

Institute of Agri Technology

Eng.D. Thesis

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**Soil incorporation of bio-solids into arable
cropping**

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degree of Doctor of Engineering**

Abstract

“The application of bio-solids to established arable crops, using shallow injection techniques developed during this study, is feasible in environmental, economic, agronomic and engineering terms”.

Novel approaches to bio-solids disposal and recycling are required to compensate for expected increases in production, and to alleviate the external pressures exerted on the water company through legislation and increased public awareness of environmental issues. A review of previous work has identified bio-solids application to arable cropping as a promising beneficial outlet for increased volumes of waste.

From this doctoral study, in collaboration with a parallel fast track project, an improved, shallow injection system has been developed, based on soil mechanics theory and extensive laboratory and field testing. Environmental pollution, in terms of odour and ammonia emissions, may be significantly reduced through the use of this system, when compared to other shallow injection or surface application methods. Nitrate leaching was found to be unaffected by the increased retention of valuable nutrients under field conditions prevailing during the study period, and no detrimental effect on agronomic performance has been identified following application to crops up to three months prior to harvest.

Economically, a market exists for this technology, through the enhanced nutrient value of the bio-solids product. However, product quality, consistency and other environmental issues require solutions before the full economic benefits and market acceptance can be realised. Theoretically, the increased application “window of opportunity” has the potential to increase producers’ operating profits substantially (1.7%/yr, Anglian Water Services Region) through reduced inventory, storage and distribution costs.

Maximisation of environmental benefits has been addressed in terms of implement control, by maintaining constant tine attitude to the soil, through a parallel linkage system. An analysis of the force system associated with the parallel linkage system, in conjunction with the development of a model to predict tine depth, was used to examine ways of optimising the dynamic performance of the system. This work demonstrated that geometric changes to the parallel linkage are unlikely to affect dynamic performance. However, the use of frictionless linkage joints in conjunction with depth control skids was shown to improve dynamic performance significantly and a novel multiple curve fitting technique was developed to improve the accuracy of the depth prediction model.

Where there is a stink of shit, there is a smell of being.

Antonin Artaud (1896-1948)

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Publications

The following publications have resulted from this study:

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Chapter 1

1.0 Introduction.

Organic waste is a necessary by-product of human existence. Historically, the impact of this on the natural environment has been minimal. However, with the advent of modern sewerage systems, in conjunction with modern technological advances in industry, large volumes of waste require sophisticated treatment processes. Water is separated from the waste and returned to the environment; however, the residual product, known as sludge, requires safe disposal.

The problem now facing water companies is how best to dispose of the sludge created during wastewater treatment. Legislation, (EC, 1991), is in force which restricts the opportunities for disposal and water companies have restructured their objectives, in this area, to reflect the current public and political concern over environmental issues (Evans, 1998). In recent years there has been a general shift away from the disposal route towards recycling, which has enabled the water industry to redefine their strategy. Associated with this change is the referral of sewage sludge as a "bio-solid", reducing the negative image of the product.

There are a number of methods suitable for the disposal/recycling of the sludge by-product, each of which has its advantages and disadvantages. However, at present, it is widely regarded that the best practical environmental option (BPEO) is through the use of agricultural land (Chambers & Rudd, 1995). Land availability, farming practice, farmers' perception of sludge and EC legislation combine to constrain the agricultural disposal route.

Sludge can contain contaminants from both industrial and domestic waste. Generally, the industrial wastewater is treated separately from domestic waste; however, both wastes may contain harmful pathogens and heavy metals (Van Den Berg 1993). Conversely, sludge also contains valuable agronomic nutrients such as nitrogen and phosphorous (Franklin 1999 & Chambers 1998). In the Anglian water region alone, the recycling of bio-solids to agriculture represents a cost of approximately £8.5 Million each year (Payne, 1998). Based on typical bio-solids analysis (Moseley *et al*, 1998), the economic value of the recycled bio-solids is approximately £4.5 Million, requiring up to 35,000 hectares of suitable land, all year round.

Through consideration of the political, environmental, agronomic and engineering implications of the recycling of bio-solids, this project aims to devise a system for the recycling of bio-solids to agriculture with minimal environmental impact.

1.1 Project conditions.

This study was initiated in 1995 by Anglian Water Services, to develop and evaluate a field system suitable for the incorporation of bio-solids into arable cropping. To achieve this, research was required to satisfy specific conditions:

- Bio-solids were accepted to be liquid and anaerobically digested in nature, approximately 4% solids content and supplied by the sponsoring organisation.
- Alteration of the composition of the bio-solids was not within the remit of the project.
- Bio-solids application rate was controlled by nitrogen content, although in recent years there has been increasing concern expressed with regard to phosphorous concentrations.
- Field trials were to be conducted on the property of Cranfield University at Silsoe, typically comprising a freely draining sandy loam soil, with no apparent water table, or a poorly drained clay soil with a perched water table.

The project was structured in two distinct sections:

1. Main study; conducted on a fast track basis to provide the sponsor with a solution within 2 years. This study considered more aspects of the bio-solids operation in brief, and was responsible for a significant contribution to the agronomic performance evaluation across both available soil types.
2. Doctoral study; conducted over a 4 year period in parallel to, but in more detail than, the main study. This study considered specific areas of the bio-solids incorporation operation in rigorous detail. Agronomic and environmental trials were conducted solely on the sandy loam soil type.

Since 1995, other influential factors, within the bio-solids recycling topic, have become important, and have been acknowledged, where necessary, within this work. However, these factors have not influenced the main project strategy.

1.2 Disposal / recycling options.

There are a number of potentially viable options available for the effective recycling, or disposal, of sewage sludge. Matthews (1995) suggests that the major opportunities are agriculture, land reclamation, incineration, land filling and marine dispersal. In addition, the Department of the Environment (DoE 1993) includes dedicated land, other beneficial uses, and a degree of uncertainty in its assessment of disposal options. However, there are also possibilities, classified as novel uses (Bruce & Davies, 1989), which are unlikely to be successful on a large scale, but make a valuable contribution to the disposal/recycling effort (Hall 1995). Current practice varies between water companies (*Table 1.1*).

Table 1.1
Disposal routes for Anglian Water and Severn Trent Water 1998

Option	Anglian Water	Severn Trent Water
Agriculture	80%	52%
Sea	8%	0%
Landfill	1%	16%
Incineration	0%	16%
Other	11%	16%

Source: Edge (1998) and Rowlands (1998)

It is noticeable that Severn Trent Water (ST) has no sea disposal, due to the "land locked" nature of the region, and relies heavily on other options such as incineration. Conversely, Anglian Water (AW) disposes to sea but sees few benefits from incineration. Both companies rely heavily on agriculture for the majority of their disposal/recycling operations.

1.2.1 Incineration.

Incineration is the combustion of sewage sludge, at high temperatures, to reduce sludge volume and provide energy. Experience of this method has shown it to be reasonably clean with regard to emissions, and an effective method for disposal (Rowlands 1998). However, a residual "ash", associated with the incineration process, requires safe disposal. At present, no beneficial outlet for incinerator ash has been found and so, disposal is achieved via landfill. The water industry is subjected to an additional levy, on what is classified as "fly ash", when disposing to landfill. This option is expensive and tends to attract strong public opposition. The quantity of sludge incinerated is projected to increase rapidly by 2005 (RCEP, 1996).

1.2.2 Landfill.

Landfill is the dumping of de-watered sludge at designated sites. This option is subject to landfill tax, which is currently c £10/wet ton. Landfill sites accepting sewage sludge are generally classified as "co-disposal", as sewage sludge is mixed with normal, household refuse (Bruce & Davies 1989). The de-watering of the sludge aids in transport over the site as most machines, involved in this process, are designed for use on household waste. The addition of lime to the bio-solids improves the filtration characteristics of the sludge (Van Den Berg, 1993). It is the objective of the EC (EC, 1998b) to reduce the quantity of organic matter disposed to landfill. Consequently, the potential of this option for increased bio-solids disposal, in the light of the Urban Wastewater Treatment Directive (91/271/EC), is reduced. It is predicted that by the end of 2005, landfill will be a minor outlet for disposal, compared to recycling to agriculture and incineration, (WRc, 1995).

1.2.3 Sea dispersal.

Sea dispersal of sewage sludge from Europe ceased on 1st January 1999. This was in accordance with the EC directive (91/271/EC). Other disposal and recycling routes will now need to absorb the effect of this legislation.

1.3 Recycling sewage sludge to agriculture.

Application of bio-solids to agricultural land is the disposal/recycling route most widely used by inland sewage treatment works (RCEP, 1996). In 1999, it is expected that almost 45% of the total UK sludge production, (tonnes of dry solids, tds), will be

applied, in some form, to agricultural land. To cope with the demand for recycling to agriculture, new methods of application must be explored to use the land available efficiently.

In consideration of the application of sewage sludge to agricultural land, implications of the application method, land availability and legislation must be addressed. The legislation pertaining to the management of sewage sludge has been reviewed extensively by Garnett & Matthews (1996). There are, predominantly, six documents of importance concerning the recycling of bio-solids to agriculture; two containing legislation and four providing guidance on compliance with the regulations. Recently, there has also been intervention from the British Retail Consortium (BRC), with co-operation from ADAS, to address consumer concerns over sludge application to crops. The primary document is the EC directive on "the protection of the environment and in particular of the soil, when sewage sludge is used in agriculture" (86/278/EEC). This is enforced in the UK by the "Sludge (use in Agriculture) Regulations" 1989. The second document is the 19th report of the Royal Commission on Environmental Pollution, which provides recommendations on the spreading of wastes onto the soil. In addition, there are documents detailing codes of good agricultural practice for the protection of soil, water and air, and agricultural use of sewage sludge (DoE, 1989). Each of these codes of practice contains guidelines for the safe recycling of sewage sludge to agriculture. Summaries of the documents, referred to above, are presented in the following sections and provide evidence that agricultural use of bio-solids is the most promising option for further research into the recycling effort.

1.3.1 EC Directive 86/278/EEC.

This directive is concerned with the use of sewage sludge on agricultural land and sets out specific guidelines for bio-solids application, with respect to treatment, land cropping and heavy metal concentrations. Potential problems associated with increased concentrations of metals are identified within the directive, which stipulates maximum permissible levels for what it classifies as potentially toxic elements (*Table 1.2*) to avoid excessive build up in the soil which may affect animals or humans, either directly or indirectly.

Table 1.2

Limit values for heavy metal concentrations in sludge for use in agriculture

Potentially toxic element:	Limit values		
	(mg/kg of dry matter)		
Cadmium	20	to	40
Copper	1000	to	1750
Nickel	300	to	400
Lead	750	to	1200
Zinc	2500	to	4000
Mercury	16	to	25

Source: 86/278/EEC

The salient points of the directive, pertinent to the application of bio-solids into arable cropping, are:

- Application to agriculture should be encouraged, providing it is used correctly and that the quality of the soil and agricultural crops is not impaired.
- Limit values for the concentrations of heavy metals in sewage sludge should not be exceeded.
- A period of time should elapse between application of sewage sludge and either grazing of animals or the harvesting of agricultural crops.
- Sludge should be treated before use in agriculture. However, raw sludge may be applied if injected or incorporated into the soil.

1.3.2 19th Report of the Royal Commission on environmental pollution.

This report highlights the impact of the UWWTD (91/271/EC) on the agricultural disposal route. It is expected that the quantity of sludge recycled to agriculture will almost double by 2005, the final implementation date of the UWWTD, compared with that of 1992. The areas of treatment, pathogens and heavy metals are discussed and a number of recommendations are made; primarily that MAFF and the Department of the Environment maintain a watching brief on the presence of new contaminants in sewage sludge which may affect its continued use on agricultural land.

1.3.3 Codes of good agricultural practice for the protection of the soil, air and water.

These codes of practice, produced by MAFF, contain specific information concerning the sludge (use in agriculture) regulations. These codes are not strict forms of legislation but provide valuable and succinct information relating to the EC legislation, especially with regard to good agricultural practice. The codes are sectioned into three main areas of potential pollution.

1.3.3.1 Air.

The code discusses the means by which odour and noxious emissions may be reduced by correct application methods. It is suggested that 44% of all odour complaints in agriculture are related to the land application of slurry (animal by-products). The production of odour is at its greatest during or immediately after application, and immediate incorporation or injection into the soil can reduce the effects of odour significantly. The code of practice suggests that no more than 50 m³/ha of slurry should be applied at any one time and, that by adopting the correct system for application, the effects of odours and noxious emissions can be minimised.

1.3.3.2 Water.

This code of practice stresses the need for careful application to avoid pollution of groundwater and watercourses. An emphasis is placed on a maximum annual application of 250 kg/ha of total nitrogen. Once again, a maximum application of 50 m³/ha is recommended. It suggests that correct assessment of crop requirements, in terms of available N, can reduce the impact of land application on water.

1.3.3.3 Soil.

The code of practice relating to soil outlines and reinforces the regulations in the sludge (use in agriculture) regulations 1989. Of primary importance is the control of heavy metal application to the soil. Whilst it is suggested that there may be some benefits for livestock of certain additional trace elements; the broad spectrum of potentially toxic elements within bio-solids requires that strict limits be adhered to. The code of practice also reinforces regulations regarding the grazing of animals, following application, and the growing and harvesting of crops likely to be eaten raw.

1.3.3.4 Revised codes of practice.

The revised air code (MAFF, 1998a) reiterates the previous code and is more specific in its identification of the sources of emissions. This code recognises that closed slot shallow injection techniques can significantly reduce odour and ammonia emissions to the environment. The revised water code (MAFF, 1998b) maintains the principles of the previous code, but incorporates the need for extra care in nitrate sensitive areas. The need for careful fertiliser management plans is emphasised. The revised soil code (MAFF, 1998c) contains more specific information on the maximum permissible concentrations of heavy metals in the soil.

1.3.3.5 DoE Code of practice.

This code of practice reinforces the EC directive 86/278/EEC. It states the maximum permissible levels of potentially toxic elements and cover application to crops. It makes reference to problems associated with odour and states that high trajectory spreading is undesirable and that incorporation or injection is preferred.

1.3.4 The ADAS safe sludge matrix.

One of the most recent advances, in terms of control of land application of bio-solids, is the ADAS safe sludge matrix. The production of the matrix has been driven by concerns expressed by the British Retail Consortium. Little information is available on the matrix at present. However, the main points are presented in *Table 1.3*.

Table 1.3
The ADAS safe sludge matrix.

Crop	Untreated sludge	Digested sludge**	Advanced treated sludge
Fruit	N	N	N
Salads	N	N	N
Vegetables	N	N***	Y
Horticulture	N	N	Y
Combinable and Animal Feed Crops	Target end date 31/12/1999*	Y	Y
Grass	Banned with effect from 31/12/98	Y	Y
Silage		Y****	Y
Grazing			
Maize	Banned with effect from 31/12/1998	Y	Y
Silage			
*	Until 31/12/2001 on certain combinable crops which are further processed		
**	Research programme must be initiated		
***	Not before vegetable crops, but may be applied in rotation		
****	Must be deep injected, not surface applied		
All applications to comply with DETR Code of Practice.			

Source: Pierrepoint and Hickman (1998)

The matrix outlines the phasing out of the use of raw sludge and increased control over the use of digested sludge. It is likely that only stabilised and pasteurised sludge will be permitted on agricultural land in the future. The major point of note, regarding the matrix and shallow injection, is that the route to grazed land is only permitted with the practice of deep injection. This must be taken into account when considering land availability.

1.2.5 Summary of legislation and codes of practice.

For the legislation and codes of practice reviewed, in the context of future application to arable cropping, it appears that the application of treated sludge, applied in sensible quantities (50 m³/ha), is a feasible way forward. Recent legislation (ADAS, 1998) will not affect application to arable cropping. Given current legislation, agriculture appears to offer the best practical option for the recycling of sewage sludge (bio-solids), both from an economic and environmental viewpoint. The recommendation for injection, or incorporation, to reduce volatile emissions in terms of odour and ammonia, combined with the reduced restrictions on bio-solid application to combinable crops, implies that shallow injection into arable crops, is a suitable option for further research. The more efficient use of available land near to sewage treatment works and the increased window of opportunity for application, resulting from current farming practice, should reduce the need for storage and satisfy the expected increase in bio-solid production.

1.3 Bio-solids treatment.

The treatment of bio-solids has become a basic requirement prior to land application (ADAS 1998). As such, it is necessary to consider the current requirements for treatment to enable application to arable cropping. There are currently four basic treatment processes:

i. **Pasteurisation.**

Pasteurisation destroys most bacterial and pathogenic organisms. It comprises heat treatment, of at least 30 minutes at 70°C, or, a minimum of 4 hours at 55°C; followed, in all instances, by primary, mesophillic, anaerobic digestion.

ii. **Mesophillic Anaerobic Digestion.**

Mesophillic anaerobic digestion is the most common treatment and requires a mean retention period of 12 days at 35°C $\pm$ 3°C, or a mean retention period of 20 days at 25°C $\pm$ 3°C, followed by a secondary retention period of at least 14 days.

iii. **Thermophillic Anaerobic Digestion.**

Thermophillic anaerobic digestion offers some of the benefits of pasteurisation. It is the retention of bio-solids for at least 7 days digestion where sludge is subjected to a minimum of 55°C for at least 4 hours.

iv. **Lime Stabilisation.**

Lime Stabilisation involves the addition of lime to reduce the number of bacterial organisms. The addition of lime raises the pH to above 12, which is sufficient to ensure that the pH remains above 12 for a period of at least 2 hours. This method of treatment can be useful for future application to acidic soils.

Source: DoE (1989)

1.4 Land availability.

At present, there is no method available for the efficient injection of bio-solids into combinable crops. Existing practice comprises application by shallow or deep injection to grassland or cereal stubble (Collins, 1996). As a result of legislation (EC 1991, EC 1998a), agricultural land is expected to receive some of the surplus resulting from the ban on sea dispersal and restrictions applying to landfill disposal. Combined with the recommendations suggested in the ADAS Safe Sludge Matrix, opportunities within agricultural recycling are limited. The total land area of grass in the UK is approximately 6.6 million hectares (MAFF, 1996) a proportion of which would be available for the application of bio-solids all year round. 3.7 million hectares is

cropped with combinable produce, creating an additional outlet between harvest and establishment of the following crop. This land could be utilised for an extended period if a system to inject into the established crop were to be developed.

1.5 Land application.

Before 1970, bio-solids were applied to land using surface application techniques only, i.e. deposition of bio-solids directly on to the soil surface. This can be achieved using a number of different methods (*Fig. 1.1*). Warner *et al* (1988), and Phillips *et al* (1988) showed that ammonia emissions, following application using the splash plate spreader (*Fig. 1.1a*), were less than those after the use of a low level applicator (*Fig. 1.1 b & c*). This may have been due to the sampling equipment used in the experiment and the atomisation of the slurry through use of the splash plate.

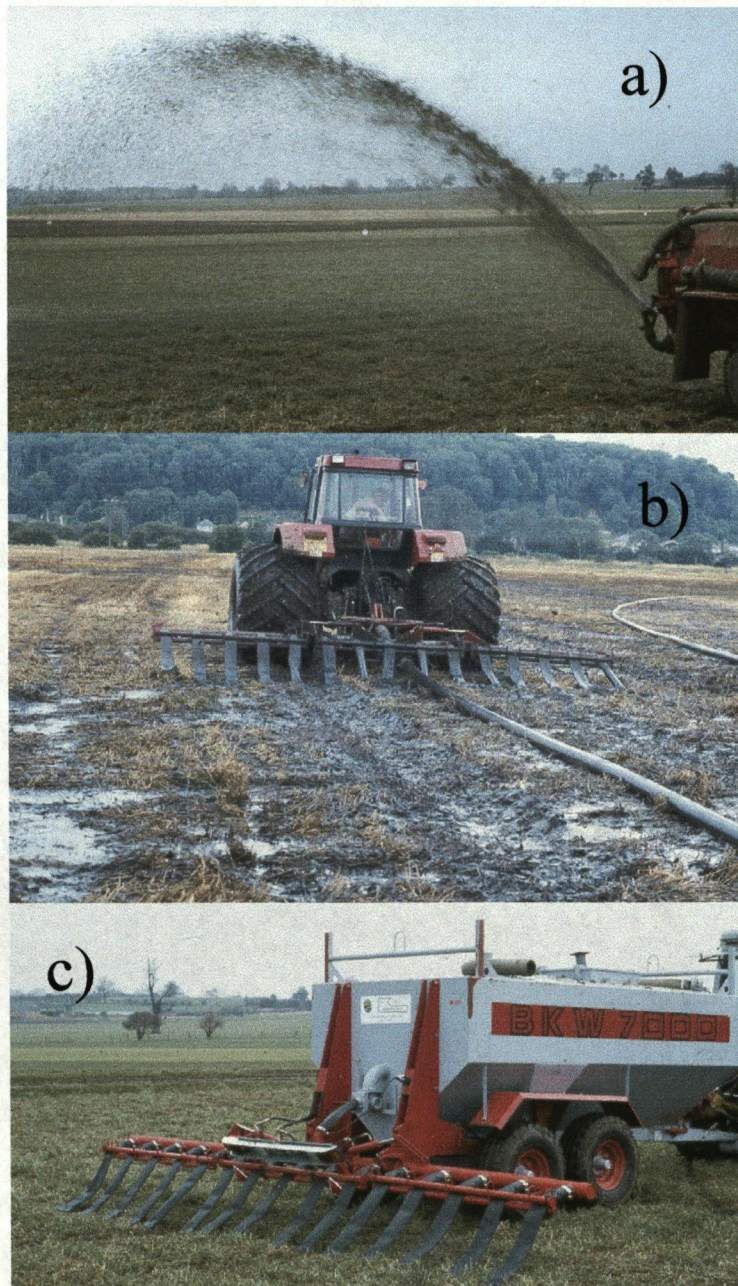


Fig. 1.1. Surface application of bio-solids; a) high trajectory splash plate, b) dribble bar with umbilical supply and c) dribble bar/tanker combination.

More recently, the use of dribble bars (Fig. 1.1b & c.) has become popular for surface application because of the significant reductions in odour associated with this technique (Stroud & Phillips, 1988).

1.5.1 Deep injection of bio-solids.

The concept of injecting liquid waste was first investigated in the early 1970's (Smith *et al*, 1973). Early systems were applying up to $250 \text{ m}^3/\text{ha}$ of slurry to a depth of 0.3 m (Gold *et al*, 1973 & Downs *et al*, 1975). The injection of bio-solids into the

soil, at depths in excess of 0.15 m, is defined as “deep” injection (Collins 1996). Negi *et al* (1976) considered ways of improving the performance of subsurface application equipment by creating sufficient voids to accept the bio-solids. They developed a procedure for calculating this, based on the work of O’Callaghan & Farelly (1964), by considering the additional void space created in the soil by the passage of a tine. The resulting implement design (Fig. 1.2.) was capable of injecting large quantities of bio-solids. However, the draught force requirement was high (5 kN at 0.15 m depth).

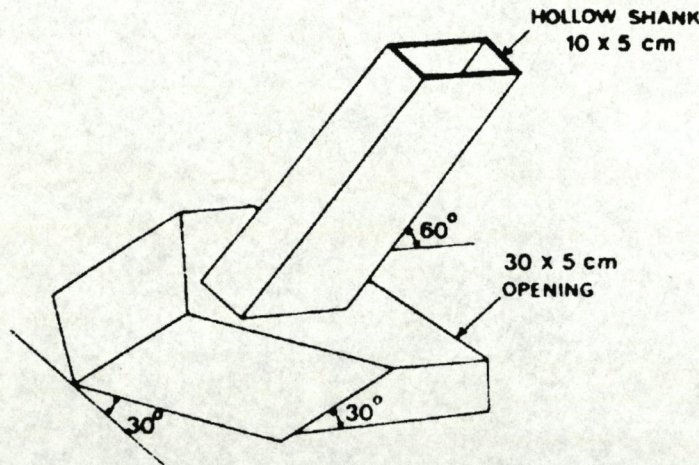


Fig. 1.2. Injector tool geometry (Negi *et al*, 1978).

Whilst these initial “deep” injectors provided sufficient soil disturbance for the application of large quantities of bio-solids, their performance, in crops such as grassland, was less than optimal.

Studies on the subsurface injection of bio-solids continued into the 1980’s. These studies used existing tillage theory (Godwin, 1974) as a basis for the development of subsurface injectors for applying bio-solids to grassland. Warner and Godwin (1988) investigated the leg rake angle, as this can affect the draught force significantly (Payne & Tanner, 1959). They combined work by Payne & Tanner (1959), Spoor & Godwin (1978), and Godwin *et al* (1981) and results suggested that, although draught force can increase by up to 500% between rake angles of 50° and 160°, the draught force becomes less sensitive to changes in leg angle when a leading tip is used. Warner & Godwin (1988) demonstrated that the degree of surface heave can be minimised by increasing the rake angle and, that the addition of wings to the tine foot can reduce the force requirement and increase the soil disturbance, thus enabling large volumes of bio-solids to be injected at shallower depths. They also found that there

was no effect on draught force, in field trials, through vibration of the injector and that, in some situations, considerable undesirable sward damage occurred. Tine spacing was found to be optimal, for applying large volumes with minimal soil disturbance, at 0.65 m for a 0.28 m winged tine working at depth.

Increasing concern over environmental issues, raised by the Sludge (*Use in Agriculture*) Regulations 1989 and the Code of Practice for the Agricultural Use of Sewage Sludge (DoE, 1989), drove researchers to progress the development of injection systems. It had been found that both odour and ammonia emissions from bio-solids could be reduced significantly by injection, compared to surface application, (Phillips *et al*, 1988). Warner *et al* (1990), showed that, although more expensive, deep injection was economically beneficial, and recommended that further studies were needed to address the effect of immediate rolling of the sward after injection on yield (Warner & Godwin, 1988). Subsequently, Warner *et al* (1991) investigated the inclusion of a press-wheel arrangement, connected to the injector by a tie bar, to assist slot closure. They found that optimal slot closure was achieved using a force of 0.5 kN (after Semple, 1986). The deep injector design that resulted from this research is illustrated in *Fig. 1.3*.



Fig. 1.3. Deep injector design; a) & b) prototype injector and c) press-wheel trials.

(Warner & Godwin, 1991).

1.5.2 Shallow injection of bio-solids.

Deep injection is now common practice for recycling bio-solids to agriculture, whereas the concept of shallow injection (<0.15 m depth) is relatively new and little

work has been published to date. Initial work concentrated on the control of odour and ammonia emissions using different application techniques. Phillips *et al* (1990) showed that benefits associated with deep injection, in terms of reduced odour and ammonia emissions, could be retained by using shallow wingless injectors. The restrictive ammonia emissions policy of the Dutch government has led to recent research on band spreading and injector design (Huijsmans *et al*, 1998). These new injector designs operate at shallow depths, typically less than 0.15 m (Collins, 1996), and, compared with surface spreading, lower emissions are observed (Huijsmans *et al*, 1997). Recent research by Huijsmans *et al* (1998) investigated the performance of some selected "shallow" injectors in terms of force requirements. It was found that, when comparing draught force at 0.05 m depth, designs that used discs or knives required greater draught than a simple trailing foot coulter. However, no indication of soil density was provided and so, these results should be viewed with caution.

To summarise, in terms of land application, deep injection methods are well established and provide an efficient means of recycling bio-solids to agriculture. Recent research, however, has shown that the use of shallow injectors may be equally efficient in terms of emissions and more efficient in terms of energy requirement and reduced crop damage.

1.6 Environmental issues relating to land application of bio-solids.

The code of practice for the agricultural use of sewage sludge identifies areas of concern relating to environmental issues; in particular, odour emissions and water contamination. The codes of good agricultural practice also highlight these issues and add that volatile ammonia is a harmful product of both sewage sludge and animal manure application. When considering the application of bio-solids to arable cropping, it is necessary to consider the implications of these effects and how they can be assessed.

1.6.1 Odour and ammonia emissions.

Many bio-solids contain substances such as hydrogen sulphide (H_2S) and ammonium (NH_4^+) as well as other strong odourants, (Burnett & Dondero, 1970; Burnett, 1969; Merkel *et al*, 1968; Miner & Hazen, 1969). Ammonium (NH_4^+) is a volatile gas and is

damaging to the environment, (Van Breeman *et al*, 1982). However, it has some economic value as a crop nutrient (Hall & Ryden, 1986).

Early research on odour and ammonia emissions was concerned with surface applications of bio-solids (Lauer *et al*, 1976). Different methods of surface application were investigated and it was found that the use of dribble bars could significantly reduce odour compared with splash plates (Stroud & Phillips, 1988).

The effect of injecting bio-solids, on odour and ammonia emissions, has been investigated by a number of researchers, (Lindvall *et al*, 1974; Hoff *et al*, 1981; Phillips *et al*, 1988; Quemada *et al*, 1988; Phillips *et al*, 1990; Morken, 1991; Moseley *et al*, 1998). Without exception, these authors encountered a reduction, in both odour and ammonia emissions, when injecting or incorporating bio-solids. Ryden and Lockyer (1985) compared surface application with injection and observed a 17% loss of the total nitrogen applied, to the atmosphere, after surface application, but less than 2% using injection. Pain *et al* (1989) experienced up to 27% loss of total applied nitrogen through volatilisation, with up to 85% of the total loss occurring within 12 hours of application. Phillips *et al* (1990) assessed the performance of a prototype shallow injector and found that both shallow and deep injection perform similarly in terms of emissions. They recommended that further research should be carried out to optimise additional benefits in terms of cost reduction and power requirements. Burglund and Hall (1988) suggest that the use of low pressure and low trajectory spreading equipment, with immediate incorporation or soil injection, are the most cost-effective ways forward for controlling odour and ammonia emissions.

1.6.2 Other losses of nitrogen.

In addition to gaseous emission, nitrogen can also be lost from the soil through leaching and denitrification (Halley, 1986). Leaching losses not only represent a loss of nitrogen as a potential crop nutrient, but also impact on the environment in terms of water quality. The application of sewage sludge to the land can improve the physical and chemical properties of soil (Epstein, 1975, & Epstein *et al*, 1976). However, it has been suggested that the application of bio-solids, in conjunction with sound management practice, is necessary to prevent pollution (Soon *et al*, 1978). Additionally, nitrate concentrations in drinking water pose a risk to health, in terms of

links between groundwater NO_3^- concentrations and infantile methaemoglobinaemia ("blue baby syndrome"), as reported by Comly (1945).

Many researchers have considered the risk of nitrate leaching with respect to the application of bio-solids to agricultural land (Smith, 1996) and the influence of crop type, soil type, application method and timing of application. Sherwood (1986) investigated nitrate leaching from grassland on two soil types, (clay and sand). Porous ceramic cups were used to sample soil water at four depths in the soil profile. Nitrate concentrations were found to be lower on the clay soil than on sand and following surface application of pig slurry, than granular fertiliser application. These results were possibly due to volatilisation losses. Simmelsgaard (1998) also studied the influence of soil type on leaching using porous ceramic suction samplers and found that leaching decreased with increasing clay content. Furrer and Stauffer (1986) carried out a lysimeter-based experiment and found that nitrate leaching was dependent on type of plant cover. In their studies, lower levels of nitrate were experienced with a permanent grass crop as compared with fallow conditions. This correlates well with De Haan (1986) who also experienced lower soil water nitrate concentration on grassland, than on arable, after the surface application of bio-solids.

Unwin (1986), using lysimeters, observed lower losses of NO_3^- when high concentrations of available N were applied to grassland than when they were applied to an arable rotation. Steenvorden (1986) suggests that bio-solids are good for the soil structure and for crop production and that injection into grassland does not increase the risk of nitrate leaching. Coker *et al*, (1987) carried out trials with lagoon-matured digested sludge and found that the timing of application had an important influence on nitrate leaching. Andrews *et al* (1997) states that an autumn application of bio-solids is only suitable when a winter cereal crop is sown, thus reinforcing these findings. It was found that the worst-case scenario, in terms of environmental impact through leaching, was an autumn application followed by a period of fallow and the establishment of a spring crop of cereals.

Safley *et al* (1981) reported increased yields following injection when compared to surface application and Cripps *et al*, (1992) indicated that the application of bio-solids positively affected corn yield due to the increased availability of nitrogen. However,

Shepherd (1996), suggests that the use of liquid digested sewage sludge presents a high leaching risk due to large amounts of available nitrogen content and also found that deep injection increased leaching problems. Blackwell (1996) compared surface application, shallow injection and deep injection and found no significant difference between methods of application, although the deep injection trials did show a trend towards increased nitrate concentrations. Collins, (1996), carried out a lysimeter and a field based study comparing the effect of shallow and deep injection methods on nitrate leaching and found that concentrations of nitrate were lower after shallow injection. This was attributed to placement of the bio-solid in close proximity to the grass roots. This work also showed that crop yield was higher following shallow injection as less damage was done to the crop by the injection equipment compared with that used for deep injection.

1.7. Engineering implications of bio-solids injection.

The development of an economically viable system for incorporating bio-solids into arable cropping, with minimal environmental impact, will require a sound engineering approach, based on established soil mechanics theory. Negi *et al* (1976) used simple soil mechanics to justify their deep injector design. It has been established that injection of bio-solids reduces ammonia emissions (Phillips *et al*, 1990) and shallow injection may be more suitable, as an application method, to arable cropping, than deep injection techniques, due to reduced nitrate concentrations in soil water (Collins, 1996; Blackwell, 1996). However, in engineering terms, application, at shallow depths, into established arable crops introduces new challenges in terms of crop damage and bio-solid incorporation without surface spillage. Little previous work has been carried out with regard to an injection system for combinable crops but McGrath (1995) considered the problems associated with wheel damage and bio-solid supply, using the commonly accepted umbilical supply system (Hann *et al*, 1987). Additionally, the use of injection, at depths less than 0.15 m, suggests that depth control systems may be required to optimise the benefits of reduced emissions and crop nutrient use. The main areas of concern can be summarised as force and control.

1.7.1 Draught force.

There is much information available in the literature on the effect of tine geometry on forces generated during tillage and the pattern of disturbance created as a result of this

geometry (O'Callaghan & Farrelly, 1964; Willat & Willis, 1965). Since the development of classical theories of soil mechanics (Terzaghi, 1943), researchers have generated models to predict the performance of implements in soil. Payne (1956) developed a prediction model, based on a logarithmic spiral, for draught force and soil disturbance for flat tines with a 90° rake angle. His work was predominantly carried out in the field, although preliminary tests were conducted in soil tanks (Siemens & Weber, 1964). Other researchers have developed simpler theories to predict the draught force of simple tillage implements.

O'Callaghan and Farrelly (1964) introduced the concept of critical depth and the two types of soil failure associated with this theory. They accepted the previous work of Payne (1956) to be true only for a tine that was working at a depth equal to, or above, its critical depth. They discovered that a different two-dimensional failure pattern existed for tines operating below this depth. A bearing capacity model was developed, for the forces acting below the critical depth of the tine, to explain the vast increases in force requirements below this depth. Hettiaratchi & Reece (1967) considered the two failure mechanisms to be acting simultaneously. They used the general soil mechanics equation to predict the upper retaining wall failure and developed the bearing capacity theory to cope with the lateral soil failure. This model included the weight of the soil and eliminated the need to use the logarithmic spiral as dimensionless N factors were used (Hettiaratchi *et al*, 1966). However, the model did not represent, fully, the crescent failure observed by Payne (1956) and compensated too much for the small rake angle tines. Godwin and Spoor (1977) attempted to bring together the previous work on tine force predictions. They developed a model for very narrow tines and used a soil bin extensively to test the effect of rake angle depth and width for tines with differing critical depths (Hann & Giessibl, 1998). Previous work was assumed to be correct i.e. below the critical depth soil fails laterally due to additional surcharge stresses. The prediction of the crescent failure was based on the general soil mechanics equation and lateral failure, on the bearing capacity work of Meyerhoff (1951). However, some empirical data is required for force estimation. This tine theory provides a basis for the design of modern injector tines. Other researchers (Ahmed & Godwin, 1983) considered the effect of wing position on penetration forces and soil disturbance for subsoiler tines. These studies investigated

the effect of positioning the wings at a significant distance rearward of the tip of the tine, on draught force and soil disturbance. No significant difference was found, although a trend towards reduced draught, as the wings were moved further rearwards was observed. Existing tine theory is a suitable method for force prediction of simple tines. However, no work to date has been identified which predicts forces associated with complex, shallow injector tines.

1.7.2 Dynamic control of implements.

The control of implements can be separated into two categories,

1. Lateral (Sideways)
2. Vertical (Up/Down)

1.7.2.1 Lateral control.

The dynamic control of implements has been investigated for many years and has concentrated mainly on the control of ploughs. Hawkins and Boa (1946) made a critical assessment of four tractor and plough combinations and stressed the importance of adequate depth control. Later research concentrated on the lateral stability of ploughs on three-point hitch systems (Reece *et al*, 1966). This research explored the mechanisms affecting the return of a plough to its original path after displacement; a necessity when working on hillsides. Cowell & Mankanjuola (1966) progressed this work and suggested that implements can be categorised as directional and non-directional:

- Directional: - an implement that has a preferred direction of travel, and which develops large side forces if pulled in a direction other than the preferred.
- Non-Directional: - an implement that develops a soil resistance only in the direction opposite to its motion through the soil.

Cowell & Mankanjuola (1966) concluded that the lateral motion of a directional implement could be expressed mathematically and that the speed of response was a function of the distance of the plough from the virtual hitch point. They also suggest that, for a directional implement, drawn from a real hitch point (trailed plough), if damping is heavy, the implement should return to within $1/10^{\text{th}}$ of its initial lateral displacement after approximately 2.3 times the length of the hitch. Jonsson (1989) confirms this theory but uses an exponential equation. Subsequently, Mankanjuola and Cowell (1970) made recommendations for optimum performance.

1.7.2.2 Vertical control.

The tractor draught control system is designed to sense changes in draught force and alters the implement depth automatically. A system of draught response was investigated by Dwyer (1969), who identified a degree of overshoot, in control systems, when ploughing over an undulating field surface. In further studies, Dwyer (1969-70) compared the performance of top and lower link sensing draught controls. During this experiment, eccentric wheels were fitted to the tractor to simulate a sinusoidal input. In a comparative study of draught force measurement, in the field and the laboratory, good agreement was found, thus confirming that field performance can be predicted from standard test data. Cowell (1969-70) also considered draught control systems and identified the need for a pure draught force sensing system. A pure draught sensing system was found to give improved response to surface undulations (Dwyer *et al*, 1974). Crolla & Pearson (1975) continued the investigation into vertical control, of implements, using draught sensing systems. They found that draught control systems are more sensitive to implement type and forward speed than to soil type.

1.7.2.3 Other dynamic performance issues.

In the mid 1970's, the emphasis of research changed to modelling the penetration performance of implements. Crolla & Pearson (1975) found that the entry of an implement, into the soil, follows the form of an exponential curve. Cowell and Sial (1976) expanded this work and developed a more rigorous equation to describe this phenomenon. The resulting equation describing penetration, was a simplified extension of the equation governing the lateral dynamic behaviour of implements (Cowell & Mekanjuola, 1966), which implies that, halving the hitch length, doubles the rate of penetration.

All of the models described above require a hitch point (either real or virtual). This suggests that vertical inclination of the implement will change as depth changes. Kepner *et al* (1978) outline the application of parallel link hitches used in agriculture, and suggest that this type of linkage is ideal for situations where a change in vertical inclination of the implement is undesirable. This type of linkage is also important for implements operating close to plants as it has a good degree of lateral rigidity. The most common form of depth control, for an implement attached to a parallel linkage,

is by depth wheel although it is sometimes controlled through the lifting mechanism. Magaña *et al* (1994) used a rear converging linkage on a planter unit, which is normally used with a parallel linkage. They found that significant benefits in weight transfer could be obtained without an adverse effect on the depth control of the implement.

1.7.2.4 Summary.

The shallow injection of bio-solids into arable cropping implies that suitable control systems are needed, to ensure that operating depth is maintained, in order to maximise any environmental or agronomic benefits and to reduce crop damage. The lateral and vertical control of implements can be achieved through careful consideration of implement purpose and design. Active systems are available to control the depth of soil-engaging implements and other linkages can be used to control implement attitude. Due consideration of control systems and modelling techniques may be essential in the design and development of a system for the shallow injection of bio-solids into arable cropping.

1.8 Management aspects.

The management of bio-solids is influenced from three main directions.

1. Legislation: forcing water companies to alter the direction of their bio-solids activity, (Garnett & Matthews, 1996).
2. Public: requiring clean water, efficient sewage treatment and low bills; thus placing more demands on the water companies to improve standards. (Reiter, 1998)
3. Water Companies desires to address the problems of legislation and public concern and also to satisfy shareholder demands for profit.

At present, little information is available on the economic implications of increased bio-solids recycling to agriculture. However, Payne (1997) indicates that, at present, the cost of recycling liquid, digested sewage sludge to agricultural land, in the Anglian water area, costs between £2.50 and £3.50/m³ (not including treatment). Lewis (1998) did not challenge this figure. A large proportion of this cost is attributed to the distribution of large volumes of liquid sludge by tanker, (Brade & Harwood, 1982; Brade & Harwood, 1992). The 19th report of the Royal Commission on environmental pollution (RCEP, 1996), suggests that bio-solids application to land

will cost approximately £65 - £100 per dry tonne of solids by 2005. This is similar to predictions of £50 - £100 for disposal to landfill. Evans (1998) describes the change in strategy of Thames Water Utility (TWU) which has, successfully, moved from the "free give-away" of bio-solids to charging between £40 and £120 per hectare, depending on transport distances. TWU has achieved this status by innovative movement into the dry bio-solids market (thermally dried cake), investing in technology to provide the market with a new, quality-assured product.

Although it is widely established that bio-solids have an economic value (Hall & Ryden, 1986), the perception, of the general public and farmers, at present dictates that cost reductions for the water companies, through the sale of bio-solids, is not possible without providing a value added service. This has been demonstrated clearly by Terra-Eco Systems, (Evans, 1998).

1.9 Future trends.

The sludge disposal issue is undergoing continuous change, both as a result of environmental concern and Europe wide legislation. The volume of production is expected to increase dramatically, over the next few years, as a result of population growth and per capita load discharged (Matthews 1995). The implementation of the ban on sea disposal and the reduction in the quantity of bio-solids being disposed of to landfill suggests that much research is necessary to develop alternative methods for appropriate disposal or recycling of sewage sludge. To cope with demand, existing methods of disposal and recycling must be exploited and novel approaches, to the problem, sought.

1.10 Summary.

The impact of recent legislation on the bio-solids industry requires that new methods for safe recycling of bio-solids be developed. A review of past studies indicates that an investigation into opportunities utilising the economic and nutrient value of bio-solids would be appropriate. The most promising approach appears to be the development of a method for incorporation of bio-solids, into established arable crops, by means of shallow injection.

The development of such a system would require investigation into environmental, agronomic, economic and engineering processes governing the land application recycling route.

1.11 Objectives.

The objectives of this study are:

1. To develop a shallow injector suitable for the application of sufficient quantities of bio-solids to established arable crops with minimum environmental impact.
2. To assess the feasibility of a system to apply bio-solids to arable cropping in terms of the market demand and economic viability, and to assess other issues that may influence the success of such a system.
3. To determine the engineering implications of a system to inject bio-solids into arable cropping and to develop engineering solutions to enable the environmental impact to be minimised, and the economic viability to be maximised.

1.12 Formal structure.

This document is structured to consider:

1. Shallow injector assessment, development and evaluation.
2. Environmental and agronomic performance.
3. Economic viability.
4. Control system evaluation to maximise environmental benefits.

Chapter 2

2.0 Critical evaluation of prototype and commercial shallow injectors.

A review of past work, presented in *Chapter 1*, suggests that the development of a shallow injector, suitable for the application of bio-solids into arable cropping, may provide an effective approach for extending the recycling operations of sewage sludge to agriculture. However, in order to assess the performance of a range of potential designs, it is desirable to model their performance. Models capable of estimating the force and disturbance of simple tines are available (Godwin & Spoor 1977). However, no models exist that can cope with the complexity of shallow injector tines. To address this problem, a small study was carried out in the Cranfield University soil dynamics laboratory at Silsoe, to evaluate some existing shallow injection equipment manufactured by Greentrac™, and some prototype shallow injectors, which were developed based on simple tine theory. The primary objective of the soil bin study was to determine the soil disturbance characteristics of the twelve injectors in the absence of any defined soil theory for complex tines. The results would enable comparisons to be made between commercially available injector tines and tines of differing geometry.

2.1 Study objectives.

The objectives of this initial study are:

1. To define performance criteria for shallow injector tines to allow efficient injection of suitable quantities of bio-solids into arable cropping.
2. To develop a method for assessing the performance of shallow injection tines and to apply this method to some commercially available and prototype shallow injector tines.
3. To use the results of the study to define design criteria for the development of an improved shallow injector.

2.2 Criteria for shallow injection into arable cropping.

Unlike shallow injection into grassland, the use of shallow injectors in an established arable crop introduces a number of engineering challenges concerned with:

- Implement width.
- Penetration ability.
- Crop separation.

- Crop damage.
- Bio-solids mixing.
- Application rates.

2.2.1. Implement width.

Intensive arable systems often adopt a tramline system, to allow the passage of fertiliser spreaders and sprayers across the land (Halley, 1986). "Tramlines" are formed during the planting operation, by blocking off two or more coulters, behind the wheels of the tractor, to produce pairs of plant free trafficking strips. This provides roadways for subsequent field operations. Commonly, the spacing between each set of tramlines can be 12, 18 or 24 m. It is essential that the working widths of the planter, fertiliser distributor and sprayer be matched. Consequently, the bio-solids application equipment must be designed with the tramline system in mind. This suggests that any injector should be efficient, in terms of power requirement, to allow injection into land adjacent to tramlines whilst adhering to the standard tramline widths mentioned above.

2.2.2. Penetration ability.

The natural ability of a tine to penetrate the soil is of particular importance under harsh conditions. The performance of a soil-engaging implement should not be limited by soil type. A tine with a small resistance to penetration, or even positive assistance to penetration, eliminates the need for additional weight to assist in penetration. This is of particular importance when considering implement width.

2.2.3. Crop separation.

Although arable crops are planted in rows; to enable injection after establishment it is necessary to provide some means of crop separation to avoid the possibility of intertwined plants wrapping around any injector tine and being ripped from the ground. Current grassland injection machinery uses cutting discs and consideration of these, or some form of separation edge, is required in the context of arable injection.

2.2.4. Crop damage.

The primary objective of arable farming is to achieve sufficiently high yields to reap a profit from the investment in time, materials and labour. In recent years, however, the profit margin associated with wheat production, for instance, has reduced dramatically, due to a slump in wheat prices (Nix 1998). It is now, therefore, more

difficult for farmers to achieve their objectives. Any yield reduction, from increased crop damage to leaves and roots, could exacerbate the situation. Damage to leaves can be reduced by adequate crop separation (*Section 2.2.2*) and evidence suggests that efficient incorporation of bio-solids can also help reduce the effect of leaf damage on yield (Warner *et al*, 1991). Restricting the lateral soil disturbance created by the injector can reduce root damage.

2.2.5. Bio-solids mixing (soil coverage/incorporation).

Research has shown that the application of bio-solids to agricultural land by means of injection, can significantly reduce the emissions of ammonia to the atmosphere and aid in the reduction of odour, (Phillips *et al* 1990). Consequently, the performance criteria, for shallow injection of bio-solids into arable cropping, must include sufficient mixing of the bio-solids to minimise emissions. Mixing can also reduce leaf damage; as other research (Warner *et al* 1991) has demonstrated that spillage onto the surface of grassland can cause sward "die-off".

2.2.6. Application rates.

Smith *et al* (1973), and Gold *et al* (1973), found that significant quantities of bio-solids could be disposed of by subsurface application. Negi *et al* (1976 & 1978) attributed the quantity of bio-solids that could be incorporated into the soil to the creation of voids by the passage of the injector. More recently, MAFF codes of practice suggest that application rates should be limited by the quantity of total nitrogen contained in the bio-solid. The maximum recommended dosage of nitrogen is currently 250 kg/ha/yr (MAFF, 1991; MAFF 1998a,b,c). An analysis of a typical composition of sewage sludge found the total nitrogen content to be $\approx 6.2\%$ of dry weight (Moseley *et al*, 1998). For a dry matter content of 4% (*Section 1.1*), the nitrogen content of 1 m³ of bio-solids will be ≈ 2.5 kg. This would indicate that the maximum annual dosage of nitrogen could be applied in one application of 100m³/ha. Other MAFF codes endorse a lower maximum application rate of 50 m³/ha (MAFF 1992; MAFF 1998a,b,c). As the nitrogen content of bio-solids varies, a safe assumption is that an injection system, suitable for the application of bio-solids into arable cropping, should be capable of applying between 50 and 150 m³/ha. Recent efforts have concentrated on the quantity of phosphorous contained in sewage sludge, and in some cases this has been the limiting factor governing application rates. It should be stressed that any bio-solids strategy, utilising sewage sludge as a fertiliser,

should consider crop nutrient requirements and soil condition, as stated in the revised MAFF codes of practice.

2.2.7. Summary of injector performance criteria.

With regard to the constraints discussed a shallow injector, suitable for the application of bio-solids into arable cropping, should satisfy the following design criteria:

1. Low draught force requirement.
2. The ability to penetrate the soil in hard conditions.
3. A cutting disc/edge for crop separation.
4. Restricted lateral soil disturbance to minimise crop root damage.
5. Sufficient void creation to allow an application of bio-solids of between 50 and 150 m³/ha.

2.3 Relevant tine theory.

In order to evaluate the design of prototype injectors, previous work on modelling the performance of soil engaging implements was considered. Godwin and Spoor (1977) suggest that draught force benefits may be gained from using small rake angles. They indicate that two distinct failure patterns occur; a three-dimensional (*crescent*) soil failure above a critical depth, and a two-dimensional (*lateral*) soil failure below critical depth. It was found that the two-dimensional failure that occurred below critical depth significantly increased the draught force requirement. However, the calculation of critical depth was rather tentative and was not suited to shallow tines. During deep injection studies (Negi *et al*, 1976), critical depth was assumed to occur at a depth equal to six times the width of the tine, and soil disturbance models suggest that the failure boundaries, following the passage of a tine, can be approximated. Smith *et al* (1988) propose that the lateral rupture distance can be estimated as either the depth of the tine or the critical depth, whichever is less, whereas Negi *et al* (1976) use the theory of Kostitsyn (1956) in approximating the lateral soil failure boundary (Fig. 2.1).

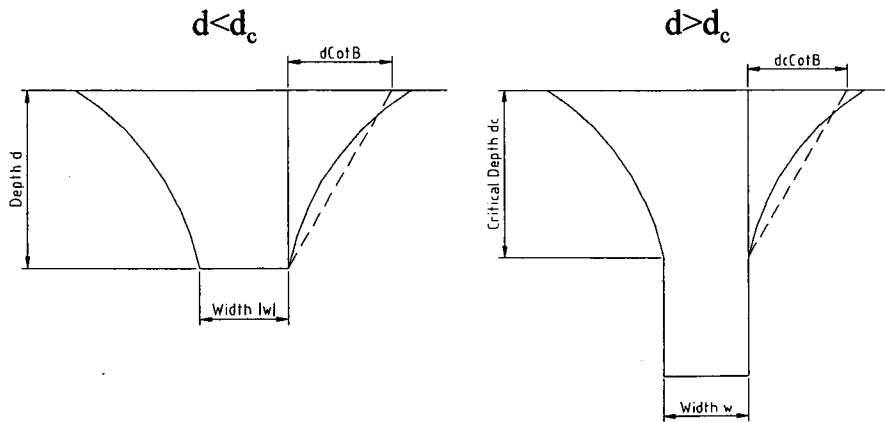


Fig. 2.1. Model for the prediction of disturbed soil area.

Typical values of d_c and $\cot\beta$ of $6w$ and 0.59 respectively, are assumed for this model. Godwin (1975b) indicated that the addition of wings to a tine might have almost the same effect as widening the complete length of the tine. This was reinforced by Spoor and Godwin (1978) who found that the addition of wings to tines increased their performance in terms of specific resistance (force per unit area of disturbed soil). By considering this work and the definition that shallow injection typically involves the application of bio-solids at depths of between 0.05 and 0.15 m (Collins 1996), some simple prototype injector tines can be developed.

2.3.1 Tine force measurement.

Measuring the forces of soil engaging implements was originally achieved by using a spring dynamometer. The dynamometer only allows rough measurements to be made, due to high fluctuations of force in tillage implements (Kepner *et al*, 1978). This system of force measurement was used by Payne & Tanner (1959), where a combination of six force dynamometers were used to measure horizontal (draught) force, vertical force and friction. Later, Godwin (1975a) developed an extended octagonal ring transducer (EORT) especially for tillage studies. The transducer provided an output that was linear and independent of the position of the load. This method is now widely used for tillage studies, (Godwin *et al*, 1987; Spoor *et al* 1987; Moseley, 1995) although simple tension link systems for force measurement are still used in the field, (Huijsmans, 1998).

2.4 Prototype injector design.

The design of the prototype injectors was structured into two specific categories. The rationale behind the prototype injector designs was such that, the effect of wings,

cutting edges, cutting discs and conceptual designs could be compared. The main project team, working parallel to this doctoral study, but on a fast track timetable, identified a number of designs to assess the tine geometry factors effecting satisfactory bio-solids incorporation. These were developed and assessed within the doctoral study programme.

2.4.1. Single piece prototype injectors.

The issue of crop separation and cutting, to reduce crop damage, and tine theory was incorporated into the design procedure. Consequently, five prototype “single piece” injectors were manufactured. These injectors can be described as:

1. 10 mm Winged Injector (10W); designed to assess the operation of a narrow winged tine within and below its expected critical depth.
2. 25 mm Winged Injector (25W); designed to assess the effect of operation well above critical depth.
3. 40 mm Winged Injector (40W); designed to establish the performance of wide wings at shallow depths.
4. 40 mm Winged Injector with separation/cutting edge, (Small). (40WNDs); to examine crop separation.
5. 40 mm Winged Injector with separation/cutting edge, (Large). (40WNDL); designed in parallel with 40WNDs to assess the best option for crop separation.

The tines mentioned above are illustrated in *Fig. 2.2*.



Fig. 2.2. Prototype single-piece injector tines.

Prototype injectors' 10W, 25W & 40W were designed to assess the appropriateness of the theory of Godwin (1974) and Spoor & Godwin (1978). Tine 10W should exhibit the high draught force penalties associated with operation below critical depth. Tines 25W and 40W should operate well above their critical depths and exhibit the effect of wings at shallow depths. The 40WNDs tine incorporates an integral cutting edge and a leading tip, as does tine 40WNDL, which is a more elaborate design with a complex cutting edge.

2.4.2. Multi-piece prototype injectors.

Two "multi-piece" prototype designs were manufactured to incorporate adjustable cutting edges, a cutting disc, 40 mm wings with intricate flutes at the rear, to aid soil mixing, and a leading tip. A small rake angle was incorporated to encourage penetration. These injectors can be described as:

6. Elaborate Injector with Short Adjustable Cutter. (ELSC).
7. Elaborate Injector with Long Adjustable Cutter. (ELLC).
8. Elaborate Injector with Cutting Disc. (ELCD).

These injectors are illustrated in *Fig. 2.3*.

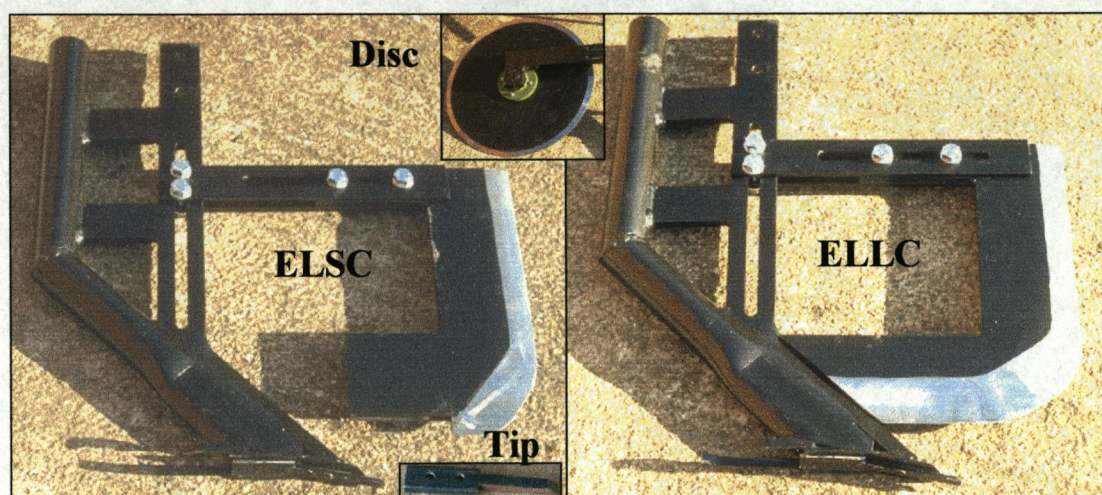


Fig. 2.3. Prototype "multi-piece" injector tines.

These elaborate injectors draw on the theory of Godwin *et al* (1981), and Spoor & Godwin (1978), which suggests that a leading tip and a rake angle less than 50° can give reduced draught force requirements. These prototype injectors are designed to illustrate the effect of different crop separation methods, as each tine will be used with the short cutter (ELSC), long cutter (ELLC) and disc cutter (ELCD).

2.5 Commercially available injectors.

Four commercially available shallow injector tines were also selected for testing, to determine whether existing shallow injector tines were capable of satisfying the performance criteria for shallow injection into established arable crops. These injectors can be described as:

9. Greentrac™ Old Shallow Injector. (OSH).
10. Greentrac™ New Shallow Injector. (NSH).
11. Greentrac™ Deep Winged Injector. (Deep).
12. Greentrac™ Slipper Foot Injector. (Slipper).

These injectors are illustrated in *Fig. 2.4*.

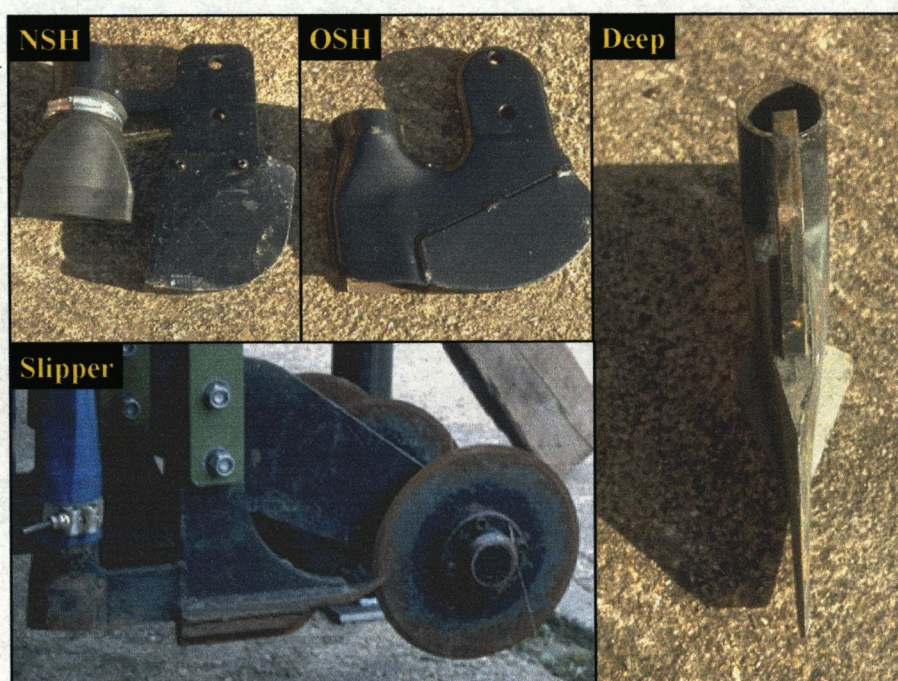


Fig. 2.4. Commercially available injector tines.

The OSH and NSH tines are similar but differ due to a slight change in design making it cheaper for users to replace the worn share. All the commercially available injector tines are designed for use with a preceding cutting disc.

2.6 Methodology.

The study was carried out at the Cranfield University soil dynamics laboratory at Silsoe, which houses a custom built, semi-automated soil bin. The use of soil tanks, or bins, for tillage studies removes the inherent variability found in field soils, allowing uniform soil conditions to be obtained following careful preparation (Siemens & Weber 1964).

2.6.1 Soil bin.

The soil bin (*Fig. 2.5*) comprises a sub-surface tank 20 m in length, 1.7 m wide and 1 m deep (Hann & Giessibl, 1998). The system uses a rail borne, cable driven soil processor, operated by an electro-hydraulically controlled winch drum, (Smith *et al*, 1987).



Fig. 2.5. Soil bin: Silsoe College soil dynamics laboratory

The processor is equipped with a number of hydraulically operated implements to facilitate soil preparation and houses an adjustable mounting plate, at the rear, for the attachment of test pieces.

2.6.1.1 Soil preparation.

The soil bin surface was prepared by scraping the soil away, to a depth of 0.2 m, and laying it in 0.05 m level layers. This was followed by six passes with the processor's flat roller. To bind the layers together, three passes with a spiked roller were made and a small amount of water was added, prior to the creation of each new layer. This preparation ("standard") allowed a relatively constant bulk density of approximately 1400 kg/m^3 and a moisture content of between 9% and 11% (dry basis) to be maintained.

2.6.2. Soil characteristics.

Standard tests have been carried out by the technicians at Cranfield University, Silsoe, to quantify the characteristics of the soil in the soil dynamics laboratory. These tests include:

- Particle size analysis (British Standards, 1990), to determine the texture of the soil, (e.g. sand, silt or clay).
- Triaxial (Terzaghi *et al*, 1996) and torsional (Osman, 1964) shear tests, to determine the cohesion (c) and the angle of shearing resistance (ϕ) of the soil.

Additionally, each soil preparation was sampled, for bulk density and moisture content, using a density ring.

2.6.3 Experimental design.

The experiment was conducted using a completely randomised design, considering each tine configuration at two depths (0.05 m & 0.075 m). Nine individual tests could be performed in each soil preparation. All tests were carried out at a speed of 0.55 m/s (2 km/h), chosen to coincide with the speed of operation in the field during agronomic trials, being conducted parallel to this study by Pullen *et al* (1997).

2.6.4 Force measurement.

Soil forces acting on each injector tine were measured using an extended octagonal ring transducer (EORT), as described by Siemens & Weber (1964) and Godwin (1975a). Each of the three channel outputs from the EORT was passed through its own strain gauge conditioning module (*Straininstall Model 91c*). Each Strain gauge module produces a stabilised 9.2 V supply to the relevant wheatstone-bridge circuit on the EORT. The strain gauge module then amplifies the small μ V return output from the strain gauges on the EORT. Any voltage offset that may result from strain gauge inaccuracy, or static load, can be removed from each strain gauge module. The amplified signal from each channel is then passed to custom-built, 7-channel, mirror input, digital (8 bit) sampling unit. This device processes the signal and outputs to a dot-matrix printer.

2.6.5 Soil disturbance measurement.

Soil disturbance was measured using a miniature soil profile meter, similar in principle to that used by Godwin, (1974). The soil profile meter was constructed from two "Vitrex" Profile Gauges, (VIT102461, 150x104 mm), such that an effective width

of operation was 0.3 m. The profile meter was capable of recording depths of up to 0.08 m. The upper and lower lateral soil failure boundaries were recorded for each test (Fig. 2.6). The upper lateral soil profile was measured relative to the soil surface prior to excavation for the measurement of the lower lateral disturbance.

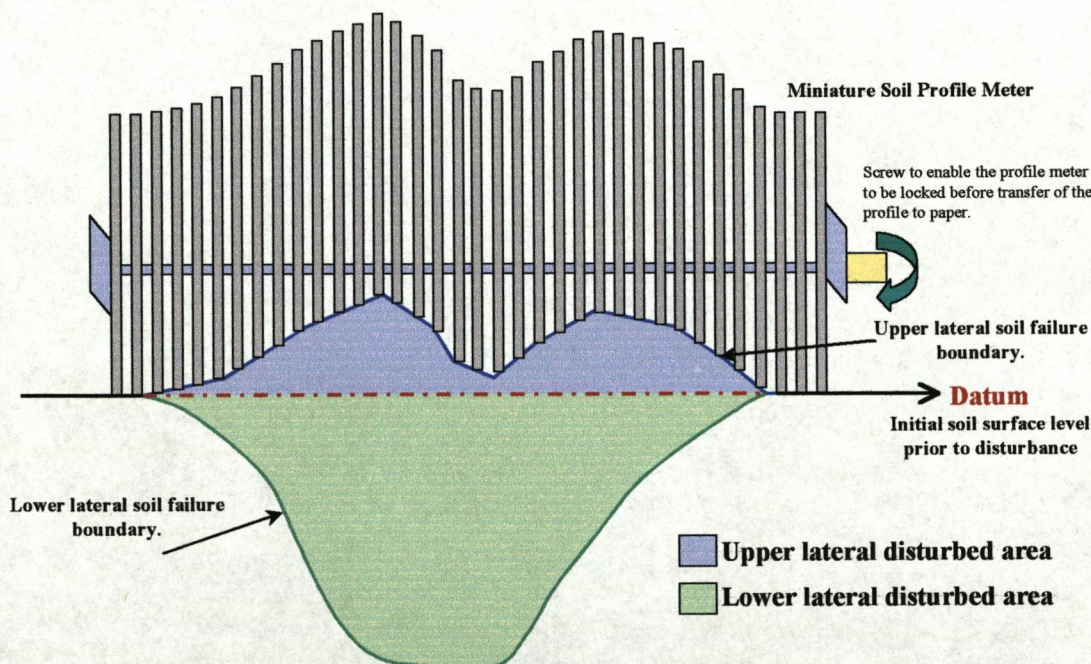


Fig. 2.6. Miniature soil profile meter and lateral soil failure pattern.

Both recorded soil profiles were subsequently digitised into a computer.

2.6.5.1. Digitising soil profiles.

Each soil profile recorded was digitised into a computer spreadsheet package to facilitate the calculation of the upper and lower lateral disturbed areas. To achieve this, each profile was split into 0.005 m wide sections, and the distance (d_x), to the extent of the profile from the datum line, was measured (Fig. 2.7).

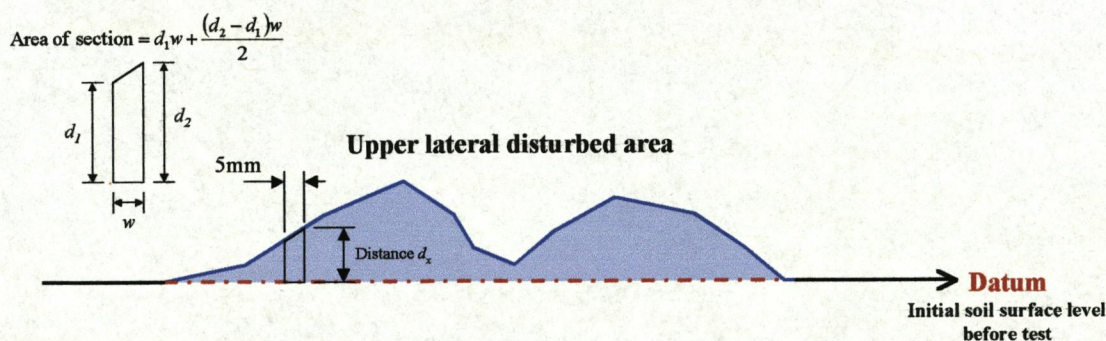


Fig. 2.7. Sectioning a soil profile.

The area of each section, across the entire width of the profile, was summed to obtain the area between the datum (original soil surface level) and the extent of the profile.

2.6.6 Performance measurements.

Sufficient measurements must be taken to allow the shallow injection criteria, established in *Section 2.2.7*, to be assessed. The measurement of draught and vertical tine forces allows the power requirement and penetration ability to be evaluated. Further to this, following work by Negi *et al* (1976 & 1978), measurement of the disturbed soil profile enables the calculation, and subsequent comparison of theoretical application rates to be made, based on the creation of new voids.

2.6.6.1 Theoretical application rate.

The theoretical application rate for each injector tine configuration, at each depth tested, can be calculated from the recorded soil profiles. When considering a unit length of disturbed soil, the passage of an injector tine through the soil causes the initial lower lateral disturbed volume to occupy both upper and lower lateral disturbed volumes. The difference in volume, therefore, contains new voids, available for the incorporation of bio-solids. It is conceded that this can only provide an indication of the pore space available for accepting bio-solids, as this assumes that none of the pores in the soil prior to disturbance, and all of the additional pore space, which occurs as a result of disturbance, are available. However, this approach does provide a repeatable procedure for comparing the relative performance, of different injector tines, under similar soil conditions. The theoretical application rate achievable will be dependent on the tine spacing on an implement. Wide tine spacings will result in less soil disturbance in one pass of the implement. Typical injector tine spacing on commercially available shallow injectors is 0.2 to 0.25 m.

The theoretical application rate may then be calculated as follows:

$$\text{Theoretical Application Rate} = ULDA \times \frac{10000}{s}$$

Where: $ULDA = \text{Upper Lateral Disturbed Area (m}^2\text{)}$
 $s = \text{Injector tine spacing (m)}$

To satisfy the criteria established for shallow injection into arable cropping, the injector tines must be capable of creating sufficient voids to allow a 50 to 150m³/ha application rate.

Some commercially available shallow injector tines rely on the production of a channel, in the soil, to accept bio-solids. This may be considered as bio-solids placement, rather than incorporation. However, the channel produced can be included in the calculation of theoretical application rate. The passage of each injector through

the soil produces two peaks in the upper, lateral disturbed profile; the lowest of these peaks is used as the starting point, for calculating the volume of bio-solids that can be accommodated within the central dip. A straight line is drawn from the lowest peak to an intersection with the profile's opposite peak (*Fig 2.8*). The area between this line and either the upper, or lower, lateral soil profile is sectioned, and the volume of a unit length calculated.

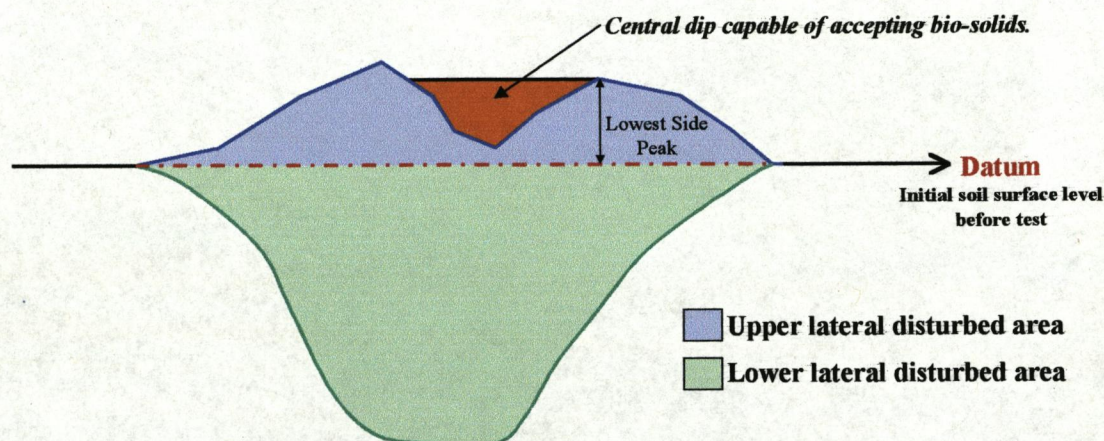


Fig. 2.8. Evaluation of the central dip.

2.6.6.2 Specific resistance and relative application efficiency.

Previous work has considered the calculation of “specific resistance” for assessing the performance of soil engaging implements (Spoor & Godwin, 1978). The “specific resistance” is defined as the force required to disturb a unit cross sectional area of soil. Additionally, Pullen *et al* (1997) used force and calculated application rates to define the “relative application efficiency”. This measurement is the draught force required to allow injection of a unit volume of bio-solids. The measurement of “relative application efficiency” is more suited to injector tine performance studies as it considers both the lower and upper lateral soil disturbance, whereas the specific resistance only considers the lower lateral soil disturbance. Both of these performance measurements require the acquisition of force and disturbance data.

2.7 Results.

The results from this study can be divided into four sections:

1. Properties of bin soil, (bulk density & moisture content, particle size, cohesion, and angle of shearing resistance).
2. Injector tine forces, (draught and vertical components).
3. Soil disturbance profiles.
4. Performance calculation.

2.7.1 Soil properties of bin soil.

Results from three replicates of bulk density and moisture content, from each soil bin preparation, were analysed statistically, (Fig. 2.9). No significant difference between soil preparations, for either bulk density or moisture content, was observed.

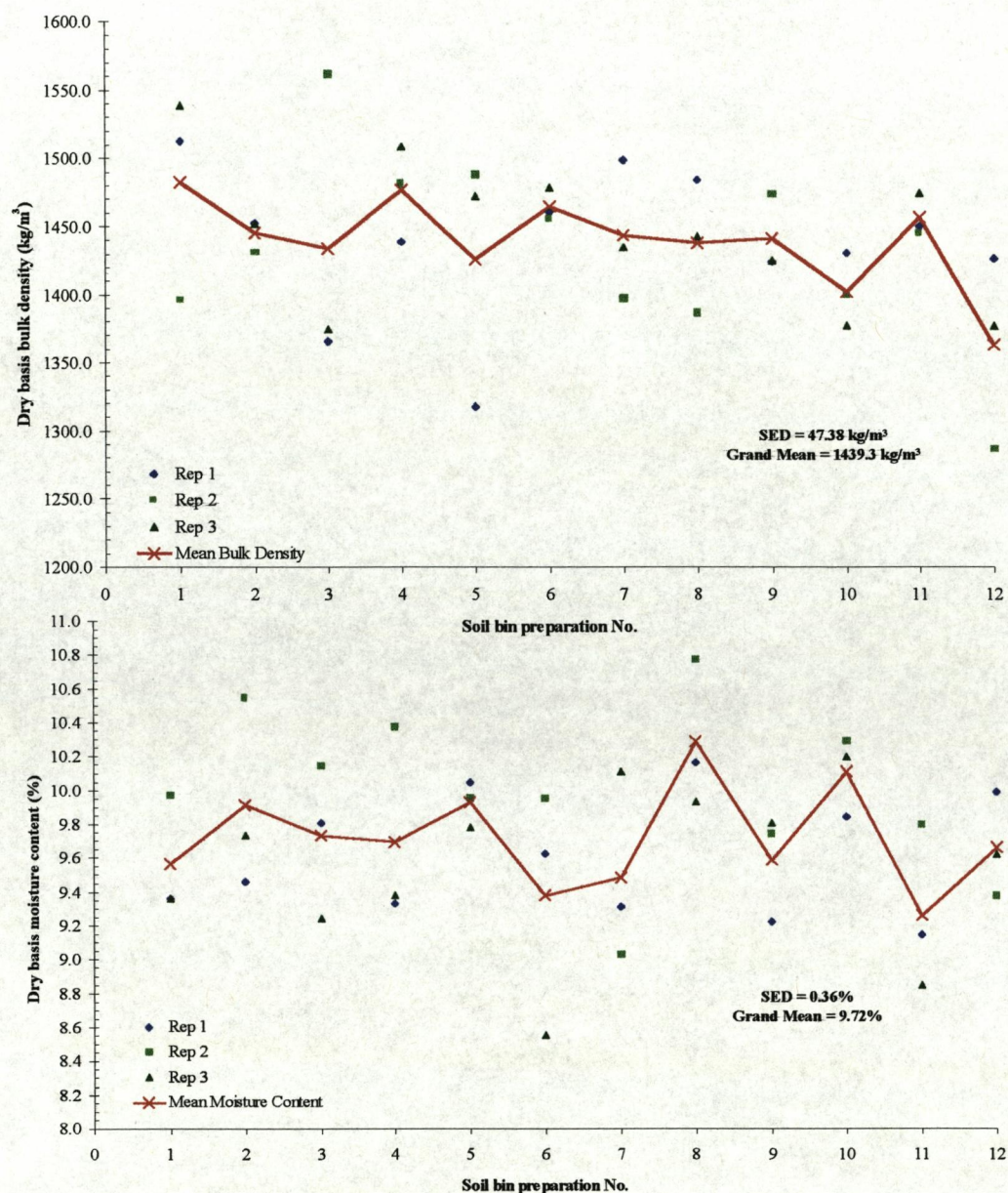


Fig. 2.9. Dry bulk density & moisture content for each soil bin preparation.

A particle size analysis (Table 2.1), carried out prior to testing, showed good agreement with results obtained by other authors (Desbiolles, 1994; Hatherill, 1993) who used the soil dynamics laboratory extensively.

Table 2.1

Soil particle size analysis.

	Mean Fraction (%)
Coarse Sand	8.15
Sand	41.94
Fine Sand	18.03
Total Sand	68.12
Silt	22.11
Clay	9.77

Cohesion and angle of shearing resistance were determined using an in-situ torsional shear box test. Values of 7 kN/m^2 and 23° for cohesion and angle of shearing resistance respectively, at a moisture content of 10.5 % and dry bulk density of 1450 kg/m^3 , show good agreement with Hatherill (1993), ($C=7 \text{ kN/m}^2$, $\phi = 29^\circ$), and Desbiolles (1994), ($C=8.8 \text{ kN/m}^2$, $\phi = 23.3^\circ$).

2.7.2 Injector tine forces.

Draught and vertical forces were found to differ significantly between injector tines. An analysis of draught force shows that force increases with depth for all tines. However, no effect of vertical force on depth was observed. Draught and upward vertical force (resistance to penetration), for all injectors tested, is presented in *Fig. 2.10*.

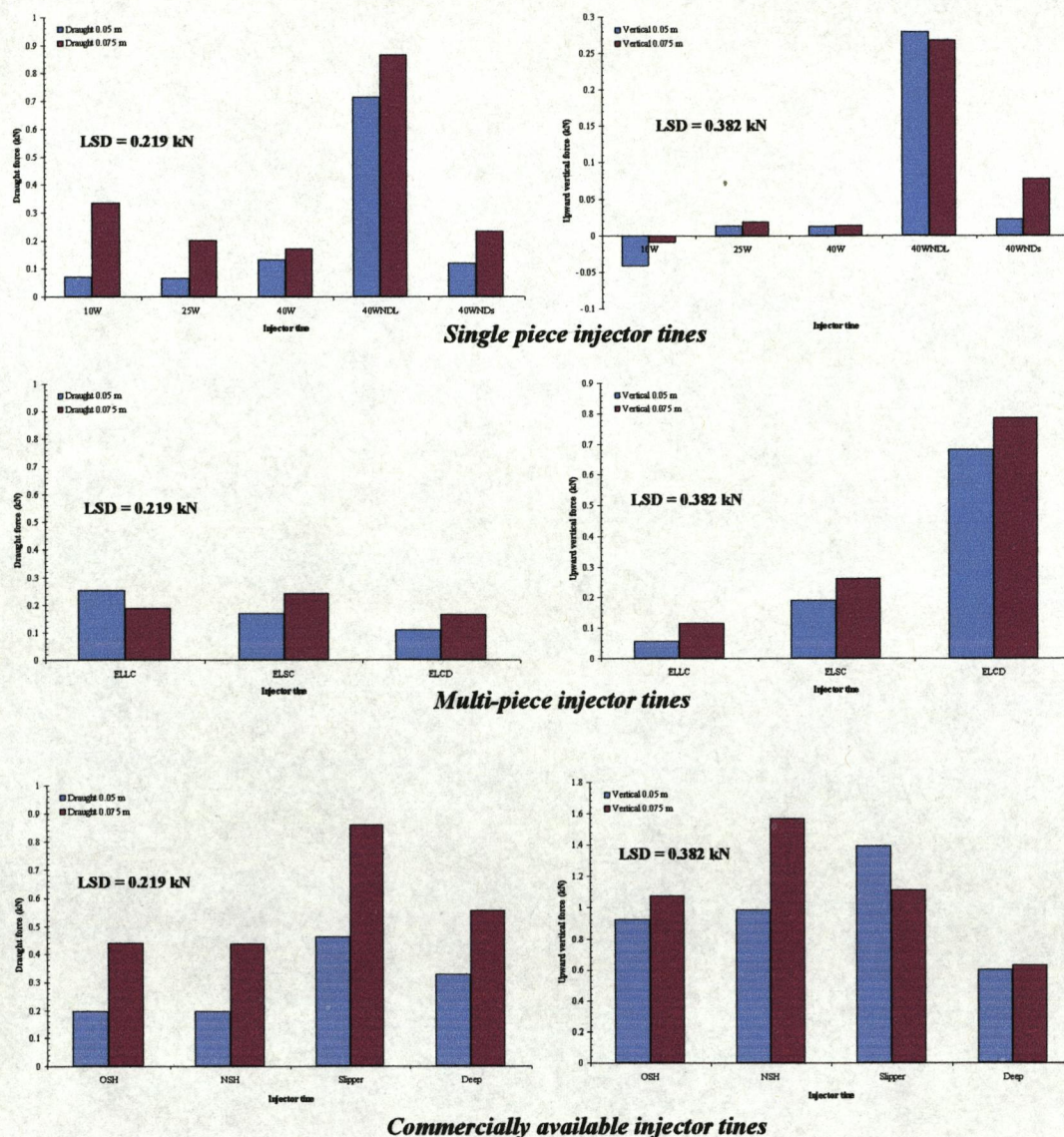


Fig. 2.10. Draught & upward vertical forces for all injector tines tested at two depths (0.05 & 0.075 m).

A full analysis of the force, disturbance and performance characteristics, of the injector tines tested, is presented in *Appendix 1.1*.

2.7.3 Soil disturbance.

The soil disturbance profiles are illustrated in *Appendix 1.1*. With little exception, all profiles resulted in the production of some form of central depression. An analysis of variance (*Appendix 1.2*) showed that all the commercial injector tines produced large central dips. The elaborate multi-piece tines, although reducing the cross-sectional area of the dip, still performed poorly in this respect. However, the simple, single piece injectors performed well.

The lower, lateral, soil disturbance profiles were analysed by regression. An important performance criterion, for reducing the severity of crop damage, is minimal lateral disturbance. The analysis illustrated that a gaussian curve fitted the disturbed profiles well. The regression analysis estimated constant parameters based on mean depth, mean width across the soil bin and mean disturbed area. The estimates of the parameters for the fitted gaussian curve are shown in *Table 2.2*.

The curves fitted are described by the equation:

$$y = A + B \times \text{Gauss}((x - m) / s)$$

$$\text{Where Gauss} = \alpha + \frac{\beta}{\sqrt{2\pi}} \exp \left[\frac{-(x_i - \mu)^2}{2\sigma^2} \right] + \varepsilon_i$$

The constant A refers to a datum and was constrained to zero.

Table 2.2.

Constant parameters for the Gaussian curves fitted.

Injector	Var%	0.05m operating depth			Var%	0.075m operating depth		
		S	M	B		S	M	B
10W	98	21.873	140.741	-2728.9	96.6	34.864	142.822	-5647.5
25W	95	24.475	147.458	-3076	96.5	34.199	138.738	-6245.8
40W	95.5	29.39	146.418	-4394.6	94.8	39.648	138.975	-7588
40WNDs	95.5	33.423	142.343	-3957.3	97.5	40.866	139.028	-7531.7
40WNDL	91.9	35.843	143.262	-4644.7	91.6	43.871	146.073	-8089
ELLC	93.7	23.693	140.163	-2405.9	96.3	25.186	141.802	-4407.8
ELSC	93.8	23.885	139.327	-2599.3	96.3	33.146	139.555	-6231
ELCD	97.5	23.359	140.438	-2657.2	90.6	31.989	139.49	-5940
OSH	92.5	33.085	142.257	-3781.3	93	39.382	149.112	-7399
NSH	95.6	22.392	139.214	-2750.4	90.5	37.797	140.318	-7270
Slipper	83.9	39.75	135.333	-4512	95.5	37.839	142.467	-7048
Deep	93.8	40.605	138.189	-4471	84.8	48.19	147.23	-8093

Soil disturbance predictions were calculated based on Negi *et al* (1976) and Smith *et al* (1988) (*Section 2.3*). Comparisons of the two prediction theories, in relation to the observed soil disturbances, are presented in *Table 2.3*. The predictions, (for calculating the lower lateral disturbed area), based on an assumed failure boundary at 45° from the operating or critical depth (whichever is less) as proposed by Smith *et al* (1988), show good agreement for all injectors, except the multi-piece prototype tines, but overestimates the disturbed area for all tines.

Table 2.3.

Comparison of soil disturbance prediction models.

Injector	Operating depth = 0.05 m				Operating depth = 0.075 m			
	Actual disturbance (mm ²)	Critical depth (mm)	Disturbance prediction (45 degree) (d ² cot β)		Actual disturbance (mm ²)	Critical depth (mm)	Disturbance prediction (45 degree) (d ² cot β)	
10W	2730	0.06	3000	1975	5657	0.06	4350	2874
25W	3048	0.15	3750	2725	6222	0.15	7500	5193.75
40W	4342	0.24	4500	3475	7517	0.24	8625	6318.75
40WNDs	3963	0.24	4500	3475	7468	0.24	8625	6318.75
40WNDL	4642	0.24	4500	3475	8075	0.24	8625	6318.75
ELLC	2467	0.24	4500	3475	4460	0.24	8625	6318.75
ELSC	2557	0.24	4500	3475	6237	0.24	8625	6318.75
ELCD	2657	0.24	4500	3475	5990	0.24	8625	6318.75
OSH	3772	0.15	3750	2725	7417	0.15	7500	5193.75
NSH	2688	0.15	3750	2725	7313	0.15	7500	5193.75
Slipper	4558	0.15	3750	2725	7027	0.15	7500	5193.75
Deep	4390	0.39	5750	4725	8053	0.39	10500	8193.75

The model proposed by Negi *et al* (1976), presented as $d^2 \cot \beta$ in Table 2.3 above, tends to underestimate the disturbed area for the single piece and commercial injector tines, but shows good agreement with the elaborate multi-piece injectors. In essence, existing soil disturbance models are suitable for modelling the lower lateral disturbed area of complex injector tines.

2.7.4 Performance measurements.

The performance of the injector tines tested was assessed, based on tine spacings of 0.2 and 0.25 m, including and discounting the central dip of each profile (Table 2.4). It has been stated that the dip in the soil profile, produced by an injector tine, facilitates bio-solid placement rather than incorporation, which is undesirable. An analysis of the "Theoretical Application Rate" indicated that there was a significant difference (@ 95% level) between injector tines and operating depth. A small interaction between injector tines and operating depth was observed, although this was not significant. "Relative Application Efficiency" highlighted statistical significance between injector tines but, as both draught force and possible application rate increased with depth, the effect of operating depth and the interaction between injector and depth was not significant.

Table 2.4
Performance of injector tines.

0.05m Depth		Theoretical application rates (m³/ha)				Relative application efficiency N/(m³/ha)			
Tine Spacing		0.2m Incl Dip	0.25m Incl Dip	0.2m No Dip	0.25m No Dip	0.2m Incl Dip	0.25m Incl Dip	0.2m No Dip	0.25m No Dip
Injector									
10W		67.60	54.10	35.50	28.40	1.16	1.45	2.40	3.00
25W		61.70	49.40	39.30	31.50	1.07	1.34	1.70	2.10
40W		86.70	69.30	58.80	47.10	1.48	1.85	3.20	4.00
40WNDs		68.50	54.80	32.60	26.10	1.76	2.20	3.70	4.60
40WNDL		166.70	133.40	113.30	90.70	4.50	5.63	6.40	8.00
ELLC		149.00	119.20	74.40	59.50	1.50	1.88	3.10	3.90
ELSC		95.50	76.40	25.30	20.20	1.85	2.32	7.30	9.10
ELCD		89.20	71.40	16.80	13.50	1.27	1.59	1.00	1.20
OSH		48.00	38.40	10.40	8.30	3.75	4.68	5.60	7.00
NSH		73.10	58.50	32.90	26.30	2.71	3.39	6.00	7.60
Slipper		108.00	86.40	37.10	29.70	4.31	5.39	30.10	37.60
Deep		154.30	123.50	12.80	10.30	2.06	2.58	16.70	20.90

0.075m Depth		Theoretical application rates (m³/ha)				Relative application efficiency N/(m³/ha)			
Tine Spacing		0.2m Incl Dip	0.25m Incl Dip	0.2m No Dip	0.25m No Dip	0.2m Incl Dip	0.25m Incl Dip	0.2m No Dip	0.25m No Dip
Injector									
10W		138.20	110.50	97.60	78.10	2.56	3.19	3.50	4.30
25W		70.50	56.40	44.80	35.90	2.99	3.74	5.50	6.90
40W		154.80	123.80	99.80	79.90	1.12	1.40	1.80	2.30
40WNDs		138.50	110.80	96.70	77.30	1.70	2.13	2.70	3.30
40WNDL		176.30	141.00	130.90	104.70	4.92	6.15	6.80	8.50
ELLC		126.50	101.20	91.20	72.90	1.49	1.87	2.00	2.60
ELSC		117.60	94.10	84.90	67.90	2.01	2.52	3.00	3.80
ELCD		167.90	134.30	144.50	115.60	1.00	1.25	1.20	1.50
OSH		151.10	120.90	90.20	72.20	2.97	3.72	4.90	6.10
NSH		125.40	100.30	51.70	41.40	4.21	5.26	4.90	6.20
Slipper		194.00	155.20	98.40	78.70	4.76	5.96	10.20	12.80
Deep		268.40	214.70	91.10	72.90	1.99	2.49	5.90	7.40

Fig. 2.11 illustrates the specific resistance, of the tested injector tines, at both operating depths. As with "Relative Application Efficiency", a significant difference between injector tines was observed. However, no depth effect or tine depth interaction was apparent.

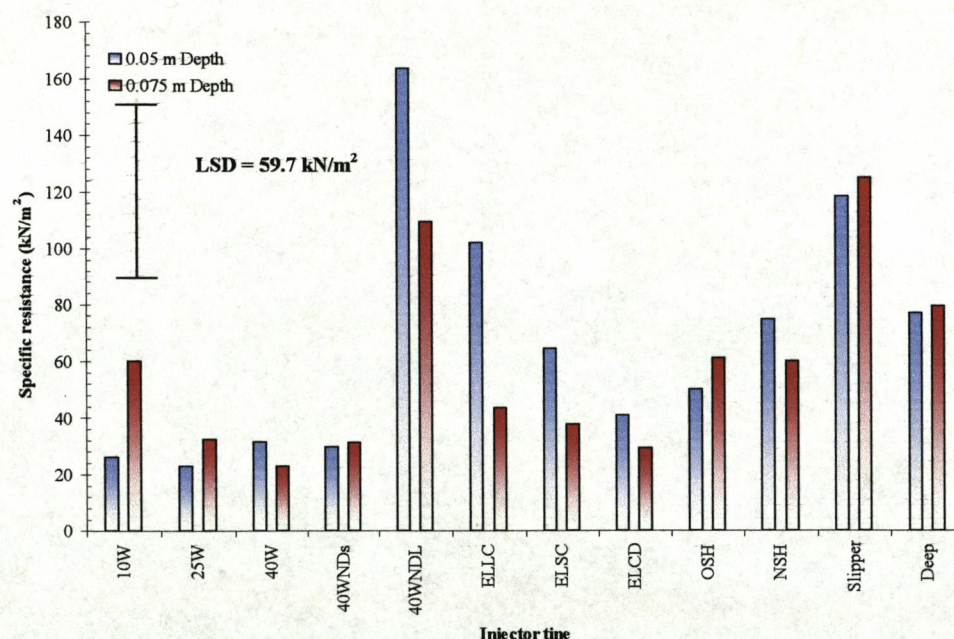


Fig 2.11. Specific resistance (kN/m^2) for injector tines tested.

The data collected for this study and the resulting performance calculations are presented in *Appendix 1.3*. The performance measures outlined allow effective comparisons to be made between injector tines.

2.8 Discussion.

An analysis, of the performance of the prototype and commercial injector tines, suggests that no individual injector tested satisfies all the criteria for shallow injection of bio-solids into arable cropping. Soil disturbance profiles show that existing models can be used, to approximate the area of disturbance expected, for a complex tine. The models, which have been shown to approximate the complex injector tine disturbance, do not require soils data such as cohesion and angle of internal friction. A discussion, on the performance of the three types of injector tines, is presented below.

2.8.1 Single piece prototype injectors.

With the exception of tine 40WNDL, all the simple, single piece, prototype injectors exhibit low power and penetration requirements, (<0.15 kN and <0.25 kN respectively). However, their ability to produce the necessary soil disturbance is less than optimal at shallow depths. Void volume, produced at 0.05 m operating depth, is only sufficient to allow < 60 m^3/ha based on a 0.2 m tine spacing. In comparison, tine 40WNDL required much more power (0.714 kN) and, in addition, significant

assistance, in terms of penetration force (0.279 kN), but created sufficient voids to allow the application of $>90 \text{ m}^3/\text{ha}$ based on a wider 0.25 m tine spacing.

This performance explains the shortfalls of 40WNDL in comparison to the other single piece injectors and suggests that some concessions may be necessary in the design of an optimal injector. It was also observed that increasing the wing width did not significantly effect the draught or vertical force requirements of the injectors, but contributed to an increased lower lateral disturbed area. Tines 10W, 25W, 40W & 40WNDs were able to satisfy the application rate requirement at 0.075 m operating depth, subject to a tine spacing of 0.2 m. However, analysis of the soil profiles for these tines, suggests that the lateral width of disturbance could impinge on the crop root zone, causing crop damage.

2.8.2 Multi-piece injectors.

These elaborate injectors exhibited similar draught force requirements but an increased penetration force is required, when a cutting disc is used (0.787 kN). Application rates (not including the central dip) only satisfied the performance criteria when the operating depth was increased to 0.075 m, for the elaborate tines using a cutting edge, resulting in an increase in lateral disturbance. ELCD had a tendency to reduce the area of the central dip, at 0.075 m operating depth, resulting in an increased application rate (not including the central dip). This implies that the use of a cutting disc, rather than a cutting edge, may enhance soil mixing. The relative application efficiency and specific resistance was improved, through the use of a cutting disc, rather than an adjustable cutting edge.

2.8.3 Commercially available injectors.

The vertical force requirements for these tines were generally greater than for any of the prototype injectors. Draught force requirements were low for the old and new shallow injectors ($< 0.2 \text{ kN @ } 0.05 \text{ m}$), whereas the slipper and deep injectors required significantly higher force. The design of current, commercial, shallow injectors is such that a channel is produced and filled with bio-solids. The result of this design is that sufficient volume for the application of bio-solids is only achieved if the central dip is included. Based on 0.2 m tine spacing, the slipper and deep injectors created sufficient disturbance to allow an application of $>100 \text{ m}^3/\text{ha}$. However, when discounting the central dip, this reduced to $< 40 \text{ m}^3/\text{ha}$. Theoretical application rates, neglecting the central dip, showed that, even at a depth of 0.075 m,

the specified application rate could not be achieved. The slipper foot injector exhibits similar draught force requirements to the 40WNDL, although the resistance to penetration is somewhat higher.

2.8.4 Summary.

The results and discussion suggest that a balance must be made between low force requirements and the maximum theoretical application rates. None of the commercially available injectors exhibited ideal performance characteristics, reinforcing the need for a new injector design, to enable efficient incorporation of bio-solids into arable cropping with minimal environmental impact to be achieved.

The soil disturbance profiles of the injectors tested indicate an undesirable increase, in the lateral soil disturbance, with increased operating depth. Results suggest that the operating depth of shallow injectors, for use with arable crop applications of bio-solids, should be kept to a minimum to avoid tine/crop interaction. In general, the winged injectors promoted better incorporation, characterised by a reduction in the central dip created. The use of a cutting disc and a leading tine tip, on the multi-piece injector, increased its performance in terms of relative application efficiency. The performance of the prototype and commercial injector tines suggests that two possible combinations may prove sufficient to satisfy the criteria for the incorporation of bio-solids into arable cropping:

1. A simple, winged injector with a leading tip and cutting disc.
2. A single piece, winged injector with an integral cutting edge.

2.9 Study Conclusions.

Based on the conditions and restrictions presented in *Section 1.1*:

- Criteria for the performance of shallow injector tines for injecting bio-solids into established arable crops with minimal environmental impact have been established.
- A method of injector tine assessment has been developed, and a number of prototype and commercially available injectors have been tested in conjunction with the fast track project
- From the results of the assessments above, it is recommended that two types of shallow injector should be developed for further trials:
 1. A simple, winged injector with a leading tip and cutting disc.

2. A single piece, winged, injector with an integral cutting edge.

Chapter 3

3.0 Injector tine development.

3.1 Introduction.

Criteria for the performance of an injector tine suitable for the injection of bio-solids into arable cropping, were considered in *Chapter 2*. Subsequently, a number of single-piece, multi-piece and commercially available injectors were evaluated in a soil dynamics laboratory study to allow assessment of their performance. The results of this study suggested that a simple winged design with a cutting disc for crop separation, or a more complicated single-piece winged tine with a cutting edge for crop separation, would be appropriate for the specific application of bio-solids incorporation into arable cropping.

In this chapter, two improved injector tine designs are proposed and evaluated in a soil dynamics laboratory study, in comparison to one selected single piece injector and one selected commercially available injector. Additionally, further implications of injector tine design are discussed, in relation to environmental impact and economic performance.

3.2 Improved injector tine design.

Previous theory on tine design for predicting force and the extent of soil disturbance has been discussed (*Section 2.3*), and good agreement between existing soil disturbance theory and statistical modelling has been found for single-piece, multi-piece and commercially available injector tines. However, the modelling of soil disturbance as a design aid for injector tine development, based on the established criteria for application to arable cropping (*Section 2.2.7*), requires the ability to model the upper lateral soil disturbance profiles. Models capable of this are not available and the modelling of the lower disturbed profile is of little practical use in the design process.

The force, disturbance and performance results calculated from the initial study, allow detailed designs to be outlined. Other considerations in the design process should consider environmental, economic and logistical implications (*i.e. equipment availability*). A summary of these design considerations is presented, culminating in the proposal of two designs, conforming to the recommendations in *Section 2.9*.

3.2.1 Main design considerations.

This further study concentrates on the evaluation of two distinct designs, identified as a result of the initial injector study. The primary considerations in the design of a new injector are those of force requirement (both draught and penetration), combined with the mode and extent of soil disturbance. The design of any new injector must satisfy the criteria outlined in *Section 2.2.7*, with due consideration of the results of the initial study and existing tine theory.

3.2.1.1 Injector tine forces.

Existing tine theory, described in *Section 1.7.1*, has suggested that the combination of a small rake angle and wing attachment may provide an efficient means of creating sufficient soil disturbance for the incorporation of bio-solids. Results from the initial study suggest that increasing the wing width will reduce the resistance to penetration (vertical force opposing penetration) and increase the draught force requirement. The use of a cutting edge or cutting disc increases the resistance to penetration when in combination with an injector, but has only a small draught force component, (*Appendix 2.1*).

3.2.1.2 Soil disturbance.

The primary purpose of promoting soil disturbance is to allow sufficient voids to be created to accept bio-solids, without spillage onto the soil surface, reducing the exposure of bio-solids to the atmosphere and subsequent, potentially harmful emissions. From the results of the initial study, lateral soil disturbance was observed to increase with operating depth. These results, combined with tine theory, reinforce the need for wing attachments and the use of a leading tip. A wing width of between 0.025 m and 0.04 m, combined with either a cutting edge or a cutting disc may create sufficient void space at shallow depth.

3.2.2 Other design considerations.

Additional tine design criteria relate to engineering, environmental and economic conditions.

3.2.2.1 Engineering considerations.

An injector tine must have some facility to accept application pipes and the capability of attachment to the equipment providing the necessary bio-solids distribution system.

During this study, the field equipment available comprised a Greentrac™ slipper foot injection system. The slipper foot system uses the Greentrac™ rotary distribution head mounted on an implement toolbar. Injector tines are attached to the toolbar through a parallel linkage to maintain a constant tine/soil attitude, discussed later in *Section 7*.

3.2.2.2 Environmental considerations.

The design of an injector suitable for the incorporation of bio-solids into arable cropping must not only consider crop manipulation, but should endeavour to promote incorporation rather than placement in the soil. This may reduce the quantity of bio-solids exposed to the atmosphere thus encouraging greater crop use of available nutrients through a reduction in volatile losses.

3.2.2.3 Economic considerations.

Injector design should be appropriate for fabrication using techniques that minimise production costs. The economic considerations draw on engineering and environmental implications to provide a marketable product at reasonable cost.

3.3 Improved injector designs.

3.3.1 Retrofit design.

The retrofit design (*Appendix 2.2a*) fulfils the need for a shallow injector tine, suitable for the effective incorporation of bio-solids using existing distribution systems. The injector has been designed, specifically, to allow easy fitting to the Greentrac™ slipper foot injection system.

3.3.1.1 Design rationale.

The concept behind the design considers the need for an injector tine that can provide better incorporation of bio-solids while allowing easy fitting to existing, shallow injection systems. The injector should still be suitable for attachment to a tramline injection system, to enable application of bio-solids to arable cropping systems. As such, three design sections were identified:

1. Tine head: - the piece of the retrofit design that interfaces between an implement's linkage system and the soil engaging tine.
2. Application device: - the section that interfaces a system's supply method with the soil engaging tine.

3. Soil engaging tine: - the section of the retrofit tine that produces the desired soil forces and disturbance.

3.3.1.2 Mounting head.

The mounting head must allow subsequent fitting of the soil engaging tine and the application device. The mounting head design allows the fitting of these components, by machined slots, with roll pin fixings (*Fig. 3.1a*). The use of this design allows full interchangeability with different soil engaging tines and application devices.

3.3.1.3. Application device.

The application device, specifically designed for retrofit attachment to the Greentrac™ slipper foot injector, simply comprises an application tube shaped to allow bio-solids placement, immediately behind the soil engaging tine, as it passes through the soil. This section exerts no direct influence on the performance of the injector except when operating at extreme depths (*Fig. 3.1c*).

3.3.1.4 Soil engaging tine.

This component was designed with due consideration of the results from the initial injector tine evaluation (*Section 2.9*) and pertinent tine theory. It comprises a narrow, backward raked shank of 0.003 m thickness, with a 0.035 m wide wing section with a pointed tip. The wings and tip of this section allow a clearance angle, between the horizontal and the base of the wing piece, of 10°. This tine leg also houses the soil deflection plates, to allow free flow of soil around the ancillary application tube. The tine leg is attached to the mounting head through the use of roll pins, thus allowing easy replacement when worn. This tine design is expected to provide a suitable soil disturbance profile, with low force requirements, to satisfy the criteria for shallow injection into arable cropping (*Fig 3.1b*).

3.3.1.5 Crop separation.

Many existing, shallow injection systems use cutting discs, which precede the injector and as such, the retrofit injector outlined above, has been designed specifically for use with a disc type of crop separation device (*Fig. 3.1d*). The disc used on the Greentrac™ slipper foot injection system is illustrated in *Appendix 2.2b*.

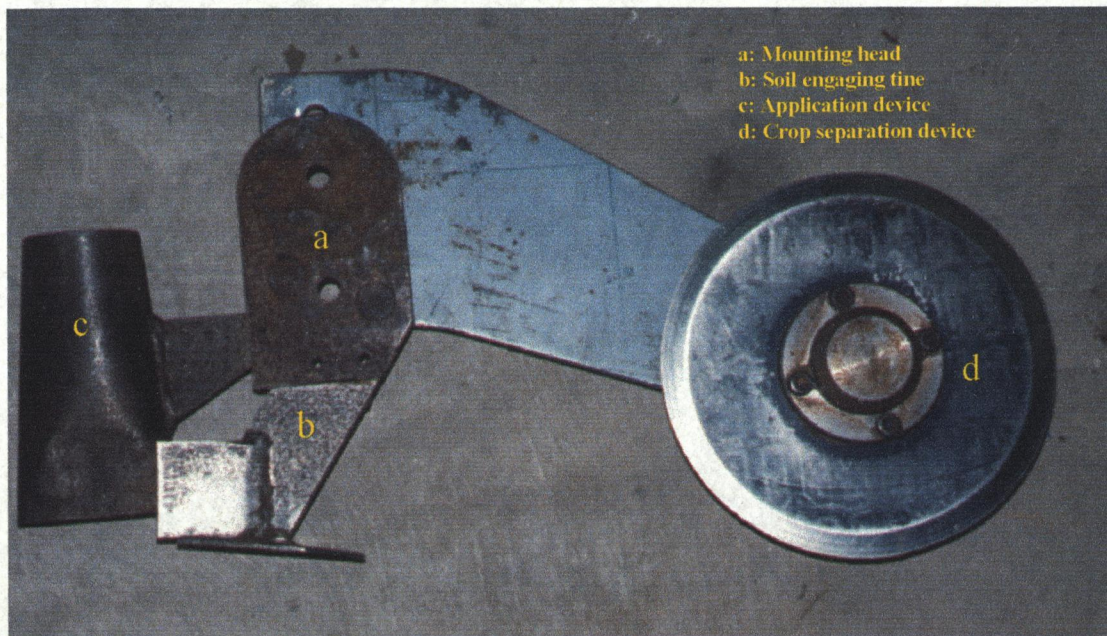


Fig. 3.1 Main injector tine components.

