam can be calculated.

Cam position is measured using a reed switch and Hall Effect transducer. The transducer detects the 23 teeth of a gear mounted onto the motor and 5 volt pulses that are counted by a general purpose I/O (PC30) board fitted to the autonomous vehicle's PC. The same general purpose I/O provides an analogue output used to control the proportional hydraulic valve. To determine the start of a new rotation, and define cam position the reed switch is activated for each rotation, thus resetting the counter. Therefore, the PC30 counts in steps of 23, which equates to 15.6^0. Even with coarse counting resolution adequate control of the cam was provided in the development stages.

Cam position is synchronised with the vision guidance system to ensure that when a plant is detected the mechanism is fully closed. As soon as the vehicle moves forward the vision system constantly checks vehicle position, (at a rate of 25 frames per second) cam position, and plant spacing to ensure synchronisation. If the spacing is not aligned, then motor speed is adjusted accordingly via the proportional control valve. The proportional control valve operates between 6 and 9 volts, with 6 volts equating to no displacement and 9 volts maximum displacement. For a set forward speed a voltage between 6 and 9 volts is fed to the proportional control valve via the amplification circuit detailed in Figure 7-7. The circuit, labelled 1 to 3 in red represents the input and output stages of the system. Signals 1 and 2 send an output to the PC30 board on the computer, and after being processed with the vision guidance sends output 3 to the amplification circuit, which activates the Danfoss (PVGH 32) proportional control valve. The onboard computer of the autonomous vehicle provided the control signal for the amplification circuit, based on techniques developed by Southall *et al.* (1999).

The voltage regulator provides a constant output of 5 volts to the Hall Effect transducer which senses gear tooth position and also provides 5 volts to the amplification circuit which is needed to drive the proportional control valve. The amplification circuit and proportional control valve are based on the techniques developed by Home (1999).

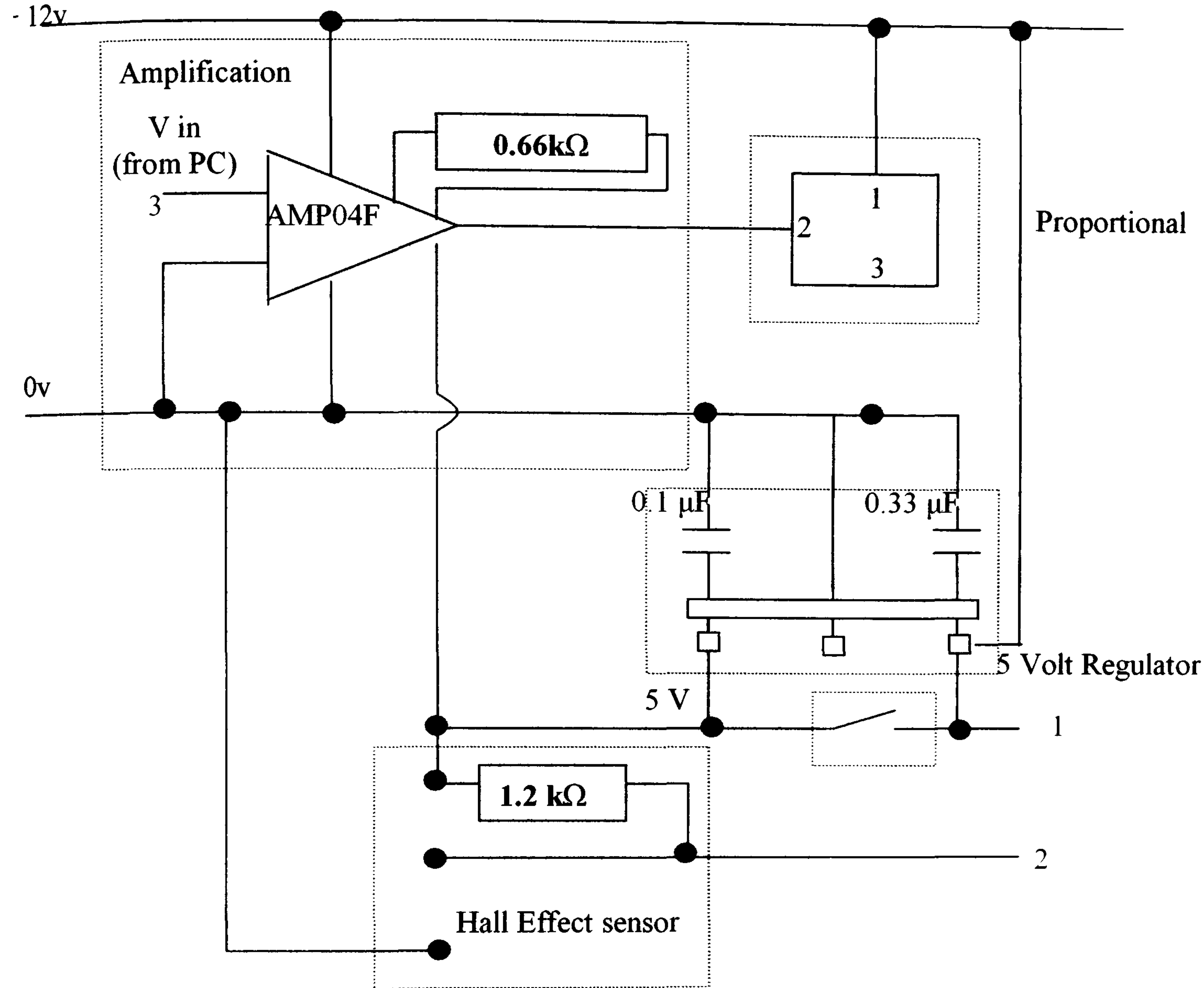


Figure 7-7 Mechanism A control hardware

7.4.4 Trials with mechanism A

Initial laboratory experiments simulated a plant spacing of 0.5 m using white polystyrene cups placed on a concrete floor for contrast. The results showed that the control hardware between the mechanism and the vision guidance system functioned correctly. The phase relationship between cup and motor angle was maintained at forward speeds of 0.5 m/s to 1 m/s (1.8 – 3.6 km/h), showing very repeatable performance. Figures 7-8 and 7-9 illustrate the operation of mechanism A as it passes by the imitation plants.

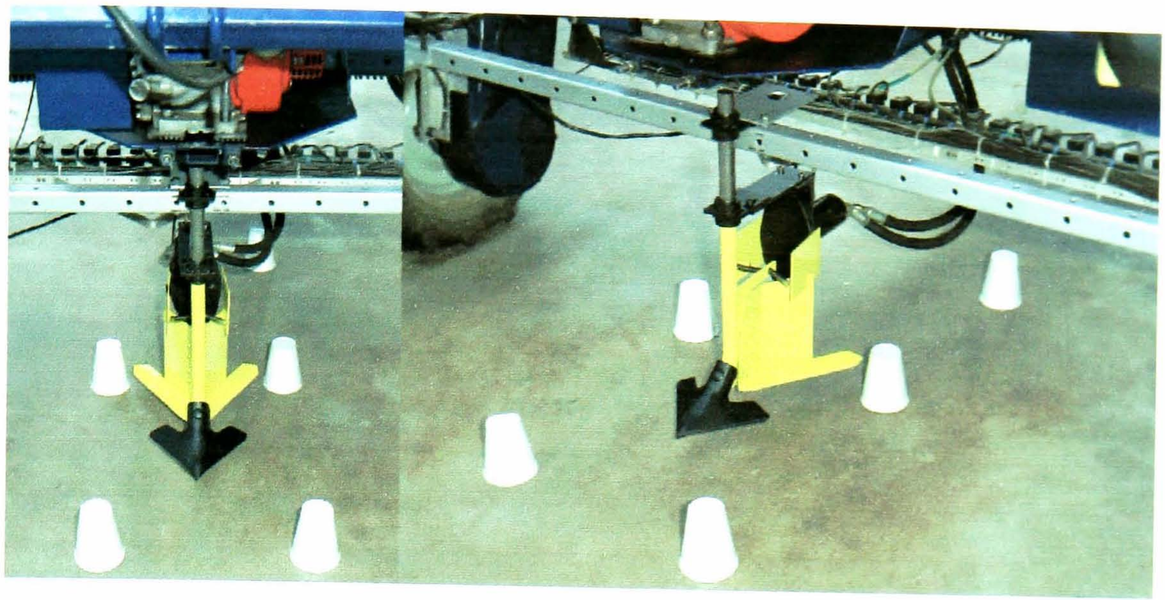


Figure 7-8 Mechanism A retracted

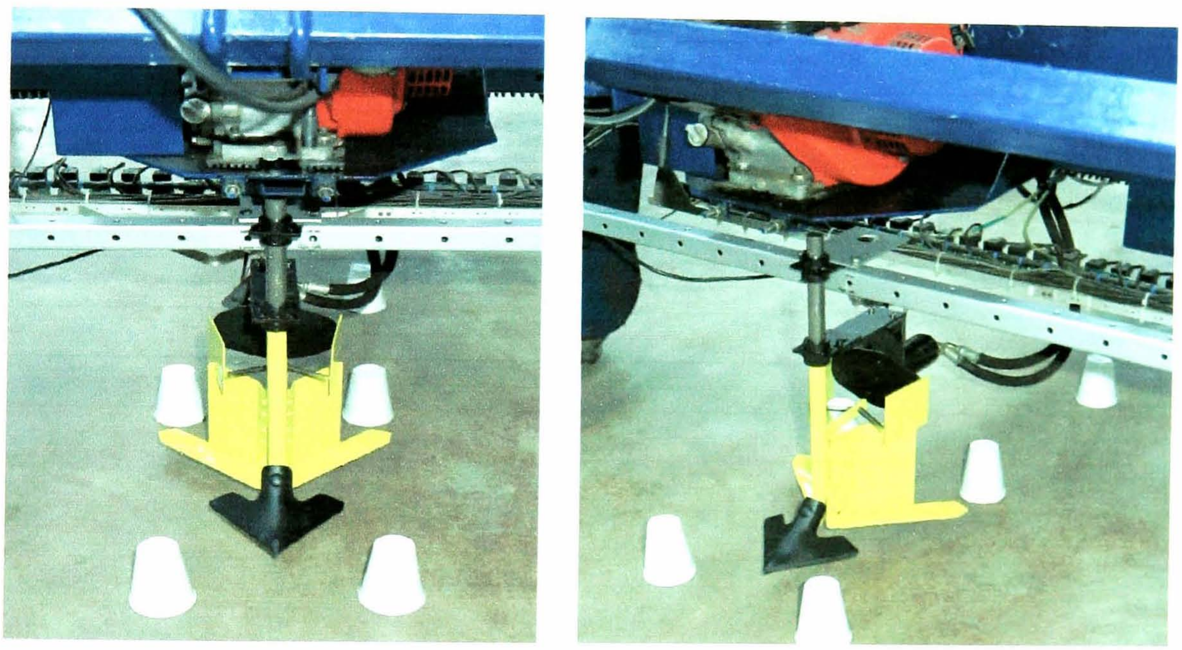


Figure 7-9 Mechanism A open

Speeds less than 0.5 m/s resulted in an erratic response; factors contributing to this were poor lateral positioning at slow speeds, and the coarse resolution of motor position. Laboratory investigations were based on uniform cup spacing along the row of 0.5 m and proved so successful that the principle of a phase relationship approach with opening blades was maintained and further developed. It was also decided that the autonomous vehicle, although useful in initial trials would not be used for field experiments as the lateral positioning obtained from the vehicle was not as a good as that obtained from a vision guided side shift system.

7.5 Field investigations

7.5.1 Objectives

To investigate the working parameters of an inter and intra-row weeding mechanism on various intra-row plant spacings and speeds to establish the limits of a new weed mechanism, here in after referred to as mechanism B. In addition to mechanism B development, replicate that of actual transplanted crops to record whether the weeding system can adapt to variations in intra-row spacing.

7.5.2 Design

Field experiments were broken down into three sections (listed below) to ensure the mechanism and control system were fully evaluated.

- Intra row spacing variation
- Changing forward speed
- Variations in intra row spacing along the run.

In order to maximise the time in the field it was decided that real plants would not be used, due to possible establishment problems and the number required to undertake the experiments listed above. Instead green plastic discs with a nominal diameter of 70 mm were hot glued onto 10 mm dowels, approximately 150 mm long, which were placed 100 mm into the soil. The use of artificial plants enabled the intra-row spacing to be changed along the row in a relatively short period of time, whilst simulating a planted crop as shown in Figure 7-10.

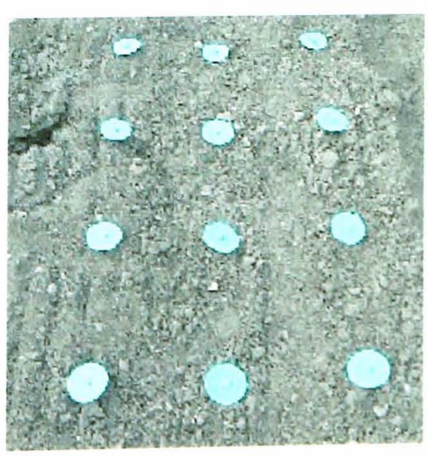


Figure 7-10 Artificial plants on a 0.5 m intra-row spacing

Artificial plants in the field were set on the square within the transplanted bout, however the mechanism could be simply modified to enable the module to straddle individual rows, thus enabling hoeing in plants on the diamond, which is the preferred method for achieving a uniform plant stand. This may also improve the lateral positioning as the camera would see more plants in the image.

Intra-row spacings of 0.25 m to 0.6 m were investigated at speeds ranging from 0.17 m/s to 2.22 m/s with mechanism B. Previous analysis of the mechanism was based on a uniform spacing, but in reality this is not achieved when using transplanters, therefore, variations in pitch were investigated by replanting the artificial plants at the recorded spacing of the Pelican transplanter outlined in Section 6.3.5. Tundra cabbage with a mean intra-row spacing of 0.33 m and Cauliflower with a mean intra-row spacing of 0.49 m were chosen.

The vision software was further developed to allow for variations in intra-row spacing. If successful weeding can be undertaken then the grower/ farmer can purchase the new weeding system, without having to worry about compatibility.

7.5.2.1 Modelling

In order to reduce development time the next mechanism (B), was specifically designed to be soil engaging, and was fully modelled and evaluated in Solid works, an engineering drawing package. This enabled component lengths, swing distances and blade positions to be modified, enabling a range of designs to be analysed quickly reducing development time and cost. Figure 7-11 shows Mechanism B in model format. A general assembly for mechanism B can be found in Appendix A.5-3.

Mechanism B was designed to meet the design criteria in Section 7-1 whilst being of simple design to minimise the number of moving parts, and ensuring as many as possible were out of the soil to reduce wear. A positive actuation of the mechanism was incorporated as shown in Figure 7-12, to ensure the blades in the intra-row would be retracted to ensure a fail safe system.

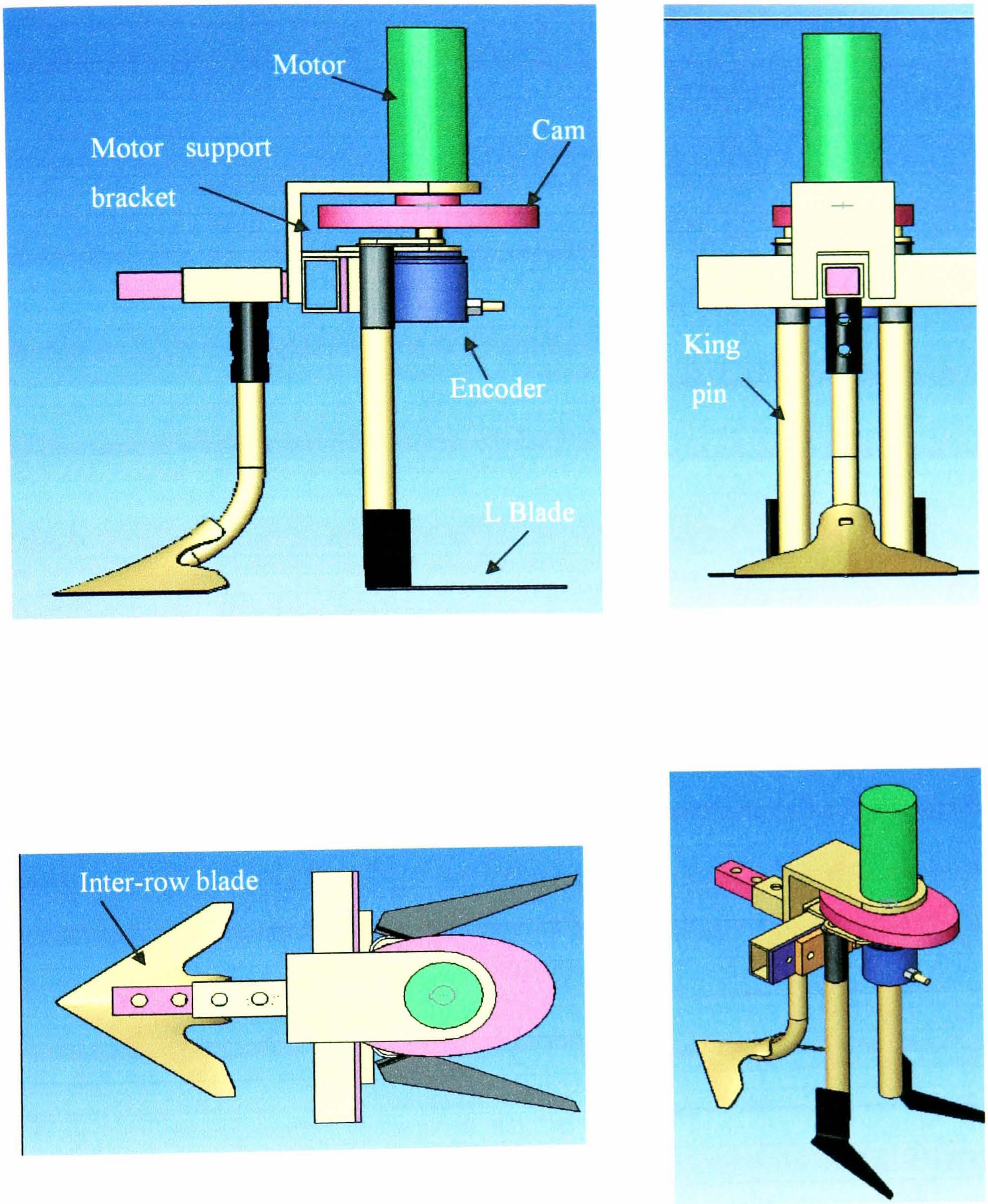


Figure 7-11 Mechanism B model

The cam is directly keyed to the motor and as the motor and cam rotate so the cam followers detailed in Figure 7-12 move along the cam track. The elliptical cam track results in a minimum and maximum cycle every 180^0 rotation. The software has a fail safe system, to ensure if the vision loses plant position the blades retract and this positive arrangement ensures that this happens.

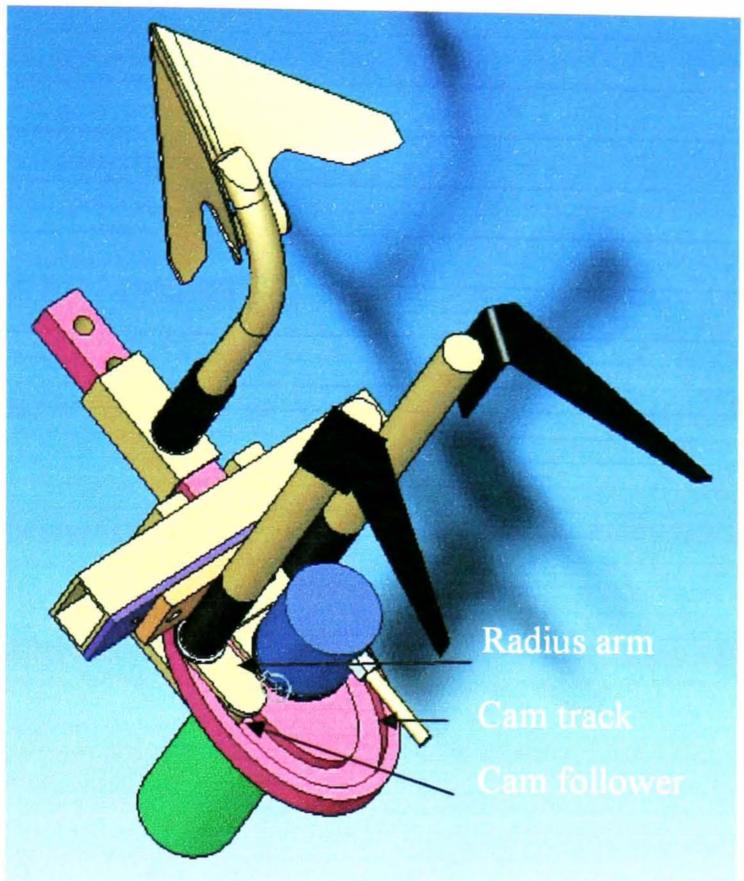


Figure 7-12 Mechanism B positive drive arrangement

The cam follower is welded to the radius arm which is keyed to the king pin, which in turn oscillates the L blades. A king pin type assembly was selected as movement occurs away from the soil, thus increasing component life. The only components to be moving in the soil are the L blades which are designed to be cutting at a depth of 25 mm. The digital encoder is fixed to the underside of the cam and provides the vision guidance software with an accurate position of cam location, replacing the gear tooth sensor that was used on mechanism A. The inter-row hoe blade is attached at the front of the mechanism with a narrow leg of 20 mm, to reduce soil disturbance. The leg can be moved forwards to ensure the soil is at rest before contacting the L blades. Optimisation of the inter row blade is achieved by setting the L blades rest position so that when fully retracted they will be cutting in the inter-row position.

It can be seen that with the elliptical cam fitted as shown in Figure 7-13, the crop is not cut nor does the blade enter the crop root zone. This cam was used during the field experiments detailed in the following section. This is not the perfect cam as the opening phase is too shallow to allow rapid entry into the intra-row, yet it was one that could be machined in-house and provided a good starting point for weed control.

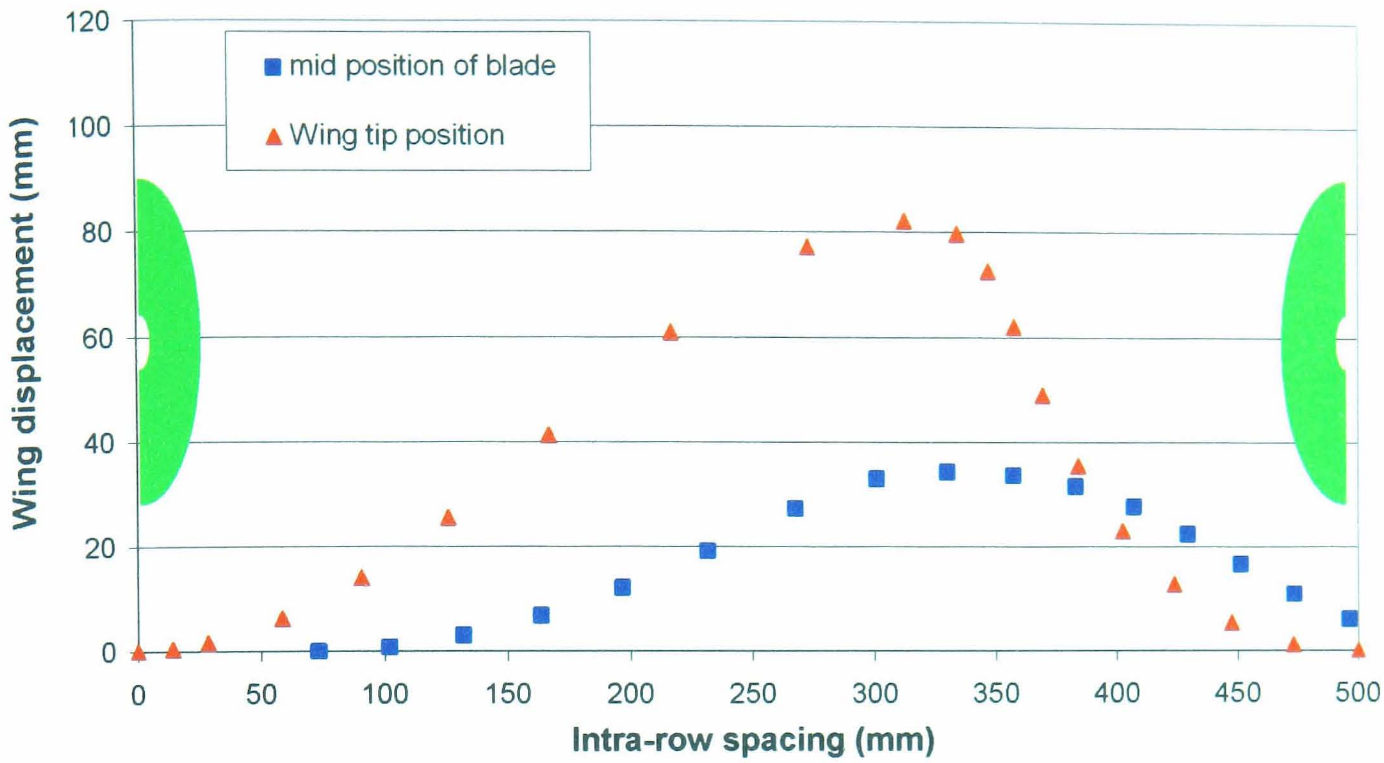


Figure 7-13 Wing path profile

Figure 7-13 show two sets of profile points one in red and one in blue. The red line represents the profile of the wing tip when travelling forwards. It can be seen that the rate of opening is gentle, with a rapid retraction. The blue line represents the mid point of the blade as this will be further forward than the tip, due to the width of the blade. Modelling blade position ensured that the cam profile and thus blade position would not cause any crop damage. It must be remembered that in addition to cutting, soil displacement will occur which will increase the overall treated area of weed control.

7.5.2.2 Field Equipment

A tractor and toolbar approach shown in Figure 7-14 was the preferred option for field trials and would be of similar form for large scale field work. The advantage of this approach is that an inbuilt hydraulic supply is available on most tractors, depth control can be easily changed using the three point linkage, and growers would only have to find the capital for a weeding implement rather than a vehicle and implement. If growers already used an inter-row hoe with vision guidance, then a software upgrade could combine both the lateral positioning and the phase between the plant and the mechanism.

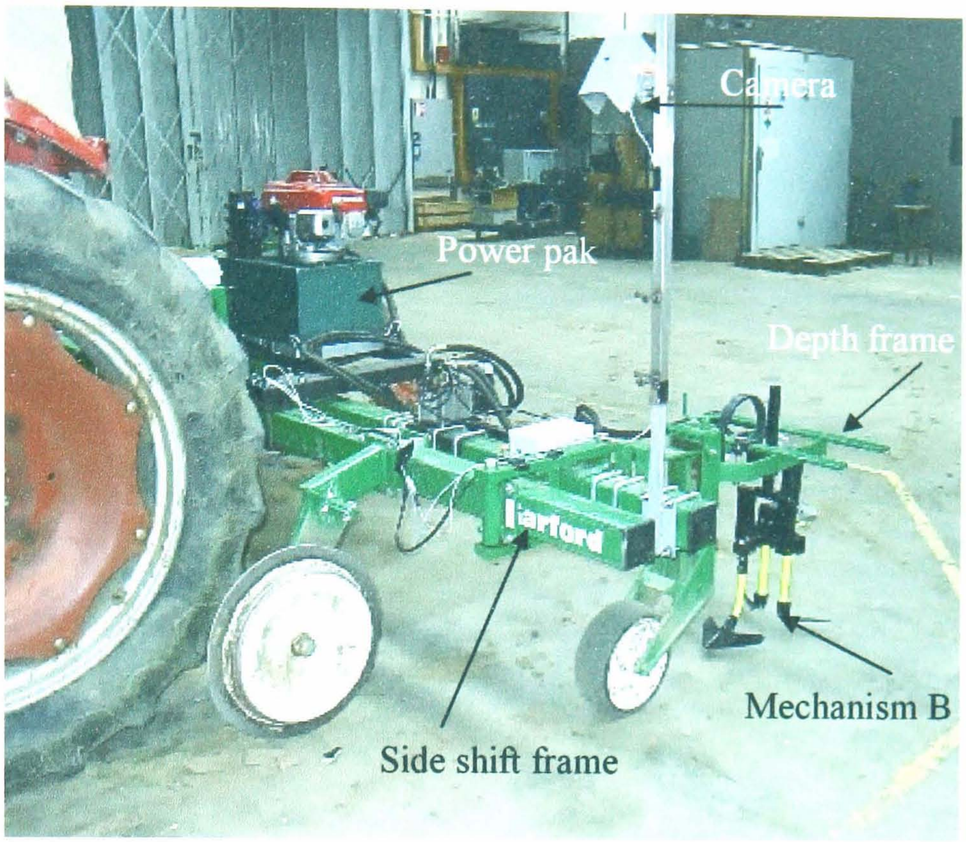


Figure 7-14 Tractor and toolbar with mechanism B, mounted for field investigations

The side shifting tool bar shown in Figure 7-14 is the same 4 m cereal hoe used for the lateral positioning experiments detailed in Chapter 3. Although an oil supply could have been taken from the tractor, the power Pak was used to provide a steady supply and was mounted in the centre of the implement. Mechanism B is directly mounted to the forward fixed depth frame attached to the side shifting beam. The universal fitting of mechanism B enables a standard inter-row hoe to be converted into an inter- and intra row weeding machine in modular form. Figure 7-15 shows Mechanism B mounted to the conventional depth frame in more detail.

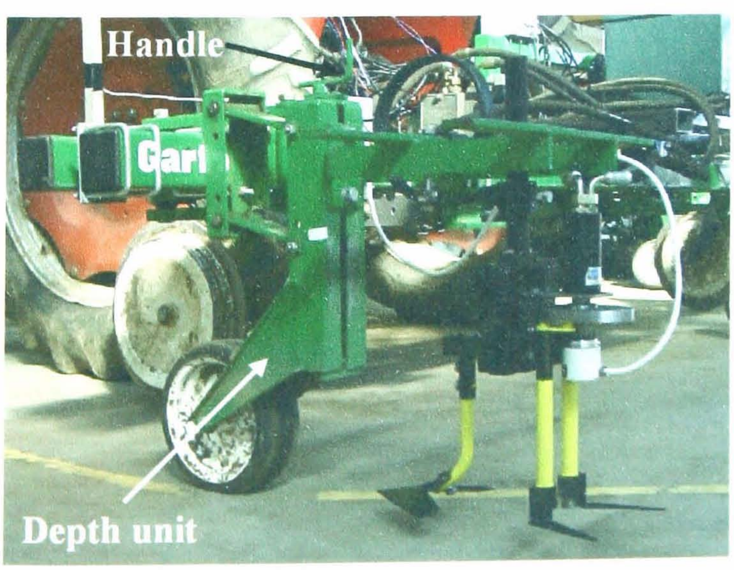


Figure 7-15 Mechanism B mounted to depth frame

The parallel linkage connecting the depth frame to the rear side shifting frame facilitates ground contour following. The cultivation mechanism support frame is attached to the wheel housing in such a way that cultivation depth can be set by rotation of a handle, which rotates a screw thread to which the support frame is attached.

Figure 7-15 shows a traditional inter-row hoe blade mounted to the centre of the unit, with the two extending L blades to either side. This arrangement would locate exactly between two rows, controlling the intra-row weeds on either side. Spacing of the kingpins and rotation of the L blades, enables the optimum working width of the inter-row hoe blade to be achieved.

The main operational and control differences compared to Mechanism A, are that the motor has been designed to be mounted overhead, thus raising it out of the soil, and an encoder has been fitted to provide accurate feedback on motor position to the control software, as the original gear and sensor resolution was too coarse.

7.5.3 Measurement of field performance

In order to determine the efficacy of the weeding system the dye application rig detailed in Chapter 3 was used to profile the wing tip as shown mounted to the mechanism B in Figure 7-16. The solenoid valve was fitted to the moving L blade, thus jetting a green dye trace onto the soil that was measured to ensure the crop was not damaged. These measurements meant that mechanism B was not soil engaging.

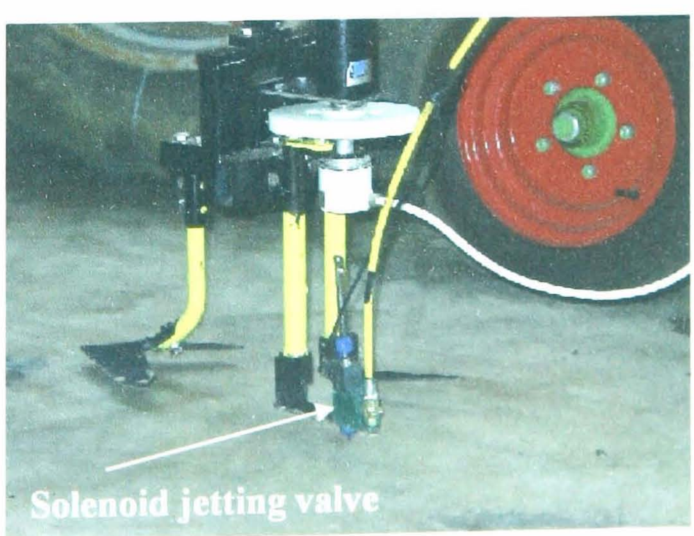


Figure 7-16 Dye rig mounted on mechanism B for field evaluation

At the start of each run the dye application unit was reset, the correct tractor forward speed was selected and the mechanism was lowered 20 mm above the soil surface. The complete system is shown in Figure 7-17, where the tractor and tool bar with Mechanism B can be seen compete with the dye trace apparatus.

Figure 7-17 Field evaluation of Mechanism B

As the tractor moved forward so the dye trace was jetted onto the soil, and it was then measured several times along the run, to obtain a mean result of tip position between the plants as shown in Figure 7-18.

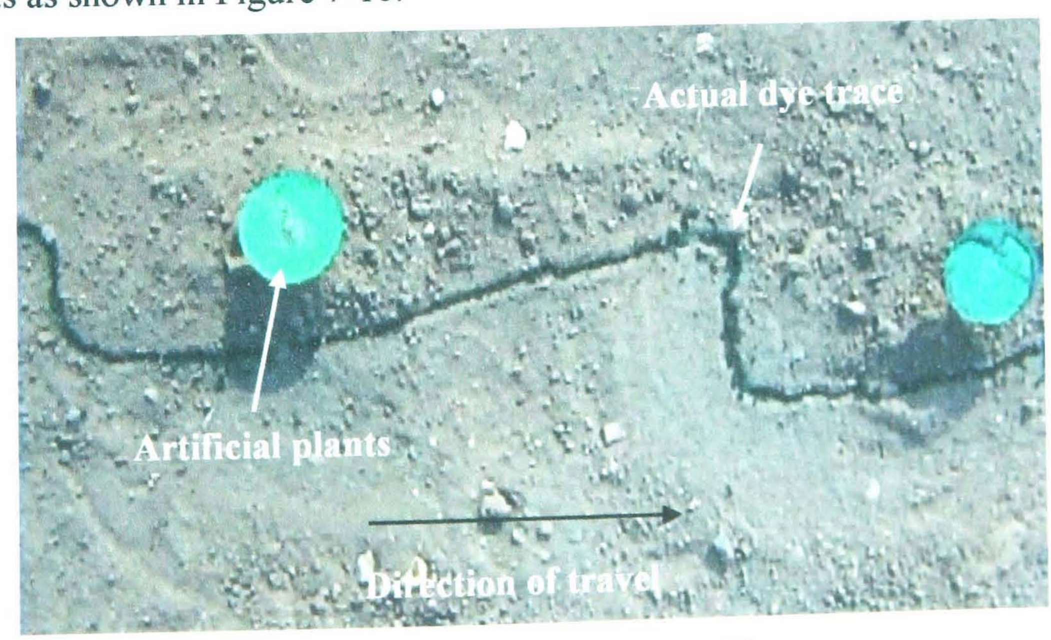


Figure 7-18 Dye trace on soil

The mean recorded measurements from each run provide mean cutting area for a given forward speed and plant spacing. These measurements were then plotted to calculate the area cut by the blade as shown in Figure 7-19 detailing the cut area on a 0.3 m spacing at 1.19 m/s (4.3 km/h).

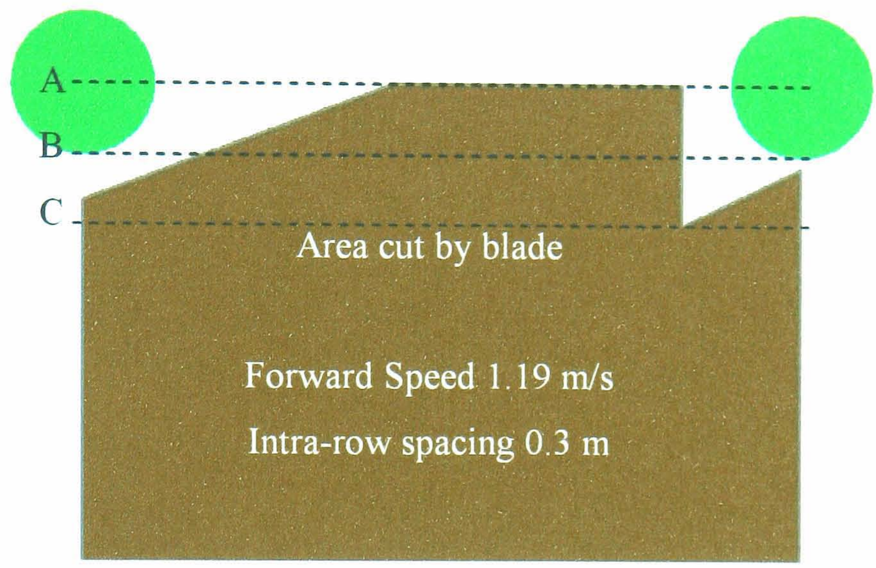


Figure 7-19 Diagrammatic representation of cut area

Line A represents the crop row centre line, line B simulates the true start of the intra-row and line C represents where the guided inter-row hoe blade would travel. Soil engaging investigations were also undertaken at 25 mm deep to ensure there were no mechanical problems with the mechanism.

7.5.4 Results

An initial assessment of weeding performance in terms of potential damage was undertaken, where the tractor was driven at a range of speeds to investigate whether the tip of the blade impinged on the artificial crop root zone. At intra-row spacings of 0.6 m and 0.5 m the blade successfully avoided the crop root zone (analysed by measuring the dye trace) when the tractor was travelling at speeds between 0.17 m/s to 2.2 m/s. On a spacing of 0.3 m the blades avoided entering the root zone up to speeds of 1.19 m/s, but at 2.2 m/s 17% of the crop root zone was entered, although no artificial plants were removed. A further reduction in plant spacing to 0.25 m achieved unsatisfactory results with over 70% of the root zone being affected throughout the speed range. If the mechanism and software were further developed then it would be possible to hoe down to 0.2 m – 0.25 m making mechanical weed control of sugar beet feasible.

Following the initial field assessment it was decided that a target of 0.25 m with the current design would be discounted for further experiments. Two typical plant spacings of 0.5 m and 0.3 m were investigated quantitatively by measuring the dye trace around each plant.

During the experiments it was discovered that the lateral positioning of the system was not performing optimally due to the very short run length, resulting in a guidance error of 37 mm. In practice this can be reduced to circa 30 mm and, therefore, the results have been modified to represent the weeded area with improved lateral positioning. This adjustment is justified as changes in the lateral positioning software have improved the overall positioning accuracy to that of what is commercially achieved with vision guidance.

Table 7-4 presents the area treated and controlled (based on a weed control efficacy of 95% for cutting) for inter-row hoeing in field vegetables, and compares unguided hoeing with guided hoeing for completeness. The area treated is less than values presented in Section 3.3 as there is a greater area available for treatment in widely spaced crops unlike cereal crops, where there is no gap along the row. The same values of lateral positioning error and bias were used as detailed in Table 3-3 but 3 times the variability was used with a crop zone clearance of 30 mm instead of 20 mm.

Table 7-4 Weed control by maximising blade width for a 0.5 m wide row spacing

Intra-row spacing	Maximised guided hoe		Standard width unguided hoe	
(m)	Area %	Controlled %	Area %	Controlled %
0.3	67.5	64.1	56.0	53.2
0.5	80.5	76.5	73.7	70.0

It can be seen that on a close intra-row spacing (0.3 m) that maximising the width has more of an effect, therefore comparisons of weed control must be compared with the same intra-row widths. All comparisons against mechanism B throughout this section will compared against guided inter-row hoeing as the technologies are similar on row widths of 0.5 m.

The results in Table 7-5 present the area that mechanism B covered compared with guided inter-row weeding alone at speeds of 0.57 m/s and 1.19 m/s, at an intra-row spacing of 0.5 m and 0.3 m. Only the tip position has been recorded, which as shown in Figure 7-13 is probably under estimating the overall area cut.

Table 7-5 Cut area of mechanism B compared to a guided inter-row control

	0.57 m/s			1.19 m/s		
Plant spacing	Mechanism B	Inter row only	Improvement factor	Mechanism B	Inter row only	Improvement factor
0.5 m	88.1%	80.5 %	**1.09**	87.8%	80.5 %	**1.09**
0.3 m	87.8%	67.5%	**1.30**	93.2%	67.5%	**1.38**

The results show the percentage of area cut in the inter- and intra-row with mechanism B at the speeds of 0.57 m/s (2 km/h) and 1.19 m/s (4.3 km/h) on a row spacing of 0.5 m and 0.3 m. The L blade did not enter the crop root zone of 30 mm, thus no crop damage would have occurred. The weeding efficacy is also compared directly with that of a guided mechanical inter-row hoe (detailed in Chapter 3), on a 0.5 m row spacing.

The values in Table 7-5 suggest that better control is achieved on an intra-row spacing of 0.3 m rather than 0.5m. This was due to the weeding system being optimised for a spacing of 0.3 m along the row. Control changes should have been undertaken to factor for the wider pitch, instead the blade returned prematurely to the closed position. It is also worth mentioning that weeding on an area term is being considered therefore, there is less intra-row area on a narrow intra-row spacing than a wide spacing, hence the decreases in weeding efficacy on increased intra-row spacing.

Table 7-5 shows that the greatest improvement in area cut with mechanism B compared to inter-row hoeing alone is at an intra-row spacing of 0.3 m at 1.19 m/s. On a spacing of 0.3 m at speeds of 0.57 m/s and 1.19 m/s, 12.2 % and 7.8 % were untargeted compared to 32.5% untargeted with a guided inter-row hoe. Improvements of 30% and 38% in weed coverage over the inter-row hoe were obtained at speeds of 0.57 and 1.19 m/s respectively. On a spacing of 0.5 m at speeds of 0.57 m/s and 1.19 m/s, 11.9 % and 12.2 % of the area respectively remained uncontrolled, compared to the fixed unguided inter-row hoe where 19.5 % remained uncontrolled. Improvements in weed control are less on an intra-row spacing of 0.5 m with 9% for speeds of 0.57 and 1.19 m/s.