3.3.2 Improved 40WNDL design, (40WNDLi).

This stand-alone tine is, primarily, the 40WNDL injector tine produced with improved materials and will be referred to as 40WNDLi. This design (*Appendix 2.2c*) is a true single piece injector with an integral cutting edge, rather than an auxiliary cutting disc, to affect adequate crop separation, and incorporates the following unique design features:

- Construction from 0.003 m, heat-treated, sheet plate for improved hardness and durability. The use of this plate facilitates incorporation of a series of cutting edges, to assist crop separation and trash cutting ability.
- A complex wing configuration, incorporating a 0.04 m wing width with a 10° clearance angle between the horizontal and the base of the wing attachment. In addition, the wings are angled downwards, from the centre line, at 5° to the lateral horizontal plane. This combination of wing geometry promotes a lifting and separating action.
- Moulded deflectors are attached by weld to the tine to enhance soil flow around an application tube without reducing the wing contact area.
- The main body of the injector comprises a cutting edge. The angle of the cutting edge in relation to the soil is dependent on the depth of operation, but promotes separation at the upper extent of the tine and cutting at soil level. The angled sections are sharpened for this purpose.

3.4 Methodology.

The methodology for evaluating the improved injectors described above was identical to that outlined in *Section 2.6*, with the exception of the use of a larger soil profile meter for measuring the lower lateral disturbed area at depths greater than 0.08 m.

3.4.1 Experimental design.

A randomised block design, incorporating the two improved tines and the 25W and NSH (*Appendix 2.2d*) injectors for comparative purposes, was adopted. The study took place in the Cranfield University soil dynamics laboratory at Silsoe. In addition, the Greentrac™ “slipper foot” injector tine was evaluated in terms of force requirements, as equipment constraints required the use of this injector in subsequent field trials.

3.4.1.1 Injectors.

The injectors tested were:

1. Single piece 25 mm winged prototype injector (25W)
2. Greentrac™ New Shallow Injector (NSH)
3. Improved 40WNDL injector (40WNDLi)
4. Simple Retrofit design, with and without cutting disc (Retro)
5. Greentrac™ Slipper Foot injector (Slipper) forces only.

3.4.1.2 Measurements.

The following data was recorded:

1. Draught force (kN)
2. Vertical force (kN)
3. Upper soil profile disturbance (mm^2)
4. Lower lateral soil disturbance (mm^2)
5. Dry basis soil moisture content (%)
6. Dry Basis soil bulk density (kg/m^3)

These measurements were used to assess the performance of each injector at a range of depths.

3.4.1.3 Depth.

Each injector, (except Retro), was tested at four operating depths, across and beyond their practical operating limits. The depths selected were 0.05, 0.075, 0.1 and

0.125 m. The maximum operating depths of tines 25W, 40WNDLi, NSH and Retro are 0.08, 0.1, 0.11 and 0.07 respectively. The retro injector tine was tested to a maximum depth of 0.1 m, as at 0.125 m, heavy interaction with the mounting head would have occurred. The analysis of the forces required to operate the Greentrac™ slipper foot injector was carried out at all of the depths stated above. However, in practice this tine will rarely achieve an operating depth >0.05 m.

3.5 Results.

Presentation of the results of this evaluation is similar in structure to those presented in the initial study in *Chapter 2*. However, the increased number of data points for force allows curves to be fitted to both the draught and vertical force results. A full statistical analysis of all the measurements taken and the regression analysis of the force data are presented in *Appendix 2.3*.

3.5.1 Soil properties.

Three replicates of dry bulk density (kg/m^3) and moisture content (%) were taken for each soil bin preparation. The results indicate that there were no significant differences between soil preparations (*Fig. 3.2*).

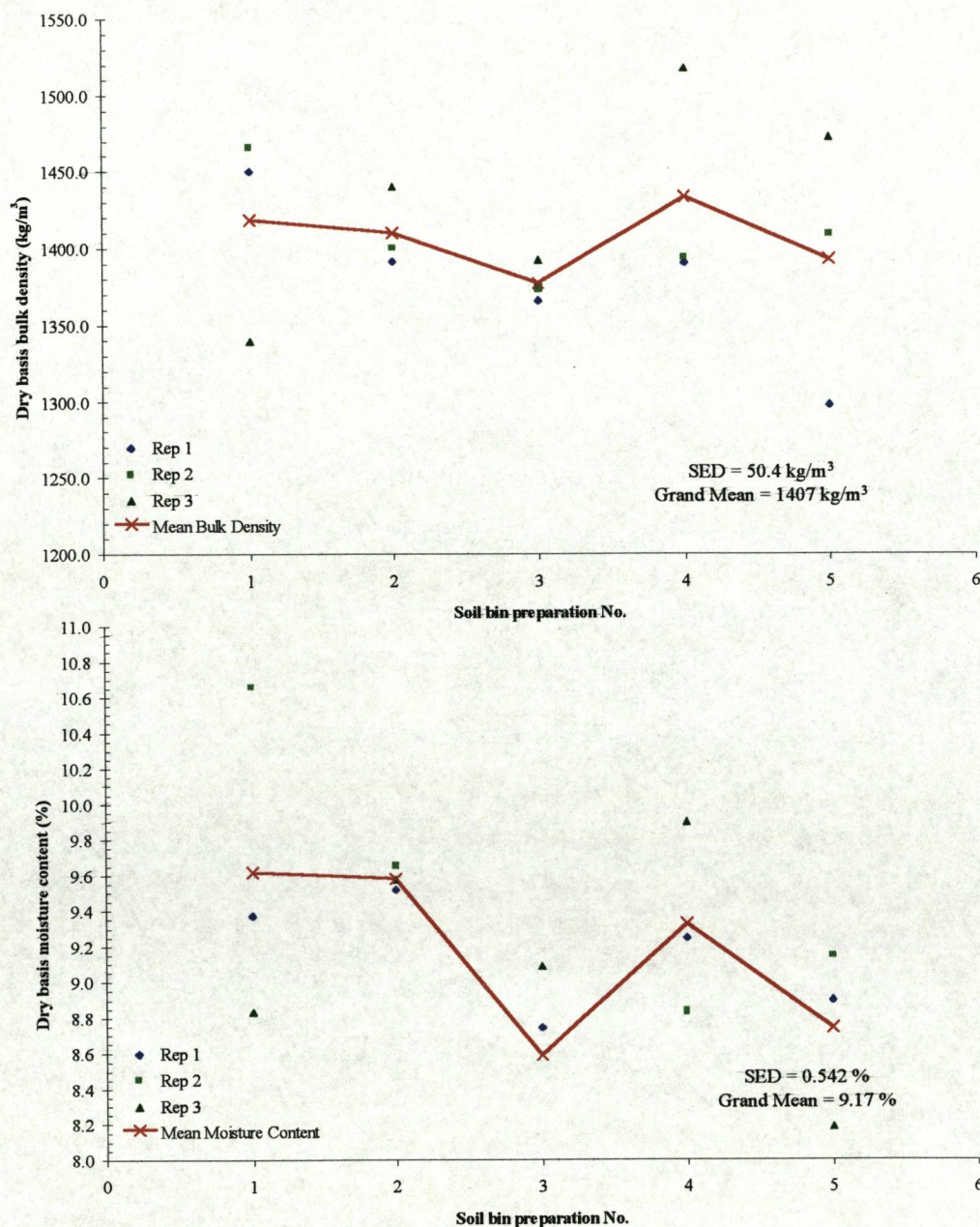


Fig. 3.2. Bulk density & moisture content (dry basis) for each soil bin preparation.

3.5.2 Force measurement.

The mean draught force requirement of each injector, tested at a range of depths, clearly illustrates the effect of crop separation method on power requirement (Fig. 3.3).

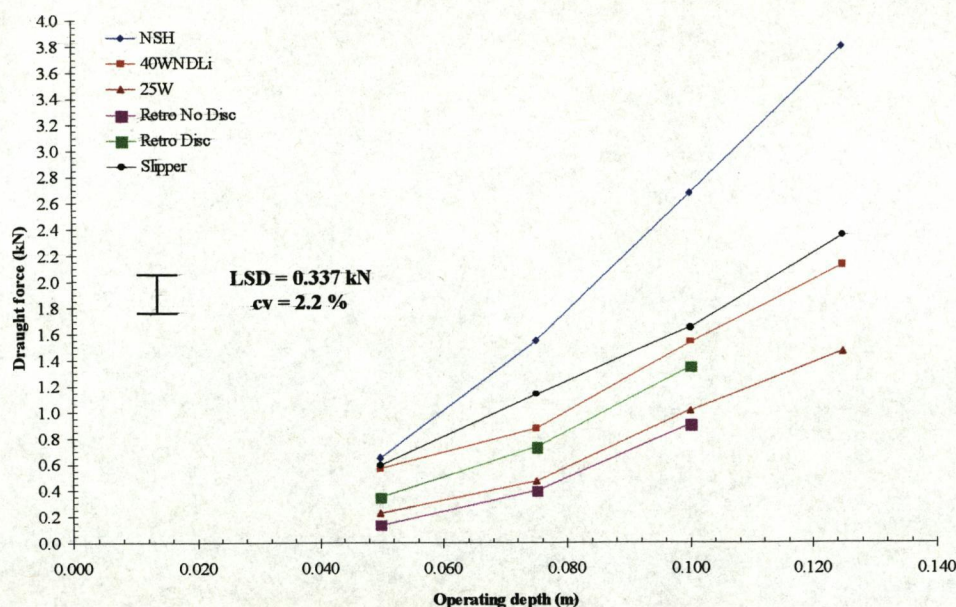


Fig. 3.3, Mean draught force requirements (kN) with depth for the injector tines tested.

The effect of operating the Greentrac™ NSH tine below the recommended working limits can be observed in Fig. 3.3, which illustrates a significant increase in the draught force requirement. This is due, mainly, to the disc used with this tine (Appendix 2.1d). The same disc was used with the Retro tine, which allowed a safe operating depth of 0.07 m, above which, interaction with the disc bearing assembly was observed.

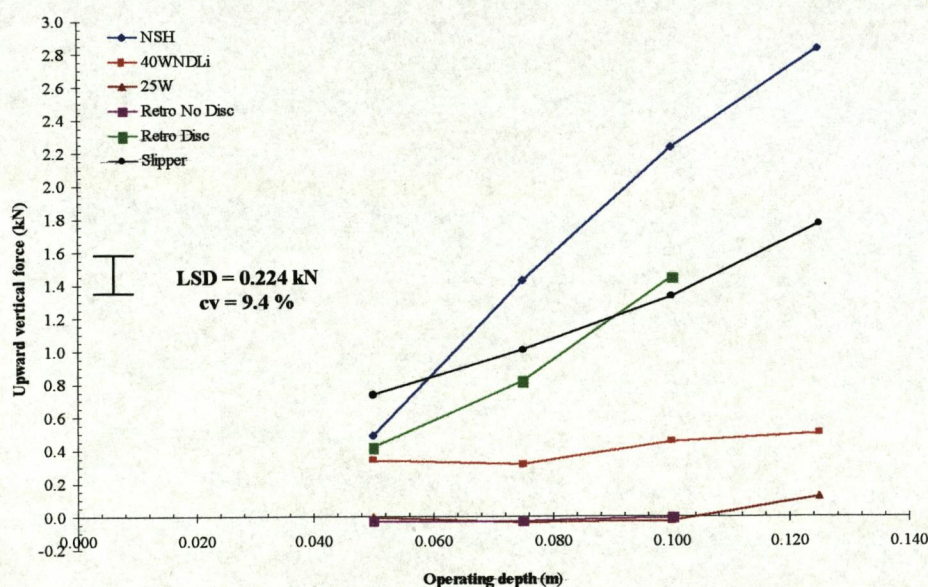


Fig. 3.4. Mean upward vertical force (kN) over the tested depth range.

The vertical force results, which provide a measure of the tine's ability to assist or resist penetration into the soil, clearly highlight the effect of the cutting disc and demonstrate that the use of an integral cutting edge is preferable (*Fig. 3.4*). Although forces are similar between tines at a depth of 0.05 m, rapid increases are observed as both the tine and disc are operated beyond their design limits. As with the draught forces, the use of a leading tip appears to compensate for an increased wing width, as both 25W and Retro (no disc) performed similarly.

3.5.3 Soil disturbance.

The soil disturbance profiles (*Appendix 2.4*) illustrate a marked increase in lateral disturbance, when the tines are operated below the design limits of the implement. The soil profiles illustrate how the lower lateral disturbance changes when a disc is used, compared to either a cutting edge or no separation device. The use of a disc tends to restrict the width of the disturbance, possibly due to compaction around the disc prior to the action of the tine on the soil. This desirable effect on injector performance is costly in terms of vertical force requirement, for injectors that rely on bio-solids placement (by the action of slot production) rather than incorporation. However, it is apparent that, although the use of a cutting edge produces a soil disturbance profile with a minimal central dip, further reductions in the lower lateral disturbance is desirable.

3.5.4 Performance analysis.

The specific resistance (*Fig. 3.5*) provides a suitable performance indicator for tines operating in situations where maximum soil disturbance is desirable. Spoor and Godwin (1978) found this measurement suitable for sub-soiler studies. However, it does not account for the upper disturbed area and the resulting increase in void space. In general, a high specific resistance indicates a high power requirement for a small degree of disturbance.

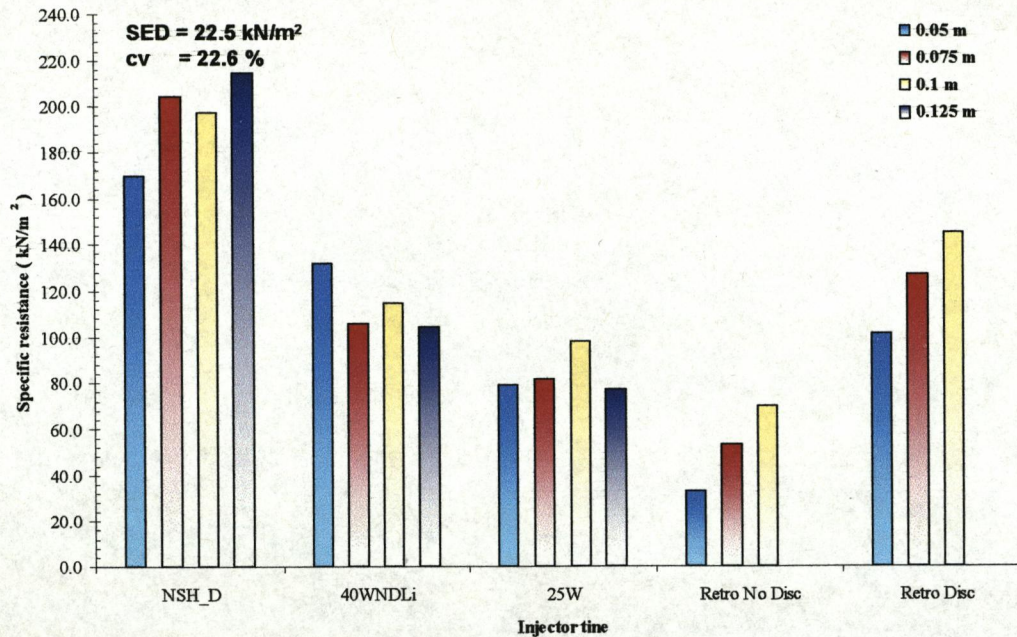


Fig. 3.5, Specific resistance over the experimental depth range.

No significant effect of depth on specific resistance was observed, as both soil disturbance and draught force increase with operating depth. Injectors not employing a cutting or separating device achieved the lowest specific resistance (52.3 kN/m² and 83.3 kN/m² for the Retro no disc and 25W respectively). These were followed by the improved designs, which incorporated either a cutting disc or an integral cutting edge (114 kN/m² and 124.6 kN/m² for 40WNDLi and Retro disc respectively). The commercial NSH injector exhibited the highest specific resistance (196.4 kN/m²) which, combined with the degree of dip in soil disturbance profiles, questions the suitability of existing systems for the application of bio-solids to cropping.

As described earlier, the use of “relative application efficiency” (N/m³/ha) is better suited to injector time evaluation as the useful void area is included. Additionally, the injector tines tested were assessed for their capability to satisfy the application rate criteria presented in Section 2.2.6.

Table 3.1

Theoretical application rate and relative application efficiency.

Injector	Depth	Theoretical application rates (m ³ /ha)				Relative application efficiency N/(m ³ /ha)			
		0.2m Incl Dip	0.25m Incl Dip	0.2m No Dip	0.25m No Dip	0.2m Incl Dip	0.25m Incl Dip	0.2m No Dip	0.25m No Dip
25W	0.05 m	104.00	83.20	71.20	56.90	2.20	2.74	3.37	4.20
40WNDL		77.20	61.70	60.20	48.20	7.74	9.68	10.58	13.20
NSH		84.50	67.60	36.80	29.50	9.16	11.46	27.67	34.60
Retro & Disc		135.60	108.50	66.80	53.50	2.57	3.21	5.41	6.80
Retro No Disc		96.00	76.80	60.20	48.20	1.58	1.97	3.28	4.10
25W	0.075 m	151.60	121.30	98.00	78.40	3.20	4.00	5.28	6.60
40WNDL		160.50	128.40	121.70	97.40	5.42	6.78	7.17	9.00
NSH		166.50	133.20	114.20	91.40	9.25	11.57	14.40	18.00
Retro & Disc		157.50	126.00	86.10	68.90	4.66	5.82	8.71	10.90
Retro No Disc		229.90	183.90	147.60	118.10	1.77	2.21	2.70	3.40
25W	0.1 m	192.80	154.20	123.50	98.80	5.42	6.77	8.73	10.90
40WNDL		233.70	187.00	138.30	110.70	6.62	8.28	11.50	14.40
NSH		166.30	133.00	10.90	8.70	16.46	20.58	182.16	227.70
Retro & Disc		228.80	183.00	115.60	92.50	5.85	7.31	16.50	20.30
Retro No Disc		319.20	255.40	180.30	144.30	3.19	3.99	5.78	7.20
25W	0.125 m	274.60	219.70	129.70	127.70	5.79	7.24	9.53	11.90
40WNDL		267.00	213.60	167.30	133.80	8.11	10.13	12.78	16.00
NSH		231.20	185.00	48.30	38.70	18.46	23.07	20.30	25.40
Retro & Disc		*	*	*	*	*	*	*	*
Retro No Disc		*	*	*	*	*	*	*	*

Both the theoretical application rate and the relative application efficiency for the tines under test were found to differ significantly. The data in *Table 3.1* shows that concessions in terms of forces may have to be accepted to produce the soil disturbance required. Application rate data is presented graphically in *Fig. 3.6*, and is compared with the expected limits referred to in *Section 2.2.6*.

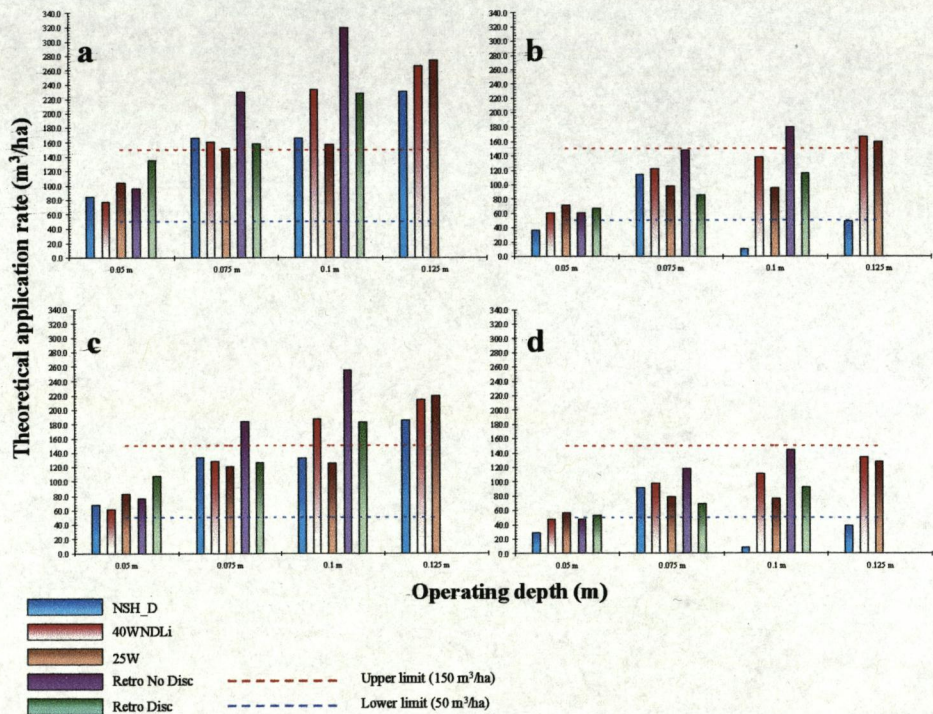


Fig. 3.6. Theoretical application rates for all injector tines compared with acceptable limits at a) 0.2 m spacing including dip, b) 0.2 m spacing not including dip, c) 0.25 m spacing including dip, d) 0.25 m spacing not including dip.

Discounting the central dip, only the 40WNDLi and the retrofit injector without a disc are capable of injecting the upper limit, based on the criteria established earlier. The retrofit injector, however, produces an undesirable degree of lateral disturbance when used without a cutting disc. This suggests that a complete field development of the single piece 40WNDLi, which uses the integral cutting edge as a crop cutting and separation device, is the most promising way forward.

3.6 Discussion.

The development and laboratory testing of the improved injector tines has progressed the design and evaluation process significantly. Considering each design individually:

- The 25W tine is only capable of satisfying the application rate criteria at operating depths on or above 0.075 m, including the central dip in the disturbed soil profile. Tine forces are acceptable in terms of low draught and low resistance to penetration, and the resulting soil disturbance patterns observed are encouraging. However, as this injector would need to operate at, or above, its maximum designed operating depth, to satisfy all the criteria outlined earlier, this injector design would be unsuitable for further development.
- The 40WNDLi tine performs well in terms of vertical force, soil disturbance, void space creation, and theoretical application rate. Higher relative application efficiencies, indicating poor performance, compared to the other tines tested are a result of slightly higher draught force requirements. However, considering the soil disturbance produced, it is apparent that concessions in this respect may be necessary to obtain the desired soil disturbance.
- The NSH tine is a commercially available injector that relies on slot production for bio-solids placement, rather than incorporation. This is highlighted when theoretical application rates discounting the central dip are considered. This tine could not satisfy the application rate criteria at any of the depths tested. High draught force requirements result in excessive relative application efficiencies, although the indicated optimum depth for injection appears to be 0.075 m.
- The retrofit tine and disc combination exhibits acceptable soil disturbance profiles in terms of the lateral disturbance, and performs well in terms of theoretical application rates. Resistance to penetration is higher than that of the 40WNDLi as a result of the cutting disc, which although insignificant (@ 95% level), suggests

that an integral cutting edge may be more efficient than a disc for the purposes of bio-solids application to arable cropping.

- The retrofit tine with no disc out-performs all other injectors with regard to application rate ability, and also exhibits low force requirements (draught and vertical) resulting in impressive application efficiencies. However the extent of lateral disturbance increases the risk of crop damage. This results in the development of a central dip that is less than optimal for the purpose of bio-solids incorporation. The performance of this injector concurs with observations by Spoor & Godwin (1978) who state that: the leading tip of a soil engaging implement is dominant and that the use of such a design may reduce draught forces. It may be said that a 0.025 m wide winged tine with a tip as wide as its wings, creates a similar force to a 0.035 m wide injector with a pointed leading tip.

3.6.1 Identified trends.

From the performance data gathered, it is noticeable that the injectors tested fall into three distinct categories. When considering mean theoretical application rates including the central dip and irrespective of operating depth, the performance of the 25W and 40WNDLi tines are similar ($\approx 180 \text{ m}^3/\text{ha}$ and $\approx 145 \text{ m}^3/\text{ha}$ at 0.2 and 0.25 m spacing respectively). Both the retrofit tine configurations also perform similarly, when considering the theoretical application rate discounting the central dip. ($\approx 220 \text{ m}^3/\text{ha}$ and $\approx 175 \text{ m}^3/\text{ha}$ at 0.2 and 0.25 m spacing respectively). The NSH injector stands out individually, with a significantly lower ability to apply sufficient quantities of bio-solids (162.1 and $129.7 \text{ m}^3/\text{ha}$ at 0.2 and 0.25 m spacing respectively).

From these results it is proposed that the 40WNDLi tine should be evaluated under field conditions to assess expected emission reductions in terms of ammonia volatilisation and odour concentration, resulting from bio-solid incorporation rather than placement. Additionally, any effect on the agronomic performance of the crop should be observed. Based on this study, results suggest that the 40WNDLi tine is capable of incorporating bio-solids in sufficient quantities during shallow injection. There is now a clear need for an economic evaluation and market survey to establish

the saleability of this new technology, as well as further development of a control system to maintain injector tine performance.

3.7 Study conclusions.

The following conclusions have been drawn from this study:

- The commercially available injectors tested are unsuitable for the application of bio-solids into arable cropping. This is due to high force requirements and the mode of soil disturbance that produces an open channel, facilitating bio-solids placement rather than incorporation.
- The use of an integral cutting edge for crop separation compares similarly with a cutting disc in terms of draught force requirement, but requires less assistance to penetrate the soil when used on a winged injector with a leading tip.
- The use of a cutting disc restricts the lateral soil disturbance of a simple winged injector tine with a leading tip.
- When discounting the central dip produced by the passage of an injector tine, only the 40WNDLi injector was capable of satisfying the application rate performance criteria within its permissible operating depth range.

Chapter 4

4.0 Environmental assessment of shallow injection.

4.1 Introduction.

The development of the 40WNDLi injector, described in *Chapter 3*, requires field validation to determine possible environmental and agronomic benefits of bio-solids incorporation. Phillips *et al* (1990) tested a shallow, wingless tine operating at 0.075 m and found that reductions in both NH_3 and odour emissions may be possible by shallow injection techniques compared to conventional surface application. In terms of odour emissions, shallow and deep injection exhibited similar odour concentrations (133 ± 97 and 182 ± 100 thousand odour units (OU)/m³ for shallow and deep application respectively). Higher emissions were attributed to splash plate spreading and irrigation-type application techniques (349 ± 130 and 6520 ± 5690 thousands of odour units, OU/m³ respectively).

Environmentally, in addition to the loss of available nitrogen (NH_4^+) to the atmosphere, issues associated with the loss of nitrogen through leaching should be considered. According to Collins (1996), environmental benefits in terms of reduced nitrate concentrations in soil water may be achieved by shallow injection into the crop root zone. Other authors have suggested that timing of application and soil type are of importance (Coker *et al*, 1987, Andrews *et al*, 1997, Sherwood 1986). Application of bio-solids to clay soils, rather than sands, are generally expected to result in less leaching of nitrate; particularly if it applied to a growing crop, e.g. grassland, or arable, rather than to fallow conditions. A comprehensive review of literature concerning the measurement of environmental losses was conducted to determine which techniques would be most appropriate for proposed field trials to investigate the environmental performance of the 40WNDLi injector, compared to conventional application methods.

4.1.1 Odour emissions measurement.

Perception of odour concentration varies between people due to the psychophysical processes involved. The use of olfactometry is widely regarded as a useful technique for quantifying odour in the field (Burglund *et al*, 1988). Olfactometry is the use of the human nose to measure odour concentration and offensiveness of the odorous source. An olfactometer is a device that dilutes odorous air with odour free air. These

dilutions are presented to an odour panel, in order to determine the odour threshold (Voorburg, 1986). Currently, the draft CEN standard (CEN/TC264/WG2) provides guidelines on the measurement of odour concentration by dynamic olfactometry. Initially, attempts were made to use gas chromatography for odour measurement. However, these proved unreliable when assessing low threshold odorous compounds, whereas the human nose was found to be suitable in this instance (Freeman, 1967). Early assessment of odour from animal wastes considered the offensiveness of the source (Sobel, 1972). These assessments used the syringe dilution method, (ASTM, 1972). However, this was found to be subject to improvisation and was, therefore, superseded by the design of a forced choice triangle olfactometer (Dravnieks & Prokop, 1975). The forced choice olfactometer eliminated the problems of the ASTM method by defining the order of presentation of the odorous samples. The ASTM method used a random form of sample presentation to the panellist. However, Lindvall (1970) suggests that it is almost impossible to assess odour threshold by random presentation and advocates an ascending order of sample presentation. The forced choice triangle method has been used successfully in odour studies of bio-solids, (Holmvang, 1986).

The measurement of odour comprises four main steps:

1. Sample Collection.
2. Sample dilution and presentation.
3. Indication of response.
4. Interpretation of response.

Source: Bulley and Phillips (1980).

4.1.1.1 Sample collection.

The general effect of odours can be assessed by an "on-site" method, where a number of observers are placed in the vicinity of the odour (Lindvall, 1974). This method is unsuitable for small plot studies and so the use of wind tunnels is advocated (Ryden, 1986). The wind tunnel technique was assessed by Belois & Anzion (1992), and was found to be acceptable for odour studies. This method of sampling has been accepted for inclusion in the CEN/TC264/WG2 guidelines.

Samples can be concentrated for sampling by gas chromatography, or un-concentrated, where a concentration threshold is required. Sample dilution and presentation (dynamic or static) will depend on the type of olfactometer to be used. The sampling equipment should be inert to avoid surface effects such as adsorption, desorption and condensation (Hartung, 1986). In the UK, sampling equipment is specified in guidelines and requires 40 – 50 l capacity Tedlar bags for sampling, with all pipes and valves being constructed of ptfe (Warren Springs, 1980), and more recent CEN standards reiterate these requirements (CEN, 1997).

The method of collection is by the “lung” principle. A small battery or mains operated pump is used to evacuate a container, which allows the initially deflated ptfe bag to inflate (Warren Springs, 1980).

4.1.1.2 Sample dilution, indication and interpretation of response.

Source: Current guidelines stated by CEN/TC264/WG2.

Following successful sampling, odour should be assessed within 30 hours but preferably as soon as possible. The odorous samples are presented to the odour panellists through the sniffing ports of the olfactometer. There are three modes of assessment that can be used.

i. Yes/No mode:

Panellists are asked if they perceive an odour and can respond with either yes or no.

ii. Forced choice mode:

Panellists are asked whether they can perceive an odour and to indicate the certainty of their choice (guess, inkling or certain).

iii. Three alternative forced choice mode:

requires an olfactometer with three or more ports.

Odour samples are generally presented in ascending order of concentration, although random samples can be presented to obtain the odour threshold value. The odour threshold value is the concentration of the odour (determined by the number of dilutions), at which an odour is just perceived by 50% of the panel members.

4.1.2 Measurement of ammonia emissions.

Assessment of the performance of different application methods in terms of ammonia emissions requires complex measurement procedures. Initially, micrometeorological methods based on a number of different theories (Denmead, 1983) were used:

i. **Eddy correlation method:**

Vertical transport of a gas past a point in the atmosphere is obtained by correlating the instantaneous wind speed at that point, with the instantaneous concentration. This method requires a rapid response gas detector.

ii. **Gradient diffusion method:**

This is based on the diffusion of gas along its mean concentration gradient. Gradient diffusion requires measurement at a number of heights above the surface.

iii. **Mass balance technique:**

This has been used widely in the past for emissions studies over whole fields (Ryden & McNeill, 1984). Wind speed and the concentration of NH_3 in air are measured at different heights above the plot at its downwind boundary, and a position upwind of the plot area. The flux of NH_3 is calculated from these measurements, with a continuous record of wind speed and direction.

Both eddy correlation and gradient diffusion methods are limited to situations where air has blown over the exchange surface for a long distance. Micrometeorological techniques are useful for studying the losses from grazed pasture or whole crops, where plot size is unconstrained.

Lockyer (1984) described a system of small wind tunnels to overcome the problems associated with small plots. The wind tunnels enable wind speed to be controlled over a small plot with minimal influence on the natural sward conditions. The system incorporates the use of gas pumps and bubblers containing orthophosphoric acid to trap ammonia at the entrance and rear of the tunnel. Ryden & Lockyer (1985) evaluated the system and concluded that it was suitable for studies of the factors affecting NH_3 loss from replicated experimental plots. The acid samples can be evaluated for ammonia content using colorimetry (Weatherburn, 1967). This system has been used successfully in a number of field studies, (Pain *et al*, 1990; Moal, 1995; Moseley *et al*, 1998).

4.1.3 Nitrate leaching measurement.

There are two established methods for the sampling of soil water to monitor nitrate leaching. Collins (1986) used lysimeters, which are generally small and well suited for plot studies. A more practical method of sampling soil water in the field is through the use of porous ceramic cups (Hansen & Harris, 1975). Porous ceramic cups have been reviewed extensively by Grossman & Udluft (1991). Nagpal (1982) evaluated the effectiveness of porous cup water samplers and found that, although sorption of ortho-P and potassium (K) occurred, the retention of nitrate within the ceramic membrane was minimal. More recently, improvements in the sampling technique have been made by Lord & Shepherd (1993) who advocate a rigorous technique for the installation and sampling of porous ceramic cups in nitrate studies. They suggest that the depth of installation should be at least as great as the rooting depth of water extraction by roots. It was found that installation of porous ceramic cups at depths up to 1 m, was impractical if dry conditions in summer prevailed. A number of authors have used porous ceramic cups for nitrate studies with reasonable results, (Sherwood, 1986; Steenvorden, 1986; Joshi *et al*, 1994; Blackwell, 1996; Collins, 1996; Shepherd, 1996; Simmelsgaard, 1998).

In consideration of the work outlined above, it is apparent that the application of bio-solids at shallow depth to an established winter cereal crop may provide the basis for an appropriate system for recycling bio-solids, provided consideration of crop nutrient requirement is taken into account. The use of porous ceramic cups is appropriate for soil water nitrate sampling.

4.1.4 Summary.

A simple plot-based field trial should be established to assess the environmental performance of the 40WNDLi injector tine compared to surface application and bio-solids placement by the Greentrac™ slipper foot injector. Two odour and ammonia trials and two nitrate leaching trials were conducted on a sandy loam soil on the Cranfield University Farm at Silsoe. The aim of this field study was to determine the effect of injector type on odour concentrations, ammonia emissions and nitrate concentration in the soil water, following the application of 50 m³/ha of bio-solids to an established arable crop.

4.2 Methodology.

4.2.1 Injector tine design.

Current shallow injection technology, such as the Greentrac™ slipper foot injector tine, enables bio-solids to be placed at depths of between 0.05 and 0.1 m. Commercial shallow injector tines produce a narrow slot filled with bio-solids (*Fig. 4.1a*) using a backward raked tine. Presswheels are available to improve slot closure, but these tend to squeeze the bio-solids onto the soil surface resulting in incomplete incorporation and crop damage (Warner *et al*, 1991). The improved design (*Appendix 2.2c*) utilises wings and a small clearance angle combined with an integral backward-raked cutting edge and narrow shank, to improve incorporation of bio-solids. Soil deflectors above the wings promote soil movement around the sludge application tube. The slipper foot injector tine (*Fig. 4.1b*) creates a V shaped channel in the soil and uses a cutting disc ahead of the tine to promote crop separation. The emphasis of the slipper foot injector tine is on bio-solid placement rather than incorporation.

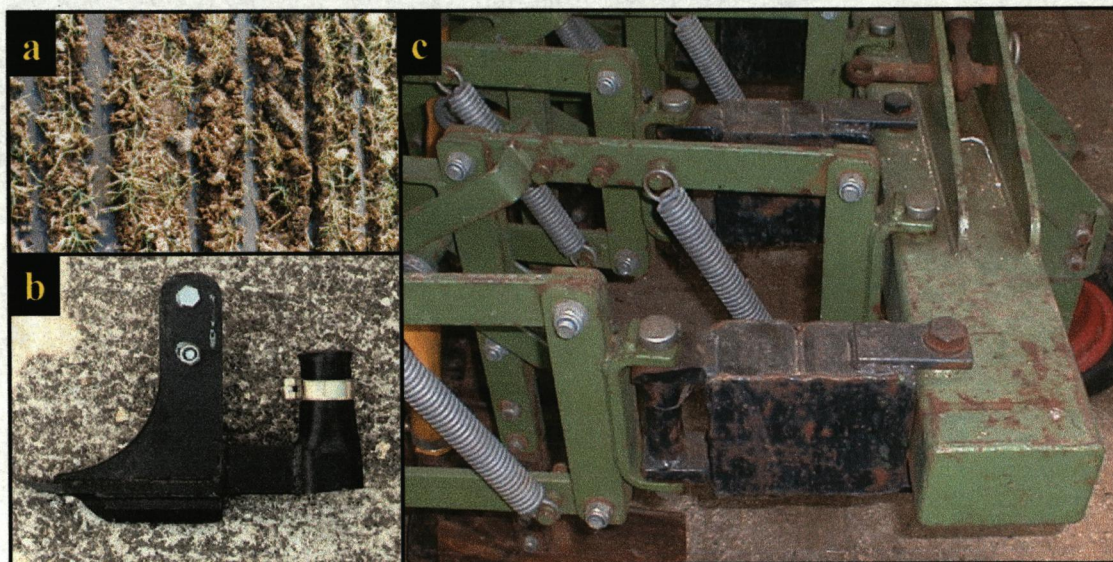


Fig. 4.1. a) Slot produced by slipper foot injector tine, b) the Greentrac slipper foot injector, c) spaced injector tines to avoid tine interaction.

The 40WNDLi injector was manufactured to fit a Greentrac™ slipper foot injection system, which had been made available for this project. Some modifications were made to the machine itself to accommodate the tine. Primarily, every other injector tine was forced rearwards of its neighbouring tines to avoid any interaction due to tine spacing (*Fig. 4.1c*).

4.2.2 Soil bin evaluation of injector tines.

The soil force and disturbance characteristics of both the Greentrac™ slipper foot injector tine and the 40WNDLi injector, have been described in *Chapters 2 and 3*. Forces, both draught and vertical, were obtained in the soil dynamics laboratory at four operating depths, up to and beyond the working limits of the injector tines. Soil disturbance profiles have also been recorded for both injectors, using the miniature soil profile meter described in *Section 2.6.5*.

4.2.3 Field application of bio-solids, (odour & ammonia).

Two sets of experiments were carried out on an area of sandy loam land, with no perceptible water table, within the same field boundary, on the Cranfield University Farm at Silsoe. Three methods of application were used for each set of tests: surface, slipper foot tine, 40WNDLi and a control, comprising no application. Altering the linkage's spring configurations controlled injector tine operating depth, such that an operating depth of 0.05 – 0.06 m was maintained. Bio-solids were applied using Greentrac™ shallow injection equipment (*Fig. 4.2a*), which, through its linkage arrangement, allows the tine vertical and lateral freedom to negotiate obstacles. Bio-solids were supplied from a tanker, via an umbilical hose, that was specially adapted for plot work, so that crop damage was avoided (*Fig. 4.2b*).



Fig. 4.2. a) slipper foot injector & b) tanker and umbilical supply for plot applications.

A combination of adjustments to the constant displacement pump on the tanker and forward speed of injection, allowed an application rate of 50 m³/ha to be maintained for all tests. Each individual plot was 10 m long and 3.5 m wide. A randomised block design was used for both sets of experiments, to enable soil variability within the experimental plot to be accounted for (*Fig. 4.3*).

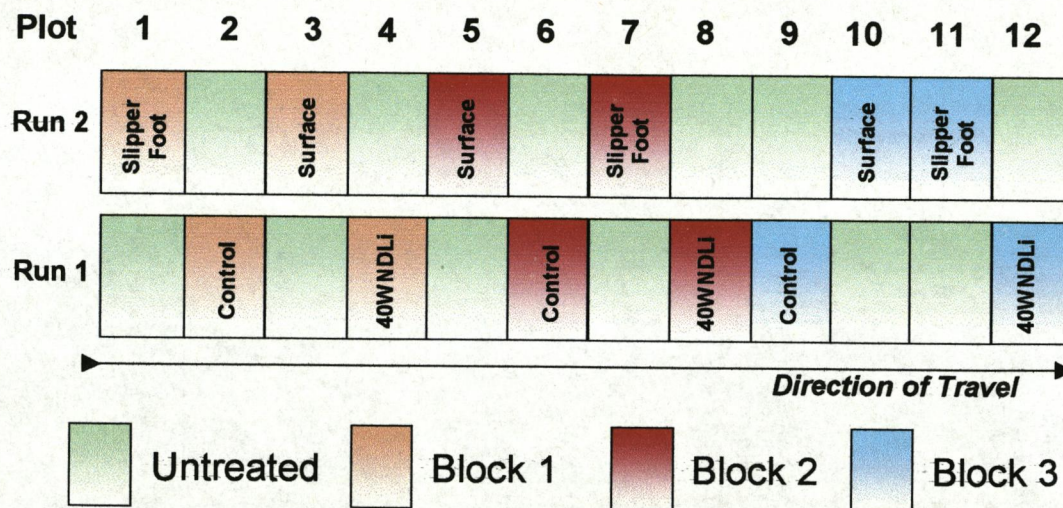


Fig 4.3. Randomised block design for odour & ammonia emissions field trials.

Manoeuvrability of the injection equipment within the constraints imposed by the sampling equipment necessitated two passes across the trial plot. The first pass (Fig. 4.3, Run 1) commenced using the 40WNDLI injector tine. Prior to the commencement of the second pass (Fig. 4.3, Run 2), the machine was fitted with the slipper foot tines. Surface applications were made using a dribble bar technique, such that the injection equipment was operated above ground level, with bio-solid being applied through the slipper foot injector tine without any soil contact. Immediately following the application of bio-solids to each plot, wind tunnels were positioned over the application area and sampling commenced. Odour samples were sent by courier to the odour laboratory for analysis within 24 h of application. All odour samples were analysed by the Institute of Grassland and Environmental Research (IGER), North Wyke, Devon. The first set of experiments was carried out in November 1996, using anaerobically digested sewage sludge applied to an established crop of winter wheat. The second set of tests was conducted using fresh pig slurry applied to an established crop of spring wheat. To enable viable comparisons to be made, the growth stage of both crops at the time of injection was between GS 22 - 26. Samples of bio-solids used in each set of experiments, were sent to the Anglian Water laboratories for nutrient analysis.

4.2.3.1 Ammonia volatilisation measurement using wind tunnels.

Ammonia volatilisation was monitored for 4 d following application of anaerobically digested sewage sludge in November, and pig slurry in May. A system of small wind

tunnels was used (Lockyer, 1984), each covering an area of 1 m^2 , with windspeed through the tunnels maintained at 1 m/s . The concentration of ammonia in the air entering and leaving each wind tunnel was measured using absorption flasks ("bubblers") containing orthophosphoric acid. The loss of ammonia from the area beneath the tunnel was calculated as the product of the volume of air that flowed through the tunnel and the differences between the concentrations of ammonia in the air entering and leaving the tunnel. Ammonia concentrations in the "bubblers" were determined using automated colorimetry at IGER's laboratory in Devon.

4.2.3.2 Odour samples.

Air samples for odour concentration measurement were collected in 30 l ptfe (nalophane) gas sampling bags with stainless steel connectors. Samples were collected using the lung principle, whereby a pressure vessel containing the sampling bag was evacuated so that sample air was drawn directly into the bag without passing through a pump. The bag filled over a period of 3-5 min. Samples were collected via ptfe tubing connected to the outlet air sampling point of the wind tunnel. Samples were taken 5 min and 24 h after application, for both sets of tests.

4.2.3.3 Olfactometry.

Odour concentration (the number of dilutions of odorous air with odourless air at which 50%, of a panel of observers, can just detect an odour) was measured, using two dynamic dilution olfactometers (Project Research Amsterdam bv.). Equipment and procedures used conformed to the guidelines of the European standard for dynamic olfactometry, currently being drafted by the Comité Européen Normalisation working group CEN/TC264/WG2 "Odours". Each olfactometer had two sniffing ports and was of forced choice type, with odourless air being presented to the panellists through one port and diluted, odorous air through the other. For each presentation, each panellist was required to indicate via a keyboard, which port contained the odorous air and the certainty of their choice (guess, inkling or certain). A panellist scored correctly only if they selected the correct port and were certain of their choice. A range of at least five dilution steps, each differing from the next by a factor of two, was presented to the panellists in steps of ascending concentration; the whole range being presented twice. Panellists' individual thresholds were calculated as the geometric mean of the highest dilution at which they consistently scored correctly, and the lowest dilution at which they scored incorrectly. The group

threshold (which equates with the odour concentration) was calculated as the geometric mean of individual panellists' thresholds, following exclusion of individual thresholds that differed from the group by more than a factor of five.

4.2.3.4 Crop management.

No sprays or fertilisers were added to either crop receiving the November or May applications of bio-solids, although irrigation was applied to the spring wheat crop in anticipation of the May odour trials to aid crop establishment during an unexpectedly dry period. A total of 0.015 m was applied evenly over the May trial plot, using a sprinkler irrigation system.

4.2.4 Field application of bio-solids, (soil water nitrate analysis).

Two separate experiments were carried out, adjacent to the site at which the odour and ammonia field trials were conducted, to assess the effect of injection method on soil water nitrate concentrations. In common with the experiments to ascertain gaseous emissions, the land was of sandy loam soil type, with no perceptible water table (upto a depth of 1 m). Bio-solids were applied in December 1997 and May 1998, to an established crop of *Riband* winter wheat with samples of bio-solids being sent to Anglian Water for analysis. As with the odour and ammonia trials, four treatments were evaluated comprising surface application using the dribble bar technique described earlier, slipper foot shallow injection, 40WNDLi injection and a control of no bio-solids application. 50 m³/ha of anaerobically digested sewage sludge was applied to the plots, which were arranged in a randomised block formation (*Fig. 4.4a & b*). Soil water samples were extracted using porous ceramic cups (Lord & Shepherd, 1993), and subsequently analysed using UV spectrometry as described in *Appendix 3.1* (Eaton *et al*, 1995).

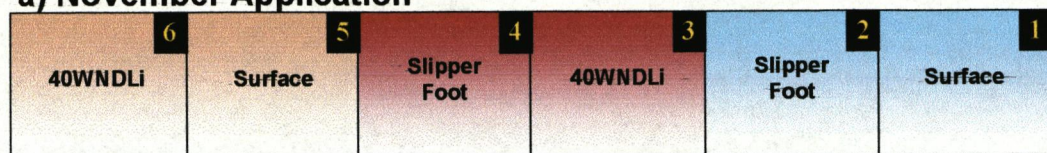
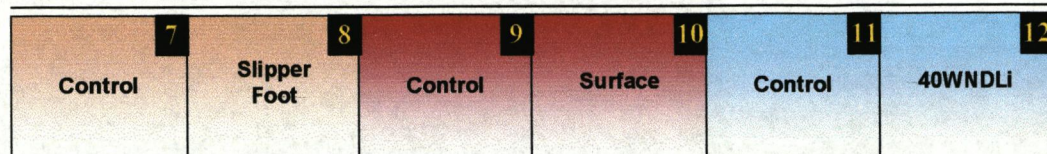
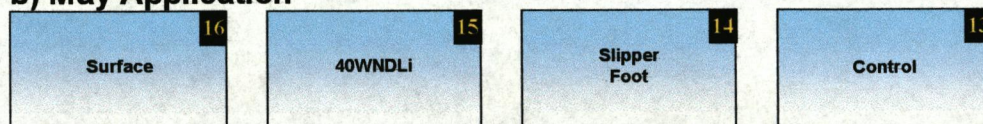
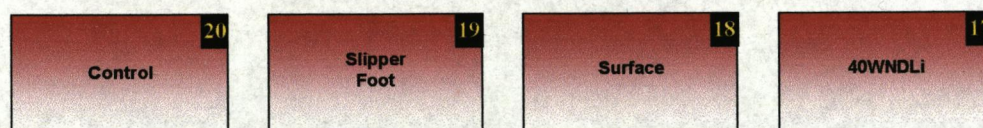
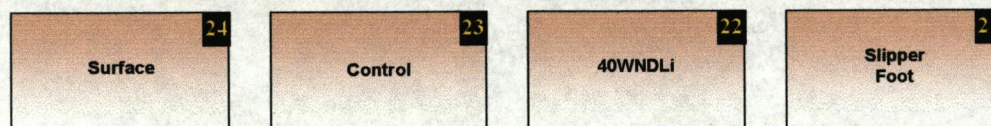
a) November Application**Tramlines****All plots 3.5 m wide x 10 m long,****b) May Application****Tramlines****Tramlines****Tramlines****All Plots 3.5 m x 15 m, with 10 m gaps for machine access**

Fig. 4.4. Randomised block design plot layout for soil water nitrate sampling following an application of anaerobically digested sewage sludge in a) December 1997 and b) May 1998.

4.2.4.1 Porous ceramic cup installation.

Porous ceramic cups were installed at the centre of each plot prior to the application of bio-solids. Soil was removed to a depth of 0.6 m using a 0.1 m Dutch auger, and the hole was back-filled with 0.01 m of fine silica sand. The cup was then placed in the hole and a further backfill was added to cover the ceramic component of the sampling device. A copious quantity of de-ionised water was added to consolidate the cup in the silica-sand filter. Soil extracted by auger, was then replaced to a depth

sufficient to cover the sampler body and a bentonite clay cap was added to prevent seepage of water down the sides of the augered hole. Finally, soil was used to complete the back filling, with the extraction tubes being buried under the soil surface on plots that were to receive injected treatments thus avoiding the possibility of instrument damage. Extraction tubes remained exposed on the control and surface plots. Following the application of bio-solids, extraction tubes from injected plots were evacuated and exposed. The first two samples from each cup were discarded to reduce the influence of the de-ionised water, used during installation, on the results.

4.2.4.2 Porous ceramic cup sampling.

Each porous ceramic cup has two extraction pipes to allow the application of suction, to initiate sampling and pressure, to extract the soil water sample. Pipe clamps were used to maintain suction within the cup for a sufficient period to allow a suitable sample volume (> 2 ml) to be collected (*Fig. 4.5*). The application of suction was achieved by attaching a syringe to the suction tube (the extraction tube being clamped) and withdrawing the plunger, creating a partial vacuum within the sampler body. Two 50 ml syringe volumes are sufficient to create the vacuum necessary. The suction pipe is then clamped to retain the vacuum within the sampler.

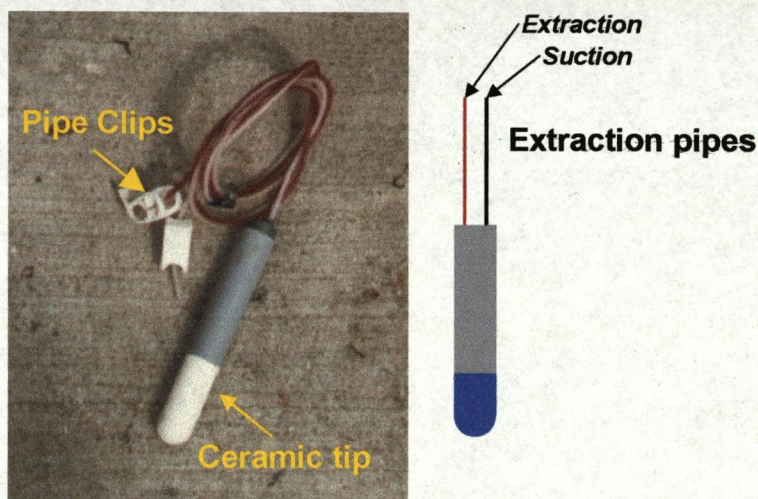


Fig. 4.5. Schematic and image of a porous ceramic cup sampling device.

Extraction of the soil water sample was carried out 2 to 4 h after the application of suction. This was achieved by unclamping both pipes, directing the extraction pipe into a suitable receptacle, and applying pressure from a 50-ml syringe in the suction pipe. Water was then forced out of the ceramic cup and taken to the laboratory for analysis. Samples were taken from all plots on a weekly basis. If storage was needed before analysis, samples were placed in a refrigerator.

4.2.4.3. Soil water sample analysis.

Soil water nitrate analysis was carried out using the ultraviolet spectrophotometric screening method (Eaton *et al.*, 1995). Water samples were diluted, where necessary, to ensure that concentrations were inside the operational limits of the procedure. The UV spectrophotometer (Philips PU8730 UV/Visible Spectrophotometer, Philips Scientific, 1989) was calibrated with standard nitrate solutions, and field samples were analysed at 220 nm for total nitrate content. No corrections were made, in this comparative study, to account for organic matter absorbency at 275 nm. The degree of pollution in terms of soil water nitrate concentration, was assessed with regard to World Health Organisation recommended limits for nitrates in potable water of 50 mg/l (W.H.O. 1993).

4.2.4.4. Climatological considerations.

Field trials to assess the effect of injection method on soil water nitrate concentrations had been initiated in the 1995/96 and 1996/97 growing seasons. However, excessively dry conditions over this period had severely restricted the ability to extract soil water samples. To overcome this situation, a programme of irrigation applications of water was invoked based on continuous monitoring of rainfall, evapotranspiration and extracted water volumes. Applications of irrigation water were made using a Briggs R1/1 63-130 boom irrigator, which comprised a 10 m boom providing a 12 m effective working width, and capable of a maximum travel of 130 m. Applications were controlled using an on-board "Program Rain Computer". Soil temperature was monitored at 0.1, 0.2 and 0.3 m, throughout the duration of the experiment, as it is accepted that nitrogen mobility is impeded at soil temperatures below 5° C (Addiscott, 1983).

4.2.4.5 Soil nitrogen sampling and analysis.

Soil samples were taken periodically, throughout the duration of the nitrate experiment. These samples were taken at depths 0 to 0.25 m and 0.25 to 0.5 m by the auger method and, subsequently, air dried for analysis in the laboratory for total nitrogen content using the Kjeldahl method (ASA, 1982). This enabled monitoring of total nitrogen in the soil to be carried out during the growing season and the effect of added nitrogen to be assessed.

4.2.4.6 Crop management.

Technical staff at the Cranfield University at Silsoe, Land Equipment Centre, in consultation with an ADAS agronomist, carried out crop management. A summary of sprays and fertilisers applied is presented in *Table 4.1*.

Table 4.1
Fertiliser and spray applications on nitrate trial plots.

Date	Plots	Application	Details
9th February 1998	All	Panther Herbicide (2 l/ha)	diflufenican + isoproturon
20th February 1998	7,9,11, 12-24	Urea (46%) N	50 kg/ha = 2.3 g/m ²
8th May 1998	All	Mirage Extra Fungicide (1 l/ha)	prochloraz + fenbuconazole
8th May 1998	All	Lorate Herbicide (30 g/ha)	lorate
8th May 1998	All	Starane 2 Herbicide (0.7 l/ha)	fluroxypyr
20th May 1998	Control Only	Nitram (34.5%) N	145 kg/ha = 5 g/m ²

Applications of granular fertiliser to control plots were carried out by hand.

4.3 Results and discussion.

The results of this work comprise a summary of the soil dynamics study of injector tine performance, and environmental effects resulting from application method (odour concentration, ammonia volatilisation and soil water nitrate concentration).

4.3.1 Injector tine performance.

The results of the soil dynamics laboratory tests on the injector tines are presented in *Fig. 4.6*. Both tines exhibited similar draught force characteristics (*Fig 4.6a*). The slightly wider 40WNDLi injector, compared with the slipper foot injector, compensates for any advantage obtained by utilising the narrow shank on the improved injector tine. Additionally, the integral cutting edge of the 40WNDLi injector tine is thought to be comparable in draught force requirement to the cutting disc used by the slipper foot tine. However, a lower vertical force requirement for the

improved tine as a result of the wings was observed, illustrating the tine's ability to penetrate and maintain depth without the need for significant downward applied force (Fig. 4.6b).

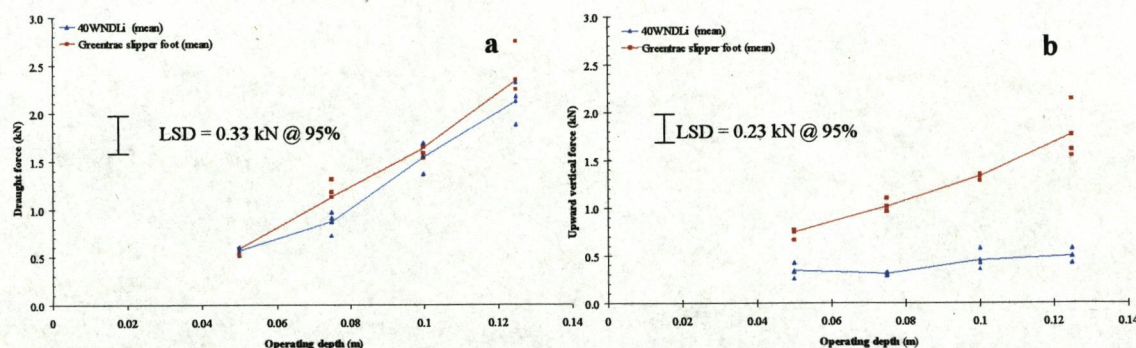


Fig. 4.6. Performance of the 40WNDLi and Greentrac slipper foot injectors in terms of a) draught force and b) upward vertical force.

Soil disturbance profiles obtained in the soil dynamics laboratory are presented in Fig. 4.7. These typify the narrow channel produced by the slipper foot injector as a result of the backward raked slot cutter, and the improved soil mixing produced by the 40WNDLi injector tine due to the incorporation of low clearance angle wings. The width of soil disturbance between the injectors is similar. However, the absence of the slot in the 40WNDLi injector's disturbance profile implies better soil mixing. Similar profiles were observed during field experiments.

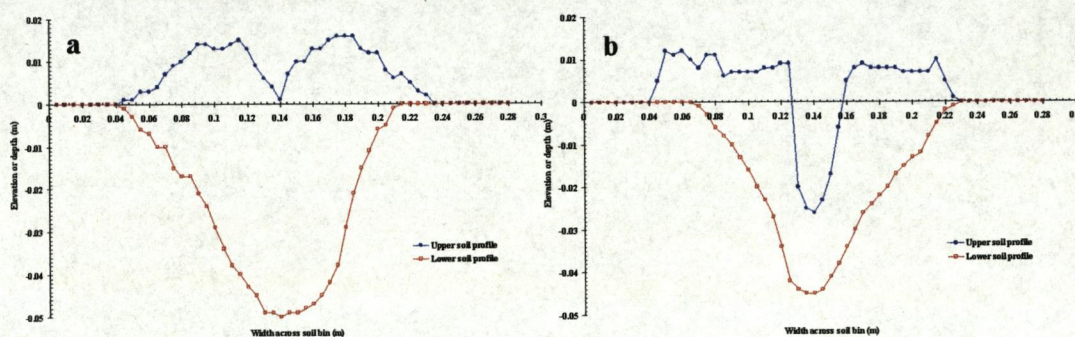


Fig. 4.7. Soil disturbance profiles for a) 40WNDLi and b) slipper foot injector tines at 0.05 m operating depth in the soil dynamics laboratory.

The slipper foot injector tine produces a narrow channel that is filled with bio-solid and hence this is not fully incorporated into the soil. The upper surface of the bio-solids is exposed to the atmosphere (Fig. 4.8a). The 40WNDLi injector tine creates a less well-defined channel as the wings of the tine promote soil mixing. This results in less exposure of bio-solids on the soil surface following application (Fig. 4.8b). The volume of additional pores was calculated from the profiles for each injector. It was found that both injectors were potentially capable of achieving an application rate of

up to 75 m³/ha, based on a 0.2 m injector spacing. However, if the area within the slot were considered undesirable for bio-solid application, the slipper foot tine would only create sufficient voids for a maximum application rate of 35 m³/ha, compared with 60 m³/ha for the 40WNDLi injection system.

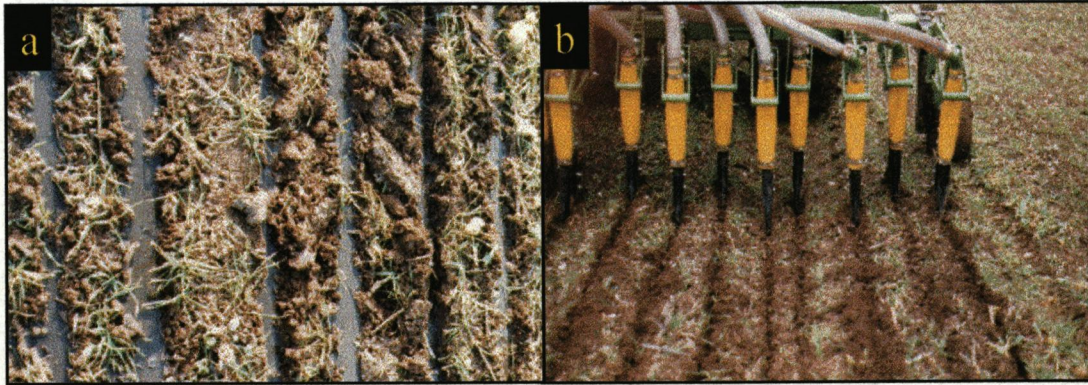


Fig. 4.8. Bio-solids placement using the slipper foot injector (a) and incorporation using the 40WNDLi injector tine (b).

4.3.2 Bio-solids properties.

An analysis of the bio-solids used for each experiment (odour, ammonia and nitrate) is presented in *Table 4.2*. The analysis illustrates the similarity between sewage sludge and pig slurry, in terms of trace elements and; the variability of sewage sludge as a bio-solid, in terms of both total and available nitrogen content. The analysis shows that the pig slurry contained almost twice the amount of nitrogen and ammonia compared with sewage sludge, with a larger percentage of solids present in the sewage sludge; although the consistency of the different bio-solids used was similar. Differences in the levels of metals within the samples can also be observed. In the context of this experiment, the primary concern is with the nitrogen and ammonia content.

Table 4.2
Bio-solids properties for each set of field trials.

Name	Units	Nitrate trials 1997/98		Odour & ammonia trials 1996/97	
		01/12/1997*	01/05/1998*	01/11/1996*	01/05/1997**
Solids	%	3.06	3.26	4.00	2.41
N-KJ (DW)	% N	5.12	4.68	6.19	12.10
NH ₄ ⁺ (DW) N	% N	1.90	2.09	1.41	2.77
P ₂ O ₅ (DW)	%	5.93	5.57	6.02	2.89
K ₂ O (DW)	%	0.33	0.34	0.25	2.07
pH	pH	7.22	6.82	7.05	6.95
Cu (DW)	mg/kg	615.00	545.00	671.00	577.00
Zn (DW)	mg/kg		1040.00	985.00	1030.00
Cd (DW)	mg/kg	1.49	3.66	1.76	0.21
Hg (DW)	mg/kg	1.53	1.59	1.51	<0.1
Pb (DW)	mg/kg	56.30	61.70	52.50	13.20
Cr (DW)	mg/kg	102.00	195.00	106.00	10.60
Mn (DW)	mg/kg		218.00	204.00	268.00
Ni (DW)	mg/kg	23.50	53.30	22.20	51.40

(DW indicates a % of dry weight)

* Anaerobically digested sewage sludge,

** Fresh pig slurry.

4.3.3 Odour concentrations.

4.3.3.1 Immediately after application.

The results of the odour concentration experiments, illustrated in *Fig. 4.9*, show that immediately after an application of anaerobically digested sewage sludge, there were no significant differences between methods of application with all concentrations being weak, and some too weak for valid measurement. A valid measurement is one that contains at least 8 data points. As each concentration is presented to 6 panellists twice, it is possible for two panellists to score incorrectly at each presentation and still obtain a valid measurement. The smallest dilution possible with the olfactometer was $\times 10$. A complete statistical analysis is presented in *Appendix 3.2*.

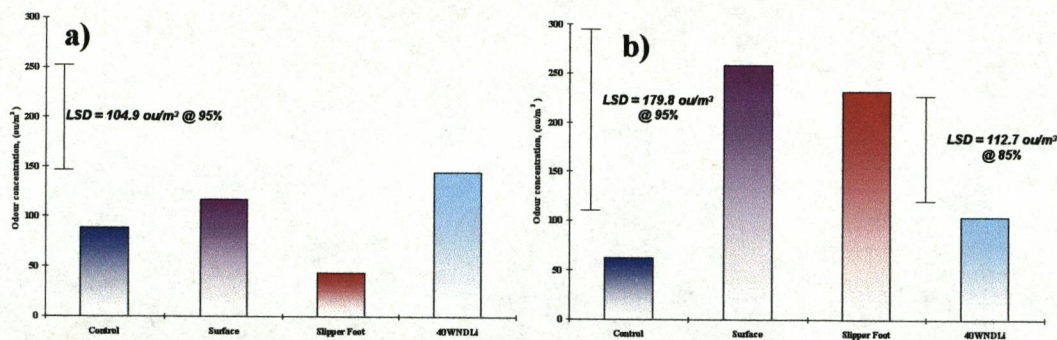


Fig. 4.9. Odour concentrations immediately following an application of a) anaerobically digested sewage sludge in November 1996 and b) fresh pig slurry in May 1997.

Typically, background concentrations (normal air upwind of the trials, uncontaminated by sludge or slurry) of odour lie in the range 50 to 150 ou/m³. Results in Fig. 4.9a indicate that odour emissions following a typical application of anaerobically digested sewage sludge are very low, regardless of the method of application. Odour concentrations immediately after application were not significantly different at the 95% level between application methods when using pig slurry, although there was evidence that concentrations were lower from the 40WNDLI injector tine, with statistical significance present at the 85% level. Variability between blocks was quite high (cv = 43.8%), but less than the November experiment with sewage sludge (cv = 53.3%). It was calculated that, for the variation experienced during this experiment, over 120 replicates would be required to produce a significant difference between treatments when using sewage sludge. However, this could be reduced to 37 replications when using the pig slurry. A simple formula was used to calculate the degrees of freedom required to observe statistical significance, between odour concentrations, using the slipper foot tine and the 40WNDLI tine:

$$L = \frac{1.96 \times \text{residual}}{\sqrt{n}}$$

Where:

- residual* = error mean square
- L* = difference between means
- n* = degrees of freedom.

Residual values were 758.3 and 3085 for sewage sludge and pig slurry respectively. Considering the cost of odour testing using olfactometry, it would not be economically viable to pursue significance at the 95% level, when comparing methods of shallow injection of bio-solids. Control values were excluded from the

statistical analysis of the pig slurry tests, due to one missing value resulting from a deflated bag, and one very high value resulting from accidental runoff from another plot. In addition, due to the direction of the wind at the time of testing, it is possible that cross contamination between plots 3 and 4 may have resulted in an artificially high concentration for the improved tine in plot 4. Concentrations from surface applied slurry were lower than may have been expected, compared with values from pig slurry spread on grassland (Pain *et al*, 1989, Pain *et al*, 1991). It is likely that this was due to rapid infiltration of the slurry into the soil. However, the presence of crop cover, preventing rapid odour release, may also have contributed to the results obtained.

4.3.3.2 Twenty-four hours after application.

Results from odour concentrations taken 24 h after application (*Fig. 4.10*), indicate no significant differences between methods of application, and are similar to control concentrations for both sewage sludge and pig slurry. This suggests that after 24 h, there is likely to be no odour nuisance resulting from the application of bio-solids to an established arable crop.

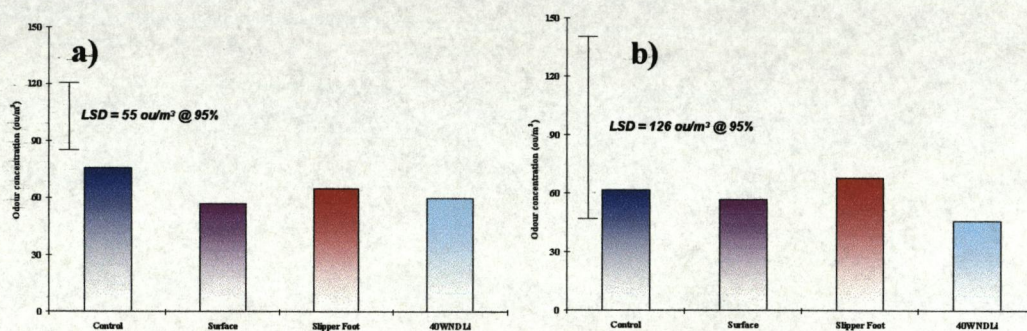


Fig. 4.10. Odour concentrations measured 24 h after the application of a) anaerobically digested sewage sludge in November 1996 and b) fresh pig slurry in May 1997.

4.3.4 Ammonia emissions.

After application of sewage sludge in November 1996, high inlet concentrations of ammonia were experienced on some plots resulting in negative emissions. At the time of testing in November, freezing temperatures occurred at night, resulting in the acid in some “bubblers” freezing despite being insulated with pipe lagging. This may explain, to some extent, the degree of variability observed during the experiment (cv = 108%, November & cv = 59%, May). The variability of the results from this experiment reduced the possibility of obtaining statistically significant differences

between methods of application (*Fig. 4.11a*). However, although not significant, the results show a trend towards reduced emissions following application by shallow injection, rather than surface application, with the possibility of further reductions in emissions using the 40WNDLi injector tine.

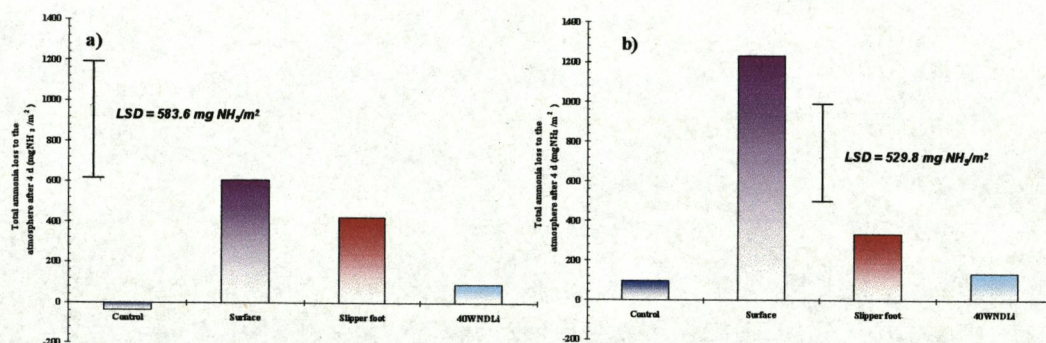


Fig. 4.11. Total ammonia loss over 4 d following application of a) anaerobically digested sewage sludge in November 1996, and b) fresh pig slurry in May 1997.

When the experiment was repeated with pig slurry in May, a significant difference in ammonia emissions (at the 95% level of confidence) was observed between surface application and shallow injection (*Fig. 4.11b*). However, no significance between the two methods of shallow injection was observed, although a significant trend towards reduced emissions through using the 40WNDLi injection system was found. A parallel curve analysis was carried out on the pig slurry ammonia data. It was found that a common curve could be fitted to both the control data and the 40WNDLi data (*Fig 4.12a*), indicating no significance between the trends of the two data sets (*Table 4.3a*). The curves fitted to the data followed an exponential equation:

$$y = A + BR^x$$

An identical analysis was carried out to compare the control data to ammonia emissions using the slipper foot injection system (*Fig 4.12b*), resulting in significantly different curve fits (*Table 4.3b*). This represents a significant trend, at the 95% level, towards reduced ammonia emissions using the 40WNDLi injection system. The significance of this trend suggests that; the use of this application method may impact less on the environment than the slipper foot shallow injector used in this experiment.

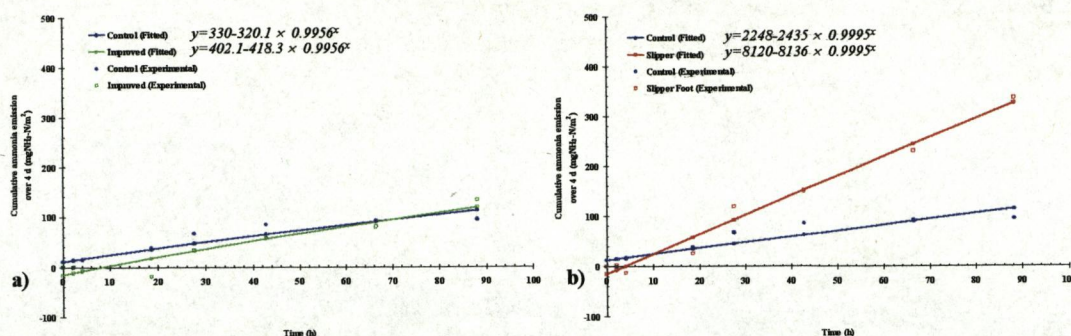


Fig. 4.12. Fitted curves, obtained by parallel curve analysis, for mean ammonia emissions over time following the injection of fresh pig slurry for a) control versus 40WNDLi injection method and b) control versus slipper foot injection method.

Table 4.3

Fitted constants *A*, *B* & *R* from trend analysis between a) control and 40WNDLi treatments, and b) control and slipper foot treatments.

Treatment	Fitted Constant					
R	0.9956					
B control	-320.1					
A control	330					
B 40WNDLi	-418.3					
A 40WNDLi	402.1					
Change	df	ss	ms	vr	Fpr	
R	2	82109	41055	12.27	<0.001	
B	1	2422	2422	0.72	0.4	
A	1	1363	1363	0.41	0.527	
Residual	43	143892	3346			

Treatment	Fitted Constant					
R	0.9995					
B control	-2435					
A control	2448					
B Slipper Foot	-8136					
A Slipper Foot	8120					
Change	df	ss	ms	vr	Fpr	
R	2	281275	140638	8.75	<0.001	
B	1	39331	39331	2.45	0.125	
A	1	80254	80254	4.99	0.031	
Residual	43	691516	16082			

df, degrees of freedom; ss, sums of squares; ms, mean square; vr, variance ratio; Fpr, F probability

It was calculated that the total nitrogen applied to each plot, using sewage sludge and pig slurry, was 123.8 and 145.8 kg/ha respectively. This corresponds to $\text{NH}_4^+\text{-N}$ availability for volatilisation of 28.2 and 33.4 kg/ha respectively. A 40% volatilisation loss of the total applied $\text{NH}_4^+\text{-N}$ was observed after surface application, with significant reductions being observed following application using the Greentrac slipper foot equipment (10 to 15%) and the 40WNDLi injection system (3 to 4%).

Emission of ammonia occurred at a fairly constant rate over much of the period, following application of sewage sludge, for all application methods (Fig. 4.13a). This

may have been due to the lower daytime temperatures experienced in November, resulting in a reduction in the mobility of nitrogen, combined with the lower $\text{NH}_4^+\text{-N}$ content of this bio-solid. With both pig slurry and sewage sludge it is evident that using the 40WNDLi injection system, in preference to either the slipper foot injection system or surface application, may reduce ammonia emissions. The rate of loss of ammonia following the application of pig slurry was initially high; with greatest losses being observed within 2 h of application. However, ammonia emission from the injection treatments occurred at a more constant, but much lower rate over the sampling period (Fig 4.13b).

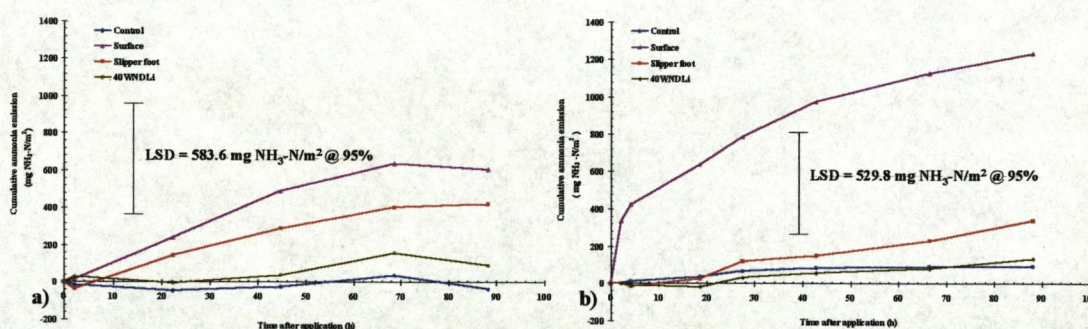


Fig. 4.13. Cumulative ammonia release over the sampling period following: a) an application of anaerobically digested sewage sludge to an established crop of winter wheat in November 1996 and b) an application of fresh pig slurry to an established crop of spring wheat in May 1997.

Other authors (Pain *et al*, 1989) have observed losses of up to 85% of the total $\text{NH}_3\text{-N}$ loss, within 12 h. However, during these experiments, only 48% of the total $\text{NH}_3\text{-N}$ lost was observed during the first 12 h after application, when pig slurry was applied on the soil surface. For shallow injection methods, under these conditions, it took up to 48 h for 50% of the total loss to be accounted for. It is thought that the presence of the established crop provided a barrier that reduced the rate of emissions within the small wind tunnels.

4.3.5 Nitrate concentration in soil water extracts.

When considering the concentration of nitrate in soil water samples following the application of bio-solids to arable cropping, rainfall and soil temperature must be considered.

4.3.5.1 Climate.

The 1997/98 growing season was considerably wetter than previous years, with over 450 mm of rain falling between the 8th December 1997 and 8th August 1998 (Fig. 4.14.). A further 50 mm of rainfall was added through irrigation during dry spells (Table 4.4). A complete analysis of precipitation during the sampling period is presented in Appendix 3.3.

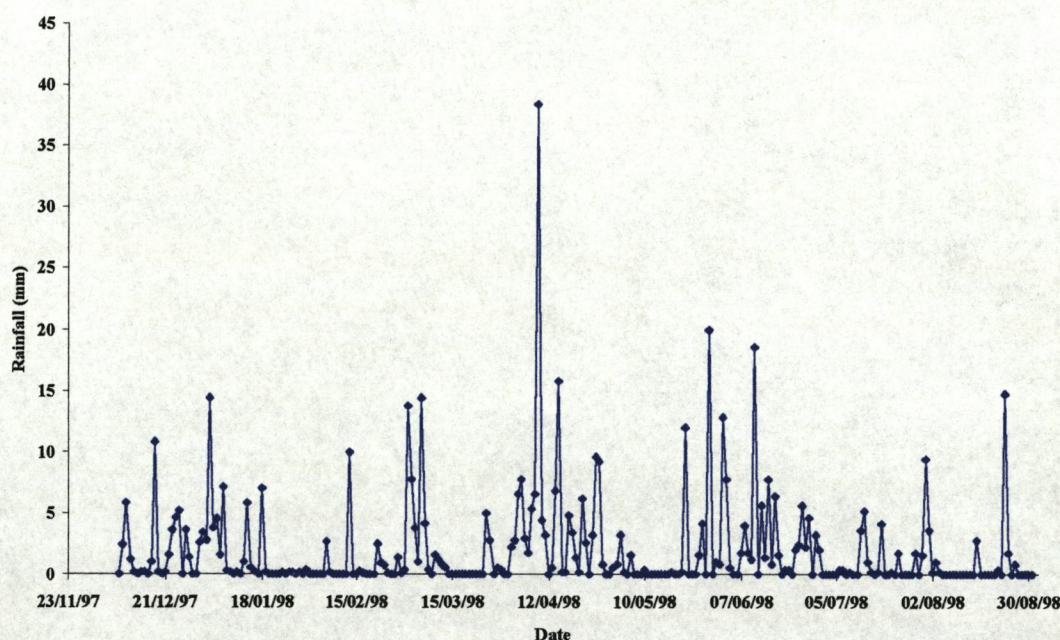


Fig. 4.14. Precipitation over trial plots including irrigation between 08/12/97 and 30/08/98.

Soil temperature at the weather station and the field trial sites differed slightly although not significantly. The automatic weather station recorded lower soil temperatures than the in-situ thermocouples during the winter cold spell. However, as the temperature increased in the spring, the soil temperatures became comparable. Soil temperatures measured by the automatic weather station and those recorded on a weekly basis by the in situ thermo-couples are presented in Fig. 4.15.

Table 4.4.
Irrigation applications.

Date	Quantity (mm)
13 th February 1998	10
2 nd March 1998	10
22 nd May 1998	10
29 th May 1998	20

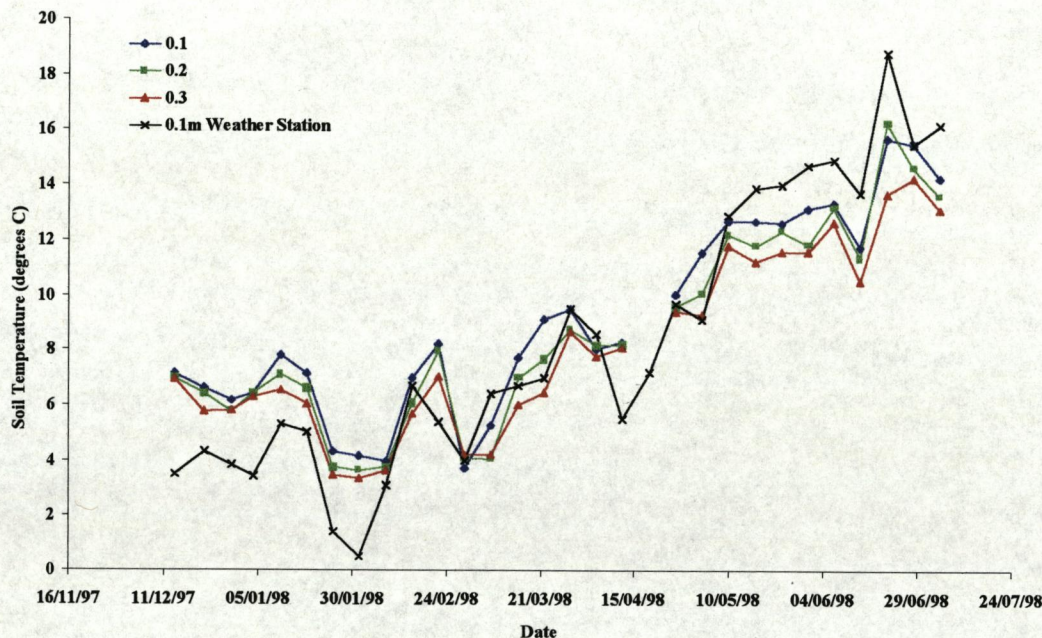


Fig. 4.15. Soil temperature measured in-situ on the control plots (December) and the soil temperature at 0.1 m measured at the Cranfield University Weather Station at Silsoe.

It is widely accepted that nitrification will not occur below approximately 5°C (Addiscott, 1983) and, on this basis; the thermal time can be calculated and expressed as day degrees. The calculation of thermal time is based on the mean daily temperature, as measured by the automatic weather station, as this allows a more accurate estimate of soil temperature to be made. Errors would be prevalent if the weekly, in situ data were used, as this measurement is based on a spot temperature at 3pm on the day of nitrate sampling.

4.3.5.2 Nitrate concentrations (December 1997).

Soil water nitrate concentrations were monitored for 28 weeks following the application of anaerobically digested sewage sludge, to an established crop of *Riband* winter wheat (*Fig. 4.16*).

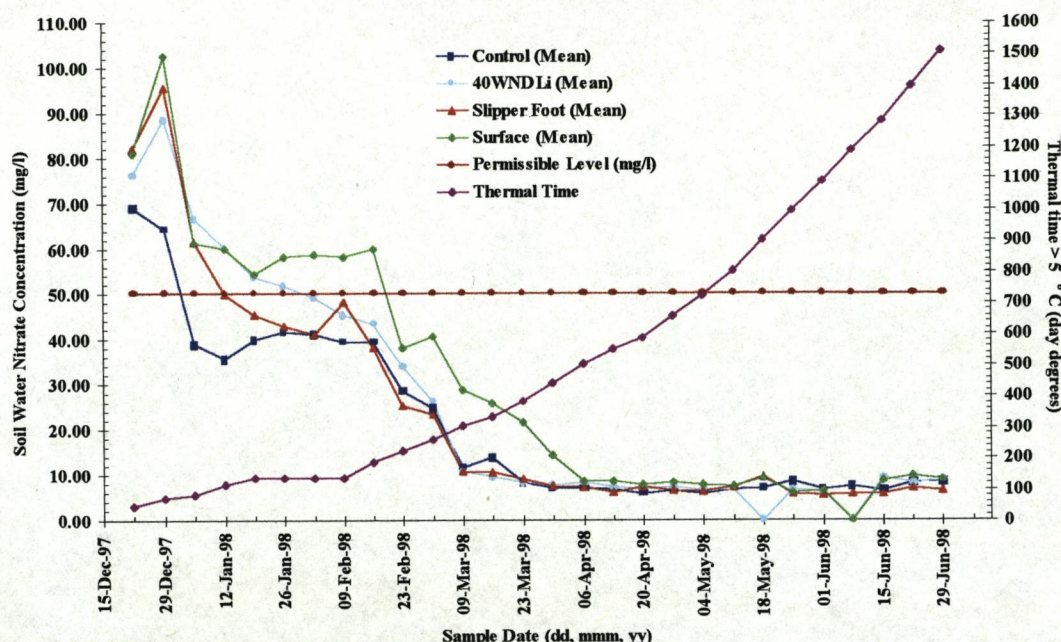


Fig. 4.16. Nitrate concentrations at 0.5 m, following an application of anaerobically digested sewage sludge in December to a freely draining sandy loam soil with no apparent water table, in relation to thermal time and the W.H.O. Permissible limit for drinking water.

Fig 4.16 illustrates the decline in nitrate concentration over the sampling period, compared with the increase in thermal time and the World Health Organisations guideline limit for the maximum permissible nitrate level, in potable water, of 50 mg/l (W.H.O., 1993). No significant differences were observed between treatments, with all methods of application, including the control, exhibiting high initial concentrations. It is thought that high temperatures and low rainfall in the three years preceding this trial contributed to the high initial nitrate concentrations. However, the control treatment does not show a peak at the same time as the applied plots, and concentrations dropped within acceptable limits shortly after monitoring commenced. A standard exponential decay curve was fitted to each treatment replicate and subsequently analysed for variance, which indicated no differences between treatments. Fitted constants for each treatment are presented in *Table 4.5*, with fitted standard curves being presented in *Appendix 3.4*. A full statistical analysis of the results from the nitrate trials is outlined in *Appendix 3.5*.

Table 4.5.

Fitted constants for fitted curves following the application of 50 m³/ha of anaerobically digested sewage sludge in December 1997.

Treatment	Fitted constant			Time to decay to 50mg/l (weeks)
	R	B	A	
Control	0.8903	72.95	0.77	3.384
40WNDLi	0.8865	101.81	-1.8	5.608
Slipper Foot	0.8634	103.16	0.96	5.063
Surface	0.9218	109.6	-10.9	7.216

All curves fitted the equation:

$$\text{Nitrate Concentration} = A + BR^{\text{Time}}$$

The time necessary for soil water nitrate concentrations to fall below the 50 mg/l limit was calculated from the derived curve fits. As expected, the control plot fell below the 50 mg/l threshold first, followed by the shallow injection plots and finally the surface applied plots.

Fig. 4.16 also illustrates a period of inactivity, in terms of nitrate concentrations, during a particularly cold spell. Soil temperatures between mid-January and mid-February fell below 5°C, resulting in a period of low nitrification. As the soil temperature increased into the spring, nitrate concentrations resumed their decline. The stabilisation of soil water nitrate concentrations at approximately 10 mg/l towards the end of the sampling period may be attributed, in part, to mineralisation of organic nitrogen. Bowden (1997), who found that all applied organic (unavailable) nitrogen would be converted to available form by mineralisation within 2500 day-degrees, confirmed this.

4.3.5.3 Nitrate concentrations (May 1998).

Nitrate concentrations, following an application of anaerobically digested sewage sludge in May 1998, showed that an application at this time did not significantly affect soil water nitrate concentrations, with all samples being well within the W.H.O. limits (*Fig. 4.17*).

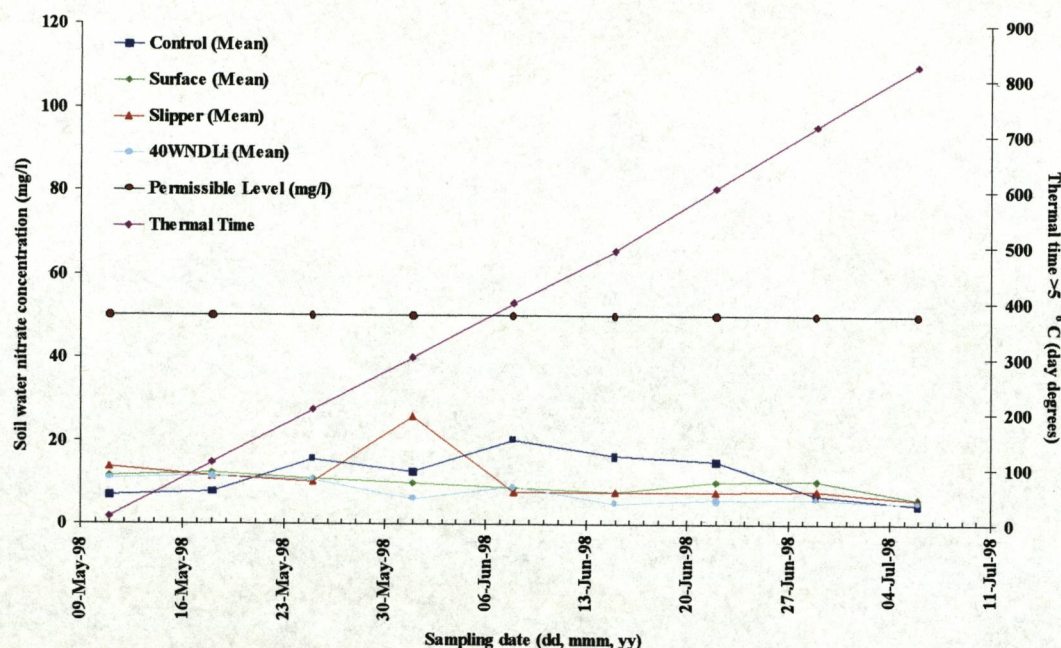


Fig. 4.17. Soil water nitrate concentrations at 0.5 m, following an application of anaerobically digested sewage sludge to an established crop of Riband winter wheat, on a freely draining sandy loam soil with no perceptible water table, in May 1998.

A significant difference between treatments was observed over the whole sampling period, following the May application. The control plot exhibited higher concentrations of nitrate than the plots treated with bio-solids. This may be explained by the quantities of nitrogen applied to the control plots during these trials. The sludge amended trial plots received 2.3 g/m^2 of Urea nitrogen in February 1998. This was followed by 7.63 g/m^2 of total nitrogen within the applied bio-solids, of which only 3.41 g/m^2 was in available form, the remainder of which is likely to become available over time. The control plots received 2.3 g/m^2 of Urea nitrogen in February 1998, followed by 5 g/m^2 of "Nitram" nitrogen, all of which is immediately available. No interactions were observed between treatments and time, indicating that all trial plots acted similarly.

4.3.5.4 Nitrate concentrations at 1 m (May 1998).

Porous ceramic cups were installed at 1 m depth across the plots designated for the May application of bio-solids. Unfortunately, insufficient moisture was available at this depth to allow appropriate samples to be extracted for analysis, supporting the decision to sample at 0.5 m on this soil type, in recognition of the freely draining nature of the trial plots and the apparent absence of a water table at a reasonable

depth. Historical climatic conditions may have been responsible for this situation, however no evidence is available to support this.

4.3.6 Total nitrogen analysis.

Throughout the experiment to assess nitrate concentrations in soil water following an application of bio-solids to arable cropping, soil and crop samples were extracted and analysed for total nitrogen content. Sampling was carried out at three times for the December plots; prior to the application of bio-solids, 12 weeks following application, and at harvest. Sampling for the May plots was undertaken twice; prior to application and at harvest.

4.3.6.1 Soil nitrogen content (December).

The analysis of total nitrogen within soil samples collected from the trial site, prior to bio-solid application, 12 weeks after application and at harvest, was achieved using the Kjeldahl method described in detail in *Appendix 3.6*. A complete statistical analysis of the results, presented in *Appendix 3.7*, shows that although on a mean basis, significance between treatments, time and depth was observed; all interactions were found to be insignificant on the December trial plots. The results are illustrated graphically in *Fig. 4.18*.

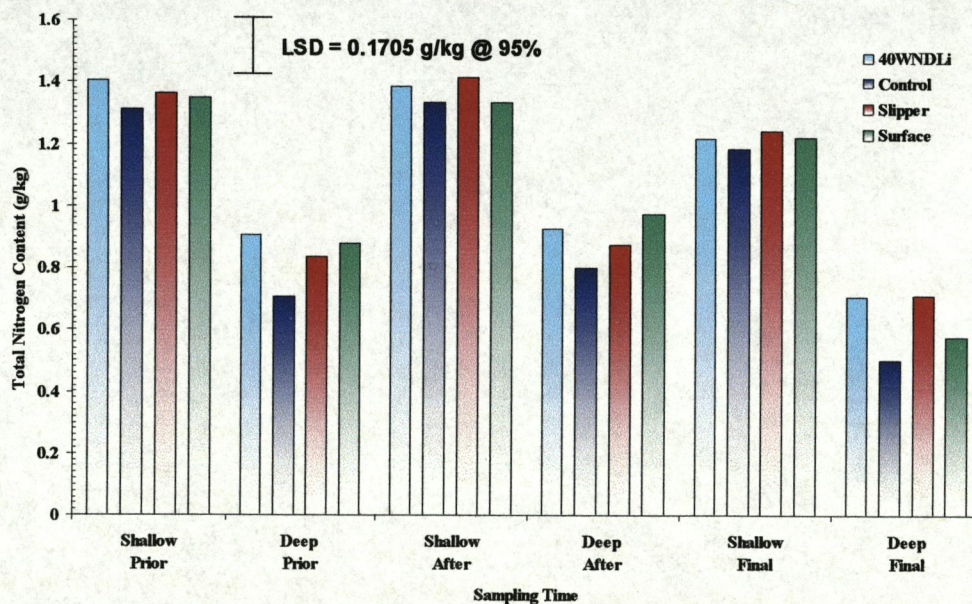


Fig. 4.18. Total soil nitrogen content at three sampling times (prior to, 12 weeks after application, and at harvest), following the application of anaerobically digested sewage sludge by three application methods and a control of no bio-solids application.

All treatments showed a decrease in soil nitrogen content with time and depth. However, all treatments reacted in a similar manner, suggesting that application method has no significant effect on the quantity of nitrogen retained and utilised in the soil.

4.3.6.2 Soil nitrogen content (May).

A statistical analysis of the results from the May applied plots, shows a significant difference on a mean basis of treatment, time and depth, but also shows significant interactions between treatment and time, and time and depth (*Appendix 3.7*). This is illustrated in *Fig 4.19*. Bio-solids amended plots show significant reductions in soil nitrogen content over time, whereas less reduction was observed in the control plots.

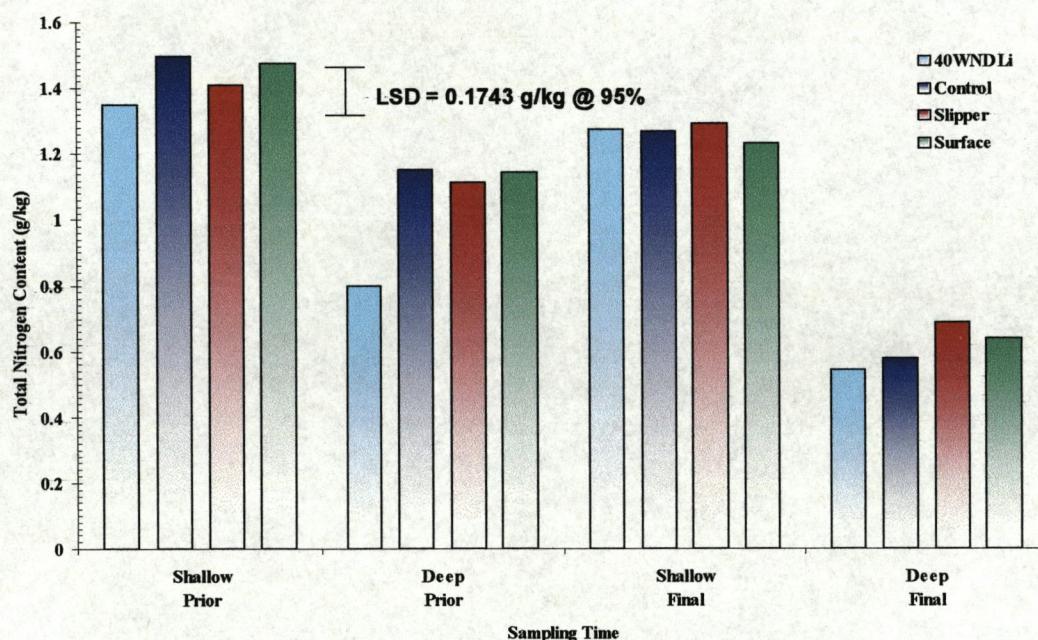


Fig. 4.19. Total soil nitrogen content at two sampling times (prior to application and at harvest) following the application of anaerobically digested sewage sludge by three application methods and a control of no bio-solids application

The reduction in soil nitrogen content of the treated plots suggests that the quantity of bio-solids supplied was insufficient to satisfy crop demand, whereas the granular application to the control plots, although still insufficient, did not result in significant depletion of residual soil nitrogen. The method of application does not affect the pattern of soil nitrogen use.

4.4 Summary.

The field trials described have established the effect of application method on odour concentrations, ammonia emissions, soil water nitrate concentrations and total soil nitrogen.

4.4.1 Injector tine forces & disturbance.

The soil force and disturbance characteristics of the injectors involved in these field trials have been discussed in previous chapters. However, in summary, the 40WNDLi injector tine produces a more uniform soil disturbance pattern, without a tendency for the production of a central channel, whereas the slipper foot tine relies on the creation of a channel for the acceptance of sewage sludge, which encourages bio-solid placement, rather than incorporation.

4.4.2 Odour concentrations.

Odour concentrations, following an application of anaerobically digested sewage sludge in December 1996, showed no significant differences between application methods and highlighted the weakness of sewage sludge as a source for odour studies. An analysis of results, from an application of pig slurry in May 1997, highlighted the differences between application methods, on odour concentrations, as a result of its strength. The use of the 40WNDLi injector can significantly reduce odour emissions (@ 85% level). However, the variability experienced during both trials, suggests that it is uneconomical to pursue significance at any higher level.

4.4.3 Ammonia volatilisation losses.

One of the greatest benefits of the 40WNDLi injector is highlighted by the reduction in ammonia emissions as a result of volatilisation. Significant reductions were observed when using shallow injection in comparison to surface application, and a significant trend towards further emission reductions was observed using a parallel curve analysis. This concurs with Phillips *et al* (1990) who suggest that ammonia emissions could be reduced by shallow injection techniques.

4.4.4 Nitrate concentrations.

Considering the reduced volatilisation losses experienced by shallow injection and the trend towards further reductions using the 40WNDLi injector, it may be expected that

increased levels of nitrate leaching could occur, due to the increased nitrogen retention, promoted by better bio-solids incorporation. However, following an application of 50 m³/ha of anaerobically digested sewage sludge in December, peak nitrate concentrations were 88.53, 95.57 and 102.43 mg/l for the 40WNDLi, slipper foot and surface applications respectively. It is possible that the efficient incorporation of bio-solids in the immediate root zone of the growing crop, may promote more rapid crop uptake than placement in a channel or on the surface. The lack of a significant increase in nitrate concentrations, following the May application of bio-solids, suggests that effective application throughout the growing season could reduce the environmental impact of the bio-solids recycling operation. In summary, the method of application does not significantly affect soil water nitrate concentrations under the field conditions specified, although there is a trend towards a more rapid decline in concentrations following application by shallow injection techniques, than by surface application. The reduced nitrate concentrations following the application of bio-solids using shallow injection, correlates well with Collins (1996) who experienced similar results.

4.4.5 Soil nitrogen content.

Method of application does not affect the quantity of total soil nitrogen significantly. Less nitrogen is prevalent at depth, and results suggest that the application of 50 m³/ha of sewage sludge, containing between 76.3 (May) and 78.3 (December) kg/ha, is insufficient to satisfy the demands of a crop of winter wheat.

4.5 Conclusions.

The following conclusions may be drawn from these field trials:

- The 40WNDLi injector tine was found to encourage greater soil/bio-solid mixing, compared to the slipper foot injector tine.
- Odour concentrations from an application of anaerobically digested sewage sludge in November were found to be similar to typical background concentrations (50 to 150 ou/m³) indicating negligible odour nuisance.
- The 40WNDLi injector tine reduced odour emissions significantly, at the 85% level, following application of pig slurry in May, compared to surface application and slipper foot injection methods.

- There is a significant reduction in ammonia emissions using shallow injection methods, rather than surface application, with a significant trend towards greater reductions through the adoption of the 40WNDLi injector system.
- The variability, between treatments when comparing methods of shallow injection is such that an uneconomical number of replications would be required, to obtain a high level of significance.
- Application method has no significant effect on soil water nitrate concentrations under the field conditions specified. However, lower peak nitrate concentrations were observed, using the 40WNDLi injector, compared with surface application and slipper foot injection methods.
- Shallow injection reduced the time taken for soil water nitrate concentrations to fall below acceptable limits, prescribed by the World Health Organisation.
- Method of application does not influence the balance of total nitrogen in the soil profile up to 0.5 m depth.

Chapter 5

5.0 Agronomic assessment of shallow injection.

5.1 Introduction.

The 40WNDLi injector tine has been designed and developed for the purpose of applying bio-solids to arable cropping. It has been shown to be beneficial in reducing both odour concentrations and ammonia emissions, without any significant effect on soil water nitrate concentrations. However, little is known about the effect that bio-solids incorporation may have on the agronomic performance of the crop. Previous studies have considered the effect of injection on grass yields, suggesting that reducing spillage onto the crop increases yield (Warner *et al*, 1991). However, the shallow injection of bio-solids into arable cropping is a new concept that has not been investigated adequately to-date. The results of a pilot study (McGrath, 1995) suggested that bio-solids application to arable cropping would have no significant effect on crop performance. However, the results of this study were found to be tentative due to lack of replication and poor crop establishment.

The aim of this section is to consider the effect of injector tine on the performance of a crop, which has been subjected to bio-solids application during its period of establishment. Two main areas of work will be reported which cover:

- i. the agronomic trials, associated with the main project (Pullen *et al*, 1997), which approached the subject of bio-solids incorporation, to arable cropping, on a fast track basis, and
- ii. the agronomic trials associated with this doctoral study.

5.2 Agronomic trials (Main project).

Source: Pullen *et al*, 1997.

Two independent field trials were established, to consider the effect of injector, soil and crop type on crop performance. The application of bio-solids was achieved using the system described in Section 4.2.3. Application rates were set at 50 m³/ha for all trials.

5.2.1 Agronomic trials 1995/96.

This study comprised of two trial sites, located on the Cranfield University Farm at Silsoe. The experiment was carried out on a clay soil, sown with winter wheat and a sandy loam soil, sown with oilseed rape.

5.2.1.1 Experimental design.

A randomised block system, comprising of four treatments and six application times throughout the growing season on each trial site was used. In addition to the effect of application method and time on crop performance, a parallel experiment to assess the effect of the umbilical hose on crop damage was undertaken. The experimental treatments, bio-solids, application times and soil types, on each trial site, are presented in *Table 5.1*.

Table 5.1.

Experimental data for the main agronomic trials in the 1995/96 growing season.