7.5.4.1 Intra-row weeding at depth

All investigations had been undertaken above the soil surface, therefore, to ensure mechanism B could operate in the soil it was set to work at a depth of 25 mm, as shown in Figure 7-20.

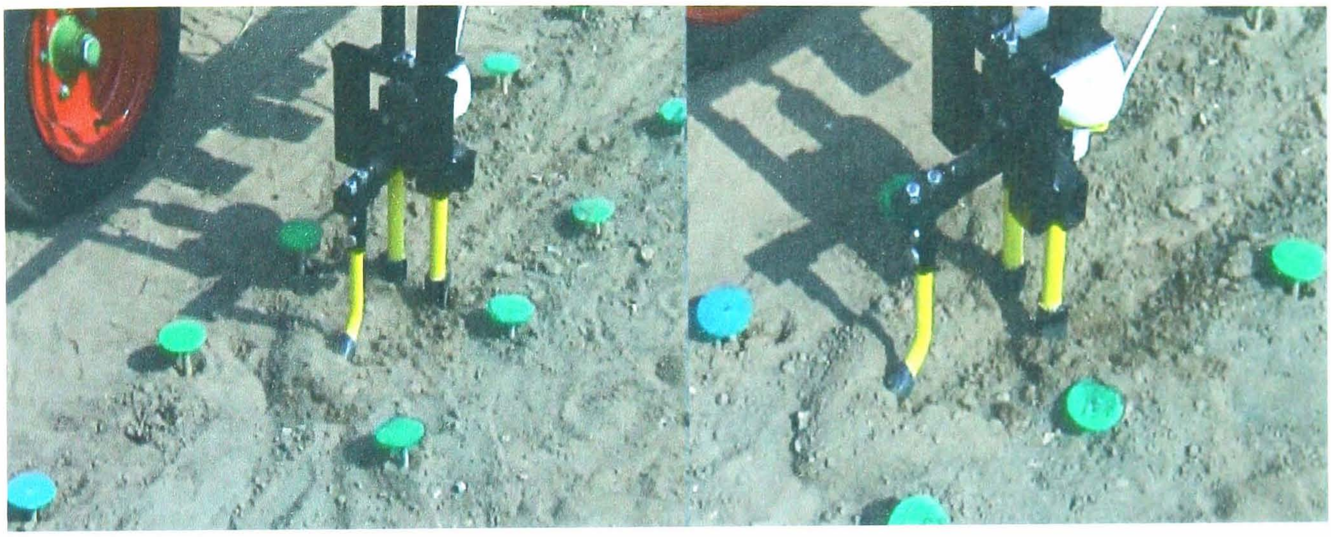


Figure 7-20 Mechanism B intra-row weeding at 25 mm deep

Dye traces were not taken but the results proved successful and none of the artificial plants were damaged (although the blade tips may have entered into the crop root zone) even at tractor speeds up to 2.2 m/s (7.9 km/h). Figure 7-20 shows mechanism B in action, the image on the left shows the mechanism retracted to avoid the plants whilst the right image shows the blade on full extension, ready to retract to avoid damage.

It can be seen in Figure 7-20 that the traditional hoe blade in the centre of the row is causing lateral soil displacement, due to its steep rake angle, however it did not bury any of the artificial plants as shown in Figure 7-21. The inter-row hoe blade would need re-designing to ensure that it did not cause excessive lateral displacement. This could be undertaken using the mass flow soil dynamics model developed in Chapter 5.

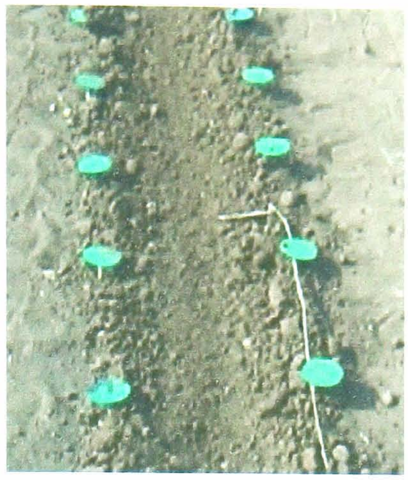


Figure 7-21 soil displacement after weeding operation

7.5.4.2 Variations in intra-row spacing

The objective of this experiment was to examine whether the control system could cope with real time variations in intra-row spacing along the row. To replicate commercial practice actual values recorded in following the transplanter with mean pitch's of 0.33 m and 0.47 m were replanted in the field. The weeding machine was operated at speeds of 0.57 m/s and 1.19 m/s. The plant spacings were based upon the results from the Pelican transplanter which had a spacing variation of 10% of the pitch.

The weeding was successful and none of the plants were damaged. On the spacing of 0.47 m, the speed was increased through the tractor range to 2.2 m/s, and the results were very promising, although no plant stems were contacted the blade tip often entered the crop root zone.

7.6 Weed control by burial

During field trials Mechanism B was operating with a zero rake angle blade to minimise soil displacement enabling the efficacy of cutting to be recorded. If rake angle was introduced onto the blade then soil displacement would increase which would improve the overall weed control through burial. The correct rake angle can be designed using the model developed in Chapter 5, to ensure forward displacement of soil does not bury the crop plant, when the blade reaches its maximum stroke.

Based on mechanism B operating principles, a blade can be theoretically designed to optimise the forward displacement of soil. It is known that sweep angle and forward velocity will affect the forward displacement of soil, therefore the sweep angle is considered when the mechanism is fully extended (34^0 for mechanism B), which results in the blade having the same velocity as tractor speed i.e. 1.19 m/s.

The blades on mechanism B are fully extended approximately 110 mm in front of the plant, (measured on an intra-row spacing of 0.5 m) therefore, assuming soil does not enter within a band of 30 mm of the plant, a rake angle of 15^0 in loose conditions would be required based on the forward translocation model (Section 5.4) and a rake angle of 30^0 in dense soil conditions. Area A on the blade in Figure 7-22 is modified to have an increased rake angle, which creates mixing of the soil without risking burial of the crop plant.

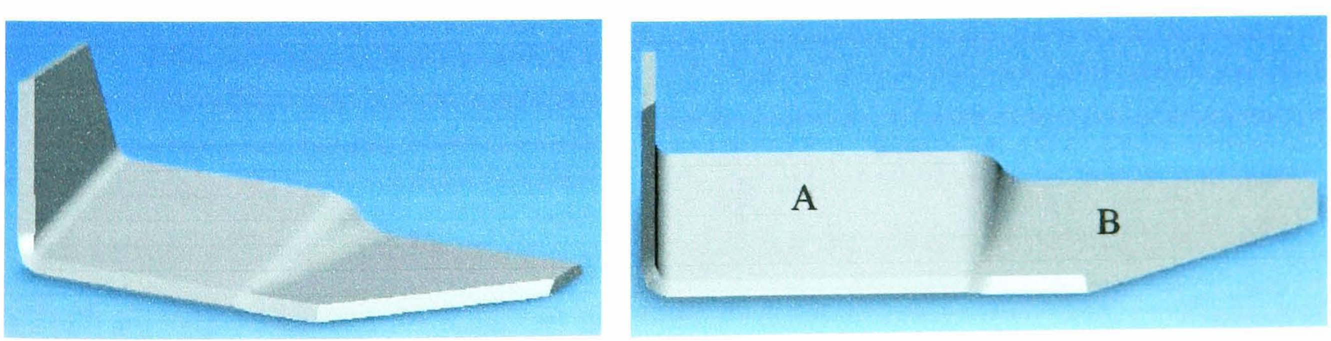


Figure 7-22 Proposed blade for soil control in the intra-row

The proposed blade in Figure 7-22 would be attached to the king pin of mechanism B as before, but it would no longer have a constant rake angle. Area A is designed with a 45^0 rake angle, and area B (that operating in the intra-row) has a 30^0 rake angle. The blade in Figure 7-22 has not been manufactured, it is purely theoretical and evaluation of blade design in the soil needs to be undertaken to ensure that the theoretical soil displacement occurs. Lateral displacement with a reduced tip angle would result in a slight decrease in soil displacement, but, as the wings are folding in, the reduced sweep angle would result in there being minimal lateral displacement as the blades pass by the plants.

Figure 7-23 illustrates the additional buried area at a row spacing of 0.5 m at a speed of 1.19 m/s, if the blade shown in Figure 7-22 was manufactured and fitted to mechanism B to provide soil displacement as predicted by the model in Chapter 5.

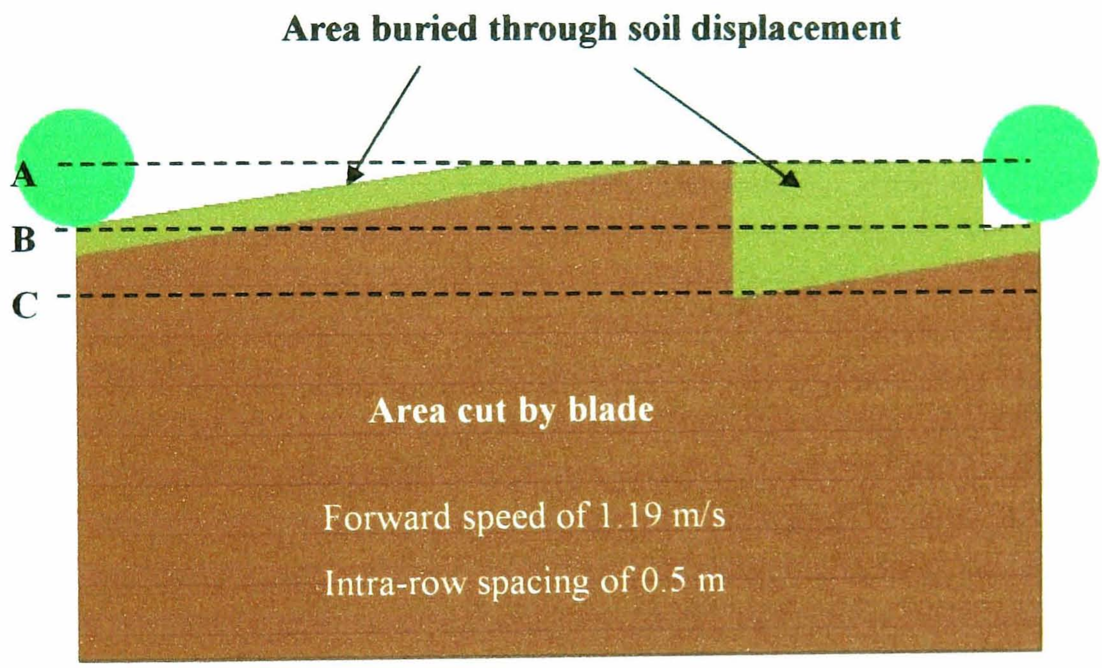


Figure 7-23 Profile of cutting and burial on 0.5 m spacing

With a new blade fitted to create burial there is a potential to cover over 95 % of the available area on an intra-row plant spacing of either 0.5 m or 0.3 m, at speeds between 0.57 and 1.19 m/s by cutting and burial.

Weed control efficacy can be calculated by applying the values for weeding efficacy through cutting and burial as outlined by Jones & Blair (1996). The study, as detailed in Chapter 3, was a laboratory investigation into weed control methods, but is the best available data to assume weed control efficacies. As field vegetables suitable for weed control along the row are broad leaf crops, then the major threat to them are broad leaf weeds, and therefore the weed control factor of broad leaf weeds has been assumed and the mean of control in wet and dry conditions has been adopted. Figures of 95% for cutting and 70% for burial are adopted for broadleaf weed control efficacy.

Therefore actual weed control for the given spacing and forward speed can be calculated by the formula expressed below.

0.95 x area cut + 0.7 x area buried

For the optimised blade discussed above the following weeding efficacy can be calculated based on Figure 7-23:

0.95 x 85.8% + 0.7 x 9.5% = **88.2%**

Table 7-6 presents the overall weeding efficacy of mechanism B with cutting and burial in dense soil conditions, (using theoretical blade design in Figure 7-22) on the two intra-row pitch spacing of 0.3 m and 0.5 m at speeds of 0.57 m/s and 1.19 m/s.

Table 7-6 Cutting and burial weeding efficacy

	Blade	**0.57 m/s**		**Blade**	**1.19 m/s**	
Spacing	Sweep/rake	Area %	Efficacy %	Sweep/rake	Area %	Efficacy %
0.5 m	**$34^0/40^0$**	96.3	89.4	**$34^0/30^0$**	95.3	88.2
0.3 m	**$34^0/30^0$**	95.1	88.5	**$34^0/22^0$**	97.4	91.4

Table 7-6 shows that for plants on a 0.3 m spacing, based on broad leaf weed control, at speeds of 0.57 m/s and 1.19 m/s, that an area of 4.9% and 2.6% respectively, remain untreated. On a spacing of 0.5 m at speeds of 0.57 m/s and 1.19 m/s, then 3.7% and 4.7 % of weeds, respectively, remain untreated. In general terms over 95% of the area is treated with a minimum weed kill efficacy of 88%.

Table 7-7 presents the guided inter-row hoe weed control efficacy based on 95% of the weeds being controlled by cutting, compared to the proposed inter- and intra-row weed control efficacy of mechanism B and a proposed new blade. It can be seen that improvements in weed control efficacy of 1.17 and 1.15 times can be achieved at speeds of 0.57 and 1.19 m/s respectively on 0.5 m spacings, whilst on 0.3 m spacings improvements of 1.38 and 1.43 times can be achieved without crop damage at 0.57 and 1.19 m/s respectively.

Table 7-7 Weed control efficacy % comparison between inter-row hoeing and mechanism B

	0.57 m/s			1.19 m/s		
Intra-row spacing	New blade	Inter row only	Improvement factor	New blade	Inter row only	Improvement factor
0.5 m	89.4%	76.5%	**1.17**	88.2%	76.5%	**1.15**
0.3 m	88.5%	64.1%	**1.38**	91.4%	64.1%	**1.43**

The actual area controlled based on dye trace performance of mechanism B and theoretical soil displacement calculations can also be compared to that of theoretical control with an optimised mechanism given by the calculation for effective weed control given in Section 6.6; the same parameters have been used for calculation purposes. Table 7-7 presents the predicted values of weed control efficacy compared to the actual values obtained by measuring the profiles.

Table 7-8 Actual area controlled V theoretical area

Spacing	WK Formula	Actual at 0.57 m/s	Actual at 1.19 m/s
0.5 m	92.6 %	89.4 %	88.2 %
0.3 m	91.3 %	88.5 %	91.4 %

The formula has no speed component and, therefore, does not account for the variations in weed control whilst operating at different speeds. However the basic formula could be applied to field operations to gain an approximate level of weed control given the plant spacing in and along the row. The parameters could also be modified to suit cam profile to represent the area left for burial.

7.7 Proposed inter- and intra-row weeding machine

The proposed inter- and intra-row weeding system shown in conceptual form (Figure 7-24) is designed to be multi purpose. Two inter-row hoe blades which are fitted can be set to the designated row spacing to suit a variety of crops with coarse spacing. The intra-row hoe blades can be spaced to provide the fine adjustment to leave the 30 mm buffer strip either side of the crop.

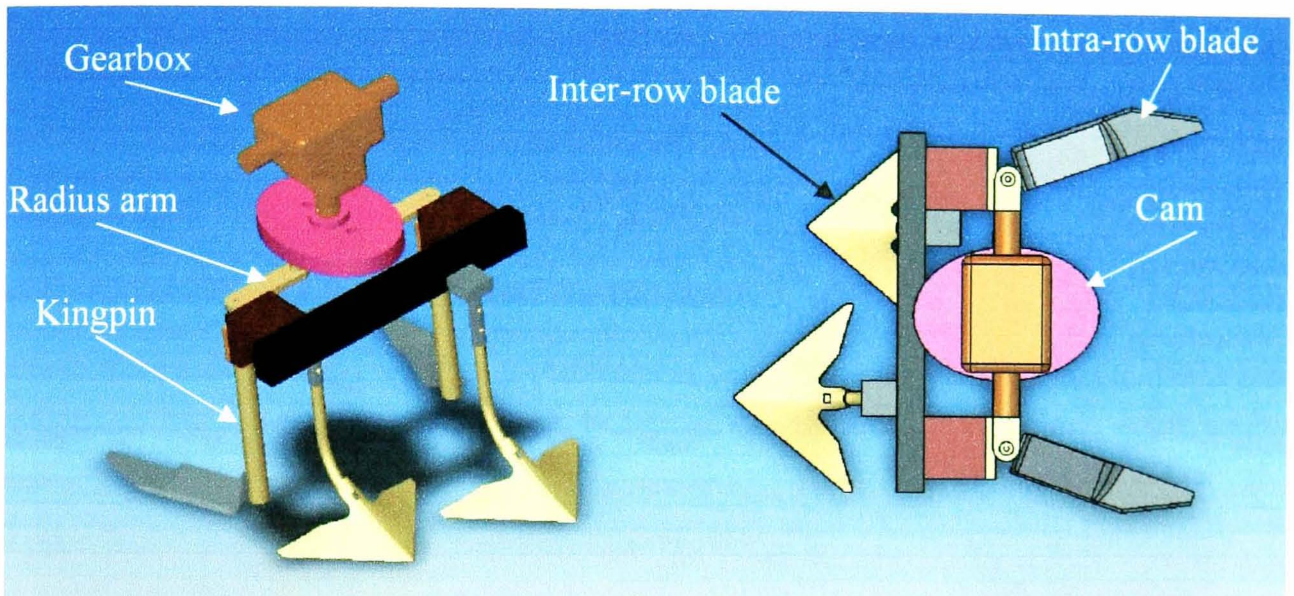


Figure 7-24 Proposed weeding system in conceptual form

Mechanism actuation is identical to that explained in Section 7.5, and would require plants to be set on the square within the drill bout. If the preferred option of transplanting was a diamond formation then either a narrower version can be used to target individual rows or straddle the row. The intra-row hoe blade fitted to the kingpins is of similar form to that presented in Figure 7-22. It is proposed that modules are driven by a hydraulic motor mounted at one end of the machine, which drives a power take off shaft the length of the implement. At each desired module location a gearbox would transmit drive to the mechanism. At the opposite end of the shaft, an encoder would be located to provide accurate information on rotational position. Although the system previously detailed is still in development phase, the experimental system had promising results, and with further test and development there is no reason why mechanical inter- and intra-row weed control should not be adopted by the organic and conventional sectors.

7.7.1 Blade re-design for high speed cereal hoeing

During this research programme the vision guidance system, "Robocrop" was successfully launched. This meant that work rates increased as operators were undertaking hoeing operations at increased working speed, some up to 10 km/h. The traditional ducksfoot blade and spring tine mounting were causing excessive soil displacement at these speeds, and therefore a new blade was designed based on the findings in this project. Figure 7-25 and 7-26 present the original and modified blade respectively. The modified high speed blade is manufactured by Garford Farm Machinery, UK.

Figure 7-25 Traditional cereal hoe blade and leg mounting

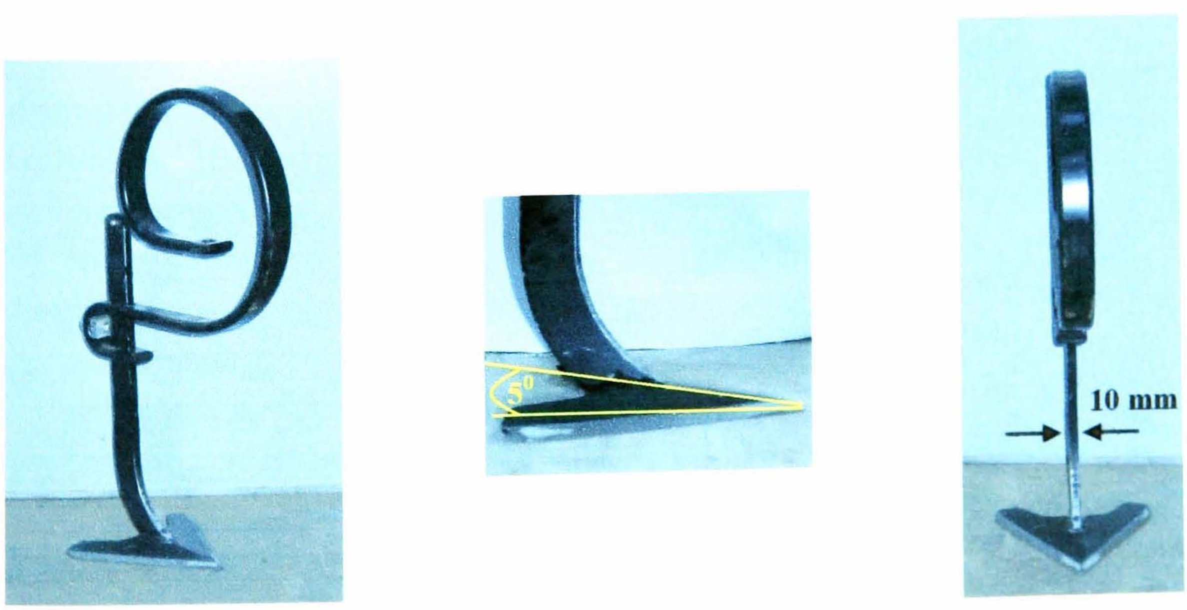


Figure 7-26 Modified cereal hoe blade and leg designed for less soil disturbance

The new blade now has a 10 mm leg mounted to the centre of the blade, which is 35 mm thinner than the mounting width on the old blade and 20 mm thinner than the spring tine itself. The effective rake angle on the high speed blade is approximately 5^0, compared to 19^0 for the traditional blade. The angle increased to 39^0 at the leg mounting area, which caused significant movement. Field observations of the new blade working at high speed have shown that there is considerably less soil disturbance, when compared to the ducksfoot blade. Further work to quantify the reduced displacement needs to be undertaken. There is good evidence to suggest that hoe blade re-design consisting of narrow legs and low rake angle blades (i.e. 10 mm leg and 5^0 rake angle blades) will be of value for high speed hoeing as there is less undesirable soil displacement.

It is estimated that the lateral displacement will reduce from 21 mm to 7 mm in dense soil, and forward displacement will be negligible with the new blade < 2 mm. Although lateral movement from the blade at 21 mm is relatively small if the hoe was off set then this would cause damage at small growth stages. The main soil disturbance came from the leg, and experimental observations showed that reducing leg width from 40 mm to 6 mm resulted in lateral displacement of soil decreasing by 138 mm to 150 mm in dense soil, which is still an excessive amount. Further laboratory studies are required to enable prediction of lateral soil displacement from the leg.

7.8 Economic analysis

To undertake a detailed economic analysis of the weeding operation, a review of the costs to manufacture a commercial machine based on the conceptual design in Section 7.7 was undertaken to determine the capital cost for the proposed system.

For costing purposes the machine has been based on a 4 m vision guided tool bar, with 5 modules which will hoe 10 rows of transplanted crops at 0.5 m. A 5 module 10 row system is shown illustratively in Figure 7-27.

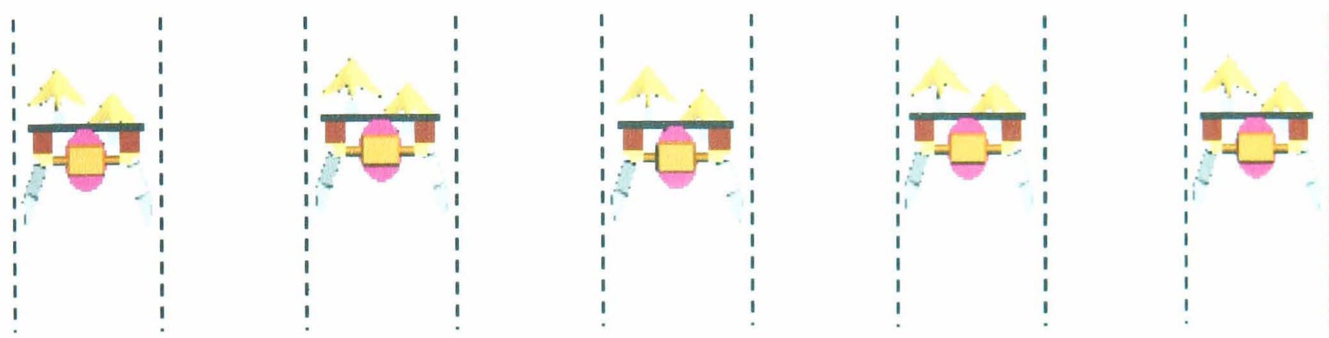


Figure 7-27 Five module, 4 m intra-row weeding machine concept

The conceptual system shown in Figure 7-27 would have power take off shafts connecting each module. It would also require the crop to be transplanted on the square within the drill bout. If the transplanter was set on the diamond for advantages in plant distribution, then a module would be required for each individual row.

7.8.1 Inter-row / intra-row costing

The prototype machine will use an existing guided tool frame by Garford Farm machinery using the "Robocrop" guidance system, with a current commercial price of £7645. An additional on cost is needed for the depth frames to support the weeding modules, which is assumed to be £200/module. Table 7-9 analyses the cost of mechanism B in terms of one off components as occurred in the development and quantities based on 100 modules.

Table 7-9 Manufacturing costs of the proposed weeding system

Description	1 Off cost	100 Off	Cost for 1 units
Material Cost	£40	£3000	£30
Motor[1]	£134	£8800	£88
Encoder[1]	£250	£19000	£190
Electronic hardware[1]	£30	£1500	£15
Cam	£200	£10000	£100
Gearbox/connecting	£150	£10000	£100
Labour	£200	£12500	£125
Assembly	£75	£4000	£40
Wring looms[1]	£10	£600	£6
Hosing[1]	£40	£2500	£25
Control Valve[1]	£250	£21500	£215
Flow regulator[1]	£100	£8000	£80
Total	**£1479**	**£101040**	**£1014**

[1] Only one unit required regardless of the number of modules

Table 7-9 presents the one off cost of components as well as the cost of bulk purchasing of 100 components. Therefore the cost of a module at scaled production would cost £1014. Individual module cost can be calculated by subtracting the fixed cost for the system resulting in an individual cost of £395/module plus the platform cost of £619 for one off components, module costs are shown graphically in Figure 7-28.

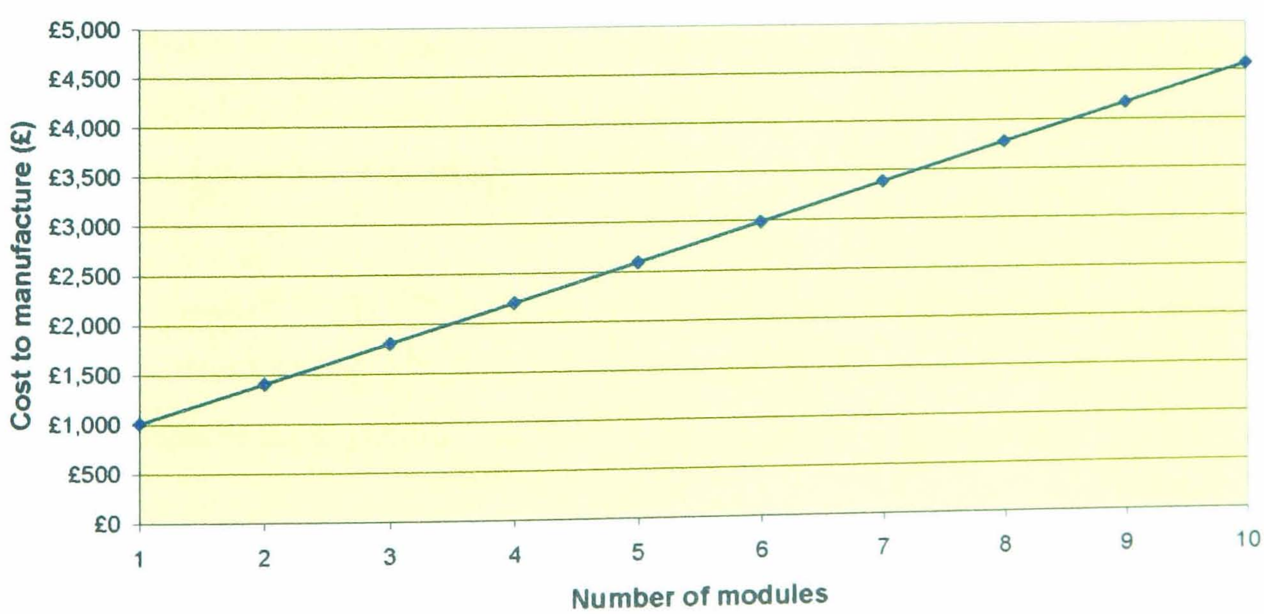


Figure 7-28 Cost to manufacture and build weeding modules

The costs in Table 7-9 reflect the cost to manufacture the complete modules and assuming a mark up value of a factor of 3, the module retail price would be a capital retail cost for a new weeding machine controlling both inter- and intra-row weeds is shown below based on a 10 row, 5 module 4 m machine.

Guided tool frame	£7645
5 module depth frames	£1000
5 modules for 9 row machine (inc. platform costs)	£7782
Total capital cost for a 9 row weeding machine	**£16,427**

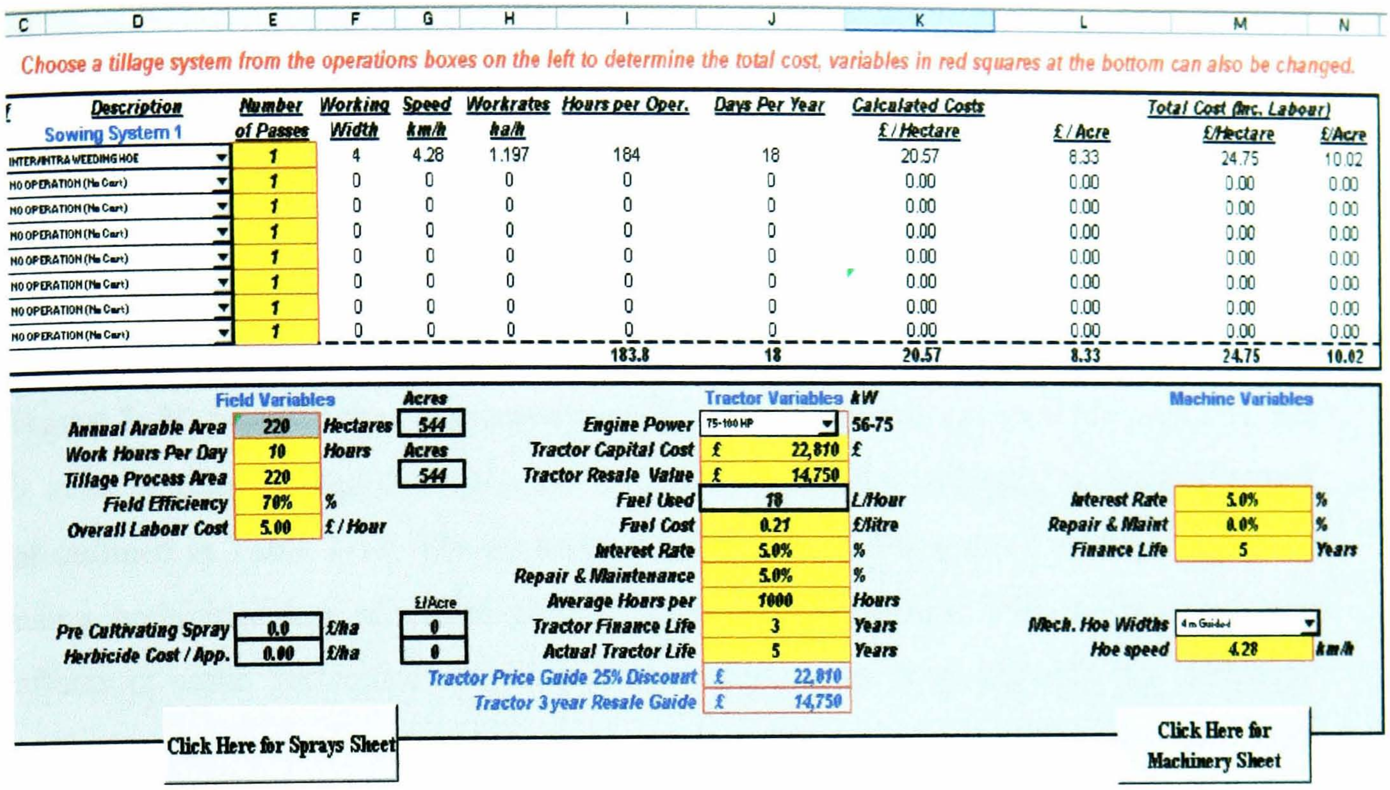
7.8.2 Economic comparisons

To aid in evaluating different scenarios to control weeds, ranging from spraying to mechanical weeding an economic calculator developed during this research will be used as detailed in Appendix A5-4.

The economic calculator was developed at the commencement of this project as a result of the MBA components to make calculations of machinery costing simple and effective for comparison purposes, and was first published in Crops (2000). The fundamental equations developed to form the basis of the economic calculator are shown in Appendix A5-4 accompanied by a description on how to use the calculator. A screen image of the calculator is presented in Figure 7- 29. Implementation of the calculator into Excel was aided by Saunders (2002) who also utilised the calculator for studies into high speed ploughing

Fixed and variable costs for both the tractor and selected implement can be easily changed to examine the effects such as forward speed, interest rates, capital cost, repairs and maintenance and labour have on the overall cost per hectare.

The calculator has over 50 implements included for economic comparisons, but for the purpose of this study economic comparisons have been undertaken against the equipment in Table 7-10.



Choose a tillage system from the operations boxes on the left to determine the total cost, variables in red squares at the bottom can also be changed.

Description Sowing System 1	Number of Passes	Working Width	Speed km/h	Workrates ha/h	Hours per Oper.	Days Per Year	Calculated Costs £ / Hectare	£ / Acre	Total Cost (inc. Labour) £/Hectare	£/Acre
INTER/INTRA WEEDING HOE	1	4	4.28	1.197	184	18	20.57	8.33	24.75	10.02
NO OPERATION (No Cart)	1	0	0	0	0	0	0.00	0.00	0.00	0.00
NO OPERATION (No Cart)	1	0	0	0	0	0	0.00	0.00	0.00	0.00
NO OPERATION (No Cart)	1	0	0	0	0	0	0.00	0.00	0.00	0.00
NO OPERATION (No Cart)	1	0	0	0	0	0	0.00	0.00	0.00	0.00
NO OPERATION (No Cart)	1	0	0	0	0	0	0.00	0.00	0.00	0.00
NO OPERATION (No Cart)	1	0	0	0	0	0	0.00	0.00	0.00	0.00
NO OPERATION (No Cart)	1	0	0	0	0	0	0.00	0.00	0.00	0.00
					183.8	18	20.57	8.33	24.75	10.02

Field Variables
Annual Arable Area 220 Hectares 544 Acres
Work Hours Per Day 10 Hours
Tillage Process Area 220 544 Acres
Field Efficiency 70% %
Overall Labour Cost 5.00 £ / Hour
Pre Cultivating Spray 0.0 £/ha 0 £/Acre
Herbicide Cost / App. 0.00 £/ha 0

Tractor Variables kW
Engine Power 75-100 HP 56-75
Tractor Capital Cost £ 22,810 £
Tractor Resale Value £ 14,750
Fuel Used 18 L/Hour
Fuel Cost 0.21 £/litre
Interest Rate 5.0% %
Repair & Maintenance 5.0% %
Average Hours per 1000 Hours
Tractor Finance Life 3 Years
Actual Tractor Life 5 Years
Tractor Price Guide 25% Discount £ 22,810
Tractor 3 year Resale Guide £ 14,750

Machine Variables
Interest Rate 5.0% %
Repair & Maint 0.0% %
Finance Life 5 Years
Mech. Hoe Widths 4 m Guided
Hoe speed 4.28 km/h

Click Here for Sprays Sheet
Click Here for Machinery Sheet

Figure 7-29 Screen image of economic calculator

Tractor selection has been based on the draft force requirements to undertake the intra & inter row weeding operation and the method of calculating the size of tractor is detailed in Appendix A5-5.

Table 7-10 Equipment comparison

Equipment	Width (m)	Speed (km/h)	Capital cost (£)	5 yr sale price (£)
Intra & Inter-row weeder	4	4.3	16427	6,077
Inter-row weeder guided	4	6	14,056	5,200
Inter-row weeder manual	4	4	8,441	3112
Band sprayer	4	4	5,448	2,016
Conventional sprayer	12	8	8,500	3,145
Cycloid hoe	3	8.5	50,000	13,977

An hourly labour rate of £5.74/h based on a 10 hour day has been assumed as this is the proposed labour rate for a casual worker on agricultural wages as detailed in Chapter 6. All machinery is considered to be new, and financed over a period of 3 years at 5% APR and kept on the farm for 5 years. Repairs and maintenance percentages are based on Nix (2002) along with recommended depreciation rates and field efficiency. Fuel usage is calculated on the mean fuel consumption from a variety of manufacturers, and agricultural diesel is based on £0.21/litre. Operating speed values are either typical or measured values. The speed selected for mechanism B was 4.3 km/h as no damage occurred at this speed regardless of intra-row spacing within the tested range. Higher speeds are feasible but increases above 4.3 km/hr may result in some crop damage.

Figure 7- 30 presents the comparative cost per hectare of the six weeding methods, but it must be remembered that each has an assumed weeding efficacy associated with it as outlined in Table 7-11. The social cost and potential damage to the environment by using herbicides has not been factored into the economics. The potential adverse effects of some herbicides or mechanical treatments on crop growth have also been neglected, as extensive reviews need to be undertaken to quantify these potential effects.

Each treatment shown in Figure 7-30 has been undertaken twice, as one weed control treatment is not enough to effectively control the weeds during the growing stage. The number of workable days to undertaken the two treatments is based on 20 days as derived in Chapter 6.

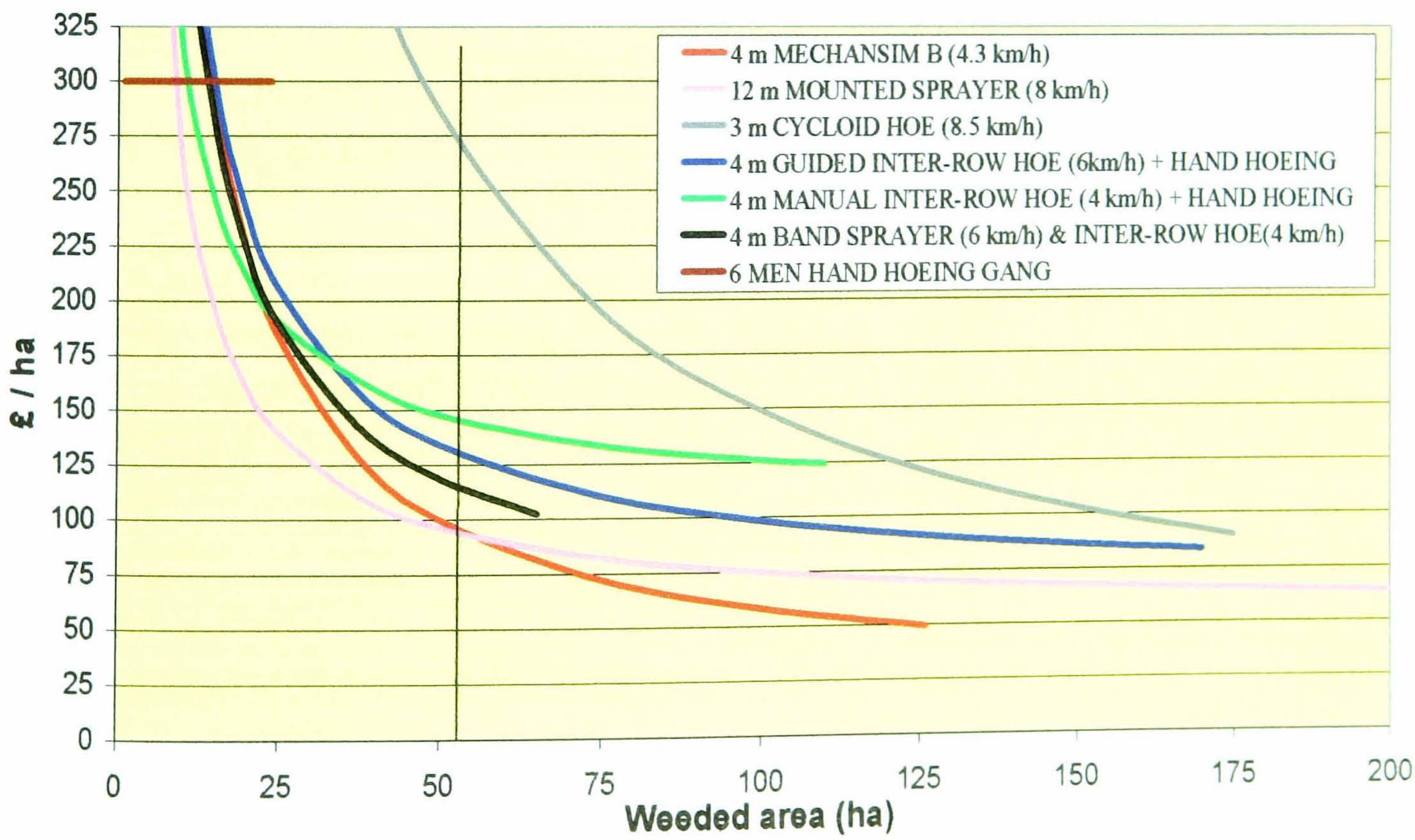


Figure 7-30 Comparative costs of weed control over 20 workable days (update)

Table 7-11 Assumed comparative weeding efficacy

Weeding Method	Controlled area (%)	Weeding efficacy (%)
Intra & Inter-row weeder	>95%	>88%
Inter-row weeder guided + hand hoe	99	95
Inter-row weeder manual + hand hoe	99	95
Band sprayer + hoe	99	95
Hand hoeing	99	97
Conventional sprayer	99	99
Cycloid hoe	unknown	unknown

All of the treatments examined for weed control have varying rates of weed control efficacy (Table 7-11) depending upon treatment type, and this should be considered when examining cost/ha.

For comparison purposes the cost of hand hoeing is assumed to be £300/ha. The line drawn on Figure 7-28 at 52 hectares represents the average size of holding in England & Wales above 20 hectares. It can be seen in Figure 7-30 that all weeding methods can cover this area twice in a season based on 20 available days. Table 7-12 details each weeding method, its cost to hoe at 52 ha, its total capacity and cost at max capacity.