	Treatment		Bio-solids properties		
	Time	% Solids	Total N % (DW)	Available N % (DW)	Total N kg/ha (@ 50m ³ /ha)
Wheat Trials	09/11/95	2.01	6.7	2.42	67.34
	28/11/95	2.32	6.38	2.36	74.01
	12/12/95	3.88	5.26	1.81	102.04
	28/02/96	4.16	5.57	1.75	115.86
	29/04/96	3.56	6.69	2.1	119.08
	03/06/96	3.14	6.68	2.5	109.59
	04/07/96	2.32	6.78	2.8	78.65
Rape Trials	09/11/95	2.01	6.7	2.42	67.34
	28/11/95	2.32	6.38	2.36	74.01
	12/12/95	3.88	5.26	1.81	102.04
	14/02/96	3.14	6.42	2.34	100.79
	12/03/96	4.13	5.29	1.74	109.24
	18/04/96	2.84	7.11	2.6	100.96
	10/05/96	2.85	6.7	2.7	95.48

Treatments	Soil Type		
	Fraction	Wheat	Rape
Greenrac Shallow (NSH)	Coarse sand	2.22%	21.48%
Greenrac Slipper Foot	Sand	6.93%	42.69%
Simulated Dribble Bar	Fine sand	4.56%	10.32%
Control (No Granular Fertiliser)	Silt	36.05%	12.86%
Control (190 kg/ha of Granular Nitrogen)	Clay	50.25%	12.65%
Control (155 kg/ha of Granular Nitrogen)	Classification	Clay	Sandy Loam

All experimental plots associated with these trials were harvested using a specially adapted Deutz Fahr M660 plot combine harvester. This machine utilised a self-cleaning and bagging system to allow individual plot yield to be calculated. Side knives were attached to the side of the cutting table, to allow efficient harvesting of the oil seed rape.

5.2.1.2 Umbilical hose experiments.

The experiment to assess the effect of the umbilical hose supply system, associated with these agronomic trials, was carried out on both trial sites, and was implemented by dragging a 10.5 m length of 0.1 m diameter hose filled with water, across a trial plot. The plots assigned for these trials were treated with bio-solids by the different application techniques presented in *Table 5.1*, prior to the passage of the umbilical

hose across the plot. Subsequent yield analysis was carried out at harvest time, by hand cutting 0.25 m² quadrats from the trial plots and hand threshing.

5.2.1.3 Results and conclusions.

The results of this mainstream field trial can be considered in two general sections:

Wheat and Rape trials:

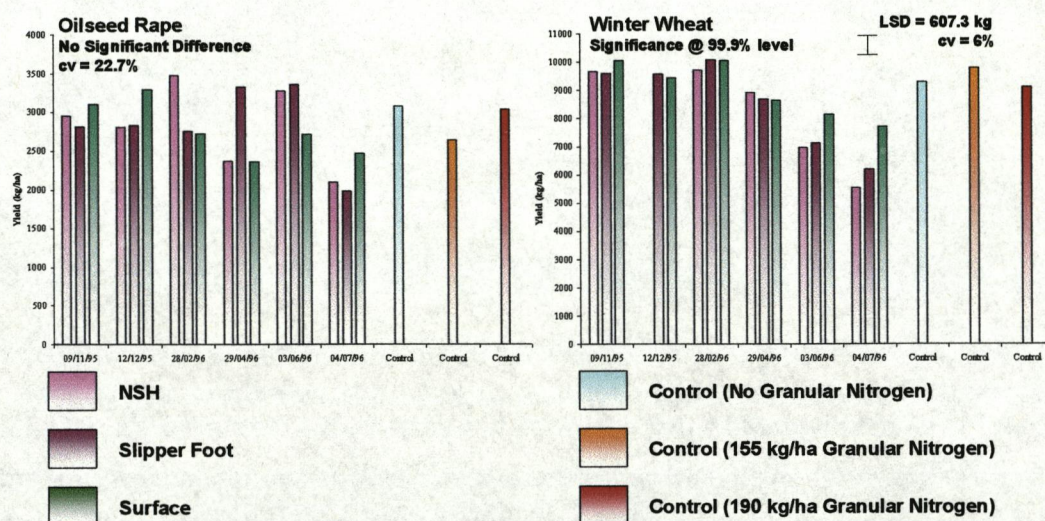


Fig. 5.1. The effect of applicator type and application timing on crop yield.
(1995/96 Trials)

Pullen *et al* (1997) reported a significant effect of applicator type and application timing on crop yield for the wheat trials, but no significant effect on the oil seed rape plots (Fig. 5.1). Both trials exhibited the detrimental effect of a late application on crop yield. This was thought to be due to crop damage, as a result of the low height of the implement toolbar being pulled through a tall crop. Surface applications of bio-solids using a dribble bar technique, similar to that described in Section 4.2.3, resulted in a lower degree of yield loss after late applications, reinforcing the need for greater implement ground clearance. This effect was particularly noticeable across the oil seed rape trial plots (Fig. 5.2).



Fig. 5.2. Crop damage caused by late bio-solids application to oilseed rape.

These trials illustrate the resilience of arable crops to mechanical manipulation throughout the growing season and suggest that; bio-solids application using existing shallow injection methods could be achieved over a wider range of growth stages than is practised at present, without significant damage. Problems were reported during these field trials in terms of injector blockages under wet conditions, and high odour was apparent after late applications in warm climatic conditions.

Umbilical hose experiment:

The results of the umbilical hose trials across both trial plots, indicate that the supply system is unlikely to have a significant affect on crop yield except when applications are made late into the season (*Fig. 5.3*).

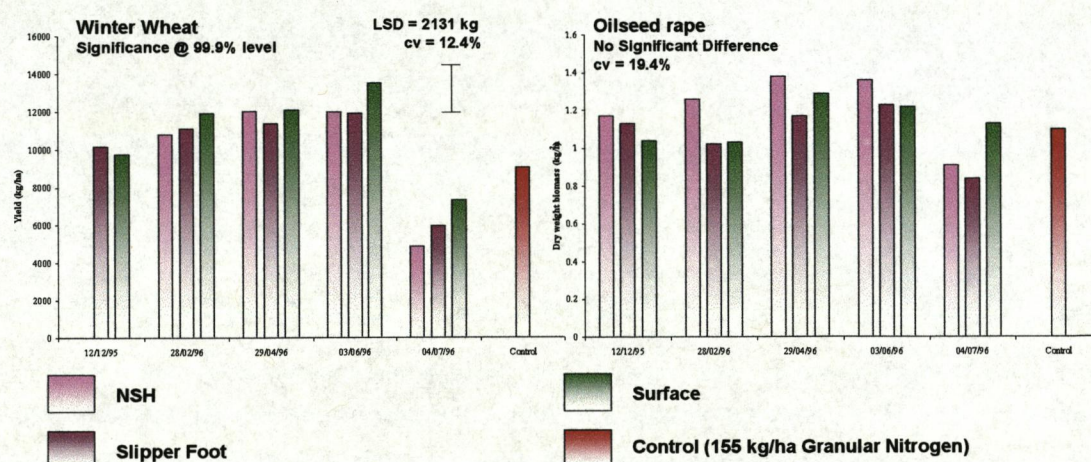


Fig. 5.3. The effect of the umbilical hose on crop yields following applications using conventional methods throughout the 1995/96 growing season.

5.2.2 Agronomic trials 1996/97.

Agronomic trials were established in the 1996/97 growing season, as part of the main project, to assess the effect of the 40WNDLi injector on crop performance. Two trial sites were chosen for this investigation, comprising a clay soil and a sandy loam soil, with winter wheat being established on both sites. Although treatments differed, the experimental design of this trial was similar to that described earlier. The experimental treatments, bio-solids, application times and soil types on each trial site are presented in *Table 5.2*.

Table 5.2

Experimental data concerning the main agronomic trials in the 1996/97 growing season.

Treatment		Bio-solids properties			
Time	% Solids	Total N % (DW)	Available N % (DW)	Total N kg/ha (@ 50m ² /ha)	
12/12/96	3.65	5.93	1.61	108.22	
04/02/97	4.37	5.45	1.45	119.08	
27/03/97	3.51	4.96	2.25	87.05	
07/05/97	3.42	5.32	2.13	90.97	
Treatments		Soil Type			
		Fraction	Home Close Site	Showground Site	
40WNDLi		Coarse sand	2.26%	9.04%	
Slipper		Sand	9.97%	37.62%	
Control (No Fertiliser)		Fine sand	5.63%	17.03%	
Control (215 kg/ha)		Silt	30.94%	22.10%	
		Clay	51.19%	14.21%	
		Classification	Clay	Sandy Loam	

All plots were harvested in the same manner as the previous year's trials. Three applications were made throughout the growing season, with the slipper foot injector tine, (Dec 96, Mar 97 and May 97), and at all four application times, stated in *Table 5.2*, for the 40WNDLi tine. Bio-solids amended plots received supplementary granular fertiliser at a reduced rate. An additional treatment, comprising two applications (Feb and Mar 97), was applied using the 40WNDLi injector to assess the effect of multiple applications on crop performance.

5.2.2.1 Results.

The results of these field trials suggest that bio-solids application during the spring period will not affect the yield of winter wheat on heavy soils, and that application is feasible on lighter soil types all year round (*Fig. 5.4*).

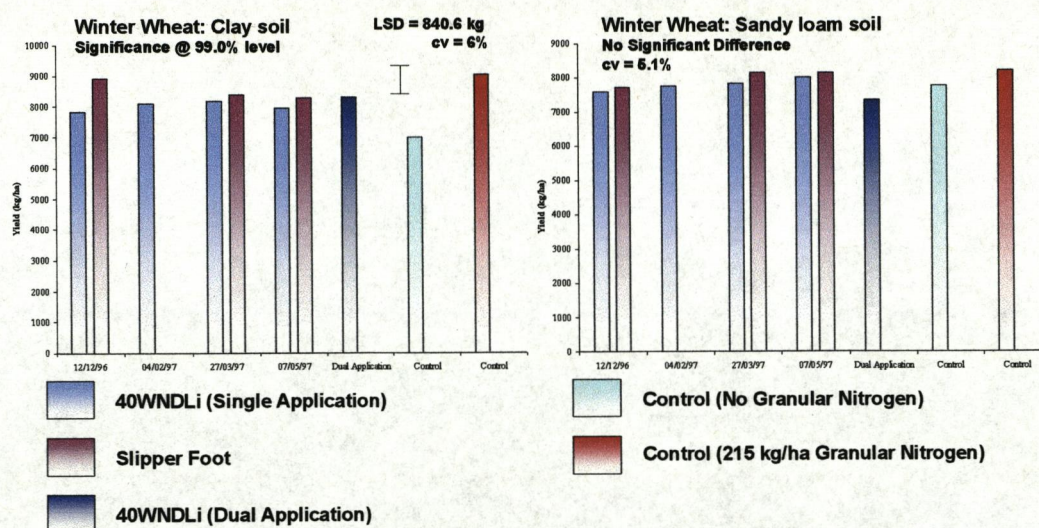


Fig. 5.4. The effect of applicator type and application timing on crop yield
(1996/97 Trials)

The yield suppression experienced on the heavier soil type was thought to be due to tine interaction under moist conditions. Some blocking between injectors was observed. Consequently, the injector tine configuration was amended as described in Section 4.2.1. Injecting twice during the growing season had no significant effect on crop yield, suggesting that bio-solids application to cropping could be used as an alternative to split applications of granular nitrogen. Lower quantities of available nitrogen were observed in the winter bio-solids samples, resulting in reduced yields following injection. However, results suggest that the supplementary application of bio-solids, in conjunction with a granular fertiliser regime, may not reduce yields.

5.2.3 Conclusions.

Pullen *et al* (1997) concluded that:

- 1) Crop yields were only affected by bio-solids application late in the growing season.
- 2) Much of the crop damage, causing yield reduction, originated from tractor wheelings.
- 3) Crop damage resulting from the injection process, could be reduced by increasing equipment ground clearance.
- 4) Existing shallow injector tines left the bio-solids in channels, resulting in odour problems in warm conditions.
- 5) The effect of the umbilical hose supply system on crop yield is insignificant, except when used at advanced growth stages.

- 6) Injector tine interaction on heavy soils may reduce yields.
- 7) Dual applications using the 40WNDLi injector, did not adversely affect crop performance.

5.3 Agronomic trials (Doctoral study).

The agronomic trials, carried out by Pullen *et al* (1997) and described above, combined with the results of the environmental assessment, presented in *Chapter 4*, indicate that, the environmental benefits achieved using the 40WNDLi injector were not obtained at the expense of crop performance. However, the limited nature of the data presented above suggested that further agronomic evidence was required to reinforce early results. Following the success of the field trials to assess the effect of injection method on soil water nitrate concentrations (*Section 4.3.5*), the field trial site was monitored to assess agronomic performance.

5.3.1 Experimental design.

The experimental plots used for assessing the concentrations of nitrate in soil water, following the application of 50 m³/ha of bio-solids in December 1997 and May 1998, were used for this study. The randomised block design, bio-solids properties, treatments and crop management for this experiment are described in *Chapter 4*.

5.3.2 Methodology.

In addition to allowing the natural growth of the crop for harvest analysis, a number of additional samples were extracted, to allow links between nitrogen input and crop uptake to be addressed. A full account of measurements taken is provided in the following sections.

5.3.2.1 Crop nitrogen measurement.

Crop nitrogen measurement was achieved by the extraction of crop samples (leaves and roots) from each trial plot. These samples were analysed for total nitrogen content, in the laboratory, using the Kjeldahl method, described in *Appendix 3.6*, after drying at 40°C for 4 days and subsequent grinding to allow passage through a 1 mm sieve. In addition to sampling crop nitrogen, shoot counts were conducted, and individual plants across each trial plot were extracted and dried. The results obtained enabled calculations of crop nitrogen content to be made on an area basis. The

sampling times are inconsistent between the two application times, and are detailed in Table 5.3.

Table 5.3.
Crop nitrogen sampling

Application time	Sampling time	N Addition (injected plots)	N Addition (control plots)
December	February (12 weeks after bio-solids application)	Total : 78 kg/ha Available : 29.07 kg/ha	None
	Harvest (August)	Total : 78 kg/ha Available : 29.07 kg/ha	23 kg/ha on 20/02/98 (Urea) 49 kg/ha on 20/05/98 (Nitram)
	April (2 weeks prior to bio-solids application)	23 kg/ha on 20/05/98 (Urea)	23 kg/ha on 20/02/98 (Urea)
	Harvest (August)	Total : 78 kg/ha Available : 29.07 kg/ha	23 kg/ha on 20/02/98 (Urea) 49 kg/ha on 20/05/98 (Nitram)
May			

December applied plots were not sampled for crop nitrogen prior to application of bio-solids. However, all plots were sampled prior to the control application of Urea nitrogen in February. The May trial plots were sampled after Urea application in February, but prior to the application of bio-solids in May. Plant counts and individual plant samples were extracted at each sample time.

5.3.2.2 Harvesting method.

Harvesting of all plots was carried out by hand between 11th and 14th August 1998. All trial plots were harvested by cutting the crop, as close to the ground as was practical, in 0.25 m² quadrats. Shoots were counted during the cutting process and stored in sealed bags prior to analysis. A total of 11 quadrats were extracted at random from each trial plot, with care being taken to avoid areas that had suffered from tractor wheelings. Following the cutting of all trial plots, laboratory processing was undertaken enabling the measurement of crop performance parameters detailed below:

- Grain yield (kg/ha)
- Grain moisture content (%)
- Total dry biomass (kg/ha)
- 1000 grain weight (kg)
- Hagberg falling number (dimensionless)

5.3.2.3 Post processing.

11 quadrats, per trial plot, were harvested and processed as follows:

- 3 replicates for yield,
- 3 replicates for biomass,

- 3 replicates for nitrogen content,
- 2 spares.

5.3.2.4 Agronomic measurements.

Yield.

- Each sample was threshed by hand. The grain collected was processed, using a Westrup Type LA-LS laboratory cleaning and grading system, (Kamas Machinery Ltd, Wetherby). The resulting crop samples were weighed and subsequently used for determination of moisture content, 1000-grain weight and Hagberg Falling Number. All results were corrected for 14% moisture content.

Biomass.

- Each sample was placed in a hessian sack and oven dried at 105°C for 18 hours, after which, each sample was weighed. No further analysis was carried out on these samples.

Moisture Content.

- A sub-sample, from the yield replicates, was dried in an oven at 130°C for 2 hrs in accordance with BS 4317: Part 3: 1987 (BSI, 1987).

Correction was made using the formula:

Corrected weight = original weight – weight loss

$$\text{weight loss} = \text{original weight} \times \left(\frac{\text{original moisture content} - \text{final moisture content}}{100 - \text{final moisture content}} \right)$$

1000 grain weight.

- Yielded grains were counted using an automatic grain counter (Numigral). 500 grains were counted and weighed, multiplied by two and corrected for 14% moisture content. Methodology and equipment, described in *Appendix 4.1*, conformed to BS 4317: Part 1: 1980 (BSI, 1980).

Hagberg Falling Number.

- Hagberg Falling Number measures the activity of alpha amylase, which indicates the extent to which the viscosity of a flour and water paste is reduced by amylolytic hydrolysis of the starch. Generally, millers prefer to avoid parcels of wheat with excessive alpha amylase activity (Kent, 1978). Sub-samples were taken from yield grain replicates and tested, according to the procedure described in *Appendix 4.2*, in accordance with BS 4317: Part 9: 1982 (BSI, 1982).

5.3.3 Results and discussion.

The results obtained from the measurements outlined above, were analysed statistically, based on the time of bio-solids application. A complete statistical analysis is presented in *Appendix 4.3*.

5.3.3.1 Crop nitrogen following an application of bio-solids in December.

The December trial plots received anaerobically digested sewage sludge, as presented in *Table 4.2*, which constituted a total nitrogen application of 78 kg/ha, of which 29.07 kg/ha was considered readily available. The mean crop nitrogen content, following crop sampling prior to the initial granular fertiliser application to the control plots, but after the application of bio-solids, and at harvest, is presented in *Fig. 5.5*.

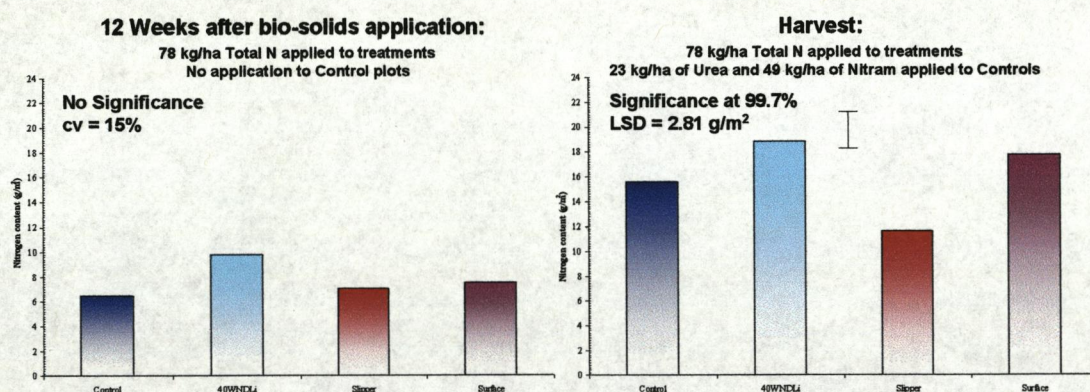


Fig. 5.5. Crop nitrogen content (g/m^2) at two sample times following an application of bio-solids in December 1997 by three application methods and a control.

A significant increase in crop nitrogen content at harvest was observed, following the application of bio-solids using the 40WNDLi injector tine. Significantly lower crop nitrogen contents were observed, for trial plots injected using the slipper foot injector, despite having similar numbers of plants over the trial area. This is thought to be a result of compaction around the tine during the injection process, which promotes deposition of bio-solids in channels, rather than incorporation. No significant effect, of application method was observed 12 weeks after application, although there was an indication that the 40WNDLi injector had utilised a greater amount of nitrogen at this time compared with the other application methods.

5.3.3.2 Crop nitrogen following an application of bio-solids in May.

Prior to the application of bio-solids in May 1998, the established crop of winter wheat received an application of Urea equivalent to 23 kg/ha of available nitrogen. The bio-solids used in the May application (anaerobically digested sewage sludge), constituted an addition of 76.28 kg/ha of total nitrogen, of which, 34.07 kg/ha was readily available. Combined with the Urea application to the trial site in February 1998, the total nitrogen applied to the plots treated with bio-solids was 99.28 kg/ha. The crop nitrogen content prior to bio-solids amendment in May and at harvest is presented in *Fig. 5.6*.

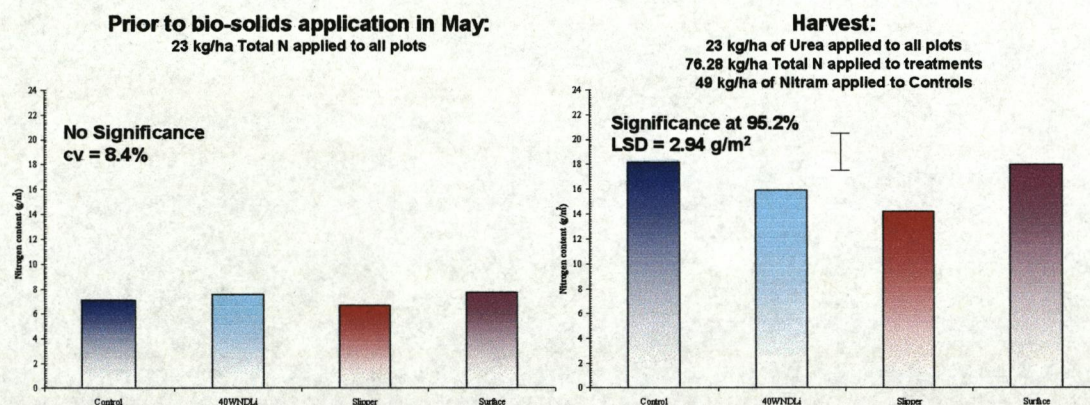


Fig. 5.6. Crop nitrogen content (g/m²), at two sample times, following an application of bio-solids in May 1998, by three application methods and a control.

The results of this study suggest that a later application of bio-solids using existing commercial shallow injection equipment may not be beneficial to the crop. Injection with the slipper foot system resulted in significantly less crop nitrogen at harvest, compared to the control, 40WNDLi and surface applied plots. However, results relating to surface application should be treated with caution, as significantly more plants were counted on these plots.

5.3.3.3 Moisture content (%).

A significant difference in moisture content was observed across the December applied plots. This is thought to be due to weather conditions during harvesting. This finding, illustrated in *Fig. 5.7*, emphasised the need for other performance data to be corrected for variations in this parameter.

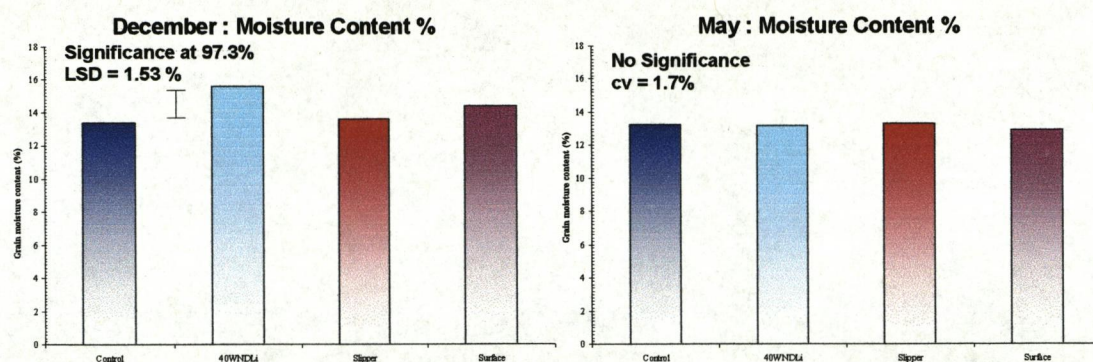


Fig. 5.7. Crop grain moisture content (%), after harvest following the application of anaerobically digested sewage sludge, in December 1997 and May 1998.

The plots established for the May application of bio-solids were harvested under consistently dry conditions, resulting in no significance between treatments.

5.3.3.4 Yield (corrected for 14% moisture content).

The crop grain yields, corrected to 14% moisture content to account for variation described above, are presented in Fig. 5.8.

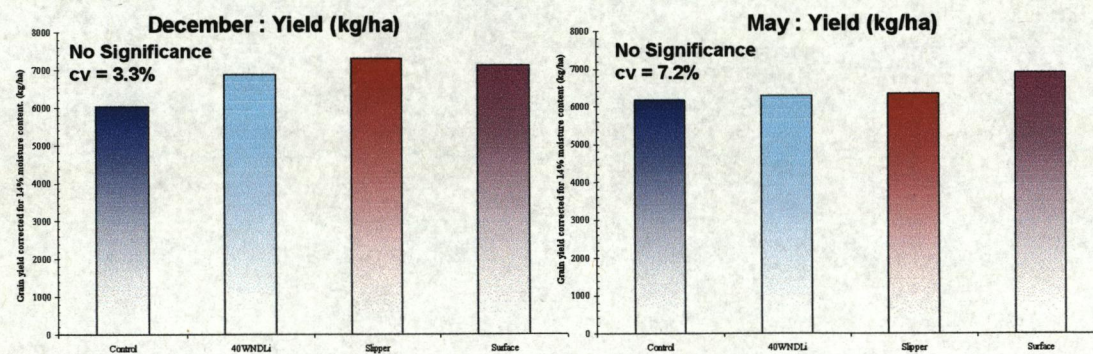


Fig. 5.8. Grain yield after harvest following the application of anaerobically digested sewage sludge in December 1997 and May 1998.

Results indicate that application technique has no significant effect on crop yield performance, although visually there was a slight increase in yield from plots that received bio-solids in December, compared with the control. This effect was absent across the May 1998 field trials. These results reinforce those of Pullen *et al* (1997), who also found no significant difference between application methods, when bio-solids were applied to a crop of winter wheat on a sandy loam soil. Results associated with the surface application during the May 1998 trials should be treated with caution, as a significantly higher number of plants were counted across these experimental plots.

5.3.3.5 1000 Grain Weight.

The measurement of the weight of 1000 yielded grains is independent of the yield, and is a good measure of grain quality. The results, presented in *Fig. 5.9*, corrected for 14% moisture content, illustrate no significant difference between treatments, although there is a visual trend towards increased weight following shallow injection of bio-solids compared to surface application and the control plots after a December application of bio-solids. Grain from trial plots that received bio-solids in May also tended towards increased 1000-grain weight compared to the control.

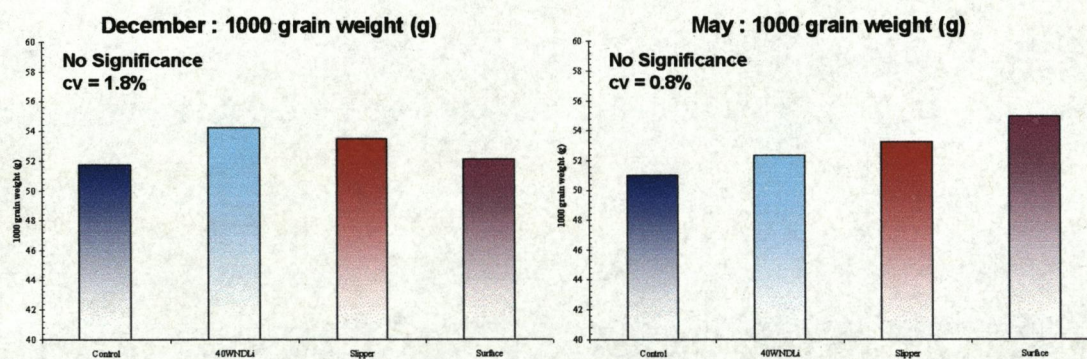


Fig. 5.9. 1000 grain weight after harvest following the application of anaerobically digested sewage sludge in December 1997 and May 1998.

5.3.3.6 Hagberg falling number.

The milling quality of wheat can significantly affect the financial return of the crop. Ideally, a falling number between 200 and 300 indicates the suitability of the crop for bread making. Less than 200 FN indicates high amylase activity and suggests that the breadcrumb is likely to be sticky. Conversely, falling numbers greater than 300 indicate very low amylase activity and suggests that the breadcrumb may be too dry. The financial reward obtainable from high quality milling wheat varies between regions and with the time of year. However, Nix (1998) suggests that milling wheat should return 10% more than feed wheat. The results from these field trials, presented in *Fig. 5.10*, clearly indicate that high quality wheat was produced. However, application method had no effect on this parameter. The application of nitrogen in the form of bio-solids compared to granular nitrogen exerted no influence on grain quality.

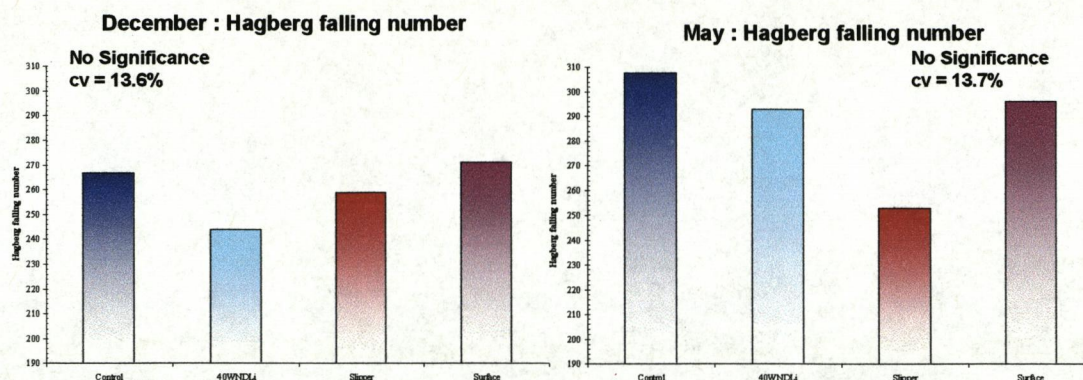


Fig. 5.10. Hagberg falling number after harvest following the application of anaerobically digested sewage sludge in December 1997 and May 1998.

5.3.3.7 Total dry biomass.

The results illustrating the total dry biomass yield presented in *Fig. 5.11*, provide an indication of the crop volume.

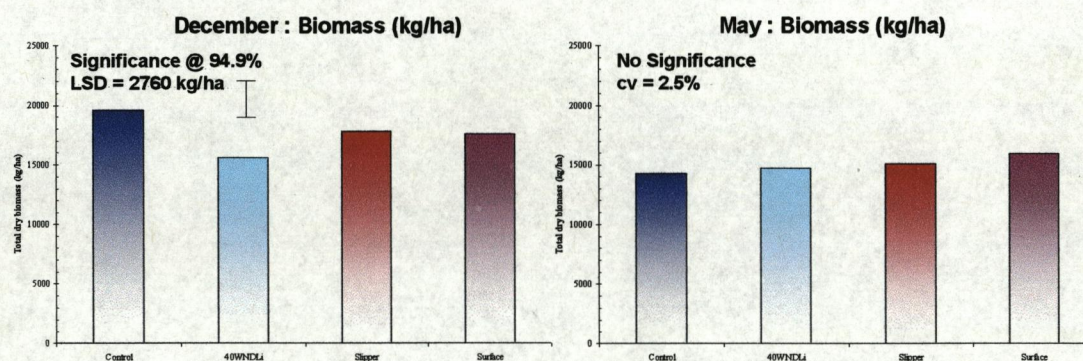


Fig. 5.11. Total dry biomass after harvest following the application of anaerobically digested sewage sludge in December 1997 and May 1998.

A slight significance was observed between the control and 40WNDLi applications after the December 1997 trials. However, the lower total crop biomass was found to be independent of crop grain yield.

5.4 Summary.

The agronomic trials, carried out to investigate the effect of bio-solids application to arable cropping on crop performance, have shown that this method of bio-solids recycling is agronomically feasible. Bio-solids application using this technology was found to be detrimental to crop performance only when applications were made late in the crop-growing season. Field trials conducted as part of the main fast-track project, suggest that a complete shallow injection system, including supply from an umbilical hose, could be used for application into both winter wheat and oilseed rape until 3

months prior to harvest, without any detrimental effect on crop yield. Additionally, it was suggested that the period available for safe application of bio-solids could be extended, by increasing the ground clearance of the injection equipment, hence reducing crop implement interaction and subsequent damage and yield loss.

Detailed field trials agreed with the results of Pullen *et al* (1997). When considering the crop performance issues discussed above, at no time was any significance observed between application techniques. This study also concurs with McGrath (1995), who carried out a preliminary investigation into the feasibility of bio-solids application to arable cropping.

Crop nitrogen measurements throughout the field trials, indicated that the 40WNDLi injector tine made better use of available nitrogen after applications of bio-solids in December 1997 (*Fig.5.5*), compared with the slipper foot injector. This may have been due to the increased availability of nitrogen as a result of lower ammonia emissions, associated with the use of the 40WNDLi injection system. An alternative theory concerns the compaction caused locally around the slipper foot injector during channel formation, reducing the ease with which bio-solids infiltrate into the soil.

The evidence generated throughout the agronomic field trials supports the environmental and agronomic viability of bio-solids injection into established arable cropping and, in addition, some significant agronomic benefits through the use of the 40WNDLi injector over existing shallow injection techniques may be possible.

5.5 Conclusions.

The following conclusions can be drawn from this study:

1. Shallow injection of bio-solids into arable cropping is possible, up to 3 months prior to harvest, with no detrimental effect on crop production.
2. Winter applications of bio-solids using the 40WNDLi injection system may promote early crop development through increased available nitrogen utilisation, as a result of reduced ammonia emissions.
3. The use of bio-solids as a fertiliser for arable crops, showed a trend towards increased 1000 grain weight

4. The umbilical system supplying current shallow injection systems does not affect crop performance, except when used during the later stages of crop development.

Chapter 6

6.0 Economic evaluation of shallow injection into arable cropping.

6.1 Introduction.

The 40WNDLi shallow injector tine, described in previous chapters, has been shown to have acceptable performance characteristics, in terms of environmental benefits, with no adverse effects on the agronomic performance of the crop. This supports the concept of the shallow injection of bio-solids into arable cropping as a viable alternative to current disposal/recycling techniques. However, economic viability throughout the design, development and implementation of the system is of paramount importance, if widespread adoption is to be achieved.

Recent advances in the treatment of bio-solids have resulted in the production of solid granular products, suitable for land application. This has allowed innovators to apply a charge for these enhanced products (Evans 1998), hence reducing the cost to the water utility for bio-solids recycling. This change of emphasis suggests that the development of a value-added product may create a demand that could reduce the costs associated with the disposal of bio-solids.

Additionally, the development of improved systems, which reduce environmental impact and enhance product value by utilising waste more efficiently, increases the degree of positive, public perception, hence adding hidden value to the product.

The aims of this chapter are to address the issues of bio-solids management in terms of the theoretical value of the product to the stakeholders, the economic gains possible by the implementation of an enhanced product in the market, and the user's perception of the application of bio-solids to agricultural land. Although such a study will not allow a definitive strategy for pricing to be developed, it will provide a guideline for future marketing purposes.

6.2 Stakeholders.

It is accepted that many people who hold an influence over a company, or the events that affect that company, will belong to a stakeholder group (Johnson and Scholes, 1993). A stakeholder group is one that contains people who have similar interests in a

particular company and may be either internal, or external to the corporate group. Stakeholder analysis is particularly important to a company developing a new strategy, such as a shift in emphasis from bio-solids disposal to recycling.

6.2.1 Stakeholder identification.

The stakeholders associated with the recycling or disposal of bio-solids, have been identified and comprise five main groups. These groups are large and represent both financial and environmental interests (*Fig. 6.1*).

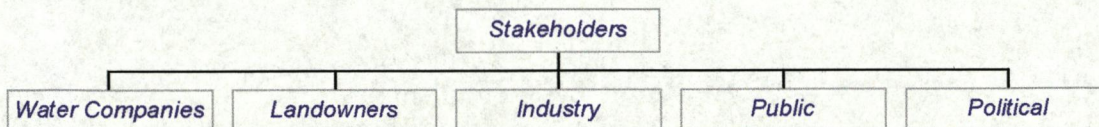
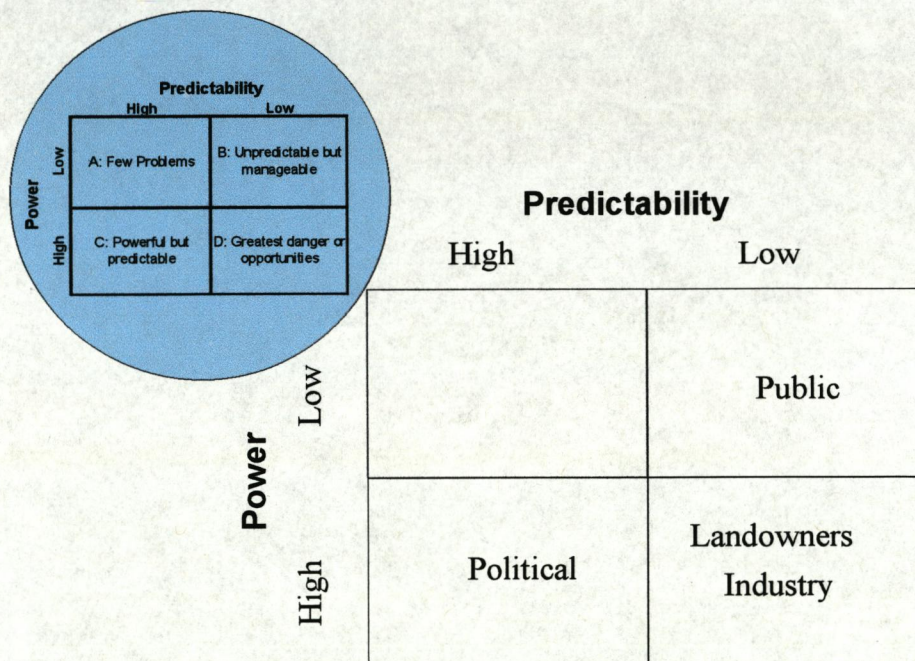


Fig. 6.1. Major stakeholder groups in the bio-solids recycling operation.

From the Water Company's perspective, the other stakeholders are external to the operation and provide varying degrees of influence on the direction of the corporate bio-solids strategy. The degree of power and influence exerted on the company can be visualised using a stakeholder mapping matrix.

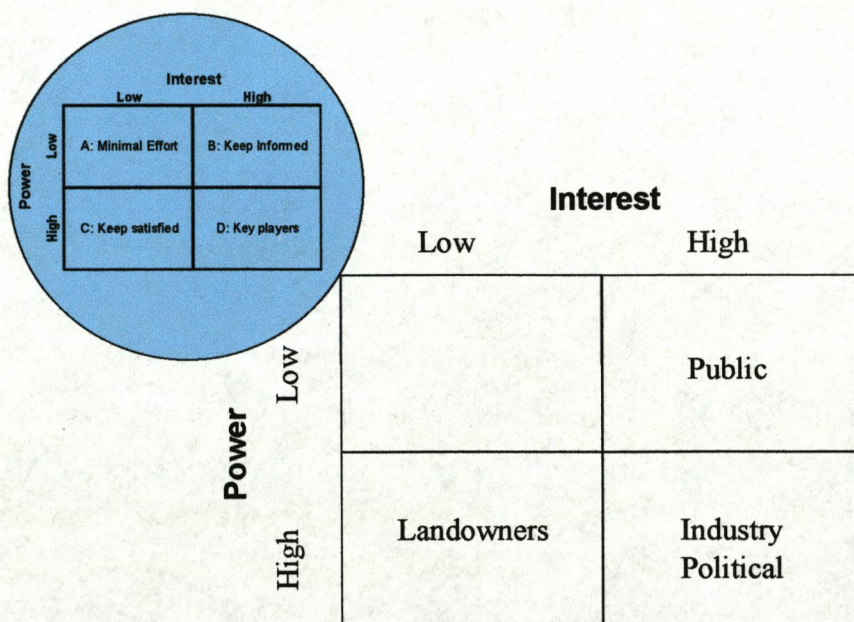


Source: Mendelow, A. (1991)

Fig. 6.2: Power and dynamism from the viewpoint of the water company in relation to external stakeholder influence.

Fig. 6.2 illustrates the influence that external stakeholders may have over the water company, with particular relation to its bio-solids recycling operation. This analysis

highlights the need for the company to be aware of the external environment, as no groups are easily manageable.



Source: Mendelow, A. (1991).

Fig. 6.3. Power and interest from the viewpoint of the water company in relation to external stakeholder influence.

The relationship between interest in the bio-solids recycling industry and the power that stakeholders can exert on the company is illustrated in *Fig. 6.3*. The use of this matrix is somewhat subjective, as landowners may have a high level of interest and power, over the issues surrounding the bio-solids recycling operation. However, it is the aim of the water company to keep their line of distribution satisfied. Similarly, the public should ideally fall, somewhere, in the middle of this matrix, as the power of public opinion and the effect of the “NIMBY” (*not in my back yard*) culture, can exert a major influence over corporate strategy. However, in general, the application of this matrix approach allows the company to focus on the emerging needs of external stakeholders.

6.2.2 Stakeholder analysis.

The stakeholder analysis described below considers the influences, costs and benefits of sewage sludge application to arable cropping from the perspective of the sponsoring organisation, Anglian Water Services Ltd. Some reference to other viewpoints may be made from time to time.

6.2.2.1 The water company (internal stakeholder).

The Water Company is the main stakeholder concerned with the application of bio-solids to agriculture, as it controls the distribution of bio-solids in its defined area. In effect, the actions of the Water Company are driven by the influences of the external stakeholders, to be discussed later. These influences can be political, environmental or financial, although the driver behind many of the strategic developments of the Water Company is political, in particular EC legislation (Fig. 6.4).

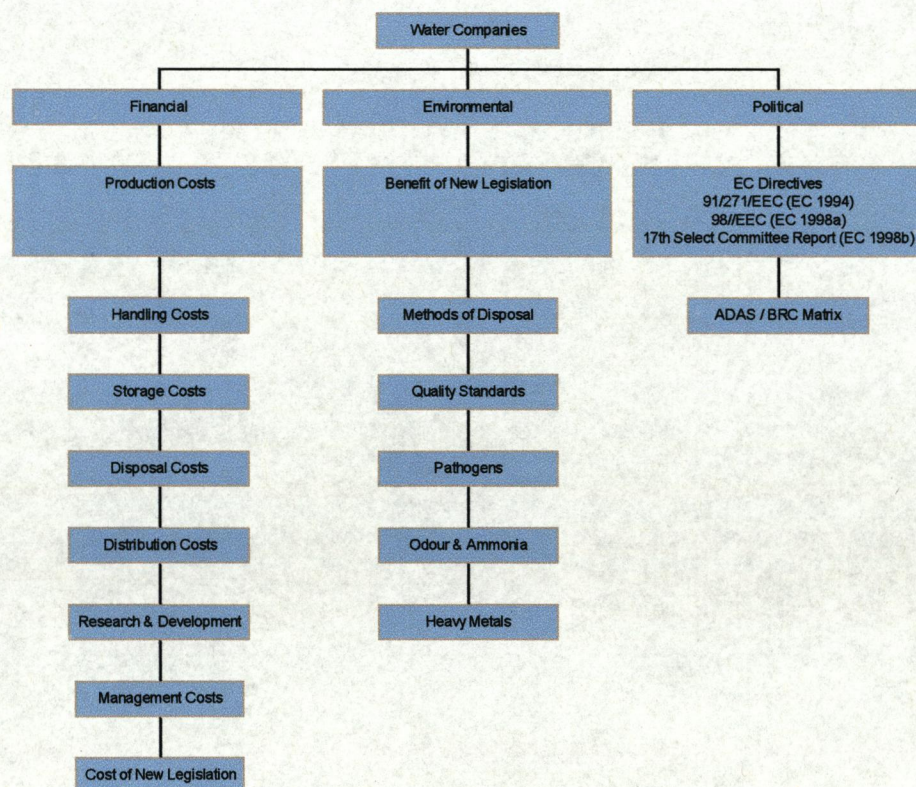


Fig. 6.4. Analysis of the influences, costs and benefits of bio-solids management on the water company as an internal stakeholder.

Current bio-solids disposal/recycling practice involves the distribution of bio-solids as a fertiliser to landowners, with the entire cost being borne by the Water Company. The result of this practice is that the entire operation represents an economic cost to the company and, as such, any new technology should seek to provide cost reductions. Although, as the internal stakeholder, the Water Company can seek to reduce the costs associated with the development of new technology to comply with legislation, it may also seek to minimise the environmental impact and add value to the product. In the context of bio-solids application to arable cropping the implementation of new legislation provides an opportunity for investment in environmental benefits.

The performance of the 40WNDLi injector system, in both laboratory and field studies, has found significant environmental benefits, suggesting that the application of bio-solids to arable cropping is a better recycling system than current land application systems, adding value to the product through emissions reductions.

The adoption of systems to incorporate bio-solids into arable cropping adds value to waste products in terms of potential cost reductions and environmental benefits as a result of new legislation.

6.2.2.2 The landowner/farmer (external stakeholder).

The primary issues that this stakeholder group is concerned with are illustrated in Fig.6.5. The issues can be categorised into financial and environmental considerations.

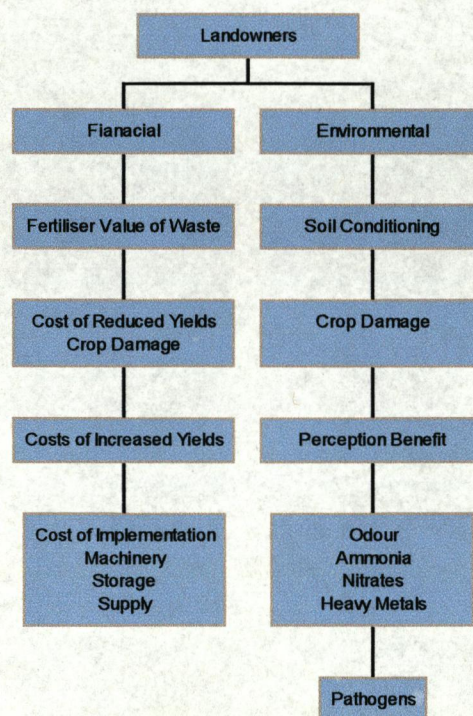


Fig. 6.5. Analysis of the influences, costs and benefits of bio-solids management on the landowner or farmer as an external stakeholder from the perspective of the water company.

This group of stakeholders is primarily concerned with the value of waste as a fertiliser, and may respond favourably to the greater retention of available nutrients by using the 40WNDLi injection system. However, this group is also unlikely to accept a reduction in agronomic performance as a result. The position of this group in the

power/interest matrix (*Fig 6.3*) indicates that the Water Company must satisfy the requirements of this group, if the new technology is to succeed. Satisfactory environmental performance is unlikely to influence the financial concerns of this group.

6.2.2.3 Industry (external stakeholder).

From the perspective of the Water Company, industry stakeholders consist of a number of sub groups:

1. Retail industry (Retailers of agricultural products, e.g. Supermarkets),
2. Manufacturing industry, (manufacturers likely to benefit from the new technology),
3. Other industries, (those unlikely to have an effect on the company).

The primary issues of concern to this group are outlined in *Fig. 6.6*.

Currently, the retail industry is in a strong position as an influencer as their position on the power/interest matrix illustrates (*Fig. 6.3*). The power of this group has enabled them to become dictators in the industry, parallel with the political influences on the bio-solids recycling operation.

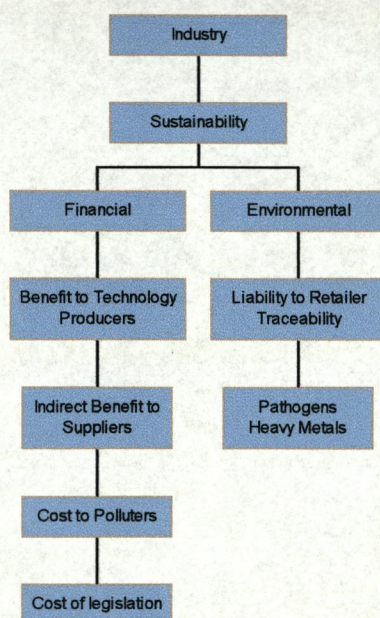


Fig. 6.6. Analysis of the influences, costs and benefits of bio-solids management on industry as an external stakeholder from the perspective of the water company.

The issue of most concern to the retail industry is that of potential health hazards to the consumers of their retail products. The development of the safe sludge matrix, with the assistance of ADAS, has allowed the retail industry to constrain the bio-

solids recycling operation, to satisfy public concern over the use of waste on crops. Pressure from the retail industry is forcing the Water Company to address the issues of pathogens and potentially toxic elements, with the end result that production costs may increase. The incorporation of bio-solids into arable cropping conforms to the guidelines within the ADAS/BRC safe sludge matrix, further enhancing the process.

Other industry groups, which have an interest in the bio-solids recycling operation, are those which provide services to water companies, or manufacture equipment associated with the land application of bio-solids. These groups are unlikely to incur additional costs as a result of the new technology, but suffer due to changes in application methods as a result of new legislation.

6.2.2.4 Public (external stakeholder).

The financial and environmental issues of concern to the public are presented in Fig. 6.7. From the perspective of the Water Company, the public bears a direct financial cost as a result of the implementation of new legislation and technology. The increasingly stringent regulations, on bio-solids quality and recycling options, results in a cost which is passed on to the public, by means of water rates.

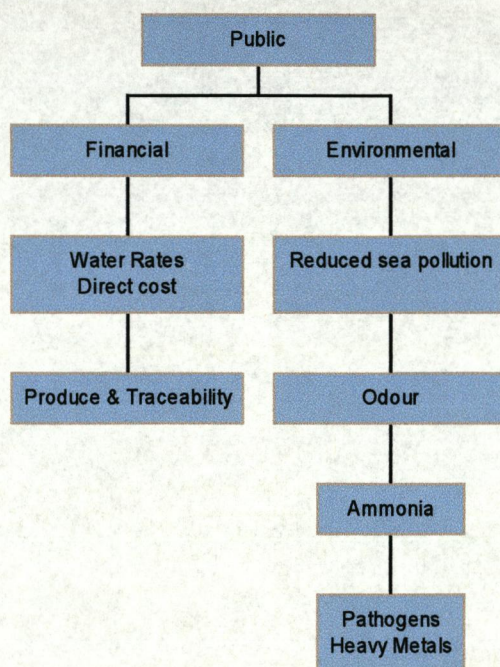


Fig. 6.7. Analysis of the influences, costs and benefits of bio-solids management on the public as an external stakeholder from the perspective of the water company.

Public concern has resulted in pressure from the retail industry, resulting in guidelines for the safe application of bio-solids to agricultural land. One of the main areas in

which the Water Company can benefit from this group is through perception of the product. This can be achieved as a direct result of new legislation that has removed the sea disposal option and, by developing a system that makes more effective use of waste with less environmental impact.

6.2.2.5 Political (external stakeholder).

The political stakeholder group drives the bio-solids management operation through the implementation of new legislation. It also uses financial penalties to reduce the popularity of what it perceives to be poor disposal practices, e.g. landfill tax, and provides funding for research into improved treatment and recycling systems, through government departments, e.g. MAFF & ADAS. The primary influences of the political body are presented in *Fig. 6.8*.

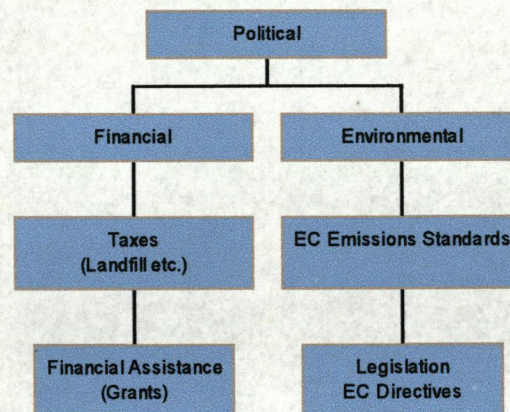


Fig. 6.8. Analysis of the influences, costs and benefits of the political stakeholder on bio-solids management from the perspective of the water company.

As the key power group in the bio-solids management process, the political influences drive further research for novel methods of bio-solids recycling. The costs of the legislation are borne initially by the Water Company, and passed on to consumers. The political body strives to provide legislation to satisfy public concern over environmental issues.

6.2.2.6 Summary of stakeholder costs and benefits.

The analysis of the stakeholders interest in the new technology of bio-solids incorporation, into arable cropping, reveals that cost minimisation and environmental benefit must be obtained by the water company, to satisfy the internal and external influencers over the new process. Field trials of the 40WNDLi injector system have revealed that many public and landowner environmental issues are satisfied. The concerns of the landowner/farmer group are of the greatest importance, as this

stakeholder group must be satisfied before the product can be accepted into the market place. External variables, such as bio-solids quality and potentially toxic elements, while outside the remit of this work, will play an important role in the future success of bio-solids application into arable cropping.

6.3 Market analysis.

The sponsoring organisations of this work were particularly interested in the viability of sewage sludge incorporation into arable cropping. Consequently, the market analysis is based on this particular bio-solid product. To assess the potential market for sewage sludge incorporation into arable cropping, a questionnaire was distributed within the farmer (landowner) stakeholder group. The recycling of sewage sludge to agriculture would not be possible without the full support and satisfaction of this group. The questionnaire was used to determine the main concerns of this demographic group in terms of environmental, agronomic and financial issues. The opportunity to invite comments and assess interest in the subject, in addition to an evaluation of environmental issues, outside the control of the project, was taken. The objectives of this management study were:

- To measure the use of sewage sludge within the stakeholder group, and to determine the acceptability of the technology of bio-solids incorporation into arable cropping.
- To establish the concerns of the respondents.
- To establish the marketability of the new technology and develop a strategy for cost reduction in the water company based on the findings.

6.3.1 Questionnaire rationale.

Reference was made throughout the questionnaire design process to the text of Oppenheim and Naftali, 1992, and Belson, 1981. The questionnaire was constructed in two main sections. The first section considers the demographic information of the respondents, which enabled the subsequent section to be analysed by group segregation, e.g. responses from section two could be analysed by user preference for bio-solids or farm type. The second section investigates the respondent's perception and acceptability of the bio-solids recycling practices, and investigates the perception of environmental and economic factors within the bio-solids sphere.

6.3.1.1 Section one: demographics.

Demographic data allows the segregation of the responses into defined groups. This enables analysis of the farmer/landowner groups most likely to be susceptible to new technology. These are considered as innovators during the product life cycle, (Christopher & McDonald, 1995). The most logical segregation of the farmers, demographically, is in terms of farm size and sewage sludge use. In this section of the questionnaire the opportunity was taken to obtain the opinion of farmers on bio-solids application to agricultural land.

Table 6.1.
Demographic questioning.

1(i) What area of land do you farm?		
0 - 50 Ha		☐
50 - 100 Ha		☐
100 - 200 Ha		☐
200 - 500 Ha		☐
Over 500 Ha		☐
1(ii) What type of operation do you own /run?		
(a) Stock :-	Cattle / Dairy	Head <input type="text"/>
	Sheep	Head <input type="text"/>
	Pigs	Head <input type="text"/>
(b) Cropping	Cereals	Hectares <input type="text"/>
	Root Crops	Hectares <input type="text"/>
	Grassland	Hectares <input type="text"/>
	Other Crops	Hectares <input type="text"/>
Please Specify <input type="text"/>		
1(iii) Please indicate your use of sewage sludge:-		
Never ☐	Currently ☐	In the past ☐
If Never,		
Would you consider using sewage sludge in the future?		YES ☐
		NO ☐
If NO, give reasons <input type="text"/>		
If Currently,		
How much sewage sludge do you apply per hectare per year? <input type="text"/>		
Under what field conditions do you apply sewage sludge?		Grassland ☐
		Stubble ☐
		Cereal Crops ☐
		Set Aside ☐
Other Please Specify <input type="text"/>		

Do you	Apply yourself? Use a contractor?	☐ ☐
If in the past, Why did you stop using sewage sludge?		

The demographic section of the questionnaire distributed is presented in *Table 6.1*. The design allows the farmer groups to be categorised by farm size, farming concern and user type. With reference to *Table 6.1*:

Question 1(i) is a question, independent of the bio-solids application subject, and applies irrespective of farm type and user group. It is anticipated that a wide range of farm size will be represented as a result of the random distribution of the questionnaire.

Question 1(ii) is a question, independent of the bio-solids application subject, and applies irrespective of farm size and user group. The response from this question may give an indication of the susceptibility, of the respondent, to the new technology, as a large cereal or pig farm may benefit more from the improved waste recycling technique, than a small stock farmer for example.

Question 1(iii) is a question, independent of the bio-solids application subject, and applies irrespective of farm size and type. It is expected that difficulties may arise in obtaining a sufficiently balanced response between user types. Consequently, the co-operation of two, large, water companies was gained and a selected proportion of the questionnaires were distributed to current and past users in the Severn Trent and Anglian Water regions. This allowed the question to be expanded such that; non-users were asked if they would be prepared to use sewage sludge in the future; current users were questioned on their use of sewage sludge and; past users were asked why they stopped using sewage sludge.

6.3.1.2 Section two: subjective questioning.

This section of the questionnaire concentrated on the acceptability of the new technology and the concerns that could influence the potential user, with regard to the incorporation of sewage sludge into arable cropping (*Table 6.2*).

Table 6.2

Subjective questions.

2(i) If a mechanically viable system were available, would you consider injecting sewage sludge into an established arable crop as a supplemental fertiliser?

YES ☐ NO ☐

2(ii) With respect to the injection of sewage sludge or other bio-solids to established arable crops, Please indicate the degree of importance of the following issues to you -

(1 = Not Important, 5 = Very Important)

	1	2	3	4	5
Crop Damage	☐	☐	☐	☐	☐
Yield Reduction	☐	☐	☐	☐	☐
Odour Emissions	☐	☐	☐	☐	☐
Ammonia Loss	☐	☐	☐	☐	☐
Pathogens	☐	☐	☐	☐	☐
Heavy Metals	☐	☐	☐	☐	☐
Traceability (Sales to the food chain)	☐	☐	☐	☐	☐
Soil Conditioning Properties	☐	☐	☐	☐	☐
Fertiliser Value of Sewage Sludge	☐	☐	☐	☐	☐
Cost of Application	☐	☐	☐	☐	☐

2(iii) Would you be prepared to invest in a system to inject sewage sludge into established arable cropping? YES ☐ NO ☐

2(iv) Would you be prepared to pay for sludge to be injected into an established arable crop on your land? YES ☐ NO ☐

2(v) Do you consider the recycling / disposal of sewage sludge to agricultural land environmentally considerate? YES ☐ NO ☐

The aim of the questionnaire is to examine the results of the subjective questioning, in relation to the demographic group information determined from *Section 1*.

Question 2(i) poses the question that indicates the responsiveness of the farmer to the principle of sewage sludge incorporation into arable cropping. The response to this question, combined with the demographic results, indicates the degree of attention that the respondent was paying to the questionnaire. Logical responses were expected, for example, a non-user, who expressed a preference not to use sewage sludge in the future, would be expected to respond negatively to this question.

Question 2(ii) addresses the concerns that the farmer may have with respect to the agronomic, environmental and economic issues, surrounding bio-solids incorporation into arable cropping. Not all the issues raised in this question are within the control of the agricultural engineer in the design process. Responses to this question should enable conclusions to be drawn on the quality of the bio-solid product, and the deciding influence on whether the technology is adopted.

Question 2(iii,iv,v) are designed, to assess the degree to which respondents consider the improved injection system to be acceptable. The first level of acceptance was established in Q2(i). A farmer with knowledge of the process of bio-solids injection will be aware that the service at present is free. An indication of willingness to invest, in an injection system, demonstrates that the respondent has commitment to the operation, provided that the concerns outlined in Q2(ii) are addressed. It may also indicate foresight, into the appropriateness of the system for farm bio-solids recycling. A respondent agreeing to both may be classified as an innovator or early adopter, in the life cycle of the technology. The final question, Q2(v), tests the respondents' alertness at the end of the questionnaire. A logical response is required at this stage, indicating an awareness of previous answers. Additionally, this question can be related to Q2(i), where a negative response may have been forthcoming. A respondent who is not prepared to accept bio-solids incorporation into arable cropping may still consider the principle a good idea. These respondents may represent the late majority, in the lifecycle of the technology, who may follow after the process has been fully verified and is popular.

6.3.2 Questionnaire distribution.

In order to ensure, as far as possible, that a representative sample of replies were received, co-operation was gained from the sponsoring organisation, Anglian Water Services Ltd, and Severn Trent Water Plc. Each water company selected a proportion of their users, at random, for inclusion in the study. Anglian Water and Severn Trent

mailed 75 and 60 questionnaires respectively to known sludge users. The author distributed a further random sample of 120 questionnaires per region.

6.3.3 Questionnaire results.

Of the 395 questionnaires distributed, 104 unspoilt papers were returned for analysis. Spoilt papers accounted for 1.8% of the returns and comprised non-farmers, incomplete papers and Royal Mail returns.

6.3.3.1 Demographic analysis.

All area groups and user types were adequately represented by the returned questionnaires. The distribution of returns, by area and user type, is presented in *Fig. 6.9.a* and *b* respectively. The majority of responses were obtained from current users and farmers with between 50 and 200 Ha.

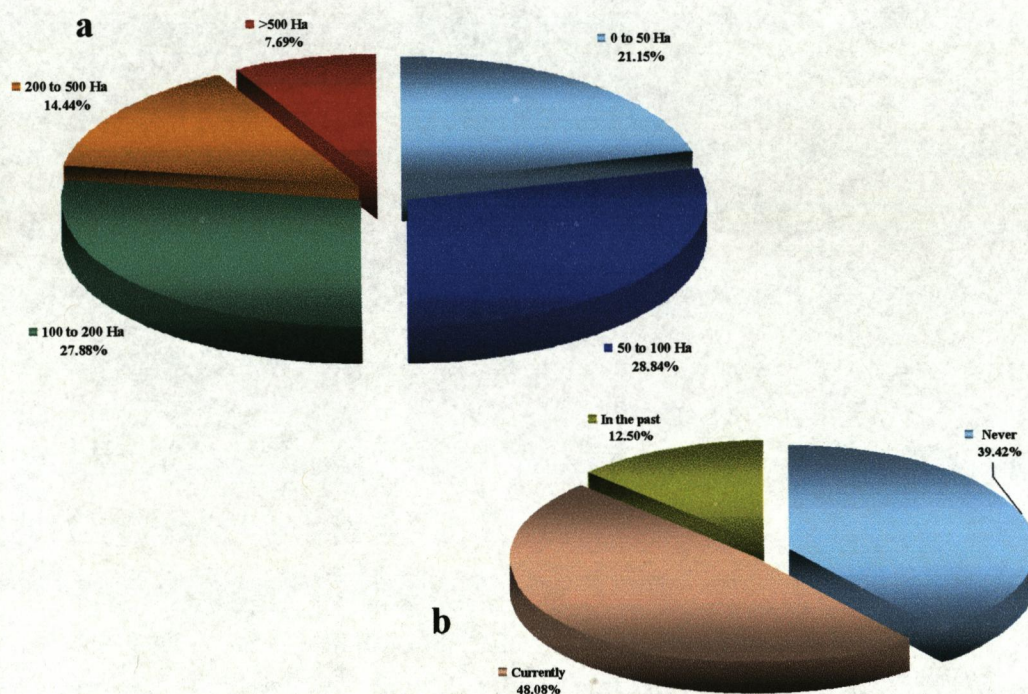


Fig. 6.9. Demographic distribution of returned papers by a) farm size and b) user type.

These two main demographic groups were analysed for statistical independence using Chi-Squared analysis (Bryman and Cramer, 1994). The analysis showed that, of the replies received, user type and area farmed were independent of each other, suggesting that a good, random distribution was achieved.

Additional information, gained from the demographic questioning, indicates that over 45% of non-users, would consider the use of sewage sludge in the future. The major concerns of those who expressed a preference not to use sewage sludge in the future were heavy metals, pathogens and odour, although some respondents said that their landlord would not permit the application of sewage sludge to their land.

Current users indicated that bio-solids are being applied to a range of farming systems (Fig. 6.10). However, in general, a large proportion of current users were unsure of the total volumes of sewage sludge applied to their land, which suggests that a high degree of trust is placed with the supplier.

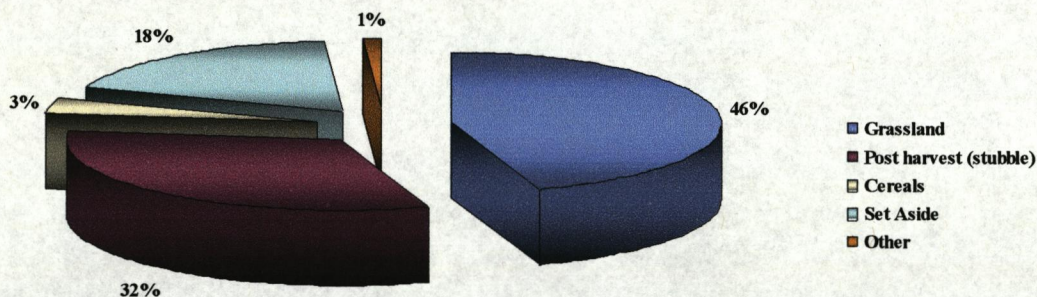


Fig. 6.10. Land type on which sewage sludge is applied by current users.

The responses from farmers who currently use of sewage sludge on cereals are of particular interest. It is suspected that this is achieved by surface application, using irrigation equipment or wide dribble bars. All current users use a contractor for sludge application, usually organised and paid for by the Water Company.

Past users indicated that on the whole, their use of sewage sludge ceased as a result of poor application by contractors and many comments were received regarding the mess left behind after application. It should be stressed that past users made continual reference to the mess caused by the dribble bar technique.

6.3.3.2 Subjective analysis.

In relation to Q2(i), it was found, by statistical evaluation, that the willingness of respondents to consider the application of bio-solids to arable cropping was dependent on user type. This analysis included the observations by non-users who expressed a preference not to utilise sewage sludge in the future and suggests that current and past

users were more likely to consider this new process than non-users. However, findings from a separate analysis, discounting the 55% of non-users unlikely to use sewage sludge in the future, suggest that the consideration of the new process was independent of user type.

These results, presented in *Table 6.3*, suggest that the majority of farmers who accept the principle or practice of bio-solids application to agricultural land, would be prepared to investigate the use of sewage sludge incorporation into established crops.

Table 6.3.

The effect of user type, on the willingness to adopt the use of shallow injection, into arable cropping.

If a mechanically viable system were available, would you consider injecting sewage sludge into an established arable crop as a supplemental fertiliser?									
Including non-users unwilling to adopt bio-solids use in the future	Observed	No	Yes		Excluding non-users unwilling to adopt bio-solids use in the future	Observed	No	Yes	
	Never	27	14	41		Never	5	14	19
	Current	16	34	50		Current	16	34	50
	Past	7	6	13		Past	7	6	13
		50	54	104			28	54	82
	Expected	No	Yes			Expected	No	Yes	
	Never	19.71	21.29	41		Never	6.49	12.51	19
	Current	24.04	25.96	50		Current	17.07	32.93	50
	Past	6.25	6.75	13		Past	4.44	8.56	13
		50	54	104			28	54	82
	χ^2	No	Yes			χ^2	No	Yes	
	Never	2.69	2.50			Never	0.34	0.18	
	Current	2.69	2.49			Current	0.07	0.03	
	Past	0.09	0.08			Past	1.48	0.77	
			χ^2 calc	10.54				χ^2 calc	2.86
			χ^2 tab	5.991				χ^2 tab	5.991
Dependent					Independent				

Table 6.3 illustrates that; of the 45% of non-users who would like to use sewage sludge in the future, over 75% would consider the use of the improved bio-solids incorporation process. Over all user groups, the option to accept bio-solids injection into established arable crops, received a positive response (>50%).

Responses associated with the agronomic, environmental and economic implications, of bio-solids incorporation into arable cropping, confirm that there is a high level of concern on many of the issues addressed in the questionnaire. This concern was found to be independent of user type and farm size for the majority of issues. However, two significant dependencies were identified, namely odour and economic value.

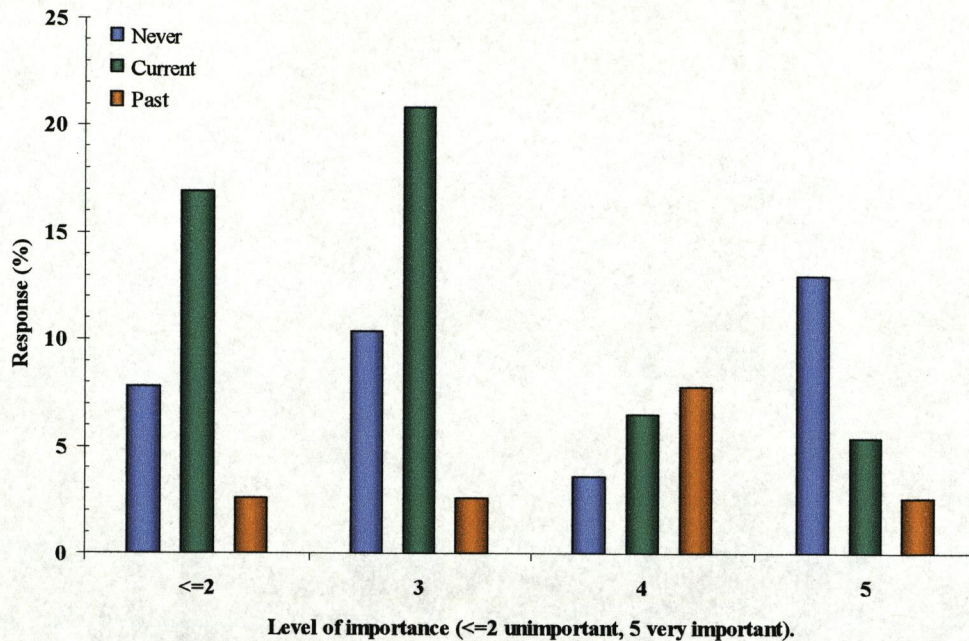


Fig 6.11: The relationship, between user type and the level of concern, associated with odour emissions.

From Fig.6.11, there is a trend towards increased concern over odour emissions, following the land application of sewage sludge from non-users, compared with current users. This result may be attributed to a lack of educational communication between the supplier and the farmer. Current users will be aware that existing sewage treatment practices, such as anaerobic digestion, reduce odour concentrations significantly, whereas non-users may be unaware of this. By discounting the responses from non-users unwilling to adopt the application of sewage sludge in the future, the relationship between concern over odour and user type becomes independent (Table 6.4). This indicates that non-users unwilling to use sewage sludge in the future do so because of odour concerns, reinforcing the need for adequate education on the subject of bio-solids application to land.

Table 6.4.

The effect of user type on the concern over odour emissions a) including and b) discounting non-users unwilling to adopt the use of sewage sludge in the future.

a)		b)	
Relationship between odour importance and user group including non-users unwilling to adopt sewage sludge in the future.		Relationship between odour importance and user group excluding non-users unwilling to adopt sewage sludge in the future.	
Level of importance of odour emissions		Level of importance of odour emissions	
Observed	<=2 3 4 5 Total	Observed	<=2 3 4 5 Total
Never	6 8 3 10 27	Never	5 6 2 3 16
Current	13 16 5 4 38	Current	13 16 5 4 38
Past	2 2 6 2 12	Past	2 2 6 2 12
	21 26 14 16 77		20 24 13 9 66
Expected	<=2 3 4 5 Total	Expected	<=2 3 4 5 Total
Never	7.36 9.12 4.91 5.61 27	Never	4.85 5.82 3.15 2.18 16
Current	10.36 12.83 6.91 7.90 38	Current	11.52 13.82 7.48 5.18 38
Past	3.27 4.05 2.18 2.49 12	Past	3.64 4.36 2.36 1.64 12
	21 26 14 16 77		20 24 13 9 66
χ^2	<=2 3 4 5 Total	χ^2	<=2 3 4 5 Total
Never	0.25 0.14 0.74 3.43	Never	0.00 0.01 0.42 0.31
Current	0.67 0.78 0.53 1.92	Current	0.19 0.34 0.82 0.27
Past	0.49 1.04 6.68 0.10	Past	0.74 1.28 5.59 0.08
	χ^2 Calc 16.78		χ^2 Calc 10.06
	χ^2 Tabulated 12.592		χ^2 Tabulated 12.592
Calc > Tab = Dependent		Calc < Tab = Independent	

All other responses relating to the agronomic, environmental and economic aspects of sewage sludge injection into arable cropping, were found to be independent of user type, with all responses indicating that a high level of importance should be placed on the issues raised. This trend was duplicated when the effect of area of land was considered. However, the economic value placed on sewage sludge as a fertiliser was found to be dependent on the area of land farmed (Fig. 6.12).

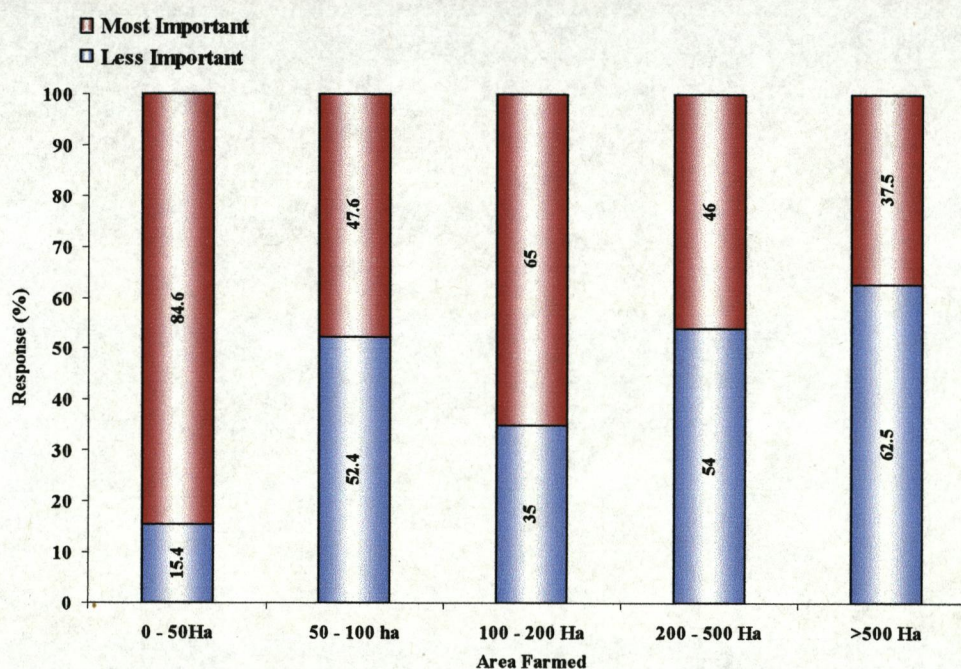


Fig. 6.12. Relationship between area farmed and the importance of the fertiliser value of bio-solids.

Respondents with small farms suggested that the value of sludge was of greater importance than the larger agricultural concerns. However, all responses considered this issue to be of above average importance, with few scores below 4.

In response to Q2 (iii), (iv) & (v), no relationship between farmed areas were observed. However, differences between user groups were discernible. The general opinion of all respondents was that investing in a system for sewage sludge injection was not acceptable. Current users were found to be less likely to accept a charge for sewage sludge, whereas 22 and 38% of non and past users respectively, indicated that a charge for sewage sludge application would be acceptable. A number of additional comments were received, associated with the proposal to pay for the goods and services, indicating that a consistent product is essential before charges would be appropriate. In response to the question of the environmentally considerate nature of sewage sludge application to agricultural land, some illogical responses were observed. Up to 20% of current users suggested that they did not feel the practice was considerate. It is suspected that this minority, primarily, utilises sewage sludge for its fertiliser value and financial savings. Non-users were split 51.5% to 48.5%, for and against the environmentally considerate nature of sewage sludge respectively. When discounting non-users unwilling to adopt sewage sludge in the future, the general consensus of this user group is that sewage sludge application to land is environmentally considerate.

This indicates a very definite split within this user group, in conjunction with other responses, this group are either all for sewage sludge application to arable cropping, or totally against this practice. This finding reduces the susceptibility of this group to targeting in the marketing process. Past users were generally in favour of the environmental nature of bio-solids application to agricultural land. However, further comments in *Section 1* from this demographic group indicate that cleaner methods are needed with better, in-field, management systems.

6.3.4 Questionnaire discussion and conclusions.

The results of this questionnaire have enabled the demand for technology to inject sewage sludge into arable cropping to be assessed. A broad sample of respondents has been achieved, representing a good distribution of user types. In general, respondents were willing to add comments during the completion of the questionnaire, a selection of which is presented in *Appendix 5.1*. Little conclusive evidence was obtained from

the analysis of data, concerning "farmed area" as a demographic group, although the financial value of sewage sludge application was found to be of greater importance to small, rather than large, farmers. The use of user type as a demographic group, revealed more about the market place and the viability of sewage sludge application to arable cropping.

6.3.4.1 Non-users.

This group has been identified from the questionnaire as a potential target market for the new technology. However, a divide within this group was identified from an analysis of responses. The responses from members of this group indicated that a high level of importance is placed on odour emissions, and further analysis of the responses to this question indicated that a proportion of this user group were against the future use of sewage sludge for this reason. The significant reductions in odour emissions obtained through pre-treatment, and the further reductions possible from the improved 40WNDLi injection system, may influence the decisions of this group and increase their potential acceptance of sewage sludge as a bio-solid and fertiliser. A proportion of non-users indicated that they were in favour of the use of sewage sludge and would be prepared to consider the use of new technology to inject bio-solids into arable cropping. However, further comment from this sub-section revealed that they were unable to accept bio-solids due to either location or the instructions from their landlords.

In conclusion, non-users are considered a significant target market for the new technology and may be prepared to accept a small levy for the product provided that consistency and quality can be maintained.

6.3.4.2 Current users.

This demographic group may be harder to convert to the new technology, although the data received suggests that a high proportion (78%) will be prepared to consider the application of sewage sludge to arable cropping as a supplemental fertiliser. The acceptance of this group as innovators of new technology is possible. However, cost reductions will be difficult to realise, as this group has used the bio-solids recycling services provided by water companies free of charge. It is not possible to speculate on the loss of customers within this group if bio-solids were sold rather than provided free of charge. This group is not particularly concerned with the environmental issues within the control of the product designer, and its response is comparable to the

concerns of other user groups. This suggests that treatment processes to produce a consistent and high quality product are required, before any full-scale commitment to bio-solids recycling to arable cropping can be realised.

6.3.4.3 Past users.

The results of this study suggest that past users are less susceptible to the new technology, due to previous poor experiences, mainly with respect to application methods and quality control during application. Active promotion of the 40WNDLi injection process may change the current opinion, as the results achieved with this system are much more acceptable in terms of appearance, compared with dribble bar surface application. Past users have indicated their awareness of the benefits of sewage sludge as a fertiliser, and this is reflected in the willingness of this user group to accept a charge for the product.

In conclusion, active promotion, improved field management, and a focus on the more susceptible user groups may lead to cost reductions through the sale of bio-solids incorporation to arable cropping as a value added system. However, the issues of product consistency and quality must be addressed before the full benefits of the 40WNDLi-injection system can be realised.

6.4 Financial implications.

A financial evaluation of different bio-solids application systems is possible provided that some basic assumptions are accepted. An in depth analysis, although more accurate, can hide the true costs and benefits of the bio-solids operation. It is for this reason that four specific areas have been identified for financial consideration: -

- Bio-solids application costs.
- Operational savings based on application method.
- Product value & environmental savings based on application method.
- Logistical savings (storage and distribution).

Four application methods were considered in this study:

- Deep Injection.
- Shallow Injection (Greentrac "Slipper Foot").
- 40WNDLi Injection.
- Dribble Bar (Surface application, low level).

6.4.1. Bio-solids application costs.

A financial analysis, based on operating cost per m^3 of bio-solids, is presented in *Table 6.5*. The following assumptions have been made: -

1. All equipment is bought outright and written off, over the life of the implement, on a straight-line basis.
2. The operating life of all equipment, based on 1200 hrs annual usage, is 5 years, after which time the resale value of all implements is 10% of the original cost.
3. All application methods require the same tractor and umbilical hose.
4. Application rates are fixed at $50 \text{ m}^3/\text{ha}$.
5. The implement width indicated is that which is common for the particular applicator.
6. Storage facilities are erected new, by contractor, and are written off on a straight-line basis over 30 yrs.

Financial information obtained from Nix (1998) and Tinkler (1999).

It can be seen from the costings presented in *Table 6.5*, that the cheapest option for bio-solids recycling is surface application using a dribble bar technique. The major factors contributing to this finding are the relative simplicity of the equipment and, hence, the low production costs and the high work rates possible due to the 6 m working width of the implement. Application using the 40WNDLi system is expensive when considered on an hourly basis. However, the increased work rates possible with this machine, compared to other injection systems, results in significant savings when costed on a volume basis.

Table 6.5.
Bio-solids application costs.

Equipment	Deep Injection	Shallow Injection	40WNDLi Injection	Dribble Bar
Tractor (90kW)	£36,000.00	£36,000.00	£36,000.00	£36,000.00
Injector	£10,000.00	£13,500.00	£18,500.00	£5,100.00
Hose ¹	£4,800.00	£4,800.00	£4,800.00	£4,800.00
Equipment Total	£50,800.00	£54,300.00	£59,300.00	£45,900.00
Workrate				
Speed ² m/s	0.55	0.55	0.55	0.55
Width (m)	2.5	3.5	4.5	6
Spot Rate (Ha/hr)	0.50	0.69	0.89	1.19
Field Efficiency (%)	0.85	0.85	0.85	0.85
Work Rate (Ha/hr)	0.42	0.59	0.76	1.01
Costs				
Equipment life	5	5	5	5
Resale value (%)	10%	10%	10%	10%
Tractor				
Depreciation	£6,480.00	£6,480.00	£6,480.00	£6,480.00
Repair & Maintenance	£3,600.00	£3,600.00	£3,600.00	£3,600.00
Insurance	£160.00	£160.00	£160.00	£160.00
Tax	£35.00	£35.00	£35.00	£35.00
Fuel & Oil	£1,312.11	£1,836.95	£2,361.80	£3,149.06
Tractor Total	£11,587.11	£12,111.95	£12,636.80	£13,424.06
Injector				
Depreciation	£1,800.00	£2,430.00	£3,330.00	£918.00
Repair & Maintenance (40%)	£4,000.00	£5,400.00	£7,400.00	£2,040.00
Insurance	£40.00	£40.00	£40.00	£40.00
Injector Total	£5,840.00	£7,870.00	£10,770.00	£2,998.00
Hose				
Depreciation	£864.00	£864.00	£864.00	£864.00
Repair & Maintenance	£960.00	£960.00	£960.00	£960.00
Insurance	£19.20	£19.20	£19.20	£19.20
Hose Total	£1,843.20	£1,843.20	£1,843.20	£1,843.20
Total Running Cost / year	£19,270.31	£21,825.15	£25,250.00	£18,265.26
Cost per hour	£16.06	£18.19	£21.04	£15.22
Labour ³	£10,756.51	£10,756.51	£10,756.51	£10,756.51
Total annual costs	£30,026.82	£32,581.66	£36,006.51	£29,021.77
Cost per hour	£25.02	£27.15	£30.01	£24.18
cost per Ha	£59.47	£46.09	£39.62	£23.95
Cost per m³	£1.19	£0.92	£0.79	£0.48

1: 400m x 100mm lay flat hose @ £12/m

2: Operational speed used in field and laboratory trials.

3: Tractor driver (NVQ level 3) based on 48 weeks work and 4 weeks holiday per year, incl NI and Liability Insurance.

6.4.2 Operational savings.

A financial analysis of the possible operational savings compared to the most expensive system (deep injection) is presented in *Table 6.6*. This analysis is based on the annual bio-solids production in the Anglian Water region.

Table 6.6

Financial analysis of potential theoretical operational savings.

Equipment	Deep Injection	Shallow Injection	40WNDLI Injection	Dribble Bar
Work Rate (ha/hr)	0.42	0.59	0.76	1.01
Application Rate (m ³ /ha)	50	50	50	50
Application Window (70%) ¹	July - October ¹²	July - October	July to March	July - October
Work Hours Possible (70%) ²	776	776	840	776
Volume Recycled (m ³ /machine)	16325.1	22855.14	31808.7	39180.24
Required No. of Machines ³	150	107	77	63
Capital Investment ⁴	£1,500,756.50	£1,447,158.06	£1,424,924.63	£318,910.76
Operating Cost (70%) ⁵	£2,914,070.36	£2,258,582.26	£1,941,329.19	£1,173,554.82
Application Window (30%) ⁶	October - July	October - July	March - July	October - July
Work Hours Possible (30%) ⁷	424	424	360	424
Volume Recycled (m ³ /machine)	8919.9	12487.86	13632.3	21407.76
No. of Machines ⁸	118	84	77	49
Capital Investment ⁹	£1,177,143.24	£1,135,102.41	£1,424,924.63	£250,142.94
Operating Cost (30%) ¹⁰	£1,248,887.30	£967,963.83	£831,998.22	£502,952.07
Total Operating Cost	£4,162,957.66	£3,226,546.09	£2,773,327.41	£1,676,506.89
No. of Machines (max)	150	107	77	63
Capital Investment	£1,500,756.50	£1,447,158.06	£1,424,924.63	£318,910.76
Total Savings:¹¹				
Capital	£0.00	£53,598.45	£75,831.88	£1,128,247.30
Operating	£0.00	£936,411.57	£1,389,630.25	£1,550,039.20

1: Based on the principle that 70% of annual applications by this method occur within the stated time period.

2: Based on data presented by McGeachan and Cooper (1994), and assuming an 8 hour working day. (Total hours not exceeding 1200)

3: No. of machines required to dispose of 70% (2.45million m³) of annual production based on recyclable volume per machine

4: No. of machines required at full cost price. (assuming no credit).

5: Application cost (£/m³) for the recycling of 70% of annual production^(a).

6: Based on the principle that 30% of annual applications by this method occur within the stated time period.

7: Based on data presented by McGeachan and Cooper (1994), and assuming an 8 hour working day. (Total hours not exceeding 1200)

8: No. of machines required to dispose of 30% (1.05million m³) of annual production based on recyclable volume per machine

9: Total capital investment in machinery required to satisfy production.

10: Total operating cost based on costings in Table 6.5

11: Total savings possible: based on the difference between the most expensive application method (deep).

12: Deep injection has been found not to affect crop performance when applied later than October, however the effects are aesthetically poor. (Blackwell 1996; Godwin 1999)

The main area of interest concerning this financial analysis is the effect of the application "window of opportunity". The costing associated with each machine assumes all annual bio-solids production is applied by a single method. Additionally, it is assumed that during the "window of opportunity", 70% of the total annual sludge production of 3.5 million m³ will be applied. Consequently, it is expected that outside of the main application window, the remaining 30% of bio-solids production are distributed. This 70/30 split in application volumes is based upon land area available throughout the year for bio-solids application. For example, deep injection is only possible between harvest and sowing (3 – 4 months), after which, land availability is reduced to set-aside and grassland. Placing an accurate split on the difference in land

availability allows each application method to be compared, based on work rates and application "windows". The reduced machinery requirement, resulting from the wider application window associated with the 40WNDLi injection system, is presented in *Table 6.6*. The Dribble Bar system still provides the greatest savings, as a direct result of increased work rates and, hence, lower application costs (*Table 6.5*).

6.4.3 Product value and financial environmental benefits.

The environmental benefits of using the 40WNDLi injector have been discussed in *Chapter 4*. The benefits of bio-solids injection, compared to surface application, have been widely recognised for many years, and work by Phillips *et al* (1990) has suggested that the reduced emissions associated with deep injection techniques are similar to those of shallow injection. Potential users will place a high value on the financial benefits of bio-solids as a fertiliser, and this can be enhanced by the use of the 40WNDLi injector and its associated reduction in losses. This may represent a potential cost reduction to the Water Company by means of a value added product. The savings due to reduced emissions are presented in *Table 6.7*.

Table 6.7

Product value and potential reductions in losses to the environment for four different application methods.

Product Value	Deep Injection	Shallow Injection	40WNDLi Injection	Dribble Bar
Nitrogen Content ⁺	6.19% (DW)	6.19% (DW)	6.19% (DW)	6.19% (DW)
Available N ⁺	1.41% (DW)	1.41% (DW)	1.41% (DW)	1.41% (DW)
Phosphorous Content (P ₂ O ₅) ⁺	6.02% (DW)	6.02% (DW)	6.02% (DW)	6.02% (DW)
Potassium Content (K ₂ O) ⁺	0.25% (DW)	0.25% (DW)	0.25% (DW)	0.25% (DW)
Solids Content ⁺	4%	4%	4%	4%
Value / m ³	£1.32	£1.32	£1.32	£1.32
Losses (N Volatilisation)	15% of Available ⁺⁺	15% of Available ⁺	4% of Available ⁺	40% of Available ⁺
Lost value / m ³	2.2p	2.2p	0.5p	6p
Total Loss (3.5m m ³ /yr)	£77,000.00	£77,000.00	£17,500.00	£210,000.00
Value of Yearly Distribution	£4,543,000.00	£4,543,000.00	£4,602,500.00	£4,410,000.00
Operational saving - environmental loss	-£77,000.00	£859,411.57	£1,372,130.25	£1,340,039.20

⁺ Source: Moseley *et al*, (1998)

⁺⁺ Source: Phillips *et al*, (1990)

Bio-solids value is based on current granular fertiliser prices (Nix, 1998). It is assumed that only available nitrogen is lost through gaseous emissions, and that all other bio-solids constituents are maintained for crop use, or lost by other mechanisms at an equal rate between application methods. If the loss of value is subtracted from the operational savings, the net operational saving can be determined (*Table 6.6*). It is apparent that the increased emissions resulting from surface application significantly

reduce the benefits of this application technique. The 40WNDLi injection system provides better financial savings overall and, it is possible that this benefit could be increased by adding a small levy on bio-solids application by this method.

6.4.4 Logistical savings.

The effect of the increased application window, associated with the 40WNDLi injection system, has been shown financially in *Table 6.6*, as a reduced number of machines would be required to recycle the annual production of bio-solids in the Anglian Water region. Other logistical benefits arise from the increased application window, in particular distribution and storage costs. Based on the 70/30 split system, described earlier, and assuming that bio-solids production remains even throughout the year, bio-solids storage requirements and hence costs can be reduced by 90%, representing a substantial saving over other application methods (*Table 6.8*).

Table 6.8

Storage requirements as a result of application window for four application methods.

	Production	Deep Injection		Shallow Injection		40WNDLi Injection		Dribble Bar	
		Application	Storage	Application	Storage	Application	Storage	Application	Storage
November	291667	131250	160417	131250	160417	306250	58336	131250	160417
December	291667	131250	320834	131250	320834	306250	43753	131250	320834
January	291667	131250	481251	131250	481251	306250	29170	131250	481251
February	291667	131250	641668	131250	641668	306250	14587	131250	641668
March	291667	131250	802085	131250	802085	306250	4	131250	802085
April	291667	131250	962502	131250	962502	262500	29167	131250	962502
May	291667	131250	1122919	131250	1122919	262500	58334	131250	1122919
June	291667	131250	1283336	131250	1283336	262500	87501	131250	1283336
July	291667	612500	962503	612500	962503	262500	116668	612500	962503
August	291667	612500	641670	612500	641670	306250	102085	612500	641670
September	291667	612500	320837	612500	320837	306250	87502	612500	320837
October	291667	612500	4	612500	4	306250	72919	612500	4
Total	3500004	3500000	1283336	3500000	1283336	3500000	116668	3500000	1283336
Storage Cost (@ £0.63/m³/yr)		£812,779.47		£812,779.47		£73,889.73		£812,779.47	

Similarly, the increased application window reduces the quantity of distribution services, in particular tankering, as distribution is more even throughout the year. Once again, the 70/30 split system has been used, requiring 291 9.08m³ tankers to distribute 70% of the Anglian Water Services bio-solids production, within a 4 month application window associated with deep injection, shallow injection and surface application. Utilising the 40WNDLi system reduces the tankering need and hence the operational cost of tankering by >50% (Brade and Harwood, 1992). The financial benefit of this saving is presented in *Table 6.9*.

Table 6.9
Distribution savings (tankering).

	Max Application m ³ /month	Tanker capacity m ³ /day	Daily distribution m ³	Tanker requirement	Tanker leasing cost £/tanker/month	labour £/tanker/month	Total Basic Tankering Cost £/yr
Deep Injection	612500	70	20417	292	1096	1584	£9,380,153.14
Shallow Injection	612500	70	20417	292	1096	1584	£9,380,153.14
Dribble Bar	612500	70	20417	292	1096	1584	£9,380,153.14
40WNDLI	306250	70	10208.3	146	1096	1584	£4,689,984.69
Potential Saving							£4,690,168.46

Data source: Brade and Harwood (1992).

Although actual data was difficult to obtain from Anglian Water services, the analysis presented indicates a potential saving of up to £6.1 million per year are feasible, which expands to over 1.7% of operating profits (Anglian Water, 1999).

6.5 Discussion.

The results of this work emphasise the need for the Water Company to be aware of the external environment influencing strategy and satisfy the needs of the stakeholders influencing the direction of the company. The issue of bio-solids management is largely driven by politics, which are primarily concerned with the perception of the electorate. Costly legislation, which has increased in intensity in recent years, causes reactive research by the company to satisfy legislation without incurring excessive cost. The use of novel approaches to problems can result in cost savings and added product value, clearly illustrated by the success of Terra Eco-Systems (Evans 1998). The market analysis, presented in *Section 6.3*, illustrates the willingness of all user groups to accept the new technology and highlights the lack of education in this subject area. Bio-solids quality issues overwhelmed agronomic and financial issues, suggesting that the issues of potentially toxic elements and pathogens must be overcome before a pricing strategy for sludge can be developed for application to arable cropping. The concerns expressed in the market analysis towards agronomic performance and emissions have been addressed through the design of the 40WNDLI injector, which incorporates bio-solids into the soil, without excessive crop damage, resulting in lower emissions of ammonia and limited detrimental effects on crop performance.

Effectively, the improved performance of the 40WNDLI injector has the potential to add significant value to the bio-solids recycling process. This is reinforced in the financial analysis of the cost of application by four methods (*Section 6.4*). The emphasis on the increased application "window of opportunity", provided by the

ability to incorporate bio-solids into arable cropping, results in considerable cost reductions through economies of scale. The extent of these cost reductions is such that the increased cost of the machine is negligible, as major savings are made across the logistical parameters (storage and distribution) of the bio-solids operation. The results of this study suggest that the following financial benefits of bio-solids incorporation into arable cropping may be accrued:

- Reduced machinery compliment (35%).
- Lower storage requirement (90%).
- Lower distribution costs resulting from more efficient use of tankers (>50%).
- Greater financial value of the product due to reduced emissions (>70%).
- Larger “application window of opportunity” hence more even use of labour and services (50%).

These benefits, combined with the added value offered by application during the crop growing season when crop demand for nutrients is higher, indicate that the incorporation of bio-solids into arable cropping could be beneficial to both the water company and its external influencers.

6.6 Conclusion.

The application of bio-solids to arable cropping is a value-added product, found to be acceptable to the user, and with the potential to significantly reduce the cost of bio-solids recycling to the Water Company.

Chapter 7

7.0 Injector tine depth control: The effect of angle of inclination on injector performance.

7.1 Introduction.

The 40WNDLi injector performed well in field trials, demonstrating its ability for improved bio-solids incorporation into arable cropping, from both environmental and agronomic considerations. Additionally, the economic viability of the 40WNDLi system has considerable potential, given a willing market and the ability to make substantial savings through economies of scale as a result of the extended “application window”. Field trials were conducted using a Greentrac™ slipper foot injection system, with the injector mounted on a parallel linkage to maintain a constant tine/soil attitude. When using a linkage of this type for tillage operations, it is usual for some form of depth control mechanism to be employed to control the linkage and implement depth (Kepner *et al*, 1978) (usually a depth wheel or cutting disc). The 40WNDLi injector tine has no such control device, for depth control assistance, relying wholly on soil conditions and the downward force applied by springs contained within the parallel linkage system (Fig. 7.1).

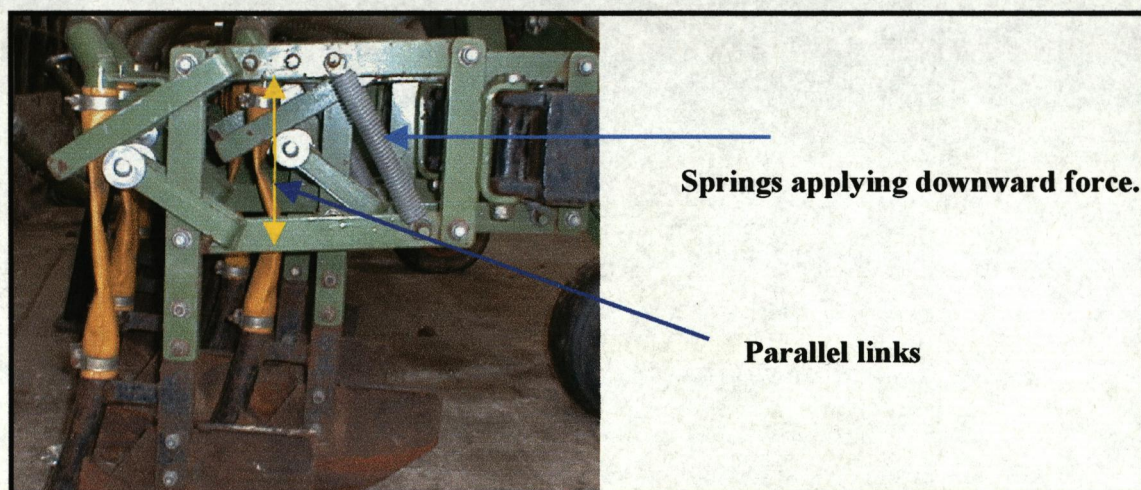


Fig. 7.1 Parallel links and springs.

The improved environmental and agronomic performance illustrated by the 40WNDLi tine during previous trials may be compromised by inadequate depth control in the field. Three scenarios have been identified:

1. Too deep; resulting in excessive lateral disturbance and increased risk of crop damage.

2. Optimal depth; resulting in insignificant crop damage and maximum environmental benefit through reduced emissions of ammonia and odour.
3. Too shallow; resulting in bio-solids spillage, onto the soil surface and, as a consequence, increased emissions of odour and ammonia.

The ability to control the 40WNDLi system at an optimal depth over field undulations is essential if maximum performance is to be realised.

To enable a constant operating depth to be maintained throughout the bio-solids application operation, other linkages could be used to allow tractor draught control systems to control implement depth. Models have been developed, which provide improved response to surface undulations using pure draught force sensing techniques (Dwyer *et al*, 1974). However, these models used linkages with real or virtual hitch points, implying that an implement would need to accept changes in angle of inclination to the soil during the tillage operation. It is possible to design linkages to take advantage of the theories of response, providing that implement performance is unaffected by changes in angle of inclination. In consideration of these factors, it is necessary to assess the performance of the 40WNDLi tine at varying angles of inclination to the soil, to establish the effect of these changes on the performance characteristics described in previous chapters.

7.1.1 Objectives.

The objectives of this study are:

- To evaluate the performance of the 40WNDLi injector tine at various angles of inclination to the soil surface and;
- To establish the type of linkage necessary to maximise the environmental and agronomic performance of the 40WNDLi injector tine.

7.2 Methodology.

A soil dynamics laboratory experiment was designed to assess the soil force and disturbance characteristics of the 40WNDLi tine, at several different angles of inclination to the soil surface. The methodology used is as described in *Section 2.6*, whereby the soil bin was prepared to a standard bulk density and moisture content, and the implement was operated at selected depths, maintaining a velocity of 0.55 m/s along a section of the prepared soil surface. Forces were measured through an

Extended Octagonal Ring Transducer (EORT) and recorded using the equipment described in *Section 2.6.4*. Measurements of the lateral and vertical extent of the upper and lower soil profiles were made using the miniature soil profile meter described earlier (*Section 2.6.5*). Soil profiles were subsequently digitised for computer analysis of selected disturbance parameters.

7.2.1 Force measurement.

In addition to recording soil forces using the signal conditioning unit and hard copy printout system, described in *Section 2.6.4*, a computer based data-logging system was used for force measurement. Each of the three channel outputs from the EORT were passed through strain gauge conditioning modules (*Straininstall Model 91c*), which amplified the small μV return output from the EORT. The signal was then diverted to a simultaneous sample and hold circuit, to remove multiplex skew, and subsequently fed to a CIO-DAS16/330 (ComputerBoards Inc, Mansfield, MA02048) analogue to digital converter, connected to a desktop computer system (P200, 32Mb RAM, Win95 O/S). Labtech Notebook (Version 10.0.2) was used for signal recording at 37 Hz and storage in text output file structure. The recorded output was processed using a computer spreadsheet to allow the signal to be smoothed. Two seconds of mean data was captured to represent the soil forces acting during each experimental run. This data was converted to force using equations derived during calibration prior to testing.

7.2.1.1 Data-logger calibration.

The computer data-logging system was calibrated prior to injector testing, by recording the EORT output during the addition of known weight to its horizontal and vertical bridge circuits. The weights added were 5, 25, 45, 65, 85 and 105 kg, with recording continuing while the weights were removed. The resulting computer generated output was plotted and 1 s time slices were meaned to represent the voltage output for the corresponding applied force. A calibration graph was subsequently produced and a fitted line applied using the computer spreadsheet package. Calibrations were carried out across the draught and vertical force channel outputs from the EORT at two levels of amplification, for data recorded by conventional methods described in *Section 2.6.4* and by computer data-logging (*Appendix 6.1*).

7.2.1.2 Data-logging; experimental procedure.

The use of a computer data-logging system required modifications to the procedure for injector tine testing, as a period of zero force input was required prior to each test allowing offsets due to gauge inaccuracy or static load to be accounted for. This was achieved by initiating data-logging 5 s prior to each run, ensuring that the injector tine was under no load. The resulting initial value, when meaned to eliminate electrical noise, could be subtracted from subsequent data to provide the actual force produced during the test.

7.2.1.3 Data processing.

All data were treated in the same manner:

- The raw output was imported into a computer spreadsheet, and each channel (draught and vertical force) was subjected to a moving average smoothing over 0.25 s, to eliminate electrical noise.
- Data was corrected for gauge inaccuracy, or static load, by subtracting a mean of 2 s (74 values at 37 Hz) of initial data from the subsequent test data.
- Data was converted to force using the calibration equations presented in *Appendix 6.1*.
- A mean of 2 s of force data relating to the test run was used as a measurement of injector tine force requirement.

The results of the computer data-logged forces were used in preference to the conventional force measurements due to increased accuracy.

7.2.2 Soil disturbance measurement.

Initial soil disturbance measurements were identical to those described in *Section 2.6.5*. However, the analysis of results, which includes the measurement of parameters outlined in *Section 2.6.5*, was more comprehensive than that described in *Chapters 2 and 3*. A number of soil disturbance parameters were identified as indicators of soil disturbance performance (*Fig. 7.2*).

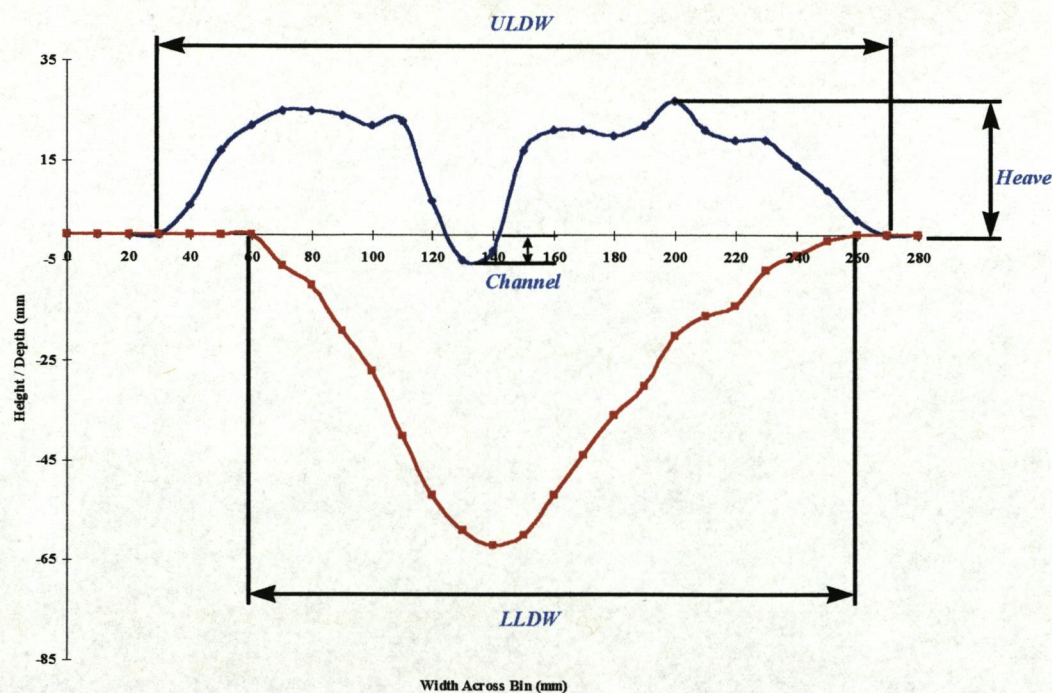


Fig. 7.2. Additional soil disturbance parameters under investigation.