Table 7-12 Economic analysis by area and capacity

Equipment	Cost (52 ha) (£/ha)	Total capacity (ha)	Total capacity cost (£/ha)
Intra & Inter weeder	£97.25	126	£49.76
[1]Inter-row weeder guided + hand	£131.75	168	£83.75
[1]Inter-row weeder manual+ hand	£146.29	110	£124.45
[2]Band sprayer + hoe	£116.17	65	£102.54
Conventional sprayer	£95.01	670	£56.34
Cycloid hoe	£275.48	180	£87.99

[1]Total area dependent upon labour availability for hand hoeing

[2] Band spraying and hoeing undertaken as two separate operations

The most expensive mechanised option reviewed at the mean holding size is the cycloid hoe, which covers the mean area of 52 ha at a cost of £275.48/ha. However, it has spare capacity and could theoretically hoe 180 ha twice within 20 days.

Manual inter-row hoeing and guided hoeing each have the additional cost of hand labour to control the remaining number of weeds that both hoes leave untreated. This makes the cost of the overall operation more expensive, with the guided hoe costing £131.75 at 52 ha and the manual hoe costing £146.29 at 52 ha. Both methods have spare capacity as long as the labour force is available to hoe the remaining weeds.

The prototype 4 m weeder based on mechanism B can hoe a maximum of 126 ha, and costs £97.25/ha at the mean holding size, making it the cheapest option for mechanical weed control throughout the range of farm holdings over 20 ha.

The remaining two weeding methods use chemicals to achieve increased weed control efficacy. The band sprayer and inter-row hoe cover the mean holding size at a cost of £116.17/ha, with a total capacity of only 65 ha. This method of spraying and mechanically weeding is cheaper than inter-row and hand hoe but the work rate, leaves very little spare capacity, it is attractive as weeding efficacy is high and only 2/3 of the chemical is used compared to conventional spraying systems. The band spraying and hoeing operations were undertaken separately, if combined then this method would not only be more cost effective but the area covered in the time available would considerably increase. The remaining method is that of the conventional 12 m sprayer with a cost/ ha at the mean holding size of £95.31 and the capacity to hoe 680 ha. The spray options although giving low cost weed control are not available to organic farmers. Conventional farmers are also under pressure from the major buyers to reduce herbicide usage, and the available herbicides are also diminishing through policy change.

7.9 Concluding discussion

Mechanism B was a successful novel method of weeding the inter- and intra-row area through cutting and burial techniques. The vision guidance system provides accurate lateral positioning and individual plant recognition. The control and phase lock loop approach to plant avoidance worked well at speeds up to 1.19 m/s with the potential to work at speeds around 2.2 m/s.

The ability of the weeding system to adapt to current transplanting machines will be a major advantage in the market place, as growers can mechanically weed at a capital investment of approximately £16,500, without having to change transplanter. For a mean holding size of 52 ha (of holdings greater than 20 ha), the most cost effective mechanical method of controlling weeds was mechanism B; costing only £2.14/ha more than the cheapest option, full chemical control. Further development is required to investigate response times, cam profile and improved software control. This will enable increased working speeds, reducing costs further. Figure 7-30 shows that mechanism B becomes cost effective against inter-row hoeing and hand labour at farm sizes greater than 25 ha. This is in line with estimates in market potential detailed in Section 6.3. If utilisation exceeds 52 ha/annum in total, then weed control using mechanism B is cheaper than spraying.

Based on evaluation of mechanism B and theoretical soil burial over 95% of the area is being treated with over 88% of that area being theoretically controlled at speeds of 0.57m/s and 1.19 m/s on intra-row plant spacings of 0.3 m and 0.5 m. The mechanical weeder also addresses the issue of labour scarcity as the work rate of the 4 m machine (1.3 ha/hr) at 1.19 m/s is 67 times greater than hand labour and a factor of three cheaper per hectare than hand hoeing at the mean holding size of 52 hectares. It copes with a plant spacing range of 0.3 m to 0.6 m at speeds up to 1.19 m/s without causing any plant damage.

The development of the novel weeding system was developed following research into current inter-row hoeing performance in terms of lateral positioning error, which identified the area to be targeted by the novel weeding system. Whilst recording lateral positioning error it was apparent that excessive soil displacement was caused, especially at higher operating speeds. Experiments undertaken in the soil laboratory enabled quantification of the parameters influencing soil displacement and an understanding of the processes. This enabled validation of the mass flow soil dynamics model which has in turn been used to design blades for the proposed inter- and intra-row weeding system.

Further field and laboratory studies are required to extend the model and ensure that the proposed blades behave in the manner in which they were designed.

Agronomic studies need to be undertaken to quantify the effects of the remaining weeds, which will be close to the crop, in terms of yield reduction and effects on plant quality. With legislative changes and pressure from the buyers there may be no option to the grower but to avoid herbicides completely. If this is the case then the proposed mechanical weeder provides an economic alternative.

8 Conclusions and Recommendations

8.1 Conclusions

This project has reviewed existing methods of weed control in order to establish the need for and specification of new machines capable of weeding both inter- and intra-row weeds. The approach taken has investigated current commercial and research guidance technologies as well as laboratory investigations into soil displacement from shallow working wide blades. The review and research has enabled an experimental inter- and intra-row weeding machine to be developed, which offers a significant increase in weeding work rate, and a reduction in the cost per hectare, with enhanced weeding efficacy. With extensive field studies to evaluate theoretical blade design, this weeding system has the potential to address the issues facing intra-row weed control in the widely spaced field vegetable market.

In particular the following conclusions can be made:

- It is possible with guided inter-row hoes, to obtain a lateral positioning accuracy of ± 30 mm irrespective of vision guidance or an additional operator. This compares to ± 42 mm for non-guided systems. Therefore on a typical row spacing for field vegetables of 0.5 m a guided hoe covers 81% of the area, compared to 74% for non guided systems.

- It is possible to predict soil forward and lateral displacement using the mass flow soil dynamics model. Soil bin laboratory studies showed that the model predicts forward displacement within 20% for blades with 45^0 and 20^0 rake angles in dense soil conditions, and 45^0 rake angle blades in loose conditions but is less accurate with reduced rake angles in loose soil. Lateral displacement predictions are typically less accurate with a maximum error of 15 mm on a nominal displacement of 10 mm for 20^0 rake angle blades and 25 mm error on a nominal lateral displacement of 110 mm for 45^0 rake angle blades in dense soil conditions.

- An experimental inter- and intra-row weed control system was designed to meet commercial operating conditions based upon the fundamental principles of soil flow over shallow working wide blades. It performed satisfactorily with commercial variations in plant spacing up to 10% and has the potential to work at speeds up to 1.2 m/s (4.3 km/h) without interfering with the soil within a 30 mm radius of the plant. At speeds of 2.2 m/s (7.9 km/h) the blade entered the 30 mm radius approximately 10% of the time but no plant stems were contacted.

- At intra-row plant spacings of 0.5 m and 0.3 m and speeds of 0.57 to 1.19 m/s over 95% of the available area is treated through either cutting and or burial with the proposed inter-and intra-row weeding system. This results in over 88% of the weeds in this area being destroyed, based on cutting and burial weed kill efficacies of 0.95 and 0.7 respectively.

- It is estimated that there is a European and USA market potential of circa 10,000 machines. Based on a work rate of 1.28 ha/hr at a proposed capital cost of £16,500 the inter- and intra-row weeding system would have an operating cost of £50/ha for a cropped area of 126 ha.

- At £50/ha the proposed weeding system is the most economically viable system at approximately 20% of the cost of hand weeding at £250-£300/ha; 60% of the cost of guided inter-row and hand hoeing at £84/ha and is 70% of the cost of conventional spraying at £70/ha for the same area.

8.2 Recommendations

- A detailed investigation on the mechanisms of mechanical weed control (e.g. cutting and burial) needs to be undertaken in field trials to support the work by Jones *et al.* (1996).

- Additional investigations into leg width and leg to blade mounting brackets to minimise soil disturbance need to be conducted, with emphasis on the distance the leg should be mounted behind the blade, as well as leg width constraints.

- Blade sliding lengths and additional rake and sweep angle combinations need to be investigated to extend the evaluation of the mass flow soil dynamics model.

- Field trials with the experimental inter- and intra-row weeding system need to be undertaken to evaluate the proposed design based on theoretical calculations. This would then lead to the development of a commercial prototype weeding system.

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Appendix 1 Lateral positioning information

A1.1 Lateral positioning control circuit diagram

The circuit diagram shown below is used to remotely activate and control the pulsing and duration of the solenoid valve used for the application of dye to record the lateral positioning error in field evaluations.

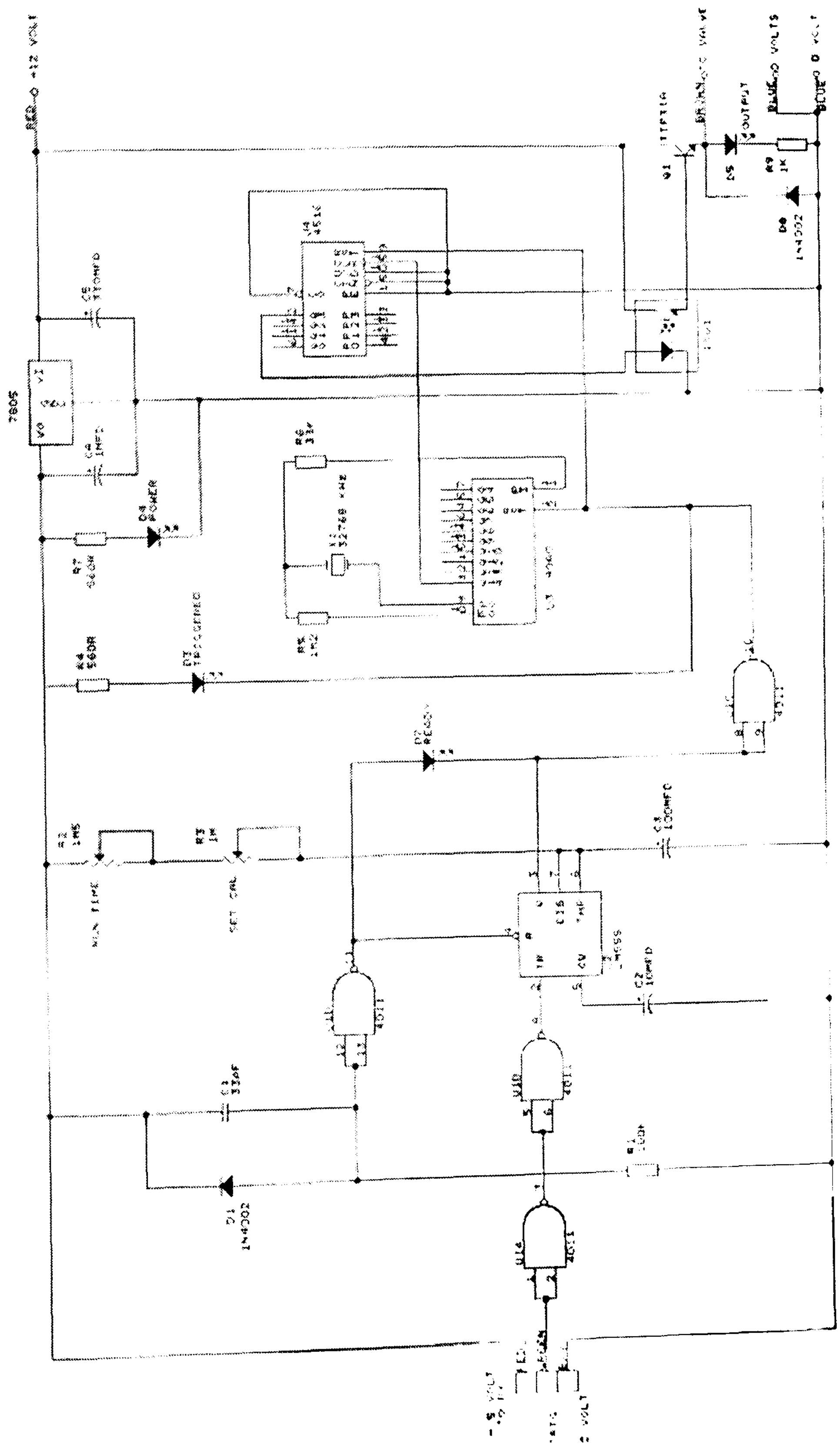


Figure A1.1-1 Lateral positioning control circuit diagram

A1.2 Summary statistics for lateral positioning

Table A1.2-1 presents summary information on the data collected during the lateral positioning experiments detailed in Chapter 3. The mean value represents the bias in the lateral positioning of the implement; ideally the mean should be zero, which would indicate the hoe blade travelled centrally between the rows.

Table A1.2-1 Lateral positioning statistical information

	Hoe A	Hoe B	Hoe C	Hoe D	Hoe E	Hoe F
Mean (mm)	11.9	-1.7	7.4	-6.7	-16.67	-9.64
Median (mm)	15.0	-3.0	10.0	-5.0	-12.5	-10.0
Minimum (mm)	50.0	-28.0	-20.0	-25.0	-40.0	-30.0
Maximum (mm)	60.0	32.0	40.0	10.0	10.0	5.0
Standard deviation (mm)	22.5	10.1	14.4	8.7	14.3	8.6
Standard error of mean (mm)	1.5	0.8	1.1	1.6	2.6	1.6

Appendix 2 Soil dynamics data

Information on soil properties used throughout the soil bin investigations and statistical data for forward and lateral displacement are presented within this Appendix.

A2.1 Mechanical properties of soil used in soil bin investigations

Fraction of sand, silt and clay

Table A2.1-1 Fraction of sand, silt and clay for soil bin laboratory studies

Fraction	Sample 1	Sample 2	Sample 3	**Mean**
Sand (%)	66.04	65.34	67.04	**66.14**
Silt (%)	20.37	21.12	20.70	**20.73**
Clay (%)	13.58	13.55	13.16	**13.16**

Five soil samples were taken along the length of the soil bin, and mixed together; three replicates were taken using the mixed soil with the pipette method. The soil used in the soil bin from the above table classifies the soil as a Sandy loam, according to the Society of Soil Science Classification, and BS 1377 part 2, 1990.

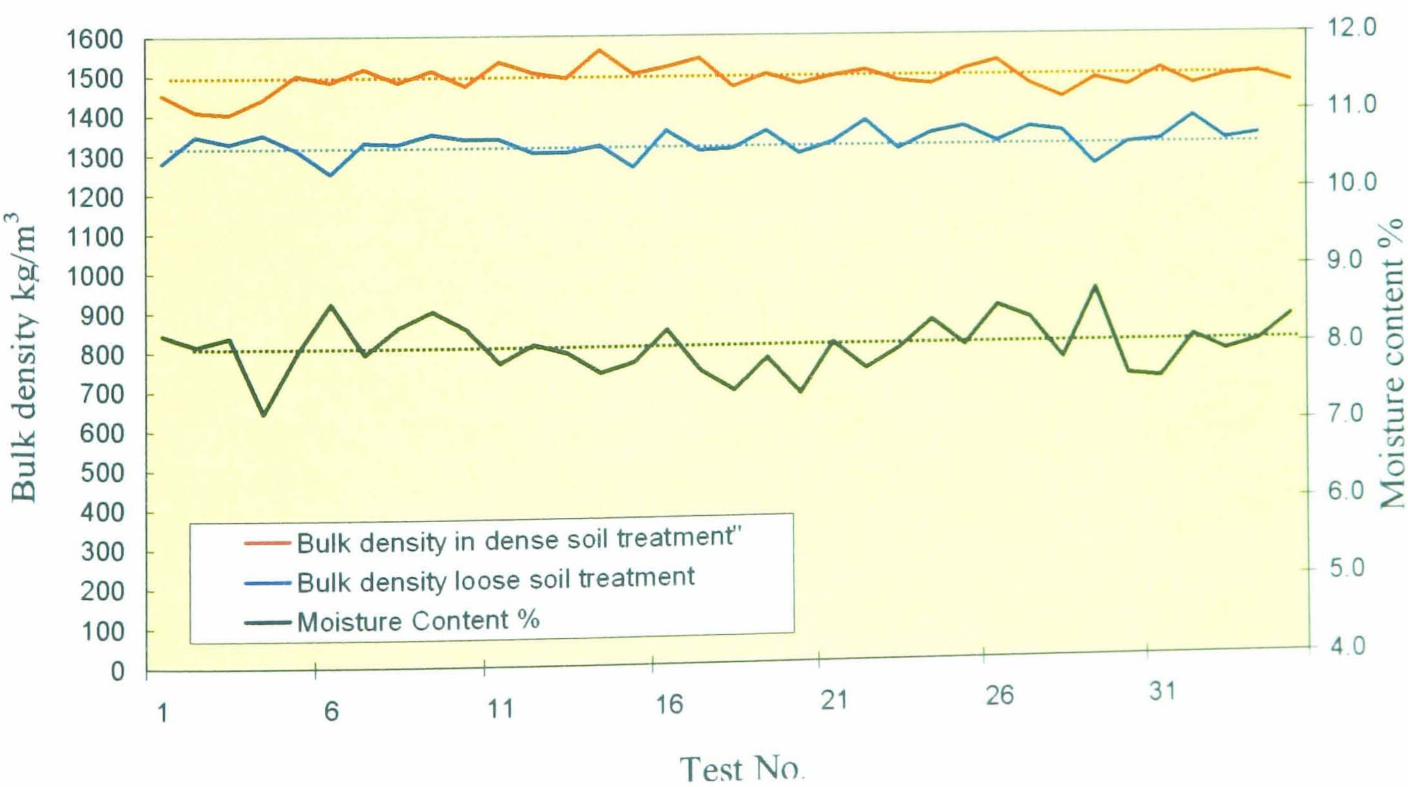


Figure A2.1-2 Soil density and moisture content during soil bin laboratory studies

Appendix 2.2 Experimental data from leg width analysis

The table below shows summary data obtained during the experiments to identify the influence changing leg width has on the forward and lateral displacement of soil.

Table A2.2-3 40 mm wide leg

40 mm leg	Forward					
Summary statistics	1 Loose	5 Loose	9 Loose	1 Dense	5 Dense	9 Dense
Number of values	9	9	9	8	9	8
Mean (m)	0.2672	0.3572	0.4059	0.3410	0.2728	1.2810
Median (m)	0.2700	0.3550	0.3650	0.3495	0.2200	1.0750
Minimum (m)	0.1950	0.2700	0.2000	0.2820	0.1250	0.4200
Maximum (m)	0.3180	0.4200	0.7100	0.3750	0.5350	2.2200
Standard deviation (m)	0.0422	0.0616	0.1520	0.0351	0.1441	0.7690
Standard error of mean (m)	0.0141	0.0205	0.0507	0.0124	0.0480	0.2720
Coefficient of Variance (%)	15.8	17.2	37.4	10.3	52.8	60.0
40 mm leg	**Lateral**					
Summary statistics	1 Loose	5 Loose	9 Loose	1 Dense	5 Dense	9 Dense
Number of values	9	9	9	8	9	8
Mean (m)	0.0213	0.0283	0.0960	0.0219	0.1210	0.2782
Median (m)	0.0200	0.0250	0.0850	0.0250	0.1000	0.2490
Minimum (m)	0.0100	0.0100	0.0170	0.0000	0.0400	0.0780
Maximum (m)	0.0450	0.0450	0.1500	0.0350	0.2600	0.6000
Standard deviation (m)	0.0117	0.0137	0.0451	0.0119	0.0681	0.1772
Standard error of mean (m)	0.0039	0.0046	0.0150	0.0042	0.0227	0.0626
Coefficient of Variance (%)	54.9	48.3	47.0	54.5	56.3	63.7

Table A2.2-4 20 mm wide leg

20 mm leg	Forward					
Summary statistics	1 Loose	5 Loose	9 Loose	1 Dense	5 Dense	9 Dense
Number of values	6	9	9	9	8	9
Mean (m)	0.2967	0.1941	0.4472	0.0344	0.6034	1.3030
Median (m)	0.2900	0.1800	0.4050	0.0150	0.5575	1.4300
Minimum (m)	0.2100	0.1620	0.2200	0.0000	0.2550	0.4800
Maximum (m)	0.3700	0.2700	0.8550	0.110	1.1000	2.4000
Standard deviation (m)	0.0653	0.0353	0.1981	0.0426	0.3167	0.5670
Standard error of mean (m)	0.0267	0.1180	0.0660	0.0142	0.1120	0.1890
Coefficient of Variance (%)	22.0	18.2	44.3	123.3	52.5	147.4
20 mm leg	**Lateral**					
Summary statistics	1 Loose	5 Loose	9 Loose	1 Dense	5 Dense	9 Dense
Number of values	6	9	9	9	8	9
Mean (m)	0.0267	0.0181	0.0756	0.0617	0.2240	0.4406
Median (m)	0.0225	0.0150	0.0900	0.0600	0.1750	0.4600
Minimum (m)	0.0000	0.0050	0.0050	0.0100	0.1420	0.3250
Maximum (m)	0.0550	0.0350	0.1100	0.1400	0.4500	0.5700
Standard deviation (m)	0.0218	0.0099	0.0325	0.0391	0.1107	0.0914
Standard error of mean (m)	0.0089	0.0033	0.0109	0.0130	0.0391	0.0305
Coefficient of Variance (%)	81.9	55.1	43.1	63.5	49.4	55.6

Table A2.2-3 6 mm wide leg

6 mm leg	Forward					
Summary statistics	1 Loose	5 Loose	9 Loose	1 Dense	5 Dense	9 Dense
Number of values	9	9	9	9	9	9
Mean (m)	0.2363	0.1042	0.1576	0.0461	0.0712	0.2678
Median (m)	0.2050	0.1000	0.1420	0.0450	0.0700	0.2400
Minimum (m)	0.1850	0.0950	0.1200	0.0220	0.0280	0.1550
Maximum (m)	0.3350	0.1170	0.2120	0.0700	0.1150	0.5400
Standard deviation (m)	0.0609	0.0086	0.0298	0.0186	0.0263	0.1217
Standard error of mean (m)	0.0203	0.0029	0.0099	0.0062	0.0088	0.0406
Coefficient of Variance (%)	25.8	8.2	18.9	40.3	36.9	45.4
6 mm leg	**Lateral**					
Summary statistics	1 Loose	5 Loose	9 Loose	1 Dense	5 Dense	9 Dense
Number of values	9	9	9	9	9	9
Mean (m)	0.0062	0.0139	0.0331	0.1322	0.0139	0.1500
Median (m)	0.0050	0.0100	0.0250	0.0150	0.0080	0.1200
Minimum (m)	0.0000	0.0050	0.0000	0.0000	0.0000	0.0650
Maximum (m)	0.0120	0.0300	0.0850	0.0300	0.0400	0.3170
Standard deviation (m)	0.0049	0.0088	0.0285	0.0097	0.0162	0.0726
Standard error of mean (m)	0.0016	0.0029	0.0948	0.0032	0.0054	0.0242
Coefficient of Variance (%)	79.1	63.2	85.93	73.2	116.6	48.4

Appendix 2.3 Experimental displacement data

Statistical summaries of forward and lateral displacement and analysis of variance are presented below.