7.2.2.1 Heave.

The heave of soil above a datum (original soil surface) allows an assessment of the effect of increasing the angle of the wings to the horizontal to be made. It is expected that changing the angle of inclination of the injector tine, will affect the degree of heave experienced.

7.2.2.2 Lateral disturbed width.

The width of soil disturbed during the passage of the injector tine through the soil can be segregated into two categories; the upper and lower lateral (ULDW & LLDW). These two parameters should enable the severity of tine/crop interference to be assessed in comparison with the normal disturbance produced in previous field and laboratory experiments. The upper lateral disturbed width (ULDW) can be used to provide an indication of the degree of throw of the soil, resulting from the effective change in geometry as a consequence of different tine inclination angles. The lower lateral disturbed width (LLDW) may provide indications of the effect of reducing the clearance angle between the tine wings and the horizontal. The maintenance of both of these parameters is essential for optimum environmental and agronomic performance.

7.2.2.3 Channel.

The production of a channel has previously been associated with existing shallow injection methods, such as the Greentrac™ slipper foot injector, which typify bio-solids placement rather than incorporation. Channel formation has been found to be undesirable, as increased harmful emissions result from bio-solids placement. A change in tine geometry resulting in the production of a channel for bio-solids placement would be considered unacceptable environmentally. The channel is defined as the extent of the central dip above or below the datum.

7.2.3 Theoretical application rate.

The theoretical application rate is a characteristic of shallow injection that must not be adversely affected by the dynamic performance of the injector. As part of the assessment of the 40WNDLi injector at varying angles of inclination, the theoretical application rate will be calculated and compared with minimum specifications for shallow injection as detailed below.

At present, bio-solids application rates are governed by nitrogen quantity (MAFF 1993), which limits the annual dosage of nitrogen to 250 kg/ha. A typical sample of sewage sludge may contain between 5 and 7 % nitrogen, on a dry weight basis, with a 4% solids content. This equates to maximum permissible single applications of 125 and 90 m³/ha. It is feasible that a single application per year may be required of the 40WNDLi system, reinforcing the need for a minimum theoretical application rate of at least 125 m³/ha, within the limits of operating depth.

The operating depth of the 40WNDLi injector is limited to 0.08 m, and is expected to perform between 0.05 m and this limit. Similarly, injector tine spacing, were the system to be fitted directly to a Greentrac™ distribution system, would be 0.2 m. However the subsequent prototype system developed by the main project team (Pullen *et al*, 1997), and produced by Greentrac, uses a 0.25 m tine spacing.

Based on the operating limits of the 40WNDLi injector and legislation regarding maximum annual permissible levels of nitrogen, the following criteria have been

derived, to assess the performance of the 40WNDLi tine at varying angles of inclination, which must be satisfied:

- A minimum theoretical application rate of $125 \text{ m}^3/\text{ha}$, below an operating depth of 0.08 m for injector tine spacing of 0.25 m.
- A theoretical application rate of $50 \text{ m}^3/\text{ha}$, at a maximum operating depth of 0.05 m for an injector tine spacing of 0.25 m.

7.2.4 Experimental design.

The 40WNDLi tine was tested at 7 angles of inclination to the horizontal, across its operational depth range (0.02 – 0.08 m). The angles tested comprised -15, -10, -5, 0, 5, 10, and 15 degrees (*Fig 7.3*). Experimental runs followed a randomised block design, to account for any variations in soil moisture content and density across the width of the soil bin.

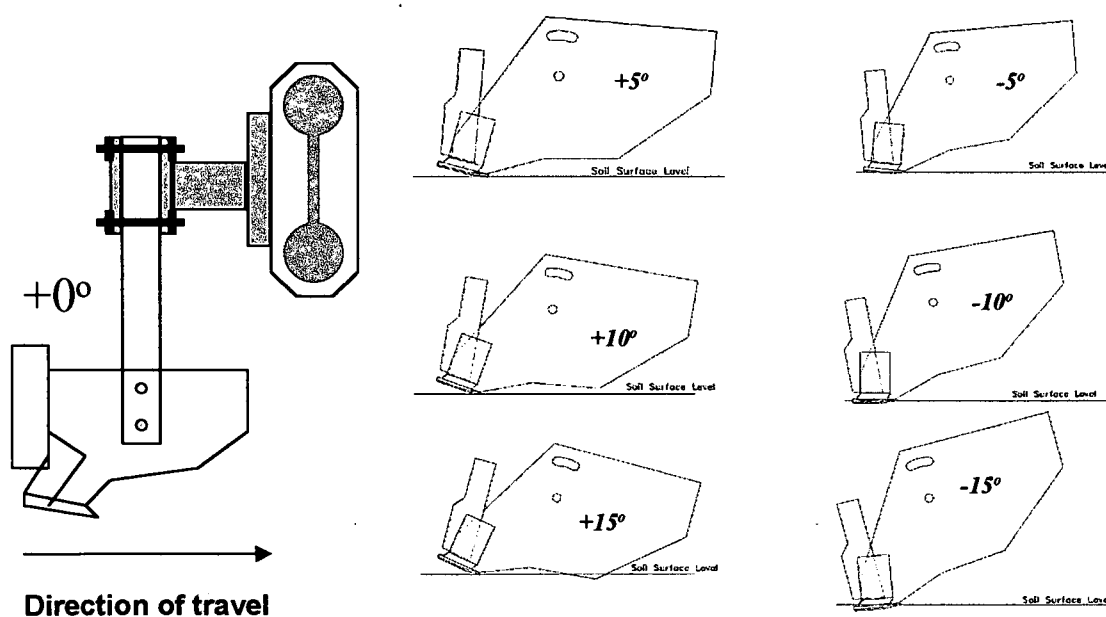


Fig. 7.3. Experimental test equipment and angles of inclination tested using the 40WNDLi injector tine.

Operating depths were measured from the point of the injector tine, resulting in other tine parts operating deeper than the point when tested at the extreme angles ($\pm 15^\circ$).

7.2.5 Soil properties.

Three replicates of soil samples for bulk density and moisture content were taken from each soil bin preparation, to allow the consistency of the test conditions to be assessed. These soil properties were calculated on a dry weight basis.

7.3 Results.

The results of this soil dynamics laboratory study were analysed statistically to assess the effect of altering the inclination of the injector tine on soil forces and disturbance characteristics. Results from a complete statistical analysis are presented in *Appendix 6.2*.

7.3.1 Soil properties.

Bulk density and moisture content was found to be constant over the period of testing, as no significant differences were observed between soil bin preparations for either soil property (*Fig. 7.4*).

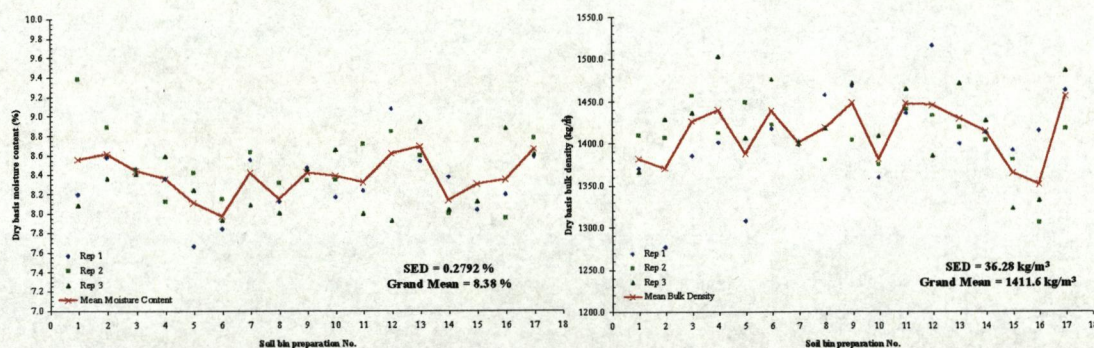


Fig. 7.4. Dry bulk density and moisture content for each soil bin preparation.

The results of these soil tests confirm that the soil bin testing facility is capable of providing constant soil conditions for laboratory studies.

7.3.2 Injector force requirements.

The force requirement of the 40WNDLi injector tine was measured by both conventional methods, described in *Chapter 2*, and by a computer data-logging system. An analysis of both sets of force data showed the results to be similar, with slightly higher variation experienced using the computer-based system, as a result of the increased resolution associated with this system. Although force was affected significantly by changes in angle of inclination, this was primarily due to testing at -15° , which is clearly illustrated in *Fig. 7.5*.

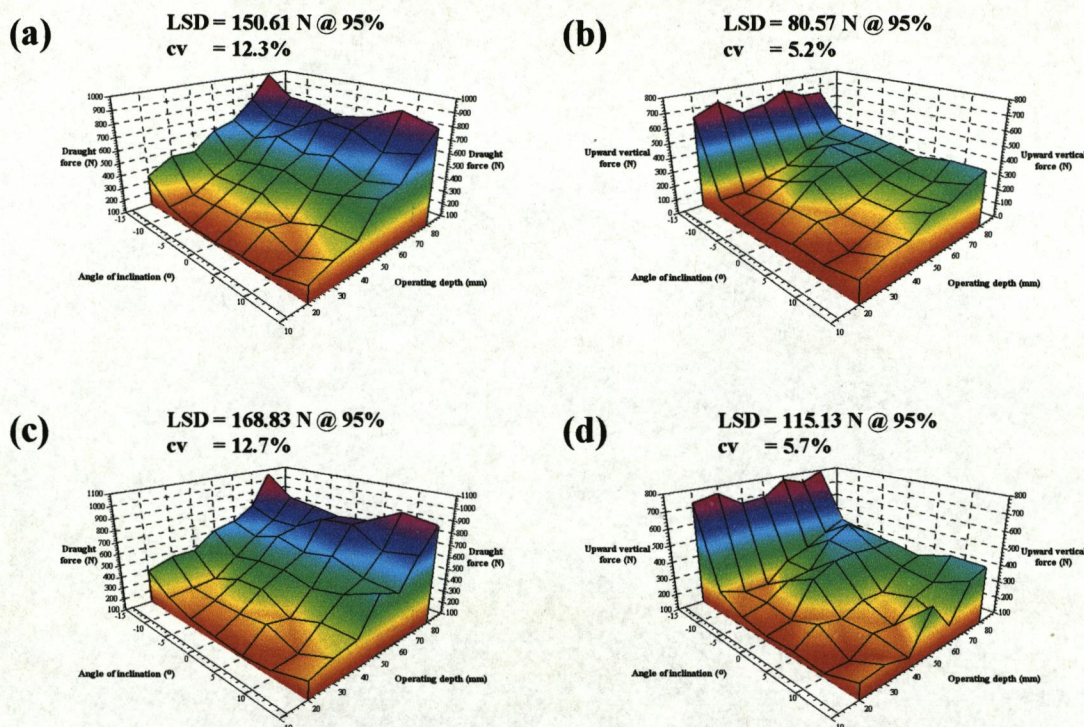


Fig. 7.5. Injector tine forces: a) draught force and b) upward vertical force using conventional data recording methods and; c) draught force and d) upward vertical force using computer data-logging equipment.

The use of the injector at an angle of inclination that results in a negative clearance angle between the wings and the soil surface, creates compaction under the tine and significantly increases the upward vertical force acting on the tine/linkage system. When discounting the extreme backward inclination (-15°), forces were generally unaffected by a change in angle of inclination.

Comparison of the forces obtained in previous soil dynamics studies using the 40WNDLi injector shows good agreement, although the results presented in *Chapter 3* are slightly higher than those experienced in this study, possibly as a result of a slightly higher soil bin moisture content in the previous study.

7.3.3 Soil disturbance characteristics.

In general, the additional soil disturbance characteristics measured illustrated little effect of angle of inclination (*Fig. 7.6*). However, a significantly wider upper lateral disturbance was observed when the injector was tested with rearward inclination (*Fig. 7.6a*).

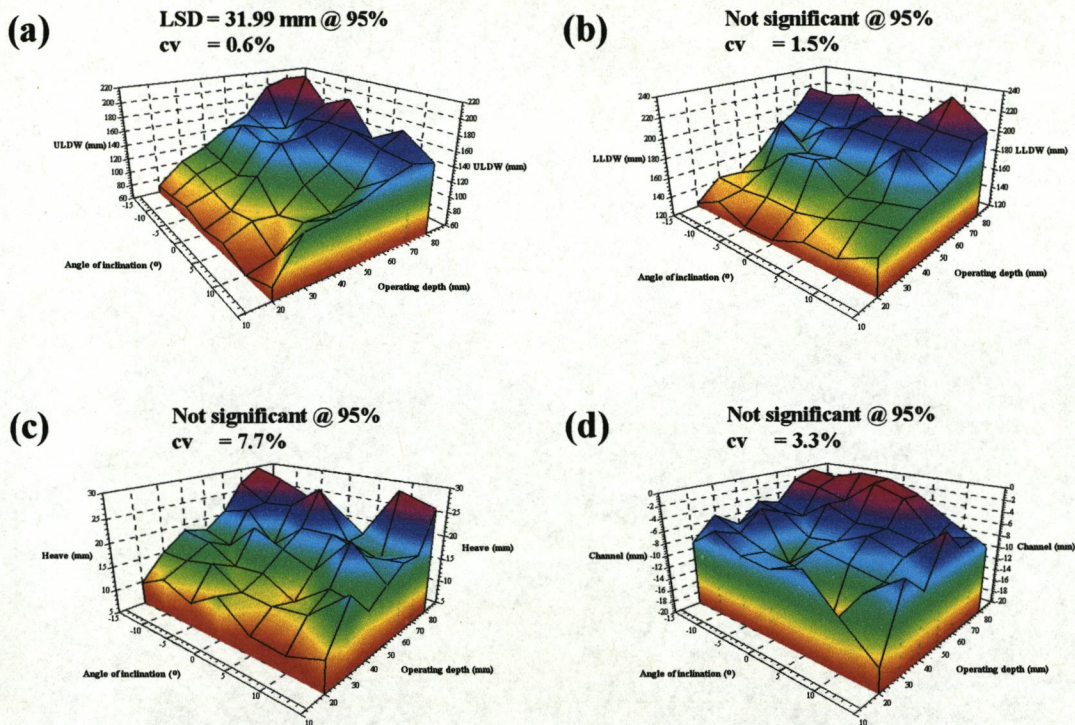


Fig 7.6. The effect of angle of inclination on a) upper and b) lower lateral

disturbance, and c) heave and d) channel, across the tested operating depth range.

Alteration of the angle of inclination by $\pm 10^\circ$ of the normal attitude of the injector is unlikely to affect the soil disturbance parameters investigated significantly. However, of more importance is the potential effect on theoretical application rates, which must conform to the criteria established in Section 2.2.6.

7.3.4 Theoretical application rates.

The theoretical application rates possible at varying degrees of inclination have been calculated based on both 0.2 and 0.25 m injector tine spacing (Fig. 7.7). All calculations discounted the central depression caused by the passage of the injector, as the use of this space for bio-solids placement has been found to be environmentally damaging by encouraging volatile emissions of ammonia.

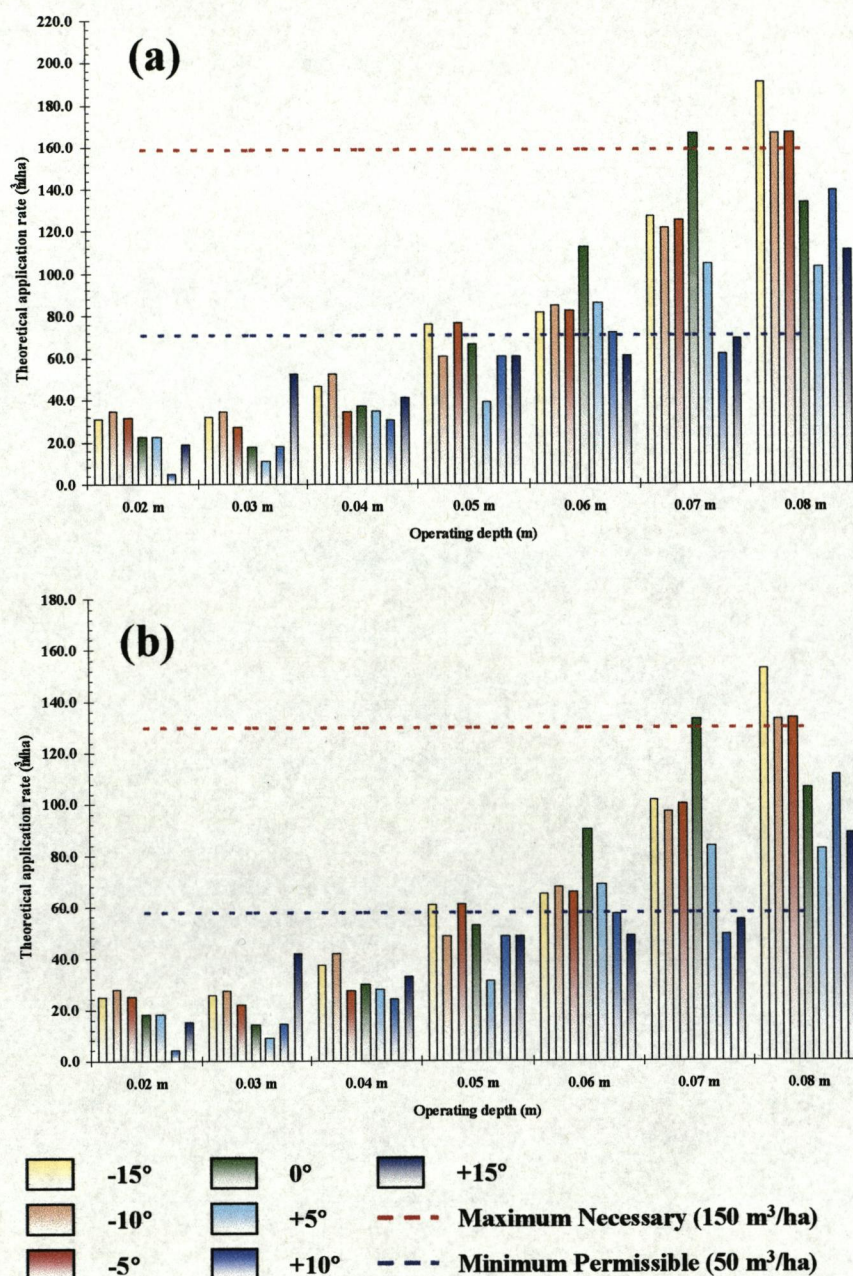


Fig. 7.7. Theoretical application rates with varying angles of inclination for the 40WNDLi injector tine at 7 depths and a) 0.2 and b) 0.25 m tine spacing.

Results from a regression analysis of the experimental data, suggest that the angle of inclination affects the theoretical application rate significantly when 0.25 m injector tine spacings are used (*Appendix 6.3*). The expected safe operating limits of the 40WNDLi injector are between 0.05 and 0.08 m, with application rates likely between 50 and 150 m³/ha. To evaluate the suitability of the geometrical variation of the injector tine in terms of its angle of inclination, valid criteria for application rates acceptable is required.

7.3.5 Performance assessment (*theoretical application rate*).

A statistical regression analysis on the performance data gathered during the tests, allowed standard exponential curves to be fitted to data relating to theoretical application rate (*Fig. 7.8*).

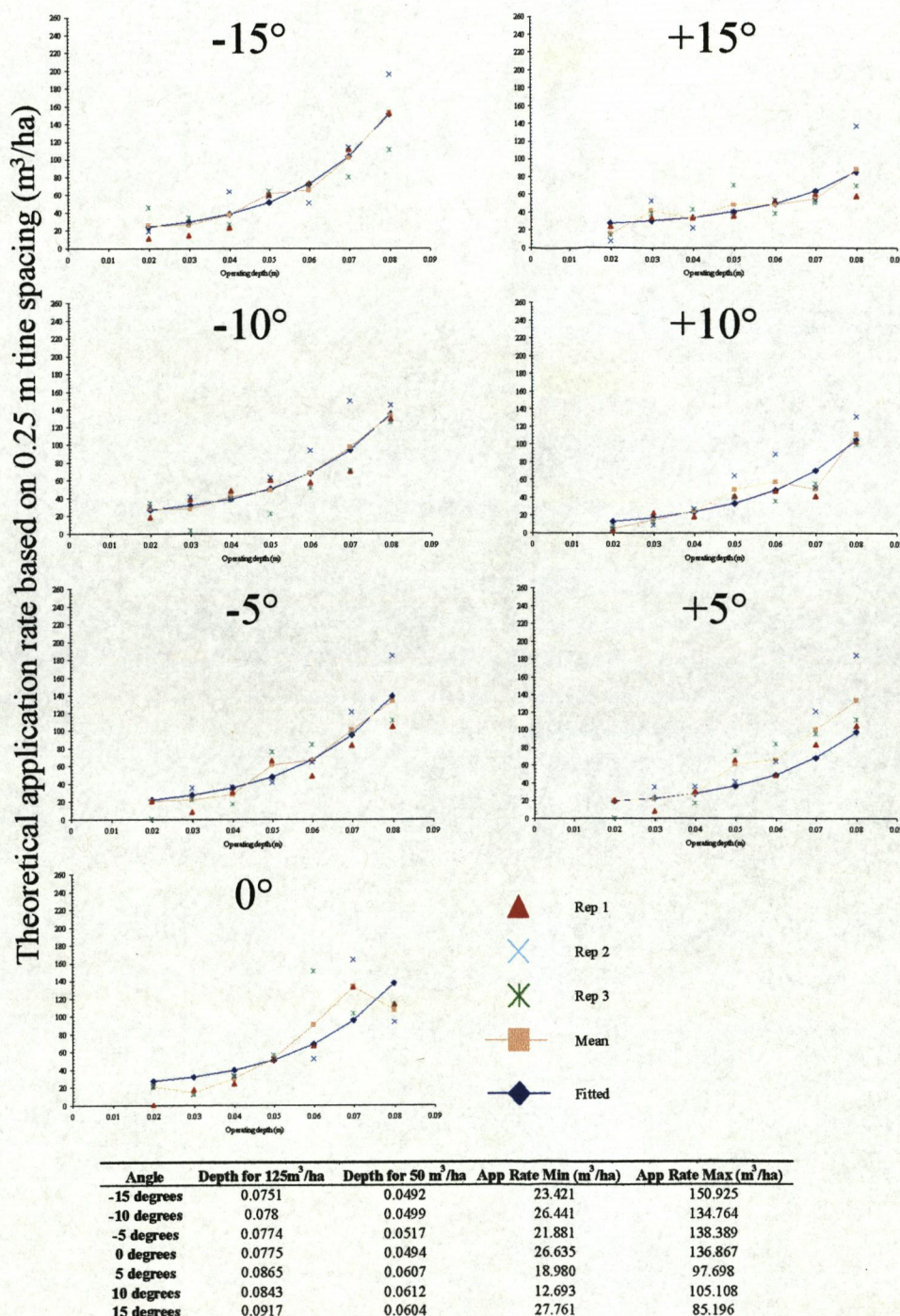


Fig. 7.8. Fitted and experimental theoretical application rates over the tested depth range at 7 angles of inclination for the 40WNDLi injector tine.

It was found that by inclining the injector forward (+5, 10 & 15°), the theoretical application rate reduced as a result of an increase in the extent of the channel produced, such that 125 m³/ha may only be applied at depths exceeding the operating limits of the injector. The minimum requirement to apply 50 m³/ha at 0.05 m has been found to be difficult to satisfy when forward inclination of the tine occurs.

7.4 Discussion.

Alteration of the angle of inclination of the 40WNDLi injector tine affects the performance of the tine in the following ways:

- Forces remain largely unaffected by angle changes, however, backward inclination to an extent that promotes compaction under the injectors' wings, significantly increases the upward vertical forces acting on the system.
- Disturbance characteristics are generally unaffected by angle changes. However, backward inclination significantly increases the extent of upper lateral disturbance, increasing the possibility of crop interaction and damage.
- Although insignificant, an increase in the size of the channel produced following forward inclination was observed. This is a result of the increased angle of the wings forcing soil upwards and outwards.
- Altering the angle of inclination of the injector affects the theoretical application rates of the injector significantly, resulting in the inability to satisfy practical requirements in terms of application rates following slight forward inclination.

The detailed statistical analysis regarding theoretical application rates, allows limits on the inclination angle of the 40WNDLi tine to be ascertained. These limits consider the practical criteria, established in *Section 7.2.3*, i.e. that at least 125 m³/ha of bio-solids can be applied within the operating limits of the injector tine (<0.08 m operating depth). The operating depth requirement needed to satisfy this application rate, was calculated based on fitted data for all the tested angles of inclination. A 2nd order polynomial curve fitted the data well (*Fig. 7.9*), illustrating that any forward inclination of the injector results in performance outside the desired working limits of the injector.

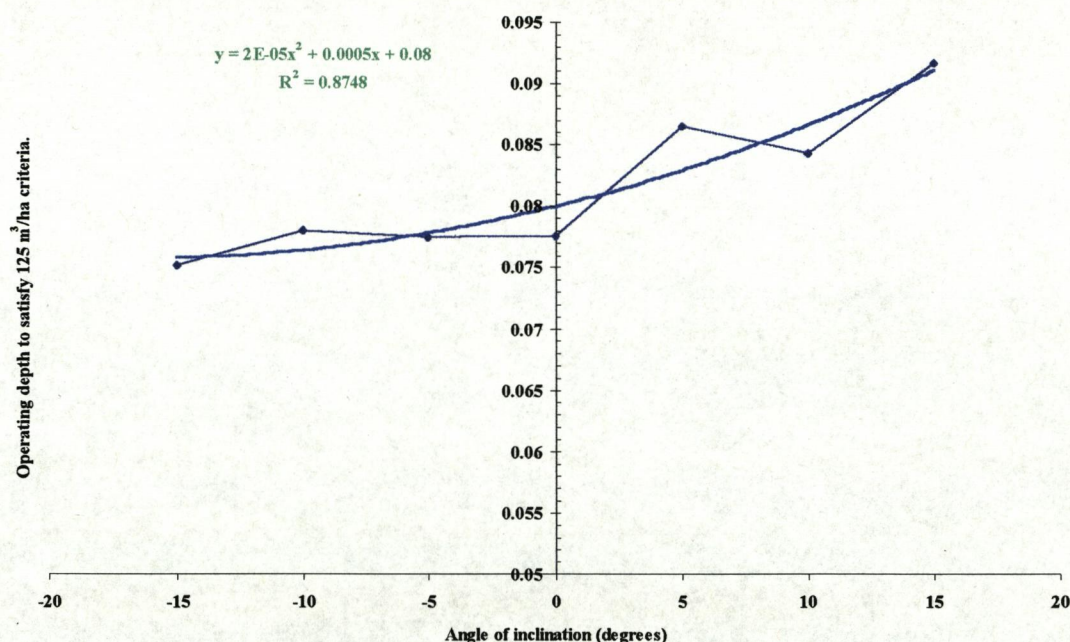


Fig. 7.9. Operating depth necessary to satisfy a theoretical application rate of 125 m³/ha at 0.25 m tine spacing at varying angles of inclination of the 40WNDLi injector.

The ability to satisfy application rate criteria, combined with the significant increases in upward vertical force at extreme backward inclinations, and the increase in upper lateral disturbance through backward inclination, suggests that allowing the 40WNDLi injector tine freedom of movement in this respect is undesirable.

To maintain the performance of the 40WNDLi tine, attachment to a parallel linkage device is necessary, restricting the injector to a single angle of inclination (0°) irrespective of operating depth. Kepner *et al* (1978) state that depth control associated with parallel linkage systems normally comprises discs or wheels to allow the surface profile to be followed. The 40WNDLi system has been designed for use without such systems, indicating that a detailed study of the dynamic performance of shallow injectors on parallel linkages is necessary to develop a suitable depth control system for the 40WNDLi injector and its associated parallel linkage system.

7.5 Conclusion.

In conclusion, to realise the environmental and agronomic performance benefits of the 40WNDLi injector through its improved soil disturbance characteristics, the angle of inclination of the tine must be restricted to its design angle (0°). This may be achieved by attachment to a parallel linkage system. However, detailed studies of the factors affecting the depth control of shallow injectors attached through the parallel linkage system are required. This will facilitate the development of a system to passively control the depth of the 40WNDLi tine, without the use of a depth wheel or cutting disc, while maintaining the desired angle of inclination of the injector.

Chapter 8

8.0 Injector tine depth control: Initial analysis of dynamic performance.

8.1 Introduction.

The study presented in *Chapter 7*, concluded that optimal soil disturbance and force characteristics of the 40WNDLi injector tine could be fully realised by maintaining a constant tine/soil attitude in work. In order to exploit the environmental benefits of using the 40WNDLi tine, optimal soil disturbance patterns and injector operating depth should be maintained. Kepner *et al* (1978) outline the principle of the parallel linkage system, found to be of particular use in situations where a degree of lateral rigidity is preferred, such as in row crop work and suggest that depth wheels normally achieve depth control. The slipper foot injection system utilises a disc cutter for crop separation and depth control. However, the 40WNDLi injector tine has been designed specifically for use without such a device.

Previous depth control studies have concentrated on both the lateral and vertical control of tractor mounted implements (Cowell & Mekanjuola, 1966; Cowell, 1969-70; Dwyer *et al*, 1974; Crolla & Pearson, 1975). These studies considered the use of "active" draught sensing systems for depth control. Modelling techniques allowed predictions to be made regarding the dynamic response of an implement to surface undulations and lateral deflections. However, these models relied on the use of linkage systems that exhibit real or virtual hitch points, about which moments may be calculated. The hitch point of a parallel linkage is at infinity as the horizontal links of the system are parallel, deeming the use of previous models for implement response impractical in this situation. Consequently, the use of depth wheel devices for depth control on parallel linkage systems has reduced the need for dynamic performance analysis on parallel linkage systems to date. In order to progress this study, there is a need for detailed research on the dynamic performance of implements attached to parallel linkages.

To enable an understanding of the factors influencing the dynamic response of injector tines to be gained, a preliminary study to assess the performance of different injection systems is necessary. Accepting that all force systems strive for equilibrium conditions, a thorough study of linkage and injector forces may allow injector tine operating depth to be predicted on a quasi-static basis. A visual comparison of

predicted (quasi-static), and observed (dynamic), soil profiles may facilitate the evaluation of dynamic performance and allow the factors influencing this performance to be identified. This may enable manipulation of the parallel linkage system to optimise dynamic performance.

8.2 Objectives.

The objectives of this preliminary study, involving the 40WNDLi, NSH and Retro injector tines, are:

- To analyse the force system of the Greentrac™ parallel linkage and combine this with accurate injector tine data, to allow predictions of the quasi-static injector tine operating depth to be made under constant soil conditions.
- To develop a methodology for the measurement of the dynamic performance of injector tines operating through parallel linkage systems.
- To use the methodology developed above to evaluate the performance of selected injector tines, when subjected to surface undulations.
- To identify the factors within the system that influence dynamic performance.

8.3 Parallel linkage.

The parallel linkage, utilised by Greentrac™ on their slipper foot injection system, comprises two vertical and two horizontal parallel bars (*Fig 8.1*). The front vertical link is fixed to the implement toolbar, and the rear vertical link moves within restrictions imposed by the horizontal links, its parallel nature maintained by the horizontal links. All links are connected by pin joints (M14×75 bolts and nylock nuts). A complete engineering drawing of the parallel linkage is presented in *Appendix 7.1*.

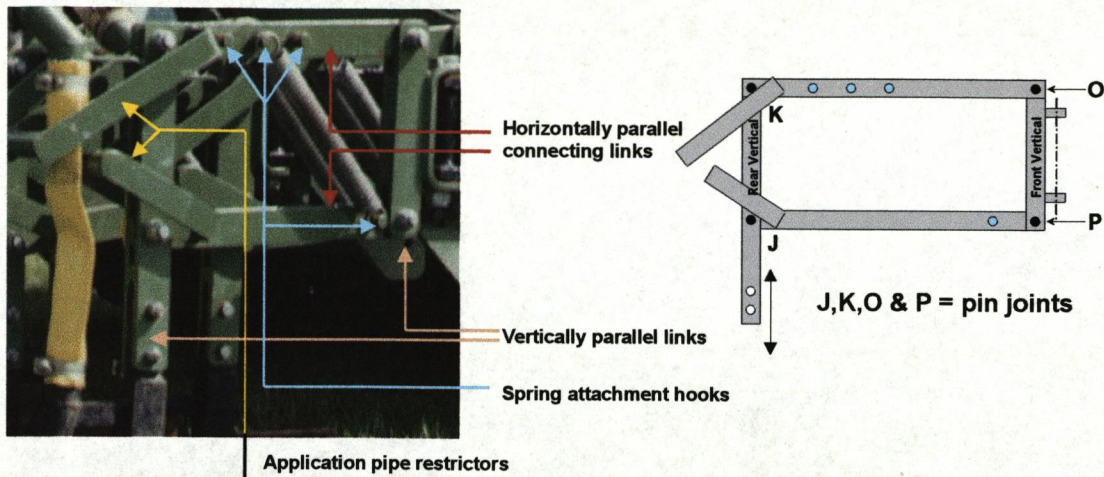


Fig. 8.1 Main components and schematic diagram, of the Greentrac parallel linkage.

8.3.1 Basic parallel linkage system.

The Greentrac™ parallel linkage combines linkage movement with bio-solids application control, using application pipe restrictors to clamp application pipes as the implement is withdrawn from work and to restrict vertical movement of the linkage.

The linkage has three main positions (Fig. 8.2):

1. Rest.
2. Work.
3. Maximum displacement.

8.3.1.1 Rest.

At rest, (i.e. withdrawn from work), the linkage is at its lowest position, restricted from further downward vertical movement by the application pipe restrictors attached to the upper and lower horizontal links.

8.3.1.2 In work.

During field operation the parallel linkage is free to move in the vertical plane, with a maximum operating displacement of 0.257 m. 10° of lateral freedom is afforded either side of the normal direction of travel.

8.3.1.3 Maximum displacement.

At the maximum vertical displacement of the linkage, i.e. the opposite of the linkage position at rest, the lower application pipe restrictor butting up against the back face of the rear vertical link restricts linkage movement.

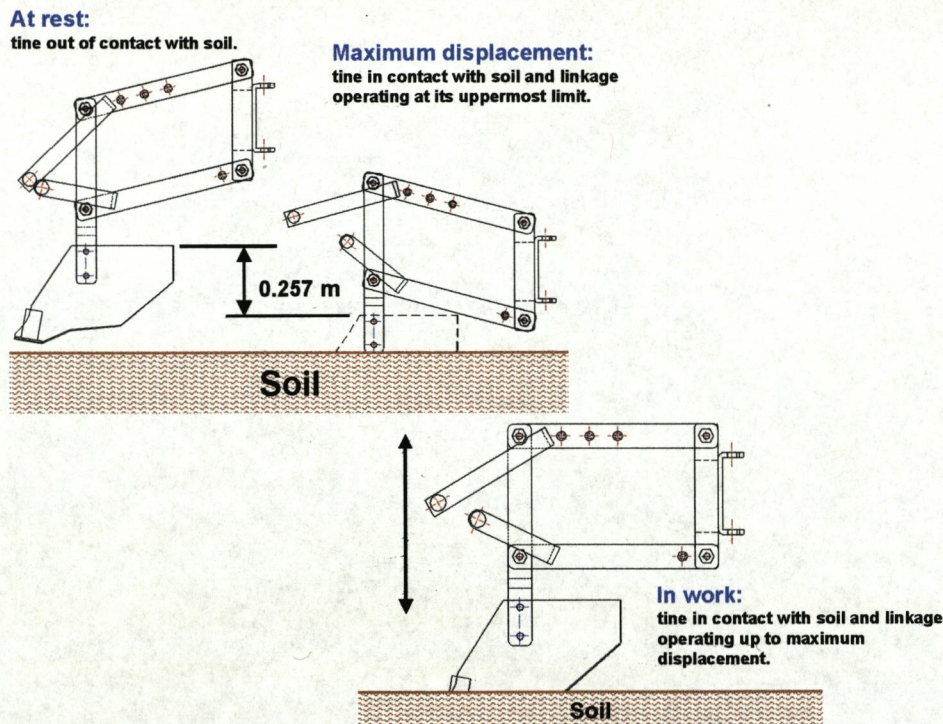


Fig. 8.2. Operational parameters of the Greentrac parallel linkage.

8.3.2 Applied spring force.

The parallel linkage, in addition to allowing a constant implement attitude (angle of inclination) to the soil, allows downward force to be applied to assist soil penetration. This system was primarily designed for use with the slipper foot injector, which relies on channel production in the soil and bio-solids placement (an operation, which requires significant downward force). The results, presented in *Section 4.3.1*, suggest that although the need for applied downward force is significantly lower for the 40WNDLi tine, the soil dynamics laboratory analysis, using a sandy loam soil, identified a need for at least 0.5 kN of downward force.

Downward force is applied by up to two springs, which may be attached to the horizontal links of the system. Fig 8.3 illustrates the locations of these springs, which extend as the rear vertical link is raised or forced upwards, as a result of either lowering the hitch point, or soil forces acting on the tine forcing the injector out of work.

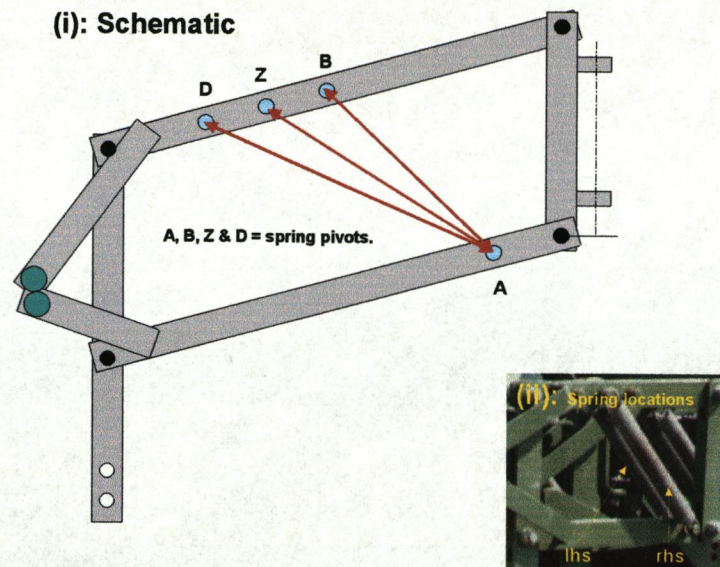


Fig. 8.3. Spring locations on the parallel linkage, allowing downward vertical force to be applied.

Springs may be attached on both the right and left hand side of the horizontal parallel links (Fig 8.3ii), between spring pivots **AB**, **AZ**, or **AD** (Fig 8.3i).

8.3.3 Force analysis.

To better understand the relationship between the parallel linkage, which uses internal springs, and the complex 40WNDLi injector tine, a comprehensive force analysis was carried out.

Nomenclature

α	Angle of the spring/s to the horizontal.	(°)
δ	Angle of the resultant tine force R_f to the horizontal.	(°)
θ	Angle of the horizontal links to the horizontal (at linkage rest, $\theta = +ve$).	(°)
F_h	Horizontal component of spring force about spring pivot "A"	(N)
M	Mass of the linkage measured at the rear vertical link	(N)
T_m	Mass of the injector tine configuration	(N)
T_e	extension of the injector tine configuration below the rear vertical link	(mm)
d	Operating depth of injector tine	(mm)
V_f	Vertical component of the injector tine configuration force, -ve = upwards	(N)
D_f	Horizontal component of the injector tine configuration force	(N)
R_f	Resultant injector tine configuration force acting at δ to the horizontal.	(N)
d_1	Perpendicular distance from spring to horizontal link pivot "P"	(mm)
d_2	Perpendicular distance from spring to horizontal link pivot "O"	(mm)
d_3	Perpendicular distance from R_f to the imaginary horizontal link pivot "Q"	(mm)
H_h	Hitch height distance from toolbar centre to soil surface	(mm)
C	Distance from horizontal link pivot J to soil surface	(mm)
N	Vertical distance between horizontal link pivots "J" and "O"	(mm)
L_1	Distance between link pivot "O" and spring pivot "a" along "OJ"	(mm)
L_2	Distance between link pivot "P" and spring pivot "b,c or d" along "PK"	(mm)

L_1	Length between pivots of horizontal links	(mm)
L_4	Vertical distance between horizontal links	(mm)
L_5	Length of extension of the rear vertical link from pivot "J" to injector.	(mm)
L_6	Vertical distance from pivot "O" to toolbar centre.	(mm)
A	Spring pivot on lower horizontal link	(mm)
B	Spring pivot on upper horizontal link L_2 from "P"	(mm)
Z	Spring pivot on upper horizontal link L_2 from "P"	(mm)
D	Spring pivot on upper horizontal link L_2 from "P"	(mm)
SL	Spring length	(mm)
DL	Unstrained spring length (constant)	(mm)
N_s	Number of springs	
R	Spring rating	(N/mm)
F_{ab}	Force acting along the spring as a result of its extension	(N)
F_R	Spring force acting between spring pivots a distance d_3 from pivot "P"	(N)
Y_{ab}	Vertical distance between spring pivots	(mm)
X_{ab}	Horizontal distance between spring pivots	(mm)
L_r	Resultant anti-clockwise linkage moment	(Nmm)
T_r	Resultant clockwise injector tine moment	(Nmm)
L_f	Downward linkage force acting at $L_3 \cos \theta$ from X-X	(N)
T_f	Upward injector tine restoring force acting at $L_3 \cos \theta$ from X-X	(N)
X-X	Plane about which all moments are taken	

Sign Convention.

A sign convention is necessary to enable the force system to be evaluated correctly. With reference to *Fig. 8.4*, angles of δ below the horizontal datum of the soil surface are considered positive and contribute to the clockwise restoring moment, resulting from the passage of the injector system through the soil. Consequently, angles of δ above the horizontal datum are considered negative, as they assist the anti-clockwise linkage moment promoting tine penetration into the soil.

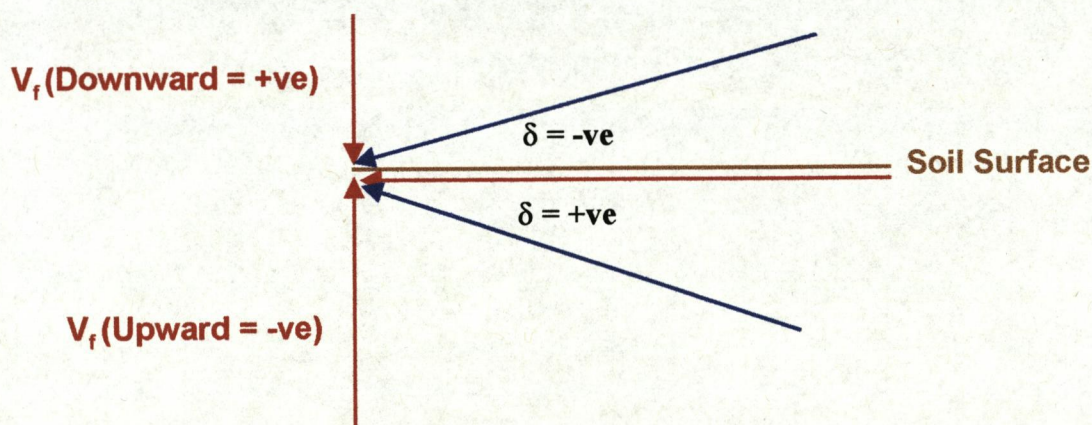


Fig. 8.4 Sign convention relating to δ

Similarly, with reference to *Fig. 8.5*, angles of θ above the horizontal datum where the parallel joining links are at right angles to the supporting vertical links are

considered negative, and angles of θ below the horizontal datum are considered positive.

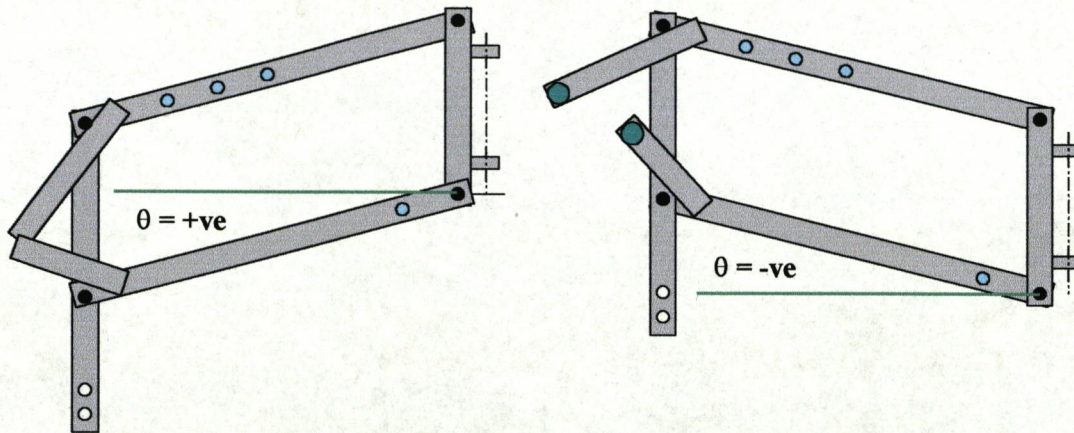


Fig. 8.5 Sign convention relating to θ

For equilibrium in the force system, the sum of the moments about the plane X-X (Fig. 8.6) must equal zero, and may be expressed as:

$$L_r + T_r = 0 \quad [1]$$

Where:

L_r = Linkage moment (-ve) acting anti-clockwise about a real datum in the plane X-X (Fig. 8.6)

T_r = Tine moment (+ve) acting clockwise about an imaginary datum in the plane X-X (Fig 8.6)

Fig 8.6 illustrates the force system, from which the linkage action and opposing tine reaction may be derived.

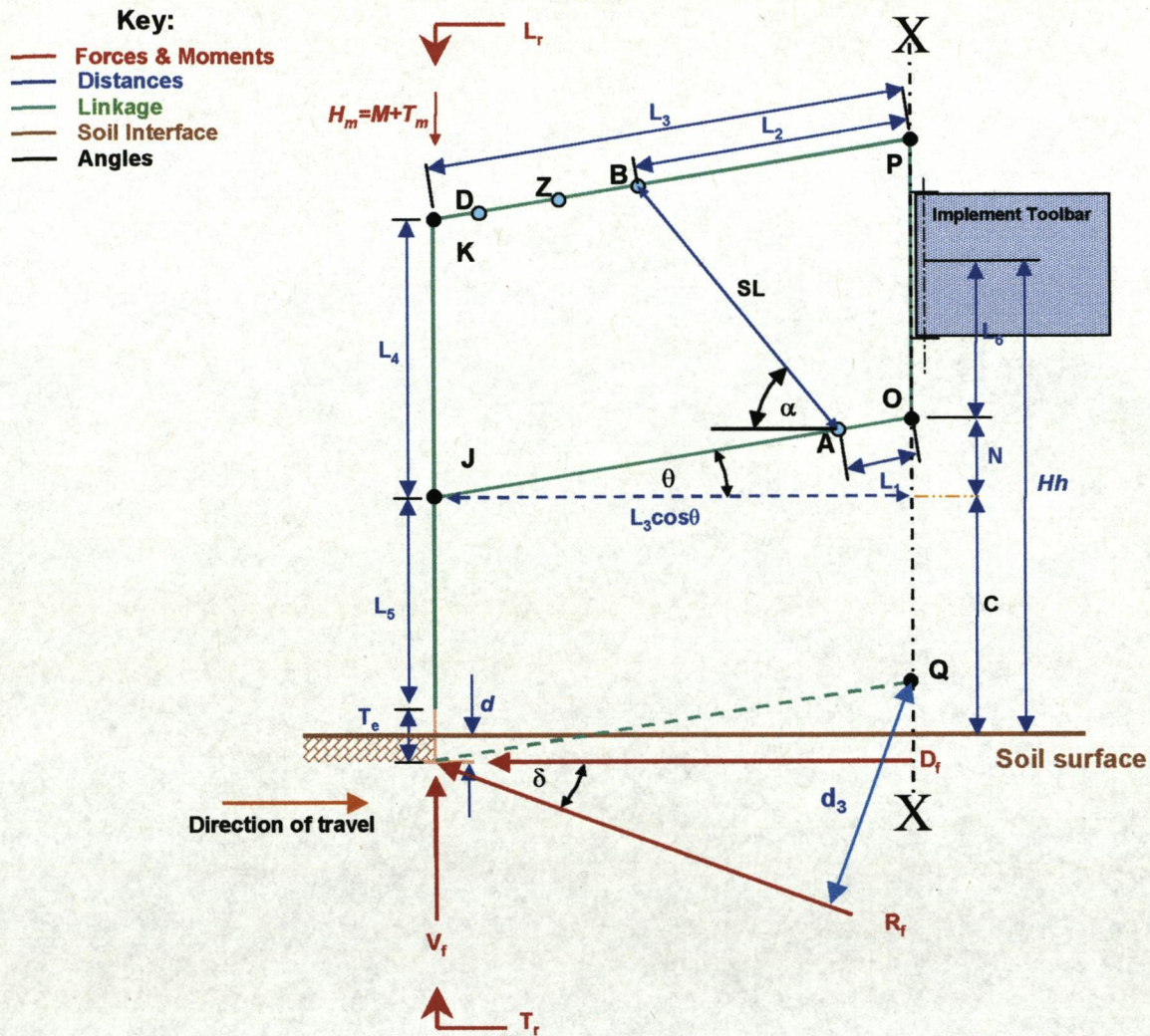


Fig. 8.6. Parallel linkage force system.

The system is complex as T_r is dependent on d , which affects θ , SL and hence L_r , which also affects d .

8.3.3.1 Linkage force analysis.

L_r consists of a number of forces resulting from the equivalent mass of the linkage and tine system, and the forces applied as a result of the spring system within the parallel linkage. As such, L_r may be expressed as:

$$L_r = L_f L_3 \cos \theta + H_m \quad [2]$$

A change in the hitch height of the implement toolbar has an effect on N , which is a function of θ . A change in θ results in a change in the resultant anti-clockwise moment L_r , resulting in a change in operating depth (d) of the injector tine. The

change in d results in a change in the clockwise restoring moment produced by the injector tine configuration, affecting θ once more.

$$\theta = \sin^{-1}\left(\frac{N}{L_3}\right) \quad [3]$$

Where:

$$N = Hh - C - L_6 \quad [4]$$

and:

$$C = L_5 + T_e - d \quad [5]$$

Substituting [4] and [5] in [3] gives;

$$\theta = \sin^{-1}\left(\frac{Hh - L_6 - (L_5 + T_e - d)}{L_3}\right) \quad [6]$$

Considering the anti-clockwise moments about the plane X-X, and with reference to Fig. 8.7:

$$L_f L_3 \cos \theta = F_r d_1 \quad [7]$$

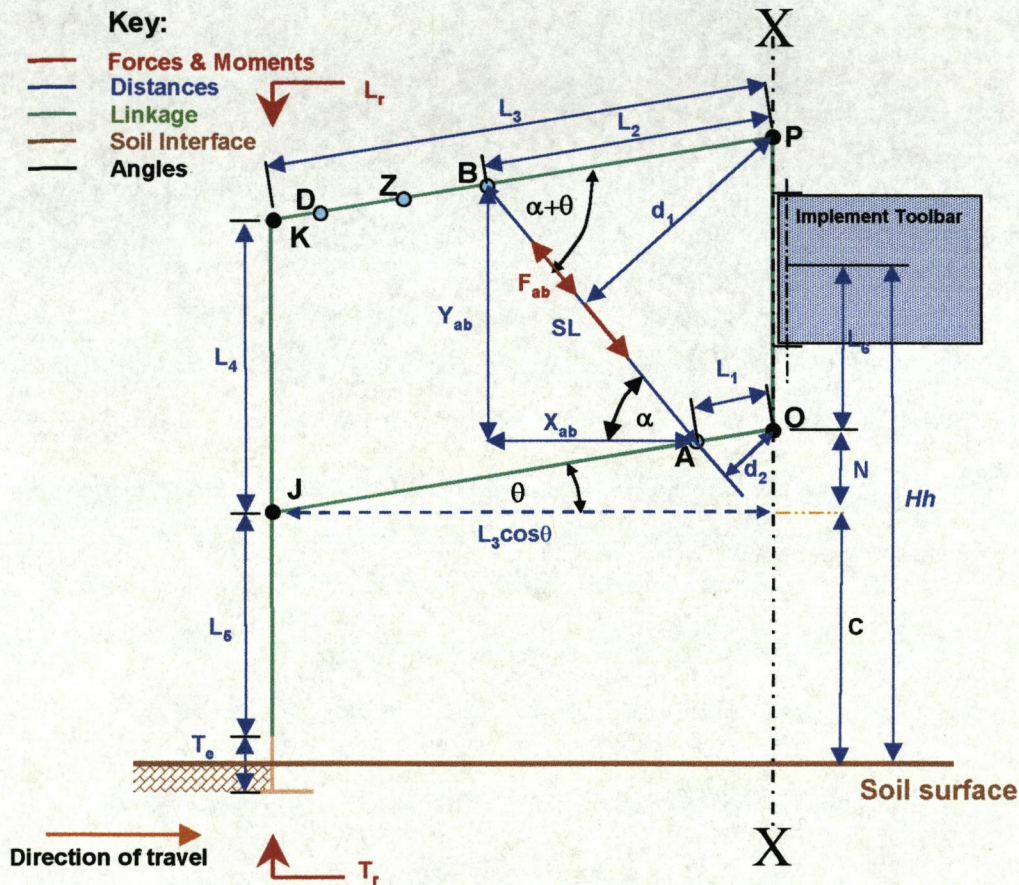


Fig. 8.7. Spring force schematic.

Where:

$$F_r d_1 = F_{ab} d_1 - F_{ab} d_2 \quad [8]$$

Considering the force F_{ab} :

$$F_{ab} = N_s R (SL - DL) \quad [9]$$

Where the spring length (SL) may be expressed as:

$$SL = \sqrt{X_{ab}^2 + Y_{ab}^2} + 10 \quad [10]$$

Where the addition of 10 accounts for the radius of the spring pivots and:

$$X_{ab} = (L_2 - L_1) \cos \theta \quad [11]$$

$$Y_{ab} = L_4 - (L_2 - L_1) \sin \theta \quad [12]$$

Considering the distances d_1 and d_2 :

$$d_1 = L_2 \sin(\alpha + \theta) \quad [13]$$

$$d_2 = L_1 \sin(\alpha + \theta) \quad [14]$$

where:

$$\alpha = \tan^{-1} \left(\frac{Y_{ab}}{X_{ab}} \right) \quad [16]$$

Hence by substituting [9], [11], [12], [13] & [14] in [7], the equation representing the linkage moment is:

$$L_r = N_s R \left[\left\{ \left((L_2 - L_1)^2 \cos^2 \theta + \left(L_4 - (L_2 - L_1) \sin \theta \right)^2 \right)^{1/2} - DL \right\} + 10 \right] (L_2 - L_1) \sin(\alpha + \theta) + Hm \quad [17]$$

acting anti-clockwise about the plane X-X.

8.3.3.2 Tine force analysis.

The forces acting on the system as a result of tine action comprise draught and vertical forces (Fig 8.8).

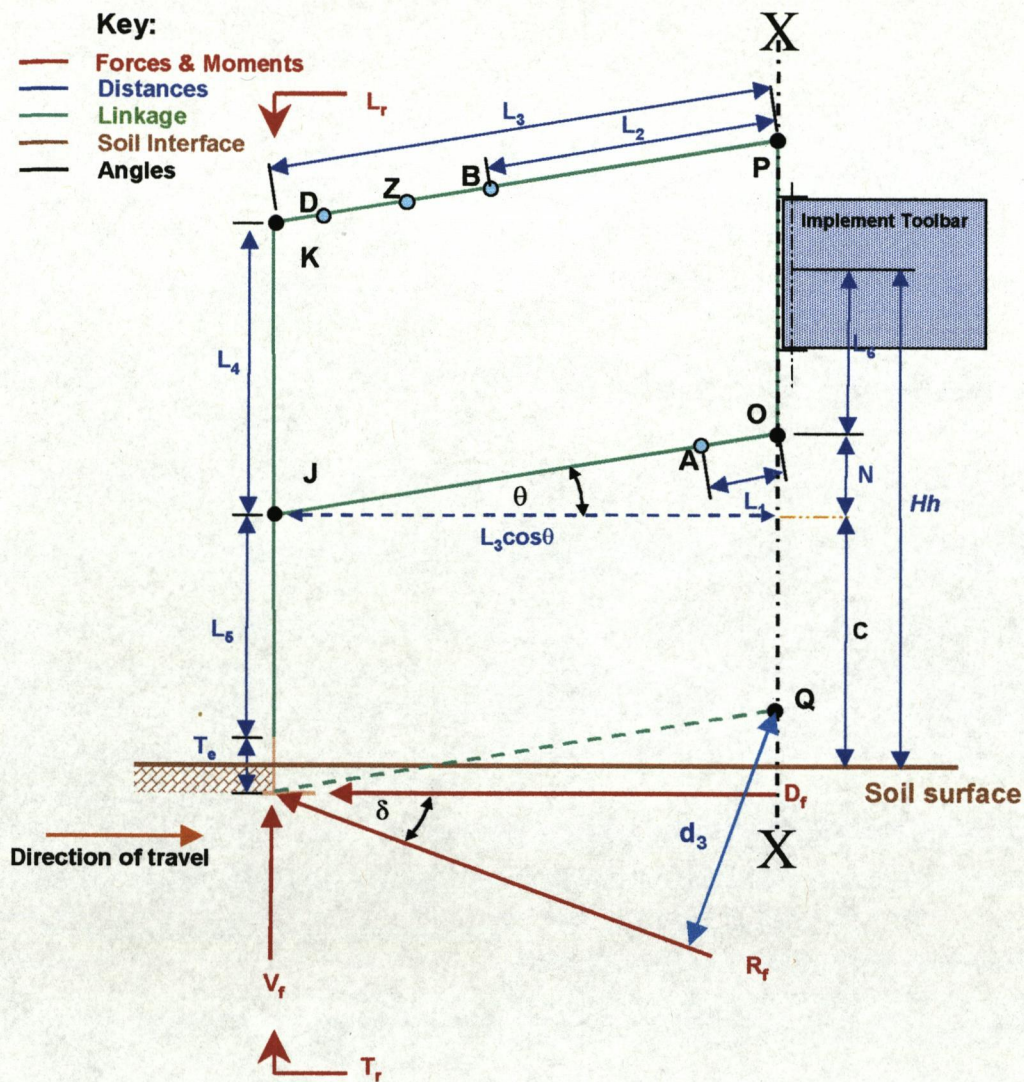


Fig. 8.8. Tine force analysis on the parallel linkage system.

The resultant force opposing the action of the linkage comprises a clockwise moment about Q (in the plane of X-X; *Fig. 8.6*), (*Fig. 8.8*), which can be expressed as:

$$T_r = T_f L_3 \cos \theta \quad [18]$$

Where:

$$T_f L_3 \cos \theta = R_f d_3 \quad [19]$$

The resultant tine force can be expressed as:

$$R_f = \sqrt{D_f^2 + V_f^2} \quad [20]$$

Acting at δ to the horizontal where:

$$\delta = \tan^{-1} \left(\frac{V_f}{D_f} \right) \quad [21]$$

and:

$$d_3 = l_3 \sin(\theta + \delta) \quad [22]$$

Hence the resultant clockwise moment opposing the linkage can be expressed as:

$$T_r = \sqrt{D_f^2 + V_f^2} L_3 \sin(\theta + \delta) \quad [23]$$

Acting clockwise about the plane X-X

8.3.3.3 General solution.

Combining the anticlockwise moment created by the linkage [17] and the clockwise restoring moment produced by the injector tine configuration in the soil [23], the general expression representing the moment system may be summarised as:

$$N_f R \left[\left\{ (L_2 - L_1)^2 \cos^2 \theta + (L_4 - (L_2 - L_1) \sin \theta)^2 \right\}^{1/2} - DL \right] + 10 \left[(L_2 - L_1) \sin(\alpha + \theta) + Hm = \sqrt{D_f^2 + V_f^2} L_3 \sin(\theta + \delta) \right] \quad [24]$$

Where:

$$\alpha = \tan^{-1} \left(\frac{L_4 \sec \theta}{L_2 - L_1} - \tan \theta \right) \quad [25]$$

$$\delta = \tan^{-1} \left(\frac{V_f}{D_f} \right) \quad [26]$$

$$\theta = \sin^{-1} \left(\frac{Hh - L_6 - (L_5 + T_e - d)}{L_3} \right) \quad [27]$$

Which may be translated directly to downward applied and upward restoring forces by dividing each side of equation [24] by:

$$L_3 \cos \theta \quad [28]$$

As both components of the general solution depend on d , the equation is implicit and requires iterative methods for solution. To enable quick comparisons to be made between predicted quasi-static and actual experimental operating depths in subsequent soil dynamics experiments, a computer spreadsheet model was developed to solve the force system for changes in hitch height, either as a result of surface undulations, or tractor hitch movement. This model is presented in *Appendix 7.2*. Similarly, an experimental verification of the linkage forces acting down the rear vertical link of the system, is presented in *Appendix 7.3*.

8.3.4 Injector tine forces.

The purpose of the system force analysis is to enable predictions of operating depth under dynamic conditions to be made, permitting dynamic performance assessment. To ensure that the system analysis is as accurate as possible, detailed injector tine force data are required, within and above the operating limits of the injector tines selected for dynamic study. Consequently, a soil dynamics laboratory study was conducted; to determine the forces associated with 5 selected injector tine configurations. The injector configurations used were:

1. NSH (without cutting disc).
2. NSH (with cutting disc).
3. Retro-fit (without cutting disc).
4. Retro-fit (with cutting disc).
5. 40WNDLi.

8.3.4.1 Methodology and experimental design.

Each injector tine configuration was replicated three times for draught and upward vertical force, at 0.01 m depth intervals, between 0.01 and 0.1 m. A randomised block design was used, to account for any variability in soil conditions across the width of the soil bin. Experimental procedure and equipment were identical to those described in *Section 2.6*. As in previous soil bin studies, dry bulk density and moisture content were monitored throughout the test period.

8.3.4.2 Results.

A statistical analysis of the soil conditions, in terms of bulk density and moisture content over the duration of injector tests, revealed no difference between soil bin preparations (*Fig. 8.9*). A complete statistical analysis of soil properties and injector forces is presented in *Appendix 7.4*. A low degree of variation ($cv = 4.4\%$) was experienced over the test period, resulting in a mean bulk density and moisture content of 1443 kg/m^3 and 9.7% respectively.

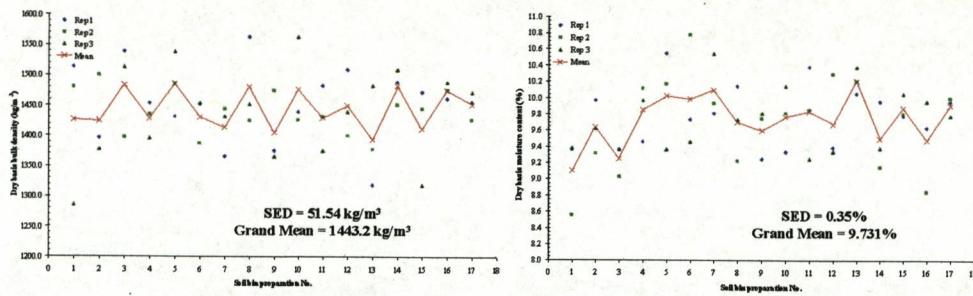


Fig. 8.9. Soil bin properties over the duration of injector tine tests.

A statistical analysis of both draught and vertical soil tine forces confirmed that each injector tine configuration was different in these respects. Subsequently, second order polynomial curves were fitted to mean draught and vertical force data, to allow tine reaction forces to be predicted dependent on depth. This enabled an experimental verification of the force system, presented in Section 8.3.3, to be achieved. Draught and vertical force data and fitted curves are presented in Figs 8.10 and 8.11 respectively.

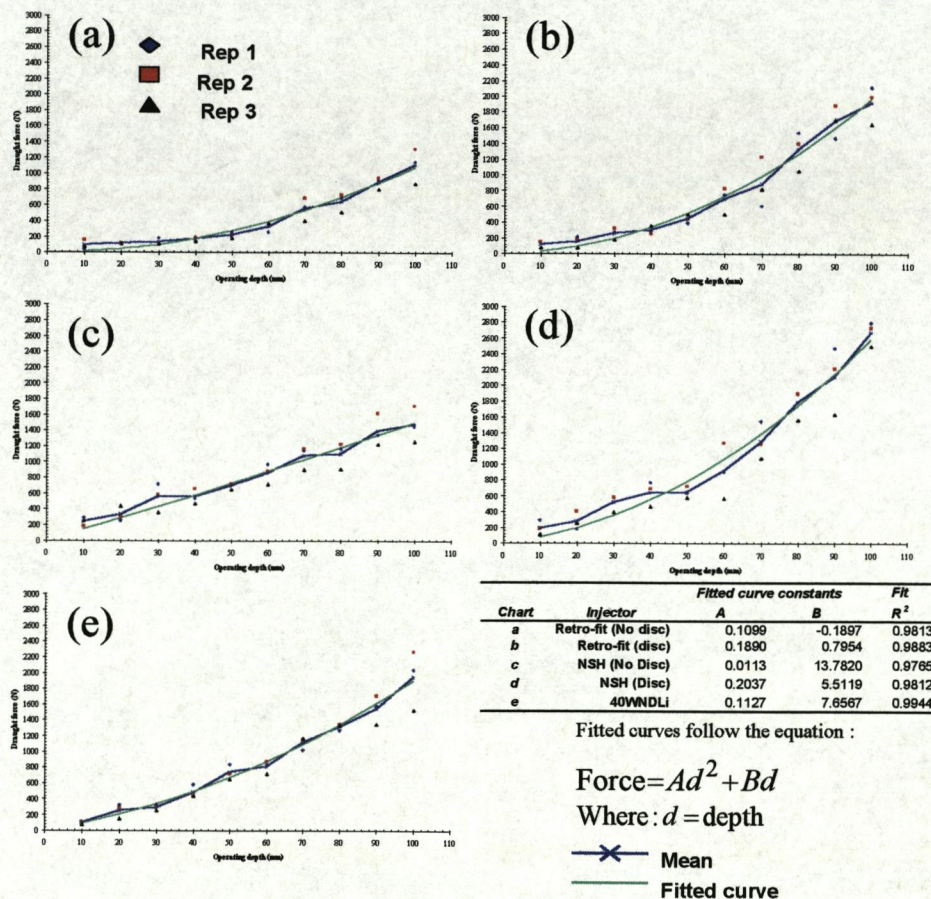


Fig 8.10. Draught force data and fitted curves and their constants, for the five injector tine configurations under investigation.

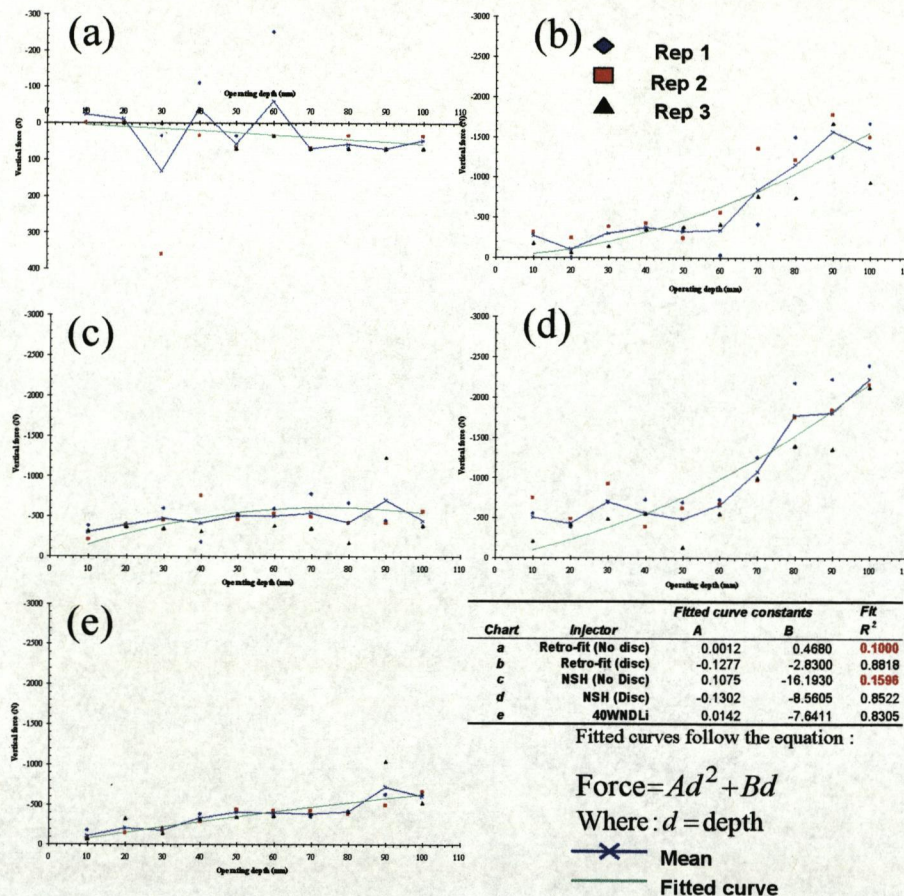


Fig. 8.11. Vertical force data and fitted curves and their constant's for the five injector tine configurations under investigation. (-ve forces indicate upward direction).

In order to use force data within a prediction model based on the derived force system, it is necessary to assign a convention to represent the direction of the vertical forces acting on the injector tines. Upward vertical forces oppose the action of the parallel linkage and are considered as negative in value, whereas downward vertical forces assist linkage action and are considered positive.

8.3.4.3 Discussion.

In general, mean force curves representing injector performance, over the depth range of 0 to 0.1 m, fitted the experimental data well. However, the vertical force data relating to the retrofit injector and the NSH injector operating without cutting discs, did not allow sufficiently accurate curves to be fitted for reliable inclusion in the quasi-static depth prediction model presented previously (Section 8.3.3). These injector tines are designed specifically for use with a cutting disc as a means of crop separation and depth control. The inability to fit regression curves to the vertical force

data for these injectors, reinforces the need to use injectors in the configuration for which they were designed. The results from this soil dynamics study suggest that; the inclusion of the above mentioned injector configurations in a depth prediction model should be avoided.

8.3.4.4 Conclusions.

Three of the five injector tine configurations assessed were found to be suitable for inclusion in the quasi-static depth prediction model, derived in *Section 8.3.3* and presented in *Appendix 7.2*. Two injector tine configurations:

1. Retro-fit without crop separation/cutting disc, and;
2. NSH without crop separation/cutting disc,

did not give sufficiently consistent data to allow accurate curves to be fitted. The degree of fit of a second order polynomial curve to the data retrieved during testing was poor ($R^2 < 0.2$).

8.3.5 Graphical presentation of the force system.

Better representation of the force system may be gained by graphical analysis, facilitating observations of the applied linkage forces and the injector tine restoring forces. A graphical analysis also allows rapid, but approximate, determination of the operating depth at which the force system is in equilibrium. If all forces within the system are considered positive, *Fig 8.12* clearly illustrates the applied linkage and injector tine restoring forces. The point at which the force curves intersect represents the operating depth at equilibrium. By combining these forces, the resultant force acting on the system can be plotted revealing, in more clarity, the approximate depth at which equilibrium will occur.

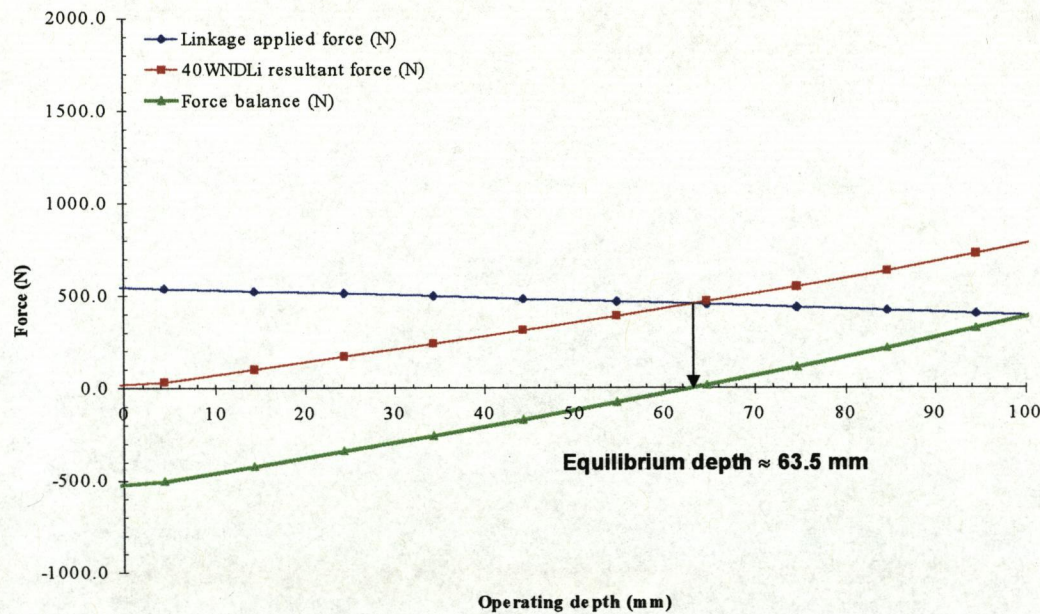


Fig 8.12. Graphical representation of the force system allowing rapid determination of operating depth at equilibrium.

The conditions, presented in *Fig.8.12*, are representative of the 40WNDLi injector tine utilising the parallel linkage system, with 2 springs between spring pivots A and C. The model, described in *Appendix 7.2*, predicts an equilibrium depth of 61.94 mm, subject to the establishment of certain linkage parameters. Subsequent experiments will show that the modelled depth is in good agreement with experimentally derived operating depths.

8.4 Initial study of the dynamic performance of selected injector tines.

8.4.1 Introduction.

The force analysis and the development of the model, presented in *Appendix 7.2*, allows the predicted quasi-static operating depths to be compared with experimental dynamic tine depth profiles. Comparisons of experimental and predicted operating depth have been carried out in the past using active tractor draught control systems, enabling subsequent modifications of tractor draught control systems to be made to improve the dynamic performance of ploughs (Dwyer, 1969-70). A soil dynamics laboratory experiment was carried out to record the response of injector tines, in terms of changes in operating depth, to a simulated step change in soil surface level or implement toolbar elevation. The results will enable comparisons with predicted quasi-static operating depth, (which neglects inertia and friction), and the

experimental observed depth. Subsequent visual comparison of experimental and predicted depth may establish common factors influencing the dynamic performance of the bio-solids application system. It is expected that the identification of any influencing factors will assist in a strategy to develop the injector tine/linkage system, to realise improvements in dynamic performance and depth control.

8.4.1.1 Objectives.

In consideration of the work presented earlier in this chapter, the objectives of this preliminary study are:

- To develop a methodology for measuring injector tine depth profiles under soil dynamics laboratory conditions.
- To use the developed methodology to record the dynamic performance of selected injector tines when presented with soil surface and hitch height variations.
- To analyse and visually compare experimental depth profiles with predicted quasi-static depth profiles.
- To identify common factors between treatments, which exhibit an influence over an injector tine's ability to maintain an equilibrium operating depth (perform well dynamically).

8.4.2 Methodology.

To enable an analysis of the dynamic performance of selected injector tines to be carried out, it is necessary to provide an experimental condition that simulates a step change in soil surface level and implement toolbar height. The use of the soil dynamics laboratory reduces the complexity of the task as flat, repeatable, soil preparations are possible with relative ease. Dwyer (1969-70) addressed the problem of dynamic response measurement by using eccentric rear tractor wheels to produce a sinusoidal input. This simulated variation in the attitude of the tractor/implement combination to an imaginary soil surface and enabled the performance of draught control systems to be analysed.

The measurement of the depth performance and response to soil surface changes requires the use of constant soil parameters, providing the desired injector tine restoring forces to complete the parallel linkage force system analysis. Consequently, the use of the soil dynamics laboratory and suitable instrumentation will provide the necessary conditions to assess dynamic performance.

8.4.2.1 Conditions of response and experimental design.

In consideration of the study presented earlier in this Chapter, the primary group of injector tine configurations under investigation comprises:

- 40WNDLi injector.
- NSH injector with crop separation/cutting disc.
- Retrofit injector tine with crop separation/cutting disc.

As the ability to fit curves to injector tine force data for the other two injectors identified in *Section 8.3.4* was impeded, the NSH and retro-fit injector tines operating without crop separation or cutting devices will be tested, but results should be treated with caution.

To develop a procedure for the assessment of dynamic performance, it is necessary to recognise the cause of undulation within the tractor implement system, and investigate the effect of all variable parameters within the system. The use of bio-solids incorporation equipment on a tractor mounted distribution system, produces two distinct conditions associated with the passage of the tractor implement combination over undulating ground. *Fig. 8.13* illustrates four scenarios within the system, capable of influencing the dynamic performance of the bio-solids incorporation operation.

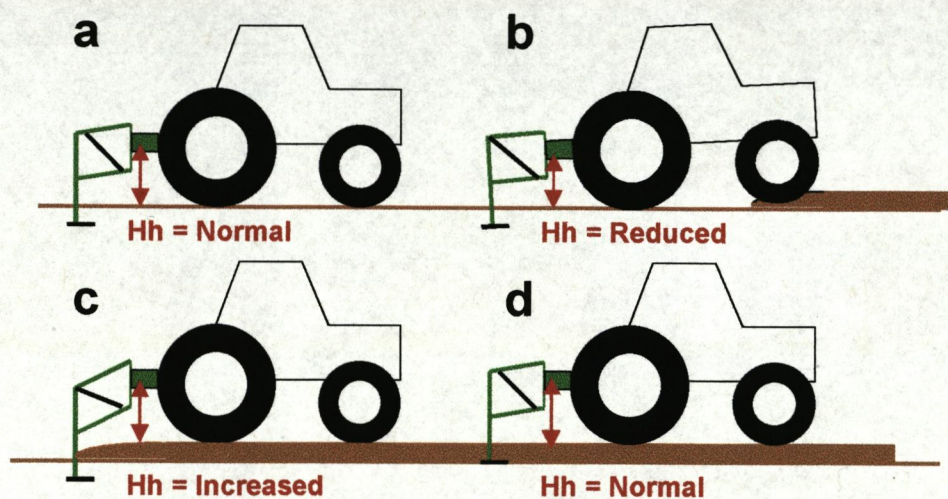


Fig. 8.13. Dynamic conditions of the tractor implement system.

Fig. 8.13 a and *d* represent the normal conditions prior to and following, a ground surface change. *Fig. 8.13 b* illustrates the effective reduction in hitch height as a result of the tractor mounting the undulation, where the soil surface at the injector tine remains flat. Similarly *Fig. 8.13 c* illustrates the condition where the tractor system remains constant, and a hitch height change is induced by a change in surface level. Considering the identification of two main possible changes, the following experimental conditions were selected based on a randomised block design, to account for variations in soil properties across the width of the soil bin:

1. Five injector tines (Three of primary interest, two for completion with previous studies).
2. Three replications.
3. Three spring conditions: No springs, 2 springs between pivots AB (*Fig. 8.3*), and 2 springs between pivots AZ.
4. Four hitch height conditions:
 - i. Flat soil surface (enabling operating depth at equilibrium to be determined).
 - ii. Uneven soil surface and constant toolbar elevation.
 - iii. Constant soil surface and implement toolbar change at 0.05 m/s.
 - iv. Constant soil surface and implement toolbar change at 0.1 m/s.

The retrofit injector tine operating without a crop separation/cutting device was only subjected to testing under a single spring condition (2 springs between pivots AB), as further applied downward force resulted in the total burial of the injector tine.

8.4.2.2 Soil surface generation.

The implements within the soil bin processor unit were utilised to produce an uneven soil surface for dynamic performance assessment. A sinusoidal surface was constructed on the base of a standard preparation, described in *Section 2.6.1.1*, using the following procedure:

- A standard soil preparation was constructed.
- The soil scoops, contained within the processor unit enabling soil manipulation and transport, were used to remove a single circular depression of 1.2 m in diameter and 0.05 m in depth from the top soil layer, at a predetermined position, along the length of the standard soil surface.

- The removed soil was deposited 0.5 m in front of the created depression, and compacted using a hand roller prior to rolling 5 times, with the processor's own compaction equipment.

The resulting soil surface, presented in *Fig. 8.14*, allowed one undulation per soil preparation to be maintained.

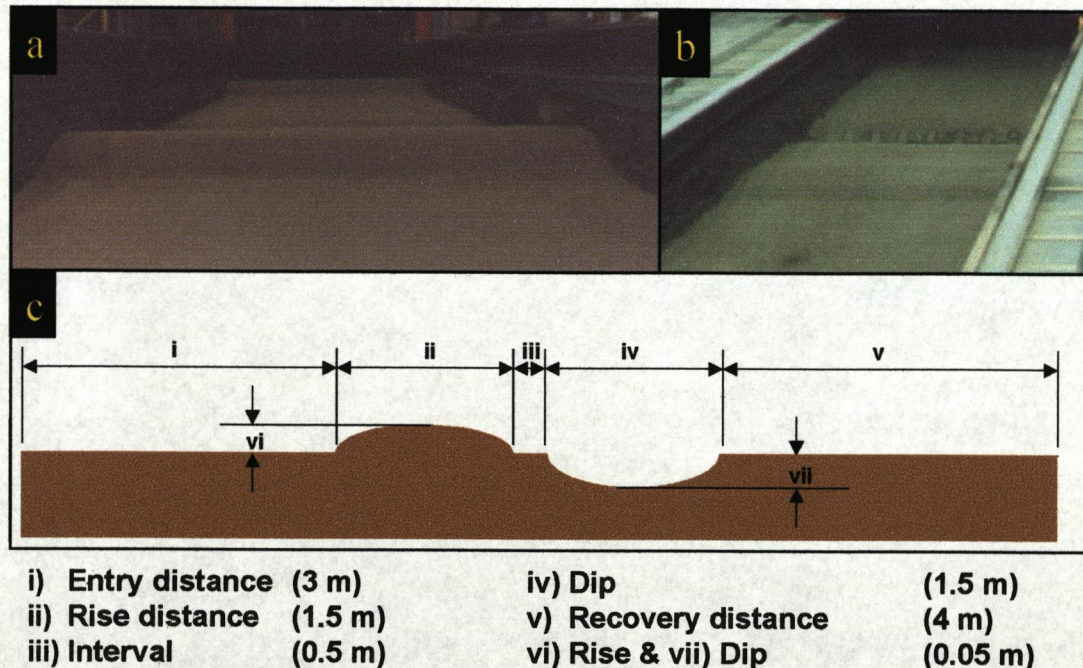


Fig. 8.14. a) & b) Uneven soil surface created using the soil bin processor unit and c) the approximate dimensions of the soil surface resulting.

The production of the soil surface may have induced variations in soil properties across the rise and dip sections. However, the comparative nature of the experiment, maintains the ability to assess dynamic performance between injector tine configurations. Small differences between experimental and predicted operating depth may also be experienced, as a result of the soil preparation, although these are expected to be minimal.

8.4.2.3 Implement toolbar (hitch height) variation simulation.

The effect of variations in hitch height on tine performance can be calculated by adjusting the position of the mounting plate on the rear of the processor unit to simulate implement toolbar movement. However, as adjustment to plate position is normally achieved by manual operation of a hydraulic spool valve whilst the processor is stationary, an automatic system was required to vary the toolbar height under dynamic conditions. To achieve this, a double acting electro-magnetic spool

valve system was attached to the soil bin processor's hydraulic system, and electrical connections were made to the processors control system, enabling semi-automatic remote operation of the implement mounting plate. To control the speed of movement of the adjustable mounting plate, an adjustable flow control valve was positioned in the hydraulic system. This was adjusted to give the desired rate of elevation and descent of the bio-solids application equipment. A number of procedures were evaluated to simulate an implement toolbar height variation on a replicable basis, resulting in the establishment of a video link between the processor unit and the control room. The video link enabled viewing of a rule, mounted on the side of the rear adjustable mounting plate, allowing accurate adjustments to the elevation of the mounting plate to be made via the remote hydraulic operation, described above. The valid replication of the simulated implement toolbar height change was dependent on the skill of the operator adjusting the remote hydraulic system.

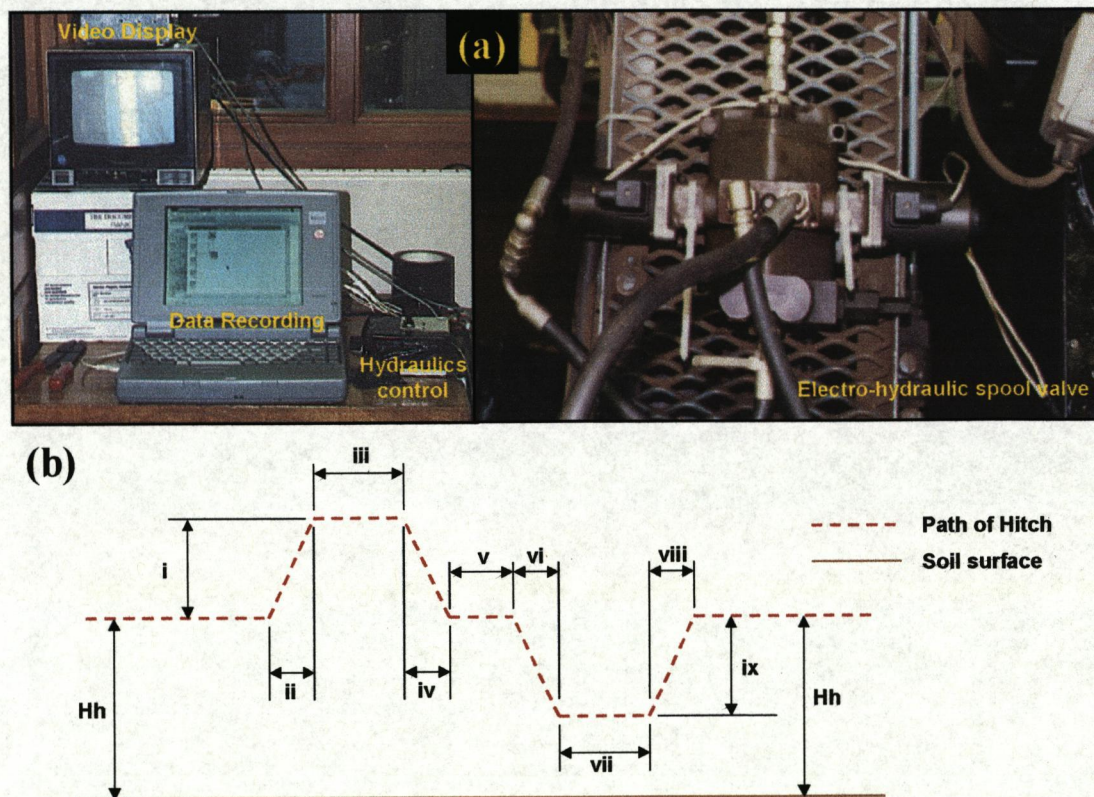


Fig. 8.15. Hitch height study: a) equipment used to vary hitch height and b) resulting hitch path above the soil surface achieved.

The operation of the equipment, illustrated in Fig. 8.15, allowed an elevation and depression of the hitch path of 0.05 m (i & ix). The slopes produced (ii, iv, vi & viii), result from the speed of operation of the rear mounting plate on the soil bin processor, and the forward speed during testing (0.55 m/s). The operator, using his own sense of

timing to replicate the hitch path, controlled the delay areas (iii, v, & vii). The same operator was used for all experiments.

8.4.2.4 Displacement measurement.

Early tillage studies that required the measurement of displacement, used complex linkages and drum recorders (Hawkins & Boa, 1946). Cowell & Mekanjuola (1966) measured displacement using rotary potentiometers. However, in later field tests to assess the penetration performance of ploughs, more basic manual techniques were used (Cowell & Sial, 1976). Godwin *et al* (1987) considered the measurement of mole plough depth using a number of measurement methods. Under field conditions, they found that laser receiver masts (Anon. 1981) were the most convenient option. However, for soil bin studies, where the rails of the soil tank provide a suitable datum, the use of linear variable displacement transducers (LVDT), (Cook & Rabinowicz, 1963), were found to be adequate.

To measure the path of the injector and linkage combination in relation to the soil surface, two LVDTs were used (RDP Electronics Type DCT60000: 340 mm max displacement). One was attached to the parallel linkage arrangement at the rear vertical leg, the other connected to a land wheel arrangement to follow the soil profile.

Fig. 8.16 illustrates the experimental equipment layout used.

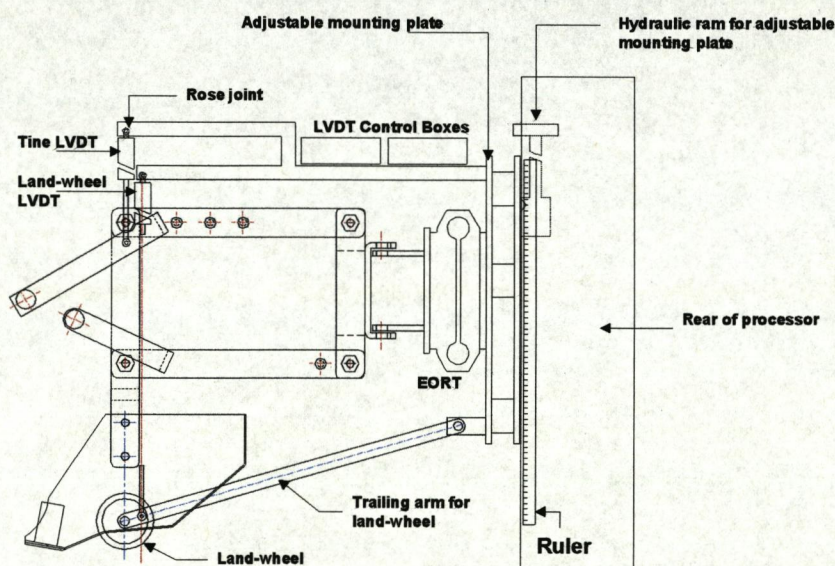


Fig. 8.16. Experimental test apparatus for measuring the dynamic response of an injector tine to variations in the soil surface and hitch height.

8.4.2.5 Instrumentation and data handling.

All data was logged by computer capture techniques. Each of the three channel outputs, from the EORT, was passed through strain gauge conditioning modules (*Straininstall Model 91c*), which amplified the small μV return output from the EORT. The EORT and LVDT (no amplification) signals were transferred through a simultaneous sample and hold circuit to remove multiplex skew, and subsequently fed to an Advantech DACpad-71B DA&C Card, with PCMCIA interface for connection to a laptop computer (DX2/50, 12Mb RAM, Win95). Advantech Genie (Version 2) was used for signal recording at 37 Hz and storage in text output file structure. The calibration equations are presented in *Appendix 7.5* and data captured from each test was converted to represent either force, or displacement. Moving average smoothing, over 0.25 s, was applied to the amplified data to reduce the effect of electrical noise.

8.4.2.6 Experimental procedure.

The experimental procedure for each individual test was identical, the only variations being the type of soil preparation and the need to raise or lower the implement toolbar height automatically. Standard hitch heights were assigned to each injector tine combination such that, prior to the commencement of each test, the angle of the horizontal links to the soil surface was $\approx 10^\circ$ (*Fig.8.5*). This corresponded to Hh being 427, 399 and 376 mm for the 40WNDLi, NSH and Retrofit combinations respectively. To allow zero data to be captured, indicating the position of each LVDT when both injector tine combination and land-wheel were resting on the soil surface, 5 s of data was collected at the start of each test. During this time, the injector tine was rested on a steel plate on the soil surface, to eliminate any static penetration resulting from applied linkage spring force. The test was subsequently initiated, allowing the tine and linkage to negotiate the soil surface undulation, or simulated implement toolbar height variation, along the entire length of the soil preparation (≈ 11 m). Three tests were carried out in each soil preparation, at a speed of 0.55 m/s coinciding with the expected speed of field operation of the equipment. Captured data was saved on computer disk and analysed using spreadsheet software.

8.4.2.7 Experimental error.

Due to the nature of the experimental equipment, small errors resulting from lateral movement of the linkage and injector system are possible. However, these are

expected to be small, and due to the comparative nature of this evaluation, all tests were subject to the same possible variations.

8.4.2.8 Dynamic performance.

In the context of this preliminary study, the dynamic performance of an injector tine configuration will be assessed by its ability to maintain modelled equilibrium. This may be achieved by visual comparisons between experimental depth profiles and predicted quasi-static depth profiles obtained using the model, presented in *Appendix 7.2*. A close correlation between predicted and experimental values is indicative of the ability of the injector tine configuration to maintain equilibrium.

8.4.3 Results.

The results from this preliminary study can be segregated into four distinct categories:

1. Soil properties.
2. Flat soil surface verification of modelled and experimental operating depths.
3. Dynamic response to an uneven soil surface.
4. Dynamic response to a change in implement toolbar elevation.

8.4.3.1 Soil properties.

The analysis of soil bulk density (kg/m^3 dry basis) over the period of testing revealed no significant differences between soil preparations, with an overall mean of 1347.4 kg/m^3 and a standard error of 36.63 kg/m^3 . Moisture content (% dry basis), between soil preparations, followed a similar pattern, with variation between tests comparable to those previously experienced ($\text{cv} = 4.5\%$), suggesting that for the duration of the test period, including weekend inactivity, no significant variation in the primary soil properties occurred. The bulk density and moisture content over the test period are presented in *Fig. 8.17 and 8.18* respectively, with a full statistical analysis of this data presented in *Appendix 7.6*.

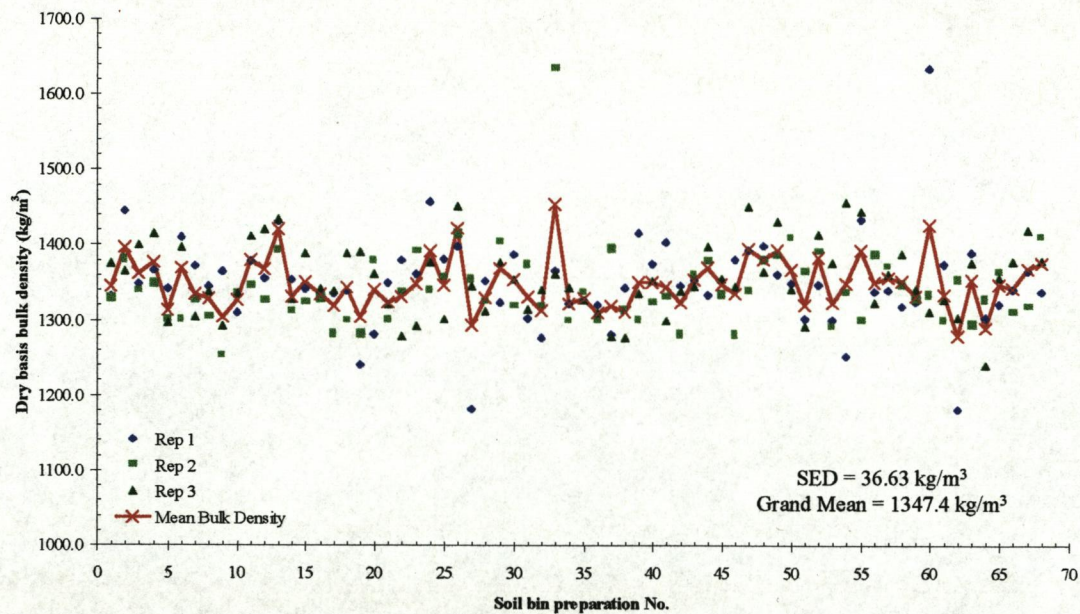


Fig. 8.17. Dry basis bulk density of soil bin preparations during the test period.

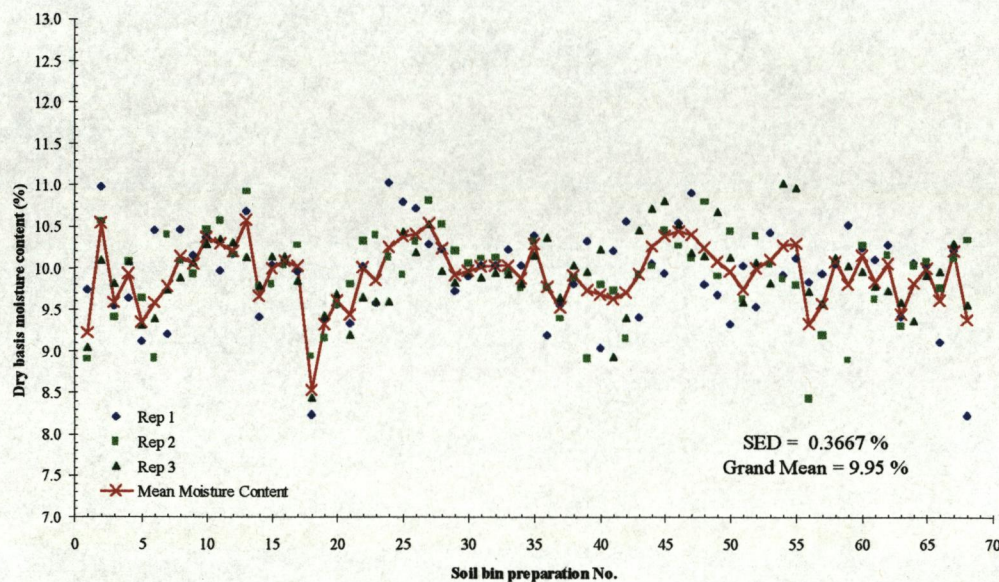


Fig. 8.18. Dry basis moisture content of soil bin preparations during the test period.

8.4.3.2 Verification of modelled tine depth using flat soil surface dynamic testing.

Mean operating depth profiles for each injector tine configuration under evaluation, are presented in *Appendix 7.7*. Experimental depths attained in this experiment show good agreement with predicted operating depths, presented in *Table 8.1*. It is apparent that the inability to fit accurate curves to vertical force data for the NSH and Retrofit injector tines, operating without crop separation/cutting devices, has not affected the prediction model adversely in this instance.

Table 8.1
Observed and predicted tine operating depths.

Tine	Spring location	No. of Springs	Predicted depth	Mean depth (experimental)	Range (experimental)	Difference
40WNDLI	None	0	18.36 mm	29.03 mm	3.5 mm	10.67 mm
	Ab	2	40.34 mm	39.47 mm	5.8 mm	0.87 mm
	Ac	2	61.94 mm	69.67 mm	13 mm	7.73 mm
NSH (No Disc)	None	0	10.39 mm	6.67 mm	14.5 mm	3.72 mm
	Ab	2	25.15 mm	38.10 mm	32 mm	12.95 mm
	Ac	2	44.34 mm	81.37 mm	18.3 mm	37.03 mm
NSH (Disc)	None	0	19.16 mm	10.03 mm	1.7 mm	9.13 mm
	Ab	2	30.34 mm	31.43 mm	24.6 mm	1.09 mm
	Ac	2	40.74 mm	39.47 mm	11.6 mm	1.27 mm
Retro-fit (No disc)	None	0	85.87 mm	91.04 mm	2.2 mm	5.17 mm
	Ab	2	94.36 mm	105.32 mm	20.8 mm	10.96 mm
Retro-fit (Disc)	None	0	28.35 mm	14.06 mm	17.02 mm	14.29 mm
	Ab	2	41.54 mm	44.25 mm	10.29 mm	2.71 mm
	Ac	2	53.14 mm	55.36 mm	15.18 mm	2.22 mm

The comparison between experimental and predicted operating depths, under constant soil conditions provided by the soil bin equipment, indicates that the analytical force system and experimental injector tine performance properties can be combined to produce a model suitable for evaluation of dynamic performance. Errors must be accepted due to:

- i) Small variations in soil properties, resulting in slight changes in experimental operating depth, and;
- ii) Variation in instrumentation output, caused by lateral movement of either the injector/linkage combination, or the land-wheel.

The effect of inertia on the linkage/tine configuration is expected to be negligible, as Schuring and Emori (1964) found inertial effects to be insignificant at speeds less than $\sqrt{5gw}$, where w is tine width. This finding was confirmed by Wheeler and Godwin (1996), who expanded on previous theory to account for soil failure on both sides of narrow tines, to allow the critical speed at which inertial effects become significant to be calculated ($\sqrt{5gw + 0.6d}$). It is accepted that injector tines are not simple narrow tines in definition. However, even considering changes in geometry resulting in a complex tine form, critical speeds are well in excess of the standard operating speed (2 km/h, 0.55 m/s), used in soil dynamics laboratory and field experiments (Table 8.2).

Table 8.2
Critical inertial speeds.

Tine	Width (w)	$d = 0.05$ m	$d = 0.06$ m	$d = 0.07$ m	$d = 0.08$ m
40WNDLi	0.04 m	5.08 km/h	5.08 km/h	5.09 km/h	5.10 km/h
NSH	0.025 m	4.03 km/h	4.04 km/h	4.05 km/h	4.06 km/h
Retrofit	0.035 m	4.76 km/h	4.77 km/h	4.77 km/h	4.78 km/h

After Wheeler and Godwin (1996).

8.4.3.3 Dynamic response to an uneven soil surface.

Results from the measurement of dynamic performance of the selected injector tine combinations, when tested over a sinusoidal soil surface while maintaining a constant hitch height above the original soil surface, are presented in *Appendix 7.8*. Good agreement is shown between predicted quasi-static operating depths and experimental values. The generated soil surface and resulting dynamic performance of each injector tine configuration can be segregated into four distinct sections (*Fig. 8.19*).

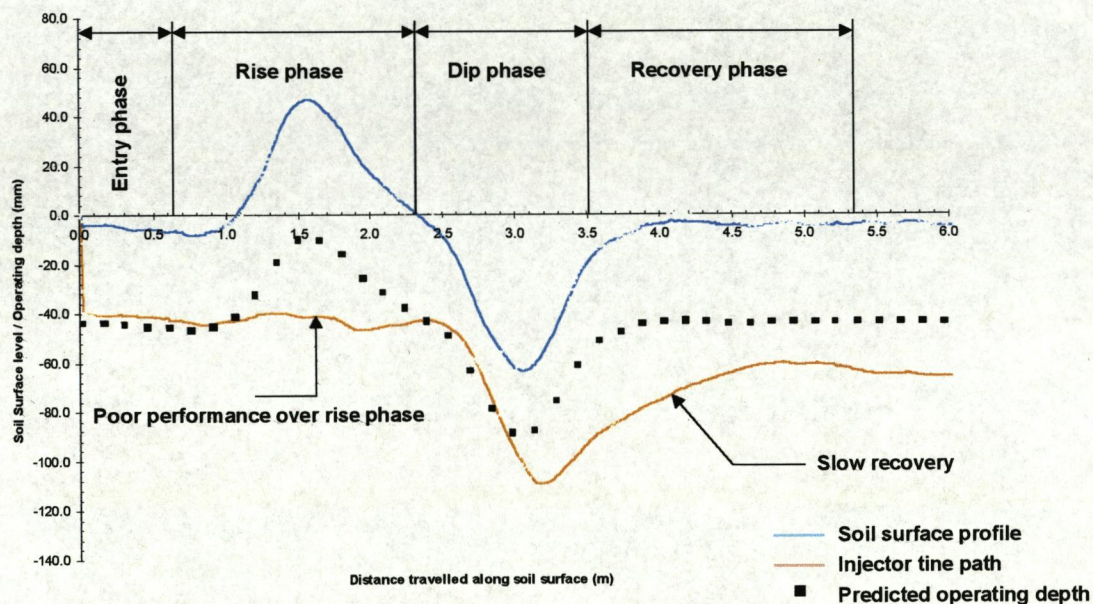


Fig. 8.19. Dynamic performance phases (sinusoidal soil surface change).