Table A2.3-1 Soil displacement over a 0-20 blade

0-20 (2003)	Forward					
Summary statistics	4 Loose	7 Loose	10 Loose	4 Dense	7 Dense	10 Dense
Number of values	18	26	26	18	27	24
Mean (m)	0.0757	0.1265	0.1484	0.0175	0.0272	0.0376
Median (m)	0.0750	0.1250	0.1450	0.0150	0.0200	0.0400
Minimum (m)	0.0550	0.0970	0.1200	0.0000	0.0050	0.0120
Maximum (m)	0.0880	0.1520	0.1850	0.0400	0.0850	0.0700
Standard deviation (m)	0.0097	0.1720	0.0175	0.0118	0.0212	0.0135
Standard error of mean (m)	0.0023	0.0034	0.0034	0.0028	0.0041	0.0028
Coefficient of Variance (%)	12.8	13.6	11.8	67.2	78.0	36.0
0-20 (2003)	**Lateral**					
Summary statistics	4 Loose	7 Loose	10 Loose	4 Dense	7 Dense	10 Dense
Number of values	27	25	27	18	25	25
Mean (m)	0.0148	0.0098	0.0159	0.0175	0.0184	0.0326
Median (m)	0.0150	0.0100	0.0150	0.0150	0.0200	0.0300
Minimum (m)	0.0020	0.0000	0.03500	0.0050	0.0000	0.0200
Maximum (m)	0.0250	0.0150	0.0050	0.0400	0.0420	0.0500
Standard deviation (m)	0.0065	0.0046	0.0082	0.0102	0.0087	0.0069
Standard error of mean (m)	0.0013	0.0092	0.0016	0.0024	0.0017	0.0014
Coefficient of Variance (%)	43.9	47.1	51.5	58.2	47.2	21.3

Table A2.3-2 Soil displacement over a 0-45 blade

0-45 (2003)	Forward					
Summary statistics	4 Loose	7 Loose	10 Loose	4 Dense	7 Dense	10 Dense
Number of values	20	26	26	22	25	25
Mean (m)	0.3459	0.4606	0.6662	0.2047	0.371	0.5838
Median (m)	0.3500	0.4535	0.6550	0.1800	0.3600	0.5750
Minimum (m)	0.1400	0.4150	0.6050	0.1250	0.3250	0.5000
Maximum (m)	0.5300	0.5350	0.7450	0.3530	0.4400	0.6900
Standard deviation (m)	0.0958	0.0342	0.0374	0.0579	0.3450	0.0462
Standard error of mean (m)	0.0214	0.0670	0.0073	0.0123	0.0690	0.0092
Coefficient of Variance (%)	6.2	7.4	5.6	28.3	9.3	7.9
0-45 (2003)	**Lateral**					
Summary statistics	4 Loose	7 Loose	10 Loose	4 Dense	7 Dense	10 Dense
Number of values	13	27	25	23	23	24
Mean (m)	0.0374	0.0353	0.0358	0.0511	0.0601	0.0954
Median (m)	0.0400	0.0350	0.0350	0.0500	0.0600	0.1000
Minimum (m)	0.0100	0.0000	0.0200	0.0250	0.0450	0.0500
Maximum (m)	0.0600	0.0800	0.0550	0.0800	0.0850	0.1500
Standard deviation (m)	0.0141	0.0164	0.0091	0.0137	0.0115	0.0283
Standard error of mean (m)	0.0039	0.0032	0.0018	0.0029	0.0024	0.0058
Coefficient of Variance (%)	37.7	46.5	25.4	26.9	19.2	29.6

Table A2.3-3 Soil displacement over a 45-20 blade

45-20 (2003)	Forward					
Summary statistics	4 Loose	7 Loose	10 Loose	4 Dense	7 Dense	10 Dense
Number of values	18	27	27	27	27	26
Mean (m)	0.1985	0.1309	0.1227	0.0169	0.0244	0.0364
Median (m)	0.2000	0.1280	0.1200	0.0150	0.0220	0.0335
Minimum (m)	0.1550	0.1050	0.0850	0.0000	0.0120	0.0200
Maximum (m)	0.2250	0.1740	0.2000	0.0320	0.0420	0.0600
Standard deviation (m)	0.1780	0.0690	0.0266	0.0092	0.0077	0.0096
Standard error of mean (m)	0.0042	0.0137	0.0051	0.0018	0.0015	0.0019
Coefficient of Variance (%)	9.0	10.4	21.7	54.1	31.4	26.3
45-20 (2003)	**Lateral**					
Summary statistics	4 Loose	7 Loose	10 Loose	4 Dense	7 Dense	10 Dense
Number of values	19	27	27	18	20	18
Mean (m)	0.0236	0.0168	0.0196	0.0087	0.0068	0.0129
Median (m)	0.0100	0.0170	0.0200	0.0075	0.0090	0.0175
Minimum (m)	0.0000	0.0000	0.0050	0.0000	0.0000	0.0000
Maximum (m)	0.1250	0.0400	0.0400	0.0200	0.0200	0.0300
Standard deviation (m)	0.0311	0.0070	0.0100	0.0071	0.0064	0.0116
Standard error of mean (m)	0.0071	0.0013	0.0019	0.0017	0.0014	0.0027
Coefficient of Variance (%)	131.8	41.4	51.2	81.0	93.6	89.7

Table A2.3-4 Soil displacement over a 45-45 blade

45-45 (2003)	Forward					
Summary statistics	4 Loose	7 Loose	10 Loose	4 Dense	7 Dense	10 Dense
Number of values	25	27	25	24	26	26
Mean (m)	0.3265	0.3742	0.4649	0.1738	0.2215	0.3437
Median (m)	0.3000	0.3750	0.4520	0.1700	0.2135	0.3150
Minimum (m)	0.2020	0.3150	0.4100	0.13500	0.01800	0.2350
Maximum (m)	0.4800	0.4550	0.5620	0.2300	0.3050	0.5600
Standard deviation (m)	0.0921	0.0400	0.0456	0.0260	0.0327	0.0940
Standard error of mean (m)	0.0184	0.0077	0.0091	0.0053	0.0064	0.0184
Coefficient of Variance (%)	28.2	2.1	2.0	15.0	14.8	27.3
45-45 (2003)	**Lateral**					
Summary statistics	4 Loose	7 Loose	10 Loose	4 Dense	7 Dense	10 Dense
Number of values	23	22	27	21	21	21
Mean (m)	0.1957	0.0985	0.1744	0.04810	0.0462	0.0817
Median (m)	0.1950	0.0925	0.1850	0.0400	0.0400	0.0800
Minimum (m)	0.1150	0.0420	0.1000	0.0100	0.0250	0.0100
Maximum (m)	0.2600	0.1980	0.2350	0.1200	0.0850	0.1850
Standard deviation (m)	0.0388	0.0421	0.0400	0.0310	0.0174	0.0513
Standard error of mean (m)	0.0081	0.0090	0.0077	0.0068	0.0038	0.0112
Coefficient of Variance (%)	19.8	42.8	22.9	64.4	37.6	62.8

Table A2.3-5 Soil displacement over a 0-20 blade

0-20 (2002)	Forward					
Summary statistics	1 Loose	5 Loose	9 Loose	1 Dense	5 Dense	9 Dense
Number of values	14	15	18	16	18	17
Mean (m)	0.2096	0.1341	0.1421	0.0120	0.0190	0.0375
Median (m)	0.2315	0.1250	0.1390	0.0100	0.0200	0.0350
Minimum (m)	0.0500	0.1150	0.1020	0.0050	0.0000	0.0000
Maximum (m)	0.3750	0.1800	0.1800	0.0250	0.0320	0.0770
Standard deviation (m)	0.1032	0.0650	0.0780	0.0049	0.0097	0.0212
Standard error of mean (m)	0.0276	0.0216	0.0217	0.0012	0.0023	0.0051
Coefficient of Variance (%)	49.2	16.1	15.2	40.8	51.0	56.4
0-20 (2002)	Lateral					
Summary statistics	1 Loose	5 Loose	9 Loose	1 Dense	5 Dense	9 Dense
Number of values	14	17	18	16	18	17
Mean (m)	0.0419	0.0221	0.0193	0.0051	0.0176	0.0381
Median (m)	0.0340	0.0200	0.0200	0.0000	0.0200	0.0350
Minimum (m)	0.0150	0.0100	0.0050	0.0000	0.0080	0.0160
Maximum (m)	0.0900	0.0500	0.0400	0.0170	0.0250	0.0600
Standard deviation (m)	0.0234	0.0111	0.0092	0.0070	0.0049	0.0125
Standard error of mean (m)	0.0063	0.0027	0.0022	0.0017	0.0017	0.0030
Coefficient of Variance (%)	55.9	50.2	47.8	137.5	27.9	32.9

Table A2.3-6 Soil displacement over a 45-20 blade

45-20 (2002)	Forward					
Summary statistics	1 Loose	5 Loose	9 Loose	1 Dense	5 Dense	9 Dense
Number of values	6	14	17	13	18	18
Mean (m)	0.1412	0.1481	0.1286	0.0161	0.0289	0.0289
Median (m)	0.1475	0.1500	0.1250	0.0090	0.0300	0.0250
Minimum (m)	0.0400	0.0920	0.1000	0.0000	0.0120	0.0080
Maximum (m)	0.2300	0.1820	0.1770	0.0500	0.0420	0.0700
Standard deviation (m)	0.0789	0.0234	0.0159	0.0143	0.0080	0.0170
Standard error of mean (m)	0.0322	0.0063	0.0039	0.0040	0.0019	0.0040
Coefficient of Variance (%)	55.9	15.8	12.4	89.0	27.8	58.9
45-20 (2002)	Lateral					
Summary statistics	1 Loose	5 Loose	9 Loose	1 Dense	5 Dense	9 Dense
Number of values	4	14	17	11	11	17
Mean (m)	0.1400	0.0371	0.0201	0.0074	0.0065	0.0125
Median (m)	0.1500	0.0250	0.0200	0.0100	0.0050	0.0100
Minimum (m)	0.1050	0.0100	0.0050	0.0000	0.0000	0.0000
Maximum (m)	0.1550	0.0950	0.0500	0.0100	0.0200	0.0350
Standard deviation (m)	0.0235	0.0275	0.0098	0.0042	0.0074	0.0097
Standard error of mean (m)	0.0117	0.0073	0.0024	0.0013	0.0022	0.0024
Coefficient of Variance (%)	16.8	74.1	48.8	57.1	112.6	77.5

Table A2.3-7 Soil displacement over a 45-45 blade

45-45 (2002)	Forward					
Summary statistics	1 Loose	5 Loose	9 Loose	1 Dense	5 Dense	9 Dense
Number of values	17	17	15	16	13	15
Mean (m)	0.1818	0.2632	0.4443	0.0972	0.2209	0.3983
Median (m)	0.1750	0.2650	0.4300	0.0800	0.2100	0.4100
Minimum (m)	0.0600	0.1050	0.3200	0.0350	0.1400	0.3150
Maximum (m)	0.3700	0.3900	0.5500	0.2050	0.3300	0.5450
Standard deviation (m)	0.0954	0.2850	0.0819	0.0530	0.052	0.0619
Standard error of mean (m)	0.0231	0.0876	0.0211	0.0132	0.0153	0.0160
Coefficient of Variance (%)	52.5	33.3	18.4	54.5	25.0	15.5
45-45 (2002)	**Lateral**					
Summary statistics	1 Loose	5 Loose	9 Loose	1 Dense	5 Dense	9 Dense
Number of values	15	14	16	13	14	15
Mean (m)	0.1217	0.1550	0.1988	0.0642	0.1357	0.1147
Median (m)	0.1250	0.1575	0.2000	0.0650	0.1375	0.1050
Minimum (m)	0.0500	0.1050	0.0800	0.0050	0.0550	0.0400
Maximum (m)	0.2000	0.2200	0.3150	0.1450	0.2350	0.2250
Standard deviation (m)	0.0485	0.0276	0.0580	0.0526	0.0650	0.0500
Standard error of mean (m)	0.0125	0.0074	0.0145	0.0146	0.0174	0.0129
Coefficient of Variance (%)	39.9	17.8	29.2	81.8	47.9	43.6

Analysis of variance for forward displacement at the 5% level for all blades

Variate: forward displacement

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F pr.
fnvelocity	2	0.2103934	0.1051967	129.35	<.001
density	1	0.2211568	0.2211568	271.94	<.001
Rake	1	1.5449304	1.5449304	1899.67	<.001
sweep	1	0.0475964	0.0475964	58.53	<.001
fnvelocity.density	2	0.0008418	0.0004209	0.52	0.599
fnvelocity.Rake	2	0.1907559	0.0953780	117.28	<.001
density.Rake	1	0.0005500	0.0005500	0.68	0.415
fnvelocity.sweep	2	0.0629676	0.0314838	38.71	<.001
density.sweep	1	0.0101626	0.0101626	12.50	<.001
Rake.sweep	1	0.0783156	0.0783156	96.30	<.001
fnvelocity.density.Rake	2	0.0001097	0.0000549	0.07	0.935
fnvelocity.density.sweep	2	0.0067584	0.0033792	4.16	0.022
fnvelocity.Rake.sweep	2	0.0185403	0.0092702	11.40	<.001
density.Rake.sweep	1	0.0003432	0.0003432	0.42	0.519
fnvelocity.density.Rake.sweep	2	0.0050071	0.0025035	3.08	0.056
Residual	46(2)	0.0374100	0.0008133		
Total	69(2)	2.4114707			

```
* MESSAGE: the following units have large residuals.
 *units* 28        -0.0854    s.e. 0.0228
*units* 30          0.0691    s.e. 0.0228
*units* 62         -0.0540    s.e. 0.0228
*units* 63          0.0750    s.e. 0.0228
```

***** Tables of means *****

Variate: forward displacement

Grand mean 0.2275

fnvelocity	1	2	3
	0.1680	0.2158	0.2988

density	1300.00	1500.00
	0.2830	0.1721

Rake	20.00	45.00
	0.0811	0.3740

sweep	0.00	45.00
	0.2533	0.2018

fnvelocity	density	1300.00	1500.00
1		0.2266	0.1094
2		0.2728	0.1589
3		0.3495	0.2481

fnvelocity	Rake	20.00	45.00
1		0.0811	0.2548
2		0.0757	0.3560
3		0.0864	0.5113

density	Rake	20.00	45.00
1300.00		0.1337	0.4322
1500.00		0.0284	0.3158

fnvelocity	sweep	0.00	45.00
1		0.1563	0.1796
2		0.2440	0.1877
3		0.3595	0.2382

density	sweep	0.00	45.00
1300.00		0.2968	0.2691
1500.00		0.2097	0.1345

Rake	sweep	0.00	45.00
20.00		0.0738	0.0883
45.00		0.4327	0.3153

	density	1300.00		1500.00	
fnvelocity	Rake	20.00	45.00	20.00	45.00
1		0.1371	0.3161	0.0251	0.1936
2		0.1283	0.4173	0.0231	0.2947
3		0.1357	0.5633	0.0370	0.4593

	density	1300.00		1500.00	
fnvelocity	sweep	0.00	45.00	0.00	45.00
1		0.1897	0.2635	0.1229	0.0958
2		0.2930	0.2526	0.1949	0.1229
3		0.4076	0.2914	0.3113	0.1850

	Rake	20.00		45.00	
fnvelocity	sweep	0.00	45.00	0.00	45.00
1		0.0545	0.1077	0.2581	0.2515
2		0.0738	0.0776	0.4142	0.2978
3		0.0931	0.0796	0.6259	0.3967

	Rake	20.00		45.00	
density	sweep	0.00	45.00	0.00	45.00
1300.00		0.1168	0.1507	0.4768	0.3876
1500.00		0.0308	0.0260	0.3886	0.2431

		Rake	20.00		45.00	
fnvelocity	density	sweep	0.00	45.00	0.00	45.00
1	1300.00		0.0757	0.1985	0.3037	0.3285
	1500.00		0.0333	0.0169	0.2125	0.1746
2	1300.00		0.1258	0.1309	0.4603	0.3742
	1500.00		0.0218	0.0244	0.3681	0.2213
3	1300.00		0.1488	0.1227	0.6665	0.4601
	1500.00		0.0374	0.0366	0.5852	0.3333

*** Standard errors of means ***

Table	fnvelocity	density	Rake	sweep
rep.	24	36	36	36
d.f.	46	46	46	46
e.s.e.	0.00582	0.00475	0.00475	0.00475

Table	fnvelocity density	fnvelocity Rake	density Rake	fnvelocity sweep
rep.	12	12	18	12
d.f.	46	46	46	46
e.s.e.	0.00823	0.00823	0.00672	0.00823

Table	density sweep	Rake sweep	fnvelocity density Rake	fnvelocity density sweep
rep.	18	18	6	6
d.f.	46	46	46	46
e.s.e.	0.00672	0.00672	0.01164	0.01164

Table	fnvelocity Rake sweep	density Rake sweep	fnvelocity density Rake sweep
rep.	6	9	3
d.f.	46	46	46
e.s.e.	0.01164	0.00951	0.01646

(Not adjusted for missing values)

*** Standard errors of differences of means ***

Table	fnvelocity	density	Rake	sweep
rep.	24	36	36	36
d.f.	46	46	46	46
s.e.d.	0.00823	0.00672	0.00672	0.00672

Table	fnvelocity density	fnvelocity Rake	density Rake	fnvelocity sweep
rep.	12	12	18	12
d.f.	46	46	46	46
s.e.d.	0.01164	0.01164	0.00951	0.01164

Table	density sweep	Rake sweep	fnvelocity density Rake	fnvelocity density sweep
rep.	18	18	6	6
d.f.	46	46	46	46
s.e.d.	0.00951	0.00951	0.01646	0.01646

Table	fnvelocity Rake sweep	density Rake sweep	fnvelocity density Rake sweep
rep.	6	9	3
d.f.	46	46	46
s.e.d.	0.01646	0.01344	0.02328

(Not adjusted for missing values)

*** Least significant differences of means (5% level) ***

Table	fnvelocity	density	Rake	sweep
rep.	24	36	36	36
d.f.	46	46	46	46
l.s.d.	0.01657	0.01353	0.01353	0.01353

Table	fnvelocity density	fnvelocity Rake	density Rake	fnvelocity sweep
rep.	12	12	18	12
d.f.	46	46	46	46
l.s.d.	0.02343	0.02343	0.01913	0.02343

Table	density sweep	Rake sweep	fnvelocity density Rake	fnvelocity density sweep
rep.	18	18	6	6
d.f.	46	46	46	46
l.s.d.	0.01913	0.01913	0.03314	0.03314

Table	fnvelocity Rake sweep	density Rake sweep	fnvelocity density Rake sweep
rep.	6	9	3
d.f.	46	46	46
l.s.d.	0.03314	0.02706	0.04687

(Not adjusted for missing values)

***** Stratum standard errors and coefficients of variation *****

Variate: forward displacement

d.f.	s.e.	cv%
46	0.02852	12.5

Analysis of variance for lateral displacement at the 5% level, for blades with sweep

Variate: Lateral displacement

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F pr.
fn_velocity	2	3663.4	1831.7	2.37	0.103
Rake	1	169841.7	169841.7	219.55	<.001
density	1	48935.4	48935.4	63.26	<.001
fn_velocity.Rake	2	8222.9	4111.5	5.31	0.008
fn_velocity.density	2	7082.4	3541.2	4.58	0.014
Rake.density	1	11173.7	11173.7	14.44	<.001
fn_velocity.Rake.density	2	3424.3	1712.1	2.21	0.118
Residual	58(2)	44868.2	773.6		
Total	69(2)	296583.0			