Considering each injector tine configuration individually:

i) 40WNDLi injector tine dynamic performance observations.

Entry under experimental conditions correlated well with predicted quasi-static operating depths. The rise phase was tackled well by the tine/linkage system when no applied spring force was used. However, increases in the applied downward linkage force reduced the performance of the injector tine during this stage. The artificial dip

was negotiated with ease. However, the downward slope was greater than the 10° clearance angle of the winged tine and resulted in the injector sliding down the dip on its wings, in some instances. Greater applied spring force reduced this effect. Recovery was satisfactory, both when no applied linkage spring force was present, and when applied linkage force, and hence operating depth, was greater. Small amounts of applied linkage force resulted in slow recovery to predicted operating depths in this phase of each test.

ii) NSH injector tine and disc, dynamic performance observations.

The use of the cutting disc during these tests, revealed the ability of such a device to control injector tine operating depth. Under all spring conditions at all phases, this tine/linkage system performed well, although better agreement was observed as operating depth increased. These results reinforce the validity of the force model, described earlier, suggesting that a combination of analytical and experimental force derivations can be used successfully in modelling injector tine performance.

iii) NSH injector tine without disc, dynamic performance observations.

Under non-sprung linkage conditions this injector tine followed the soil profile, but failed to penetrate sufficiently to achieve the necessary soil disturbance required for effective bio-solids incorporation. Under sprung linkage conditions, the NSH injector followed a similar pattern to that of the 40WNDLi injector tine, failing to rise in the rise phase, and exhibiting a slow recovery following the dip phase.

iv) Retro-fit injector tine and disc, dynamic performance observations.

In common with the observations of the NSH injector tine and disc combination, the retrofit injector tine and disc performed well over all phases. A slight advance in response can be observed in the profiles, presented in *Appendix 7.8*, resulting from the lead of the disc ahead of the injector tine. LVDT measurements were taken at the tine, whereas the disc was the overriding influence during these experiments. Good correlation between experimental and predicted operating depths reinforces the validity of the force model, and establishes the cutting disc as an effective depth control device.

v) Retro-fit injector tine without disc, dynamic performance observations.

The modelled predictions of the retrofit injector tine, operating without any form of depth control device, followed the observed performance well. Unfortunately, the improved dynamic performance is achieved at the expense of operating depth, as the

retrofit injector exhibited a propensity to over penetrate, which resulted in it operating outside the design parameters of the injector tine. Increasing the applied spring force resulted in further increases in operating depth, and subsequent improvements in the ability of the system to maintain equilibrium.

In summary, the observed dynamic performances were found to correlate well with force model predictions under conditions where depth control devices were used and at increased operating depths.

8.4.3.4 Dynamic response to changes in implement toolbar height.

Operating depth profiles in relation to implement toolbar variation at two speeds (50 mm/s and 100 mm/s), are presented in *Appendix 7.9* and *7.10* respectively. No apparent differences in the speed of simulated implement toolbar movement and the response of the injector tine to the variation are discernible. Once again, good agreement is observed between predicted and observed values. The simulated implement toolbar height variation and resulting dynamic operating depth performance, of each injector tine configuration, can be segregated into four distinct sections (*Fig. 8.20*).

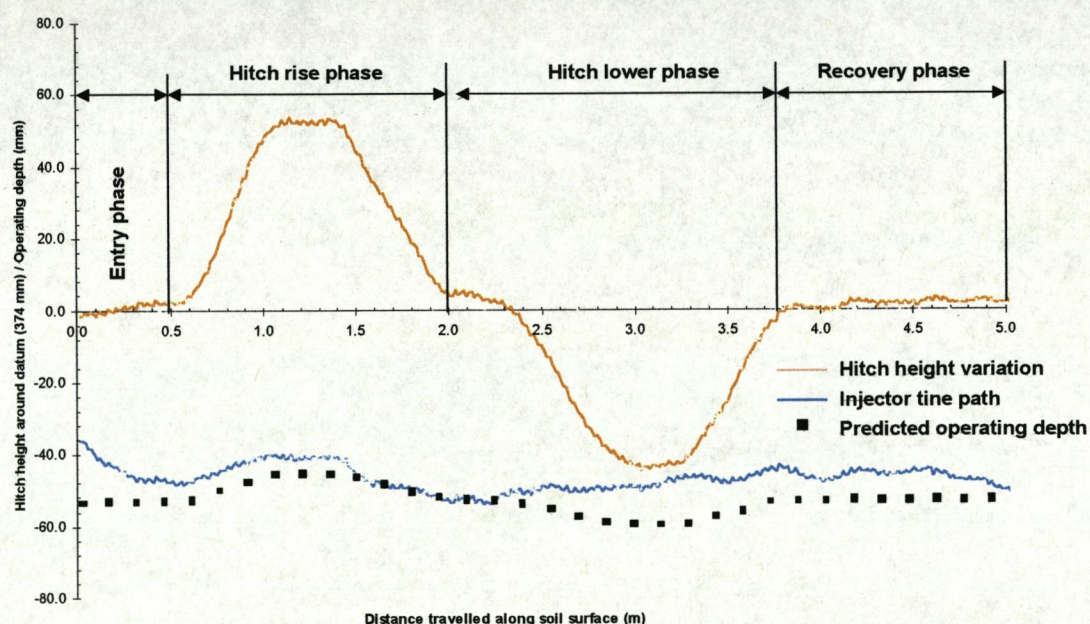


Fig. 8.20. Dynamic performance phases (simulated implement toolbar variation).

Considering each injector tine configuration individually:

i) 40WNDLi injector tine, dynamic performance observations.

Alterations to the implement toolbar height had little impact on the operating depth of the 40WNDLi tine. Good agreement between predicted quasi-static operating depths and observed depths was achieved under all linkage conditions. The greatest depth changes were observed under large applied linkage force conditions, where the 40WNDLi tine maintained equilibrium conditions well. Increasing the rate of implement toolbar variation did not appear to affect the dynamic performance of this injector tine adversely.

ii) NSH injector tine and disc, dynamic performance observations.

Under non-sprung conditions this injector tine failed to penetrate adequately following the flat soil surface and hence maintaining a constant minimal depth throughout the test. Under the influence of springs, rate of entry was observed to be slow. However, the tine configuration responded well to changes in implement toolbar height. More positive responses were observed when the injector tine was operating at greater depths, with increased spring force applied through the linkage. Increasing the speed of simulated implement toolbar variation did not appear to affect the dynamic performance of this injector tine configuration.

iii) NSH injector tine without disc, dynamic performance observations.

The dynamic performance of the NSH injector without a cutting disc was observed to be similar to that when a disc was included in the configuration. Similarly, no effect of speed of implement toolbar variation was observed.

iv) Retro-fit injector tine and disc, dynamic performance observations.

Observations of the dynamic performance of the retrofit and cutting disc combination were in close agreement with the predicted quasi-static performance. The configuration maintained a constant operating depth irrespective of hitch height variation throughout the duration of testing. This reaction may be perceived to be a reduction in response. However, in consideration of predicted values for operating depth, dynamic performance appeared to be unaffected by the simulated hitch height variations. Once again, the rate of simulated implement toolbar variation was not observed to affect the dynamic performance of this injector tine configuration.

v) Retro-fit injector tine without disc, dynamic performance observations.

This injector tine configuration appeared to follow the predicted operating depth well, with improvements in response apparent with increasing applied spring force and

hence increase operating depth. However, the operating depth of this tine, under experimental conditions, far exceeded its design limits. Speed of simulated implement toolbar variation did not appear to affect the performance of the injector tine.

8.4.4 Discussion.

Considering the close agreement between observed and predicted operating depths, the quasi-static model may be used to compare the dynamic performance of the injector tine configurations under evaluation. Little benefit has been obtained from the study of implement toolbar variation. However, a common factor between all injector tine configurations appears to be the improvement in dynamic performance with increasing operating depth. During this study, the effect of friction in the linkage joints has not been considered. However, comparatively, this does not affect the results on the whole. For subsequent studies, a comparison between pinned joints and bearings should be carried out to assess any frictional effects.

8.4.4.1 Improved dynamic performance with increased operating depth.

To establish the factors influencing the common trend towards improved ability to maintain equilibrium with increasing operating depth, it is necessary to consider the graphical presentation of the force system, as operating depth affects both the tine and linkage actions. *Fig 8.21* illustrates the applied linkage forces (2 springs between pivots AZ, *Fig. 8.3*) and the opposing injector tine forces associated with the NSH injector tine and disc configuration.

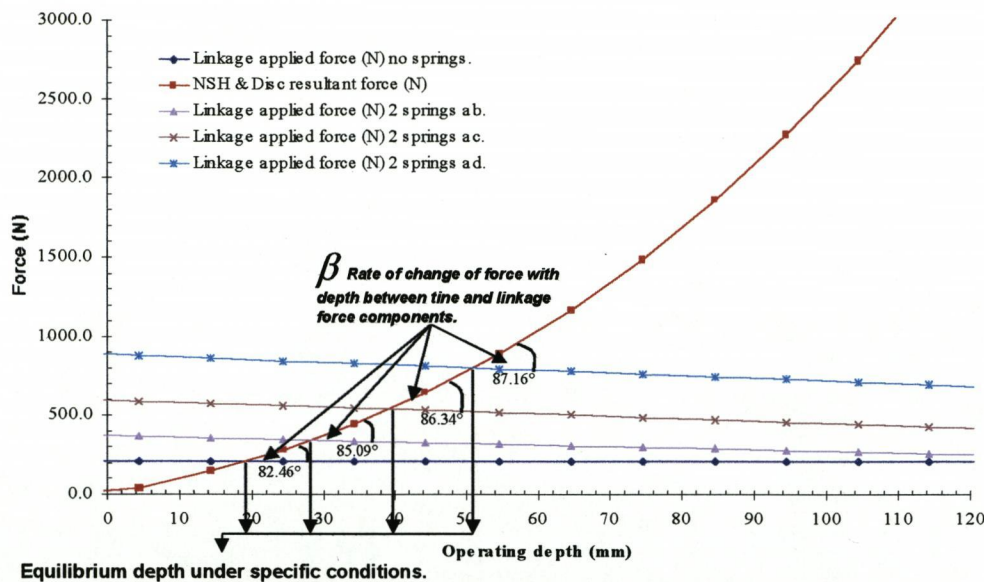


Fig. 8.21. Graphical presentation of applied linkage and opposing injector tine forces including increasing angle β with depth.

It has been identified by observation, that an injector tine's ability to maintain equilibrium improves with operating depth, and the relationship between the two forces acting within the system (β) also changes with depth (Fig. 8.21). The fact that the system is implicit, and each action of the linkage is heavily dependent on the reaction by the tine, any common factor must relate to both aspects of the force system. In line with the observation that performance improved with operating depth, the rate of change of force with depth ($\tan \beta$) was identified as increasing with operating depth, suggesting that this may be a common factor influencing performance. Other factors, which may have influenced the dynamic performance of the injector tine configurations under evaluation, have been eliminated due to the comparative nature of this preliminary study. It was thought that the effect of linkage geometry might have a significant effect on the dynamic performance of the injector tines. However, the results of this preliminary study indicate that all tines perform similarly, illustrating a higher ability to maintain equilibrium (better dynamic performance) with increasing applied spring force, and hence operating depth. Consequently, the combination of evidence supports a direct relationship between linkage and tine forces (β) and dynamic performance. To further clarify this theory, β was calculated for each injector tine configuration under different spring conditions.

8.4.4.2 Determining the action of β under different linkage conditions.

The relationship between the applied linkage forces and opposing injector tine soil forces may be obtained by manipulation of the equation governing the force system.

From equation [1];

$$L_r + T_r = 0$$

when d is at equilibrium.

Therefore, by rearranging [24] and differentiating with respect to d gives the rate of change of force with depth (slope at the intercept with the x -axis, Fig. 8.12), such that trigonometry may be used to determine the angle between the slope and the axis. A computer based mathematics package, Maple for Windows (Version 5), was used to calculate the differential equation describing the slope of the resultant force curve, which was found to be:

$$\begin{aligned} \frac{\delta F}{\delta d} = & \frac{1}{2} \left[\frac{NsR \left(-2 \frac{(L_2 - L_1)^2 N}{L_3^2} - 2 \frac{\eta(L_2 - L_1)}{L_3} \right) L_2 \sin \rho}{\sqrt{\sigma}} + NsR(\sqrt{\sigma} + 10 - DL) L_2 \cos \rho \left(\frac{-\frac{1}{L_3 \sqrt{\gamma}} + \frac{\eta N}{(L_2 - L_1)^{1/2} L_3^2}}{1 + \frac{\eta^2}{(L_2 - L_1)^2 \gamma}} + \frac{1}{L_3 \sqrt{\gamma}} \right) \right] \\ & - \frac{1}{2} \left[\frac{NsR \left(-2 \frac{(L_2 - L_1)^2 N}{L_3^2} - 2 \frac{\eta(L_2 - L_1)}{L_3} \right) L_1 \sin \rho}{\sqrt{\sigma}} - NsR(\sqrt{\sigma} + 10 - DL) L_1 \cos \rho \left(\frac{-\frac{1}{L_3 \sqrt{\gamma}} + \frac{\eta N}{(L_2 - L_1)^{1/2} L_3^2}}{1 + \frac{\eta^2}{(L_2 - L_1)^2 \gamma}} + \frac{1}{L_3 \sqrt{\gamma}} \right) \right] \\ & + \left(NsR(\sqrt{\sigma} + 10 - DL) L_2 \sin \rho - NsR(\sqrt{\sigma} + 10 - DL) L_1 \sin \rho \right) \frac{N}{L_3^3 \gamma^{3/2}} - \frac{\sqrt{Df^2 + Vf^2} \cos \left(\varepsilon + \tan^{-1} \left(\frac{Vf}{Df} \right) \right)}{L_3 \gamma} \\ & - \frac{\sqrt{Df^2 + Vf^2} \sin \left(\varepsilon + \tan^{-1} \left(\frac{Vf}{Df} \right) \right) N}{L_3^2 \gamma^{3/2}} \end{aligned}$$

[29]

Where:

$$\gamma = 1 - \frac{N^2}{L_3^2} \quad [30]$$

$$\varepsilon = \sin^{-1} \left(\frac{N}{L_3} \right) \quad [31]$$

$$\eta = L_4 - \frac{(L_2 - L_1)N}{L_3} \quad [32]$$

$$\rho = \tan^{-1} \frac{\eta}{(L_2 - L_1)\sqrt{\gamma}} + \varepsilon \quad [33]$$

$$\sigma = (L_2 - L_1)^2 \gamma + \eta^2 \quad [34]$$

To establish the rate of change of force with depth at equilibrium for each injector tine configuration, specific conditions were entered into [29] concurrent with the experimental trials described earlier. The specific conditions are presented in *Table 8.3*. Calculated values of β are presented in *Table 8.4*.

Table 8.3

System properties used to ascertain β for each injector tine configuration at equilibrium.

Linkage parameter	Units	Injector tine configuration				
		40WNDLi	NSH & Disc	NSH (No Disc)	Retrofit & Disc	Retrofit (No Disc)
L_1	mm	52.0	52.0	52.0	52.0	52.0
L_2	mm	ab = 190	ab = 190	ab = 190	ab = 190	ab = 190
		ac = 250	ac = 250	ac = 250	ac = 250	ac = 250
		ad = 310	ad = 310	ad = 310	ad = 310	ad = 310
L_3	mm	400.0	400.0	400.0	400.0	400.0
L_4	mm	250.0	250.0	250.0	250.0	250.0
L_5	mm	185.0	185.0	185.0	185.0	185.0
L_6	mm	115.0	115.0	115.0	115.0	115.0
Hh	mm	427.5	399.5	399.5	374.5	374.5
Tm	N	16.5	98.4	43.7	72.8	18.0
T_e	mm	173.0	145.0	145.0	120.0	120.0
M	N	107.0	107.0	107.0	107.0	107.0
DL	mm	256.0	256.0	256.0	256.0	256.0
R	N/mm	6.3	6.3	6.3	6.3	6.3
Ns		2.0	2.0	2.0	2.0	2.0

Table 8.4

β at equilibrium depth under all spring conditions for the injector tine configurations under evaluation.

Injector tine Configuration	Result	Units	Applied spring force conditions			
			No springs	Ns=2 ($L_2 = ab$)	Ns=2 ($L_2 = ac$)	Ns=2 ($L_2 = ad$)
40 WNDLI	β	$^\circ$	81.63	83.32	84.65	85.85
	d	mm	18.36	40.34	61.94	85.08
	$\tan \beta$	N/mm	6.79	8.53	10.68	13.78
NSH & Disc	β	$^\circ$	82.46	85.09	86.34	87.16
	d	mm	19.56	30.34	41.14	52.74
	$\tan \beta$	N/mm	7.55	11.64	15.63	20.15
NSH (No Disc)	β	$^\circ$	79.42	84.34	86.64	88.28
	d	mm	11.18	25.15	45.14	83.88
	$\tan \beta$	N/mm	5.35	10.12	17.03	33.30
Retrofit & Disc	β	$^\circ$	84.47	86.30	87.16	87.76
	d	mm	29.14	41.54	53.54	65.93
	$\tan \beta$	N/mm	10.33	15.46	20.15	25.56
Retrofit (No Disc)	β	$^\circ$	81.75	82.81	85.13	*
	d	mm	85.87	94.36	119.12	*
	$\tan \beta$	N/mm	6.89	7.93	11.73	*

The results pertaining to injector tine configurations utilising depth control or crop separation devices are of primary interest (40WNDLI, NSH & Disc and retrofit & disc), whose force data is easily and accurately fitted by 2nd order polynomial curves, increasing the validity of the results presented above ($R^2 > 0.85$). The two remaining injector tines produce similar results in relation to β , indicating that dynamic performance may be improved by modification of the system to increase β for all injector tines. However, accurate curve fits could not be fitted to the vertical force data of these injector tines suggesting that caution be exercised when attempting to interpret the data.

In summary, it is thought that the rate of change of force with depth ($\tan \beta$) within the injector tine and linkage system has an effect on the system's ability to maintain equilibrium and hence perform well dynamically. The relationship between operating depth and β , presented above, combined with the experimental observations indicating the conditions under which dynamic response is improved, reinforces the validity of this link.

8.5 Study conclusions.

The following conclusions have been drawn from this initial study into the dynamic performance of injector tines:

1. The force system derived earlier adequately represents the injector tine/linkage system, and has been verified experimentally with predicted equilibrium operating

depths under specific linkage conditions showing good agreement with observed experimental results.

2. Accurate injector tine force data, obtained experimentally in the absence of any definitive model for complex tine force modelling, may be used in conjunction with analytical force analysis to produce an accurate model for the prediction of equilibrium operating depth for shallow injector tines operating on a parallel linkage.
3. Observed dynamic performance improves as operating depth increases for all injector tine configurations, independent of soil conditions, speed and inertia, as a direct result of the injector tine/linkage combination.
4. Rate of change of force with depth ($\tan \beta$) increases for all tines with increasing equilibrium depth.
5. A relationship has been established between 3 and 4 above, linking improved dynamic performance with depth.

8.6 Summary

The establishment of a relationship between improved dynamic performance and the rate of change of force with depth ($\tan \beta$) suggests that improvements in dynamic response over a wider depth range may be possible by manipulation of the force system components. As it has been established in previous chapters that soil disturbance and forces are optimal for current designs, linkage manipulation may provide a key to improved equilibrium depth control. To establish the feasibility of linkage manipulation, a sensitivity analysis of the geometric components of the parallel linkage system is necessary to determine the properties of the parallel linkage that may be changed to improve dynamic response by increasing β across the operating depth range of injector tines. While the use of a number of injector tine configurations has been useful in identifying the common factors that are observed to influence dynamic response, further study should concentrate on the 40WNDLi injector tine, which has been identified as providing better soil incorporation of bio-solids than the other tines evaluated previously.

Chapter 9

9.0 Injector tine depth control: Sensitivity analysis of parallel linkages.

9.1 Introduction.

The force model and provisional dynamic study, presented in *Chapter 8*, proposes a link between an injector tine's ability to maintain equilibrium when attached to a parallel linkage, and the force system controlling the equilibrium operating depth. Essentially, it was found that the rate of change of force within the linkage/tine system increased with operating depth. As both the injector tine and linkage performance are dependent on operating depth, the combined effect of the two force systems needs to be considered.

Previous studies into the soil disturbance and force characteristics of a selected number of injector tine configurations has revealed that the 40WNDLi injector tine, which incorporates an integral cutting edge and no depth control device, provides the desired characteristics suitable for bio-solids incorporation into arable cropping. Manipulation of the injector tine to attain improved dynamic performance in terms of depth control and ability to maintain predicted equilibrium conditions is undesirable. It is likely that alteration of the injector tine will adversely affect the soil force and disturbance characteristics of the 40WNDLi tine. Consequently, a thorough analysis of the linkage geometry and the effect of geometric manipulation on the rate of change of force with operating depth is necessary. A study of this type would highlight the areas of the linkage geometry that may be changed to maximise β , previously identified as a major common factor within the force system influencing the dynamic performance.

9.2 Objectives.

In view of the theory and observations presented in *Chapter 8*, there is a need to maintain injector tine geometry to provide the acceptable soil forces and disturbance characteristics associated with the 40WNDLi injector tine. The objectives of this study are:

- To assess the effect of geometric changes, to the Greentrac™ parallel linkage, on the rate of change of force with operating depth ($\tan \beta$).

- To establish the parameters of the linkage, if any, which may be changed to increase β , with the aim of improving the dynamic performance of the 40WNDLi injector time mounted on a parallel linkage.

9.3 Sensitivity analysis.

Mathematical analysis may be used on a derived force system to assess the effect of changes within that force system, on a defined parameter. Partial differentiation is commonly used to achieve this type of analysis, as it allows the effect of a change in one parameter of the system to be assessed in relation to another. In the context of this analysis, the effect of geometric change on β is required, which will reveal the dimensional parameters of the linkage that may be manipulated to maximise β .

9.3.1 Principal geometric parameters of the parallel linkage.

Manipulation of any of the parameters associated with the geometry of the parallel linkage are likely to affect operating depth, by altering the magnitude of the applied spring force. Consequently, the operating depth must be considered in any analysis of sensitivity. *Fig 9.1* illustrates the parallel linkage and the dimensions that may be changed to assess sensitivity of the linkage to β .

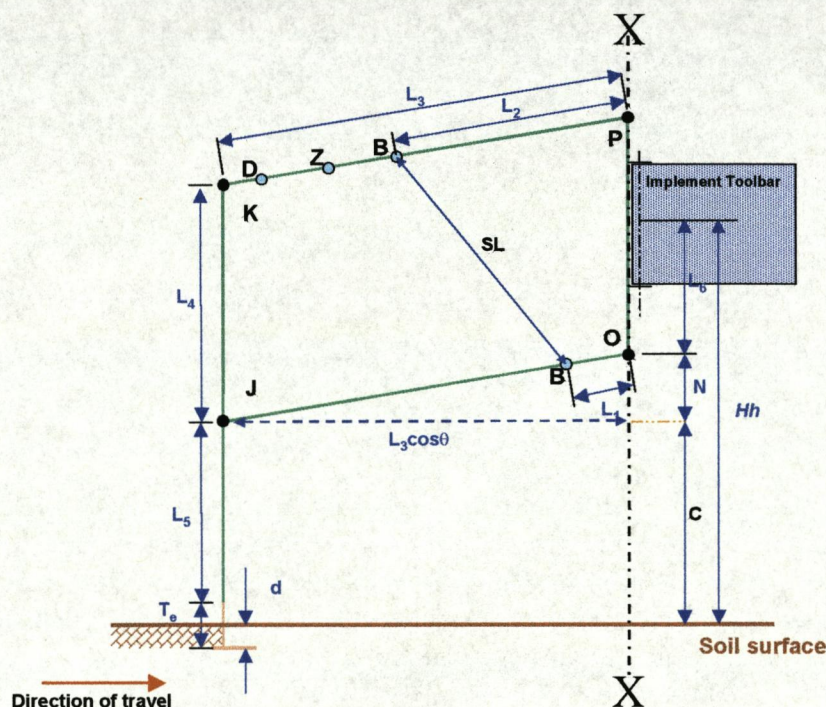


Fig. 9.1. Parallel linkage geometry.

The possibilities for dimensional change within the parallel linkage are distances L_1 through L_6 , all of which will, in some way, affect SL. Similarly, the spring rating R may also be adjusted. No changes should be made to the injector tine so that T_e remains constant.

9.3.2 Method.

The parameter that has been identified as being concurrent with observed improvements in dynamic response is β ($^\circ$), which denotes the rate of change of force with operating depth in angular terms. With reference to *Table 8.4*, $\tan \beta$ is calculated by rearranging the governing equation [24] and differentiating with respect to d , the result of which is presented as equation [29]. By substituting parameters specific to an injector tine and linkage configuration into [29], the rate of change of force with depth may be ascertained. Consequently, further partial differentiation of [29] with respect to individual linkage parameters will reveal the effect of those parameters on the rate of change of force with depth. To achieve the second order partial differentiation of the governing equation with respect to the geometry of the parallel linkage, Maple V (for Windows 3.1) was used.

9.3.3 The effect of alterations to L_1 on $\tan \beta$.

Equation [29] was partially differentiated with respect to L_1 to determine the effect on $\tan \beta$, and hence β , of changing dimension L_1 between 5 and 100 mm. The resulting equation [31] is presented in *Appendix 8.1*. Specific values relating to the linkage and 40WNDLi injector tine were entered into the equation for values of d between 0 and 0.1 m, and for L_1 , between 0 and 0.1 m (*Table 9.1*).

Table 9.1

Linkage/tine parameters consistent with the 40WNDLi tine and variable L_1 .

Parameter	Value		Parameter	Value	
DL	256	mm	Ns	2	
L_2	250	mm	M	109 N	
L_3	400	mm	T_m	16.43 N	
L_4	250	mm	Hh	427.5 mm	
L_5	185	mm	Te	173 mm	
L_6	115	mm	Df	$0.1127d^2+7.6567d$	
R	6.3	N/mm	Vf	$-0.0142d^2+7.6411d$	

The three dimensional nature of the results illustrating the sensitivity of L_1 with depth are presented in Fig. 9.2.

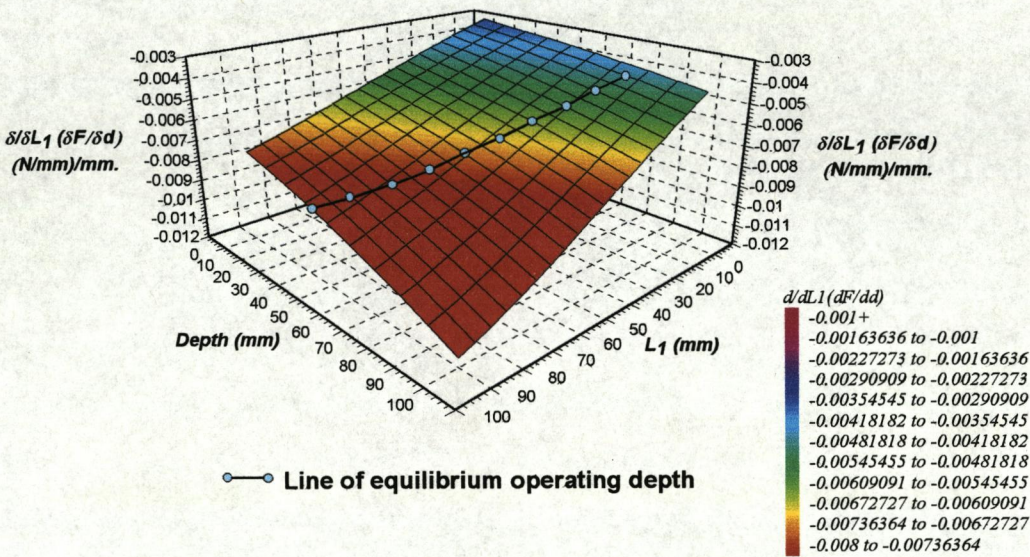


Fig. 9.2. The sensitivity of $\tan \beta$, to changes in L_1 , across the injector tine depth range, in relation to the operating depth at equilibrium, for specific linkage/tine dimensions.

It can be observed that changing the position of L_1 results in a net reduction in $\tan \beta$, and hence β , as a result of the reduction in spring force created by this adjustment. Fig. 9.2 illustrates the reduction in equilibrium depth as L_1 increases, and the small

changes to $\tan \beta$ that this particular dimensional manipulation would induce. This agrees with the observations made in *Section 8.4.4.1*, which suggest that β increases with equilibrium operating depth. However, in this situation, as the equilibrium depth decreases, so does β . Consequently, manipulation of the dimension L_1 will directly affect the dynamic performance of the system, although the reduction in equilibrium operating depth resulting from increasing L_1 will reduce performance.

9.3.4 The effect of alterations to L_2 on $\tan \beta$.

In consideration of the result presented in *Section 9.3.3*, it may be expected that altering the parameter L_2 will have a similar minimal effect on $\tan \beta$. By partially differentiating [29] with respect to L_2 , the equation illustrating the sensitivity of $\tan \beta$ to this change is presented in *Appendix 8.2*.

A three dimensional representation of the sensitivity of $\tan \beta$ to changes in L_2 is presented in *Fig. 9.3*. A reduction in the rate of change of $\tan \beta$ with increasing L_2 is illustrated. This can be attributed to the gradient of the resultant force approaching maximum limits.

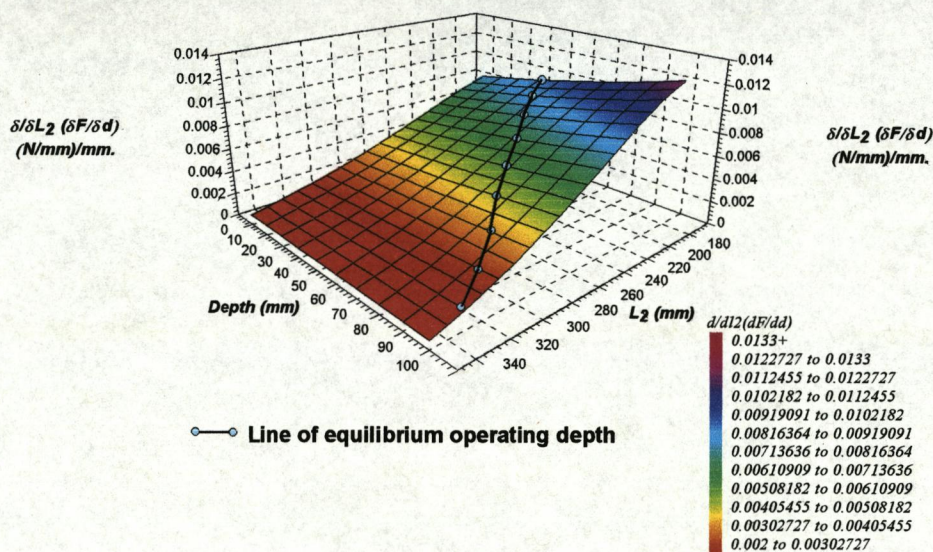


Fig. 9.3. The sensitivity of $\tan \beta$, to changes in L_2 , across the injector tine depth range, in relation to the operating depth, at equilibrium, for specific linkage/tine dimensions.

The linkage/tine conditions used in producing the three-dimensional plot, presented in *Fig. 9.3*, are similar to those presented in *Table 9.1*. However, L_1 remains constant at

52 mm and L_2 becomes variable between the limits 190 – 380 mm. The result of this investigation reveals that adjusting the dimension L_2 will have little effect on $\tan \beta$, and hence β , although the equilibrium depth will be increased resulting in a positive effect on the rate of change of force with depth.

9.3.5 The effect of alterations to L_3 on $\tan \beta$.

The parameter L_3 refers to the distance between the parallel vertical links. For systems with real or virtual hitch points Cowell and Mekanjuola (1966) proposed that reducing the distance from the implement to the hitch point, would improve the dynamic response of an implement. This was achieved by reducing the distance within which the implement would return to within 10% of its equilibrium position following lateral displacement. Although this theory is not applicable to the parallel linkage system as the hitch point is located at infinity, the effect of increasing or reducing the distance of the rear vertical arm from the plane X-X is of interest.

Partial differentiation of [29] with respect to L_3 reveals the equation expressing the sensitivity of $\tan \beta$ to manipulation of this linkage parameter [55], presented in *Appendix 8.3*. By substituting set linkage parameters consistent with the use of the 40WNDLi injector tine under soil dynamics laboratory conditions (*Table 9.2*), across the depth range of fitted tine force curves, a three dimensional plot of the rate of change of β with depth can be observed (*Fig. 9.4*).

Table 9.2

Linkage/tine parameters associated with the 40WNDLi tine and variable L_3 .

Parameter	Value		Parameter	Value
DL	256	mm	Ns	2
L_1	52	mm	M	109 N
L_2	190	mm	Tm	16.43 N
L_4	250	mm	Hh	427.5 mm
L_5	185	mm	Te	173 mm
L_6	115	mm	Df	$0.1127d^2 + 7.6567d$
R	6.3	N/mm	Vf	$-0.0142d^2 + 7.6411d$

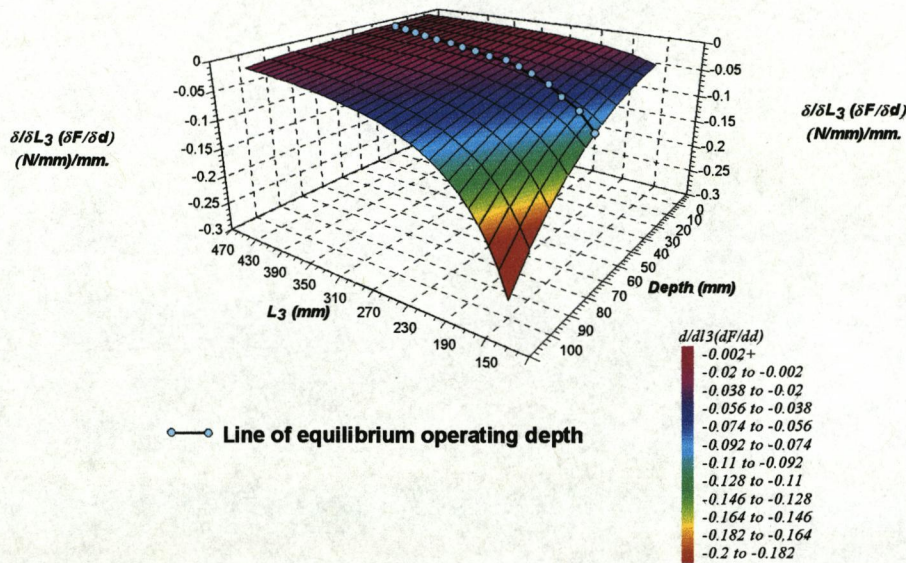


Fig. 9.4. The sensitivity of $\tan \beta$, to changes in L_3 , across the injector tine depth range, in relation to the operating depth at equilibrium, for specific linkage/tine dimensions.

Manipulation of L_3 has a negative effect on $\tan \beta$ across the entire operating range and beyond. As the length of the horizontal links is decreased, the negative effect magnifies. Extending the length L_3 has the effect of reducing the applied downward force if the force in the springs remains constant. This inevitably results in a reduction in equilibrium operating depth. It may be concluded that manipulation of L_3 will have no positive effect on $\tan \beta$ and hence β . Consistent with the observations presented in Chapter 8, manipulation of L_3 is unlikely to have any positive effect on the dynamic response of the 40WNDLi injector tine. A point of interest in observing the three dimensional profile in Fig. 9.4, is the rate at which the sensitivity of $\tan \beta$ to changes in L_3 increases in negativity as depth increases and L_3 decreases. This is primarily due to the spring effect, as the governing equation does not consider a springed linkage condition where SL is less than DL . Therefore, compression force is assumed under this situation.

9.3.6 The effect of alterations to L_4 on $\tan \beta$.

The dimension L_4 refers to the distance between the lower and upper horizontal links. Manipulation of this geometric parameter either by reduction or increase directly affects the spring length. A reduction in L_4 under certain spring conditions may cause

the equation governing the force system to calculate a negative force, indicating some spring compression. Partially differentiating [29] with respect to L_4 results in an equation describing sensitivity of $\tan \beta$ to manipulation of L_4 (Appendix 8.4). A three dimensional surface plot illustrating the effect of varying L_4 on the rate of change of force with depth ($\tan \beta$) is presented in Fig. 9.5. The conditions specific to this analysis are presented in Table 9.3.

Table 9.3

Linkage/tine parameters associated with the 40WNDLi tine and variable L_4 .

Parameter	Value	Parameter	Value
DL	256 mm	Ns	2
L_1	52 mm	M	109 N
L_2	190 mm	T_m	16.43 N
L_3	400 mm	Hh	427.5 mm
L_5	185 mm	Te	173 mm
L_6	115 mm	Df	$0.1127d^2 + 7.6567d$
R	6.3 N/mm	Vf	$-0.0142d^2 + 7.6411d$

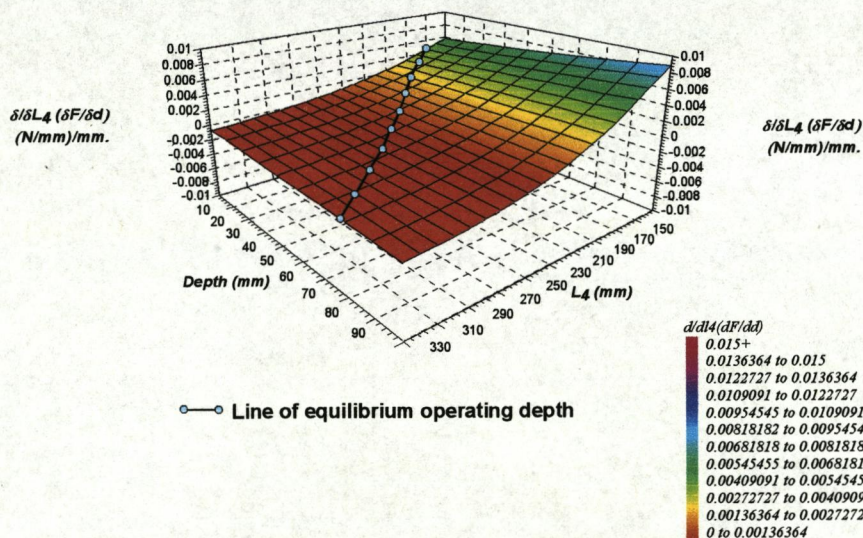


Fig. 9.5. The sensitivity of $\tan \beta$, to changes in L_4 , across the injector tine depth range, in relation to the operating depth at equilibrium for specific linkage/tine dimensions.

Fig. 9.5. illustrates the effect of changing L_4 on $\tan \beta$, which has been identified as a common factor associated with improved dynamic performance. During this analysis, compression forces applied by the linkage springs as a consequence of a spring length (SL) that is less than the unstrained length (DL) have been considered. Consequently, when the spring is considered to be in compression as a result of L_4 manipulation, there is a small but positive effect on $\tan \beta$. This affords us the best indication yet that restoring forces are dominant, and that the action of the parallel linkage, while necessary to provide penetration force, reduces the injector tines ability to maintain equilibrium.

9.3.7 The effect of alterations to L_5 on $\tan \beta$.

The parameter L_5 is the distance between the lower horizontal link at the rear of the linkage and its attachment point with the injector tine. It was found that alterations to this dimension, while maintaining constant conditions with respect to the other linkage dimensions, did not affect the equilibrium depth. The sensitivity of $\tan \beta$ to changes in L_5 was also evaluated by partial differentiation. The resulting equation is presented in *Appendix 8.5*. Constant parameters (*Table 9.4*) were combined with the variable L_5 between 100 and 300 mm to produce a three dimensional surface plot (*Fig. 9.6*).

Table 9.4

Linkage/tine parameters consistent with the 40WNDLi tine and variable L_5 .

Parameter	Value	Parameter	Value
DL	256 mm	Ns	2
L_1	52 mm	M	109 N
L_2	190 mm	T_m	16.43 N
L_3	400 mm	Hh	427.5 mm
L_4	250 mm	Te	173 mm
L_6	115 mm	Df	$0.1127d^2 + 7.6567d$
R	6.3 N/mm	Vf	$-0.0142d^2 + 7.6411d$

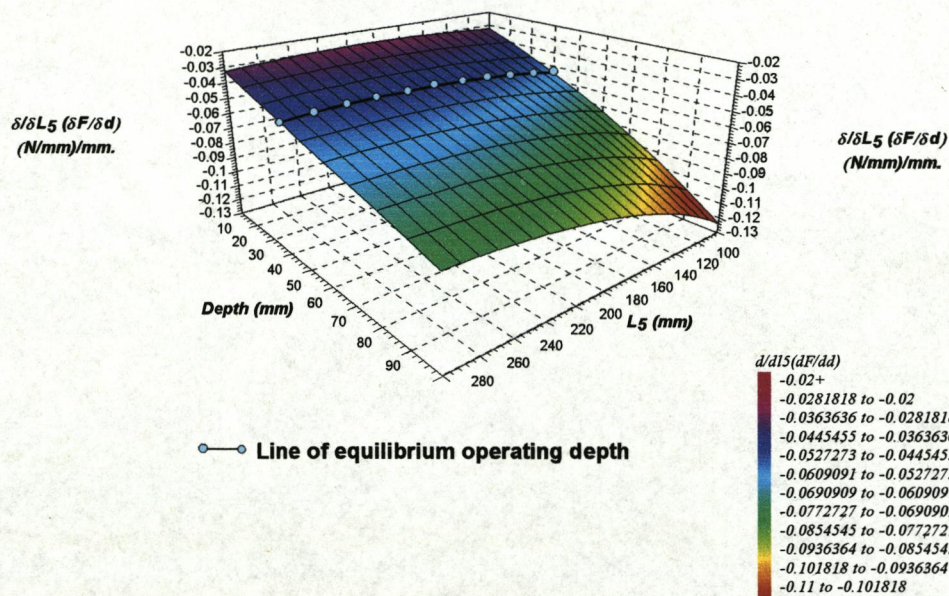


Fig. 9.6. The sensitivity of $\tan \beta$, to changes in L_5 , across the injector tine depth range, in relation to the operating depth at equilibrium, for specific linkage/tine dimensions.

The rate of change of $\tan \beta$ across the depth range, and the extent of the analysis with respect to L_5 , illustrates that little effect may be achieved by manipulation of this linkage parameter. The equilibrium operating depth remains unaffected by altering L_5 further reducing any possible effect. In addition, the effect of $\tan \beta$ on the system is negative, suggesting a reduction in the dynamic performance of the injector tine and linkage system.

9.3.8 The effect of alterations to R on $\tan \beta$.

The spring rating R has a direct relationship with the position of the linkage. The force exerted by the springs opposes the action of the 40WNDLi injector to exit from the soil. Increasing the spring rating has the effect of increasing the operating depth of the system at which equilibrium conditions occur. A three dimensional analysis of the system, utilising specific conditions, is presented in Table 9.5, revealing that increasing the rating of the spring (R) has no effect on $\tan \beta$ (Fig. 9.7) and hence β .

Table 9.5

Linkage/tine parameters associated with the 40WNDLi tine and variable R.

Parameter	Value	Parameter	Value
DL	256 mm	Ns	2
L ₁	52 mm	M	109 N
L ₂	190 mm	Tm	16.43 N
L ₃	400 mm	Hh	427.5 mm
L ₄	250 mm	Te	173 mm
L ₅	185 mm	Df	$0.1127d^2 + 7.6567d$
L ₆	115 mm	Vf	$-0.0142d^2 + 7.6411d$

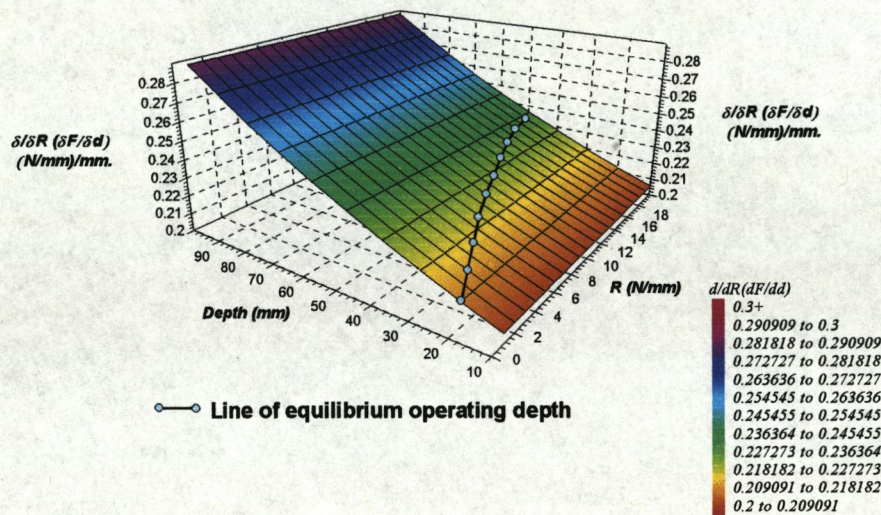


Fig. 9.7. The sensitivity of $\tan \beta$, to changes in R , across the injector tine depth range, in relation to the operating depth, at equilibrium, for specific linkage/tine dimensions. The general effect of increasing R is to increase the operating depth at equilibrium. It may therefore be concluded that alteration of this parameter is unlikely to have a positive effect on the dynamic performance of the system directly, but will make a small contribution by means of increasing d . The equation representing the relationship between R and $\tan \beta$ is presented in Appendix 8.6.

9.4 Discussion.

The analysis presented above has shown how insensitive the manipulation of the geometric parameters of the parallel linkage are to $\tan \beta$, and hence β . In general, the

effect of manipulating the majority of the parameters described is negative, and under all situations the degree of change is very small. Upon further analysis of *Fig. 8.12*, it can clearly be observed that the linkage force tends towards zero with increasing depth, further illustrating the negative effect on β . However, as both the linkage and injector tine have a direct effect on the operating depth at equilibrium, the complete system requires verification. This suggests that to improve the dynamic performance of the parallel linkage and injector tine system, other methods are required. The greatest changes were observed when spring compression conditions were forced on the system as a result of shortening L_4 for example. In this case it was clear that under tension, the force assisting penetration resulted in a negative effect on the rate of change of β , whereas upon compression this effect became positive. A compression force exerted by the springs in this situation assists the tine in exiting the soil. This effect, combined with the small negative effect of the linkage on the system, confirms that the injector tine geometry must be modified to improve the dynamic performance of the system.

9.4.1 Other methods of improving dynamic performance.

The inability to manipulate the linkage to provide improved dynamic performance suggests that some form of tine manipulation is necessary. To achieve this without affecting the soil disturbance characteristics of the 40WNDLi injector tine requires the use of either an active system for depth control, or the application of a barrier to reduce the possibility of the tine exceeding its maximum operating depth. The use of an active depth control system would increase the complexity, and cost, of the injection equipment such that the production of a 12 m system, for tramline use, would be unfeasible. It was therefore decided that the use of a barrier system would be the most suitable method for controlling and improving injector tine dynamic performance on a parallel linkage system.

9.5 A geometrical barrier for depth control.

In the context of this thesis, a geometrical barrier for depth control is considered to be an attachment to the 40WNDLi injector tine, which severely affects the forces acting on the tine at the point at which the operating depth of the injector tine is considered optimal. It is also necessary that the influence of such a barrier does not affect the soil disturbance characteristics of the injector tine. In consideration of the need for such a

device, work by Singh (1982) and Magalhães (1985) was considered. Singh (1982) suggested that the vertical dynamic behaviour of mole plough drainage equipment could be improved by small changes in tine tip angle. Subsequently, Magalhães (1985) expanded upon this work and suggested that a change as small as $2.5^\circ - 3^\circ$ would be sufficient to achieve the improvement in drainage grade dynamics. The manipulation of the tip of the 40WNDLi injector tine while in work would require complex systems and would inevitably affect the soil disturbance characteristics of the injector. However, the attachment of a skid type device to the shank of the injector tine at its maximum operating depth would provide a barrier to further penetration, even in the event of increased assisting forces provided by the linkage.

9.5.1 Injector tine skids.

Following the work of Singh (1982) and Magalhães (1985), side skids were designed to attach to the shank of the 40WNDLi at an angle of 3° to the horizontal. It is thought that these skids would act in a similar manner to the tip of the tine once the maximum operating depth of the injector tine had been reached. The force and disturbance properties of the 40WNDLi injector tine, the soil flow around the tine and the general dimensions of the injector tine were considered during this design process. The resulting injector tine utilised two skids, one each side of the tines shank, extending 0.015 m either side of the shank without exceeding the lateral extent of the tines wings, and well forward of the tine tip. A full engineering drawing of the amended injector tine is presented in *Appendix 8.7*. The position of the skids was such that soil contact would be apparent at an operating depth of 0.07 m, with total soil contact along the entire length of the skids at 0.08 m. Following the theory that has been reviewed and the force and sensitivity analysis of the system, it is expected that subsequent experimental testing of the amended system will reveal localised increases in β across the operating depth range of the 40WNDLi injector tine. It may therefore be possible to consider the soil forces acting on a complex tine in sections between regions of geometric change, rather than by simply fitting a general model to represent both draught and vertical forces.

9.6 Conclusions.

In conclusion, an analysis of the sensitivity of β to changes to the parallel linkage system has revealed that manipulation of the linkage is unlikely to affect this parameter and hence improve the dynamic performance of the tine. A more appropriate way forward may be to manipulate the tine itself. Furthermore, the application of skids to the sides of the 40WNDLi shank mounted forward of the tine tip to avoid excessive interaction with soil flow around the tine, may provide a suitable means of improving dynamic depth control/performance and requires verification. Additionally, with reference to the observations made in *Section 8.4.4*, an analysis of the effect of linkage joint type is necessary to assess the influence of friction within the linkage on the dynamic performance of the system.

9.7 Recommendations for final study.

To conclude this investigation into the soil incorporation of bio-solids into arable cropping, a final study to evaluate the effect of injector tine manipulation by means of skids is required. This should be combined with a detailed force analysis of the modified injector. This may provide verification of the relationship between tine modification and β described in previous sections. Additionally, an assessment of the effect of friction within the pin joints of the linkage is required.

Chapter 10

10.0 Injector tine depth control: Final experimental study.

10.1 Introduction.

Factors that appear to influence the vertical dynamic behaviour of complex injector tines, when used in conjunction with a parallel linkage arrangement with integral springs have been discussed in previous sections. It was suggested that one common factor associated with all results of the initial dynamic study was an increase in the rate of change of force with depth ($\tan \beta$), which correlated with improved dynamic performance. Additionally, a thorough analysis of the force system resulting in the production of a computer based quasi-static model to predict operating depth at equilibrium, showed good agreement with experimental results. Subsequently, the use of the force system analysis was used in collaboration with some basic mathematical principles to ascertain the sensitivity of $\tan \beta$ to changes in the geometry of the parallel linkage system. It was found that manipulation of many of the critical linkage parameters resulted in a negative effect on $\tan \beta$, hence not affecting β positively. Subsequently, it was concluded that manipulation of the linkage was unlikely to significantly affect the dynamic performance of the system. To further develop the hypothesis, some form of injector tine manipulation would be required to generate any improvements in depth control.

With reference to Singh (1982) and Magalhães (1985), the use of skids mounted to the shank of the 40WNDLi injector was considered to be the most promising way forward. Care was taken in the design of the skids to avoid interaction with the wings of the injector, which tend to promote soil mixing. An angle of 3° (to the horizontal) was applied to the skids to provide a degree of dynamic stability. It is thought that the use of skids will provide a step increase in force requirement at maximum operating depth allowing a localised increase in β (and $\tan \beta$) at the point of the step, resulting in an improvement in dynamic performance. The final experimental study aims to assess the effect of adding skids to the tine on the dynamic performance in relation to β . Additionally, the effect of friction within the linkage system on the dynamic performance requires analysis.

10.2 Study objectives.

The objectives of this final study are:

- To assess the performance of the 40WNDLi injector tine with skids in terms of draught and vertical force, fitting curves to represent the performance of the tine across and beyond the operational depth range and highlighting the phases of operation of the injector.
- To compare the performance of the 40WNDLi injector tine, operating with and without skids and to relate any improvement in dynamic performance to the force analysis and β .
- To assess the effect of linkage joint friction on the dynamic performance of the parallel linkage and 40WNDLi system, and to make recommendations on joint type.
- To outline the final specification of the injection system for the soil incorporation of bio-solids into arable cropping.

10.3 Force analysis (40WNDLi injector with depth control skids).

The 40WNDLi injector tine was subjected to draught and vertical force testing in the soil dynamics laboratory at Cranfield University, Silsoe, according to the methodology described in *Section 2.6*. No assessment of soil disturbance was carried out during this study. To generate sufficient data for the fitting of curves to the operating depth “stages” resulting from the addition of the skids to the injector, forces were measured at 0.01 m increments between 0.01 and 0.13 m. Each test was replicated three times in a randomised block formation across the width of the soil bin to account for variations in soil density associated with the experimental equipment. In line with previous force studies, soil properties were monitored throughout the duration of testing.

10.3.1 Soil properties.

An analysis of the soil samples taken throughout the period of testing revealed no significant difference between soil bin preparations (*Fig 10.1*). A complete statistical analysis is presented in *Appendix 9.1*.

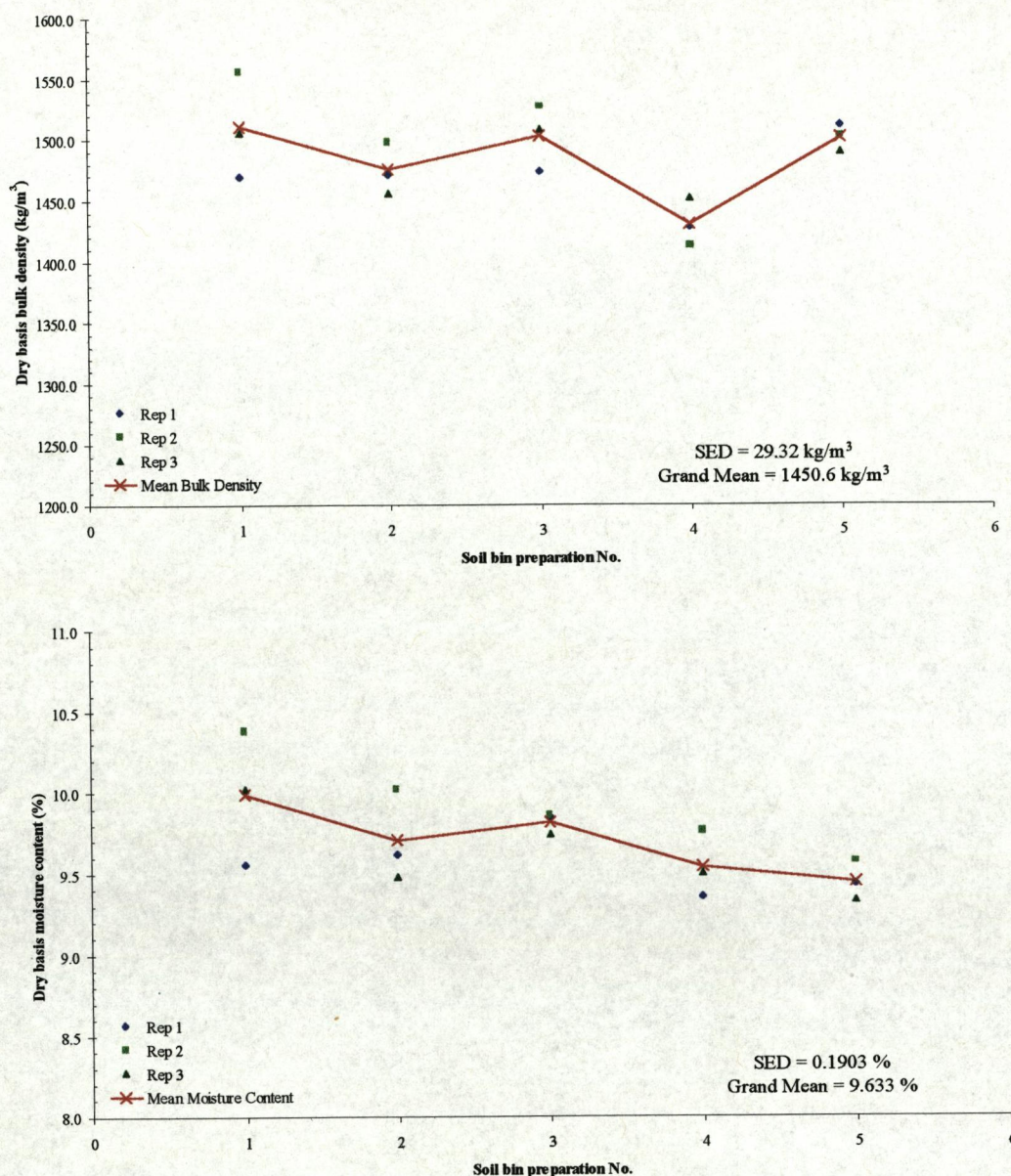


Fig. 10.1. Soil properties over the duration of injector tine testing.

10.3.2 Injector tine forces.

Injector tine forces obtained using the equipment described in *Section 2.6.4* resulted in data suitable for curve fitting. All force data (draught and vertical) was examined visually to identify trends between step changes due to the injector tines geometry. A draught and vertical force pattern, which allowed the fitting of three separate curves to each set of data was identified.

10.3.2.1 Fitting a three-stage curve to force data.

To enable a constant multiple-curve to be fitted to data from the soil surface to a depth of 0.13 m, each of the three separate curves was required to interact with each other.

An incremental procedure was used to enable three individual and independent curves to be fitted to one set of force data. The same procedure was applied to both draught and upward vertical force data.

- 1) The stages of force were identified and their depth limits established. In this situation, the 40WNDLi injector tine exhibited three stages of draught and vertical force:
 - i. 0 to 0.04 m operating depth (Stage 1)
 - ii. 0.04 to 0.09 m operating depth (Stage 2)
 - iii. 0.09 to 0.13 m operating depth (stage 3)
- 2) An initial curve was fitted to data relating to Stage 1 where the intercept of the curve was constrained to zero, corresponding to an expected zero force associated with no soil contact. The resulting equation representing the forces acting on the injector tine during Stage 1, was used to establish the force at the maximum depth limit of Stage 1. A second order polynomial curve was found to fit the data well.
- 3) Data relating to Stage 2 was subjected to a fitted curve such that the point at the initial operating limit (0.04 m) coincided with the upper limit force value of the Stage 1 curve. The curve was not constrained to intercept the force axis at zero, as the equation representing Stage 2 is only suitable between the limits established above. This equation was used to establish the force acting at the upper depth limit of this stage. Once again, a second order polynomial was found to fit the data well.
- 4) Data relating to Stage 3 was treated in a similar manner to Stage 2. The force acting at the lower depth limit was forced to coincide with the force relating to the maximum depth limit of the Stage 2 curve. The curve fitted to this final stage was not constrained to intercept the force axis at zero, and is only valid for the operating depth limits for Stage 3 outlined above. Consistent with Stages 1 & 2, a second order polynomial was fitted to the force data.

10.3.2.2 Draught force.

Fig 10.2 illustrates the three stage curve fit for the 40WNDLi injector tine operating with skids for improved depth control, compared to the single stage curve fit representing soil forces without the use of any depth control system.

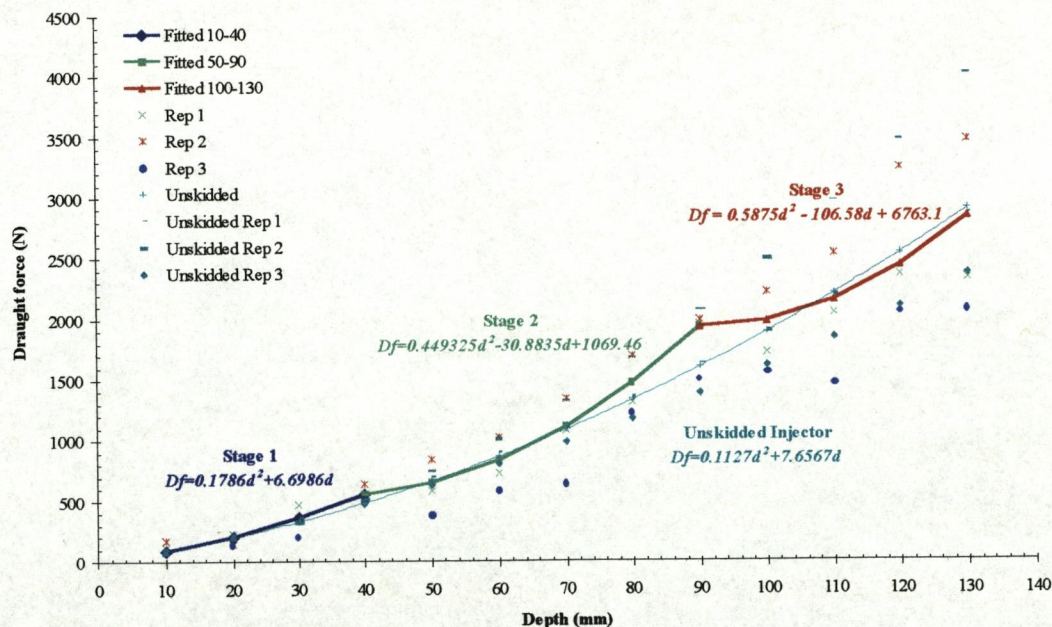


Fig 10.2. Draught force for the 40WNDLi injector tine with skids, using a three stage curve fit, and a single stage curve fit for the same tine operating without any depth control system.

Localised increases in the rate of change of draught force with depth can be observed between 30 and 40 mm, and 80 and 90 mm.

10.3.2.3 Upward vertical force.

The upward vertical force properties of the 40WNDLi injector tine operating with and without depth control skids is presented in Fig. 10.3. A three-stage curve fit has been applied to data from the skidded tine and a single curve fit was found to be appropriate from data for the non-skidded tine. The localised changes in the rate of change of force with depth identified in Fig 10.2 are also apparent, but somewhat amplified, in Fig 10.3.

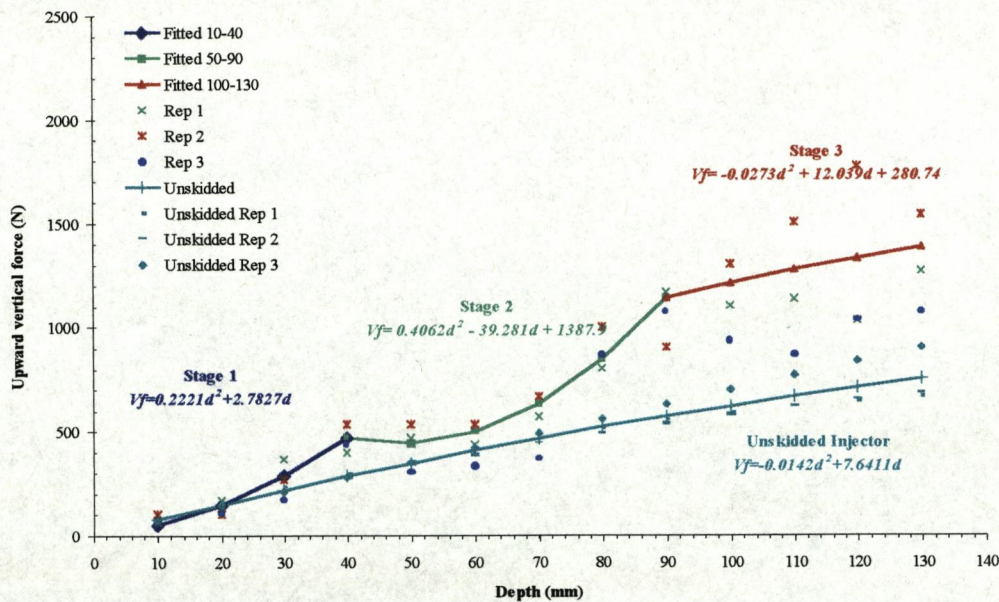


Fig 10.3. Upward vertical force, for the skidded 40WNDLi injector tine, using a three stage curve fit and; a single stage curve fit, for the same tine operating without any depth control system.

10.3.2.4 Resultant force.

A three-stage curve fit was also found to be appropriate for the resultant force data acting at an angle δ ($^\circ$) to the horizontal, generated by combining the draught and vertical force data (Fig. 10.4).

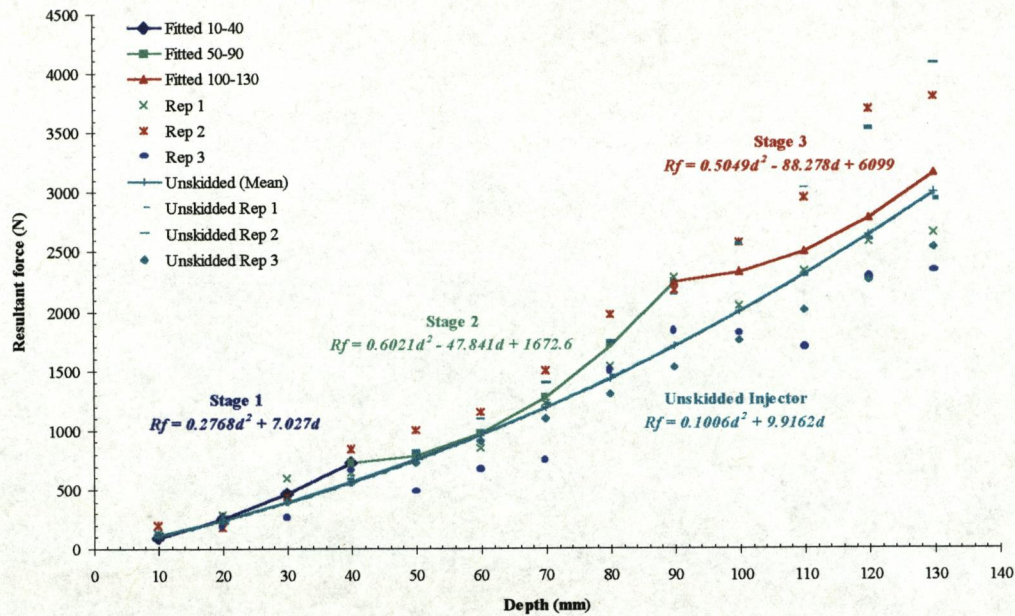


Fig 10.4. Resultant force for the skidded 40WNDLi injector tine using a three stage curve fit, and a single stage curve fit for the same tine operating without any depth control system.

10.3.2.5 The three-stage curve fit and β .

The change in the pattern of the resultant tine force on the injector/linkage system, as a result of the addition of skids to the narrow shank of the 40WNDLi tine, will directly influence the rate of change of force with depth ($\tan \beta$). The effect of β has been identified as a common factor associated with improved dynamic performance of the injector and parallel linkage system. The linkage model, presented in *Appendix 7.2*, was amended to accommodate the multiple draught and vertical force equations resulting from the addition of skids to the shank of the 40WNDLi injector tine. The effect of the improved curve fits on the operating depth at equilibrium, in addition to the rate of change of force with depth ($\tan \beta$), was examined (*Table 10.1*).

Table 10.1

The effect of a three-stage curve fit on operating depth at equilibrium and β .

L ₂	NS	40WNDLi with Skids				40WNDLi without Skids			
		Equilibrium Depth (d), mm.	β at d	$\tan \beta$	Experimental depth, mm.	Equilibrium Depth (d), mm.	β at d	$\tan \beta$	Experimental depth, mm.
190	1	25.95	86.16	14.89	27.28	30.34	82.49	7.58	34.52
190	2	31.14	86.84	18.11	30.55	40.34	83.32	8.54	34.5
250	1	32.34	86.91	18.52	30.71	43.94	83.28	8.49	36.78
250	2	53.94	83.08	8.23	39.11	61.94	84.65	10.68	53.32
310	1	49.14	72.85	3.24	35.85	59.54	84.18	9.81	64.87
310	2	71.12	87.79	25.91	69.74	85.08	85.85	13.78	85.81

Experimental depths obtained using the 40WNDLi injector tine with skids were extracted from dynamic experimental work, concentrating on the ability of the 40WNDLi injector to respond to an upward change in soil height. This work is presented later. It can be seen from *Table 10.1* that β is higher at certain stages using the three-stage curve fit method, than by the single curve fit used for expressing the performance of the tine without any depth control device. Similarly, it is interesting to note that; experimental depths were closer to modelled depths when β was high (>85). The increased value of β is expected to result in improved dynamic performance.

10.4 Further analysis of the dynamic performance of the 40WNDLi injector tine.

To evaluate the effect of the addition of skids to the shank of the 40WNDLi injector tine under dynamic conditions, a further study was conducted in the soil dynamics laboratory at Cranfield University, Silsoe. Additionally, the effect of linkage joint type was also investigated.

10.4.1 Study objectives.

The objectives of this final dynamic study were:

- 1) To assess the effect of joint type on the dynamic performance of the injector/linkage system.
- 2) To assess the effect of the addition of skids to the shank of the 40WNDLi injector tine on the dynamic performance of the injector/linkage system.

10.4.2 Methodology.

The methodology for the dynamic study of the injector tine/linkage system was similar to that described in *Section 8.4.2*. However, certain aspects of the experiment were altered to allow a better indication of dynamic response to be achieved.

10.4.2.1 Experimental design.

Contrary to the design presented in *Section 8.4.2.1*, this final dynamic study considered the individual performance of the 40WNDLi injector tine. Additionally, the step changes in either soil surface level or hitch height were also modified. The experimental design relating to the dynamic assessment of linkage joint type comprised 6 spring conditions, 4 step input changes and two linkage types (*Table 10.2*). The experiment was carried out in a randomised block design using the 40WNDLi injector tine operating without depth control skids. Similarly, the experiment to assess the effect of the depth control skids comprised two injector tines, 6 spring conditions and 4 step input surface/hitch changes (*Table 10.2*). This experiment utilised a modified linkage, which housed low friction bearings following the results of the previous joint comparison experiment.

Table 10.2

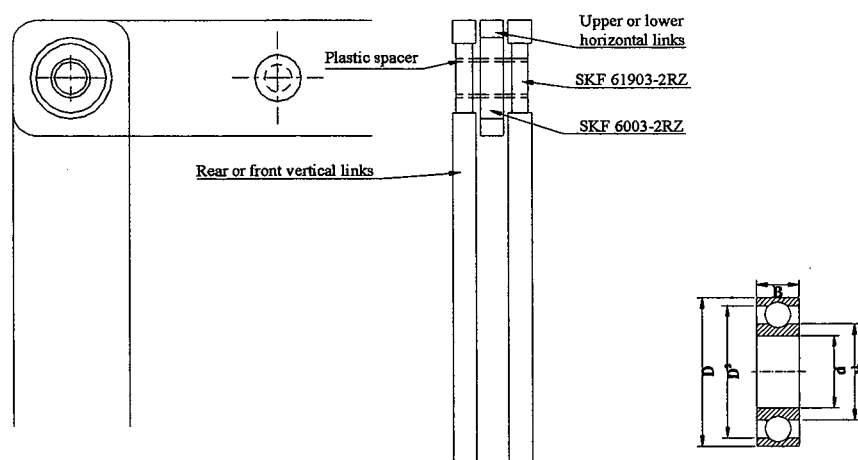
Experimental design relating to the two proposed dynamic studies.

Design option	Joint comparison	Depth control device comparison
Linkage	1. Pin jointed linkage 2. Low friction bearing joints.	1. Low friction bearing joints.
Tine	1. 40WNDLi without skids.	1. 40WNDLi without skids. 2. 40WNDLi with skids.
Step change	UP = 0.05 m upward soil surface change, DP = 0.05 m downward soil surface change, HU = 0.05 m upward hitch height change, HD = 0.05 m downward hitch height change.	
Springs	S1 = L ₂ @ 190 mm, 1 spring; S2 = L ₂ @ 190 mm, 2 springs; S3 = L ₂ @ 250 mm, 1 spring; S4 = L ₂ @ 250 mm, 2 springs; S5 = L ₂ @ 310 mm, 1 spring; S6 = L ₂ @ 310 mm, 2 springs.	
Blocks	3, (Left, middle & right)	

10.4.2.2 Linkage.

To assess the effect of joint type on the dynamic performance of an injector/parallel linkage system, modifications to the Greentrac™ parallel linkage were necessary. It was decided that low friction bearings would provide a suitable and cheap alternative

to the rather crude pins used on the commercial system. The bearing arrangement used in all parallel link joints is as presented in *Fig. 10.5*. Slightly narrower bearings were fitted to the front and rear vertical links to allow a dot punch method of bearing fixing. The bearing housed in the horizontal links was press fitted. The deep grooved ball bearings used offer a low coefficient of friction (0.0015), and are sealed at both sides to protect against contamination by soil particles. The cost of adding bearings to the linkage was approximately £110. The addition of this joint type to a full-scale machine would increase the cost by £2000, which is insufficient to adversely affect the economic evaluation, presented in *Chapter 6*.



Bearing Code	D (mm)	D ₂ (mm)	d ₁ (mm)	d (mm)	B (mm)
61903-2RZ	35	31.2	22.7	17	10
6003-2RZ	30	27.8	20.4	17	7

Fig. 10.5. Deep groove ball bearing joint type and bearing dimensions.

10.4.2.3 Tine.

The 40WNDLi injector was modified to accept depth control skids as presented in *Appendix 8.7*. The skids were designed to bolt onto the original 40WNDLi injector tine (*Appendix 2.2c*). No other modifications were applied to the injector tine.

10.4.2.4 Soil surface/hitch height step change.

The soil surface and hitch height step changes were modified with respect to earlier work, to allow better determination of the dynamic response of the injector tine/linkage combination. In previous studies, to facilitate visual identification of the common factors that may influence the dynamic performance of the configuration, a sinusoidal input was used. This method was considered suitable for preliminary

studies, but the ability to measure the dynamic performance was found to be arduous. Previous studies considering the penetration performance of implements have measured the time taken to reach a proportion of the operating depth at equilibrium, and related this measurement to proposed theories (Cowell and Sial, 1976). The use of a single step change rather than a complex sinusoidal change may allow this method to be extended to this study. Four individual changes were selected (Table 10.2) and are presented graphically in Fig 10.6.

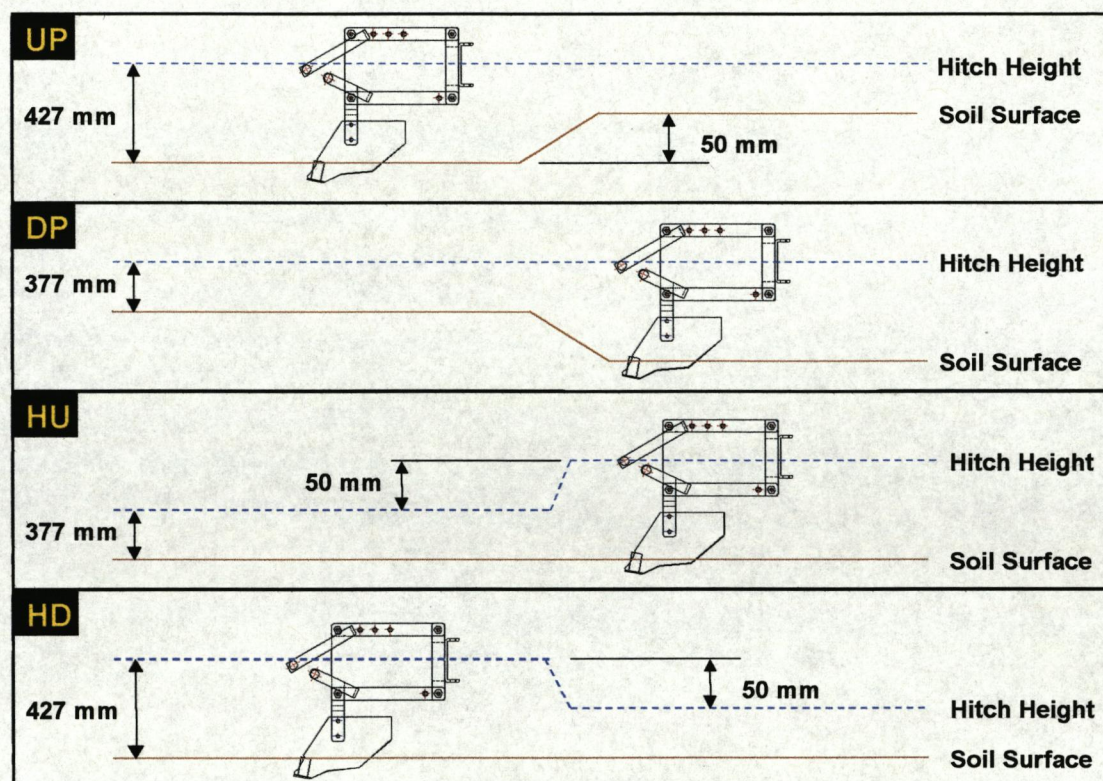


Fig. 10.6. Four individual step changes, chosen to facilitate subsequent analysis of dynamic performance.

Standard soil surface preparations were used to perform the hitch height step change tests (HU & HD), according to the procedure described in Section 2.6.1.1. For the tests involving step changes in soil surface level a simplified method, similar to that described in Section 8.4.2.2 was used. In essence, a standard soil preparation was prepared to a penultimate level, after which, the addition of a 0.05 m layer of soil was added to the last half of the prepared surface and rolled 6 times with the processors' flat roller. This produced a soil surface that was suitable for the UP tests. To produce a soil surface suitable for the DP tests, a standard soil preparation was prepared and a 0.05 m depth of soil was scraped from the last half of the prepared surface.

10.4.2.5 Spring conditions.

In contrast to the preliminary work described in *Chapter 8*, six spring conditions were used during testing. The use of a non-sprung linkage was not included in these final dynamic studies.

10.4.2.6 Instrumentation and data handling.

Instrumentation during testing was similar to that described in *Section 8.4.2.5*. However, the A/D interface card, computer system and software used for data capture were modified as a result of a system upgrade in the soil dynamics laboratory. The data capture system used in this final dynamic study is as described in *Section 7.2.1*. Captured data was manipulated by moving average smoothing over 0.25 s to remove electrical noise. The test results were synchronised with each other, such that the step changes for each set of tests coincided, to allow statistical analysis.

10.4.2.7 Experimental procedure.

Each test was carried out at a speed of 0.55 m/s (2 kph) along the entire length of the soil bin. The hitch height was pre-set for each test, such that the hitch height was 427 mm and 377 mm for UP, HD and DP, HU tests respectively. A 5 s delay was staged after the commencement of data logging, prior to the start of the soil processor. Additionally, the injector tine was rested on a steel plate during this period to enable datum's to be established for subsequent data analysis. HU and HD tests used the system described in *Section 8.4.2.3* allowing a visual display of the implement hitch height to be observed in the soil dynamics laboratory control room during each test. The hitch height change for each HU and HD test was noted as operator error resulted in some degree of variation in this parameter.

10.4.2.8 Soil properties.

Soil conditions in the soil bin were monitored for bulk density and moisture content on a dry basis throughout testing. Where soil surfaces contained upper and lower levels (UP & DP) three replications were taken from each level.

10.4.3 Dynamic performance assessment method.

In contrast to the analysis of dynamic performance presented in *Chapter 8*, which was based on visual identification, a more comprehensive method for dynamic performance assessment was required in this final experimental study. In the absence

of any definitive theory for the assessment of dynamic behaviour, an assessment method was developed. Three primary methods for the assessment of dynamic performance were devised:

1. Distance taken to reach 85% of final depth attained (based on actual depth profiles), "Actual Performance".
2. Distance taken to attain 85% of modelled depth (based on actual surface profiles and modelled and experimental depth profiles, "Combined Performance".
3. Difference between modelled and experimental operating depth both prior to, and after, change in soil surface level or hitch height, "Depth Performance".

The rationale behind each performance assessment will be discussed individually.

10.4.3.1 Actual performance.

Each individual test was assessed for the actual performance of the injector/linkage configuration. All tests were compared and synchronised, such that the soil surface change or hitch height variation coincided, and the data representing the start of the test was discarded. The resulting soil surface and depth profile is presented in *Fig. 10.7*.

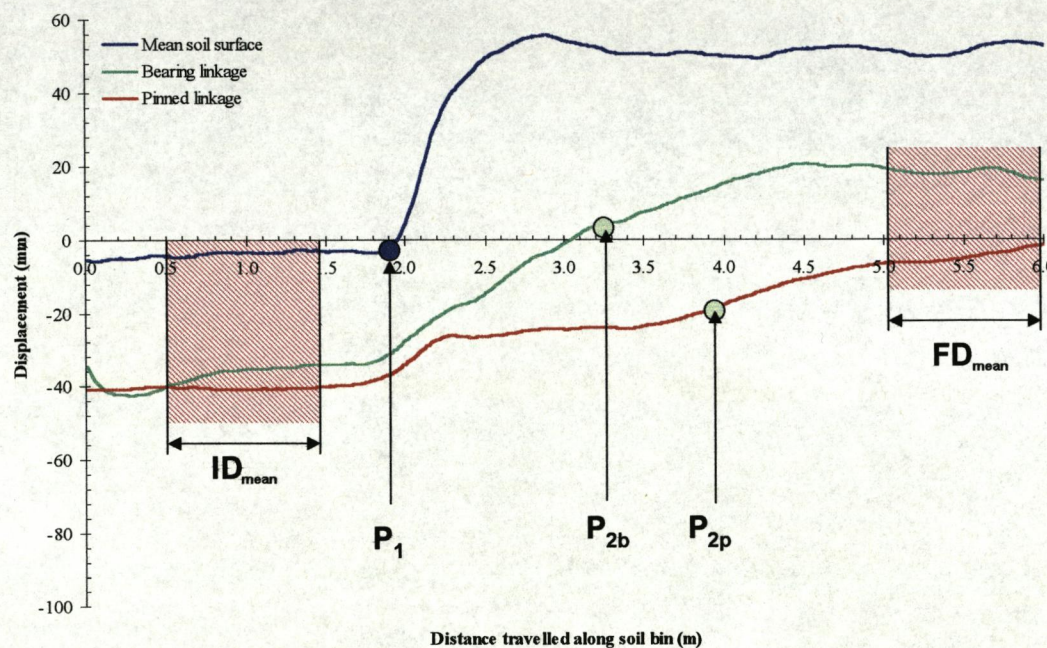


Fig. 10.7. Actual tine performance assessment parameters.

The initial and final tine depths (ID_{mean} & FD_{mean}) are calculated. The operating depth of the tine according to *Fig 10.7* is the difference between the mean soil surface and either the pinned, or the bearinged linkage. P_1 is identified manually as the point at

which the soil surface, or hitch point variation, commences. 85% of the difference between the initial and final operating depth is calculated, and test data is analysed to ascertain the distance along the soil bin at which the 85% depth was achieved. Simply subtracting the start position (P_1) from P_{2b} or P_{2p} reveals the time of response to the step change. As all tests were treated in the same manner the difference in performance between tine and linkage configurations may be assessed and compared. The use of 85% as the performance criteria in this analysis is not arbitrary, as it was expected that even 3 to 4 m after the step change the linkage and tine system may still be attempting to attain a point of equilibrium, and that FD_{mean} may not represent a constant parameter. This is reinforced in *Fig 10.7* as it can clearly be seen that the pinned linkage depth profile is still attempting to rise.

10.4.3.2 Combined performance.

It is apparent that the “Actual performance” measurement does not consider the depths that the tine and linkage system should attain during each test and after the step change in soil surface level or hitch height. The “combined performance” measurement addresses this shortfall on a similar principal to that described above.

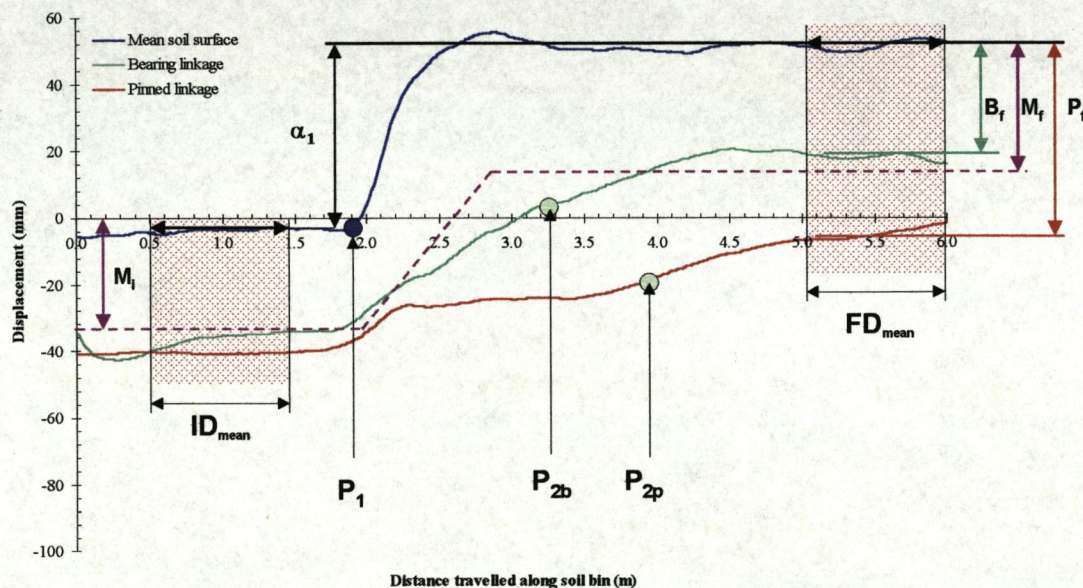


Fig 10.8. Combined performance assessment parameters.

Fig 10.8 illustrates a number of parameters used to calculate the level of the 85% performance based on predicted and experimental results. The equation used to calculate the level at which the distances P_{2b} and P_{2p} are located can be expressed as:

$$\text{distance} = (-M_i) + 0.85(\alpha_1 - [M_f - M_i]) \quad [95]$$

This calculates the distance about the datum at which 85% of the modelled depth has been attained, based on the experimental difference in surface level or hitch height variation $[\alpha_1]$. The distances travelled along the soil bin (P_{2b} and P_{2p}) are then extracted from the data. It can be seen from *Fig 10.8*. that the pin jointed linkage and tine configuration, in this case, are unlikely to attain 85% of the modelled depth resulting in a missing value. In reality the missing values indicate an extremely poor performance. However, for the purpose of analysis the values are treated as missing, allowing the statistical package to eliminate very poor performances.

10.4.3.3 Depth performance.

This assessment method allows a comparison to be made between the predicted operating depth for specific conditions and the mean depth attained experimentally, before and after the change in soil surface level or hitch height variation. The difference between predicted and experimental depth is corrected by squaring and square rooting to eliminate negative values (signifying an experimental depth below modelled depth). The differences may then be analysed statistically. A low difference signifies better performance based on the analysis presented in *Chapter 8*, whereas a high difference signifies poor performance.

10.5 Results.

The results of this final study comprise

1. Quantification of the prevailing soil conditions during testing and their relation to previous soil dynamics studies.
2. A comparison of joint type (bearings vs. pinned joints) on the dynamic and quasi-static depth performance.
3. A comparison of depth control device (skids) on the dynamic and quasi-static depth performance.

10.5.1 Soil properties.

The results of the soil tests for bulk density and moisture content on a dry basis are segregated into three distinct components:

- Bearinged linkage dynamic study (40WNDLi injector without skids),
- Pin jointed linkage dynamic study, (40WNDLi injector without skids),
- Bearing joints and depth control skids dynamic study (40WNDLi with skids).

A complete statistical analysis of all soil samples extracted throughout testing is presented in *Appendix 9.2*. Similarly, graphical presentation of the soil properties is presented in *Appendix 9.3*. The statistical analysis demonstrated that there were no significant differences between soil preparations, soil surface levels or dynamic studies in terms of bulk density and moisture content. Once again this reinforces the suitability of the soil dynamics laboratory and the soil bin for studies of this nature.

10.5.2 Joint comparison.

Following data analysis, a statistical analysis of the response and depth performance using the methods described in *Section 10.4.3*, revealed a number of significant effects. Each assessment method is considered individually below and the full statistical analysis is presented in *Appendix 9.4*.

10.5.2.1 Actual performance between joint types.

The results, based on the actual experimental performance of the 40WNDLi injector tine and parallel linkage combination utilising varied spring conditions, revealed a significant effect of joint type (@ 89.2% level) on the dynamic response of the system. Tests conducted using the linkage with bearing type joints responded quicker to changes in soil surface elevation or hitch height variation than those tests conducted using a pin jointed linkage. A significant difference observed between type of change (UP/DP/HU/HD), revealed that faster responses were more likely to be associated with hitch movements or downward soil surface changes. This indicates that the issue of dynamic response is more important when considering upward soil surface changes, as these significantly increase the implement response time irrespective of joint type.

One of the most interesting results considers the interaction between spring configuration and type of change. It was found that response distance reduced with increasing spring force applied to the system in the case of the upward soil surface change. This supports the theory presented in *Chapter 8* suggesting that the rate of change of force with depth ($\tan \beta$) increases dynamic performance. In contradiction however, downward soil surface changes induce a tendency for longer response distances. This can be explained as follows: a reduction in soil surface height is, in effect, similar to an increase in the hitch height, which reduces the degree of applied

downward force and consequently reduces the operating depth. Once again the theory proposed in *Chapter 8* is reinforced as β reduces with operating depth resulting in poorer dynamic performance. Pertinent results relating to actual dynamic performance are presented in *Table 10.3*.

Table 10.3.

Pertinent results relating to actual performance assessment following the dynamic study into the effect of joint type on dynamic performance.

Distance travelled to attain 85% of final operating depth after change (m)					
Type of change		DP	HD	HU	UP
Spring configuration	S1	0.944	0.298	0.21	1.103
	S2	0.757	0.812	0.432	1.906
	S3	0.506	0.391	0.354	1.49
	S4	0.907	0.429	0.929	0.966
	S5	0.877	1.073	1.387	0.971
	S6	1.211	0.805	0.892	0.823
	Mean	0.867	0.635	0.701	1.210
Bearings		Pins			
Grand Mean:		0.757 m	0.95 m		

10.5.2.2 Combined performance between joint types.

The analysis of the results considering the dynamic performance in relation to predicted equilibrium operating depths reveals significance across the whole range of joint type, soil surface changes, variations in hitch height and spring configuration. Additionally, interactions were observed between all treatments. The analysis revealed that the use of bearings compared to pin joints halves the response distance (mean response distance for bearings and pins was 0.551 and 1.11 m respectively). The degree of significance observed should be treated with caution as missing values, omitted from the statistical analysis, relate to exceptionally poor performance during testing, mainly due to an inability to attain 85% of the modelled depth change. This performance measure, while giving a general indication of the general dynamic performance, masks the true nature of the significance. A subsequent analysis of depth performance revealed the reasons for the high level of significance observed using this assessment method.

10.5.2.3 Depth performance between joint types (Prior to change).

An analysis of the depth performance of the 40WNDLi injector tine operating on the parallel linkage revealed that; the substitution of bearings for the conventional pin joints in the linkage reduced the difference between experimental and predicted

operating depth significantly. The average difference between experimental and predicted depth was found to be halved, correlating well with the slight errors exhibited by the experimental verification of the linkage model presented in *Chapter 8*. In general, the interaction between joint type and spring configuration results in an increase in error between experimental and predicted operating depths, as applied spring force increases (*Table 10.4*). Similarly, the interaction between all treatments (significant at 93.1 % level) shows that this increase is common to both joint types although the difference between experimental and predicted depth is generally lower when the bearing jointed linkage is used (*Table 10.5*).

Table 10.4

The interaction between joint type and spring configuration based on depth performance assessment.

Difference between experimental and modelled operating depth prior to surface or hitch change (mm).			
	Joint type	Bearings	Pins
Spring configuration	S1	4.33	8.24
	S2	9.68	13.2
	S3	11.54	18.5
	S4	12.4	31.73
	S5	13.64	27.59
	S6	6.79	20.52
	Mean	9.73	19.96

LSD = 4.198 mm @ 95%

Table 10.5

The interaction between joint type, spring configuration and type of change (HU/HD/UP/DP) based on depth performance assessment.

Difference between experimental and modelled operating depth prior to surface or hitch change (mm).						
Bearings	Change:	DP	HD	HU	UP	Mean
Spring configuration	S1	5.34	1.74	7.15	3.09	4.330
	S2	16.91	6.77	10.69	4.35	9.680
	S3	13.32	4.5	21.64	6.7	11.540
	S4	10.02	17.45	8.51	16.63	13.153
	S5	22.2	15.74	7.35	9.28	13.643
	S6	9.08	3.62	5.23	9.23	6.790
	Mean	12.812	8.303	10.095	8.213	9.86
Pins	Change:	DP	HD	HU	UP	Mean
Spring configuration	S1	8.28	5.59	15.75	3.35	8.243
	S2	20.17	9.45	17.62	5.54	13.195
	S3	22.01	12.68	25.52	13.81	18.505
	S4	38.47	25.68	39.85	22.91	31.728
	S5	28.97	26.65	29.01	25.73	27.590
	S6	23.62	15.13	22.8	20.53	20.520
	Mean	23.587	15.863	25.092	15.312	19.96

LSD = 8.395 mm @ 95%

No difference between joint types was observed between the experimental and predicted operating depths, after the negotiation of a step change in either soil surface level or hitch height. Mean values of this depth performance parameter were 11.91 and 12.1 mm for the bearing and pin jointed linkage respectively. In comparison to measurements prior to the surface or hitch height change, the difference measured after was similar to the values for bearing joints in the prior analysis.

10.5.2.4 Discussion: Joint comparison.

The assessment methods used for analysis illustrate the slightly significant effect of the use of bearings rather than pin joints, in improving the dynamic performance of the injector tine/linkage system under evaluation. This, combined with the ability of the model to better predict experimental operating depths, suggests that for the study to assess the effect of depth control skids, a linkage utilising bearing joints should be considered. The use of bearings reduces any frictional effects within the linkage allowing freer movement, and a better indication of response may be achievable using this type of joint. The use of the “combined performance” analysis technique gave variable results but when used in comparison with the depth performance assessment method, better indications of system performance in relation to modelled predictions are possible.

10.5.3 A dynamic study of the effect of depth control skids on dynamic performance.

An analysis of the results relating to the use of the 40WNDLi injector tine operating with and without skids was carried out to assess the dynamic performance, and the relationship between experimental and predicted operating depth, and a comparison between depth and experimental dynamic performance. A complete statistical analysis of this work is presented in *Appendix 9.4*. Each method of performance assessment will be considered individually.

10.5.3.1 Actual performance.

The use of skids on the 40WNDLi injector tine significantly increased the rate of response (at 90% level of significance), by reducing the distance travelled to attain 85% of the final operating depth (*Fig. 10.9a*). High variation was experienced during this experiment ($cv = 60\%$) suggesting that the real effect may be more significant if more accurate instrumentation were possible. However, the use of the soil dynamics

laboratory reduces the variation considerably, indicating that the test procedure or method of depth measurement requires amendment for subsequent studies of this type. In common with the joint comparison trials, the type of step change was found to affect the degree of dynamic response significantly. The 40WNDLi injector tine responds better to a lowering of the soil surface or an upward hitch movement than to the opposite scenario (*Fig 10.9b*).

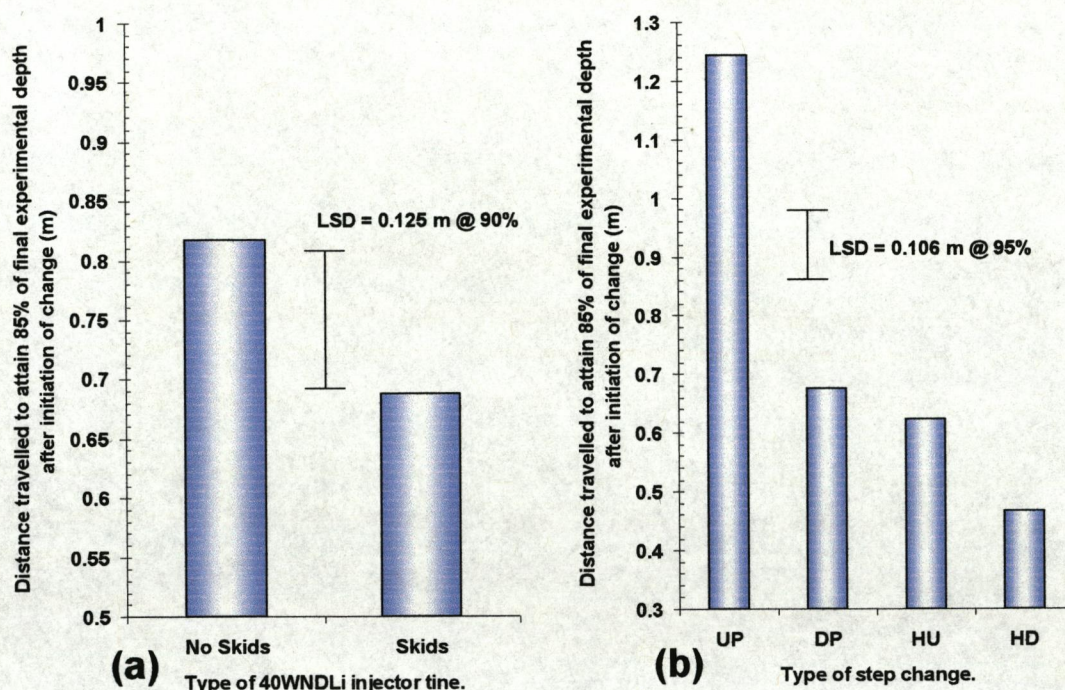


Fig 10.9. The effect of a) the use of skids and b) type of step change on dynamic response of the 40WNDLi injector tine.

The significance observed supports the theory of increased dynamic response by increasing the rate of change of force with depth ($\tan \beta$). An interaction between spring configuration and type of tine was not observed to be significant. However, it was expected that, from *Table 10.1*, clear indications of improved response would be expected from spring configurations S4 and S6. From this experiment a reduction in the distance taken to achieve 85% of the final operating depth was observed (*Table 10.6*).

Table 10.6.

The relationship between type of tine and spring configuration irrespective of type of step change.

Distance taken to achieve 85% of final experimental operating depth measured from the start of the step change irrespective of type of change (m)						
	Spring configuration					
	S1	S2	S3	S4	S5	S6
40WNDLi without skids	0.769	0.792	0.794	0.710	0.891	0.948
40WNDLi with skids	0.520	0.547	0.901	0.505	0.856	0.797

10.5.3.2 Combined performance.

In contrast to the joint comparison discussed earlier, the assessment of the combined performance of the 40WNDLi tine with and without the depth control skids revealed little significant effect of any type. Therefore, it may be suggested, based on the significance of this performance measurement, that reducing friction has a greater effect on dynamic performance than the use of depth control skids, in the context of the “combined” performance measurement.

10.5.3.3 Depth performance (prior to change).

It is expected that the improved three-stage curve fit, added to the dynamic model and presented in *Appendix 7.2*, will allow better prediction of experimental operating depth. An analysis of the difference between experimental and predicted operating depths indicates that the use of skids and the three-stage curve fit model reduces the error in this prediction technique significantly. The difference is clearly presented in *Fig 10.10a* where a significant reduction in difference was observed irrespective of any influence from the type of change (*Fig 10.10b*).

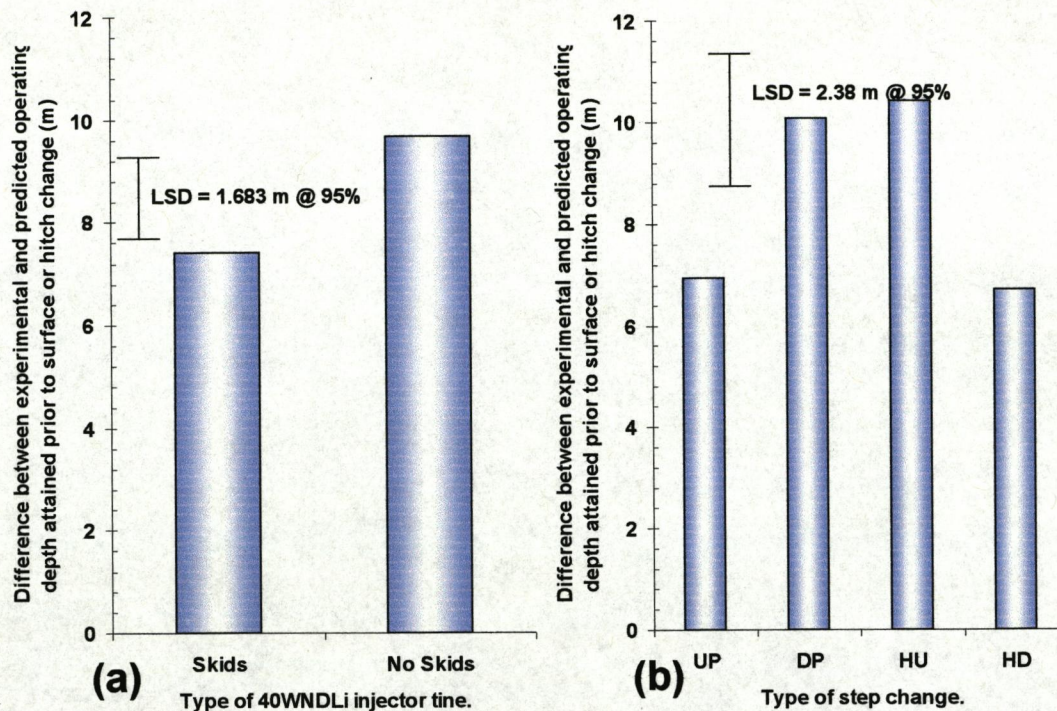


Fig 10.10. a) The significant effect of the use of skids, for depth control and improved response device, and b) the insignificant effect of type of step change on the difference between experimental and predicted operating depth prior to change.

10.5.3.4 Depth performance (after change).

It is significant that the use of the skids attached to the 40WNDLi injector tine combined with the use of a three stage curve fit in the quasi-static model results in better prediction of operating depth (Fig 10.11a). Discounting the type of tine, the type of change is insignificant in this case (Fig 10.11b). However, an interaction exists between type of tine and change, emphasising the contribution that the addition of skids add to improved prediction using the three-stage curve fitting technique (Table 10.7).

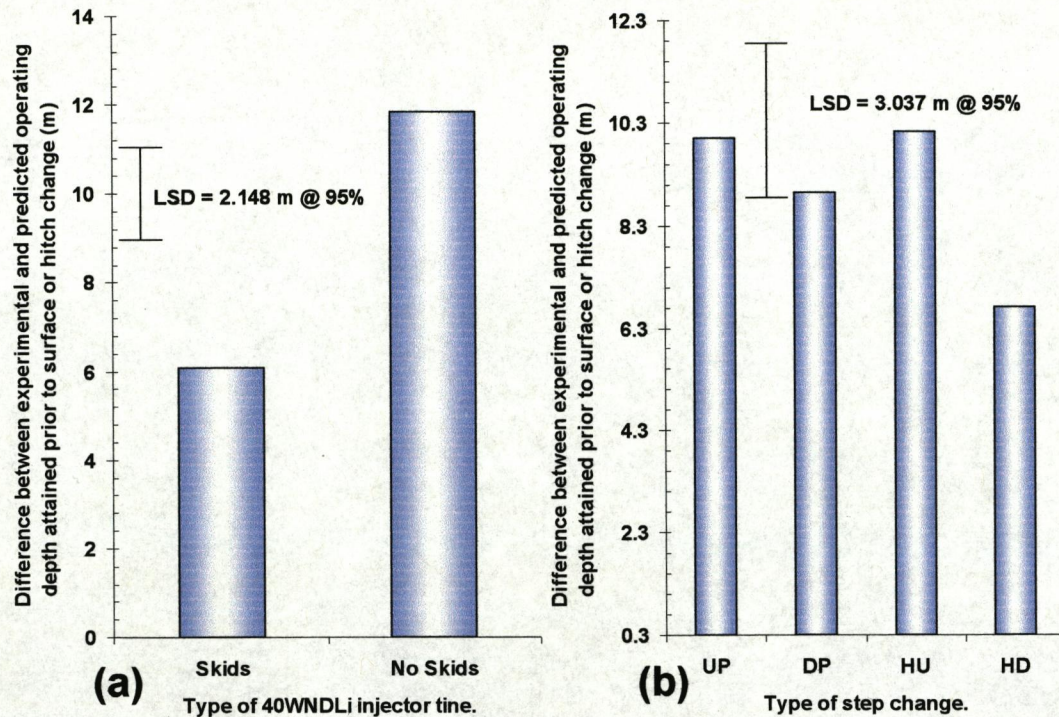


Fig 10.11. a) The significant effect of the use of skids for depth control and improved response device and b) the insignificant effect of type of step change on the difference between experimental and predicted operating depth *after change*.

Table 10.7

The interaction, between type of change in the soil surface and, the performance of the 40WNDLi tine with, and without skids, with reference to the difference between experimental and predicted operating depth.

Difference between experimental and predicted operating depth (m)				
	Spring configuration			
	UP	DP	HU	HD
40WNDLi without skids	15.53	10.08	13.04	8.65
40WNDLi with skids	4.44	7.82	7.19	4.77

LSD = 4.295 m @ 95%

10.5.3.5 The effect of skids on maximum operating depth.

One of the prime reasons for the use of skids on the 40WNDLi injector tine, in addition to improving the dynamic response of the tine and improving the relationship between experimental and predicted depths, is the ability to restrain the tine from exceeding its maximum operating depth. It has been stated previously that the

40WNDLi injector tine is unsuitable for operation below a depth of 0.08 m. The positioning of the skids, described in *Chapter 9*, is such that soil interaction occurs below the threshold level of 0.08 m, altering the force profile of the tine to assist in maintaining a suitable operating depth (<0.08 m). The statistical analysis of the depths attained, presented in *Appendix 9.5*, shows that, in general, the 40WNDLi injector tine is capable of operating without exceeding the maximum operating depth of the tine under all spring configurations and soil conditions encountered in the soil bin (*Table 10.8*). When the maximum operating depth of the injector tine was exceeded, the degree to which this was done was minimal (<0.005 m).

Table 10.8.

Experimental operating depth of the 40WNDLi injector tine, for all types of change and spring configurations, operating with and without the depth control skids.

Experimental depth of the 40WNDLi injector tine (mm)									
Prior to change					After change				
40WNDLi without skids					40WNDLi without skids				
	UP	DP	HU	HD		UP	DP	HU	HD
S1	33.79	35.94	38.48	27.98	S1	35.67	32.11	38.49	34.20
S2	37.31	39.24	46.33	31.70	S2	37.81	34.52	31.07	37.84
S3	36.41	45.02	52.23	38.81	S3	41.25	40.42	47.41	51.28
S4	51.88	81.77	98.64	42.84	S4	70.06	59.11	87.79	84.77
S5	61.77	68.45	87.64	44.69	S5	83.00	54.46	52.50	83.45
S6	87.44	109.43	106.19	80.40	S6	112.51	81.86	89.83	110.20
40WNDLi with skids					40WNDLi with skids				
	UP	DP	HU	HD		UP	DP	HU	HD
S1	26.30	29.02	30.12	24.28	S1	33.02	26.87	22.97	30.01
S2	29.81	34.72	37.68	30.92	S2	34.26	33.28	27.21	35.91
S3	33.13	38.59	35.87	29.37	S3	43.60	28.55	27.64	32.59
S4	35.75	64.93	45.56	40.51	S4	75.41	52.10	36.11	72.07
S5	36.43	44.97	43.77	38.30	S5	73.08	29.38	38.79	70.12
S6	69.27	76.67	74.84	73.61	S6	84.46	71.97	70.43	82.75

10.5.3.6 Discussion: Depth control device.

The use of skids on the side of the 40WNDLi injector tine has enabled improved depth control and dynamic performance to be achieved. However, the level of significance of the latter is only 90%. It is apparent that the use of the three stage curve fitting technique for injector tine force data, improves predictions of depth and quasi-static performance compared to the single stage technique. The tine force data treated in this manner indicated that if the visual identification of the main parameters affecting dynamic performance were correct, improved dynamic performance could be expected under limited spring configurations. The conditions under which improvements were expected were S4 and S6 spring conditions. Although

insignificant, indications that small benefits were obtainable under these conditions were apparent and slightly improved dynamic performance was obtained. In addition to this observed improvement, the ability of the skids to restrain the injector tine from exceeding its maximum operating depth is significant. The mean soil surface and tine profiles under all conditions is presented in *Appendix 9.6*. However, the differences are not easily discernable by this presentation method. In addition to the graphical presentation, a video CD containing computer based video footage of the 40WNDLi with and without skids on up and downward surfaces is attached to this document, and a description of the contents of this CD is presented in *Appendix 9.7*.

The improved modelling technique afforded by the ability to fit multiple curves to force data has increased the level of accuracy of depth prediction suggesting that complex tines, which are unsuitable for mathematical models (Godwin, 1974) may be analysed in this manner for dynamic studies.

10.6 Conclusions

The following conclusions have been extracted from this final dynamic study:

- Multiple curves can be fitted to injector tine force data to improve analysis of the tines' force system; significantly improving the accuracy of the quasi-static model, developed to predict injector tine operating depth, under variable conditions.
- The use of bearings in place of conventional pin joints improves the dynamic response of the tine/linkage system (@ 89.2% level) and, in addition, reduces the difference between experimental and predicted operating depth.
- The attachment of skids to the side of the 40WNDLi injector tine significantly improves the dynamic response of the system, irrespective of the type of change presented to the tine or the spring conditions under which the system is operating.
- Under spring configurations S4 and S6, where β is increased by the addition of the skids, shown by three individual curves being fitted to the tine force data, an observed increase in dynamic performance is apparent, although insignificant statistically.
- The final specification for the injector tine/linkage system should utilise the parallel linkage, with bearings for joints and skids for improved dynamic performance and depth control.

Chapter 11

11.0 Synopsis.

In 1995, when this research was initiated, the need for research into bio-solids recycling was driven primarily by EU legislation controlling the disposal of waste to sea. Subsequently, consumer groups such as the British Retail Consortium, have provided guidelines for the protection of the retail consumer in relation to health issues. Although the practice of bio-solids application to land is well established, novel approaches for recycling the increasing volume of waste with the reduction in options available for disposal imposed by legislation are required. The history of bio-solids application has been discussed, and the common methods for achieving disposal/recycling have been identified. However, these do not utilise the nutrients contained within bio-solids efficiently. Bio-solids application to arable crops, permitted by shallow injection as a result of the BRC/ADAS safe sludge matrix, may provide a more suitable method for the efficient use of nutrients.

Initial studies to optimise the incorporation of bio-solids into arable cropping concentrated on the development of soil tine theory, to gain a fundamental understanding of the factors affecting injector tine performance. The performance of existing shallow injection equipment and prototype designs under controlled experimental conditions was assessed during soil dynamics laboratory studies into injector tine force and soil disturbance characteristics. It was found that existing shallow injectors promoted bio-solids placement in narrow channels in the soil rather than through efficient incorporation. Subsequently, it was also discovered that a suitable soil disturbance pattern could be achieved using small wings on a narrow tine shank without excessive tine forces and lateral soil disturbance, which may have affected roots adversely. The issues of crop separation/cutting were considered, resulting in the identification of two different designs of shallow tine for the purpose of injection into cropping:

1. Single piece injector tine with integral cutting edge, (40WNDLi).
2. Simple tine and cutting disc assembly, (Retrofit).

Further soil dynamics laboratory studies were conducted with refined injector tines to assess their suitability for field trials, and their performance in terms of improvements in environmental issues such as odour and ammonia emissions, soil water nitrate

concentrations and agronomic performance. The 40WNDLi injector tine with its integral cutting edge was found to be the most suitable option for this application.

Subsequent field trials confirmed that the 40WNDLi injector was capable of reducing odour emissions significantly (@ 85% level of significance) compared with the channel producing shallow injector tines. In addition, it was found that ammonia emissions could be reduced significantly by adopting shallow injection, and subsequent trend analysis indicated that further reductions might be possible by using the improved 40WNDLi tine compared with existing shallow injection techniques. The environmental savings in terms of reduced nutrient loss contribute enormously to the value of the product and provide potential agronomic benefits. It was found that the increased quantity of available nitrogen deposited in the soil as a result of lower gaseous emissions did not affect soil water nitrate concentrations adversely in comparison to existing shallow injection methods, under the field conditions prevailing during the study.

Extensive agronomic field trials, conducted as part of the main project contract, in addition to the agronomic trials for this doctoral study, confirmed that efficient bio-solids incorporation may be carried out well into the growing season, without significant effect on crop performance. Similarly, the supply system, in the form of an umbilical hose, is unlikely to affect crop performance adversely unless it is used late in the growing season.

Following the promising results obtained in laboratory and field trials, an assessment of the management issues surrounding bio-solids incorporation into arable cropping was conducted. Primarily, customer perception and acceptability were investigated using questionnaire techniques. The assistance of Anglian and Severn Trent water companies enabled questionnaires to be distributed to three important user groups (non, current and past users). Demographic and specific information was requested such that contingency analysis could be used to interpret the results. It was found that although, in principle, the application of bio-solids to arable cropping would be acceptable to farmers, other issues such as pathogens and potentially toxic elements must be addressed before bio-solids (sewage sludge) application to land would be more widely accepted. It was identified that poor product perception within the non-

user group of farmers resulted from a lack of education, and that consistency and quality of application requires attention by the water company. Results from the questionnaire suggest that application using the 40WNDLi injector system represents a value added system, and that a small proportion of farmers would be willing to pay for improved application techniques, contributing to a cost reduction for producers.

A theoretical economic analysis of the financial implications of differing injection systems including the improvements possible from better nutrient retention revealed that small savings are possible by using the 40WNDLi injection system, compared to other injection and surface application techniques. More substantial potential savings are achievable in terms of economies of scale resulting from an increased application "window of opportunity". The ability to recycle greater quantities of bio-solids over longer periods of time reduces storage capacity and distribution inventory needs, based on the assumptions presented in *Chapter 6*. It was calculated that a potential cost reduction of 1.7% (>£6m/yr) of Anglian Water Services operating profit was theoretically realisable through the full integration of a bio-solids to cropping system.

Following the identification of the market and economic potential of the improved injection system for arable cropping, further studies were conducted to investigate the dynamic performance and control of the injection operation to optimise and maintain environmental performance. It was suggested that adequate depth control systems would be needed to maintain constant injector tine operating depth to avoid the possibility of surface spillage through operation at too shallow depths (< 0.04 m) and; potential crop damage resulting from excessive operating depth (> 0.08 m). A search and review of literature identified a lack of research relating to dynamic control of parallel linkage systems, and an abundance of research relating to linkages which exhibit hitch points and that follow established response theory.

Consequently, an investigation into injector tine performance at differing angles of inclination to the soil was undertaken to establish the linkage requirements for the 40WNDLi shallow injector. It was discovered that the maintenance of soil disturbance and force characteristics associated with the environmental field trials, was only possible if a constant attitude of the tine to the soil was maintained. This indicated that the use of the 40WNDLi injector should be limited to parallel linkage situations. The absence of a real or virtual hitch point associated with the parallel linkage rendered

the use of existing response theory unsuitable and prompted the need for a thorough investigation of the factors influencing the dynamic performance of parallel linkages.

Further investigation into the dynamic performance of complex injector tine/parallel linkage systems required the development of a quasi-static model to predict equilibrium operating depth, enabling actual dynamic performance to be compared to equilibrium performance. A thorough force system analysis was completed and verified experimentally, enabling the development of a dynamic performance methodology for soil dynamics laboratory conditions to be initiated. Replicable soil surfaces were generated and an automatic system to remotely alter implement hitch height was developed for the Cranfield University soil dynamics laboratory at Silsoe.

An initial dynamic study was carried out using five injector tine configurations to enable visual comparisons to be made between actual and predicted performance, and to allow the identification of any common factors that may be associated with improved dynamic performance of the injector tine/linkage system. It was found that as operating depth increased, so did the dynamic performance of all injector tine configurations. Each system was assessed with the aim of identifying common trends relating to all injector tine configurations with increasing operating depth. One such factor identified was the difference between the gradients of the applied downward force exerted by the linkage and the restoring force produced by the injector tine (β). This equates to the rate of change of resultant force with depth at equilibrium operating depth ($\tan \beta$), and this was found to increase for all tines with operating depth. No other factors relating to the whole implicit system were identified.

A geometric sensitivity analysis of the parallel linkage system was carried out to assess the effect of altering all the main geometric parameters of the parallel linkage on $\tan \beta$. It was found that altering the geometry of the linkage would not affect $\tan \beta$, and that tine manipulation would be required in order to improve the dynamic performance of the injector tine/linkage system. To achieve the required depth control and compliment the dynamic response of the system, two depth control skids were designed and attached to each side of the 40WNDLi's narrow shank. Force analysis showed that a multiple curve fit method would be more appropriate to account for the

geometric changes in the tine at certain operating depths than a single curve fit. In particular, a change in force pattern was observed at approximately 0.04 m operating depth and at 0.075 m operating depth coinciding with the interaction of the cutting edge and the skids with the soil surface respectively.

A methodology for the fitting of multiple second order polynomial curves to draught, vertical and resultant force data was developed. Subsequent inclusion of these curves in the quasi-static model derived earlier, improved the accuracy of equilibrium depth prediction. The improved depth prediction, verified experimentally, coincided with localised increases in β , resulting from the manipulation of the 40WNDLi injector tines geometry. A final dynamic study was undertaken to establish the effect of the skids on the dynamic performance of the system, in conjunction with an additional study to consider the effect of linkage friction. It was found, following the development of criteria to assess dynamic and operating depth performance, that the use of bearings significantly reduced the response time (@ 89.2% level of significance) and increased the accuracy of the quasi-static model for operating depth prediction (@ 95% level of significance).

The addition of skids to the sides of the 40WNDLi injector tine significantly improved the dynamic response of the system to soil surface and hitch height variation (@ 90% level of significance) when operated on the parallel linkage. In particular, although singularly insignificant, improvements in dynamic response were observed under spring conditions that promoted an operating depth coincident with the step changes in tine geometry (0.04 and 0.075 m). This evidence reinforces the relationship between β and dynamic performance. Additionally, the use of multiple curves to represent injector tine force performance improved the accuracy of the quasi-static prediction model developed for this study. Furthermore, the use of skids as depth control devices for injector tines eliminates the risk of exceeding maximum operating depths (within 5%), and it is expected that reductions in crop damage are possible as a consequence.

Bio-solids incorporation into established arable cropping is possible with minimal environmental and agronomic impact, providing that adequate implement control

systems are developed, and that frictional effects within the system linkage are minimised. The economic potential of such a system is significant (potentially > £6m/yr), and provides the farmer with a value added product with a higher nutritional value through reduced environmental losses and savings in crop fertiliser requirements. The soil incorporation of bio-solids into arable cropping using the 40WNDLi injection system should be considered as the best available technique for bio-solids recycling to land without entailing excessive cost.

Chapter 12

12.0 Conclusions.

Based on the project criteria established by the sponsoring organisation, and experimental conditions experienced throughout the duration of this project the following conclusions have been drawn from this study:

- A system for the incorporation of bio-solids into arable cropping has been developed and is currently in production (*Fig. 12.1*), which allows sufficient quantities of bio-solids to be incorporated into arable cropping (50 to 150 m³/ha) with minimal environmental impact.
 - Existing, commercially available, injector tines are unsuitable for bio-solids incorporation into arable cropping due to high tine force requirements and their mode of soil disturbance, which promotes placement rather than incorporation.
 - A narrow, winged, single piece injector tine (40WNDLi) has been found to produce satisfactory soil disturbance, enabling the incorporation of appropriate quantities of bio-solids into arable crops.
 - The use of the 40WNDLi injector tine reduces odour emissions significantly (@ 85%), as a result of more complete soil incorporation following bio-solids application to arable cropping, when compared to other shallow and surface application techniques.
 - Shallow injection of bio-solids into arable cropping significantly reduces ammonia emissions compared to surface application methods, with a significant trend towards further reductions following application by the 40WNDLi injector system.
 - For the field conditions encountered during this project, application technique has no significant effect on soil water nitrate concentrations and; shallow injection reduced the time taken for nitrate concentrations to fall below W.H.O. prescribed limits (50 mg/l) compared to surface application.
 - Shallow injection of bio-solids is possible into arable cropping up to three months prior to harvest with no detrimental effect on crop performance.
 - Umbilical supply systems are unlikely to affect crop performance except when used during later stages of crop development.

- The feasibility of a system to incorporate bio-solids into arable cropping, both in terms of marketing and economics, has been assessed and found to be acceptable to the landowner and economically viable to the water company.
 - Active promotion, improved field management and a focus on the most susceptible user groups may enable bio-solids to be sold as a value added system.
 - The issues of product consistency and quality must be addressed by the producer before the full market and economic potential of the 40WNDLi injection system can be realised.
 - The increased application “window of opportunity”, afforded by the adoption of shallow injection into arable cropping, provides the producer with the potential to realise substantial economies of scale through reduced storage and distribution inventories (> £6m per year).
 - Reductions in ammonia emissions, by application using the 40WNDLi system, represent a potential saving to the producer through added product value.
- The engineering implications of a system to incorporate bio-solids into arable cropping have been considered and developed to ensure that the environmental benefits of the 40WNDLi injection system can be optimised.
 - A constant angle of inclination of the 40WNDLi injector tine to the soil should be maintained if environmental benefits resulting from the improved soil disturbance of this injector are to be fully realised.
 - A suitable depth control system is necessary to ensure that instances of very shallow application, (surface spillage), and deep application, (crop damage), are avoided to maintain the environmental and agronomic benefits of the 40WNDLi injection system.
 - A thorough analysis of the force system, relating to complex injector tines operating on a parallel linkage system, has been completed resulting in the production of a quasi-static depth prediction model to describe the implicit nature of the system.

- The quasi-static model shows good agreement with experimental operating depths for injector tines operating in their designed configurations.
- A method for the dynamic analysis of complex injector tines under soil dynamics laboratory conditions has been developed resulting in the ability to assess the dynamic response of injector tine/linkage systems to variations in soil surface or hitch height.
- Through observation of operating depth and soil surface level profiles, the increasing rate of change of system forces with depth ($\tan \beta$) has been identified as a common factor associated with improved dynamic response of complex injector tines operating on parallel linkage systems.
- A sensitivity analysis of the parallel linkage/injector tine force system has found that manipulation of linkage geometry is unlikely to affect the rate of change of system force with depth ($\tan \beta$).
- The use of bearing joints (low friction) rather than pins (high friction) in the parallel linkage, improves the dynamic response of the injector tine/linkage system significantly (@ 89.2% level).
- Multiple curves can be fitted to complex injector tine force data to improve the accuracy of quasi-static depth prediction models.
- The addition of skids to the 40WNDLi injector tine significantly improves the dynamic response of the injector/linkage system (@ 90% level of significance). Increases in dynamic response at certain depths may be attributed to localised increases in β resulting from the multiple curve fit technique.
- Under the conditions evaluated during this study, the use of skids on the 40WNDLi injector tine operating under the influence of applied force from a parallel linkage will reduce the likelihood of the maximum design operating depth being exceeded.



Fig. 12.1. The production model based on the development of the 40WNDLi injector tine; known as the “Greentrac Growing Crop Injector”.

Recommendations for further work.

This study has identified a number of areas that would be suitable for further study.

These can be summarised as:

- The development of a system capable of utilising field tramlines. The use of such a system would eliminate the need for the crop to be trafficked during the bio-solids incorporation operation.
- Further development of the theory relating to the dynamic performance of complex tines mounted on parallel linkage systems.
- Development of the quasi-static model for predicting operating depth of injector tines in differing soil types
- Verification of the multiple-curve fitting technique, by its application to other complex tines.
- Full scale field trials, covering a number of soil and crop types, to further validate the agronomic effects of bio-solids incorporation into arable cropping.
- Further studies of the fate of nitrogen, following the application of bio-solids to different arable crops, to enable the development of a management practice for the use of this method of bio-solids recycling in agriculture.

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Appendix 1

Appendix 1.1.

Soil disturbance profiles

Single piece prototype designs

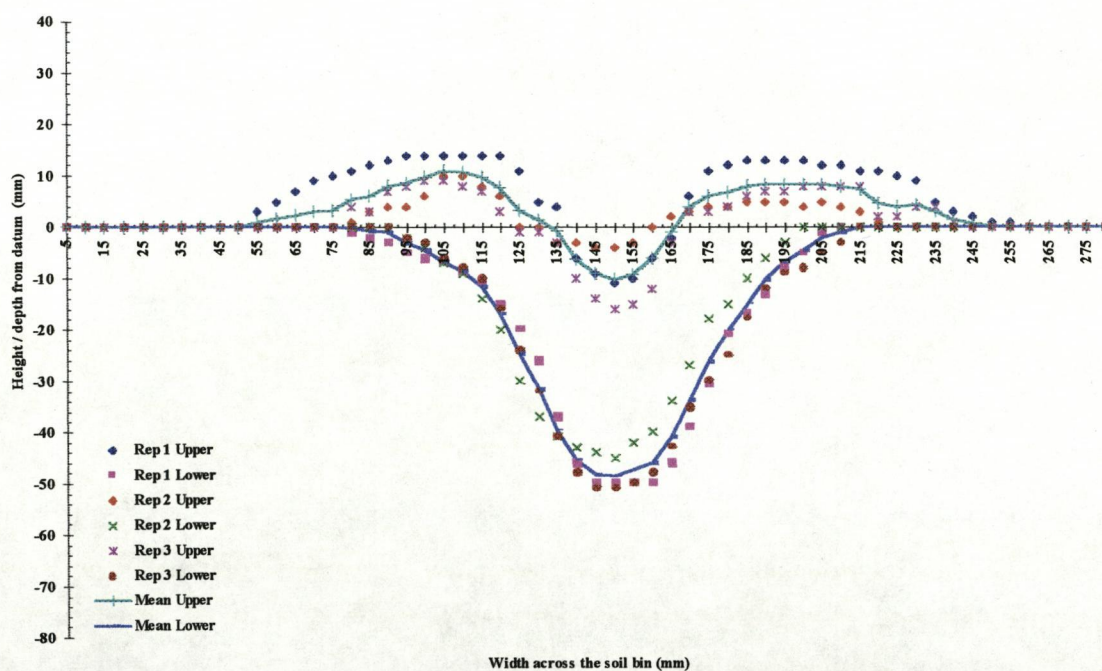


Fig. Ap1.1a: Soil disturbance profiles for the 10W injector operating at 0.05 m depth.

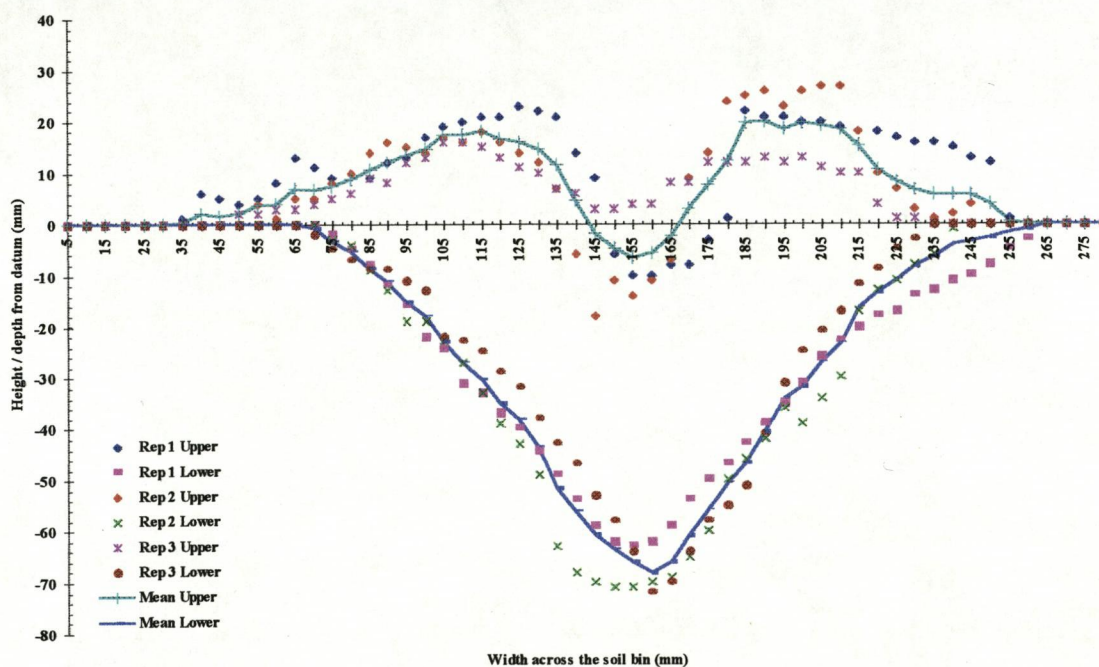


Fig. Ap1.1b: Soil disturbance profiles for the 10W injector operating at 0.075 m depth.

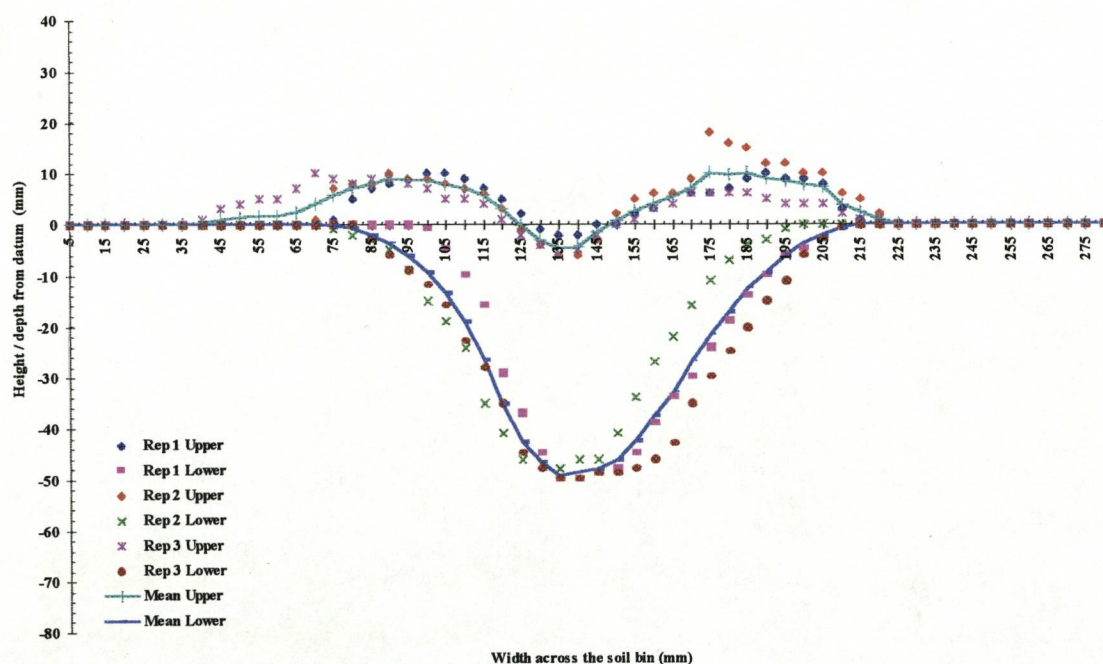


Fig. Ap1.1c: Soil disturbance profiles for the 25W injector operating at 0.05 m depth.

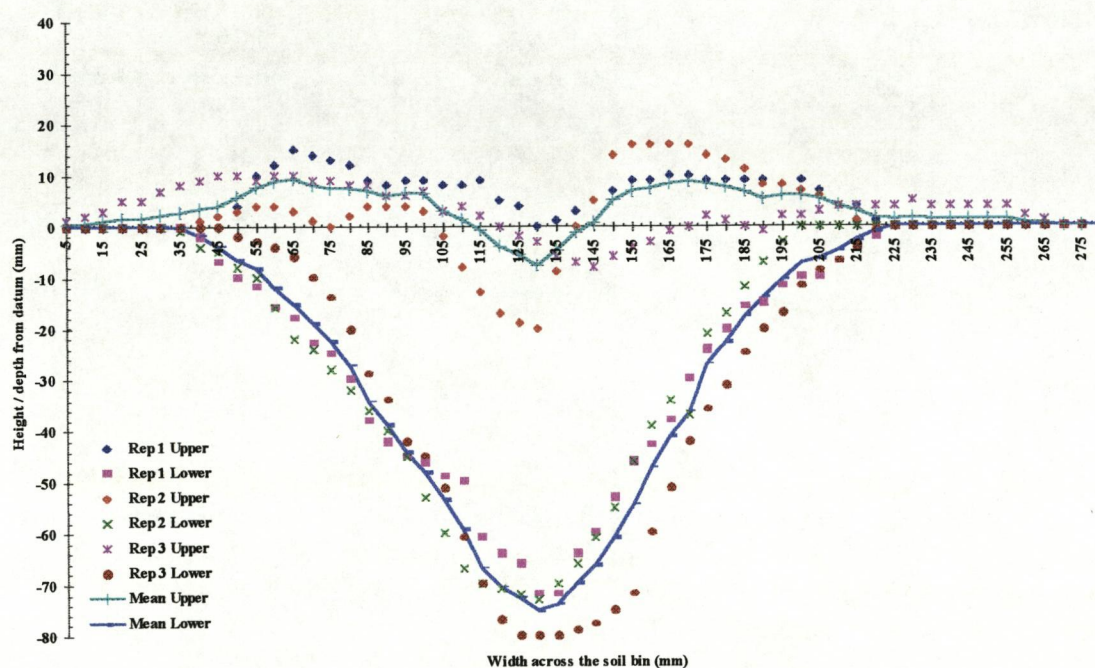


Fig. Ap1.1d: Soil disturbance profiles for the 25W injector operating at 0.075 m depth.

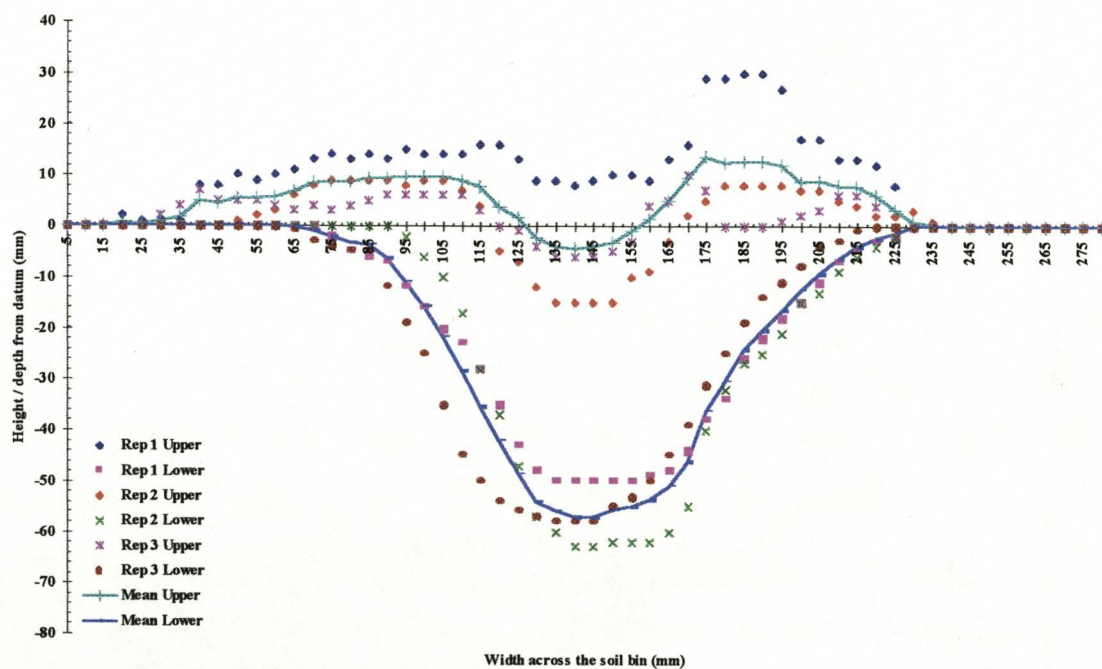


Fig. Ap1.1e: Soil disturbance profiles for the 40W injector operating at 0.05 m depth.

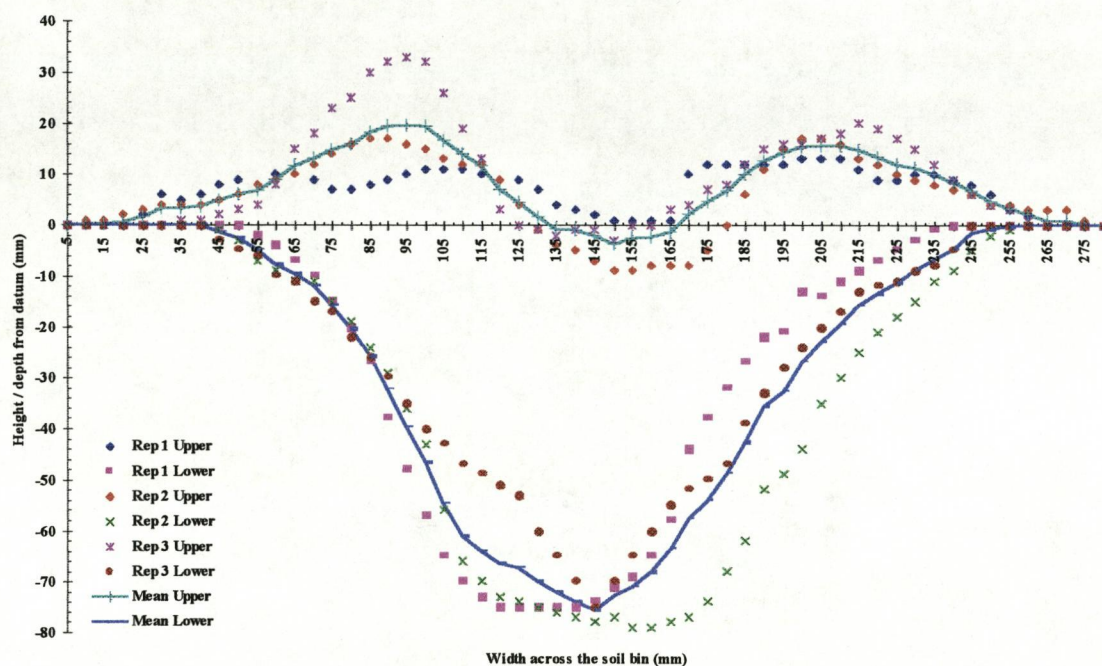


Fig. Ap1.1f: Soil disturbance profiles for the 40W injector operating at 0.075 m depth.

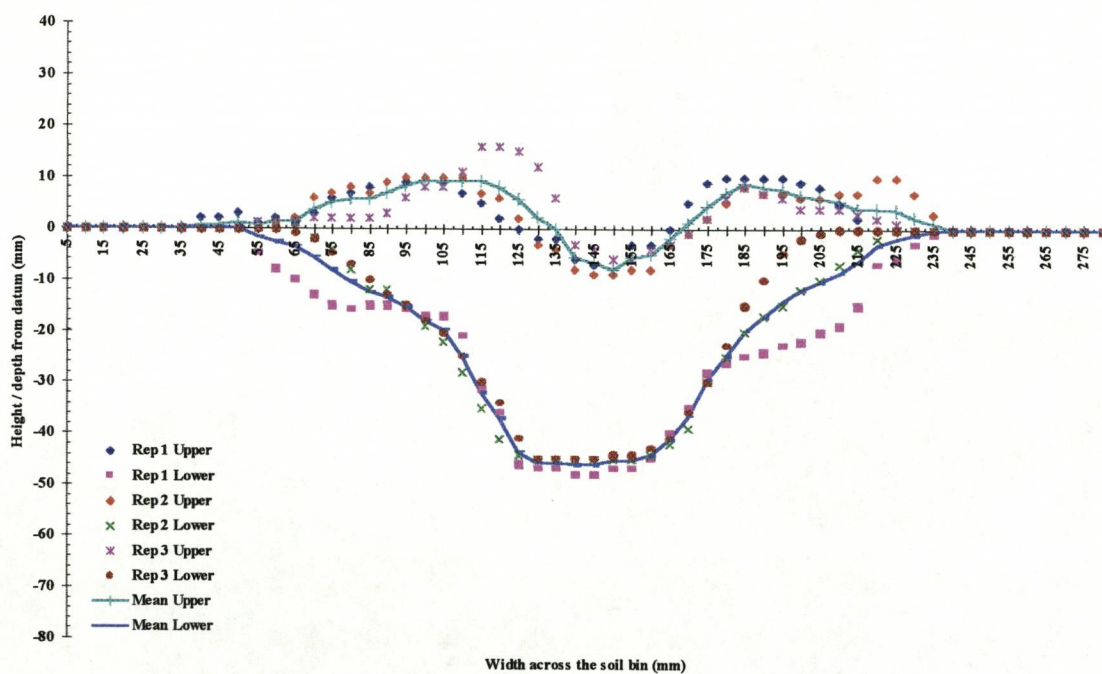


Fig. Ap1.1g: Soil disturbance profiles for the 40WNDs injector operating at 0.05 m depth.

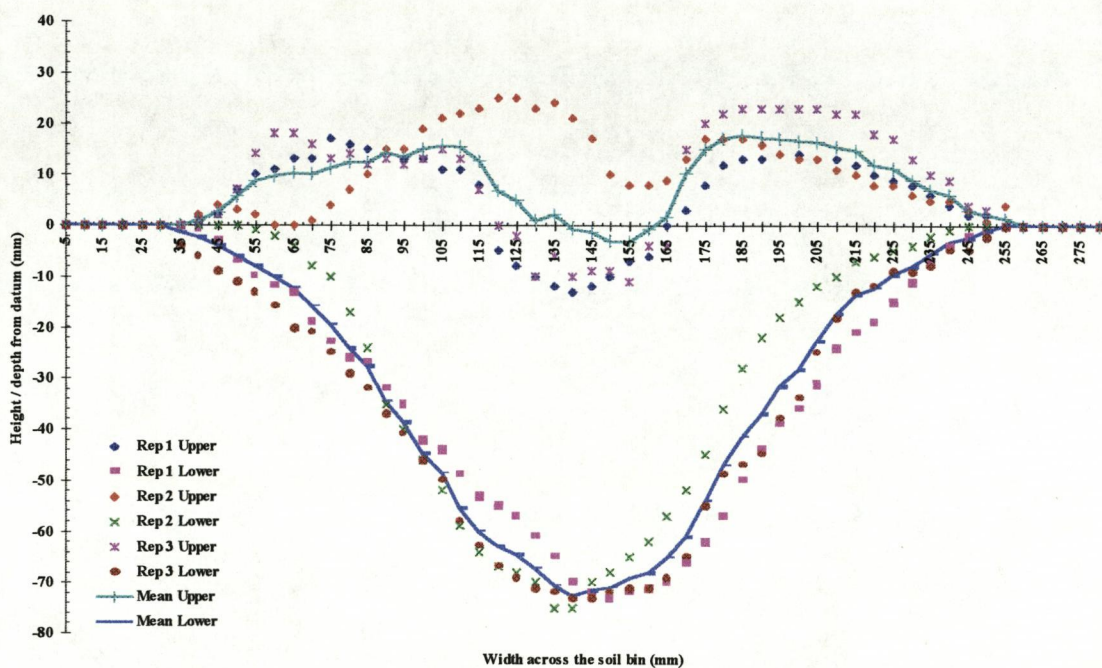


Fig. Ap1.1h: Soil disturbance profiles for the 40WNDs injector operating at 0.075 m depth.

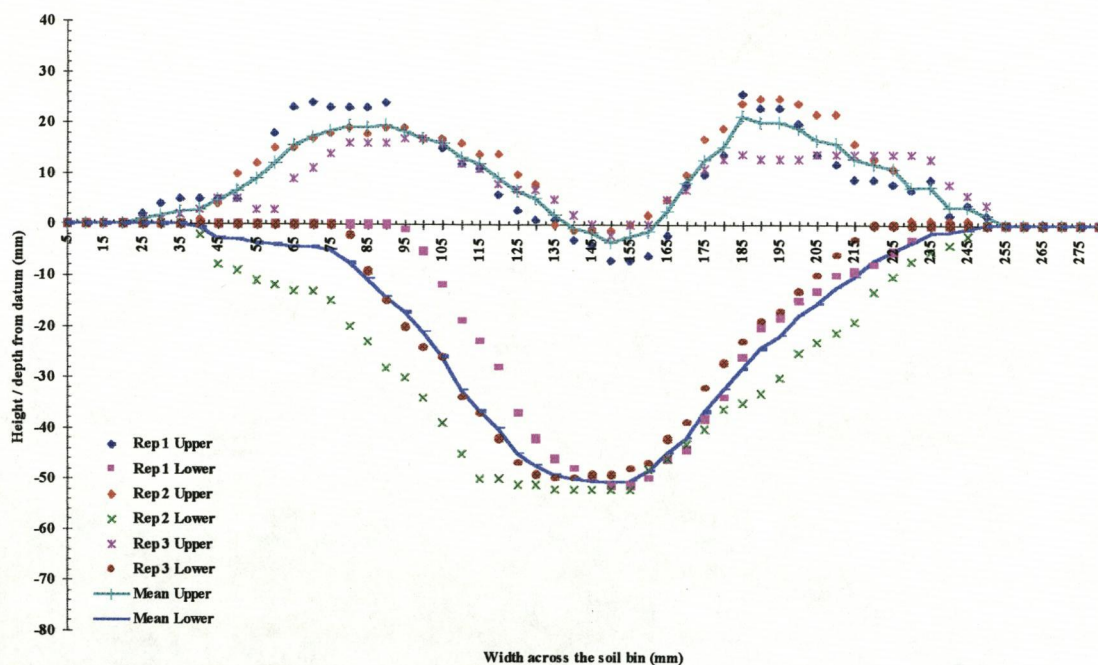


Fig. Ap1.1h: Soil disturbance profiles for the 40WNDL injector operating at 0.05 m depth.

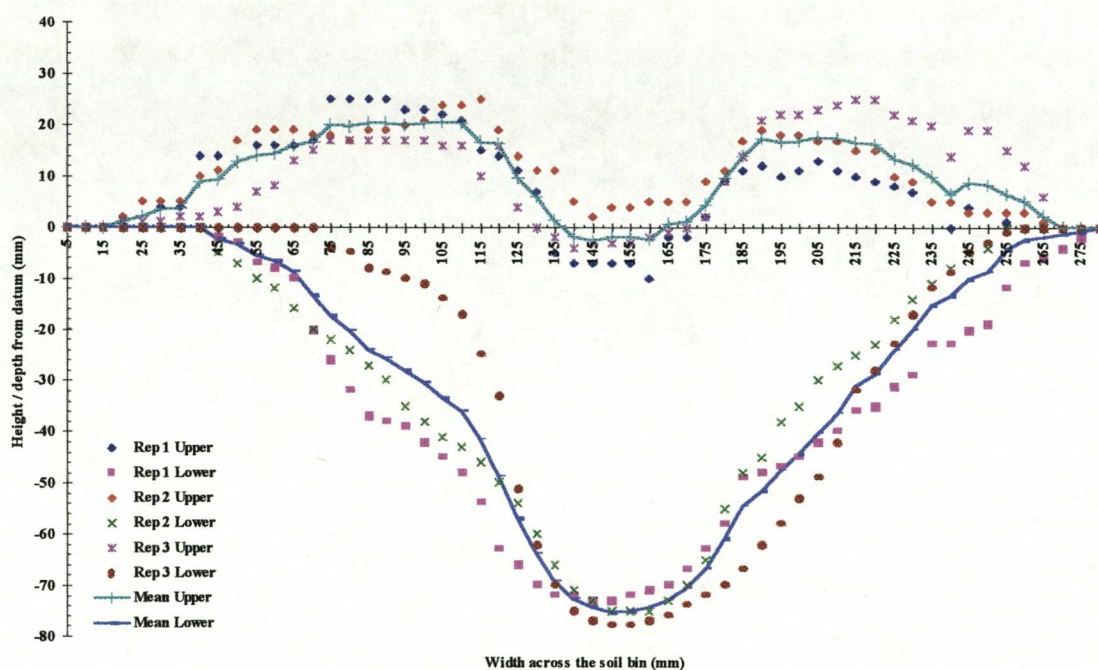


Fig. Ap1.1i: Soil disturbance profiles for the 40WNDL injector operating at 0.075 m depth.

Multi piece prototype designs

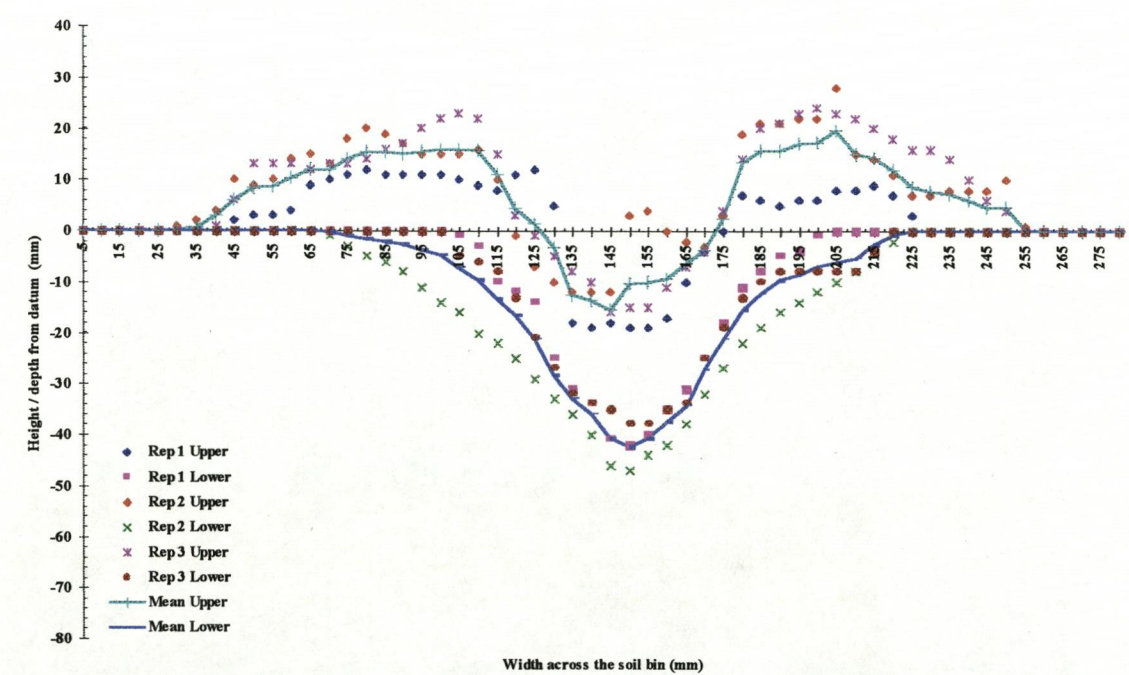


Fig. Ap1.2a: Soil disturbance profiles for the ELLC injector operating at 0.05 m

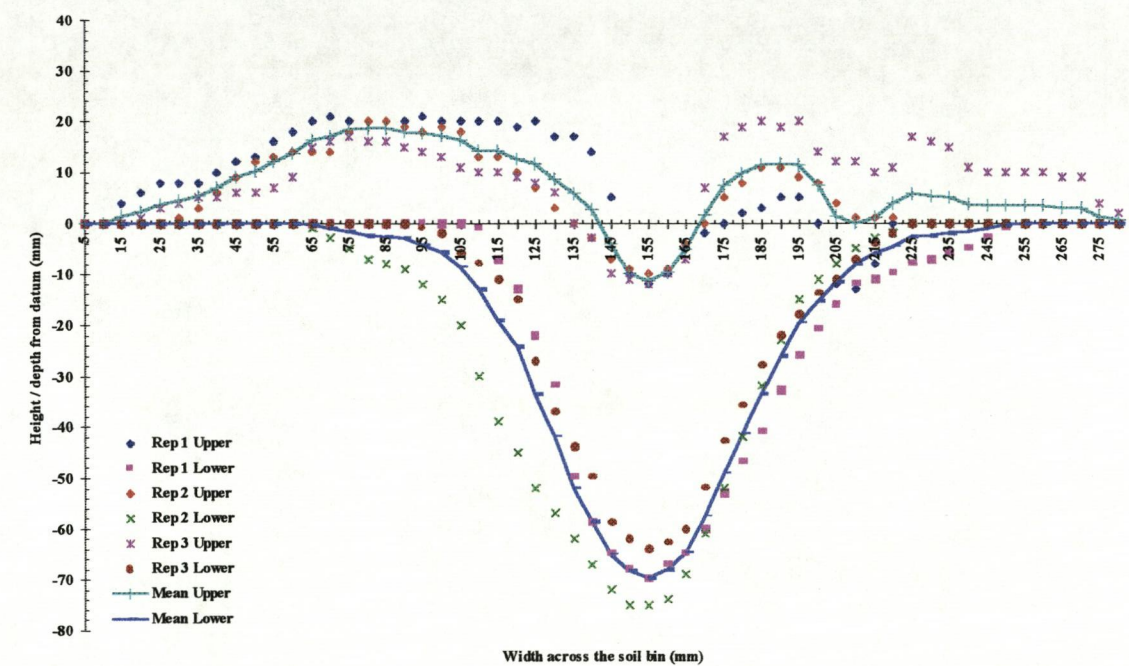


Fig. Ap1.2b: Soil disturbance profiles for the ELLC injector operating at 0.075 m

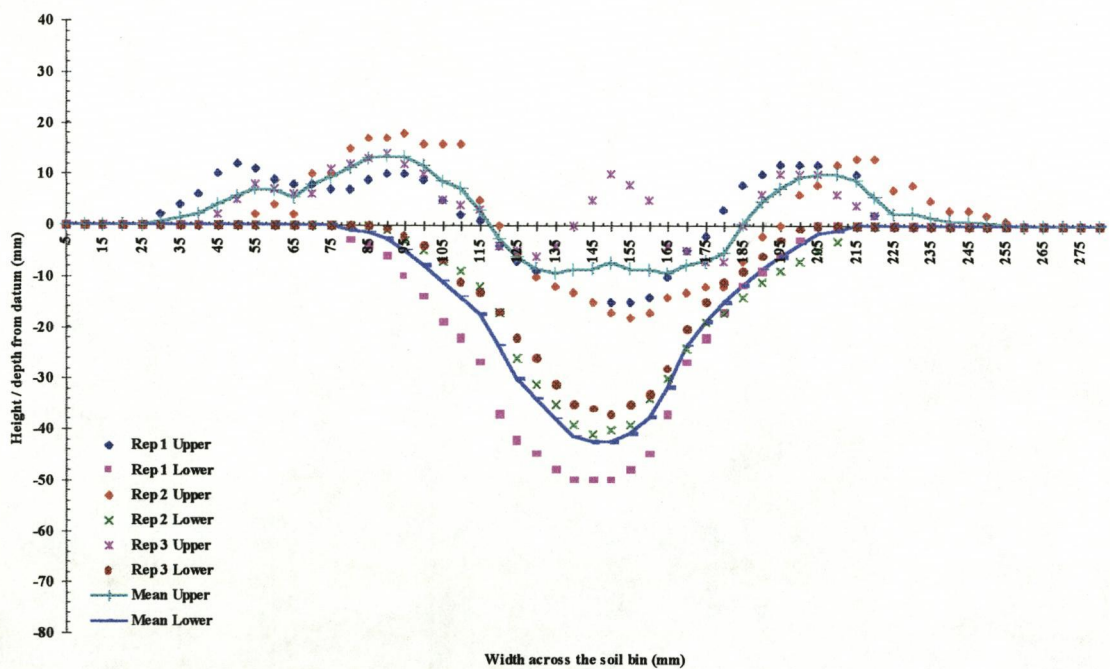


Fig. Ap1.2c: Soil disturbance profiles for the ELSC injector operating at 0.05 m

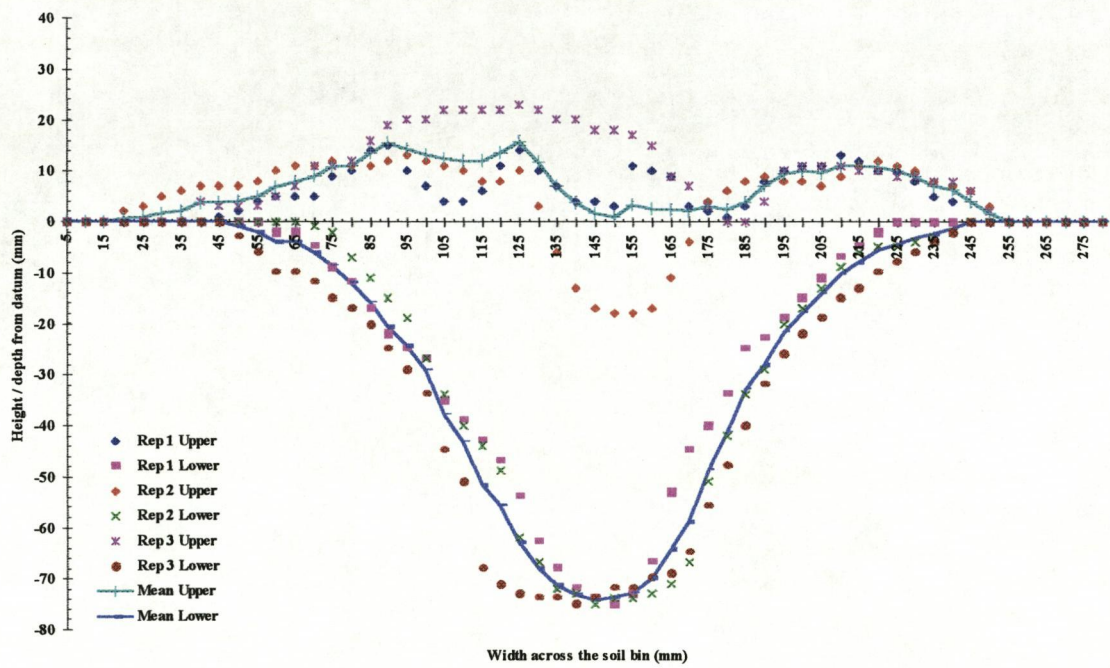


Fig. Ap1.2d: Soil disturbance profiles for the ELSC injector operating at 0.075 m

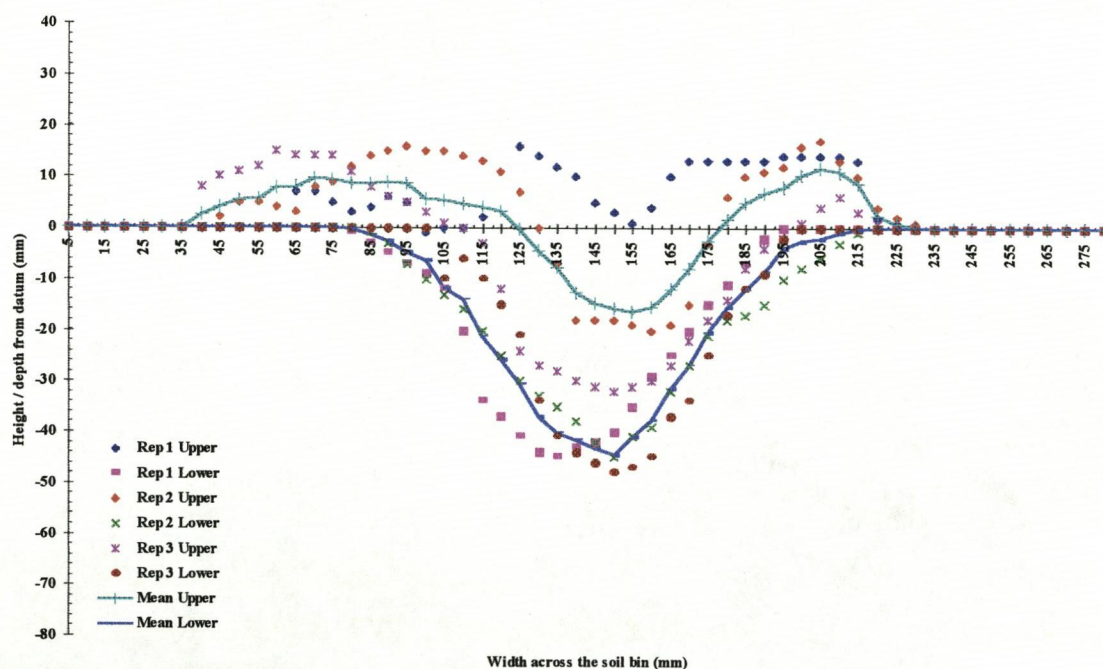


Fig. Ap1.2e: Soil disturbance profiles for the ELDC injector operating at 0.05 m

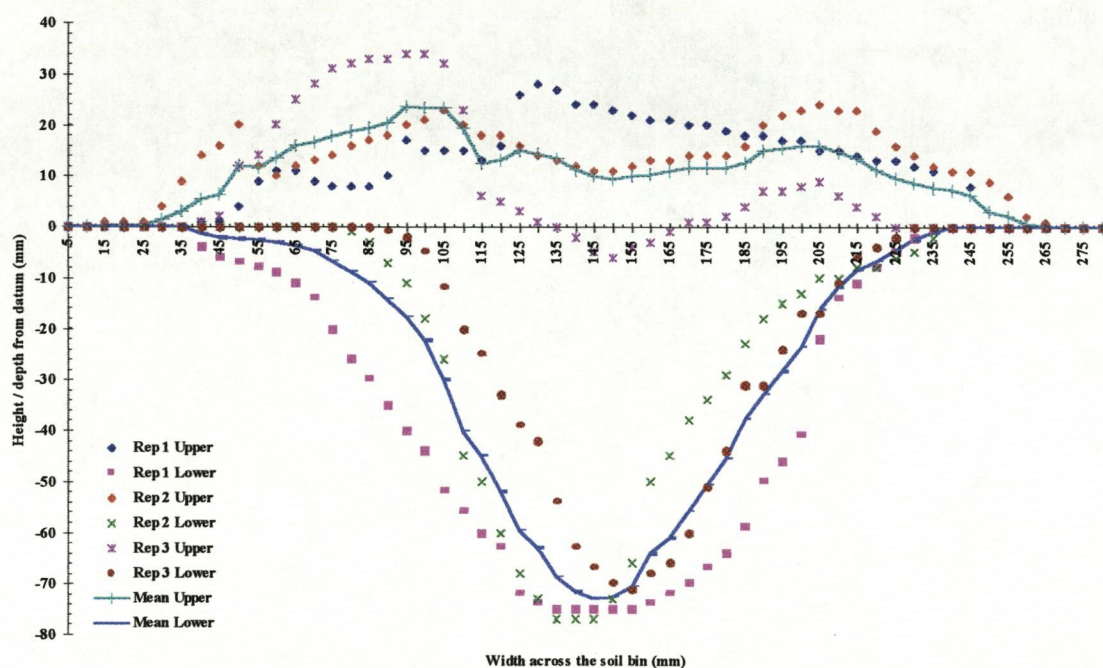


Fig. Ap1.2f: Soil disturbance profiles for the ELDC injector operating at 0.075 m

Commercially available injector tines

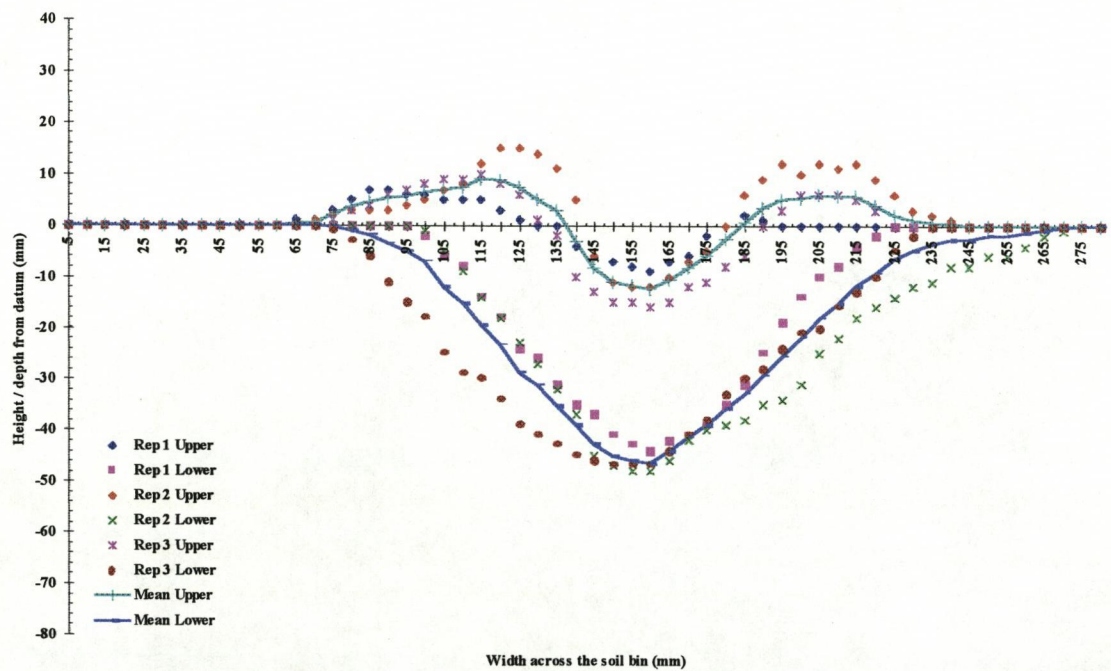


Fig. Ap1.3a: Soil disturbance profiles for the OSH injector operating at 0.05 m

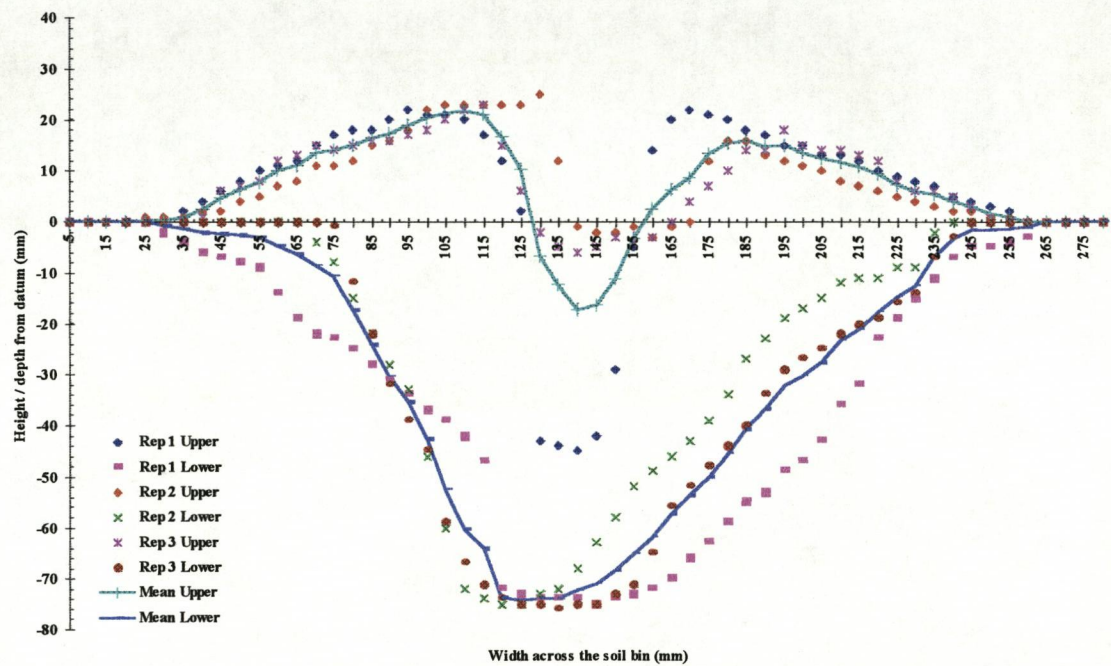


Fig. Ap1.3b: Soil disturbance profiles for the OSH injector operating at 0.075 m

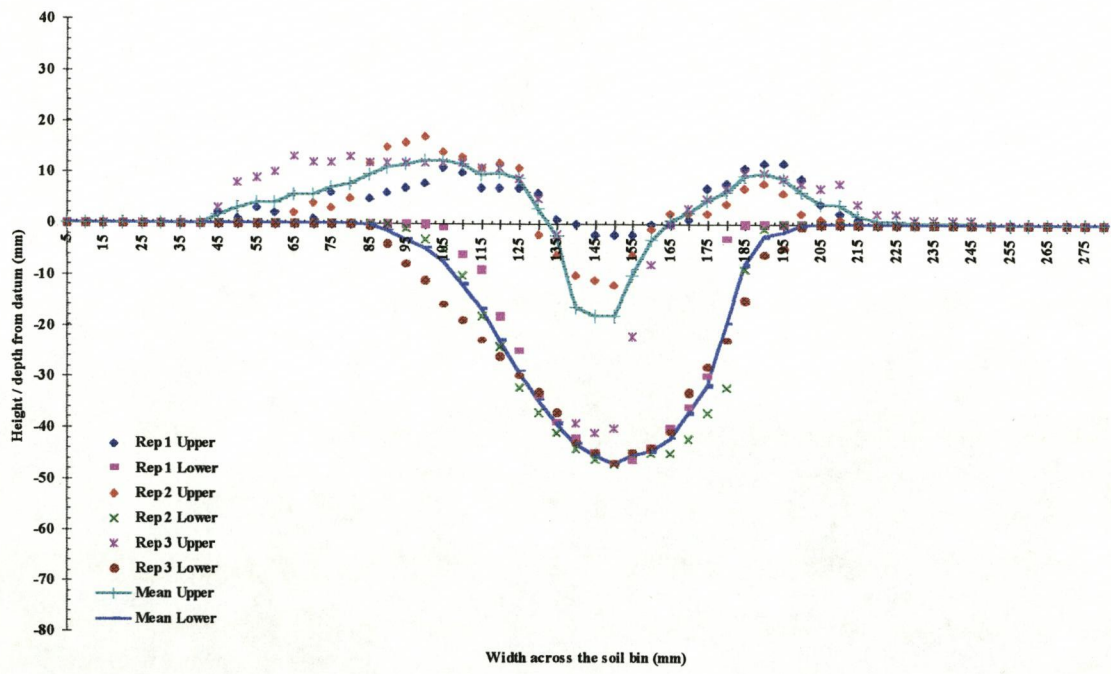


Fig. Ap1.3c: Soil disturbance profiles for the NSH injector operating at 0.05 m

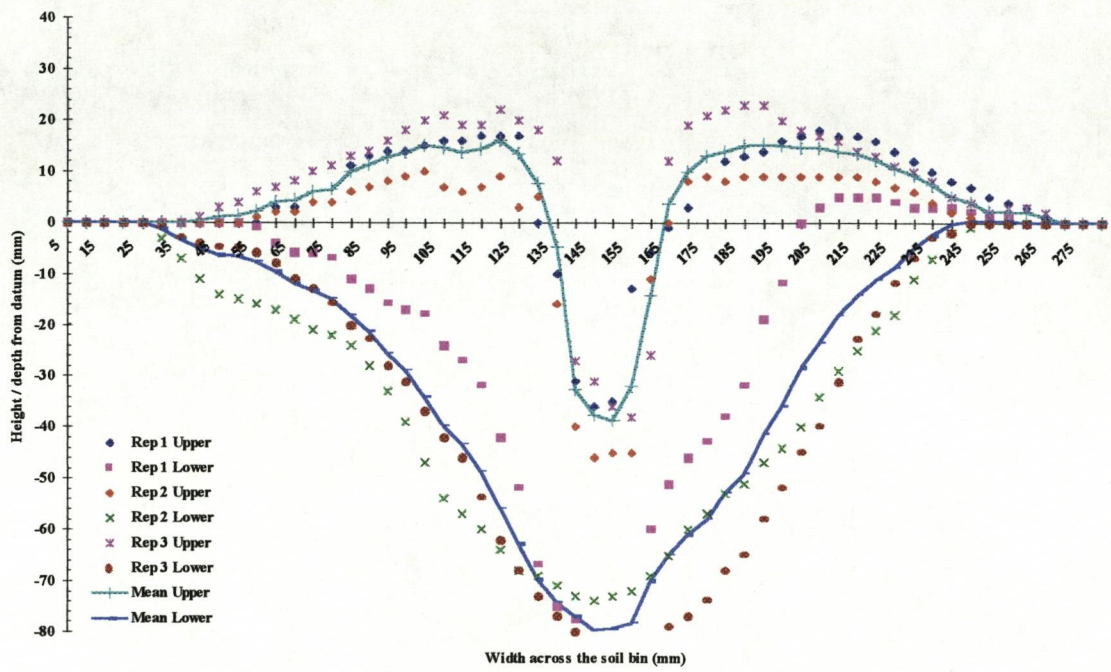


Fig. Ap1.3d: Soil disturbance profiles for the NSH injector operating at 0.075 m

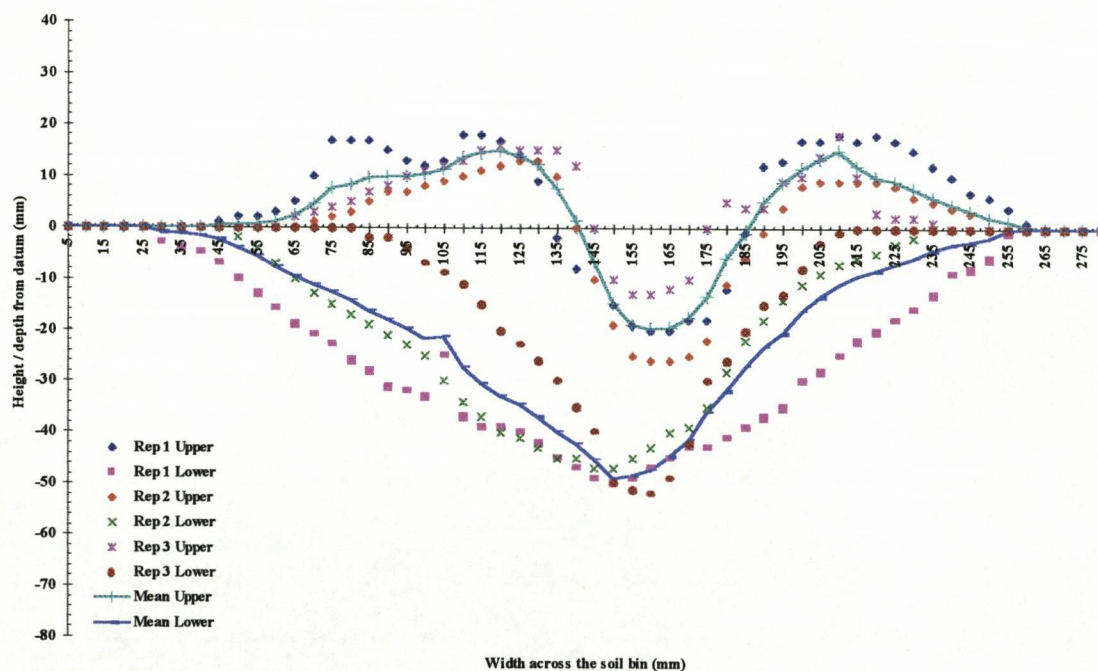


Fig. Ap1.3e: Soil disturbance profiles for the Slipper injector operating at 0.05 m

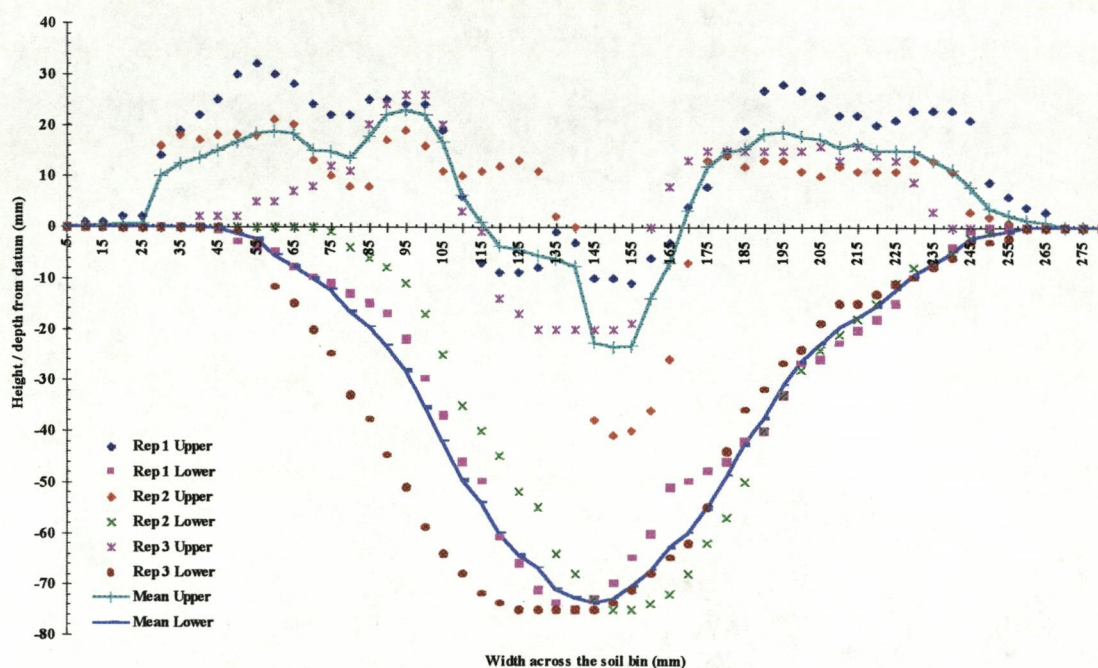


Fig. Ap1.3f: Soil disturbance profiles for the Slipper injector operating at 0.075 m

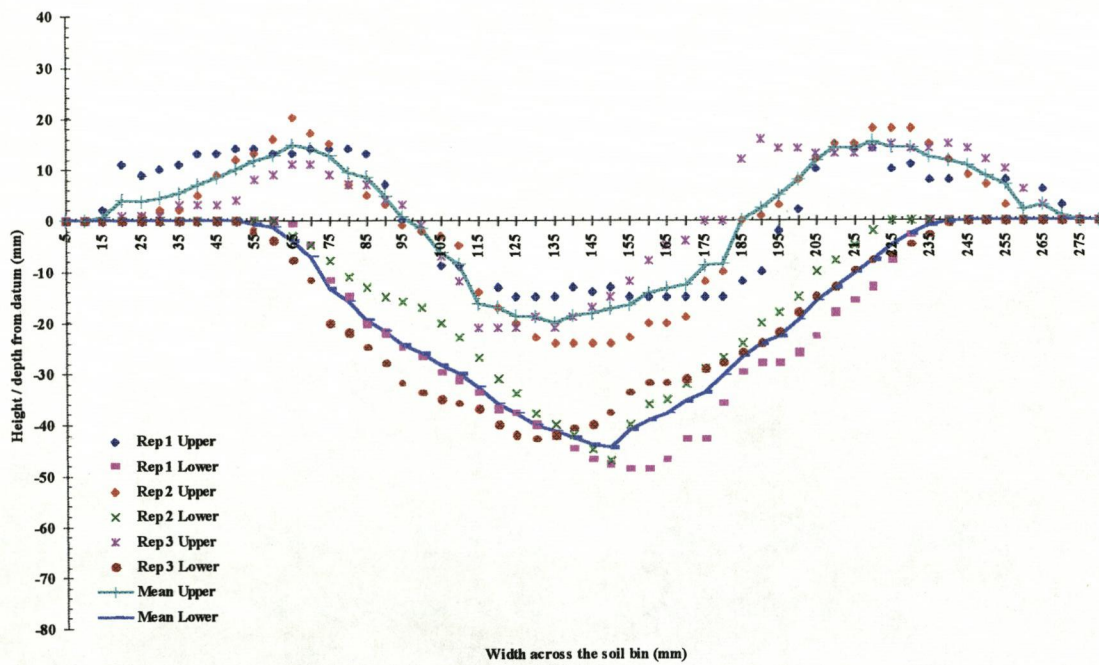


Fig. Ap1.3g: Soil disturbance profiles for the Deep injector operating at 0.05 m

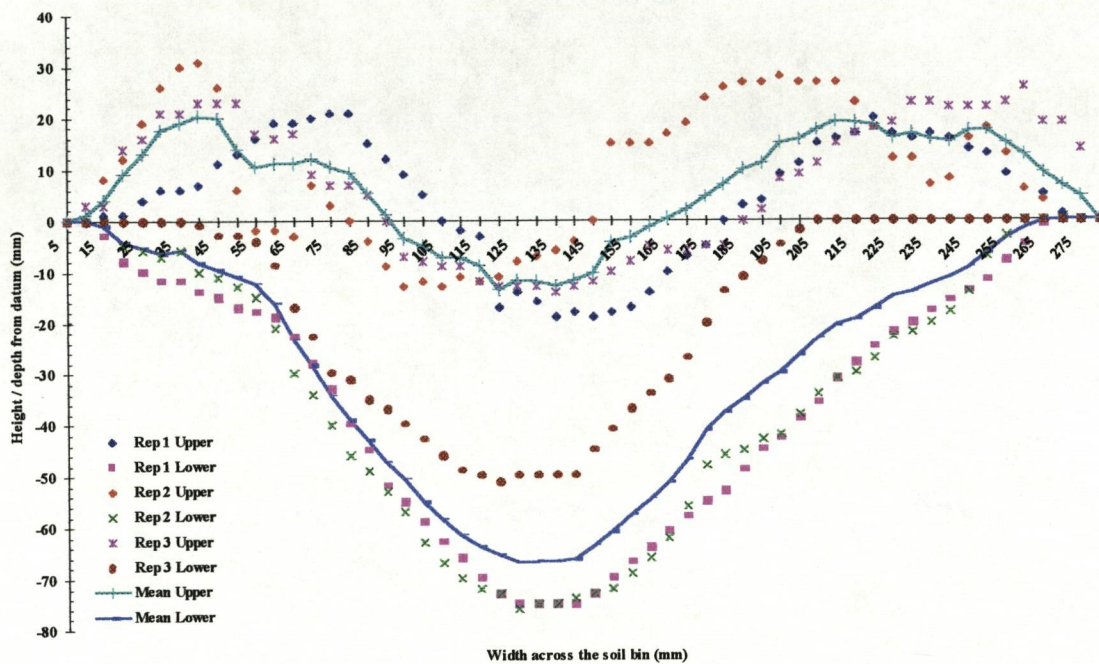


Fig. Ap1.3h: Soil disturbance profiles for the Deep injector operating at 0.075 m

Appendix 1.2.

Statistical analysis of soil properties, injector forces, soil disturbance and injector performance.

Genstat 5 Release 3.2 (PC/Windows 95) 9 April 1999 11:29:37
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Summary statistics for Bulk_Density (kg/m³)

Number of observations = 36
Number of missing values = 0
Mean = 1439.294
Median = 1443.629
Minimum = 1285.762
Maximum = 1562.136
Range = 276.374
Lower quartile = 1397.990
Upper quartile = 1476.304
Variance = 3307.351
Standard deviation = 57.510
Standard error of mean = 9.585
Coefficient of variation = 3.996

Summary statistics for Moisture Content (%)

Number of observations = 36
Number of missing values = 0
Mean = 9.717
Median = 9.787
Minimum = 8.552
Maximum = 10.772
Range = 2.220
Lower quartile = 9.363
Upper quartile = 10.020
Variance = 0.230
Standard deviation = 0.479
Standard error of mean = 0.080
Coefficient of variation = 4.933

***** Analysis of variance *****
Bulk_Density (kg/m³)Variate: Bulk_Density (kg/m³)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Bin_Fit	11	34935.	3176.	0.94	0.519
Residual	24	80822.	3368.		
Total	35	115757.			

***** Tables of means *****

Variate: Bulk_Density (kg/m³)

Grand mean 1439.3

Bin_Fit	1.00	2.00	3.00	4.00	5.00	6.00
7.00	1482.4	1444.9	1433.9	1476.3	1425.9	1464.7
1443.4						
Bin_Fit	8.00	9.00	10.00	11.00	12.00	
1437.8	1440.8	1402.1	1456.4	1362.9		

*** Standard errors of differences of means ***

Table	Bin_Fit
rep.	3
d.f.	24
s.e.d.	47.38

*** Least significant differences of means ***

Table	Bin_Fit
rep.	3
d.f.	24
l.s.d.	97.79

***** Stratum standard errors and coefficients of variation *****

Variate: Bulk_Density (kg/m³)

d.f.	s.e.	cv%
24	58.03	4.0

***** Analysis of variance *****
Moisture Content (%)

Variate: Moisture Content (%)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Bin Fit	11	2.9627	0.2693	1.27	0.298
Residual	24	5.0804	0.2117		
Total	35	8.0431			

***** Tables of means *****

Variate: Moisture Content (%)

Grand mean 9.717

Bin_Fit	1.00	2.00	3.00	4.00	5.00	6.00
7.00	9.563	9.914	9.731	9.695	9.928	9.377
9.482						
Bin_Fit	8.00	9.00	10.00	11.00	12.00	
10.289	9.591	10.109	9.260	9.664		

*** Standard errors of differences of means ***

Table	Bin_Fit
rep.	3
d.f.	24
s.e.d.	0.3757

*** Least significant differences of means ***

Table	Bin_Fit
rep.	3
d.f.	24
l.s.d.	0.7753

***** Stratum standard errors and coefficients of variation *****

Variate: Moisture Content (%)

d.f.	s.e.	cv%
24	0.4601	4.7

***** Analysis of variance *****
Area Below Datum (mm²)

Variate: Area Below Datum

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Tine	11	5.671E+07	5.156E+06	4.28	<.001
Depth	1	1.964E+08	1.964E+08	162.89	<.001
Tine.Depth	11	7.174E+06	6.522E+05	0.54	0.865
Residual	48	5.787E+07	1.206E+06		
Total	71	3.181E+08			

***** Tables of means *****

Variate: Area Below Datum

Grand mean 5135.

Tine	10W	25W	40W	40WNDL	40WNDs	Deep
ELCD	4193.	4636.	5929.	6358.	5716.	6222.
4317.						

Tine	ELLC	ELSC	NSH	OSH	Slipper
3463.	4397.	5001.	5594.	5793.	

Depth	50.00	75.00
3483.	6786.	

Tine	Depth	50.00	75.00
10W	2730.	5657.	
25W	3048.	6223.	
40W	4342.	7517.	
40WNDL	4642.	8075.	
40WNDs	3963.	7468.	
Deep	4390.	8053.	
ELCD	2643.	5990.	
ELLC	2467.	4460.	
ELSC	2557.	6237.	
NSH	2688.	7313.	
OSH	3772.	7417.	
Slipper	4558.	7027.	

*** Standard errors of differences of means ***

Table	Tine	Depth	Tine Depth
rep.	6	36	3
d.f.	48	48	48
s.e.d.	633.9	258.8	896.5

*** Least significant differences of means ***

Table	Tine	Depth	Tine Depth
rep.	6	36	3
d.f.	48	48	48
l.s.d.	1274.6	520.4	1802.6

***** Stratum standard errors and coefficients of variation *****

Variate: Area Below Datum

d.f.	s.e.	cv%
48	1098.0	21.4

***** Analysis of variance *****
Area Above Datum (mm²)

Variate: Area Above Datum

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
---------------------	------	------	------	------	-------

Appendix 1.2

Tine	11	13220027.	1201821.	2.73	0.008
Depth	1	20009138.	20009138.	45.39	<.001
Tine.Depth	11	8032326.	730211.	1.66	0.113
Residual	48	21158921.	440811.		
Total	71	62420412.			

***** Tables of means *****

Variate: Area Above Datum

Grand mean 1343.

Tine	10W	25W	40W	40WNDL	40WNDs	Deep
ELCD	1331.	842.	1587.	2443.	1293.	1039.

Tine	ELLC	ELSC	NSH	OSH	Slipper
1613.	1656.	1102.	847.	1007.	1355.

Depth	50.00	75.00
	816.	1870.

Tine	Depth	50.00	75.00
10W		710.	1952.
25W		787.	897.
40W		1177.	1997.
40WNDL		2267.	2618.
40WNDs		652.	1933.
Deep		257.	1822.
ELCD		337.	2890.
ELLC		1488.	1823.
ELSC		505.	1699.
NSH		658.	1035.
OSH		208.	1805.
Slipper		742.	1968.

*** Standard errors of differences of means ***

Table	Tine	Depth	Tine	Depth
rep.	6	36	3	3
d.f.	48	48	48	48
s.e.d.	383.3	156.5	542.1	

*** Least significant differences of means ***

Table	Tine	Depth	Tine	Depth
rep.	6	36	3	3
d.f.	48	48	48	48
l.s.d.	770.7	314.6	1090.0	

***** Stratum standard errors and coefficients of variation *****

Variate: Area Above Datum

d.f.	s.e.	cv%
48	663.9	49.4

***** Analysis of variance ***** Area of Dip (mm²)

Variate: Area of Dip

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Tine	11	32381968.	2943815.	12.46	<.001
Depth	1	39786.	39786.	0.17	0.683
Tine.Depth	11	5853954.	532178.	2.25	0.026
Residual	48	11342014.	236292.		
Total	71	49617720.			

***** Tables of means *****

Variate: Area of Dip

Grand mean 1155.

Tine	10W	25W	40W	40WNDL	40WNDs	Deep
ELCD	727.	480.	828.	988.	778.	3188.

Tine	ELLC	ELSC	NSH	OSH	Slipper
958.	1098.	1030.	1138.	985.	1666.

Depth	50.00	75.00
	1132.	1179.

Tine	Depth	50.00	75.00
10W		642.	812.
25W		448.	513.
40W		557.	1098.
40WNDL		1068.	908.
40WNDs		718.	838.
Deep		2830.	3546.
ELCD		1448.	468.
ELLC		1491.	706.
ELSC		1406.	654.
NSH		803.	1473.
OSH		752.	1217.
Slipper		1419.	1913.

*** Standard errors of differences of means ***

Table	Tine	Depth	Tine	Depth
rep.	6	36	3	3
d.f.	48	48	48	48
s.e.d.	280.6	114.6	396.9	

*** Least significant differences of means ***

Table	Tine	Depth	Tine	Depth
rep.	6	36	3	3
d.f.	48	48	48	48

l.s.d.	564.3	230.4	798.0
--------	-------	-------	-------

***** Stratum standard errors and coefficients of variation *****

Variate: Area of Dip

d.f.	s.e.	cv%
48	486.1	42.1

***** Analysis of variance ***** Draught Force (kN)

Variate: Draught Force

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Tine	11	3.02809	0.27528	15.53	<.001
Depth	1	0.43786	0.43786	24.71	<.001
Tine.Depth	11	0.25842	0.02349	1.33	0.240
Residual	48	0.85073	0.01772		
Total	71	4.57510			

***** Tables of means *****

Variate: Draught Force

Grand mean 0.313

Tine	10W	25W	40W	40WNDL	40WNDs	Deep
ELCD	0.203	0.135	0.153	0.790	0.177	0.443

Tine	ELLC	ELSC	NSH	OSH	Slipper
0.136	0.220	0.204	0.317	0.319	0.660

Depth	50.00	75.00
	0.235	0.391

Tine	Depth	50.00	75.00
10W		0.071	0.334
25W		0.067	0.203
40W		0.133	0.172
40WNDL		0.714	0.865
40WNDs		0.119	0.234
Deep		0.329	0.556
ELCD		0.108	0.164
ELLC		0.253	0.187
ELSC		0.169	0.240
NSH		0.198	0.437
OSH		0.198	0.440
Slipper		0.461	0.859

*** Standard errors of differences of means ***

Table	Tine	Depth	Tine	Depth
rep.	6	36	3	3
d.f.	48	48	48	48
s.e.d.	0.0769	0.0314	0.1087	

*** Least significant differences of means ***

Table	Tine	Depth	Tine	Depth
rep.	6	36	3	3
d.f.	48	48	48	48
l.s.d.	0.1545	0.0631	0.2186	

***** Stratum standard errors and coefficients of variation *****

Variate: Draught Force

d.f.	s.e.	cv%
48	0.1331	42.5

***** Analysis of variance ***** Vertical Force (kN)

Variate: Vertical Force

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Tine	11	16.31194	1.48290	27.39	<.001
Depth	1	0.07846	0.07846	1.45	0.235
Tine.Depth	11	0.62064	0.05642	1.04	0.426
Residual	48	2.59838	0.05413		
Total	71	19.60943			

***** Tables of means *****

Variate: Vertical Force

Grand mean 0.460

Tine	10W	25W	40W	40WNDL	40WNDs	Deep
ELCD	-0.026	0.017	0.014	0.273	0.050	0.614

Tine	ELLC	ELSC	NSH	OSH	Slipper
0.735	0.086	0.225	1.279	1.000	1.252

Depth	50.00	75.00
	0.427	0.493

Tine	Depth	50.00	75.00
10W		-0.042	-0.010
25W		0.014	0.019
40W		0.013	0.014
40WNDL		0.279	0.267
40WNDs		0.023	0.077
Deep		0.602	0.627
ELCD		0.684	0.787
ELLC		0.058	0.115
ELSC		0.190	0.261
NSH		0.987	1.571
OSH		0.924	1.075
Slipper		1.393	1.112

Appendix 1.2

*** Standard errors of differences of means ***

Table	Tine	Depth	Tine Depth
rep.	6	36	3
d.f.	48	48	48
s.e.d.	0.1343	0.0548	0.1900

*** Least significant differences of means ***

Table	Tine	Depth	Tine Depth
rep.	6	36	3
d.f.	48	48	48
l.s.d.	0.2701	0.1103	0.3820

***** Stratum standard errors and coefficients of variation *****

Variate: Vertical Force

d.f.	s.e.	cv%
48	0.2327	50.6

***** Analysis of variance *****

**Application Possible 0.2m Tine Spacing Incl
Dip (m³/ha)**

Variate: Application Possible 0.2m Tine Spacing Incl Dip

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Tine	11	99363.	9033.	6.13	<.001
Depth	1	54583.	54583.	37.01	<.001
Tine.Depth	11	28887.	2626.	1.78	0.084
Residual	48	70787.	1475.		
Total	71	253621.			

***** Tables of means *****

Variate: Application Possible 0.2m Tine Spacing Incl Dip

Grand mean	124.9
ELCD	Tine 10W 25W 40W 40WNDL 40WNDs Deep
128.6	102.9 66.1 120.7 171.5 103.5 211.4
Depth	Tine ELLC ELSC NSH OSH Slipper
	137.7 106.6 99.2 99.6 151.0
Depth	50.00 75.00
	97.4 152.4
Tine	Depth 50.00 75.00
10W	67.6 138.2
25W	61.7 70.5
40W	86.7 154.8
40WNDL	166.7 176.3
40WNDs	68.5 138.5
Deep	154.3 268.4
ELCD	89.2 167.9
ELLC	149.0 126.5
ELSC	95.5 117.6
NSH	73.1 125.4
OSH	48.0 151.1
Slipper	108.0 194.0

*** Standard errors of differences of means ***

Table	Tine	Depth	Tine Depth
rep.	6	36	3
d.f.	48	48	48
s.e.d.	22.17	9.05	31.36

*** Least significant differences of means ***

Table	Tine	Depth	Tine Depth
rep.	6	36	3
d.f.	48	48	48
l.s.d.	44.58	18.20	63.04

***** Stratum standard errors and coefficients of variation *****

Variate: Application Possible 0.2m Tine Spacing Incl Dip

d.f.	s.e.	cv%
48	38.40	30.7

386.....

***** Analysis of variance *****

**Application Possible 0.25m Tine Spacing Incl
Dip (m³/ha)**

Variate: Application Possible 0.25m Tine Spacing Incl Dip

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Tine	11	63592.2	5781.1	6.13	<.001
Depth	1	34933.4	34933.4	37.01	<.001
Tine.Depth	11	18487.9	1680.7	1.78	0.084
Residual	48	45303.7	943.8		
Total	71	162317.1			

***** Tables of means *****

Variate: Application Possible 0.25m Tine Spacing Incl Dip

Grand mean 99.9

Tine	10W	25W	40W	40WNDL	40WNDs	Deep
ELCD	82.3	52.9	96.6	137.2	82.8	169.1
102.9						
Tine	ELLC	ELSC	NSH	OSH	Slipper	
	110.2	85.3	79.4	79.7	120.8	
Depth	50.00	75.00				
	77.9	121.9				
Tine	Depth	50.00	75.00			
10W		54.1	110.5			
25W		49.4	56.4			
40W		69.3	123.8			
40WNDL		133.4	141.0			
40WNDs		54.8	110.8			
Deep		123.5	214.7			
ELCD		71.4	134.3			
ELLC		119.2	101.2			
ELSC		76.4	94.1			
NSH		58.5	100.3			
OSH		38.4	120.9			
Slipper		86.4	155.2			

*** Standard errors of differences of means ***

Table	Tine	Depth	Tine Depth
rep.	6	36	3
d.f.	48	48	48
s.e.d.	17.74	7.24	25.08

*** Least significant differences of means ***

Table	Tine	Depth	Tine Depth
rep.	6	36	3
d.f.	48	48	48
l.s.d.	35.66	14.56	50.44

***** Stratum standard errors and coefficients of variation *****

Variate: Application Possible 0.25m Tine Spacing Incl Dip

d.f.	s.e.	cv%
48	30.72	30.7

***** Analysis of variance *****

**Application Possible 0.2m Tine Spacing not
Including Dip (m³/ha)**

Variate: Application Possible 0.2m Tine Spacing not Including Dip

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Tine	11	33050.	3005.	2.73	0.008
Depth	1	50023.	50023.	45.39	<.001
Tine.Depth	11	20081.	1826.	1.66	0.113
Residual	48	52897.	1102.		
Total	71	156051.			

***** Tables of means *****

Variate: Application Possible 0.2m Tine Spacing not Including Dip

Grand mean	67.1
ELCD	Tine 10W 25W 40W 40WNDL 40WNDs Deep
80.7	66.5 42.1 79.3 122.1 64.6 52.0
Depth	Tine ELLC ELSC NSH OSH Slipper
	82.8 55.1 42.3 50.3 67.7
Depth	50.00 75.00
	40.8 93.5
Tine	Depth 50.00 75.00
10W	35.5 97.6
25W	39.3 44.8
40W	58.8 99.8
40WNDL	113.3 130.9
40WNDs	32.6 96.7
Deep	12.8 91.1
ELCD	16.8 144.5
ELLC	74.4 91.2
ELSC	25.3 84.9
NSH	32.9 51.7
OSH	10.4 90.2
Slipper	37.1 98.4

*** Standard errors of differences of means ***

Table	Tine	Depth	Tine Depth
rep.	6	36	3
d.f.	48	48	48
s.e.d.	19.17	7.82	27.11

*** Least significant differences of means ***

Table	Tine	Depth	Tine Depth
rep.	6	36	3
d.f.	48	48	48
l.s.d.	38.54	15.73	54.50

***** Stratum standard errors and coefficients of variation *****

Variate: Application Possible 0.2m Tine Spacing not Including Dip

d.f.	s.e.	cv%
48	33.20	49.4

***** Analysis of variance *****
Application Possible 0.25m Time Spacing not Including Dip (m³/ha)

Variate: Application Possible 0.25m Time Spacing not Including Dip

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Time	11	21152.0	1922.9	2.73	0.008
Depth	1	32014.6	32014.6	45.39	<.001
Time.Depth	11	12851.7	1168.3	1.66	0.113
Residual	48	33854.3	705.3		
Total	71	99872.7			

***** Tables of means *****

Variate: Application Possible 0.25m Time Spacing not Including Dip
Grand mean 53.7

Time	10W	25W	40W	40WNDL	40WNDs	Deep
ELCD	53.2	33.7	63.5	97.7	51.7	41.6
64.5						

Time	ELLC	ELSC	NSH	OSH	Slipper
Depth	66.2	44.1	33.9	40.3	54.2
Depth	50.00	75.00			
	32.6	74.8			
Time	Depth	50.00	75.00		
10W		28.4	78.1		
25W		31.5	35.9		
40W		47.1	79.9		
40WNDL		90.7	104.7		
40WNDs		26.1	77.3		
Deep		10.3	72.9		
ELCD		13.5	115.6		
ELLC		59.5	72.9		
ELSC		20.2	67.9		
NSH		26.3	41.4		
OSH		8.3	72.2		
Slipper		29.7	78.7		

*** Standard errors of differences of means ***

Table	Time	Depth	Time Depth
rep.	6	36	3
d.f.	48	48	48
s.e.d.	15.33	6.26	21.68

*** Least significant differences of means ***

Table	Time	Depth	Time Depth
rep.	6	36	3
d.f.	48	48	48
l.s.d.	30.83	12.59	43.60

***** Stratum standard errors and coefficients of variation *****

Variate: Application Possible 0.25m Time Spacing not Including Dip

d.f.	s.e.	cv%
48	26.56	49.4

***** Analysis of variance *****
Relative Application Efficiency Time Spacing 0.2m Incl Dip (N/(m³/ha))

Variate: Relative Application Efficiency Time Spacing 0.2m Incl Dip

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Time	11	100.633	9.148	7.58	<.001
Depth	1	2.319	2.319	1.92	0.172
Time.Depth	11	11.346	1.031	0.86	0.588
Residual	48	57.900	1.206		
Total	71	172.199			

***** Tables of means *****

Variate: Relative Application Efficiency Time Spacing 0.2m Incl Dip
Grand mean 2.47

Time	10W	25W	40W	40WNDL	40WNDs	Deep
ELCD	1.86	2.03	1.30	4.71	1.73	2.03
1.13						

Time	ELLC	ELSC	NSH	OSH	Slipper
Depth	1.50	1.93	3.46	3.36	4.54
Depth	50.00	75.00			
	2.29	2.64			
Time	Depth	50.00	75.00		
10W		1.16	2.56		
25W		1.07	2.99		
40W		1.48	1.12		
40WNDL		4.50	4.92		
40WNDs		1.76	1.70		
Deep		2.06	1.99		
ELCD		1.27	1.00		
ELLC		1.50	1.49		
ELSC		1.85	2.01		
NSH		2.71	4.21		
OSH		3.75	2.97		
Slipper		4.31	4.76		

*** Standard errors of differences of means ***

Table	Time	Depth	Time Depth

rep.	6	36	3
d.f.	48	48	48
s.e.d.	0.634	0.259	0.897

*** Least significant differences of means ***

Table	Time	Depth	Time Depth
rep.	6	36	3
d.f.	48	48	48
l.s.d.	1.275	0.520	1.803

***** Stratum standard errors and coefficients of variation *****

Variate: Relative Application Efficiency Time Spacing 0.2m Incl Dip

d.f.	s.e.	cv%
48	1.098	44.5

***** Analysis of variance *****
Relative Application Efficiency Time Spacing 0.25m Incl Dip (N/(m³/ha))

Variate: Relative Application Efficiency Time Spacing 0.25m Incl Dip

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Time	11	157.243	14.295	7.59	<.001
Depth	1	3.626	3.626	1.92	0.172
Time.Depth	11	17.734	1.612	0.86	0.588
Residual	48	90.462	1.885		
Total	71	269.065			

***** Tables of means *****

Variate: Relative Application Efficiency Time Spacing 0.25m Incl Dip

Grand mean 3.08

Time	10W	25W	40W	40WNDL	40WNDs	Deep
ELCD	2.32	2.54	1.63	5.89	2.16	2.53
1.42						

Time	ELLC	ELSC	NSH	OSH	Slipper
Depth	1.87	2.42	4.32	4.20	5.67
Depth	50.00	75.00			
	2.86	3.31			
Time	Depth	50.00	75.00		
10W		1.45	3.19		
25W		1.34	3.74		
40W		1.85	1.40		
40WNDL		5.63	6.15		
40WNDs		2.20	2.13		
Deep		2.58	2.49		
ELCD		1.59	1.25		
ELLC		1.88	1.87		
ELSC		2.32	2.52		
NSH		3.39	5.26		
OSH		4.68	3.72		
Slipper		5.39	5.96		

*** Standard errors of differences of means ***

Table	Time	Depth	Time Depth
rep.	6	36	3
d.f.	48	48	48
s.e.d.	0.793	0.324	1.121

*** Least significant differences of means ***

Table	Time	Depth	Time Depth
rep.	6	36	3
d.f.	48	48	48
l.s.d.	1.594	0.651	2.254

***** Stratum standard errors and coefficients of variation *****

Variate: Relative Application Efficiency Time Spacing 0.25m Incl Dip

d.f.	s.e.	cv%
48	1.373	44.5

***** Analysis of variance *****
Specific Resistance (kN/m²)

Variate: Specific Resistance

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Time	11	84840.	7713.	5.83	<.001
Depth	1	1491.	1491.	1.13	0.294
Time.Depth	11	11823.	1075.	0.81	0.628
Residual	48	63506.	1323.		
Total	71	161661.			

***** Tables of means *****

Variate: Specific Resistance

Grand mean 62.2

Time	10W	25W	40W	40WNDL	40WNDs	Deep
ELCD	43.1	27.6	27.2	136.5	30.5	78.2
35.1						

Time	ELLC	ELSC	NSH	OSH	Slipper
Depth	72.9	51.1	67.6	55.7	121.5
Depth	50.00	75.00			
	66.8	57.7			
Time	Depth	50.00	75.00		

Appendix 1.2

10W	26.2	60.0
25W	22.8	32.3
40W	31.6	22.8
40WNDL	163.6	109.4
40WNDs	29.6	31.3
Deep	76.9	79.5
ELCD	40.9	29.3
ELLC	101.9	43.8
ELSC	64.4	37.8
NSH	75.1	60.0
OSH	50.1	61.3
Slipper	118.3	124.8

*** Standard errors of differences of means ***

Table	Time	Depth	Time Depth
rep.	6	36	3
d.f.	48	48	48
s.e.d.	21.00	8.57	29.70

*** Least significant differences of means ***

Table	Time	Depth	Time Depth
rep.	6	36	3
d.f.	48	48	48
l.s.d.	42.22	17.24	59.71

***** Stratum standard errors and coefficients of variation *****

Variate: Specific Resistance

d.f.	s.e.	cv%
48	36.37	58.4

***** Analysis of variance *****

**Relative Application Efficiency 0.2m Time
Spacing Not Including Dip. (N/(m³/ha))**

Variate: Relative Application Efficiency 0.2m Time Spacing Not Including Dip.

Source of variation	d.f. (m.v.)	s.s.	m.s.	v.r.	F pr.
Time	11	1805.43	164.13	1.86	0.071
Depth	1	150.89	150.89	1.71	0.198
Time.Depth	11	674.33	61.30	0.69	0.738
Residual	46(2)	4068.03	88.44		
Total	69(2)	6577.86			

***** Tables of means *****

Variate: Relative Application Efficiency 0.2m Time Spacing Not Including Dip.

Grand mean 5.8

Table	Time	10W	25W	40W	40WNDL	40WNDs	Deep
ELCD		2.9	3.6	2.5	6.6	3.2	11.3

1.1

Table	Time	ELLC	ELSC	NSH	OSH	Slipper
		2.6	5.2	5.5	5.3	20.1

Table	Depth	50.00	75.00
		7.3	4.4

Table	Time	Depth	50.00	75.00
10W			2.4	3.5
25W			1.7	5.5
40W			3.2	1.8
40WNDL			6.4	6.8
40WNDs			3.7	2.7
Deep			16.7	5.9
ELCD			1.0	1.2
ELLC			3.1	2.0
ELSC			7.3	3.0
NSH			6.0	4.9
OSH			5.6	4.9
Slipper			30.1	10.2

*** Standard errors of differences of means ***

Table	Time	Depth	Time Depth
rep.	6	36	3
d.f.	46	46	46
s.e.d.	5.43	2.22	7.68

(Not adjusted for missing values)

*** Least significant differences of means ***

Table	Time	Depth	Time Depth
rep.	6	36	3
d.f.	46	46	46
l.s.d.	10.93	4.46	15.46

(Not adjusted for missing values)

***** Stratum standard errors and coefficients of variation *****

Variate: Relative Application Efficiency 0.2m Time Spacing Not Including Dip.

d.f.	s.e.	cv%
46	9.40	161.6

***** Analysis of variance *****

**Relative Application Efficiency 0.25m Time
Spacing Not Including Dip. (N/(m³/ha))**

Variate: Relative Application Efficiency 0.25m Time Spacing Not Including Dip.

Source of variation	d.f. (m.v.)	s.s.	m.s.	v.r.	F pr.
Time	11	2821.0	256.5	1.86	0.071
Depth	1	235.7	235.7	1.71	0.198
Time.Depth	11	1053.6	95.8	0.69	0.738
Residual	46(2)	6356.4	138.2		
Total	69(2)	10278.1			

***** Tables of means *****

Variate: Relative Application Efficiency 0.25m Time Spacing Not Including Dip.