* MESSAGE: the following units have large residuals.

units 1	89.0	s.e. 25.0
units 49	75.7	s.e. 25.0

***** Tables of means *****

Variate: Lat_move

Grand mean 68.5

fn_velocity	1	2	3
	66.1	61.3	78.2

Rake	20.00	45.00
	19.9	117.1

density	1300.00	1500.00
	94.6	42.4

fn_velocity	Rake	20.00	45.00
1		28.1	104.1
2		16.8	105.8
3		15.0	141.4

fn_velocity	density	1300.00	1500.00
1		105.5	26.7
2		76.9	45.6
3		101.3	55.1

Rake	density	1300.00	1500.00
20.00		33.6	6.3
45.00		155.6	78.6

	Rake	20.00		45.00	
fn_velocity	density	1300.00	1500.00	1300.00	1500.00
1		51.0	5.2	160.0	48.2
2		29.7	3.8	124.2	87.3
3		20.0	10.0	182.7	100.2

*** Standard errors of differences of means ***

Table	fn_velocity	Rake	density	fn_velocity Rake
rep.	24	36	36	12
d.f.	58	58	58	58
s.e.d.	8.03	6.56	6.56	11.35

Table	fn_velocity density	Rake density	fn_velocity Rake density

rep.	12	18	6
d.f.	58	58	58
s.e.d.	11.35	9.27	16.06

(Not adjusted for missing values)

*** Least significant differences of means (5% level) ***

Table	fn_velocity	Rake	density	fn_velocity Rake
rep.	24	36	36	12
d.f.	58	58	58	58
l.s.d.	16.07	13.12	13.12	22.73

Table	fn_velocity density	Rake density	fn_velocity Rake density
rep.	12	18	6
d.f.	58	58	58
l.s.d.	22.73	18.56	32.14

Appendix A3 Forward translocation- worked example

Appendix A.3.1 Forward Translocation worked example

An example of the derived formula for predicting the forward translocation of soil is shown below.

$$FT'_t = \left[\left(\frac{V_b}{V'_s} - \cos\delta\right) l'\right] + \left[\left(\frac{V'_z + \sqrt{V'^{\,2}_z + 2gZ_o}}{g}\right) V'_y\right]$$

where,

$$V'_s = \frac{V_b\ d_1\ \rho_1}{d'_2\ \rho_f\ (1 + e\ \frac{l'}{w} \sin\ \psi)}$$

$$d_2 = \left[\frac{d_l}{\sin\beta}\right] \sin\left[\delta + \beta\right]$$

$$l' = \frac{l \sin\alpha}{\sin\delta}$$

$$\delta = \tan^{-1}(\cos\psi . \tan\alpha)$$

$$\beta = 45 - \frac{\phi}{2}$$

$$V_z' = V'_s \sin\delta$$

$$V_y' = V_b - V_s' \cos\delta$$

$$V_{sx}' = e\ V_s' \sin\psi$$

ρ_f loose $= \rho_l$ loose

ρ_f dense $= 0.58\ \rho_l$ dense

$w = 0.2$
$\psi = 45^0$
$\alpha = 45^0$
$\rho_l = 1493\ kg/m^3$
$\rho_f = 0.58\rho_l$
$\varphi = 37^0$
$d_l = 0.025$
$l = 0.1\ m$
$V_b = 3\ m/s$
$Z_0 = 0.0707\ m$

Table A3.1-1 Worked example of forward translocation

Factor	Values	Result
δ	$\tan^{-1}(\cos 45 * \tan 45)$	35.26^0
β	$45 - \frac{37}{2}$	26.5^0
d_2	$\left[\frac{0.025}{\sin\ 26.5}\right] \sin\left[35.26 + 26.5\right]$	0.0494 m
l'	$\frac{0.1 * \sin 20}{\sin 35.26}$	0.123 m
V'_s	$\frac{3 * 0.025 * 1493}{0.0494 * 866(1 + (0.225 * \frac{0.123}{0.2} \sin 45)}$	2.384 m/s
V_z'	2.384*sin 35.26	1.376 m/s
V_y'	3- (2.384* cos 35.26)	1.053 m/s
t_f	$t'_f = \frac{1.376 + \sqrt{1.376^2 + 2 * 9.81 * 0.0707}}{9.81}$	0.325 s

Therefore:

Total forward translocation:

$$0.396\ m = \left[\left(\frac{3}{2.384} - \cos 35.26\right) 0.123\right] + \left[0.325 * 1.053\right]$$

Appendix A.4 Transplanter accuracy and weed control

Transplanter accuracy information and derivation of the weed control formula are detailed found within this Appendix.

Appendix A.4.1 Transplanter accuracy

Table A4.1-1 Transplanter accuracy

Pelican - Cauliflower	Inclusive of wheel slip	Exclusive of wheel slip
Mean (m)	0.492	0.479
Median (m)	0.480	0.480
Minimum (m)	0.060	0.380
Maximum (m)	1.090	0.600
Standard deviation (m)	1.030	0.042
Standard error of mean (m)	0.012	0.005
Coefficient of Variance (%)	23.7	8.7
Pelican - Calabrese	Inclusive of wheel slip	Exclusive of wheel slip
Mean (m)	0.440	0.406
Median (m)	0.410	0.400
Minimum (m)	0.240	0.330
Maximum (m)	1.080	0.560
Standard deviation (m)	0.135	0.041
Standard error of mean (m)	0.014	0.005
Coefficient of Variance (%)	30.6	10.0
Pelican - Cabbage	Inclusive of wheel slip	Exclusive of wheel slip
Mean (m)	0.330	0.330
Median (m)	0.280	0.280
Minimum (m)	0.390	0.390
Maximum (m)	0.110	0.110
Standard deviation (m)	0.029	0.029
Standard error of mean (m)	0.006	0.006
Coefficient of Variance (%)	8.7	8.7
Hand planted Brussels sprouts	Inclusive of wheel slip	Exclusive of wheel slip
Mean (m)	0.559	0.550
Median (m)	0.555	0.550
Minimum (m)	0.170	0.330
Maximum (m)	1.060	0.680
Standard deviation (m)	0.890	0.054
Standard error of mean (m)	0.103	0.007
Coefficient of Variance (%)	8.5	9.8

Appendix A.4.2 Weed control formula derivation

The illustration below defines the areas 1 – 5 and the formula for calculating each area is described below.

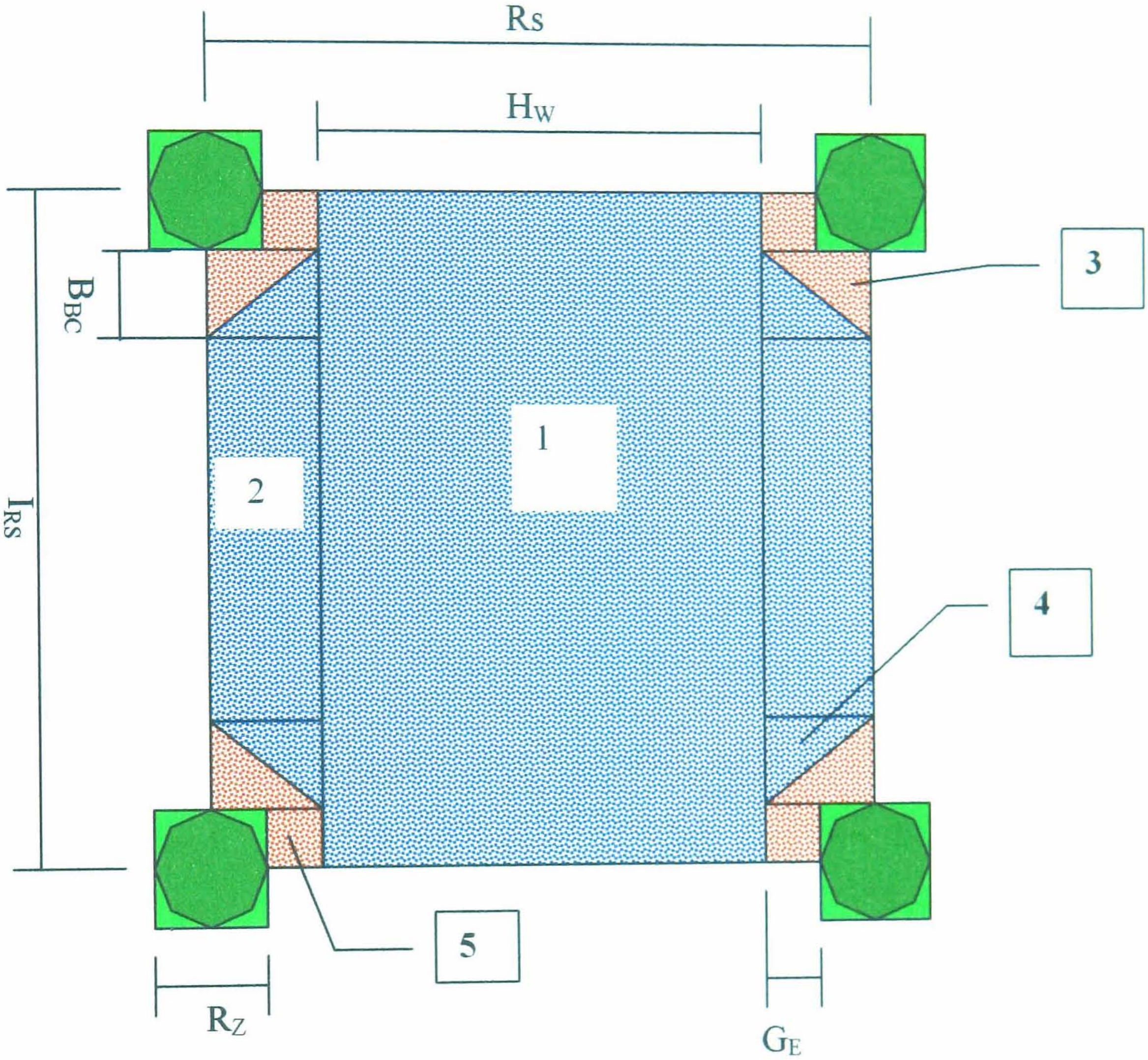


Figure A4.2-1 Target areas for weed control

Nomenclature

HW	=	Hoe blade width	
RS	=	Row spacing	
IRS	=	Intra-row spacing	
RZ	=	Root Zone	
GE	=	Guidance error	
BBC	=	Burial before cutting	
EC	=	Effective cutting	(Blue areas)
EB	=	Effective burial	(Red areas)
EWK	=	Effective weed kill	
EA	=	Effective area	

Area 1 = Weed kill by cutting due to hoe blade : (IRS*HW*EC)
Area 2 = Weed Kill due to cutting by intra-row device: [(RS-HW)*(IRS-RZ-(2*BBC)]*EC
Area 3 = Weed kill due to burial via intra-row device : [(RS-HW)*BBC]*EB
Area 4 = Weed Kill due to cutting by intra-row device: [(RS-HW)*BBC]*EC
Area 5 = Weed Kill due to burial via intra row device : [RZ*(RS-RZ-HW)]*EB

Each of the five areas are multiplied by an EC or EB term, which refers to the efficacy of weeding by employing cutting or burial respectively. Collection of terms EC and EB result in an overall equation that can be used to represent the treated area, and the effectiveness factored in. The effective weed kill (EWK) by area is detailed below.

$$\textbf{EWK} = \Big\{(IRS*HW)+\big[(RS-HW)*BBC\big]+\big[(RS-HW)*(IRS-RZ-(2*BBC))\big]\Big\}*EC)+$$
$$\Big\{\big[RZ*(RS-RZ-HW)\big]+\big[(RS-HW)*BBC\big]\Big\}*EB$$

The effective area EA can also be calculated by knowing the intra-row and inter row spacing and subtracting the root zone clearance zone as shown below.

$$\textbf{EA} = (IRS*RS)-RZ^2$$

The weed kill (WK) percentage in terms of unit area available for weeding is also given below.

$$\textbf{WK\%} = EWK/EA * 100$$

Appendix A5 Intra-row weeding Appendix

Force prediction, for hoe blade draught force and acceleration for the intra-row weeding system are detailed along with the general assembly for mechanism B and Economic analysis of weeding systems. Calculations for tractor specification are also included within this Appendix.

A5-1 Hoe blade force prediction

In order to determine the forces on a new hoe blade the Wheeler & Godwin (1996) formula for force prediction has been used. Their formula is expressed below along with the values used for force prediction.

$$H_t = \left[(\gamma d^2 N_\gamma + cdN_c + qdN_q)(w + d(m - \frac{1}{3}(m-1)) + (\frac{\gamma v^2 N_a d}{g}(w + 0.6d)) \right] \sin(\alpha + \delta)$$

The following values were used: -

γ = 14.94 kN/m^3

d = 0.035

c = 10 kN/m^2

φ = 37^0

α = 45^0

δ = 24^0

N_a = 1.183

$N\gamma$ = 1.75

N_{ca} = 2.22

m = 1.98

w = 0.55 m

Therefore H_t = 0.761 kN

Based on Wheeler & Godwin (1996) a predicted horizontal force component of 0.761 kN for a 0.55 m wide blade operating at 0.035 m depth with a 45^0 rake in dense soil conditions is obtained.

A5-2 Forces due to acceleration

Additional motor power will be required due to overcome the force due to acceleration of the blades opening. The following pages calculate the forces required and all assumptions are stated where necessary.

For constant angular acceleration, α, the equation of motion for angular displacement, θ, is:

$$\theta = \omega_0 t + \frac{1}{2}\alpha t^2$$

Where ω_0 is the initial angular velocity and t is time. In this case $\omega_0 = 0$

Therefore, $$\theta = \frac{1}{2}\alpha t^2$$

Re-arranging: $$\alpha = \frac{2\theta}{t^2} \qquad (1)$$

Assumption – Motor speed is 100 revolutions per minute; each quarter of a rotation is a min or max position of the cam.

One revolution or cycle takes a time of 60/100 = 0.6 seconds

The blade is first at its central position after (0.6/4) = 0.15 s when it has rotated through 22^0 or $11\pi/90$ rad.

Hence from Equation 1:

$$\alpha = \frac{2\frac{11\pi}{90}}{0.15^2} = 34.13 \text{ rad/s}^2$$

The blade is assumed to be 0.125 long x 0.025 m wide x 0.003 m thick and the mass of the blade is assumed to be 0.0702 kg.

The moment of inertia, I, of a blade, assuming it is rotating about an axis normal to its plane, through a point at the end adjacent to the cam track, is given as follows:

$$I = \frac{M}{12}(a^2 + 4b^2)$$

Where a and b are the mean width and length, assumed to be equal to 0.025 m and 0.150 m, respectively.

Hence I is given by:

$$I = \frac{0.0702}{12}(0.025^2 + 4 * 0.15^2)$$

$$I = 5.302 \times 10^{-4} \text{ kg.m}^2$$

The torque required to provide the motion is given by:

$$T = I\,\alpha$$

i.e. $$T = 5.302 \times 10^{-4} \times 34.13$$

$$T = 18.10 \times 10^{-3} \text{ Nm}$$

Assuming the same torque is required for acceleration and deceleration for the whole cycle, the torque required by the two blades is:

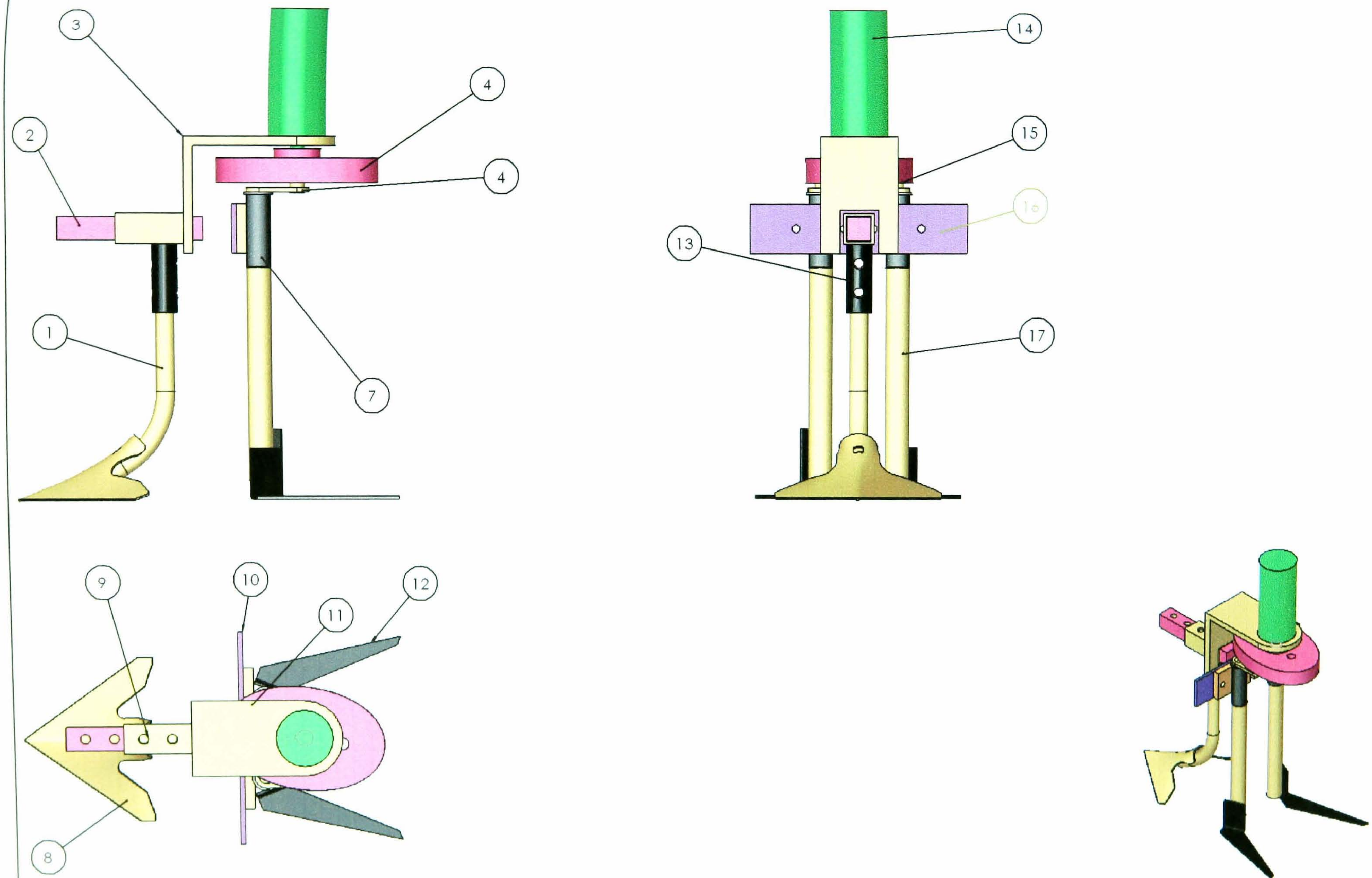
Total torque requirement = $18.10 \times 10^{-3} \times 4$ = **0.0724 Nm**

Therefore it can be assumed that the force required due to acceleration is negligible.

A5-3 Mechanism B - General assembly

Component List

1	Inter-row support leg
2	Leg support mounting
3	Motor mounting bracket
4	Cam
5	Encoder mounting bracket
6	Digital encoder
7	King pin housing
8	Inter-row hoe blade
9	Adjustable leg support bracket
10	Back plate
11	King pin mounting plate
12	Intra row 'L' blade
13	Leg mounting collar
14	Hydraulic motor
15	Cam follower
16	Front mounting bracket
17	King pin



DO NOT SCALE - IF IN DOUBT ASK
REMOVE ALL BURRS & SHARP EDGES

TITLE
DATE Mechanism B GENERAL ASSEMBLY

FIRST ANGLE PROJECTION
UNLESS OTHERWISE STATED

SILSOE RESEARCH INSTITUTE ENGINEERING DESIGN
An Institute of the B.B.S.R.C.
WREST PARK SILSOE BEFORD MK45 4HS
TEL (01525) 860000 FAX (01525) 860156

DRN	MATT HOME 16/04/03
CKD	
DATE	
APP	
DATE	

UNLESS OTHERWISE STATED
DIMENSIONS IN MILLIMETRES

UNLESS STATED
TOLERANCES ARE:-
WHOLE NUMBERS ± 1
TWO DECIMAL PLACES ± 0.1
ONE DECIMAL PLACE ± 0.3

MATERIAL	DRG NO
FINISH	No OFF
ITEM No	SHT 1 OF 1

Appendix A5-4 Economic cost calculator

The following pages contain a description on the operation and use of the tillage costing spreadsheet, followed by the variables used in the economic analysis in Section 7.7.

The spreadsheet shown in Figure A5.4-1 allows a maximum combination of eight different field operations to be undertaken one after another, but is based on the same tractor being used for all operations. If different tractors are required for the operations then it is best to evaluate the model on a single operation at any one time, as the spreadsheet can be configured specifically for each task, rather than a general approach for all operations.