Grand mean 7.3

Table	Time	10W	25W	40W	40WNDL	40WNDs	Deep
ELCD		3.7	4.5	3.2	8.3	4.0	14.1

1.4

Table	Time	ELLC	ELSC	NSH	OSH	Slipper
		3.2	6.4	6.9	6.6	25.2

Table	Depth	50.00	75.00
		9.1	5.5

Table	Time	Depth	50.00	75.00
10W			3.0	4.3
25W			2.1	6.9
40W			4.0	2.3
40WNDL			8.0	8.5
40WNDs			4.6	3.3
Deep			20.9	7.4
ELCD			1.2	1.5
ELLC			3.9	2.6
ELSC			9.1	3.8
NSH			7.6	6.2
OSH			7.0	6.1
Slipper			37.6	12.8

*** Standard errors of differences of means ***

Table	Time	Depth	Time Depth
rep.	6	36	3
d.f.	46	46	46
s.e.d.	6.79	2.77	9.60

(Not adjusted for missing values)

*** Least significant differences of means ***

Table	Time	Depth	Time Depth
rep.	6	36	3
d.f.	46	46	46
l.s.d.	13.66	5.58	19.32

(Not adjusted for missing values)

***** Stratum standard errors and coefficients of variation *****

Variate: Relative Application Efficiency 0.25m Time Spacing Not Including Dip.

d.f.	s.e.	cv%
46	11.76	161.6

Appendix 1.3.

Force, disturbance and performance data.

50mm Depth	Area Up	Area Down	Dip	Draught	Vertical	Specific Resistance	App Pos 0.2	App Pos 0.25	App Pos No Dip 0.2	App Pos No Dip 0.25	N/m ² /ha	N/m ² /ha	N/m ² /ha	N/m ² /ha	N/m ² /ha	N/m ² /ha
Time					↑+ve↑						RAE0.2	N/m ² /ha	RAE0.25	N/m ² /ha	RAE0.25 No Dip	RAE0.25 No Dip
10W	1440	2845	752.5	0.1124	-0.0416	39.508	109.625	87.7	72.000	57.600	1.025	1.282	1.561	1.951	1.561	1.951
10W	400	2455	317.5	0.0674	-0.0416	27.454	35.875	28.7	20.000	16.000	1.879	2.348	3.370	4.213	3.370	4.213
10W	290	2890	855	0.0333	-0.0416	11.522	57.250	45.8	14.500	11.600	0.582	0.727	2.297	2.871	2.297	2.871
25W	740	2830	427.5	0.0674	0.0142	23.649	58.375	46.7	37.000	29.600	1.155	1.443	1.822	2.277	1.822	2.277
25W	950	2765	347.5	0.0889	0.0139	32.152	74.875	59.9	47.500	38.000	1.187	1.484	1.872	2.339	1.872	2.339
25W	670	3530	367.5	0.0449	0.014	12.720	51.875	41.5	33.500	26.800	0.866	1.082	1.340	1.675	1.340	1.675
40W	2740	4085	242.5	0.2536	0.0104	62.081	149.125	119.3	137.000	109.600	1.701	2.126	1.851	2.314	1.851	2.314
40W	285	4425	997.5	0.0674	0.0281	15.232	64.125	51.3	14.250	11.400	1.051	1.314	4.730	5.912	4.730	5.912
40W	505	4515	430	0.0787	0	17.431	46.750	37.4	25.250	20.200	1.683	2.104	3.117	3.896	3.117	3.896
40WND	660	4520	725	0.1685	0.0281	37.279	69.250	55.4	33.000	26.400	2.433	3.042	5.106	6.383	5.106	6.383
40WND	635	3895	965	0.1	0.014	25.674	80.000	64	31.750	25.400	1.250	1.563	3.150	3.937	3.150	3.937
40WND	660	3475	462.5	0.0899	0.0278	25.871	56.125	44.9	33.000	26.400	1.602	2.002	2.724	3.405	2.724	3.405
40WNDL	2260	3760	1712.5	0.8813	0.2019	181.197	198.625	138.9	113.000	90.400	3.430	4.288	6.029	7.537	6.029	7.537
40WNDL	2495	6020	872.5	0.5714	0.2095	94.917	168.375	134.7	124.750	99.800	3.394	4.242	4.580	5.725	4.580	5.725
40WNDL	2045	4145	617.5	0.8901	0.3667	214.741	133.125	106.5	102.250	81.800	6.686	8.358	8.705	10.881	8.705	10.881
ELLC	490	1955	942.5	0.0562	0.0278	28.747	71.625	57.3	24.500	19.600	0.785	0.981	2.294	2.867	2.294	2.867
ELLC	1980	3260	1612.5	0.2967	0.0621	91.012	179.625	143.7	99.000	79.200	1.652	2.065	2.997	3.746	2.997	3.746
ELLC	1995	2185	1917.5	0.4066	0.0828	186.087	195.625	156.5	99.750	79.800	2.078	2.598	4.076	5.095	4.076	5.095
ELSC	450	3265	1360	0.2697	0.3193	82.603	90.500	72.4	22.500	18.000	2.980	3.725	11.987	14.983	11.987	14.983
ELSC	305	2390	1977.5	0.0909	0.0555	38.033	114.125	91.3	15.250	12.200	0.796	0.996	5.961	7.451	5.961	7.451
ELSC	760	2015	880	0.1461	0.1944	72.506	82.000	65.6	38.000	30.400	1.782	2.227	3.845	4.806	3.845	4.806
ELCD	1325	2635	290	0.1124	0.5969	42.657	80.750	64.6	66.250	53.000	1.392	1.740	1.697	2.121	1.697	2.121
ELCD	665	2780	1712.5	0.1111	0.9131	39.964	118.875	95.1	33.250	26.600	0.935	1.168	3.341	4.177	3.341	4.177
ELCD	-980	2515	2342.5	0.1011	0.5414	40.109	68.125	54.5	-49.000	-39.200	1.484	1.855	-2.063	-2.579	-2.063	-2.579
OSH	45	2995	360	0.0667	0.4	22.270	20.250	16.2	2.250	1.800	3.294	4.117	29.644	37.036	29.644	37.036
OSH	690	4060	882.5	0.3933	1.706	96.872	78.625	62.9	34.500	27.600	5.002	6.253	11.400	14.250	11.400	14.250
OSH	-110	4260	1015	0.1333	0.6664	31.291	45.250	36.2	-5.500	-4.400	2.946	3.682	-24.236	-30.295	-24.236	-30.295
NSH	790	2325	582.5	0.236	1.24	101.505	68.625	54.9	39.500	31.600	3.439	4.299	5.975	7.468	5.975	7.468
NSH	610	2820	615	0.1348	0.7627	47.801	61.250	49	30.500	24.400	2.201	2.751	4.420	5.525	4.420	5.525
NSH	575	2920	1212.5	0.2222	0.9579	76.096	89.375	71.5	28.750	23.000	2.486	3.108	7.729	9.661	7.729	9.661
Deep	320	4895	2815	0.4333	0.6753	88.927	156.750	125.4	16.000	12.800	2.777	3.471	27.206	34.008	27.206	34.008
Deep	-20	3680	3617.5	0.4052	0.5694	110.109	179.875	143.9	-1.000	-0.800	2.253	2.816	*	*	*	*
Deep	470	4595	2057	0.1461	0.56	31.795	126.350	101.08	23.500	18.800	1.156	1.445	6.217	7.771	6.217	7.771
Slipper	1220	6295	1750	0.4944	1.96	78.539	148.500	118.8	61.000	48.800	3.329	4.162	8.105	10.131	8.105	10.131
Slipper	70	4460	1377.5	0.2386	1.0967	53.498	72.375	57.9	3.500	2.800	3.297	4.121	68.171	85.214	68.171	85.214
Slipper	935	2920	1130	0.6508	1.121	222.877	103.250	82.6	46.750	37.400	6.303	7.879	13.921	17.401	13.921	17.401

75mm Depth Time	Area Up	Area Down	Dip	+ve/-up Vertical	Specific Resistance	App Poss 0.2	App Poss 0.25	App Poss No Dip 0.2	App Poss No Dip 0.25	N/m ³ /ha		N/m ³ /ha		N/m ³ /ha		N/m ³ /ha	
										RAE 0.2	RAE 0.25	RAE 0.2	RAE 0.25	RAE 0.2	RAE 0.25	RAE 0.2	RAE 0.25
10W	2490	5745	1047.5	0.479	83.377	176.875	141.5	124.500	99.600	2.708	3.385	3.847	4.809	3.847	4.809	3.847	4.809
10W	1855	6105	1040	0.1775	29.075	144.750	115.8	92.750	74.200	1.226	1.533	1.914	2.392	1.914	2.392	1.914	2.392
10W	1510	5120	347.5	0.3465	67.676	92.875	74.3	75.500	60.400	3.731	4.664	4.589	5.737	4.589	5.737	4.589	5.737
25W	1360	6010	282.5	0.1348	22.429	82.125	65.7	68.000	54.400	1.641	2.052	1.982	2.478	1.982	2.478	1.982	2.478
25W	510	6025	602.5	0.2045	33.942	55.625	44.5	25.500	20.400	3.676	4.596	8.020	10.025	8.020	10.025	8.020	10.025
25W	820	6635	652.5	0.2697	40.648	73.625	58.9	41.000	32.800	3.663	4.579	6.578	8.223	6.578	8.223	6.578	8.223
40W	1905	6975	367.5	0.1222	17.520	113.625	90.9	95.250	76.200	1.075	1.344	1.283	1.604	1.283	1.604	1.283	1.604
40W	1575	8820	1542.5	0.2135	24.206	155.875	124.7	78.750	63.000	1.370	1.712	2.711	3.389	2.711	3.389	2.711	3.389
40W	2510	7755	1385	0.1798	26.617	194.750	155.8	125.500	100.400	0.923	1.154	1.433	1.791	1.433	1.791	1.433	1.791
40WNDs	1240	7755	1190	0.236	30.432	121.500	97.2	62.000	49.600	1.942	2.428	3.806	4.758	3.806	4.758	3.806	4.758
40WNDs	2495	6510	185	0.2	30.722	134.000	107.2	124.750	99.800	1.493	1.866	1.603	2.004	1.603	2.004	1.603	2.004
40WNDs	2065	8140	1137.5	0.2667	32.764	160.125	128.1	103.250	82.600	1.666	2.082	2.583	3.229	2.583	3.229	2.583	3.229
40WNDL	2165	9095	910	0.8132	89.412	153.750	123	108.250	86.600	5.289	6.611	7.512	9.390	7.512	9.390	7.512	9.390
40WNDL	3000	7845	722.5	0.6044	77.043	186.125	148.9	150.000	120.000	3.247	4.059	4.029	5.037	4.029	5.037	4.029	5.037
40WNDL	2690	7285	1090	1.1785	161.771	189.000	151.2	134.500	107.600	6.235	7.794	8.762	10.953	8.762	10.953	8.762	10.953
ELLC	1800	4395	262.5	0.1778	40.455	103.125	82.5	90.000	72.000	1.724	2.155	1.976	2.469	1.976	2.469	1.976	2.469
ELLC	1405	5255	757.5	0.1461	27.802	108.125	86.5	70.250	56.200	1.351	1.689	2.080	2.600	2.080	2.600	2.080	2.600
ELLC	2265	3730	1097.5	0.236	63.371	168.125	134.5	113.250	90.600	1.404	1.755	2.084	2.605	2.084	2.605	2.084	2.605
ELSC	1476	5550	675	0.1461	26.324	107.500	86.04	73.800	59.040	1.358	1.698	1.980	2.475	1.980	2.475	1.980	2.475
ELSC	1105	5985	1057.5	0.2556	42.707	108.125	86.5	55.250	44.200	2.364	2.955	4.626	5.783	4.626	5.783	4.626	5.783
ELSC	2515	7175	230	0.3182	44.348	137.250	109.8	125.750	100.600	2.318	2.898	2.530	3.163	2.530	3.163	2.530	3.163
ELCD	3140	8060	0	0.1461	18.127	157.000	125.6	157.000	125.600	0.931	1.163	0.931	1.163	0.931	1.163	0.931	1.163
ELCD	3535	5230	715	0.191	36.520	212.500	170	176.750	141.400	0.899	1.124	1.081	1.351	1.081	1.351	1.081	1.351
ELCD	1995	4680	690	0.1556	33.248	134.250	107.4	99.750	79.800	1.159	1.449	1.560	1.950	1.560	1.950	1.560	1.950
OSH	1480	8615	1872	0.4091	47.487	167.600	134.08	74.000	59.200	2.441	3.051	5.528	6.910	5.528	6.910	5.528	6.910
OSH	2035	6320	640	0.5444	86.139	133.750	107	101.750	81.400	4.070	5.088	5.350	6.688	5.350	6.688	5.350	6.688
OSH	1900	7315	1140	0.3667	50.130	152.000	121.6	95.000	76.000	2.413	3.016	3.860	4.825	3.860	4.825	3.860	4.825
NSH	1240	5045	1512.5	0.3111	61.665	137.625	110.1	62.000	49.600	2.260	2.826	5.018	6.272	5.018	6.272	5.018	6.272
NSH	15	8425	1420	0.5506	65.353	71.750	57.4	0.750	0.600	7.674	9.592	9.592	11.938	9.592	11.938	9.592	11.938
NSH	1850	8470	1487.5	0.4494	53.058	166.875	133.5	92.500	74.000	2.693	3.366	4.858	6.073	4.858	6.073	4.858	6.073
NSH	1180	9740	3010	0.2697	27.690	209.500	167.6	59.000	47.200	1.287	1.609	4.571	5.714	1.287	1.609	4.571	5.714
Deep	9685	3647.5	3647.5	0.7831	81.064	304.375	243.5	122.000	97.600	2.579	3.224	6.435	8.044	6.435	8.044	6.435	8.044
Deep	1845	4735	3980	0.6145	129.778	291.250	233	92.250	73.800	2.110	2.637	6.661	8.327	6.661	8.327	6.661	8.327
Slipper	3355	6740	2567.5	1.0312	152.997	296.125	236.9	167.750	134.200	3.482	4.353	6.147	7.684	6.147	7.684	6.147	7.684
Slipper	1465	6250	1572.5	0.8283	132.528	151.875	121.5	73.250	58.600	5.454	6.817	11.308	14.135	11.308	14.135	11.308	14.135
Slipper	1085	8090	1597.5	0.7186	88.826	134.125	107.3	54.250	43.400	5.358	6.697	13.246	16.558	13.246	16.558	13.246	16.558

Appendix 2

Appendix 2.1.

The effect of a cutting disc on draught and vertical forces

A small study, to assess the effect of a cutting disc in terms of its contribution to overall injector tine forces, was carried out using the commercial NSH injector. The NSH injector tine was tested in the soil dynamics laboratory for draught and vertical force requirement according to the methodology described in *Section 2.6.4*. The experiment was based on a randomised block design using three replications. The disc used was of a larger diameter than that described in *Appendix 2.2b*, to reduce the effect on soil forces of contact with the disc hub. Both the injector and disc were pulled through the soil individually and in combination at a depth of 0.075 m on a standard soil preparation.

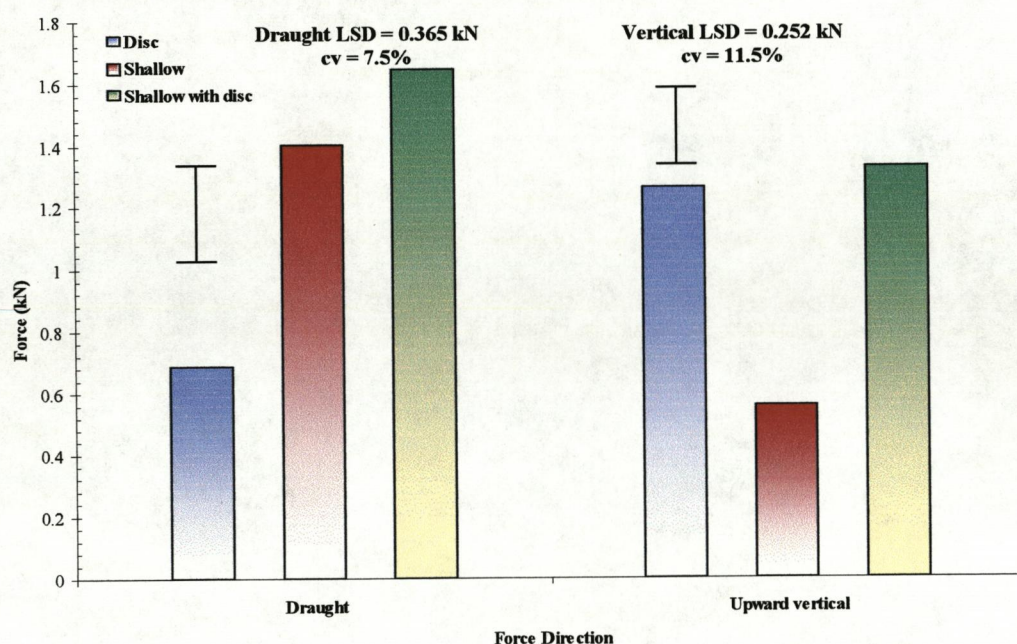
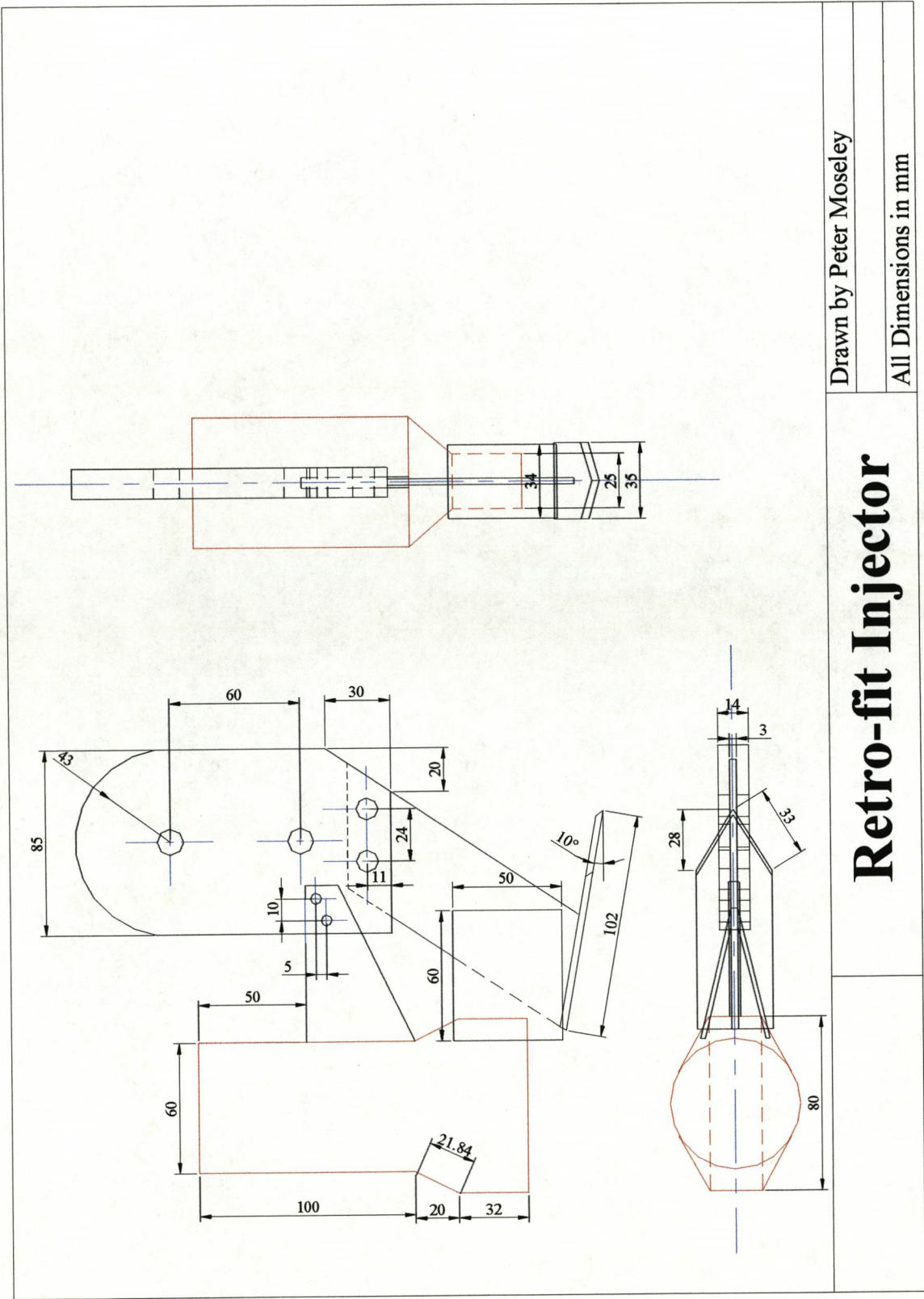


Fig. Ap. 2.1. The effect of a cutting disc on draught and upward vertical force of the commercial NSH injector tine in a soil dynamics laboratory.

It was found that the addition of the cutting disc did not increase the draught force requirement significantly (*Fig. 2.1.1*), although a 17% increase was observed. The addition of the cutting disc did however affect the upward vertical force significantly. The upward vertical force of the NSH tine was increased by 137%. It can therefore be concluded that the addition of a cutting disc is unlikely to affect the draught force performance of an injector but will introduce the need for additional downward force to aid soil penetration.

Appendix 2.2a.

Retrofit Injector Tine



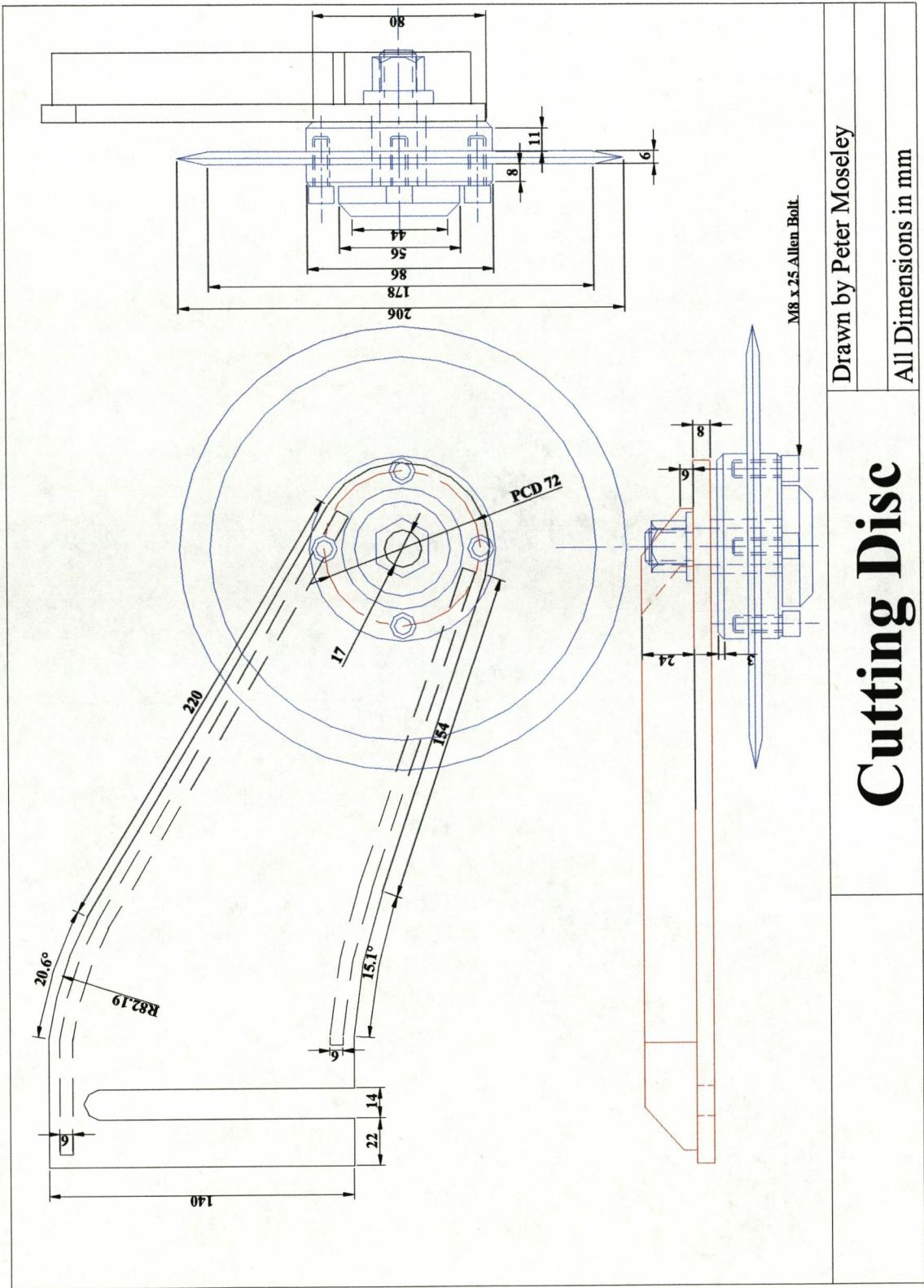
Drawn by Peter Moseley

All Dimensions in mm

Retrofit Injector

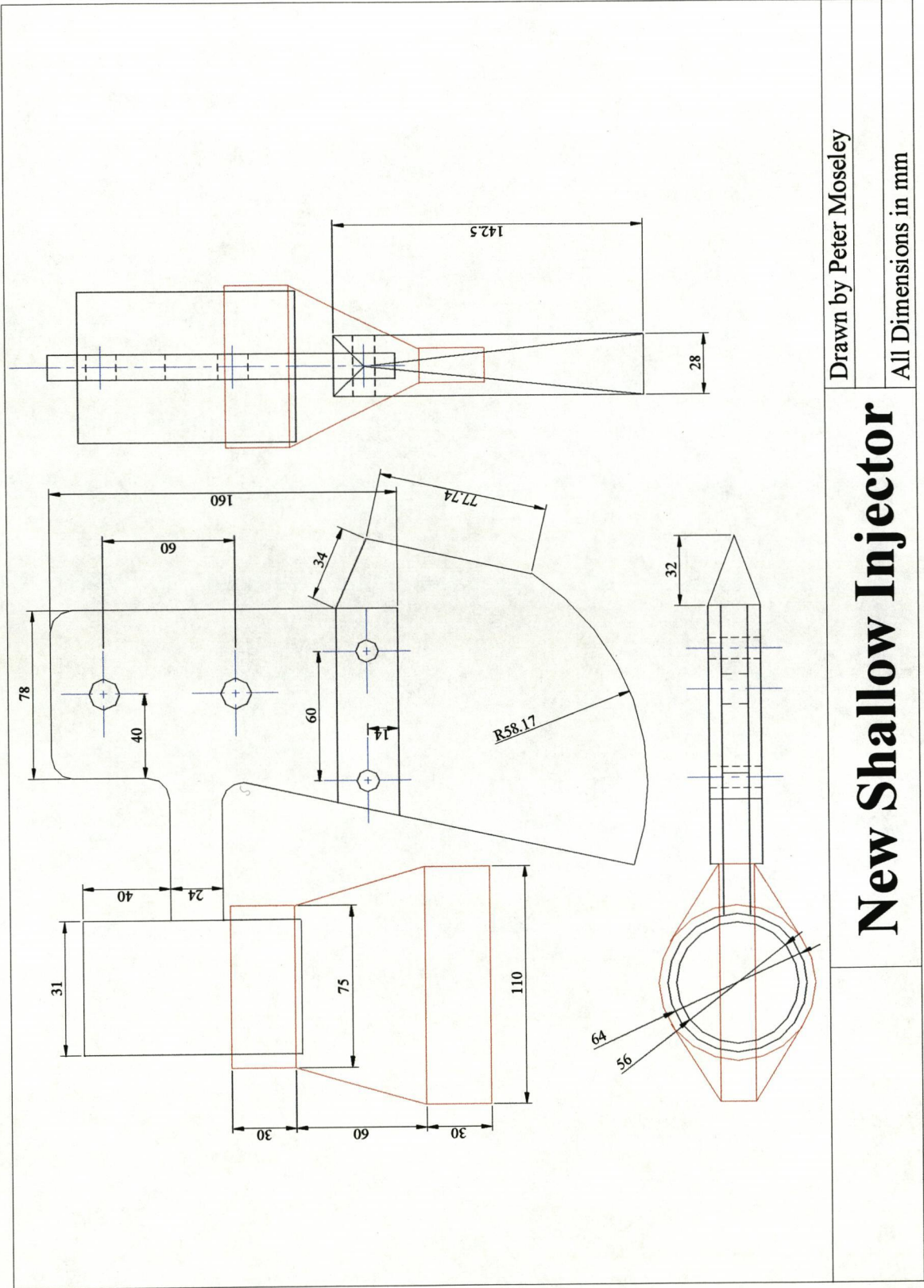
Appendix 2.2b.

Cutting Disc



Appendix 2.2d.

NSH



Drawn by Peter Moseley

All Dimensions in mm

New Shallow Injector

Appendix 2.3.

Complete statistical analysis.

***** Analysis of variance *****

Variate: Bulk Density (kg/m ³)					
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	7158.	3579.	0.94	
rep.*Units* stratum					
Bin	4	5860.	1465.	0.39	0.814
Residual	8	30426.	3803.		
Total	14	43444.			

***** Tables of means *****

Grand mean	1407.				
Bin	1.00	2.00	3.00	4.00	5.00
	1418.	1410.	1377.	1434.	1393.

*** Standard errors of differences of means ***

Table	Bin
rep.	3
d.f.	8
s.e.d.	50.4

*** Least significant differences of means ***

Table	Bin
rep.	3
d.f.	8
l.s.d.	116.1

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
rep	2	26.8	1.9
rep.*Units*	8	61.7	4.4

***** Analysis of variance *****

Variate: Moisture Content (%)					
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	0.0452	0.0226	0.05	
rep.*Units* stratum					
Bin	4	2.7438	0.6860	1.56	0.275
Residual	8	3.5215	0.4402		
Total	14	6.3105			

***** Tables of means *****

Grand mean	9.17				
Bin	1.00	2.00	3.00	4.00	5.00
	9.62	9.58	8.59	9.33	8.74

*** Standard errors of differences of means ***

Table	Bin
rep.	3
d.f.	8
s.e.d.	0.542

*** Least significant differences of means ***

Table	Bin
rep.	3
d.f.	8
l.s.d.	1.249

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
rep	2	0.067	0.7
rep.*Units*	8	0.663	7.2

***** Analysis of variance *****

Variate: Lower Disturbed Area (mm ²)					
Source of variation	d.f. (m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	2.885E+06	1.442E+06	0.64	
Rep.*Units* stratum					
Tine	4	6.309E+07	1.577E+07	7.00	<.001
Depth	3	1.959E+09	6.532E+08	289.78	<.001
Tine.Depth	10 (2)	3.039E+07	3.039E+06	1.35	0.246
Residual	34 (4)	7.664E+07	2.254E+06		
Total	53 (6)	1.697E+09			

***** Tables of means *****

Grand mean	10451.				
Tine	25W	40WNDLI	NSH_D	RetroD	RetroND
	9523.	11780.	10821.	9017.	11113.
Depth	50.00	75.00	100.00	125.00	
	3684.	7104.	12154.	18861.	

Tine	Depth	50.00	75.00	100.00	125.00
25W		2805.	5782.	10623.	18883.
40WNDLI		4355.	8583.	13530.	20650.
NSH_D		3822.	7710.	13922.	17830.
RetroD		3480.	5848.	9317.	17423.
RetroND		3957.	7597.	13378.	19520.

*** Standard errors of differences of means ***

Table	Tine	Depth	Tine Depth
rep.	12	15	3
d.f.	34	34	34
s.e.d.	612.9	548.2	1225.8

(Not adjusted for missing values)

*** Least significant differences of means ***

Table	Tine	Depth	Tine Depth
rep.	12	15	3
d.f.	34	34	34
l.s.d.	1245.6	1114.1	2491.2

(Not adjusted for missing values)

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	268.6	2.6
Rep.*Units*	34	1501.3	14.4

Variate: Upper Disturbed Area (mm²)

Source of variation	d.f. (m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	858779.	429389.	0.60	
Rep.*Units* stratum					
Tine	4	20620822.	5155206.	7.25	<.001
Depth	3	18738378.	6246126.	8.79	<.001
Tine.Depth	10 (2)	14118325.	1411833.	1.99	0.067
Residual	34 (4)	24163088.	710679.		
Total	53 (6)	72481286.			

***** Tables of means *****

Grand mean	2104.				
Tine	25W	40WNDLI	NSH_D	RetroD	RetroND
	2262.	2438.	1052.	1985.	2783.
Depth	50.00	75.00	100.00	125.00	
	1181.	2271.	2275.	2688.	

Tine	Depth	50.00	75.00	100.00	125.00
25W		1423.	1960.	2470.	3193.
40WNDLI		1205.	2435.	2767.	3345.
NSH_D		737.	2285.	218.	967.
RetroD		1337.	1722.	2312.	2568.
RetroND		1205.	2952.	3607.	3367.

*** Standard errors of differences of means ***

Table	Tine	Depth	Tine Depth
rep.	12	15	3
d.f.	34	34	34
s.e.d.	344.2	307.8	688.3

(Not adjusted for missing values)

*** Least significant differences of means ***

Table	Tine	Depth	Tine Depth
rep.	12	15	3
d.f.	34	34	34
l.s.d.	699.4	625.6	1398.8

(Not adjusted for missing values)

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	146.5	7.0
Rep.*Units*	34	843.0	40.1

Variate: Area of Dip (mm²)

Source of variation	d.f. (m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	4310982.	2155491.	5.85	
Rep.*Units* stratum					
Tine	4	9302721.	2325680.	6.32	<.001
Depth	3	39795030.	13265010.	36.02	<.001
Tine.Depth	10 (2)	4942777.	494278.	1.34	0.249
Residual	34 (4)	12519876.	368232.		
Total	53 (6)	58793030.			

***** Tables of means *****

Grand mean 1780.

Tine	25W	40WNDLI	NSH_D	RetroD	RetroND
	1353.	1254.	2191.	2039.	2063.
Depth	50.00	75.00	100.00	125.00	
	808.	1193.	2288.	2831.	
Tine	Depth	50.00	75.00	100.00	125.00
25W		657.	1072.	1386.	2298.
40WNDLI		338.	774.	1908.	1996.
NSH_D		953.	1046.	3108.	3658.
RetroD		1375.	1428.	2263.	3090.
RetroND		716.	1646.	2778.	3114.

*** Standard errors of differences of means ***

Table	Tine	Depth	Tine Depth
rep.	12	15	3
d.f.	34	34	34
s.e.d.	247.7	221.6	495.5

(Not adjusted for missing values)

*** Least significant differences of means ***

Table	Tine	Depth	Tine Depth
rep.	12	15	3
d.f.	34	34	34
l.s.d.	503.5	450.3	1006.9

(Not adjusted for missing values)

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	328.3	18.4
Rep.*Units*	34	606.8	34.1

Variante: Draught Force (kN)

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.02883	0.01442	0.35	
Rep.*Units* stratum					
Tine	4	14.92505	3.73126	90.64	<.001
Depth	3	31.45246	10.48415	254.69	<.001
Tine.Depth	10(2)	3.74658	0.37466	9.10	<.001
Residual	34(4)	1.39958	0.04116		
Total	53(6)	47.17085			

***** Tables of means *****

Grand mean 1.243

Tine	25W	40WNDLI	NSH_D	RetroD	RetroND
	0.790	1.276	2.158	1.155	0.826
Depth	50.00	75.00	100.00	125.00	
	0.384	0.802	1.494	2.292	
Tine	Depth	50.00	75.00	100.00	125.00
25W		0.223	0.469	1.008	1.459
40WNDLI		0.570	0.873	1.535	2.126
NSH_D		0.649	1.543	2.681	3.799
RetroD		0.347	0.728	1.344	2.203
RetroND		0.130	0.397	0.903	1.874

*** Standard errors of differences of means ***

Table	Tine	Depth	Tine Depth
rep.	12	15	3
d.f.	34	34	34
s.e.d.	0.0828	0.0741	0.1657

(Not adjusted for missing values)

*** Least significant differences of means ***

Table	Tine	Depth	Tine Depth
rep.	12	15	3
d.f.	34	34	34
l.s.d.	0.1683	0.1506	0.3367

(Not adjusted for missing values)

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	0.0268	2.2
Rep.*Units*	34	0.2029	16.3

Variante: Upward Vertical Force (kN)

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.15470	0.07735	3.47	
Rep.*Units* stratum					
Tine	4	25.02066	6.25516	280.73	<.001
Depth	3	6.26071	2.08690	93.66	<.001
Tine.Depth	10(2)	6.25886	0.62589	28.09	<.001
Residual	34(4)	0.75759	0.02228		
Total	53(6)	36.37601			

***** Tables of means *****

Grand mean 0.664

Tine	25W	40WNDLI	NSH_D	RetroD	RetroND
	0.015	0.401	1.742	1.037	0.123
Depth	50.00	75.00	100.00	125.00	
	0.241	0.497	0.822	1.095	
Tine	Depth	50.00	75.00	100.00	125.00
25W		-0.009	-0.037	-0.013	0.120
40WNDLI		0.337	0.314	0.453	0.501
NSH_D		0.485	1.423	2.229	2.831
RetroD		0.421	0.817	1.443	1.469
RetroND		-0.027	-0.033	-0.003	0.554

*** Standard errors of differences of means ***

Table	Tine	Depth	Tine Depth
rep.	12	15	3
d.f.	34	34	34
s.e.d.	0.0609	0.0545	0.1219

(Not adjusted for missing values)

*** Least significant differences of means ***

Table	Tine	Depth	Tine Depth
rep.	12	15	3
d.f.	34	34	34
l.s.d.	0.1238	0.1108	0.2477

(Not adjusted for missing values)

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	0.0622	9.4
Rep.*Units*	34	0.1493	22.5

Variante: Specific Resistance (kN/m²)

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	344.5	172.3	0.25	
Rep.*Units* stratum					
Tine	4	139915.1	34978.8	51.64	<.001
Depth	3	3445.5	1148.5	1.70	0.186
Tine.Depth	10(2)	6822.0	682.2	1.01	0.457
Residual	34(4)	23029.4	677.3		
Total	53(6)	161586.4			

***** Tables of means *****

Grand mean 114.1

Tine	25W	40WNDLI	NSH_D	RetroD	RetroND
	83.3	114.0	196.4	124.6	52.3
Depth	50.00	75.00	100.00	125.00	
	103.0	114.2	124.4	114.8	
Tine	Depth	50.00	75.00	100.00	125.00
25W		79.4	81.5	95.2	77.1
40WNDLI		131.6	105.7	114.4	104.2
NSH_D		169.9	204.1	197.4	214.4
RetroD		101.1	126.8	145.1	125.2
RetroND		33.0	53.1	69.9	53.1

*** Standard errors of differences of means ***

Table	Tine	Depth	Tine Depth
rep.	12	15	3
d.f.	34	34	34
s.e.d.	10.62	9.50	21.25

(Not adjusted for missing values)

*** Least significant differences of means ***

Table	Tine	Depth	Tine Depth
rep.	12	15	3
d.f.	34	34	34
l.s.d.	21.59	19.31	43.18

(Not adjusted for missing values)

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	2.93	2.6
Rep.*Units*	34	26.03	22.8

Variante: Possible Application Rate: 0.2 m Spacing Incl Dip (m³/ha)

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	14834.	7417.	3.73	
Rep.*Units* stratum					
Tine	4	43963.	10991.	5.52	0.002
Depth	3	258848.	86283.	43.33	<.001
Tine.Depth	10(2)	28150.	2815.	1.41	0.216
Residual	34(4)	67697.	1991.		
Total	53(6)	329822.			

***** Tables of means *****

Grand mean 194.2

	Tine	25W	40WNDLi	NSH_D	RetroD	RetroND
		180.7	184.6	162.1	201.2	242.3
	Depth	50.00	75.00	100.00	125.00	
		99.5	173.2	228.1	276.0	
	Tine	Depth	50.00	75.00	100.00	125.00
	25W		104.0	151.6	192.8	274.6
	40WNDLi		77.2	160.5	233.7	267.0
	NSH_D		84.5	166.5	166.3	231.2
	RetroD		135.6	157.5	228.8	283.0
	RetroND		96.0	229.9	319.2	324.1

*** Standard errors of differences of means ***

Table	Tine	Depth	Tine	Depth
rep.	12	15	3	
d.f.	34	34	34	
s.e.d.	18.22	16.29	36.43	

(Not adjusted for missing values)

*** Least significant differences of means ***

Table	Tine	Depth	Tine	Depth
rep.	12	15	3	
d.f.	34	34	34	
l.s.d.	37.02	33.11	74.04	

(Not adjusted for missing values)

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	19.26	9.9
Rep.*Units*	34	44.62	23.0

Variate: Possible Application Rate: 0.25 m Spacing Incl Dip (m²/ha)

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	9494.	4747.	3.73	
Rep.*Units* stratum					
Tine	4	28137.	7034.	5.52	0.002
Depth	3	165663.	55221.	43.33	<.001
Tine.Depth	10(2)	18016.	1802.	1.41	0.216
Residual	34(4)	43326.	1274.		
Total	53(6)	211086.			

***** Tables of means *****

Grand mean 155.4

	Tine	25W	40WNDLi	NSH_D	RetroD	RetroND
		144.6	147.7	129.7	160.9	193.8
	Depth	50.00	75.00	100.00	125.00	
		79.6	138.5	182.5	220.8	
	Tine	Depth	50.00	75.00	100.00	125.00
	25W		83.2	121.3	154.2	219.7
	40WNDLi		61.7	128.4	187.0	213.6
	NSH_D		67.6	133.2	133.0	185.0
	RetroD		108.5	126.0	183.0	226.4
	RetroND		76.8	183.9	255.4	259.2

*** Standard errors of differences of means ***

Table	Tine	Depth	Tine	Depth
rep.	12	15	3	
d.f.	34	34	34	
s.e.d.	14.57	13.03	29.15	

(Not adjusted for missing values)

*** Least significant differences of means ***

Table	Tine	Depth	Tine	Depth
rep.	12	15	3	
d.f.	34	34	34	
l.s.d.	29.62	26.49	59.23	

(Not adjusted for missing values)

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	15.41	9.9
Rep.*Units*	34	35.70	23.0

Variate: Possible Application Rate: 0.2 m Spacing Not Incl. Dip (m²/ha)

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	2147.	1073.	0.60	
Rep.*Units* stratum					
Tine	4	51552.	12888.	7.25	<.001
Depth	3	46846.	15615.	8.79	<.001
Tine.Depth	10(2)	35296.	3530.	1.99	0.067
Residual	34(4)	60408.	1777.		
Total	53(6)	181203.			

***** Tables of means *****

Grand mean 105.2

	Tine	25W	40WNDLi	NSH_D	RetroD	RetroND
		113.1	121.9	52.6	99.2	139.1
	Depth	50.00	75.00	100.00	125.00	
		59.1	113.5	113.7	134.4	
	Tine	Depth	50.00	75.00	100.00	125.00
	25W		71.2	98.0	123.5	159.7
	40WNDLi		60.2	121.7	138.3	167.3
	NSH_D		36.8	114.2	10.9	48.3
	RetroD		66.8	86.1	115.6	128.4
	RetroND		60.2	147.6	180.3	168.3

*** Standard errors of differences of means ***

Table	Tine	Depth	Tine	Depth
rep.	12	15	3	
d.f.	34	34	34	
s.e.d.	17.21	15.39	34.42	

(Not adjusted for missing values)

*** Least significant differences of means ***

Table	Tine	Depth	Tine	Depth
rep.	12	15	3	
d.f.	34	34	34	
l.s.d.	34.97	31.28	69.94	

(Not adjusted for missing values)

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	7.33	7.0
Rep.*Units*	34	42.15	40.1

Variate: Possible Application Rate: 0.25 m Spacing Not Incl. Dip(m²/ha)

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	1374.	687.	0.60	
Rep.*Units* stratum					
Tine	4	32993.	8248.	7.25	<.001
Depth	3	29981.	9994.	8.79	<.001
Tine.Depth	10(2)	22589.	2259.	1.99	0.067
Residual	34(4)	38661.	1137.		
Total	53(6)	115970.			

***** Tables of means *****

Grand mean 84.1

	Tine	25W	40WNDLi	NSH_D	RetroD	RetroND
		90.5	97.5	42.1	79.4	111.3
	Depth	50.00	75.00	100.00	125.00	
		47.3	90.8	91.0	107.5	
	Tine	Depth	50.00	75.00	100.00	125.00
	25W		56.9	78.4	98.8	127.7
	40WNDLi		48.2	97.4	110.7	133.8
	NSH_D		29.5	91.4	8.7	38.7
	RetroD		53.5	68.9	92.5	102.7
	RetroND		48.2	118.1	144.3	134.7

*** Standard errors of differences of means ***

Table	Tine	Depth	Tine	Depth
rep.	12	15	3	
d.f.	34	34	34	
s.e.d.	13.77	12.31	27.53	

(Not adjusted for missing values)

*** Least significant differences of means ***

Table	Tine	Depth	Tine	Depth
rep.	12	15	3	
d.f.	34	34	34	
l.s.d.	27.98	25.02	55.95	

(Not adjusted for missing values)

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	5.86	7.0
Rep.*Units*	34	33.72	40.1

Variate: Relative application efficiency, 0.2 m Incl. Dip.N/(m²/ha)

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	19.292	9.646	1.27	
Rep.*Units* stratum					
Tine	4	790.937	197.734	25.96	<.001
Depth	3	214.657	71.552	9.39	<.001
Tine.Depth	10(2)	112.390	11.239	1.48	0.191
Residual	34(4)	258.992	7.617		
Total	53(6)	1386.819			

***** Tables of means *****

Grand mean 6.55

Tine	25W	40WNDLi	NSH_D	RetroD	RetroND
	4.15	6.97	13.33	5.23	3.06
Depth	50.00	75.00	100.00	125.00	
	4.65	4.86	7.51	9.18	
Tine	Depth	50.00	75.00	100.00	125.00
25W		2.20	3.20	5.42	5.79
40WNDLi		7.74	5.42	6.62	8.11
NSH_D		9.16	9.25	16.46	18.46
RetroD		2.57	4.66	5.85	7.87
RetroND		1.58	1.77	3.19	5.69

*** Standard errors of differences of means ***

Table	Tine	Depth	Tine Depth
rep.	12	15	3
d.f.	34	34	34
s.e.d.	1.127	1.008	2.254

(Not adjusted for missing values)

*** Least significant differences of means ***

Table	Tine	Depth	Tine Depth
rep.	12	15	3
d.f.	34	34	34
l.s.d.	2.290	2.048	4.580

(Not adjusted for missing values)

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	0.694	10.6
Rep.*Units*	34	2.760	42.1

Variate: Relative application efficiency, 0.25 m Incl. Dip.N/(m²/ha)

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	30.14	15.07	1.27	
Rep.*Units* stratum					
Tine	4	1235.89	308.97	25.96	<.001
Depth	3	335.39	111.80	9.39	<.001
Tine.Depth	10(2)	175.60	17.56	1.48	0.191
Residual	34(4)	404.68	11.90		
Total	53(6)	2166.94			

***** Tables of means *****

Grand mean 8.19

Tine	25W	40WNDLi	NSH_D	RetroD	RetroND
	5.19	8.72	16.67	6.54	3.82
Depth	50.00	75.00	100.00	125.00	
	5.81	6.08	9.39	11.48	
Tine	Depth	50.00	75.00	100.00	125.00
25W		2.74	4.00	6.77	7.24
40WNDLi		9.68	6.78	8.28	10.13
NSH_D		11.46	11.97	20.58	23.07
RetroD		3.21	5.82	7.31	9.83
RetroND		1.97	2.21	3.99	7.11

*** Standard errors of differences of means ***

Table	Tine	Depth	Tine Depth
rep.	12	15	3
d.f.	34	34	34
s.e.d.	1.408	1.260	2.817

(Not adjusted for missing values)

*** Least significant differences of means ***

Table	Tine	Depth	Tine Depth
rep.	12	15	3
d.f.	34	34	34
l.s.d.	2.862	2.560	5.729

(Not adjusted for missing values)

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	0.868	10.6
Rep.*Units*	34	3.450	42.1

Variate: Relative application efficiency, 0.2 m Not Incl. Dip.N/(m²/ha)

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	14.63	7.31	0.14	
Rep.*Units* stratum					
Tine	4	30025.00	7506.25	139.07	<.001
Depth	3	15903.64	5301.21	98.22	<.001
Tine.Depth	10(2)	44432.91	4443.29	82.32	<.001
Residual	31(7)	1673.17	53.97		
Total	50(9)	60501.81			

***** Tables of means *****

Grand mean 16.91

Tine	25W	40WNDLi	NSH_D	RetroD	RetroND
	6.73	10.51	61.13	6.23	-0.06
Depth	50.00	75.00	100.00	125.00	
	10.06	7.65	44.94	4.98	
Tine	Depth	50.00	75.00	100.00	125.00
25W		3.37	5.28	8.73	9.53
40WNDLi		10.58	7.17	11.50	12.78
NSH_D		27.67	14.40	182.16	20.30
RetroD		5.41	8.71	16.50	-5.70
RetroND		3.28	2.70	5.78	-11.99

*** Standard errors of differences of means ***

Table	Tine	Depth	Tine Depth
rep.	12	15	3
d.f.	31	31	31
s.e.d.	2.999	2.683	5.999

(Not adjusted for missing values)

*** Least significant differences of means ***

Table	Tine	Depth	Tine Depth
rep.	12	15	3
d.f.	31	31	31
l.s.d.	6.117	5.471	12.234

(Not adjusted for missing values)

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	0.605	3.6
Rep.*Units*	31	7.347	43.4

Variate: Relative application efficiency, 0.25 m Not Incl. Dip. N/(m²/ha)

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	22.86	11.43	0.14	
Rep.*Units* stratum					
Tine	4	46914.37	11728.59	139.07	<.001
Depth	3	24849.42	8283.14	98.22	<.001
Tine.Depth	10(2)	69426.01	6942.60	82.32	<.001
Residual	31(7)	2614.34	84.33		
Total	50(9)	94534.02			

***** Tables of means *****

Grand mean 21.1

Tine	25W	40WNDLi	NSH_D	RetroD	RetroND
	8.4	13.1	76.4	7.8	-0.1
Depth	50.00	75.00	100.00	125.00	
	12.6	9.6	56.2	6.2	
Tine	Depth	50.00	75.00	100.00	125.00
25W		4.2	6.6	10.9	11.9
40WNDLi		13.2	9.0	14.4	16.0
NSH_D		34.6	18.0	227.7	25.4
RetroD		6.8	10.9	20.6	-7.1
RetroND		4.1	3.4	7.2	-15.0

*** Standard errors of differences of means ***

Table	Tine	Depth	Tine Depth
rep.	12	15	3
d.f.	31	31	31
s.e.d.	3.75	3.35	7.50

(Not adjusted for missing values)

*** Least significant differences of means ***

Table	Tine	Depth	Tine Depth
rep.	12	15	3
d.f.	31	31	31
l.s.d.	7.65	6.84	15.29

(Not adjusted for missing values)

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	0.76	3.6
Rep.*Units*	31	9.18	43.4

Polynomial Regression
NSH Drought

$$Y = -2.7E-02 + 5.01E-03X + 2.09E-04X^2$$

$$R-Sq = 0.976$$

Analysis of Variance

SOURCE	DF	SS	MS	F	P
Regression	2	28.0553	14.0277	240.177	2.10E-10
Error	12	0.7009	0.0584		
Total	14	28.7562			

SOURCE	DF	Seq SS	F	P
Linear	1	26.1759	131.880	3.53E-08
Quadratic	1	1.8794	32.1787	1.04E-04

Polynomial Regression
40WNDLI Draught

$$Y = 6.02E-03 + 5.92E-03X + 8.90E-05X^{**2}$$

$$R-Sq = 0.974$$

Analysis of Variance

SOURCE	DF	SS	MS	F	P
Regression	2	8.22985	4.11493	224.009	3.15E-10
Error	12	0.22043	0.01837		
Total	14	8.45029			

SOURCE	DF	Seq SS	F	P
Linear	1	7.88922	182.793	4.94E-09
Quadratic	1	0.34064	18.5437	1.02E-03

Polynomial Regression
25W Draught

$$Y = -4.5E-03 - 3.67E-04X + 9.77E-05X^{**2}$$

$$R-Sq = 0.965$$

Analysis of Variance

SOURCE	DF	SS	MS	F	P
Regression	2	4.17901	2.08950	164.047	1.93E-09
Error	12	0.15285	0.01274		
Total	14	4.33186			

SOURCE	DF	Seq SS	F	P
Linear	1	3.76811	86.8919	4.04E-07
Quadratic	1	0.41090	32.2600	1.02E-04

Polynomial Regression
Retro ND Draught

$$Y = 2.88E-03 - 4.52E-03X + 1.34E-04X^{**2}$$

$$R-Sq = 0.847$$

Analysis of Variance

SOURCE	DF	SS	MS	F	P
Regression	2	1.43436	0.717178	24.9725	2.12E-04
Error	9	0.25847	0.028719		
Total	11	1.69283			

SOURCE	DF	Seq SS	F	P
Linear	1	1.16815	22.2642	8.18E-04
Quadratic	1	0.26621	9.26950	1.39E-02

Polynomial Regression
Retro Disc Draught

$$Y = 2.60E-03 - 1.81E-04X + 1.35E-04X^{**2}$$

$$R-Sq = 0.922$$

Analysis of Variance

SOURCE	DF	SS	MS	F	P
Regression	2	2.87805	1.48902	52.8603	1.06E-05
Error	9	0.25352	0.02817		
Total	11	3.23157			

SOURCE	DF	Seq SS	F	P
Linear	1	2.70900	51.8400	2.93E-05
Quadratic	1	0.26905	9.55120	1.29E-02

Polynomial Regression
Slipper Draught

$$Y = -4.6E-03 + 8.23E-03X + 8.48E-05X^{**2}$$

$$R-Sq = 0.958$$

Analysis of Variance

SOURCE	DF	SS	MS	F	P
Regression	2	9.9653	4.98263	138.272	5.17E-09
Error	12	0.4324	0.03604		
Total	14	10.3977			

SOURCE	DF	Seq SS	F	P
Linear	1	9.65627	169.315	7.87E-09
Quadratic	1	0.30899	8.57472	1.26E-02

Polynomial Regression
NSH Vertical

$$Y = -5.7E-02 + 9.59E-03X + 1.15E-04X^{**2}$$

$$R-Sq = 0.957$$

Analysis of Variance

SOURCE	DF	SS	MS	F	P
Regression	2	16.2730	8.13652	134.513	6.06E-09
Error	12	0.7259	0.06049		
Total	14	16.9989			

SOURCE	DF	Seq SS	F	P
Linear	1	15.6999	157.121	1.24E-08
Quadratic	1	0.5731	9.47492	9.57E-03

Polynomial Regression
40WNDLI Vertical

$$Y = 1.11E-02 + 6.37E-03X - 2.02E-05X^{**2}$$

$$R-Sq = 0.857$$

Analysis of Variance

SOURCE	DF	SS	MS	F	P
Regression	2	0.437421	0.218711	35.9092	8.61E-06
Error	12	0.073088	0.006091		
Total	14	0.510509			

SOURCE	DF	Seq SS	F	P
Linear	1	0.419896	60.2416	3.11E-06
Quadratic	1	0.017525	2.87733	0.115599

Polynomial Regression
25W Vertical

$$Y = 1.04E-02 - 2.35E-03X + 2.42E-05X^{**2}$$

$$R-Sq = 0.600$$

Analysis of Variance

SOURCE	DF	SS	MS	F	P
Regression	2	3.62E-02	1.81E-02	8.98148	4.13E-03
Error	12	2.42E-02	2.02E-03		
Total	14	6.04E-02			

SOURCE	DF	Seq SS	F	P
Linear	1	1.09E-02	2.87451	0.113795
Quadratic	1	2.53E-02	12.5373	4.06E-03

Polynomial Regression
Retro ND Vertical

$$Y = 8.79E-04 - 1.24E-03X + 1.18E-05X^{**2}$$

$$R-Sq = 0.270$$

Analysis of Variance

SOURCE	DF	SS	MS	F	P
Regression	2	2.24E-03	1.12E-03	1.66242	0.242983
Error	9	6.05E-03	6.73E-04		
Total	11	8.29E-03			

SOURCE	DF	Seq SS	F	P
Linear	1	2.00E-04	0.247469	0.629618
Quadratic	1	2.04E-03	3.02720	0.115872

Polynomial Regression
Retro Disc Vertical

$$Y = 2.87E-03 + 1.73E-03X + 1.26E-04X^{**2}$$

$$R-Sq = 0.887$$

Analysis of Variance

SOURCE	DF	SS	MS	F	P
Regression	2	3.38615	1.69308	35.1493	5.59E-05
Error	9	0.43351	0.04817		
Total	11	3.81967			

SOURCE	DF	Seq SS	F	P
Linear	1	3.15276	47.2744	4.32E-05
Quadratic	1	0.23339	4.84538	5.52E-02

Polynomial Regression
Slipper Vertical

$$Y = 1.40E-02 + 1.31E-02X + 5.54E-06X^{**2}$$

$$R-Sq = 0.953$$

Analysis of Variance

SOURCE	DF	SS	MS	F	P
Regression	2	5.26053	2.63026	121.114	1.11E-08
Error	12	0.26061	0.02172		
Total	14	5.52114			

SOURCE	DF	Seq SS	F	P
Linear	1	5.25921	261.026	5.50E-10
Quadratic	1	0.00132	6.07E-02	0.809549

One-Way Analysis of Variance

Analysis of Variance for NSH Draught

Analysis of Variance for Non Draght				F	P
Source	DF	SS	MS		
Depth	4	28.1404	7.0351	114.25	0.000
Error	10	0.6158	0.0616		
Total	14	28.7562			

Individual 95% CIs For Mean
Based on Pooled StDev

Level	N	Mean	StDev
0	3	0.0000	0.0000
50	3	0.6493	0.0685
75	3	1.5430	0.2043
100	3	2.6807	0.1524
125	3	3.7990	0.4881

Pooled StDev = 0.2481

0.0	1.2	2.4	3.6
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One-Way Analysis of Variance

Analysis of Variance for 40WNDLI Draught

Source	DF	SS	MS	F	P
Depth	4	8.2615	2.0654	109.42	0.000
Error	10	0.1888	0.0189		
Total	14	8.4503			

Individual 95% CIs For Mean
Based on Pooled StDev

Level	N	Mean	StDev	
0	3	0.0000	0.0000	
50	3	0.5703	0.0420	
75	3	0.8727	0.1271	
100	3	1.5353	0.1588	
125	3	2.1263	0.2263	

Pooled StDev = 0.1374

0.00	0.70	1.40	2.10
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One-Way Analysis of Variance

Analysis of Variance for 25W Draught

Source	DF	SS	MS	F	P
Depth	4	4.2042	1.0511	82.34	0.000
Error	10	0.1277	0.0128		
Total	14	4.3319			

Individual 95% CIs For Mean

Based on Pooled StDev			
Level	N	Mean	StDev
0	3	0.0000	0.0000
50	3	0.2227	0.0202
75	3	0.4687	0.0535
100	3	1.0080	0.1131
125	3	1.4483	0.2186
Pooled StDev = 0.1130			

One-Way Analysis of Variance

Analysis of Variance for Retro ND Draught					
Source	DF	SS	MS	F	P
Depth	3	1.4371	0.4790	14.99	0.001
Error	8	0.2557	0.0320		
Total	11	1.6928			

Individual 95% CIs For Mean Based on Pooled StDev			
Level	N	Mean	StDev
0	3	0.0000	0.0000
50	3	0.1300	0.0100
75	3	0.3967	0.1484
100	3	0.9033	0.3252
Pooled StDev = 0.1788			

One-Way Analysis of Variance

Analysis of Variance for Retro D Draught					
Source	DF	SS	MS	F	P
Depth	3	2.9803	0.9934	31.63	0.000
Error	8	0.2513	0.0314		
Total	11	3.2316			

Individual 95% CIs For Mean Based on Pooled StDev			
Level	N	Mean	StDev
0	3	0.0000	0.0000
50	3	0.3470	0.0514
75	3	0.7283	0.2728
100	3	1.3437	0.2204
Pooled StDev = 0.1772			

One-Way Analysis of Variance

Analysis of Variance for Slipper Draught					
Source	DF	SS	MS	F	P
Depth	4	9.9744	2.4936	58.91	0.000
Error	10	0.4233	0.0423		
Total	14	10.3977			

Individual 95% CIs For Mean Based on Pooled StDev			
Level	N	Mean	StDev
0	3	0.0000	0.0000
50	3	0.5893	0.1219
75	3	1.1317	0.2068
100	3	1.6470	0.1597
125	3	2.3503	0.3585
Pooled StDev = 0.2057			

One-Way Analysis of Variance

Analysis of Variance for NSH Vertical					
Source	DF	SS	MS	F	P
Depth	4	16.6022	4.1505	104.63	0.000
Error	10	0.3967	0.0397		
Total	14	16.9989			

Individual 95% CIs For Mean Based on Pooled StDev			
Level	N	Mean	StDev
0	3	0.0000	0.0000
50	3	0.4850	0.3030
75	3	1.4230	0.2662
100	3	2.2293	0.1514
125	3	2.8313	0.1130
Pooled StDev = 0.1992			

One-Way Analysis of Variance

Analysis of Variance for 40WNDLi Vertical					
Source	DF	SS	MS	F	P
Depth	4	0.45962	0.11491	22.58	0.000
Error	10	0.05089	0.00509		
Total	14	0.51051			

Individual 95% CIs For Mean Based on Pooled StDev			
Level	N	Mean	StDev
0	3	0.00000	0.00000
50	3	0.33700	0.08030
75	3	0.31367	0.02060
100	3	0.45267	0.11068
125	3	0.50133	0.07951
Pooled StDev = 0.07134			

One-Way Analysis of Variance

Analysis of Variance for 25W Vertical					
Source	DF	SS	MS	F	P
Depth	4	0.04876	0.01219	10.45	0.001
Error	10	0.01166	0.00117		
Total	14	0.06043			

Individual 95% CIs For Mean Based on Pooled StDev			
Level	N	Mean	StDev
0	3	0.00000	0.00000
50	3	-0.00933	0.00808
75	3	-0.03733	0.01617
100	3	-0.02700	0.00000
125	3	0.12033	0.07419
Pooled StDev = 0.03415			

One-Way Analysis of Variance

Analysis of Variance for Retro ND Vertical					
Source	DF	SS	MS	F	P
Depth	3	0.002492	0.000831	1.15	0.388
Error	8	0.005800	0.000725		
Total	11	0.008292			

Individual 95% CIs For Mean Based on Pooled StDev			
Level	N	Mean	StDev
0	3	0.00000	0.00000
50	3	-0.02667	0.01528
75	3	-0.03333	0.02082
100	3	-0.00333	0.04726
Pooled StDev = 0.02693			

One-Way Analysis of Variance

Analysis of Variance for Retro D Vertical					
Source	DF	SS	MS	F	P
Depth	3	3.3889	1.1296	20.98	0.000
Error	8	0.4308	0.0539		
Total	11	3.8197			

Individual 95% CIs For Mean Based on Pooled StDev			
Level	N	Mean	StDev
0	3	0.0000	0.0000
50	3	0.4210	0.0550
75	3	0.8173	0.3955
100	3	1.4427	0.2366
Pooled StDev = 0.2321			

One-Way Analysis of Variance

Analysis of Variance for Slipper Vertical					
Source	DF	SS	MS	F	P
Depth	4	5.2810	1.3203	54.98	0.000
Error	10	0.2401	0.0240		
Total	14	5.5211			

Individual 95% CIs For Mean Based on Pooled StDev			
Level	N	Mean	StDev
0	3	0.0000	0.0000
50	3	0.7353	0.0670
75	3	1.0063	0.0770
100	3	1.3283	0.0445
125	3	1.7667	0.3282
Pooled StDev = 0.1550			

Appendix 2.4.

Soil disturbance profiles (improved injector evaluation).

40WNDLi Injector tine.

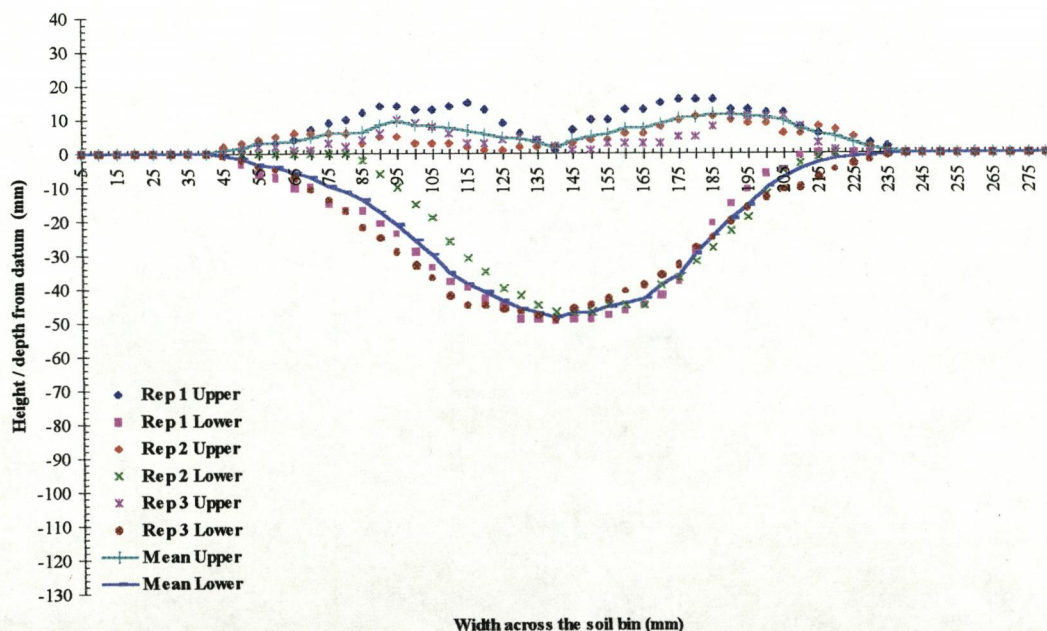


Fig. Ap 2.4.1a. Soil disturbance profiles for the 40WNDLi injector tine operating at 0.05m depth.

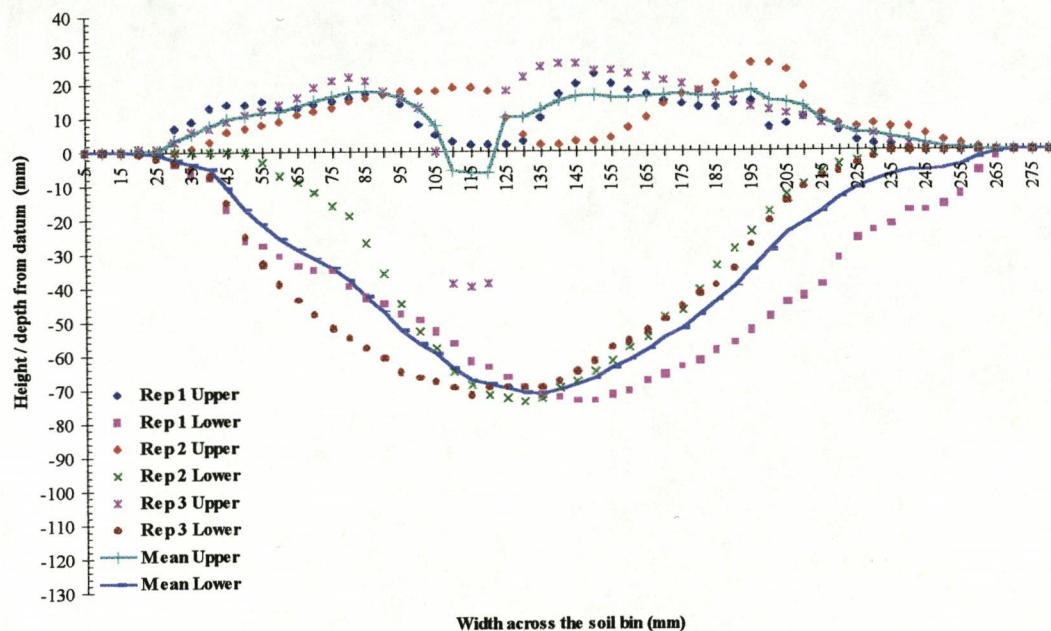


Fig. Ap 2.4.1b. Soil disturbance profiles for the 40WNDLi injector tine operating at 0.075m depth.

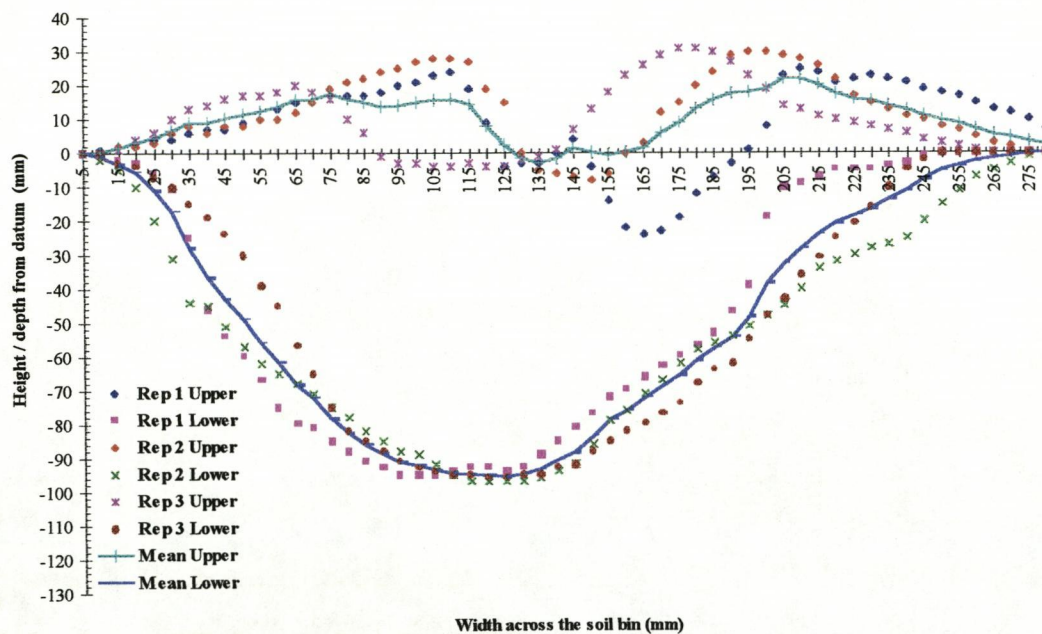


Fig. Ap 2.4.1c. Soil disturbance profiles for the 40WNDLi injector tine operating at 0.1 m depth.

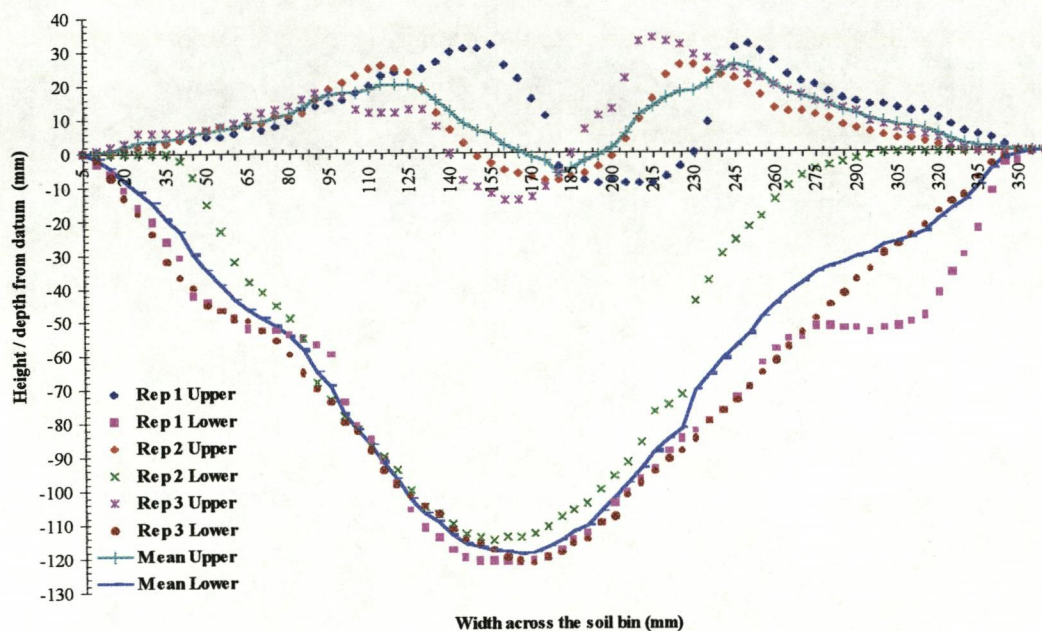


Fig. Ap 2.4.1d. Soil disturbance profiles for the 40WNDLi injector tine operating at 0.125 m depth.

Retrofit injector without disc.

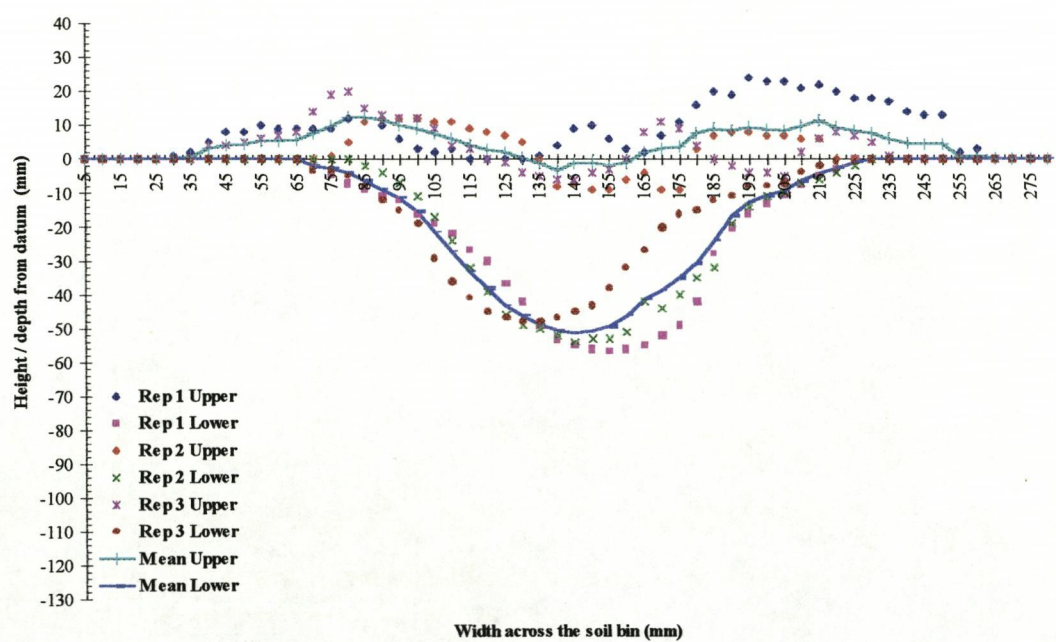


Fig. Ap 2.4.2a. Soil disturbance profiles for the Retro ND injector tine operating at 0.05 m depth.

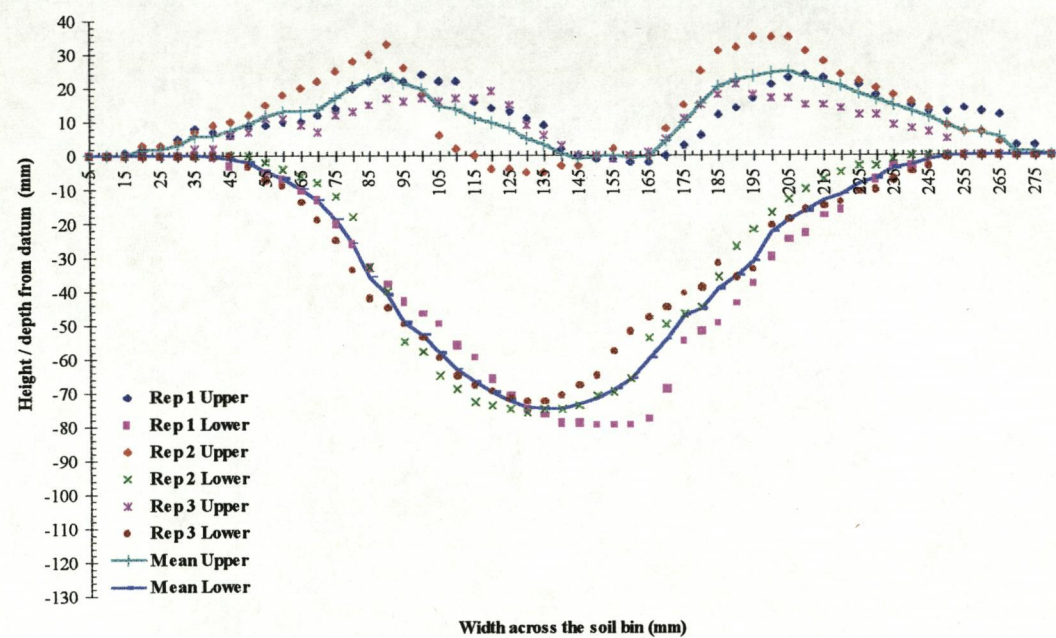


Fig. Ap 2.4.2b. Soil disturbance profiles for the Retro ND injector tine operating at 0.075 m depth.

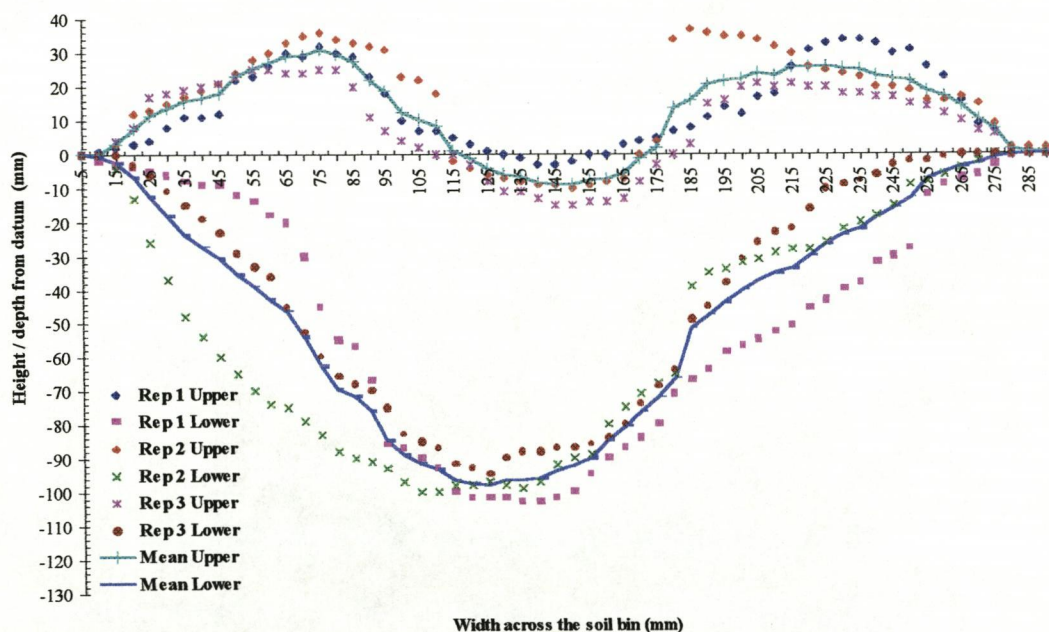


Fig. Ap 2.4.2c. Soil disturbance profiles for the Retro ND injector tine operating at 0.1 m depth.

Retrofit injector and disc.

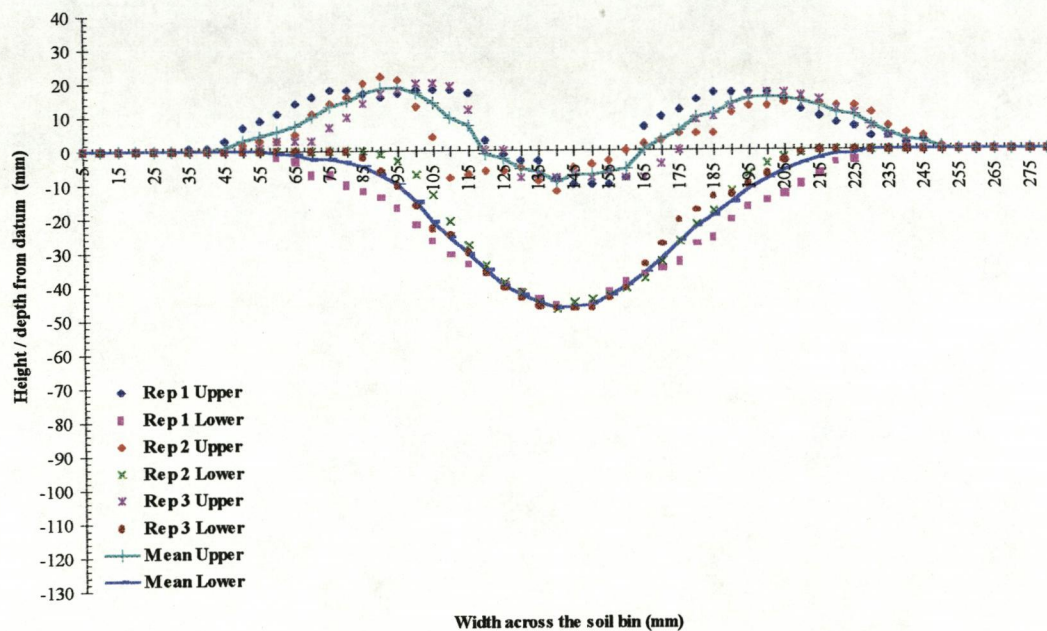


Fig. Ap 2.4.3a. Soil disturbance profiles for the Retro injector tine and disc operating at 0.05 m depth.

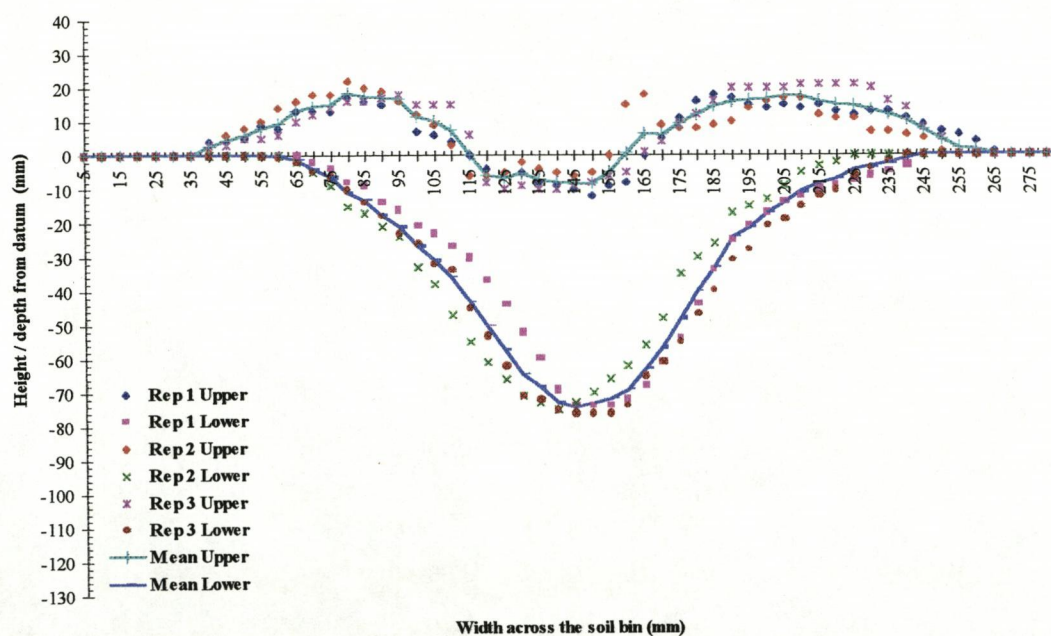


Fig. Ap 2.4.3b. Soil disturbance profiles for the Retro injector tine and disc operating at 0.075 m depth.

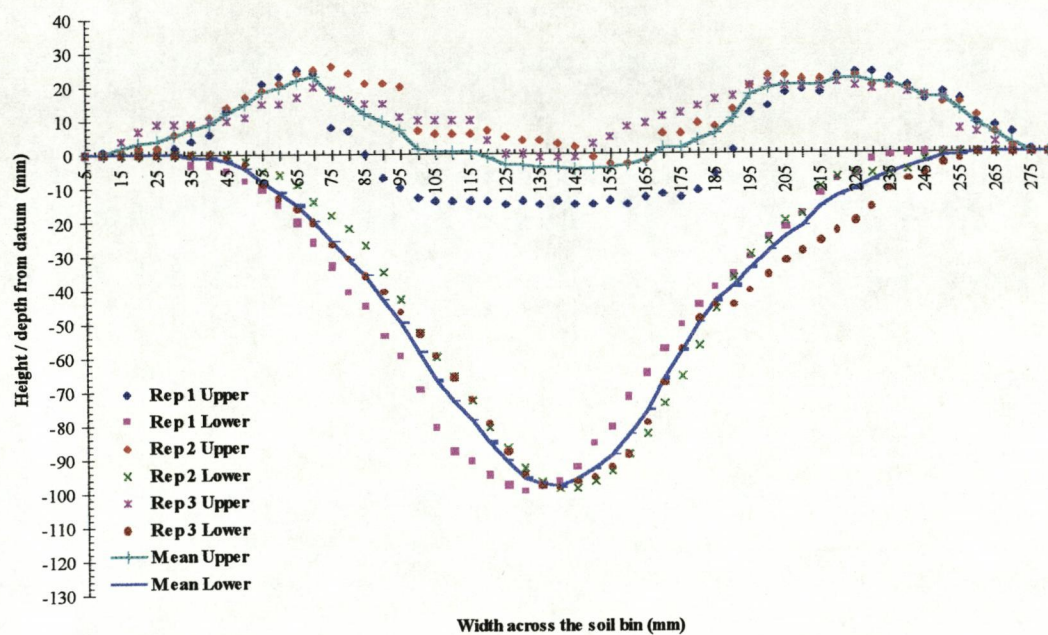


Fig. Ap 2.4.3c. Soil disturbance profiles for the Retro injector tine and disc operating at 0.1 m depth.

25W Injector tine.

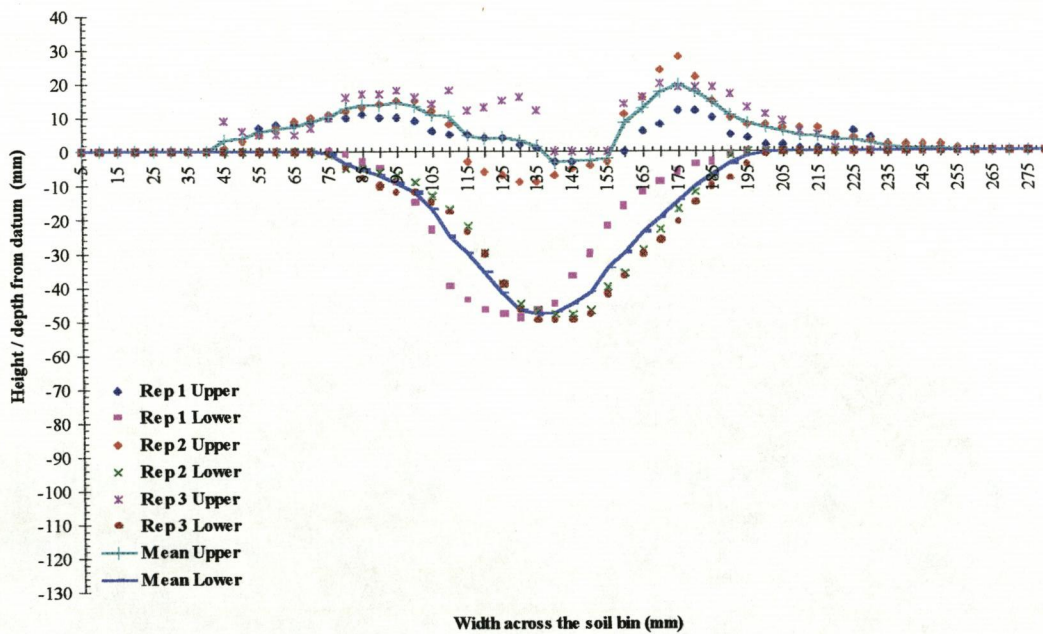


Fig. Ap 2.4.4a. Soil disturbance profiles for 25W injector tine operating at 0.05 m depth.

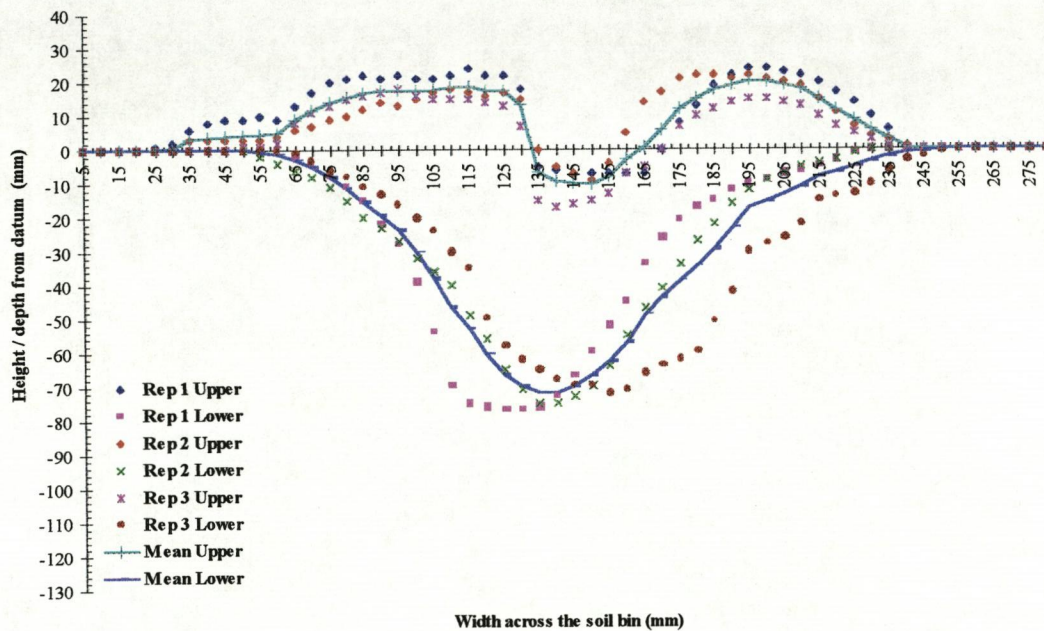


Fig. Ap 2.4.4b. Soil disturbance profiles for 25W injector tine operating at 0.075 m depth.

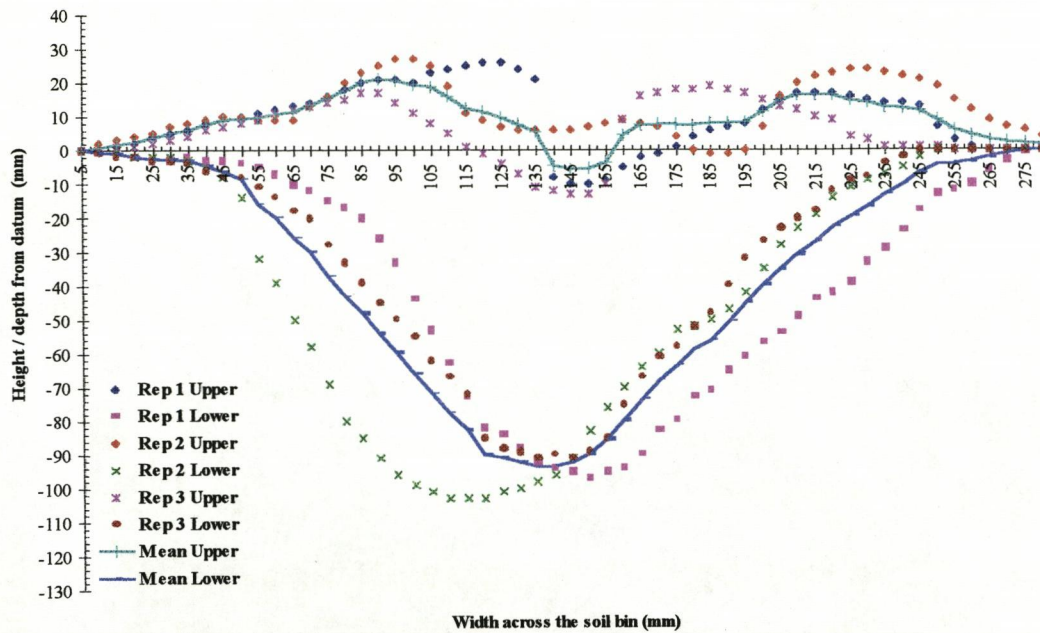


Fig. Ap 2.4.4c. Soil disturbance profiles for 25W injector tine operating at 0.1 m depth.

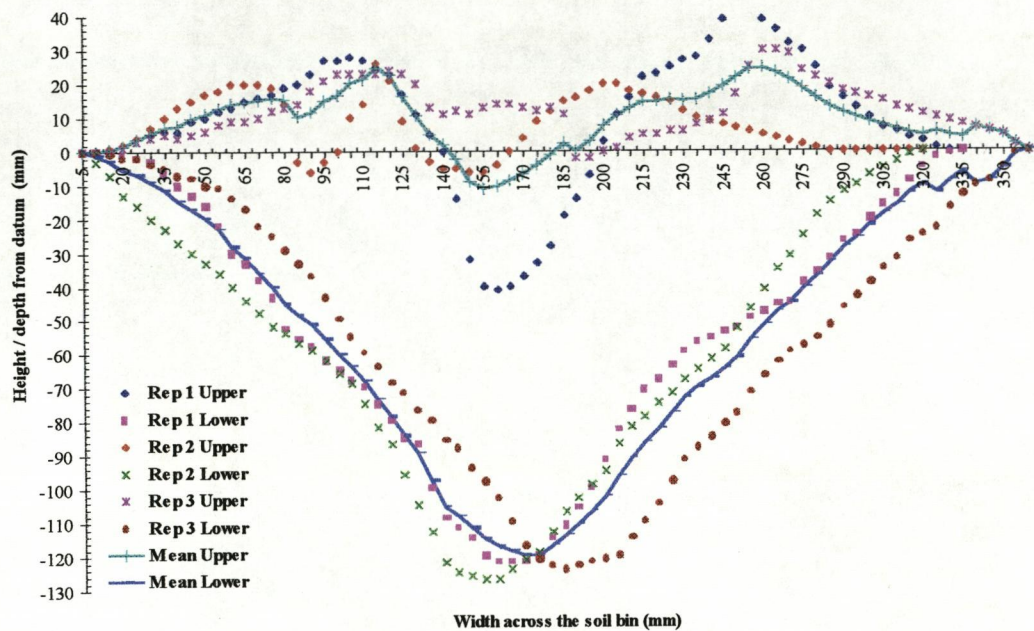


Fig. Ap 2.4.4d. Soil disturbance profiles for 25W injector tine operating at 0.125 m depth.

Greentrac NSH injector tine.

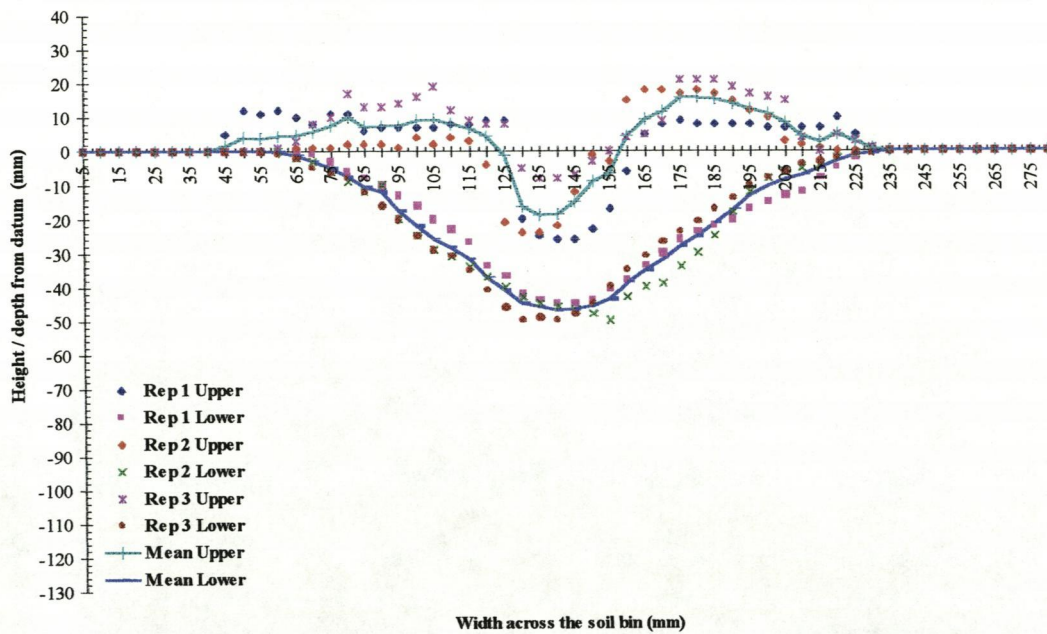


Fig. Ap 2.4.5a. Soil disturbance profiles for NSH injector tine operating at 0.05 m depth.

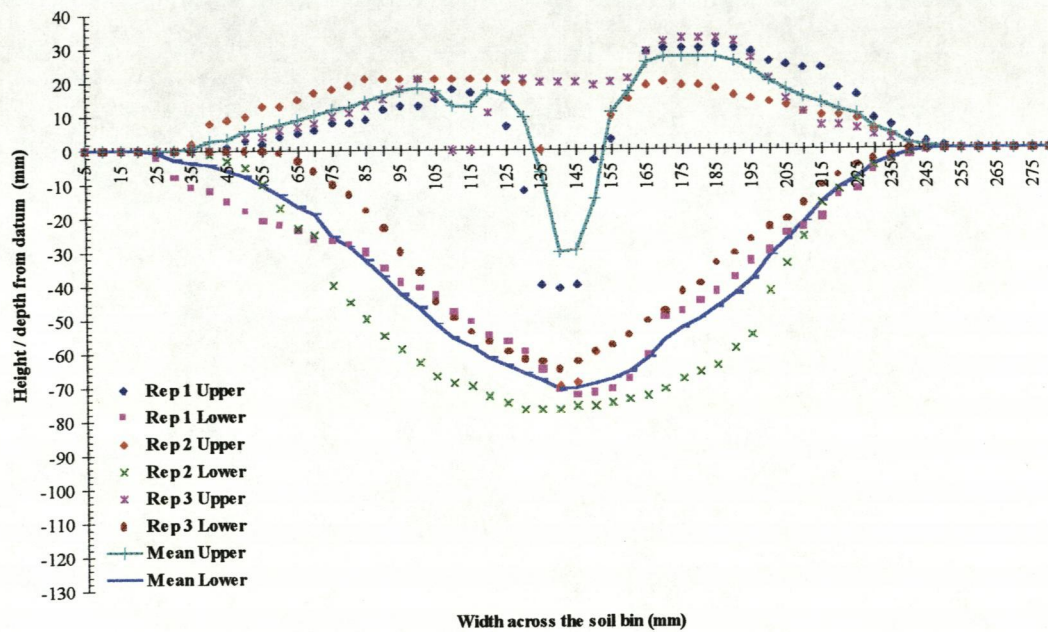


Fig. Ap 2.4.5b. Soil disturbance profiles for NSH injector tine operating at 0.075 m depth.

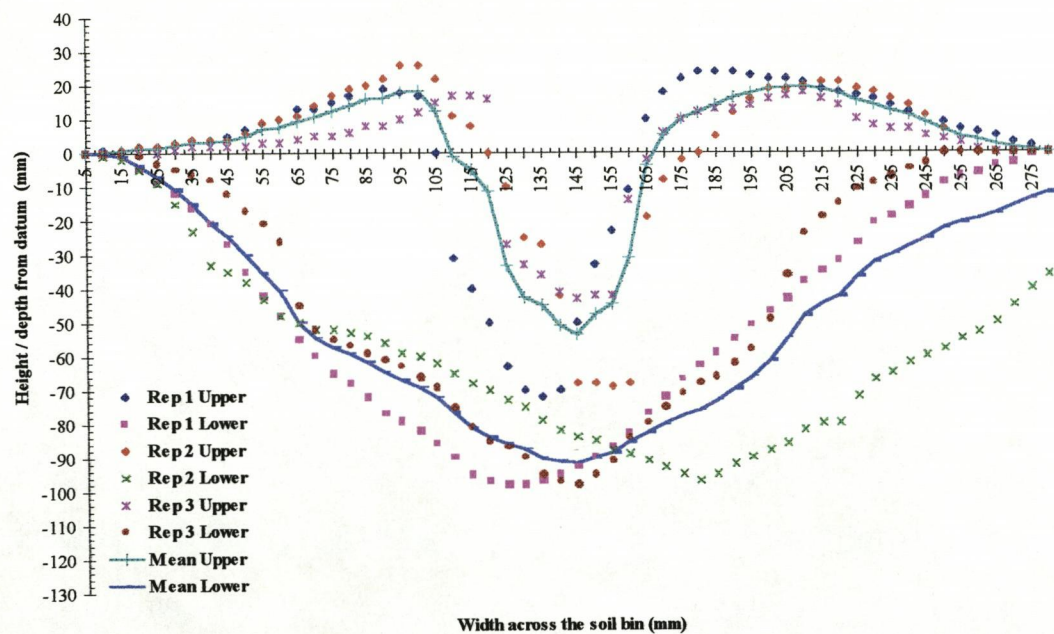


Fig. Ap 2.4.5c. Soil disturbance profiles for NSH injector tine operating at 0.1 m depth.

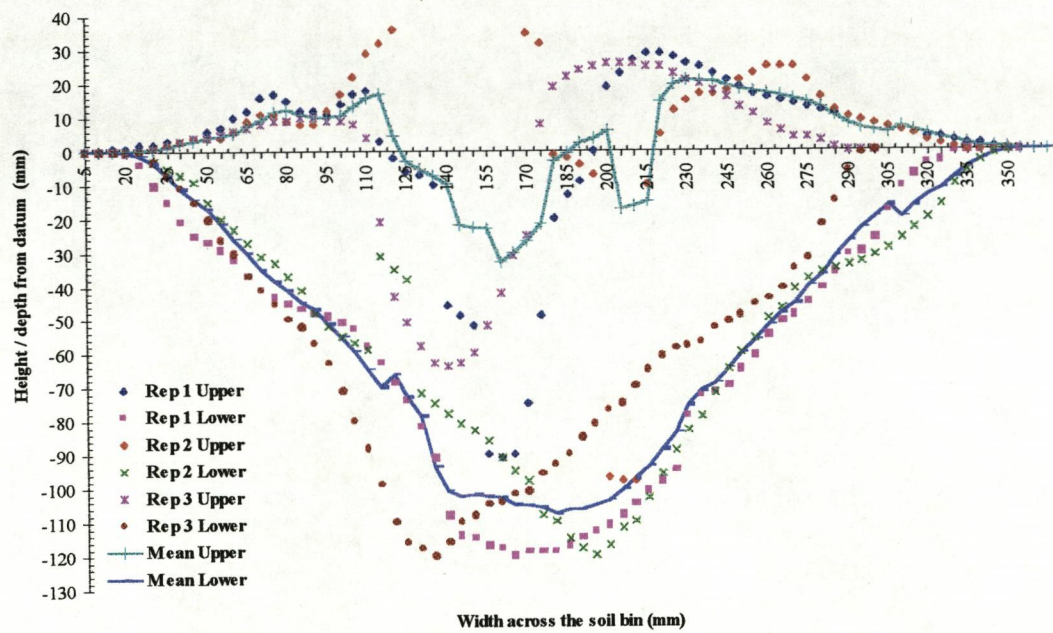


Fig. Ap 2.4.5d. Soil disturbance profiles for NSH injector tine operating at 0.125 m depth.

Appendix 3

Appendix 3.1.