Description Implement selection	Number of Passes	Working Width	Speed km/h	Workrates ha/h	Hours per Oper.	Days Per Year	Calculated Costs £ / Hectare
MECHANICAL HOE	2	4	4.3	1.29	195	20	40.86
NO OPERATION (No Cost)	1	0	0	0	0	0	0.00
NO OPERATION (No Cost)	1	0	0	0	0	0	0.00
NO OPERATION (No Cost)	1	0	0	0	0	0	0.00
NO OPERATION (No Cost)	1	0	0	0	0	0	0.00
NO OPERATION (No Cost)	1	0	0	0	0	0	0.00
NO OPERATION (No Cost)	1	0	0	0	0	0	0.00
NO OPERATION (No Cost)	1	0	0	0	0	0	0.00
					195.3	20	40.86

	Field Variables		Acres
Annual Arable Area	126	Hectares	312
Work Hours Per Day	10	Hours	Acres
Tillage Process Area	126		312
Field Efficiency	75%	%	
Overall Labour Cost	5.74	£ / Hour	
			£/Acre
Pre Cultivating Spray	0.0	£/ha	0
Herbicide Cost / App.	24.98	£/ha	10

	Tractor Variables	kW
Engine Power	50-70 HP	37-52
Tractor Capital Cost	£ 18,271	£
Tractor Resale Value	£ 11,500	
Fuel Used	15	L/Hour
Fuel Cost	0.21	£/litre
Interest Rate	5.0%	%
Repair & Maintenance	8.0%	%
Average Hours per	1000	Hours
Tractor Finance Life	3	Years
Actual Tractor Life	5	Years
Tractor Price Guide 25% Discount	£ 18,271	
Tractor 3 year Resale Guide	£ 11,500	

Figure A5.4-1 Calculator sheet (front screen)

The calculator sheet presents the selected implement working width and speed, its work rate and time to complete the operation in hours and days. The fixed and variable costs of the tractor and implement are presented in the calculated costs column and the total cost column is the combination of tractor and implement costs plus labour.

All of the calculation components rely on the correct information being entered into the yellow boxes in the four main areas of the calculator sheet: Machinery selection, Field variables, Tractor variables and Implement variables, as shown in Figure A.5.4-1. A description of how to use the spreadsheet follows:

Machinery selection

A series of drop down boxes can be found on the left hand side of the calculator sheet which contain a series of agricultural implements as shown in Figure A5.4-2. The drop down boxes are used to select the appropriate field operation to be analysed in terms of cost and work rates. The costing of the selected machinery is automatically calculated and the total cost per hectare is displayed on the right hand of the sheet.

Description	Number of Passes
MECHANICAL HOE	2
NO OPERATION (No Cost)	1
NO OPERATION (No Cost)	1
NO OPERATION (No Cost)	1
NO OPERATION (No Cost)	1
NO OPERATION (No Cost)	1
NO OPERATION (No Cost)	1
NO OPERATION (No Cost)	1

Figure A5.4- 2 Machinery selection and number of passes

Once the implement has been selected the appropriate number of passes can be entered, i.e. 2 passes have been entered for the mechanical hoe as it is often necessary to hoe the field twice.

Each implement selected is compiled on a general machinery sheet (Figure A5.4-7), which provides a typical capital cost of the implement, operating speed, working width and residual values based on depreciation factors by Nix, (2002) and a typical operating speed. These are used as a guide for comparisons, but if actual values are known or second hand equipment is being used, then the values can be changed accordingly.

Field variables

Upon selection of the appropriate implement the next section to be completed in the calculator sheet is that of field variables, shown in Figure A5.4-3. The cells requiring data entry are highlighted in yellow to establish operational costs. This section takes account of: farm size or area to be cultivated, field efficiencies, hours worked per day and labour cost, to provide accurate working costs on a specific farm scenario.

Either the annual arable area of the farm can be entered into the spreadsheet, thus spreading costs of the implement over the farm holding size, or over the tillage process area, so the implements cost can be based on the actual area covered.

	Field Variables		Acres
Annual Arable Area	175	Hectares	433
Work Hours Per Day	10	Hours	Acres
Tillage Process Area	175		433
Field Efficiency	70%	%	
Overall Labour Cost	5.74	£ / Hour	
			£/Acre
Pre Cultivating Spray	0.0	£/ha	0
Herbicide Cost / App.	24.98	£/ha	10

Figure A5.4-3 Field Variables

If more than one operation has been selected in the implement choice area, then the values in the field variables section will apply across all the selected implements. Therefore, care must be taken when comparing costs, and it may be more appropriate to cost individual operations to have control over field efficiencies, rather than an overall field efficiency value.

At the bottom of the field variables data entry area the spray section has been included, representing the costs associated with spraying in £/ha, which is added to the cost of running a sprayer, if that has been selected in the implement selection boxes. The spray sheet is discussed below.

Spray sheet

The spray sheet, is presented in Figure A5.4-4. Only a few herbicides have been entered into the spreadsheet, due to the enormous effort that would be required to include all of the available sprays and update the price each year.

Herbicide	Dosage Area % of worked area	Herbicide Dosage L/Hactare	Spray Cost £ / Litre	Cost Per Hectare £ /Hectare
None	100	2.5	£ -	£ -
None	100	1.5	£ -	£ -
Butisan S	100	1.5	£ 16.65	£ 24.98
None	100	0.0	£ -	£ -
None	100	0.0	£ -	£ -
None	100	2.0	£ -	£ -
None	100	2.0	£ -	£ -
None	100	2.0	£ -	£ -
None	100	2.0	£ -	£ -
None	100	2.0	£ -	£ -
				£24.98

Herbicide Name	Costs £ / Litre
None	£ -
Round up	£ 1.60
trifluralin	£ 1.60
None	£ -
Hawk	£ 3.80
Butisan S	£ 16.65
Laser	£ 67.50
Aromo	£ 15.75
Stomp 400	£ 22.44
Spray 5	£ 1.70

Figure A5.4-4 Spray sheet

This sheet however can be used to aid a grower, who knows what sprays are currently applied and what cost is associated with those sprays. The front calculator sheet picks up on the sprays selected when a spraying option is selected on the implement selection boxes.

Tractor Variables

Figure A5.4-5 presents the tractor variables section, data entry cells have again been highlighted in yellow. This section focuses upon the tractor required to undertake the operation/operations selected. If several operations have been selected, they will be based on the data in this box, so as mentioned before if a variety of tractors new or second hand are being used, then it is best to evaluate each operation separately. The tractor variables section is very useful as once a designated tractor power range has been selected an automatic generation of the new tractor guide price and 3 year resale price is given (shown in blue at the bottom of Figure A5.4-5). New tractor prices are based on the mean price of 5 major tractor manufacturers across the selected tractor power range. The resale guide is based on typical values for tractors with average hours worked, sold at Cambridge machinery sale, over a period of several months.

This guide and resale price can then be entered into the capital cost and resale cells at the top of the selection area, or if the tractor is already on the farm, a current price can be entered with an approximation of the price based on the value of the tractor when it will be sold.

	Tractor Variables	kW
Engine Power	50-70 HP	37-52
Tractor Capital Cost	£ 18,271	£
Tractor Resale Value	£ 11,500	
Fuel Used	15	L/Hour
Fuel Cost	0.21	£/litre
Interest Rate	5.0%	%
Repair & Maintenance	8.0%	%
Average Hours per	1000	Hours
Tractor Finance Life	3	Years
Actual Tractor Life	3	Years
Tractor Price Guide 25% Discount	£ 18,271	
Tractor 3 year Resale Guide	£ 11,500	

Figure A5.4-5 Tractor variables

Upon selection of the tractor engine power, the calculator sheet automatically generates the mean fuel consumption value based on manufactures specifications, which enables calculation of fuel used for each operation. The fixed cost of the tractor for the economic analysis is based on an average of 1000 hrs a year. An alternative approach would be to base the tractor fixed costs on the number of operational hours undertaken through tillage operations a year, but this does not take account of road work or alternative uses.

The cost of owning the tractor is also calculated in this section, if it is purchased outright then the interest rate and finance life would be zero. However the example for the intra-row weeding machine is based on everything being new and financed over three years, at an interest rate of 5%. The repairs and maintenance costs have also been included and they are based on 8% of the capital cost.

Implement Variables

The implement variables section is the last remaining area to be completed on the calculator sheet and is shown in Figure A5.4-6, which shows a simplified version of this section particular modified for investigating the effects of mechanical weeding.

In Figure A5.4-1 a mechanical hoe was selected in the implement drop down box. The implement variables section therefore applies directly to the selected implement. If a variety of implements had been selected then these variables; of interest rate, repairs & maintenance and finance life would be applied to all selected implements.

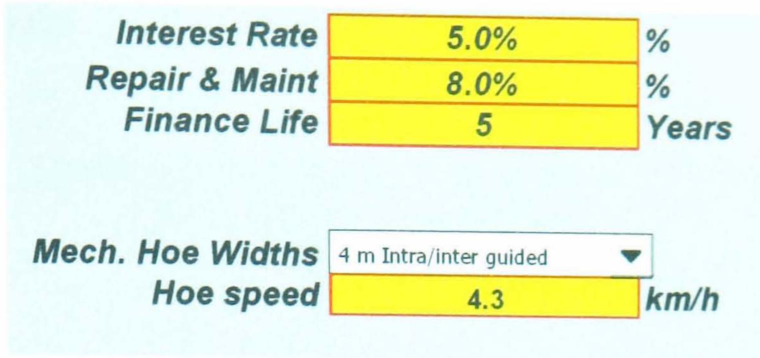


Figure A5.4-6 Implement variables

If changes are required in working width, speed, capital and residual costs then changes need to be made to the machinery sheet, however as this work is based on mechanical weed control, this section has been modified to allow the variables to be controlled easily on the same screen. The drop down box in Figure A5.4-6 has a series of mechanical inter and intra row hoes with their associated capital and residual values, as well as working speed, which can be changed for comparison purposes.

Formula for calculations

In order for the spreadsheet to provide fixed and variable costs of tractors and implements, a set of fundamental economic based formulae are used to provide the basis of the spreadsheet. The equations used to generate the spreadsheet results are detailed below.

Implement fixed costs

$$\cfrac{\cfrac{(\text{Purchase price} + (\text{Purchase price} * \text{Interest Rate} * \text{Finance life})) - \text{Residual value}}{\text{Life in years} * \text{hours per year}}}{\text{annual cropped area}}$$

Implement variable costs

$$\cfrac{\cfrac{\text{Purchase price} * \text{repairs \& maintenace \%}}{\text{hours per pass}}}{\text{workrate (ha/hr)}}$$

Tractor fixed costs

$$\frac{\dfrac{(\text{Purchase price} + (\text{Purchase price} * \text{Interest Rate} * \text{Finance life})) - \text{Residual value}}{\text{Life in years} * \text{hours per year}}}{\text{workrate}}$$

Tractor variable costs

$$\frac{\left[(\text{Fuel cost} * \text{fuel used per hour})\right] + \left[\dfrac{\text{Capital cost} * \text{repairs \& maintenance}\%}{\text{hours per year}}\right]}{\text{workrate}}$$

The above formulae form the basis for the calculations presented below in the machinery sheet. The results are then linked to the front calculation sheet for ease of use.

SYSTEMS OPERATIONS Description	Width m	Speed km/h	Workrate ha/h	Hours/Pass Hours	Fixec Costs £ / Hectare	Variable Costs £ / Hectare	Fixed Costs £/Hectare	Variable costs £/Hectare	TOTAL COST £ / Hectare	Capital Costs (£)	Residual Value (£)	Life Years
NO OPERATION (No Cost)												
POWER HARROW DRILL COMBI	4	4.75	1.33	91	£18.18	£ 10.58	£ 1.43	£ 3.47	£33.66	£16,000	£9,000	5
CULTIVATOR DRILL COMBI	3	6	1.26	96	£16.53	£ 10.58	£ 1.51	£ 3.66	£32.28	£16,000	£8,000	6
POWER HARROW	4	5.5	1.54	78.6	£8.31	£ 3.64	£ 1.24	£ 2.99	£16.17	£5,500	£1,850	5
HEAVY DISC (Simba12C 3m)	3	5.8	1.218	99.3	£9.28	£ 6.87	£ 1.56	£ 3.79	£21.50	£10,385	£4,000	8
HEAVY DISC (Simba23C 4.4m)	4.4	10	3.08	39.3	£26.57	£ 16.51	£ 0.62	£ 1.50	£45.20	£24,978	£5,500	8
HEAVY DISC (Simba34C 4.9m)	4.9	11	3.773	32.1	£28.61	£ 20.45	£ 0.50	£ 1.22	£50.78	£30,953	£11,000	8
HORSCH FG STUBBLE CULTIVATOR	4.5	5	1.575	76.8	£17.25	£ 9.89	£ 1.21	£ 2.93	£31.28	£14,960	£2,000	8
VADERSTAD STUBBLE CULTIVATOR	4.5	5	1.575	76.8	£10.55	£ 6.20	£ 1.21	£ 2.93	£20.88	£9,370	£1,500	8
SPRINGTINE CULTIVATOR	4	6	1.68	72	£1.68	£ 1.26	£ 1.13	£ 2.75	£6.81	£1,900	£750	8
SIMBA OFFSET DISC HARROW (Series 2B)	3.25	6	1.365	88.6	£11.60	£ 8.59	£ 1.39	£ 3.38	£24.97	£12,986	£5,000	8
VADERSTAD HEAVY DISC HARROWS	3.8	5	1.33	91	£11.49	£ 8.26	£ 1.43	£ 3.47	£24.65	£12,500	£4,500	8
SEEDBED HARROW	6.6	7	3.234	37.4	£1.19	£ 1.16	£ 0.59	£ 1.43	£4.36	£1,750	£750	10
PNEUMATIC DRILL	3	6	1.26	96	£13.22	£ 6.61	£ 1.51	£ 3.66	£25.01	£10,000	£4,500	5
VADERSTAD RAPID SUPER (RD 300C)	3	8	1.68	72	£25.50	£ 15.62	£ 1.13	£ 2.75	£44.99	£23,610	£11,000	6
CAMBRIDGE ROLL (SIMBA)	6.6	8	3.696	32.7	£5.64	£ 5.20	£ 0.51	£ 1.25	£12.61	£7,860	£3,000	10
SIMBA DOUBLE PRESS	4.6	10	3.22	37.6	£16.89	£ 11.21	£ 0.59	£ 1.43	£30.12	£16,959	£4,850	8
FLAT ROLLING	3	4	0.84	144	£0.88	£ 0.83	£ 2.26	£ 5.49	£9.46	£1,250	£500	10
SIMBA FREEFLOW DRILL (3M Rigid)	3	5	1.05	115.2	£38.02	£ 25.13	£ 1.81	£ 4.39	£69.35	£38,000	£19,900	6
SIMBA FREEFLOW DRILL (6M Folding)	6	4.5	1.89	64	£64.25	£ 35.26	£ 1.01	£ 2.44	£102.95	£53,314	£20,000	6
HORSCH DOUBLE DISC DRILL (3M DS/D3)	3	8	1.68	72	£30.98	£ 17.19	£ 1.13	£ 2.75	£52.05	£25,995	£10,000	6
HORSCH DOUBLE DISC DRILL (6M DS/D6)	6	8	3.36	36	£66.20	£ 34.95	£ 0.57	£ 1.37	£103.09	£52,850	£18,000	6
JOHN DEERE 740 A MULCH DRILL	6	6	2.52	48	£40.87	£ 20.99	£ 0.75	£ 1.83	£64.45	£31,740	£10,000	6
JOHN DEERE 750 A DIRECT DRILL 3M	3	6	1.26	96	£31.96	£ 16.51	£ 1.51	£ 3.66	£53.64	£24,961	£8,000	6
JOHN DEERE 750 A DIRECT DRILL 4M	4	6	1.68	72	£42.25	£ 22.58	£ 1.13	£ 2.75	£68.71	£34,141	£12,000	6
CYCLID HOE	3	8.5	1.785	67.8	£80.20	£ 33.05	£ 1.07	£ 2.58	£116.90	£50,000	£13,977	5
CASE 3000 TRAILED SPRAYER	24	10	16.8	7.2	£37.41	£ 18.60	£ 0.11	£ 0.27	£81.37	£28,125	£8,000	6
MOUNTED SPRAYER	12	8	6.72	18	£12.36	£ 5.62	£ 0.28	£ 0.69	£68.90	£8,500	£3,145	5
MECHANICAL HOE	4	4.3	1.204	201	£20.45	£ 9.29	£ 1.58	£ 6.45	£37.77	£14,056	£5,200	5
PRE-CULTIVATION SPRAYER	24	12	20.16	6	£28.05	£ 18.60	£ 0.09	£ 0.23	£46.98	£28,125	£8,000	8
PRECISION SPINNER	12	4.5	3.78	32	£3.23	£ 2.15	£ 0.50	£ 1.22	£7.11	£3,250	£150	10
BAND SPRAYER	4	6	1.68	72	£7.92	£ 3.60	£ 1.13	£ 2.75	£31.89	£5,448	£2,016	5

Figure A.5.4-7 Machinery sheet

Variables for economic analysis within Section 7.7

The values shown in the tables below were entered into the correct areas on the costing spreadsheet, and the tillage process area was changed to look at the effects of changing holding size from zero to 200 ha. It was clear to observe that increasing the overall area resulted in a decreased cost per hectare, but the limiting factor was the time to complete the operations, as discussed in Section 7.7.

Table A5.4-1 Calculator sheet variables

Variable	Rate
Work hours per day	10
Field efficiency	70 %
Labour cost	£5.74
Engine Power	37 – 52 kW
Fuel cost	£0.21
Interest Rate	5%
Repairs & maintenance	8%
Tractor hours/yr	1000
Tractor finance life	3 yrs
Implement finance life	5 yrs
Tractor life	3 yrs
Implement life	5 yrs

Table A5.4-2 Machinery sheet values

Equipment	Purchase price (£)	Residual vale* (£)	Life (years)
Inter-Intra row weeder	16427	6,077	5
Inter-row weeder – guided	£14,056	£5,200	5
Inter-row weeder – manual	£8,411	£3,112	5
Band sprayer	£5,448	£2016	5
Conventional 12 m sprayer	£8,500	£3145	5
Cycloid hoe	£50,000	£13,977	5
Tractor	£18,271	£11,500	3

* Implement residual values based on depreciation rates in Nix, 2002.

Appendix A5.5 Tractor Requirements

It is important that the correct tractor is selected as there needs to be sufficient power to undertake the operations. Over sizing the tractor may result in increased compaction, fuel consumption, running costs, capital cost as well as a potentially less manoeuvrable machine. Sufficient engine power is required to overcome the force to pull the blades through the soil as well as the rolling resistance of the tractor and implement if wheeled.

The following sections investigate the power required to operate a 4 m intra-row weeding mechanism at speeds up to 10 km/hr.

Tractor Selection

Intra–row weeding mechanism based on 4 m machine needing 10 modules

Maximum hoe blade cutting depth - 35 mm

Forward speed of 10 km/hr

Draw bar Power requirements to hoe the soil

Using the Wheeler & Godwin (1996) force prediction model as detailed in Appendix A5.2 and based on a possible working width of 550 mm (when fully extended including the inter-row blade, with an aggressive rake angle of 45^0) with a cutting depth of 35 mm in dense soil conditions (1493 kg/m^3), each blade would have a draft force requirement of 0.761 kN. Soil parameters are detailed at the end of this section.

Number of hoe blades = 10

10 x 0.761 = 7.61 kN

7.61 kN x 2.78 (10 km/hr) = **21.16 kW**

Implement rolling resistance

Power requirements due to overcome hoe rolling resistance (RR)

Assumptions: -

Hoe wheel RR	= 0.1
Rear hoe weight	= 500 kg (two steel flange wheels)
Rear hoe weight	= 500 kg (10 wheels therefore 50 kg each)

Flange wheels

0.5 x 9.81 =4.905 kN

4.905 x 0.1 = 0.4905 kN

0.4905 x 2.78 = **1.36 kW**

Depth wheels

0.5x 9.81 = 4.905 kN

4.905 x 0.1 x 2.78 = **1.36 kW**

Additional for gradient (1:100)

= [{(500+500) x9.81}/1000] x sin .57 = **0.1 kW**

Power requirement to overcome implement rolling resistance = **2.82 kW**

Tractor Rolling Resistance

Tyres	13.6 R 28	Rolling diameter	= 1120 mm
	16.6 R 36	Rolling Diameter	= 1560 mm

Tractor weight 51.31 kN

Weight Distribution approx 45/55 (front /rear)

Rolling resistant off chart for cultivated settled loam (good conditions)

Front RR = 0.11 @ 15 PSI

Rear RR = 0.08 @ 15 PSI

51.31 x 0.45 = 23.1 kN

51.35 x 0.55 = 28.21 kN

{(23.1x 0.11) + (0.08 x 28.21)} x 2.78 = **<u>13.34 kW</u>**

Additional for gradient 1:100

m.g.sin θ

51.31 x sin .57 = .51 kN

.51 x 2.78 = **<u>1.42 kW</u>**

Power to overcome rolling resistance of tractor = **<u>14.78 kW</u>**

Overall draw bar power to overcome RR

Drawbar power	13.34 kW
Intra-row weeder	2.72 kW
	16.06 kW

Gradient Factor for 1:10

Additional power requirement

Tractor	1.42 kW
Hoe	0.1 kW
	1.52 kW

Total

22.32+ 1.73 = **<u>17.58 kW</u>**

<u>Total drawbar power to hoe</u>

21.16 + 17.58 = **38.7 kW**

Engine Power = Drawbar power/ Tractive efficiency (0.8*) =

*(Losses = 10% transmission losses and 10% wheel slip)

= 38.7/.8 = **48.4 kW** (64.9 hp)

Therefore, a 4 m hoe operating at a maximum of 35 mm deep at 10 km/hr will require 48.4 kW of engine power to undertake the operation. This size tractor has been used for economic analysis of the overall weeding system.