Ultraviolet spectrophotometric screening method

This technique is only used for screening samples that have low organic matter contents. The NO_3^- calibration follows Beer's law up to 11 mg N/l. Measurement of UV absorption at 220 nm enables rapid determination of NO_3^- concentration. Because dissolved organic matter may also absorb at 220nm and NO_3^- does not absorb at 275 nm, a second measurement made at 275 nm may be used to correct for this interference.

Apparatus:

Spectrophotometer, for use at 220 nm and 275 nm with matched silica cells of 1-cm or longer light path.

Reagents:

- a) Nitrate free water: Use distilled or redistilled, deionised water of the highest purity to prepare all solutions and dilutions.
- b) Stock nitrate solution: Dry potassium nitrate (KNO_3) in an oven at 105°C for 24 h. Dissolve 0.7218 g in water and dilute to 1000 ml; 1.00 ml = 100 $\mu\text{g NO}_3^-$ -N.
- c) Intermediate nitrate solution: Dilute 100 ml stock nitrate solution to 1000 ml with water; 1.00 ml = 10.0 $\mu\text{g NO}_3^-$ -N.

Procedure:

- a) Treatment of the sample: To 50 ml clear sample, filtered as necessary, add 1 ml HCl solution and mix thoroughly.
- b) Preparation of the standard curve: Prepare NO_3^- calibration standards in the range 0 – 7 mg NO_3^- -N/l.
- c) Spectrophotometric measurement: Read absorbance and transmittance against distilled water set at zero absorbance. Use a wavelength of 220 nm to obtain NO_3^- reading and a wavelength of 275 nm to determine interference due to dissolved organic matter.

Calculation

For samples and standards, subtract two times the absorbance reading at 275 nm from the reading at 220 nm to obtain the absorbance due to NO_3^- . Construct a standard curve by plotting absorbance due to NO_3^- against NO_3^- -N concentration of standard. Obtain sample concentrations from the standard curve.

Appendix 3.2.

Statistical analysis of odour concentrations and ammonia volatilisation.

Odour concentration (December 1996, 5 min)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
blocks stratum	2	5281.	2641.	0.96	
blocks.injector stratum					
injector	3	16843.	5614.	2.04	0.210
Residual	6	16548.	2758.		
Total	11	38672.			

***** Tables of means *****

Variate: odour

Grand mean 99.

injector	control	surface	slipper	improved
	89.	117.	44.	145.

*** Standard errors of differences of means ***

Table	injector
rep.	3
d.f.	6
s.e.d.	42.9

***** Stratum standard errors and coefficients of variation *****

Variate: odour

Stratum	d.f.	s.e.	cv%
blocks	2	25.7	26.1
blocks.injector	6	52.5	53.3

Odour concentration (December 1996, 24 hr)

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F pr.
blocks stratum	2	296.0	148.0	0.20	
blocks.injector stratum					
injector	3	618.4	206.1	0.27	0.844
Residual	5(1)	3791.3	758.3		
Total	10(1)	4698.4			

***** Tables of means *****

Variate: odour

Grand mean 64.3

injector	control	surface	slipper	improved
	75.8	56.7	64.5	60.1

Appendix 3.2

*** Standard errors of differences of means ***

Table	injector
rep.	3
d.f.	5
s.e.d.	22.48

(Not adjusted for missing values)

***** Stratum standard errors and coefficients of variation *****

Variate: odour

Stratum	d.f.	s.e.	cv%
blocks	2	6.08	9.5
blocks.injector	5	27.54	42.8

Variate: Odour concentration (May 1997, 5 min)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
blocks stratum	2	11253.	5626.	0.90	
blocks.injector stratum					
injector	2	41178.	20589.	3.29	0.143
Residual	4	25032.	6258.		
Total	8	77463.			

***** Tables of means *****

Variate: odour

Grand mean 199.

injector	control	surface	slipper	improved
	259.	232.	104.	

*** Standard errors of differences of means ***

Table	injector
rep.	3
d.f.	4
s.e.d.	64.6

***** Stratum standard errors and coefficients of variation *****

Variate: odour

Stratum	d.f.	s.e.	cv%
blocks	2	43.3	21.8
blocks.injector	4	79.1	39.8

21.....

Odour concentration (May 1997, 24 hr)

Source of variation	d.f. (m.v.)	s.s.	m.s.	v.r.	F pr.
blocks stratum	2	543.	271.	0.09	
blocks.injector stratum					
injector	2	255.	127.	0.04	0.960
Residual	2(2)	6170.	3085.		
Total	6(2)	6948.			

Appendix 3.2

***** Tables of means *****

Variate: odour

Grand mean 57.

injector	control	surface	slipper improved
	57.	63.	50.

*** Standard errors of differences of means ***

Table	injector
rep.	3
d.f.	2
s.e.d.	45.4

(Not adjusted for missing values)

***** Stratum standard errors and coefficients of variation *****

Variate: odour

Stratum	d.f.	s.e.	cv%
blocks	2	9.5	16.8
blocks.injector	2	55.5	98.2

Ammonia volatilisation (December 1996)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
blocks stratum	2	63216.	31608.	0.37	
blocks.injector stratum					
injector	3	791360.	263787.	3.09	0.111
Residual	6	511961.	85327.		
Total	11	1366537.			

***** Tables of means *****

Variate: ammonia

Grand mean 270.

injector	surface	slipper improved	control
	607.	422.	89. -37.

*** Least significant differences of means ***

Table	injector
rep.	3
d.f.	6
l.s.d.	583.6

***** Stratum standard errors and coefficients of variation *****

Variate: ammonia

Stratum	d.f.	s.e.	cv%
blocks	2	88.9	32.9
blocks.injector	6	292.1	108.0

Ammonia volatilisation (May 1997)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
blocks stratum	2	38120.	19060.	0.27	
blocks.injector stratum					
injector	3	2552310.	850770.	12.10	0.006
Residual	6	421992.	70332.		
Total	11	3012422.			

***** Tables of means *****

Variate: ammonia

Grand mean 449.

injector	surface	slipper	improved	control
	1232.	336.	134.	95.

*** Least significant differences of means ***

Table	injector
rep.	3
d.f.	6
l.s.d.	529.8

***** Stratum standard errors and coefficients of variation *****

Variate: ammonia

Stratum	d.f.	s.e.	cv%
blocks	2	69.0	15.4
blocks.injector	6	265.2	59.0

Parallel Curve Analysis - Control vs Improved

Response variate: data
Explanatory: time
Fitted Curve: $A + B \cdot R^{**X}$
Constraints: $R < 1$

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	82109.	41055.	12.51	<.001
Residual	45	147677.	3282.		
Total	47	229786.	4889.		
Change	2	-82109.	-41055.	-12.51	<.001

Percentage variance accounted for 32.9
Standard error of observations is estimated to be 57.3

*** Estimates of parameters ***

	estimate	s.e.
R	0.9927	0.0168
B	-249.	423.
A	244.	430.

Appendix 3.2

*** Correlations between parameter estimates ***

estimate	ref	correlations		
R	1	1.000		
B	2	-0.993	1.000	
A	3	0.995	-1.000	1.000
		1	2	3

***** Nonlinear regression analysis *****

Response variate: data
Explanatory: time
Grouping factor: types, constant parameters separate
Fitted Curve: A + B*R**X
Constraints: R > 1

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	3	84531.	28177.	8.54	<.001
Residual	44	145255.	3301.		
Total	47	229786.	4889.		

Change 1 -2422. -2422. -0.73 <.001

Percentage variance accounted for 32.5
Standard error of observations is estimated to be 57.5

*** Estimates of parameters ***

	estimate	s.e.
R	0.9927	0.0117
B	-247.1	
A types control	244.4	
A types improved	230.2	

*** Correlations between parameter estimates ***

estimate	ref	correlations
R	1	1.000
		1

*** Accumulated analysis of variance ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Change					
+ time	2	82109.	41055.	12.44	<.001
+ types	1	2422.	2422.	0.73	0.396
Residual	44	145255.	3301.		
Total	47	229786.	4889.		

***** Nonlinear regression analysis *****

Response variate: data
Explanatory: time
Grouping factor: types, all linear parameters separate
Fitted Curve: A + B*R**X
Constraints: R > 1

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	4	85894.	21473.	6.42	<.001
Residual	43	143892.	3346.		
Total	47	229786.	4889.		

Change 1 -1363. -1363. -0.41 <.001

Percentage variance accounted for 31.6
Standard error of observations is estimated to be 57.8

Appendix 3.2

*** Estimates of parameters ***

	estimate	s.e.
R	0.9956	0.0119
B types control	-320.1	
A types control	330.0	
B types improved	-418.3	
A types improved	402.1	

*** Correlations between parameter estimates ***

estimate	ref	correlations
R	1	1.000
		1

*** Accumulated analysis of variance ***

Change	d.f.	s.s.	m.s.	v.r.	F pr.
+ time	2	82109.	41055.	12.27	<.001
+ types	1	2422.	2422.	0.72	0.400
+ time.types	1	1363.	1363.	0.41	0.527
Residual	43	143892.	3346.		
Total	47	229786.	4889.		

***** Nonlinear regression analysis *****

Response variate: data
Explanatory: time
Grouping factor: types, all parameters separate
Fitted Curve: $A + B \cdot R^{**X}$
Constraints: $R > 1$

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	5	91533.	18307.	5.56	<.001
Residual	42	138253.	3292.		
Total	47	229786.	4889.		
Change	1	-5640.	-5640.	-1.71	<.001

Percentage variance accounted for 32.7
Standard error of observations is estimated to be 57.4

*** Estimates of parameters ***

	estimate	s.e.
R types control	0.9656	0.0363
B types control	-105.9	40.9
A types control	102.4	40.7
R types improved	1.0109	0.0207
B types improved	88.	256.
A types improved	-97.	268.

*** Correlations between parameter estimates ***

estimate	ref	correlations
R types control	1	1.000
B types control	2	-0.600 1.000
A types control	3	0.867 -0.846 1.000
		1 2 3

estimate	ref	correlations
R types improved	4	1.000
B types improved	5	-0.996 1.000
A types improved	6	0.992 -0.998 1.000
		4 5 6

*** Accumulated analysis of variance ***

Change	d.f.	s.s.	m.s.	v.r.	F pr.
+ time	2	82109.	41055.	12.47	<.001
+ types	1	2422.	2422.	0.74	0.396
+ time.types	1	1363.	1363.	0.41	0.523
+ Separate nonlinear	1	5640.	5640.	1.71	0.198
Residual	42	138253.	3292.		
Total	47	229786.	4889.		

Parallel Curve Analysis - Control vs Slipper Foot

Response variate: data
 Explanatory: time
 Fitted Curve: $A + B \cdot R^{**X}$
 Constraints: $R < 1$

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	281275.	140638.	7.80	0.001
Residual	45	811101.	18024.		
Total	47	1092376.	23242.		

Change	2	-281275.	-140638.	-7.80	<.001
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Percentage variance accounted for 22.4
 Standard error of observations is estimated to be 134.

*** Estimates of parameters ***

	estimate	s.e.
R	0.9941	0.0211
B	-542.	1529.
A	535.	1545.

*** Correlations between parameter estimates ***

estimate	ref	correlations
R	1	1.000
B	2	-0.996 1.000
A	3	0.997 -1.000 1.000
		1 2 3

*** Accumulated analysis of variance ***

Change	d.f.	s.s.	m.s.	v.r.	F pr.
+ time	2	281275.	140638.	7.80	0.001
Residual	45	811101.	18024.		
Total	47	1092376.	23242.		

Response variate: data
 Explanatory: time
 Grouping factor: types, constant parameters separate
 Fitted Curve: $A + B \cdot R^{**X}$
 Constraints: $R > 1$

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	3	320606.	106869.	6.09	0.001
Residual	44	771770.	17540.		
Total	47	1092376.	23242.		

Change	1	-39331.	-39331.	-2.24	<.001
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Percentage variance accounted for 24.5
 Standard error of observations is estimated to be 132.

*** Estimates of parameters ***

	estimate	s.e.
R	0.9941	0.0148
B	-538.5	
A types control	504.0	
A types slipper	561.2	

*** Correlations between parameter estimates ***

estimate	ref	correlations
R	1	1.000
		1

*** Accumulated analysis of variance ***

Change	d.f.	s.s.	m.s.	v.r.	F pr.
+ time	2	281275.	140638.	8.02	0.001
+ types	1	39331.	39331.	2.24	0.141
Residual	44	771770.	17540.		
Total	47	1092376.	23242.		

Response variate: data
Explanatory: time
Grouping factor: types, all linear parameters separate
Fitted Curve: $A + B \cdot R \cdot X$
Constraints: $R > 1$

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	4	400860.	100215.	6.23	<.001
Residual	43	691516.	16082.		
Total	47	1092376.	23242.		
Change	1	-80254.	-80254.	-4.99	<.001

Percentage variance accounted for 30.8
Standard error of observations is estimated to be 127.

*** Estimates of parameters ***

	estimate	s.e.
R	0.9995	0.0124
B types control	-2435.	
A types control	2448.	
B types slipper	-8136.	
A types slipper	8120.	

*** Correlations between parameter estimates ***

estimate	ref	correlations
R	1	1.000
		1

*** Accumulated analysis of variance ***

Change	d.f.	s.s.	m.s.	v.r.	F pr.
+ time	2	281275.	140638.	8.75	<.001
+ types	1	39331.	39331.	2.45	0.125
+ time.types	1	80254.	80254.	4.99	0.031
Residual	43	691516.	16082.		
Total	47	1092376.	23242.		

Appendix 3.2

Response variate: data
Explanatory: time
Grouping factor: types, all parameters separate
Fitted Curve: $A + B \cdot R^{**}X$
Constraints: $R > 1$

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	5	406022.	81204.	4.97	0.001
Residual	42	686354.	16342.		
Total	47	1092376.	23242.		

Change 1 -5162. -5162. -0.32 <.001

Percentage variance accounted for 29.7
Standard error of observations is estimated to be 128.

*** Estimates of parameters ***

	estimate	s.e.
R types control	0.9656	0.0809
B types control	-105.9	91.1
A types control	102.4	90.7
R types slipper	1.0025	0.0182
B types slipper	1371.	10849.
A types slipper	-1383.	10875.

*** Correlations between parameter estimates ***

estimate	ref	correlations		
R types control	1	1.000		
B types control	2	-0.600	1.000	
A types control	3	0.867	-0.846	1.000
		1	2	3

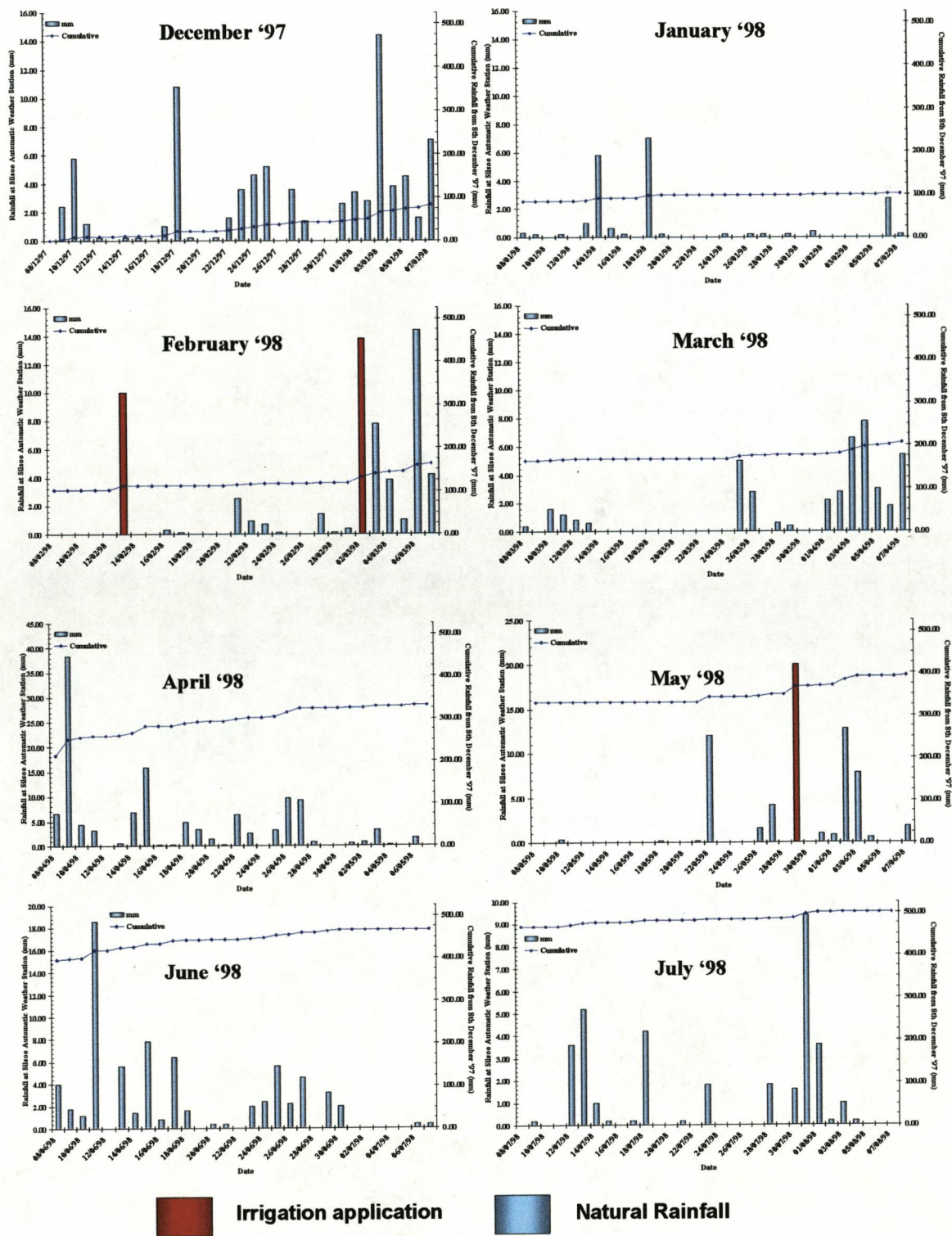
estimate	ref	correlations		
R types slipper	4	1.000		
B types slipper	5	-1.000	1.000	
A types slipper	6	1.000	-1.000	1.000
		4	5	6

*** Accumulated analysis of variance ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Change					
+ time	2	281275.	140638.	8.61	<.001
+ types	1	39331.	39331.	2.41	0.128
+ time.types	1	80254.	80254.	4.91	0.032
+ Separate nonlinear	1	5162.	5162.	0.32	0.577
Residual	42	686354.	16342.		
Total	47	1092376.	23242.		

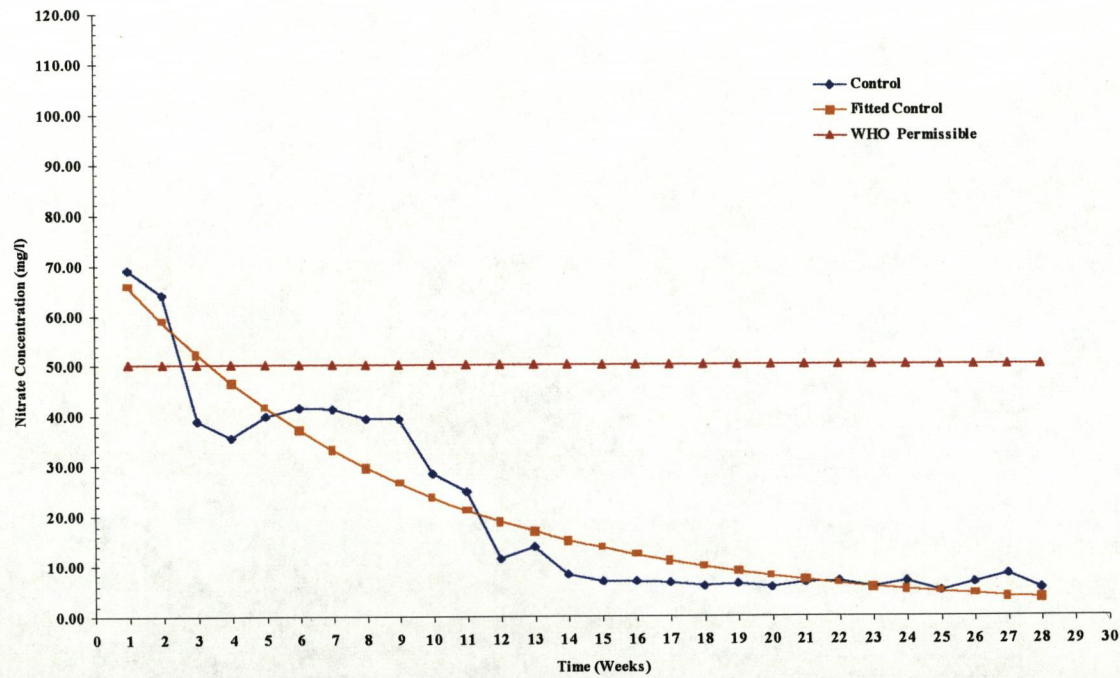
Appendix 3.3.

Climate data

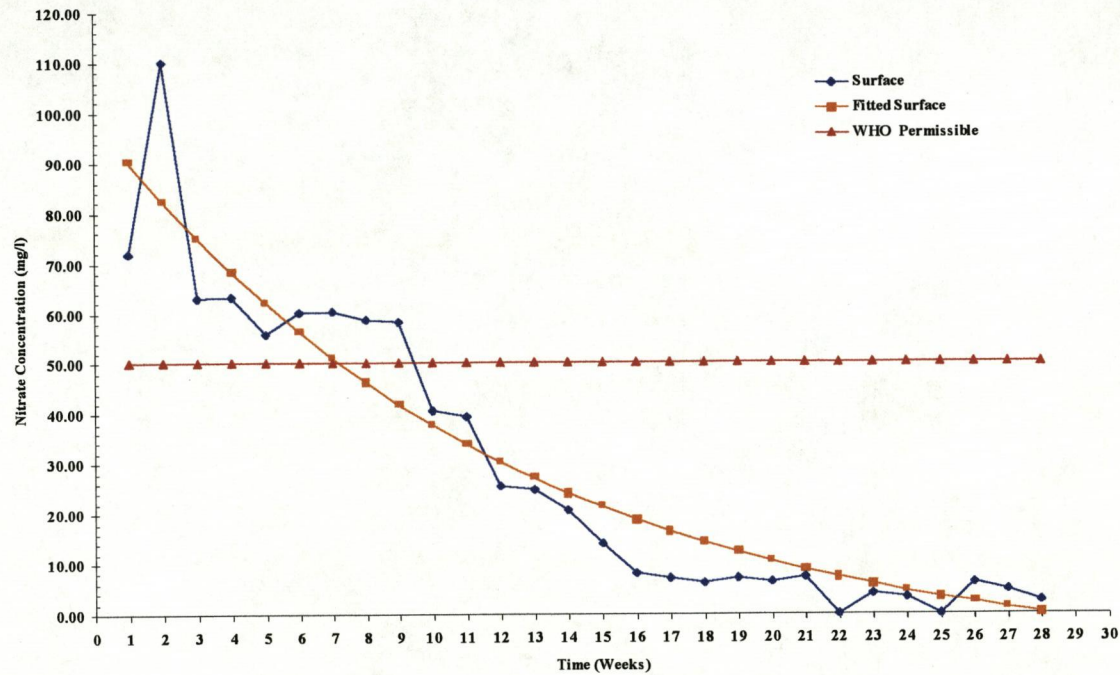


Appendix 3.4.
Nitrate concentration curve fits

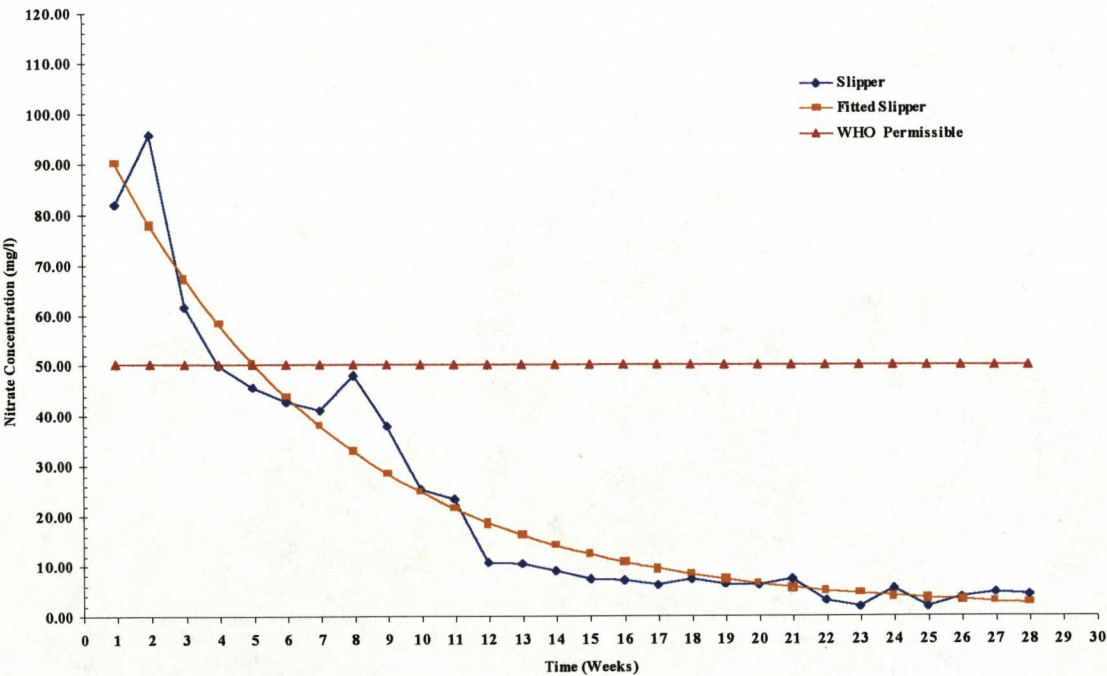
Control:



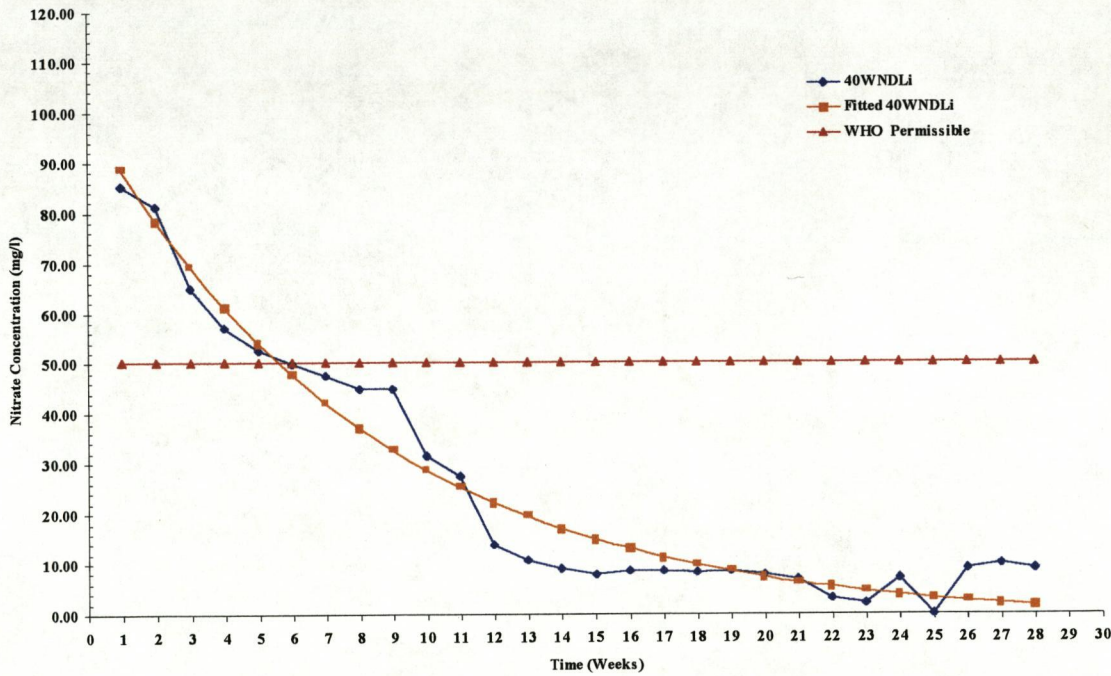
Surface:



Slipper Foot:



40WNDLi:



Appendix 3.5.

Statistical analysis of nitrate trials.

Nitrate concentrations (December 97).

Source of variation	d.f. (m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	7969.6	3984.8	18.16	
Rep.*Units* stratum					
Trt	3	5059.5	1686.5	7.69	<.001
Time	27	184664.7	6839.4	31.17	<.001
Trt.Time	78(3)	6873.2	88.1	0.40	1.000
Residual	194(28)	42569.1	219.4		
Total	304(31)	237120.6			

***** Tables of means *****

Grand mean 25.83

Trt	40WNDLi	Control	Slipper	Surface			
	26.47	21.31	23.76	31.76			
Time	1.00	2.00	3.00	4.00	5.00	6.00	7.00
	76.95	87.64	56.99	51.40	48.38	48.55	47.48
Time	8.00	9.00	10.00	11.00	12.00	13.00	14.00
	47.76	45.16	31.42	28.77	15.43	14.97	11.72
Time	15.00	16.00	17.00	18.00	19.00	20.00	21.00
	9.12	7.70	7.17	6.95	7.19	6.56	7.13
Time	22.00	23.00	24.00	25.00	26.00	27.00	28.00
	9.45	7.66	6.46	8.07	8.44	9.22	9.45
Trt	Time	1.00	2.00	3.00	4.00	5.00	6.00
40WNDLi		76.13	88.53	66.63	60.20	53.65	51.97
Control		68.83	64.03	38.84	35.59	39.94	41.48
Slipper		81.93	95.57	61.43	49.80	45.47	42.73
Surface		80.90	102.43	61.07	60.00	54.47	58.03
Trt	Time	7.00	8.00	9.00	10.00	11.00	12.00
40WNDLi		49.15	45.47	43.23	34.00	26.28	10.68
Control		41.16	39.42	39.43	28.46	24.88	11.51
Slipper		41.00	48.07	38.03	25.23	23.38	10.77
Surface		58.60	58.07	59.93	38.00	40.53	28.73
Trt	Time	13.00	14.00	15.00	16.00	17.00	18.00
40WNDLi		9.62	8.19	7.64	8.23	7.31	6.78
Control		13.76	8.28	7.02	6.90	6.74	5.88
Slipper		10.58	8.96	7.50	7.16	6.14	7.37
Surface		25.92	21.46	14.32	8.48	8.49	7.75
Trt	Time	19.00	20.00	21.00	22.00	23.00	24.00
40WNDLi		7.38	6.58	6.88	10.15	13.39	7.10
Control		6.54	5.73	6.77	6.95	9.38	6.82
Slipper		6.45	6.16	7.38	4.75	1.03	5.41
Surface		8.38	7.77	7.51	15.96	6.83	6.52
Trt	Time	25.00	26.00	27.00	28.00		
40WNDLi		8.83	9.31	8.31	9.65		
Control		8.33	6.58	8.24	9.27		
Slipper		0.99	6.66	7.99	7.44		
Surface		14.11	11.23	12.33	11.42		

*** Standard errors of differences of means ***

Table	Trt	Time	Trt Time
rep.	84	12	3
d.f.	194	194	194
s.e.d.	2.286	6.047	12.095

*** Least significant differences of means ***

Table	Trt	Time	Trt Time
rep.	84	12	3
d.f.	194	194	194
l.s.d.	4.508	11.927	23.854

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	5.965	23.1
Rep.*Units*	194	14.813	57.4

Nitrate concentrations (May 98).

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	201.54	100.77	3.31	
Rep.*Units* stratum					
Trt	3	267.06	89.02	2.93	0.041
Time	8	278.61	34.83	1.15	0.347
Trt.Time	24	1075.37	44.81	1.47	0.113
Residual	61(9)	1854.75	30.41		
Total	98(9)	3655.75			

***** Tables of means *****

Grand mean 10.85

Trt	40WNDLi	Control	Slipper	Surface			
	9.15	13.37	10.83	10.03			
Time	1.00	2.00	3.00	4.00	5.00	6.00	7.00
	11.68	11.82	11.74	13.52	11.36	9.89	10.41
Time	8.00	9.00					
	9.61	7.58					
Trt	Time	1.00	2.00	3.00	4.00	5.00	6.00
40WNDLi		10.89	11.54	10.59	6.05	8.92	8.00
Control		10.71	11.97	15.49	12.55	20.19	16.21
Slipper		13.64	11.39	10.03	25.82	7.65	7.65
Surface		11.48	12.37	10.86	9.68	8.69	7.69
Trt	Time	7.00	8.00	9.00			
40WNDLi		9.14	9.44	7.78			
Control		14.94	10.86	7.38			
Slipper		7.61	7.88	5.81			
Surface		9.95	10.26	9.32			

*** Standard errors of differences of means ***

Table	Trt	Time	Trt Time
rep.	27	12	3
d.f.	61	61	61
s.e.d.	1.501	2.251	4.502

(Not adjusted for missing values)

*** Least significant differences of means ***

Table	Trt	Time	Trt Time
rep.	27	12	3
d.f.	61	61	61
l.s.d.	3.001	4.501	9.003

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	1.673	15.4
Rep.*Units*	61	5.514	50.8

Nitrate regression analysis (December 97).

Control : One curve fits all reps

Response variate: Control
Explanatory: Date
Fitted Curve: $A + B \cdot R^{**}X$
Constraints: $R < 1$

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	25389.	12694.6	53.43	<.001
Residual	78	18531.	237.6		
Total	80	43920.	549.0		

Change	2	-25389.	-12694.6	-53.43	<.001
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Percentage variance accounted for 56.7
Standard error of observations is estimated to be 15.4

*** Estimates of parameters ***

	estimate	s.e.
R	0.8903	0.0299
B	72.95	7.13
A	0.77	5.88

Control : R & B constant, A Variable.

Response variate: Control
Explanatory: Date
Grouping factor: Rep, constant parameters separate
Fitted Curve: $A + B \cdot R^{**}X$
Constraints: $R < 1$

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	4	29130.	7282.6	37.42	<.001
Residual	76	14790.	194.6		
Total	80	43920.	549.0		

Change	2	-3741.	-1870.6	-9.61	<.001
--------	---	--------	---------	-------	-------

Percentage variance accounted for 64.6
Standard error of observations is estimated to be 13.9

*** Estimates of parameters ***

	estimate	s.e.
R	52.78	5.17
B	-0.216E-14	
A Rep 1	1.336E+32	
A Rep 2	2.834E+30	
A Rep 3	1.336E+32	

Control : R constant, A & B Variable.

Response variate: Control
 Explanatory: Date
 Grouping factor: Rep, all linear parameters separate
 Fitted Curve: $A + B \cdot R^{**}X$
 Constraints: $R < 1$

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	6	36665.	6110.82	62.33	<.001
Residual	74	7255.	98.04		
Total	80	43920.	549.00		
Change	2	-7534.	-3767.21	-38.42	<.001

Percentage variance accounted for 82.1
 Standard error of observations is estimated to be 9.90

*** Estimates of parameters ***

	estimate	s.e.
R	0.9058	0.0105
B Rep 1	113.7	
A Rep 1	-4.882	
B Rep 2	77.24	
A Rep 2	-6.138	
B Rep 3	28.98	
A Rep 3	3.069	

Control : R, A & B Variable.

Response variate: Control
 Explanatory: Date
 Grouping factor: Rep, all parameters separate
 Fitted Curve: $A + B \cdot R^{**}X$
 Constraints: $R < 1$

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.
Regression	8	37376.	4671.99	51.40
Residual	72	6544.	90.89	
Total	80	43920.	549.00	
Change	2	-711.	-355.53	-3.91

Percentage variance accounted for 83.4
 Standard error of observations is estimated to be 9.53

*** Estimates of parameters ***

	estimate	s.e.
R Rep 1	0.9214	0.0187
B Rep 1	115.77	8.54
A Rep 1	-11.8	10.5
R Rep 2	0.8629	0.0347
B Rep 2	79.07	8.64
A Rep 2	1.58	5.14
R Rep 3	0.482	0.171
B Rep 3	82.9	40.5
A Rep 3	9.64	2.02

40WNDLi : R, A & B constant.

Response variate: Improved
 Explanatory: Date
 Fitted Curve: $A + B \cdot R^{**}X$
 Constraints: $R < 1$

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	45519.	22759.6	72.37	<.001
Residual	71	22329.	314.5		
Total	73	67849.	929.4		

Change	2	-45519.	-22759.6	-72.37	<.001
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Percentage variance accounted for 66.2

Standard error of observations is estimated to be 17.7

*** Estimates of parameters ***

	estimate	s.e.
R	0.8865	0.0261
B	101.81	8.53
A	-1.80	7.09

40WNDLi : R & B constant, A variable.

Response variate: Improved

Explanatory: Date

Grouping factor: Rep, constant parameters separate

Fitted Curve: $A + B \cdot R^{**}X$ Constraints: $R < 1$

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	4	52499.	13124.8	59.00	<.001
Residual	69	15350.	222.5		
Total	73	67849.	929.4		

Change	2	-6980.	-3489.9	-15.69	<.001
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Percentage variance accounted for 76.1

Standard error of observations is estimated to be 14.9

*** Estimates of parameters ***

	estimate	s.e.
R	0.8804	0.0140
B	100.1	
A Rep 1	0.2114	
A Rep 2	12.85	
A Rep 3	-11.13	

40WNDLi : R constant, A & B variable.

Response variate: Improved

Explanatory: Date

Grouping factor: Rep, all linear parameters separate

Fitted Curve: $A + B \cdot R^{**}X$ Constraints: $R < 1$

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	6	55665.	9277.5	51.02	<.001
Residual	67	12184.	181.8		
Total	73	67849.	929.4		

Change	2	-3166.	-1583.0	-8.71	<.001
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Percentage variance accounted for 80.4

Standard error of observations is estimated to be 13.5

*** Estimates of parameters ***

	estimate	s.e.
R	0.8969	0.0121
B Rep 1	112.0	
A Rep 1	-7.802	
B Rep 2	127.4	
A Rep 2	-0.8978	
B Rep 3	63.18	
A Rep 3	-3.705	

40WNDLi : R, A & B variable.

Response variate: Improved

Explanatory: Date

Grouping factor: Rep, all parameters separate

Fitted Curve: $A + B \cdot R \cdot X$ Constraints: $R < 1$

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.
Regression	8	58742.	7342.8	52.41
Residual	65	9106.	140.1	
Total	73	67849.	929.4	

Change	2	-3077.	-1538.7	-10.98
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Percentage variance accounted for 84.9

Standard error of observations is estimated to be 11.8

*** Estimates of parameters ***

	estimate	s.e.
R Rep 1	0.8386	0.0305
B Rep 1	121.3	12.0
A Rep 1	3.49	5.08
R Rep 2	0.9505	0.0216
B Rep 2	159.1	34.0
A Rep 2	-47.7	39.1
R Rep 3	0.7109	0.0715
B Rep 3	96.2	20.4
A Rep 3	6.95	3.14

Slipper foot: R, A & B constant.

Response variate: Slipper_

Explanatory: Date

Fitted Curve: $A + B \cdot R \cdot X$ Constraints: $R < 1$

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	45371.	22685.31	263.10	<.001
Residual	72	6208.	86.22		
Total	74	51579.	697.01		

Change	2	-45371.	-22685.31	-263.10	<.001
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Percentage variance accounted for 87.6

Standard error of observations is estimated to be 9.29

*** Estimates of parameters ***

	estimate	s.e.
R	0.8634	0.0147
B	103.16	4.85
A	0.96	2.86

Slipper foot: R & B constant, A variable.

***** Nonlinear regression analysis *****

Response variate: Slipper_
 Explanatory: Date
 Grouping factor: Rep, constant parameters separate
 Fitted Curve: $A + B \cdot R^{**}X$
 Constraints: $R < 1$

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	4	45494.	11373.53	130.85	<.001
Residual	70	6084.	86.92		
Total	74	51579.	697.01		
Change	2	-124.	-61.76	-0.71	<.001

Percentage variance accounted for 87.5
 Standard error of observations is estimated to be 9.32

*** Estimates of parameters ***

	estimate	s.e.
R	0.8614	0.0100
B	102.9	
A Rep 1	0.009727	
A Rep 2	3.218	
A Rep 3	1.586	

Slipper foot: R constant, A & B variable.

Response variate: Slipper_
 Explanatory: Date
 Grouping factor: Rep, all linear parameters separate
 Fitted Curve: $A + B \cdot R^{**}X$
 Constraints: $R < 1$

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	6	45990.	7664.97	93.26	<.001
Residual	68	5589.	82.19		
Total	74	51579.	697.01		
Change	2	-496.	-247.84	-3.02	<.001

Percentage variance accounted for 88.2
 Standard error of observations is estimated to be 9.07

*** Estimates of parameters ***

	estimate	s.e.
R	0.86537	0.00979
B Rep 1	88.21	
A Rep 1	2.533	
B Rep 2	109.2	
A Rep 2	0.5543	
B Rep 3	112.0	
A Rep 3	-1.508	

Slipper foot: R, A & B variable.

Response variate: Slipper_
 Explanatory: Date
 Grouping factor: Rep, all parameters separate
 Fitted Curve: $A + B \cdot R^{**}X$
 Constraints: $R < 1$

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.
Regression	8	46182.	5772.80	70.61
Residual	66	5396.	81.76	
Total	74	51579.	697.01	

Change	2	-193.	-96.28	-1.18
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Percentage variance accounted for 88.3

Standard error of observations is estimated to be 9.04

*** Estimates of parameters ***

	estimate	s.e.
R Rep 1	0.8321	0.0296
B Rep 1	93.97	9.48
A Rep 1	5.90	3.27
R Rep 2	0.8899	0.0260
B Rep 2	109.27	8.19
A Rep 2	-5.92	8.98
R Rep 3	0.8658	0.0223
B Rep 3	111.93	8.10
A Rep 3	-1.58	4.82

Surface: R, A & B constant.

Response variate: Surface

Explanatory: Date

Fitted Curve: $A + B \cdot R^{**}X$ Constraints: $R < 1$

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	50293.	25146.4	102.48	<.001
Residual	72	17667.	245.4		
Total	74	67959.	918.4		

Change	2	-50293.	-25146.4	-102.48	<.001
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Percentage variance accounted for 73.3

Standard error of observations is estimated to be 15.7

*** Estimates of parameters ***

	estimate	s.e.
R	0.9218	0.0204
B	109.60	9.35
A	-10.9	11.6

Surface: R & B constant, A variable.

Response variate: Surface

Explanatory: Date

Grouping factor: Rep, constant parameters separate

Fitted Curve: $A + B \cdot R^{**}X$ Constraints: $R < 1$

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	4	53995.	13498.9	67.67	<.001
Residual	70	13964.	199.5		
Total	74	67959.	918.4		

Change	2	-3703.	-1851.3	-9.28	<.001
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Percentage variance accounted for 78.3

Standard error of observations is estimated to be 14.1

*** Estimates of parameters ***

	estimate	s.e.
R	0.9152	0.0120
B	106.1	
A Rep 1	3.824	
A Rep 2	-11.49	
A Rep 3	-11.54	

Surface: R constant, A & B variable.

Response variate: Surface
 Explanatory: Date
 Grouping factor: Rep, all linear parameters separate
 Fitted Curve: $A + B \cdot R^{**}X$
 Constraints: $R < 1$

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	6	56094.	9349.0	53.58	<.001
Residual	68	11866.	174.5		
Total	74	67959.	918.4		
Change	2	-2098.	-1049.2	-6.01	<.001

Percentage variance accounted for 81.0
 Standard error of observations is estimated to be 13.2

*** Estimates of parameters ***

	estimate	s.e.
R	0.9266	0.0117
B Rep 1	143.7	
A Rep 1	-18.08	
B Rep 2	103.3	
A Rep 2	-15.03	
B Rep 3	86.81	
A Rep 3	-8.435	

Surface: R, A & B variable.

Response variate: Surface
 Explanatory: Date
 Grouping factor: Rep, all parameters separate
 Fitted Curve: $A + B \cdot R^{**}X$
 Constraints: $R < 1$

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.
Regression	8	57487.	7185.9	45.29
Residual	66	10472.	158.7	
Total	74	67959.	918.4	
Change	2	-1393.	-696.7	-4.39

Percentage variance accounted for 82.7
 Standard error of observations is estimated to be 12.6

*** Estimates of parameters ***

	estimate	s.e.
R Rep 1	0.9735	0.0253
B Rep 1	247.	167.
A Rep 1	-134.	174.
R Rep 2	0.8604	0.0339
B Rep 2	104.9	11.6
A Rep 2	3.76	6.39
R Rep 3	0.9325	0.0334
B Rep 3	88.5	15.1
A Rep 3	-11.4	19.1

Analysis of Variance of Estimates

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	149.	74.	0.05	
Rep.*Units* stratum					
Treatmen	3	229.	76.	0.05	0.983
Paramete	2	125756.	62878.	43.71	<.001
Treatmen.Paramete	6	9287.	1548.	1.08	0.407
Residual	22	31645.	1438.		
Total	35	167065.			

***** Tables of means *****

Variate: Estimate

Grand mean 34.4

Treatmen	Control	Improved	Slipper	Surface
	31.0	38.0	35.1	33.5

Paramete	A	B	R
	-15.1	117.5	0.8

Treatmen	Paramete	A	B	R
Control		-0.2	92.6	0.8
Improved		-12.4	125.5	0.8
Slipper		-0.5	105.1	0.9
Surface		-47.2	146.8	0.9

*** Standard errors of differences of means ***

Table	Treatmen	Paramete	Treatmen Paramete
rep.	9	12	3
d.f.	22	22	22
s.e.d.	17.88	15.48	30.97

*** Least significant differences of means ***

Table	Treatmen	Paramete	Treatmen Paramete
rep.	9	12	3
d.f.	22	22	22
l.s.d.	37.08	32.11	64.22

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	2.49	7.2
Rep.*Units*	22	37.93	110.2

Appendix 3.6.**Total nitrogen determination****Kjeldahl method*****Introduction***

Plant growth is limited by nitrogen more than by any other element and for this reason determining amount of nitrogen in soils is very important. In most soils the bulk of nitrogen is in organic forms. The inorganic forms include nitrate that is soluble and easily leached or taken up; nitrite; ammonium and gaseous forms.

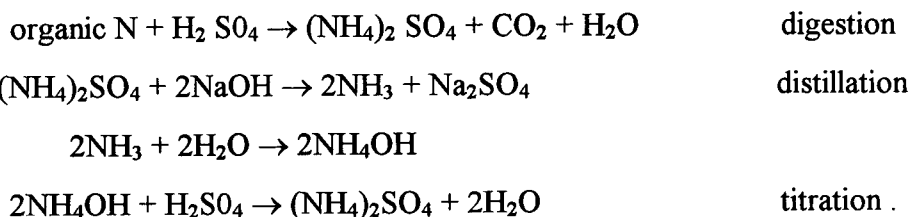
Kjeldahl procedure is satisfactory for total N analysis of most of the nitrogenous compounds to occur in soils and plant material, but it does not give accurate results with compounds containing N-N and N-O linkage (nitrites and nitrates). This method is recognised method for total N analysis and is used as a standard method by Soil Survey and ADAS.

Theory.

Organic N in the sample is converted to ammonium-nitrogen by digestion with sulphuric acid, potassium sulphate is added to raise the boiling point to about 380 °C.

Copper sulphate is used as a catalyst.

The ammonia liberated with sodium hydroxide is removed by steam distillation and determined titrimetrically. The procedure is summarised as follows:

***Procedure*****1. SAMPLE DIGESTION****- Equipment**

1. Kjeldahl digestion tubes,
2. Dispenser or measuring cylinder
3. Buchi Digestion Unit



Fig. 3.6.1. Digestion.

- Reagents

1. KJELTABS C catalyst tablets (5g K_2SO_4 + 0.1g $CuSO_4 \cdot 5H_2O$)
2. Sulphuric acid 98%, (1.84sp.gr.)

2. DIGESTION PROCEDURE

Preparation of soil digests

- ⇒ Transfer: 5g of air dry soil ground to pass 2 mm sieve, (or 2g of dry plant material ground to pass 1 mm sieve) into digestion tube and add 2 Kjeltabs C tablets. Put 4-8 glass beads into each tube and add 20 ml of conc. sulphuric acid using dispenser.
- ⇒ Switch on the digestion unit and leave for 5 - 10 minutes to warm up. Temperature regulator in position 10. Make sure that fume scrubber is set in operation. (THIS SHOULD ALWAYS BE LEFT ON).
- ⇒ Place the digestion tubes in the digestion tube holder, put the suction module with fitted gaskets on the digestion tubes and place tubes into preheated Digestion unit. Lower the heat to position 7. (If, there is too much effervescence at this setting, the heating is reduced accordingly.) NEVER INSTALL EMPTY DIGESTION TUBES.

- ⇒ Heat the flask for at least 1 hour or until the solution clears.
- ⇒ Switch the heat off on the Digestion Unit (by putting heat dial to zero). After about 15 minutes take the tubes out of the unit and leave on the rack to cool for at least 30 minutes.
- ⇒ When tubes are cold remove the suction module and switch off the Digestion Unit.
- ⇒ Samples are ready for distillation.
- ⇒ Carry out a blank digest.

Preparation of water digests

- ⇒ Pipette 10 ml of water sample into a digestion tube and add 10 of ethanol and add 2 Kjeltabs C tablets. Put 4-8 glass beads into each tube and add 20ml of conc. sulphuric acid using dispenser

3. SAMPLE DISTILLATION

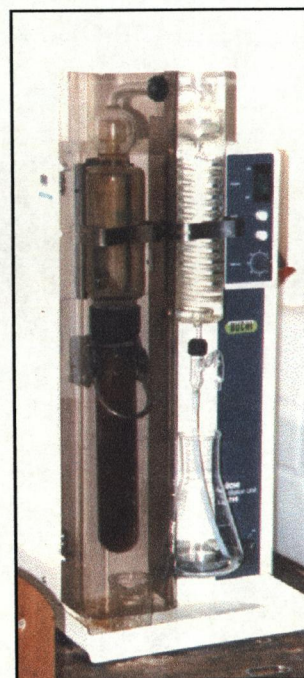
Equipment

1. Buchi Distillation Unit,
2. 500 ml conical flask,
3. 50 and 100 ml measuring cylinders.

Reagents

1. 1% Orthoboric Acid (Boric acid) 10 g of boric acid made up to 1 l with distilled water.
2. Mixing indicator SHER.
3. Sodium hydroxide 40% m/v.

- ⇒ Fill the container with NaOH (at least half),
- ⇒ Fill the second container with deionised water,
 - Turn mains water tap on. Make sure that drain pipe is placed into the drain.
- ⇒ Switch the Distillation Unit on. Aspiration stopcock should be in YES position. Wait 5-10 minutes for unit to warm up.
- ⇒ Add 50 ml of deionised water to digestion tube.
- ⇒ Add 100 ml of Boric acid to 500 ml conical flask and add 3-5 drops of SHER indicator. SOLUTION WILL BE BLUE - this is a receiver.
- ⇒ Place receiver in the right position on the distillation unit. Make sure that the tube is in the liquid.



- ⇒ Add sodium hydroxide solution 60 – 90 ml by pressing NaOH button. (The amount of sodium hydroxide is measured by means of the scale behind the distillation vessel. The amount of NaOH solution must be chosen so that a colour change to brown or blue is clearly visible.
- ⇒ Set the time for 3 minutes.
- ⇒ Press the Start switch.
- ⇒ Turn the aspiration stopcock to the NO position.
- ⇒ When distillation has finished take conical flask off (it should have green colour). Sample is ready for titration. Put the aspiration stopcock in YES position.
- ⇒ Take off the digestion tube using tongues provided. (any dripping from the plastic tube should be caught in small beaker placed under the tube)
- ⇒ Repeat the procedure until all samples has been distilled.

4. TITRATION

Equipment

1. 50 ml burette
2. Retort stand

Reagents

1. Sulphuric acid 0.1M, 0.01M, 0.005M or any other strength This will depends on amount of Nitrogen expected.
- ⇒ Titrate the solution in the receiver with sulphuric acid to a change of colour.

Green → Blue → Grey-Brown

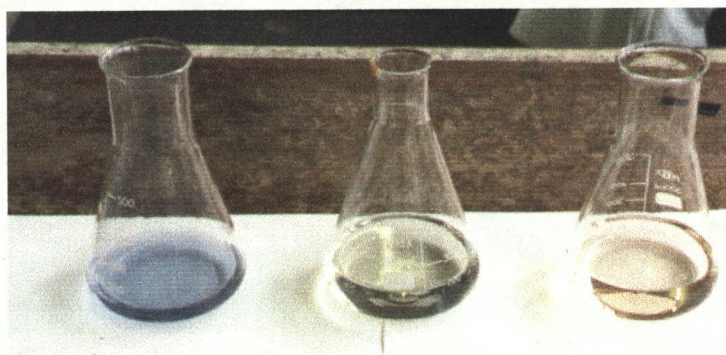
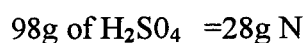


Fig 3.6.3 Titration colour changes

Titration is first performed rapidly until there is a change of colour to blue (1st point change = warning point and then titration is continued cautiously until there is a change of colour to grey-brown (2nd point of change = end point of the titration)

5. CALCULATION OF THE RESULTS

Basis of the calculation



$$\text{g N / kg soil} = \frac{T \times M \times 28}{\text{Wt of soil}}$$

$$\text{mg N / l water} = \frac{T \times M \times 28 \times 1000}{\text{Sample Volume}}$$

where : $T = T_s - T_b$ T_s = mls of H_2SO_4 in sample titration T_b = mls of H_2SO_4 in blank titration M = molarity of H_2SO_4

$$\% \text{ N} = \text{g N/kg} / 10$$

Appendix 3.7.

Statistical analysis of soil nitrogen content.

Variate: Nitrogen (December Applied Plots)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.03717	0.01858	1.73	
Rep.*Units* stratum					
Trt	3	0.14848	0.04949	4.60	0.007
Time	2	0.60737	0.30368	28.22	<.001
Depth	1	5.07052	5.07052	471.19	<.001
Trt.Time	6	0.02257	0.00376	0.35	0.906
Trt.Depth	3	0.03950	0.01317	1.22	0.312
Time.Depth	2	0.04235	0.02118	1.97	0.151
Trt.Time.Depth	6	0.03813	0.00635	0.59	0.736
Residual	46	0.49501	0.01076		
Total	71	6.50110			

***** Tables of means *****

Variate: Nitrogen

Grand mean 1.049

Trt	40WNDLi	Control	Slipper	Surface			
	1.092	0.973	1.074	1.057			
Time	After	Final	Prior				
	1.132	0.921	1.095				
Depth	Deep	Shallow					
	0.784	1.314					
Trt	Time	After	Final	Prior			
40WNDLi		1.157	0.964	1.156			
Control		1.068	0.842	1.010			
Slipper		1.144	0.977	1.099			
Surface		1.157	0.900	1.114			
Trt	Depth	Deep	Shallow				
40WNDLi		0.847	1.337				
Control		0.670	1.277				
Slipper		0.807	1.340				
Surface		0.810	1.304				
Time	Depth	Deep	Shallow				
After		0.895	1.369				
Final		0.625	1.217				
Prior		0.832	1.357				
Trt	Time	After	Final	Prior			
Depth	Deep	Shallow	Deep	Shallow			
40WNDLi		0.926	1.387	0.709	1.219	0.906	1.406
Control		0.801	1.336	0.500	1.184	0.709	1.310
Slipper		0.875	1.414	0.712	1.243	0.834	1.364
Surface		0.976	1.337	0.577	1.223	0.878	1.351

*** Standard errors of differences of means ***

Table	Trt	Time	Depth	Trt
				Time
rep.	18	24	36	6
d.f.	46	46	46	46
s.e.d.	0.0346	0.0299	0.0245	0.0599
Table	Trt	Time	Trt	
	Depth	Depth	Time	

Appendix 3.7

			Depth
rep.	9	12	3
d.f.	46	46	46
s.e.d.	0.0489	0.0424	0.0847

*** Least significant differences of means ***

Table	Trt	Time	Depth	Trt Time
rep.	18	24	36	6
d.f.	46	46	46	46
l.s.d.	0.0696	0.0603	0.0492	0.1206

Table	Trt Depth	Time Depth	Trt Time Depth
rep.	9	12	3
d.f.	46	46	46
l.s.d.	0.0984	0.0852	0.1705

***** Stratum standard errors and coefficients of variation *****

Variate: Nitrogen

Stratum	d.f.	s.e.	cv%
Rep	2	0.0278	2.7
Rep.*Units*	46	0.1037	9.9

Variate: Nitrogen (May Applied Plots)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.02542	0.01271	1.16	
Rep.*Units* stratum					
Trt	3	0.16136	0.05379	4.92	0.007
Time	1	1.09898	1.09898	100.59	<.001
Depth	1	3.22248	3.22248	294.96	<.001
Trt.Time	3	0.10471	0.03490	3.19	0.038
Trt.Depth	3	0.07084	0.02361	2.16	0.113
Time.Depth	1	0.22894	0.22894	20.96	<.001
Trt.Time.Depth	3	0.01125	0.00375	0.34	0.794
Residual	30	0.32776	0.01093		
Total	47	5.25173			

***** Tables of means *****

Variate: Nitrogen

Grand mean 1.092

Trt	40WNDLi	Control	Slipper	Surface
	0.991	1.124	1.128	1.124
Time	Final	Prior		
	0.941	1.243		
Depth	Deep	Shallow		
	0.833	1.351		

Appendix 3.7

Trt	Time	Final	Prior
40WNDLi		0.910	1.073
Control		0.924	1.325
Slipper		0.991	1.264
Surface		0.937	1.311

Trt	Depth	Deep	Shallow
40WNDLi		0.670	1.313
Control		0.866	1.383
Slipper		0.902	1.354
Surface		0.894	1.354

Time	Depth	Deep	Shallow
Final		0.612	1.269
Prior		1.053	1.433

Trt	Time	Final	Prior	
Depth	Deep	Shallow	Deep	Shallow
40WNDLi	0.542	1.277	0.797	1.349
Control	0.579	1.269	1.152	1.497
Slipper	0.687	1.295	1.116	1.412
Surface	0.641	1.233	1.147	1.475

*** Standard errors of differences of means ***

Table	Trt	Time	Depth	Trt Time
rep.	12	24	24	6
d.f.	30	30	30	30
s.e.d.	0.0427	0.0302	0.0302	0.0603

Table	Trt Depth	Time Depth	Trt Time Depth
rep.	6	12	3
d.f.	30	30	30
s.e.d.	0.0603	0.0427	0.0853

*** Least significant differences of means ***

Table	Trt	Time	Depth	Trt Time
rep.	12	24	24	6
d.f.	30	30	30	30
l.s.d.	0.0871	0.0616	0.0616	0.1232

Table	Trt Depth	Time Depth	Trt Time Depth
rep.	6	12	3
d.f.	30	30	30
l.s.d.	0.1232	0.0871	0.1743

***** Stratum standard errors and coefficients of variation *****

Variate: Nitrogen

Stratum	d.f.	s.e.	cv%
Rep	2	0.0282	2.6
Rep.*Units*	30	0.1045	9.6

Appendix 4

Appendix 4.1.

Equipment and method for determination of the mass of 1000 grains.

Equipment:

A Numigral seed counter (*Fig. Ap 4.1*) was used to count 500 grains as received from the field trials sites.



Fig. Ap 4.1. Numigral seed counter.

Procedure:

A proportion of the post-processed grain from each trial plot was placed in the seed counter and 500 grains were counted and weighed for each plot replication. This result was multiplied by two and subsequent corrections were made to account for the variability between sample moisture contents.

Example calculation:

December trial plot, Surface application, Rep 1:

1000 grain weight = 49.614 g, moisture content = 14.6 %

$$\text{Loss due to moisture correction} = 49.614 \times \left(\frac{14.6 - 14}{100 - 14} \right) = 0.346 \text{ g}$$

$$\text{Corrected 1000 grain weight} = 49.614 - 0.346 = 49.267 \text{ g}$$

Appendix 4.2.

Hagberg falling number test.

Determination of FALLING NUMBER (according to Perten Hagberg) as a measure of alpha-amylase activity in grain and flour.

ISO - standard No 3093, ICC standard No 107, AACC method 56-81A.

4.2.1 FIELD OF APPLICATION.

Applicable to grain, flour and other starch-containing products, in particular wheat and rye. Calculation of flour mixtures is possible by converting the Falling Numbers into Perten Liquefaction Numbers.

4.2.2 PRINCIPLE

The Falling Number method determines alpha-amylase activity using the starch in the sample as substrate. The method is based upon the rapid gelatinization of a suspension of flour or meal in a boiling water bath and the subsequent measurement of the liquefaction by alpha-amylase of the starch contained in the sample.

4.2.3 EQUIPMENT.

1. Falling Number Test Apparatus, Type 1400.
2. A balance with an accuracy of 0.05g
3. Laboratory mill.
4. Moisture meter for flour.

4.2.4 PROCEDURE.

4.2.4.1 Preparation of the sample

Remove dust and impurities from the laboratory sample. 300g of the grain should be prepared for grinding. If less than 200g of grain is prepared, misleading results may be obtained.

4.2.1.2 Grinding the grain.

The Falling Number Values are influenced by the particle size of the ground grain. Therefore a uniform particle size is required. The ground grain should pass through sieves with the following aperture sizes.

100% - though a sieve with an aperture of 710 microns

95 - 100% though a sieve with an aperture of 510 microns

80% or less though a sieve with an aperture of 200 to 210 microns.

The fineness is obtained when using a Falling Number Mill, equipped with a sieve with 0.8mm openings. The mill is to be fed carefully with the grain in order to avoid heating and overloading. Grinding should be continued 30-40 seconds after the last of the sample has entered the mill. Up to 1% bran particles remaining on the sieve may be discarded. The ground grain should be carefully mixed. It is essential that only the standard grinding method is used.

4.2.1.3 Preparation of flour sample.

Flour should be sifted through an 0.8mm sieve in order to separate lumps. The Falling Number determined on flour will not always be the same as that for the same grain, pulverised in the Falling Number Mill.

4.2.1.4 Moisture content of test sample

Determine the moisture content of the ground sample of flour before weighing out the test sample. The Falling Number should be determined on a sample with a moisture content of 15%. The quantity to be used when the moisture differs from 15% is given in the table below.

Moisture Content (%)	Weight	Moisture Content (%)	Weight
9.0	6.40	14.0	6.90
9.2	6.45	14.2	6.90
9.4	6.45	14.4	6.95
9.6	6.45	14.6	6.95
9.8	6.50	14.8	7.00
10.0	6.50	15.0	7.00
10.2	6.55	15.2	7.00
10.4	6.55	15.4	7.05
10.6	6.55	15.6	7.05
10.8	6.60	15.8	7.10
11.0	6.60	16.0	7.10
11.2	6.60	16.2	7.15
11.4	6.65	16.4	7.15
11.6	6.65	16.6	7.15
11.8	6.70	16.8	7.20
12.0	6.70	17.0	7.20
12.2	6.70	17.2	7.25
12.4	6.75	17.4	7.25
12.6	6.75	17.6	7.30
12.8	6.80	17.8	7.30
13.0	6.80	18.0	7.30
13.2	6.80		
13.4	6.85		
13.6	6.85		
13.8	6.85		

N.B. This refers to the sample after grinding, not the moisture content of the whole wheat. The moisture loss during grinding is usually 3-4%

4.2.5 INSTRUCTIONS FOR FALLING NUMBER APPARATUS TYPE 1400

4.2.5.1 Installation.

1. Fill the water bath with distilled water (not only de-ionised water) to 2 to 3cm below the top edge of the container (check water level control) and connect the heater to a grounded electrical supply
2. Fit the micro-switch part on top of the lid with the spring, washer and nut and connect it with the cable to the timer control box, which is connected to a grounded electrical supply.
3. Place the cooling lid on the water bath and connect the built in condenser to the cold water tap. The cooling water must flow during the entire time the apparatus is switched on.
4. Switch on the heater with the switch (2 red lights on) and bring the water to the boil (approx 30 mins) Check cooling system and water level. The water must boil vigorously during the test period (1 red light on).

NOTE the Falling Number is affected by the boiling temperature of the water, which is a function of atmospheric pressure. Since the boiling point may be as low as 97°C, it may happen, particularly at high altitude, that the figure for the Falling Number is about 10% higher than the true value. Thus it is important to correct the temperature of the boiling water bath to 100°C, for example by the addition of ethylene glycol or glycerol.

Required temperature elevation °C	Quantity to be added %	
	Ethylene glycol	glycerol
0.2	1.9	2.5
0.4	3.9	4.9
0.6	5.8	7.4
0.8	7.8	9.8
1.0	9.7	12.3
1.2	11.3	14.2
1.4	12.9	16.1
1.6	14.4	18.1
1.8	16.0	20.0
2.0	17.6	21.9

If the boiling point is raised more than 2°C there is a danger of boiling out the contents of the tube.

Temperature control is very important, but there are many practical difficulties in keeping the temperature at the right level. It is often better to have the boiling point between 98.0°C and 100°C unchanged instead of raising it to 100°C.

5. Switch on the electrical system with the blue ON/OFF switch on the timer box. Check the blue control lamp and green start light are illuminated.

4.2.5.2 Determination Of Falling Numbers (Type 1400)

1. The distilled water in the bath must boil lively during the whole test period. Check the temperature, water level and cooling system.
2. Place 25 ml distilled water of 22°C into a Viscometer tube.
3. Weigh 7.00 g of the flour or ground grain on 15% moisture content basis according to the table and transfer it into the Viscometer tube.
4. Fit a rubber stopper into the top of the Viscometer tube and shake vigorously 20 - 30 times or more if necessary to obtain a homogenous suspension.
5. Remove the stopper and place the Viscometer stirrer into the tube, scraping into the suspension any flour or ground product adhering to the walls of the tube.
6. Check that the timer unit is reset and ready for start. (Green lamp illuminated and display showing zero). If not depress red STOP switch.
7. Place the Viscometer tube with the stirrer into the boiling water bath through the hole in the lid, within 30 seconds after mixing.
8. Start the timer immediately when the Viscometer tube and stirrer has been put un the boiling water by depressing the green START switch. The electronic counter starts to count seconds.
9. At 5 seconds, when the buzzer and red light signal begins the machine automatically starts stirring the suspension with the Viscometer stirrer at the rate of 2 full strokes a second.
10. The stirring is carried out until the counter shows 60, i.e. during 55 seconds, during which time 110 full strokes (up and down movements) should be completed. The buzzer and red light signal is facilitating to keep the correct stirring rhythm, if the Viscometer stirrer is in the bottom position every time the buzzer and red light is observed.
11. At 60 seconds, when the buzzer and red signals have stopped, the 1400 automatically lifts the Viscometer stirrer to the top position and releases the Viscometer stirrer to sink under its own weight into the suspension.

12. Swing the micro-switch to its working position with the wire close to the stirrer rod.
13. When the Viscometer stirrer has fallen the predetermined distance, i.e. when the lower edge of the upper stop ring is at the same level as the top of the black stopper, the micro-switch is activated, stopping the timing and giving a buzzer signal.
14. Stop the buzzer by depressing the green START switch. The red light is still on and the counter shows the Falling Number Value. .
15. Swing back the micro-switch and remove the Viscometer tube and stirrer and put it in cold water. Both the tube and stirrer should be carefully cleaned and dried before the next test.
16. Read the Falling Number Value from the counter display. Reset the timer by pressing the red STOP switch. Check that the counter shows zero and the green START light illuminates.

4.2.5.3 Definition.

The Falling Number is defined as the total time in seconds from immersion of the Viscometer tube into the water bath until the Viscometer Stirrer has dropped down in the gelatinised suspension. The stirring time is thus included.

4.2.5.4 Accuracy of Determination.

Repeated tests on the same sample should give results within 5% of the average Falling Number Value. The importance of correct sampling is emphasised, since difference in alpha-amylase activity may occur when sub-sampling is made without the sample being well mixed.

Appendix 4.3.
Statistical analysis of Doctoral field trial results.
Crop Nitrogen Analysis

***** Analysis of variance *****

Variate: Prior Crop N (May)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	2.9416	1.4708	5.37	
Block.*Units* stratum					
Treatmen	3	1.9197	0.6399	2.34	0.173
Residual	6	1.6436	0.2739		
Total	11	6.5049			

***** Tables of means *****

Variate: Prior

Grand mean 7.26

Treatmen	Control	Improved	Slipper	Surface
	7.08	7.57	6.70	7.70

*** Standard errors of differences of means ***

Table	Treatmen
rep.	3
d.f.	6
s.e.d.	0.427

*** Least significant differences of means ***

Table	Treatmen
rep.	3
d.f.	6
l.s.d.	1.046

***** Stratum standard errors and coefficients of variation *****

Variate: Prior

Stratum	d.f.	s.e.	cv%
Block	2	0.606	8.4
Block.*Units*	6	0.523	7.2

***** Analysis of variance *****

Variate: Final Crop N (May)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	25.053	12.527	5.77	
Block.*Units* stratum					
Treatmen	3	31.571	10.524	4.85	0.048
Residual	6	13.024	2.171		
Total	11	69.648			

***** Tables of means *****

Variate: Final

Grand mean 16.57

Appendix 4.3

Treatmen	Control	Improved	Slipper	Surface
	18.20	15.90	14.22	17.95

*** Standard errors of differences of means ***

Table	Treatmen
rep.	3
d.f.	6
s.e.d.	1.203

*** Least significant differences of means ***

Table	Treatmen
rep.	3
d.f.	6
l.s.d.	2.944

***** Stratum standard errors and coefficients of variation *****

Variate: Final

Stratum	d.f.	s.e.	cv%
Block	2	1.770	10.7
Block.*Units*	6	1.473	8.9

***** Analysis of variance *****

Variate: Prior Crop N (December)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	10.677	5.338	0.98	
Block.*Units* stratum					
Treatmen	3	18.974	6.325	1.16	0.400
Residual	6	32.779	5.463		
Total	11	62.430			

***** Tables of means *****

Variate: Prior

Grand mean 7.70

Treatmen	Control	Improved	Slipper	Surface
	6.46	9.79	7.07	7.50

*** Standard errors of differences of means ***

Table	Treatmen
rep.	3
d.f.	6
s.e.d.	1.908

*** Least significant differences of means ***

Table	Treatmen
rep.	3
d.f.	6
l.s.d.	4.670

Appendix 4.3

***** Stratum standard errors and coefficients of variation *****

Variate: Prior

Stratum	d.f.	s.e.	cv%
Block	2	1.155	15.0
Block.*Units*	6	2.337	30.3

***** Analysis of variance *****

Variate: Final Crop N (December)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	12.909	6.455	3.27	
Block.*Units* stratum					
Treatmen	3	92.079	30.693	15.53	0.003
Residual	6	11.857	1.976		
Total	11	116.845			

***** Tables of means *****

Variate: Final

Grand mean 15.96

Treatmen	Control	Improved	Slipper	Surface
	15.59	18.86	11.62	17.78

*** Standard errors of differences of means ***

Table	Treatmen
rep.	3
d.f.	6
s.e.d.	1.148

*** Least significant differences of means ***

Table	Treatmen
rep.	3
d.f.	6
l.s.d.	2.809

***** Stratum standard errors and coefficients of variation *****

Variate: Final

Stratum	d.f.	s.e.	cv%
Block	2	1.270	8.0
Block.*Units*	6	1.406	8.8

Yield Analysis

***** Analysis of variance *****

Variate: Yield Corrected for 14% Moisture (December)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	783.	391.	0.30	
Block.*Units* stratum					
Treatmen	3	5309.	1770.	1.38	0.276
Rep_No	2	765.	383.	0.30	0.746
Treatmen.Rep_No	6	2007.	335.	0.26	0.950
Residual	22	28312.	1287.		
Total	35	37176.			

***** Tables of means *****

Variate: Weight

Grand mean 171.0

Treatmen	Control	Improved	Slipper	Surface
	150.9	172.3	182.6	178.0

Rep_No	1.00	2.00	3.00
	174.3	164.4	174.1

Treatmen	Rep_No	1.00	2.00	3.00
Control		137.7	151.7	163.3
Improved		178.9	165.4	172.5
Slipper		187.2	173.9	186.8
Surface		193.6	166.7	173.7

*** Standard errors of differences of means ***

Table	Treatmen	Rep_No	Treatmen
			Rep_No
rep.	9	12	3
d.f.	22	22	22
s.e.d.	16.91	14.65	29.29

*** Least significant differences of means ***

Table	Treatmen	Rep_No	Treatmen
			Rep_No
rep.	9	12	3
d.f.	22	22	22
l.s.d.	35.07	30.37	60.74

***** Stratum standard errors and coefficients of variation *****

Variate: Weight

Stratum	d.f.	s.e.	cv%
Block	2	5.71	3.3
Block.*Units*	22	35.87	21.0

***** Analysis of variance *****

Variate: Yield Corrected for 14% Moisture Content (May)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	3257.3	1628.7	2.03	
Block.*Units* stratum					
Treatmen	3	1749.9	583.3	0.73	0.548
Rep_No	2	4163.0	2081.5	2.59	0.098
Treatmen.Rep_No	6	5119.1	853.2	1.06	0.415
Residual	22	17685.5	803.9		
Total	35	31974.8			

***** Tables of means *****

Variate: Weight

Grand mean 160.8

Treatmen	Control	Improved	Slipper	Surface
	154.5	157.4	158.8	172.6

Rep_No	1.00	2.00	3.00
	161.4	147.4	173.8

Treatmen	Rep_No	1.00	2.00	3.00
Control		153.5	128.2	181.8
Improved		152.1	134.6	185.6
Slipper		164.5	147.8	164.1
Surface		175.4	179.0	163.5

*** Standard errors of differences of means ***

Table	Treatmen	Rep_No	Treatmen Rep_No
rep.	9	12	3
d.f.	22	22	22
s.e.d.	13.37	11.58	23.15

*** Least significant differences of means ***

Table	Treatmen	Rep_No	Treatmen Rep_No
rep.	9	12	3
d.f.	22	22	22
l.s.d.	27.72	24.01	48.01

***** Stratum standard errors and coefficients of variation *****

Variate: Weight

Stratum	d.f.	s.e.	cv%
Block	2	11.65	7.2
Block.*Units*	22	28.35	17.6

1000-Grain Weight Analysis

***** Analysis of variance *****

Variate: 1000 Grain Weight (December)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	21.661	10.831	1.15	
Block.*Units* stratum					
Trt	3	36.903	12.301	1.31	0.296
Rep	2	5.966	2.983	0.32	0.731
Trt.Rep	6	54.248	9.041	0.96	0.472
Residual	22	206.482	9.386		
Total	35	325.260			

***** Tables of means *****

Variate: weight

Grand mean 52.89

Trt	Control	Improved	Slipper	Surface
	51.74	54.22	53.50	52.09
Rep	1.00	2.00	3.00	
	53.18	53.17	52.31	
Trt	Rep	1.00	2.00	3.00
Control		52.64	50.84	51.75
Improved		53.96	55.94	52.77
Slipper		52.80	52.57	55.13
Surface		53.32	53.35	49.60

*** Standard errors of differences of means ***

Table	Trt	Rep	Trt Rep
rep.	9	12	3
d.f.	22	22	22
s.e.d.	1.444	1.251	2.501

*** Least significant differences of means ***

Table	Trt	Rep	Trt Rep
rep.	9	12	3
d.f.	22	22	22
l.s.d.	2.995	2.594	5.188

***** Stratum standard errors and coefficients of variation *****

Variate: weight

Stratum	d.f.	s.e.	cv%
Block	2	0.950	1.8
Block.*Units*	22	3.064	5.8

***** Analysis of variance *****

Variate: 1000 Grain Weight (May)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	4.00	2.00	0.20	
Block.*Units* stratum					
Trt	3	73.42	24.47	2.42	0.093
Rep	2	5.97	2.98	0.30	0.747
Trt.Rep	6	19.77	3.29	0.33	0.916
Residual	22	222.11	10.10		
Total	35	325.26			

***** Tables of means *****

Variate: weight

Grand mean 52.89

Trt	Control	Improved	Slipper	Surface
	51.02	52.35	53.25	54.95
Rep	1.00	2.00	3.00	
	53.18	53.17	52.31	
Trt	Rep	1.00	2.00	3.00
Control		51.38	51.68	49.99
Improved		53.75	52.79	50.50
Slipper		53.22	52.67	53.85
Surface		54.38	55.55	54.91

*** Standard errors of differences of means ***

Table	Trt	Rep	Trt Rep
rep.	9	12	3
d.f.	22	22	22
s.e.d.	1.498	1.297	2.594

*** Least significant differences of means ***

Table	Trt	Rep	Trt Rep
rep.	9	12	3
d.f.	22	22	22
l.s.d.	3.106	2.690	5.380

***** Stratum standard errors and coefficients of variation *****

Variate: weight

Stratum	d.f.	s.e.	cv%
Block	2	0.408	0.8
Block.*Units*	22	3.177	6.0

Biomass Analysis

***** Analysis of variance *****

Variate: Biomass (December)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	10458.	5229.	1.05	
Block.*Units* stratum					
Treatmen	3	45241.	15080.	3.03	0.051
Rep	2	433.	217.	0.04	0.958
Treatmen.Rep	6	16616.	2769.	0.56	0.760
Residual	22	109596.	4982.		
Total	35	182344.			

***** Tables of means *****

Variate: Biomass

Grand mean 441.

Treatmen	Control	Improved	Slipper	Surface
	490.	390.	445.	439.
Rep	1.00	2.00	3.00	
	438.	446.	439.	
Treatmen	Rep	1.00	2.00	3.00
Control		501.	493.	475.
Improved		387.	416.	367.
Slipper		458.	407.	470.
Surface		406.	467.	444.

*** Standard errors of differences of means ***

Table	Treatmen	Rep	Treatmen
			Rep
rep.	9	12	3
d.f.	22	22	22
s.e.d.	33.3	28.8	57.6

*** Least significant differences of means ***

Table	Treatmen	Rep	Treatmen
			Rep
rep.	9	12	3
d.f.	22	22	22
l.s.d.	69.0	59.8	119.5

***** Stratum standard errors and coefficients of variation *****

Variate: Biomass

Stratum	d.f.	s.e.	cv%
Block	2	20.9	4.7
Block.*Units*	22	70.6	16.0

***** Analysis of variance *****

Variate: Biomass (May)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	2063.	1031.	0.12	
Block.*Units* stratum					
Treatmen	3	8654.	2885.	0.33	0.802
Rep	2	6995.	3498.	0.40	0.673
Treatmen.Rep	6	51396.	8566.	0.99	0.457
Residual	22	190751.	8671.		
Total	35	259859.			

***** Tables of means *****

Variate: Biomass

Grand mean 376.

Treatmen	Control	Improved	Slipper	Surface
	357.	368.	378.	399.
Rep	1.00	2.00	3.00	
	366.	366.	395.	
Treatmen	Rep	1.00	2.00	3.00
Control		317.	368.	386.
Improved		396.	397.	310.
Slipper		346.	368.	421.
Surface		403.	331.	465.

*** Standard errors of differences of means ***

Table	Treatmen	Rep	Treatmen
			Rep
rep.	9	12	3
d.f.	22	22	22
s.e.d.	43.9	38.0	76.0

*** Least significant differences of means ***

Table	Treatmen	Rep	Treatmen
			Rep
rep.	9	12	3
d.f.	22	22	22
l.s.d.	91.0	78.8	157.7

***** Stratum standard errors and coefficients of variation *****

Variate: Biomass

Stratum	d.f.	s.e.	cv%
Block	2	9.3	2.5
Block.*Units*	22	93.1	24.8

Plant Count Analysis

***** Analysis of variance *****

Variate: December

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	117.4	58.7	0.57	
Block.*Units* stratum					
Treatmen	3	80.6	26.9	0.26	0.851
Residual	6	615.5	102.6		
Total	11	813.5			

***** Tables of means *****

Variate: December

Grand mean 105.6

Treatmen	Control	Improved	Slipper	Surface
	102.5	105.3	104.8	109.7

Appendix 4.3

*** Standard errors of differences of means ***

Table	Treatmen
rep.	3
d.f.	6
s.e.d.	8.27

*** Least significant differences of means ***

Table	Treatmen
rep.	3
d.f.	6
l.s.d.	20.24

***** Stratum standard errors and coefficients of variation *****

Variate: December

Stratum	d.f.	s.e.	cv%
Block	2	3.83	3.6
Block.*Units*	6	10.13	9.6

***** Analysis of variance *****

Variate: May

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	365.48	182.74	15.08	
Block.*Units* stratum					
Treatmen	3	573.85	191.28	15.79	0.003
Residual	6	72.70	12.12		
Total	11	1012.03			

***** Tables of means *****

Variate: May

Grand mean 100.5

Treatmen	Control	Improved	Slipper	Surface
	96.4	96.7	96.4	112.5

*** Standard errors of differences of means ***

Table	Treatmen
rep.	3
d.f.	6
s.e.d.	2.84

*** Least significant differences of means ***

Table	Treatmen
rep.	3
d.f.	6
l.s.d.	6.95

***** Stratum standard errors and coefficients of variation *****

Variate: May

Stratum	d.f.	s.e.	cv%
Block	2	6.76	6.7
Block.*Units*	6	3.48	3.5

Hagberg FN Analysis

***** Analysis of variance *****

Variate: HFN (December)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	10055.	5027.	1.91	
Block.*Units* stratum					
Treatmen	3	1212.	404.	0.15	0.924
Residual	6	15776.	2629.		
Total	11	27042.			

***** Tables of means *****

Variate: HFN

Grand mean 260.

Treatmen	C	I	Sl	Su
	267.	244.	259.	271.

*** Standard errors of differences of means ***

Table	Treatmen
rep.	3
d.f.	6
s.e.d.	41.9

*** Least significant differences of means ***

Table	Treatmen
rep.	3
d.f.	6
l.s.d.	102.4

***** Stratum standard errors and coefficients of variation *****

Variate: HFN

Stratum	d.f.	s.e.	cv%
Block	2	35.5	13.6
Block.*Units*	6	51.3	19.7

***** Analysis of variance *****

Variate: HFN (May)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	12331.	6166.	0.42	
Block.*Units* stratum					
Treatmen	3	5261.	1754.	0.12	0.945
Residual	6	87805.	14634.		
Total	11	105397.			

***** Tables of means *****

Variate: HFN

Grand mean 288.

Treatmen	C	I	Sl	Su
	308.	293.	253.	296.

Appendix 4.3

*** Standard errors of differences of means ***

Table	Treatmen
rep.	3
d.f.	6
s.e.d.	98.8

*** Least significant differences of means ***

Table	Treatmen
rep.	3
d.f.	6
l.s.d.	241.7

***** Stratum standard errors and coefficients of variation *****

Variate: HFN

Stratum	d.f.	s.e.	cv%
Block	2	39.3	13.7
Block.*Units*	6	121.0	42.1

Moisture Content Analysis

Variate: MC% (December)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	1.402	0.701	0.29	
Block.*Units* stratum					
Plot	3	27.125	9.042	3.70	0.027
Rep	2	3.807	1.903	0.78	0.471
Plot.Rep	6	3.616	0.603	0.25	0.955
Residual	22	53.698	2.441		
Total	35	89.648			

***** Tables of means *****

Variate: MC% (December)

Grand mean 14.26

Plot	Control	Improved	Slipper	Surface
	13.39	15.61	13.62	14.41
Rep	1.00	2.00	3.00	
	14.18	14.69	13.91	
Plot	Rep	1.00	2.00	3.00
Control		13.33	13.20	13.63
Improved		15.40	16.27	15.17
Slipper		13.47	14.13	13.27
Surface		14.50	15.17	13.57

*** Standard errors of differences of means ***

Table	Plot	Rep	Plot Rep
rep.	9	12	3
d.f.	22	22	22
s.e.d.	0.736	0.638	1.276

*** Least significant differences of means ***

Table	Plot	Rep	Plot Rep
rep.	9	12	3
d.f.	22	22	22
l.s.d.	1.527	1.323	2.645

***** Stratum standard errors and coefficients of variation *****

Variate: MC%

Stratum	d.f.	s.e.	cv%
Block	2	0.242	1.7
Block.*Units*	22	1.562	11.0

Variate: MC% (May)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	1.1506	0.5753	1.04	
Block.*Units* stratum					
Plot	3	0.7964	0.2655	0.48	0.699
Rep	2	1.1739	0.5869	1.06	0.363
Plot.Rep	6	2.7061	0.4510	0.82	0.569
Residual	22	12.1628	0.5529		
Total	35	17.9897			

***** Tables of means *****

Variate: MC% (May)

Grand mean 13.15

Plot	Control	Improved	Slipper	Surface
	13.22	13.17	13.31	12.91
Rep	1.00	2.00	3.00	
	13.37	12.92	13.17	
Plot	Rep	1.00	2.00	3.00
Control		13.80	12.73	13.13
Improved		13.70	12.83	12.97
Slipper		13.13	13.50	13.30
Surface		12.83	12.63	13.27

*** Standard errors of differences of means ***

Table	Plot	Rep	Plot Rep
rep.	9	12	3
d.f.	22	22	22
s.e.d.	0.351	0.304	0.607

*** Least significant differences of means ***

Table	Plot	Rep	Plot Rep
rep.	9	12	3
d.f.	22	22	22
l.s.d.	0.727	0.630	1.259

***** Stratum standard errors and coefficients of variation *****

Variate: MC% (May)

Stratum	d.f.	s.e.	cv%
Block	2	0.219	1.7
Block.*Units*	22	0.744	5.7

Appendix 5

Appendix 5.1.**Respondents comments following market analysis.**

1. I like spreading with a boom and cord the best.
2. I have experienced problems with application prior to planting.
3. We have been using sewage sludge for a number of years, we find the dribble bar method best of all.
4. I would only pay for sewage sludge if it were more even in its N, P & K.
5. The idea has been put forward that the water companies should pay the farmer to dispose of sewage sludge to land.
6. I would be prepared to pay for sewage sludge as long as it was cheaper than fertiliser.
7. The dribble bar applicator leaves large puddles of slurry that are hard to move.
8. Sludge injection will not fit into my farming system.
9. I will not use sewage sludge because of the heavy metals and other pollutants.
10. I won't use sewage sludge because of heavy metals.
11. I will not use sewage sludge because poisons in the human system are put directly back into the human food chain.
12. I use a trickle bar but need to develop a better methodology for the 1 million gallons of pig slurry I produce.
13. This is a heavily stocked farm and not suitable for sludge application.
14. I farm next to a farm using sewage sludge and the smell is appalling. If processed and pelleted to remove the smell and heavy metals I would consider using it.
15. I stopped using sewage sludge because of poor application by contractors.
16. I stopped using sewage sludge because there was no supervision given to field operators, some areas were swamped with sludge, mainly on the turns and headlands. This resulted in grass areas dying and the inconsistency of the sludge resulted in stripes in my field.
17. I would be prepared to use sewage sludge if I could see clear benefits.
18. It has to go somewhere. Is anything more sensible than land application?
19. My opinion of sewage sludge depends on prior treatment.
20. I do not use sewage sludge because I can't get it.
21. My landlord won't allow me to inject sewage sludge. (x4)

Appendix 6

Appendix 6.1.

EORT Calibration using conventional measurement techniques and computer data-logging methods.

Calibration of the EORT was carried out using both conventional data capture techniques (Section 2.6.4) and by computer data logging techniques (Section 7.2.1). Calibration was achieved by adding weights to the EORT in both the horizontal and vertical plane to excite an output through both horizontal and vertical channel outputs. Two levels of amplification were considered, allowing a large range of forces to be accurately recorded.

6.1.1 Conventional data recording (calibration)

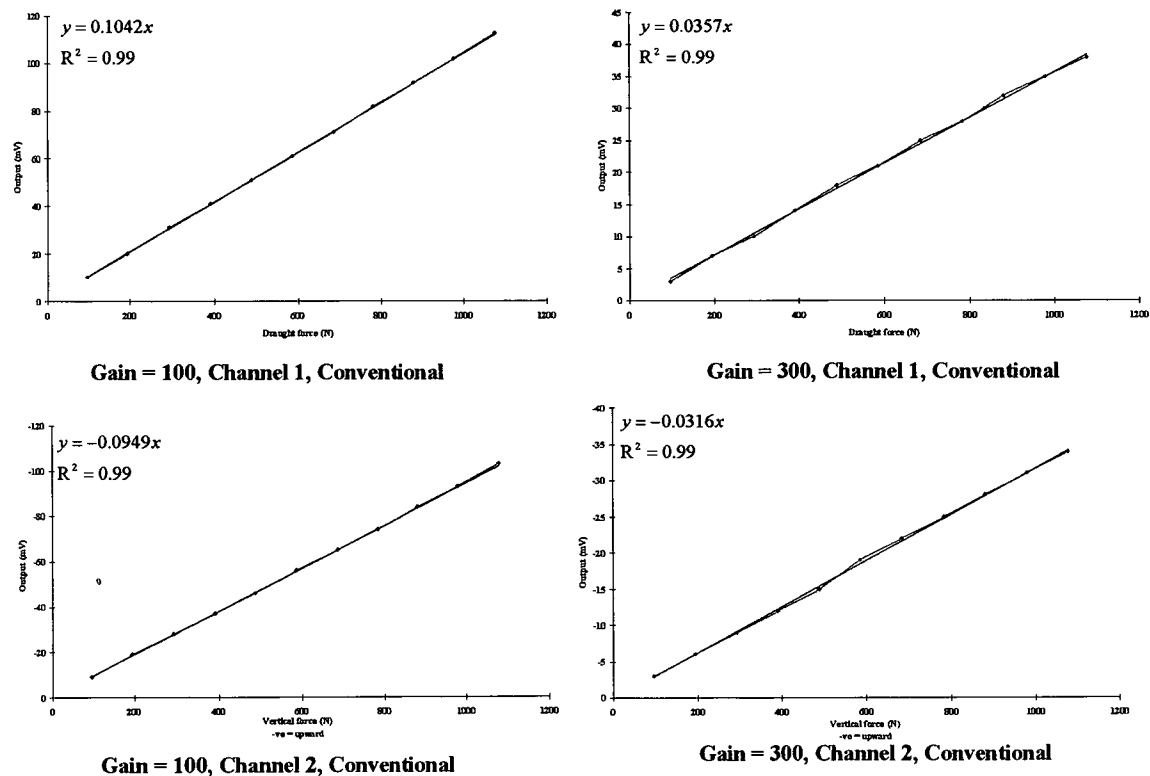


Fig. 6.1.1 Calibration curves for EORT output through conventional data recording equipment, at 2 levels of amplification for both draught and vertical force.

6.1.2 Computer Data recording (calibration).

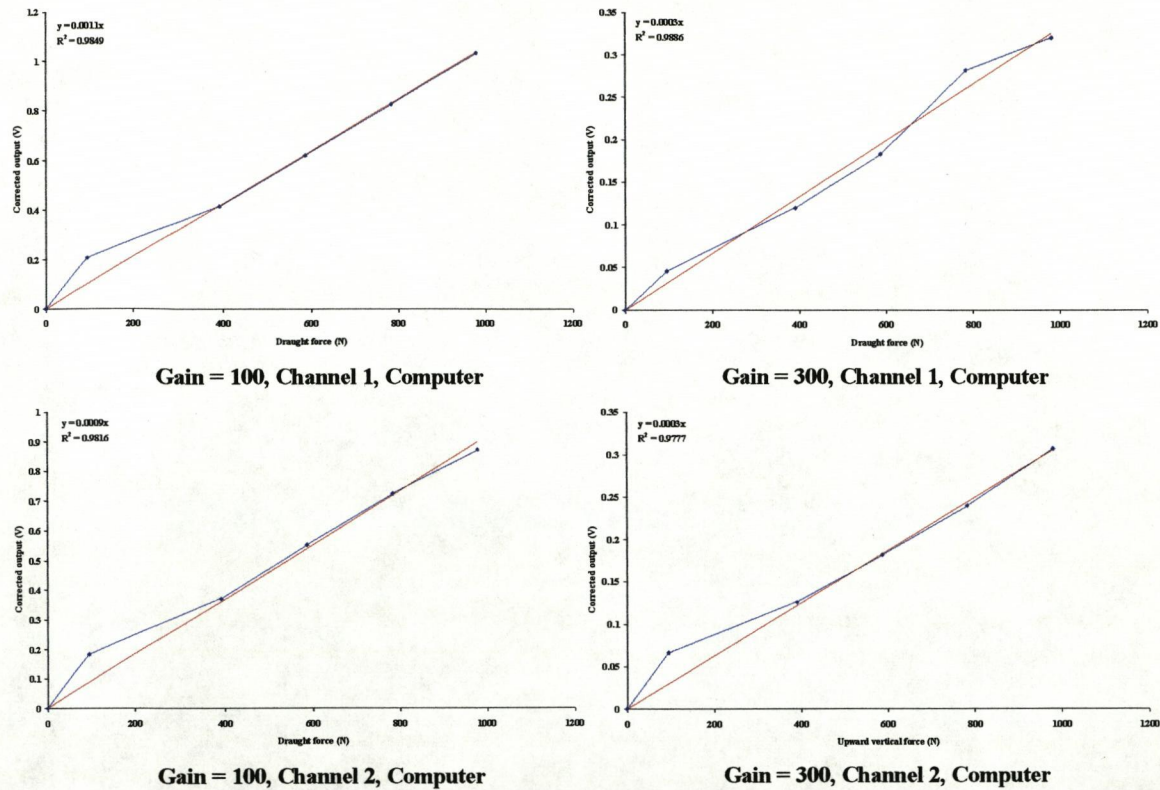


Fig. 6.1.1 Calibration curves for EORT computer based data recording equipment, at 2 levels of amplification for both draught and vertical force.

Appendix 6.2.
Statistical analysis

Moisture content % (dry basis)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Bin_Fit	16	2.0681	0.1293	1.11	0.388
Residual	34	3.9752	0.1169		
Total	50	6.0433			

***** Tables of means *****

Grand mean 8.382

Bin_Fit	1.00	2.00	3.00	4.00	5.00	6.00	7.00
	8.557	8.610	8.440	8.357	8.107	7.973	8.423
Bin_Fit	8.00	9.00	10.00	11.00	12.00	13.00	14.00
	8.147	8.420	8.390	8.320	8.620	8.697	8.140
Bin_Fit	15.00	16.00	17.00				
	8.303	8.340	8.657				

*** Standard errors of differences of means ***

Table	Bin_Fit
rep.	3
d.f.	34
s.e.d.	0.2792

*** Least significant differences of means ***

Table	Bin_Fit
rep.	3
d.f.	34
l.s.d.	0.5674

***** Stratum standard errors and coefficients of variation *****

d.f.	s.e.	cv%
34	0.3419	4.1

Bulk density kg/m³ (dry basis)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Bin_Fit	16	53036.	3315.	1.68	0.101
Residual	34	67144.	1975.		
Total	50	120180.			

***** Tables of means *****

Grand mean 1411.6

Bin_Fit	1.00	2.00	3.00	4.00	5.00	6.00	7.00
	1382.1	1370.5	1425.9	1438.9	1387.4	1438.6	1399.9
Bin_Fit	8.00	9.00	10.00	11.00	12.00	13.00	14.00
	1418.1	1447.7	1381.2	1446.7	1444.9	1429.6	1414.4
Bin_Fit	15.00	16.00	17.00				
	1365.0	1350.9	1455.2				

*** Standard errors of differences of means ***

Table	Bin_Fit
rep.	3
d.f.	34
s.e.d.	36.28

*** Least significant differences of means ***

Table	Bin_Fit
rep.	3
d.f.	34
l.s.d.	73.74

***** Stratum standard errors and coefficients of variation *****

d.f.	s.e.	cv%
34	44.44	3.1

Upper lateral disturbed width (ULDW) mm.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	65.3	32.7	0.08	
Rep.*Units* stratum					
Angle	6	12435.4	2072.6	5.32	<.001
Depth	6	208949.7	34824.9	89.39	<.001
Angle.Depth	36	23793.2	660.9	1.70	0.022
Residual	96	37401.4	389.6		
Total	146	282644.9			

*** Standard errors of differences of means ***

Table	Angle	Depth	Angle Depth
rep.	21	21	3
d.f.	96	96	96
s.e.d.	6.09	6.09	16.12

*** Least significant differences of means ***

Table	Angle	Depth	Angle Depth
rep.	21	21	3
d.f.	96	96	96
l.s.d.	12.09	12.09	31.99

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	0.82	0.6
Rep.*Units*	96	19.74	15.3

Lower lateral disturbed width (LLDW) mm.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	654.4	327.2	0.91	
Rep.*Units* stratum					
Angle	6	4733.3	788.9	2.18	0.051
Depth	6	101161.9	16860.3	46.67	<.001
Angle.Depth	36	15238.1	423.3	1.17	0.268
Residual	96	34678.9	361.2		
Total	146	156466.7			

*** Standard errors of differences of means ***

Table	Angle	Depth	Angle Depth
rep.	21	21	3
d.f.	96	96	96
s.e.d.	5.87	5.87	15.52

*** Least significant differences of means ***

Table	Angle	Depth	Angle Depth
rep.	21	21	3
d.f.	96	96	96
l.s.d.	11.64	11.64	30.80

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	2.58	1.5
Rep.*Units*	96	19.01	10.9

Heave (mm)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	189.56	94.78	4.85	
Rep.*Units* stratum					
Angle	6	272.19	45.37	2.32	0.039
Depth	6	3215.24	535.87	27.44	<.001
Angle.Depth	36	902.57	25.07	1.28	0.169
Residual	96	1875.10	19.53		
Total	146	6454.67			

*** Standard errors of differences of means ***

Table	Angle	Depth	Angle Depth
rep.	21	21	3
d.f.	96	96	96
s.e.d.	1.364	1.364	3.609

*** Least significant differences of means ***

Table	Angle	Depth	Angle Depth
rep.	21	21	3
d.f.	96	96	96
l.s.d.	2.707	2.707	7.163

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	1.391	7.7
Rep.*Units*	96	4.420	24.4

Channel (mm)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	4.59	2.29	0.15	
Rep.*Units* stratum					
Angle	6	258.56	43.09	2.76	0.016
Depth	6	982.56	163.76	10.49	<.001
Angle.Depth	36	831.82	23.11	1.48	0.067
Residual	96	1498.08	15.61		
Total	146	3575.61			

*** Standard errors of differences of means ***

Table	Angle	Depth	Angle Depth
rep.	21	21	3
d.f.	96	96	96
s.e.d.	1.219	1.219	3.225

*** Least significant differences of means ***

Table	Angle	Depth	Angle Depth
rep.	21	21	3
d.f.	96	96	96
l.s.d.	2.420	2.420	6.402

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	0.216	3.3
Rep.*Units*	96	3.950	59.4

Upper disturbed volume (mm³)

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	3.244E+06	1.622E+06	6.29	
Rep.*Units* stratum					
Angle	6	7.677E+06	1.280E+06	4.96	<.001
Depth	6	1.030E+08	1.716E+07	66.55	<.001
Angle.Depth	36	1.459E+07	4.053E+05	1.57	0.043
Residual	93(3)	2.398E+07	2.578E+05		
Total	143(3)	1.502E+08			

*** Standard errors of differences of means ***

Table	Angle	Depth	Angle Depth
rep.	21	21	3
d.f.	93	93	93
s.e.d.	156.7	156.7	414.6

*** Least significant differences of means ***

Table	Angle	Depth	Angle Depth
rep.	21	21	3
d.f.	93	93	93
l.s.d.	311.2	311.2	823.3

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	181.9	13.0
Rep.*Units*	93	507.8	36.2

Lower disturbed volume (mm³)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	3.902E+05	1.951E+05	0.39	
Rep.*Units* stratum					
Angle	6	2.186E+07	3.643E+06	7.34	<.001
Depth	6	6.723E+08	1.120E+08	225.84	<.001
Angle.Depth	36	4.293E+07	1.193E+06	2.40	<.001
Residual	96	4.763E+07	4.961E+05		
Total	146	7.851E+08			

*** Standard errors of differences of means ***

Table	Angle	Depth	Angle Depth
rep.	21	21	3
d.f.	96	96	96
s.e.d.	217.4	217.4	575.1

*** Least significant differences of means ***

Table	Angle	Depth	Angle Depth
rep.	21	21	3
d.f.	96	96	96
l.s.d.	431.5	431.5	1141.6

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	63.1	1.6
Rep.*Units*	96	704.4	18.3

Theoretical application rate (m³/ha); 0.2 m tine spacing.

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	8110.5	4055.3	6.29	
Rep.*Units* stratum					
Angle	6	19193.2	3198.9	4.96	<.001
Depth	6	257387.1	42897.8	66.55	<.001
Angle.Depth	36	36472.7	1013.1	1.57	0.043
Residual	93(3)	59947.2	644.6		
Total	143(3)	375494.8			

*** Standard errors of differences of means ***

Table	Angle	Depth	Angle Depth
rep.	21	21	3
d.f.	93	93	93
s.e.d.	7.84	7.84	20.73

*** Least significant differences of means ***

Table	Angle	Depth	Angle Depth
rep.	21	21	3
d.f.	93	93	93
l.s.d.	15.56	15.56	41.17

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	9.10	13.0
Rep.*Units*	93	25.39	36.2

Theoretical application rate (m³/ha); 0.25 m tine spacing.

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	5190.7	2595.4	6.29	
Rep.*Units* stratum					
Angle	6	12283.7	2047.3	4.96	<.001
Depth	6	164727.7	27454.6	66.55	<.001
Angle.Depth	36	23342.5	648.4	1.57	0.043
Residual	93(3)	38366.2	412.5		
Total	143(3)	240316.7			

*** Standard errors of differences of means ***

Table	Angle	Depth	Angle Depth
rep.	21	21	3
d.f.	93	93	93
s.e.d.	6.27	6.27	16.58

*** Least significant differences of means ***

Table	Angle	Depth	Angle Depth
rep.	21	21	3
d.f.	93	93	93
l.s.d.	12.45	12.45	32.93

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	7.28	13.0
Rep.*Units*	93	20.31	36.2

Draught force by conventional instrumentation (N)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	335294.	167647.	19.41	
Rep.*Units* stratum					
Angle	6	423251.	70542.	8.17	<.001
Depth	6	7457464.	1242911.	143.93	<.001
Angle.Depth	36	227043.	6307.	0.73	0.856
Residual	96	828985.	8635.		
Total	146	9272038.			

*** Standard errors of differences of means ***

Table	Angle	Depth	Angle Depth
rep.	21	21	3
d.f.	96	96	96
s.e.d.	28.68	28.68	75.87

*** Least significant differences of means ***

Table	Angle	Depth	Angle Depth
rep.	21	21	3
d.f.	96	96	96
l.s.d.	56.92	56.92	150.61

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	58.49	12.3
Rep.*Units*	96	92.93	19.5

Upward vertical force using conventional instrumentation (N)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	25918.	12959.	5.24	
Rep.*Units* stratum					
Angle	6	3046898.	507816.	205.49	<.001
Depth	6	961630.	160272.	64.85	<.001
Angle.Depth	36	289916.	8053.	3.26	<.001
Residual	96	237238.	2471.		
Total	146	4561601.			

*** Standard errors of differences of means ***

Table	Angle	Depth	Angle Depth
rep.	21	21	3
d.f.	96	96	96
s.e.d.	15.34	15.34	40.59

*** Least significant differences of means ***

Table	Angle	Depth	Angle Depth
rep.	21	21	3
d.f.	96	96	96
l.s.d.	30.45	30.45	80.57

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	16.26	5.2
Rep.*Units*	96	49.71	16.0

Draught force using computer data acquisition (N)

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	399468.	199734.	18.46	
Rep.*Units* stratum					
Angle	6	389996.	64999.	6.01	<.001
Depth	6	7986551.	1331092.	123.00	<.001
Angle.Depth	36	367366.	10205.	0.94	0.567
Residual	87(9)	941515.	10822.		
Total	137(9)	9528673.			

*** Standard errors of differences of means ***

Table	Angle	Depth	Angle Depth
rep.	21	21	3
d.f.	87	87	87
s.e.d.	32.10	32.10	84.94

*** Least significant differences of means ***

Table	Angle	Depth	Angle Depth
rep.	21	21	3
d.f.	87	87	87
l.s.d.	63.81	63.81	168.83

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	63.85	12.7
Rep.*Units*	87	104.03	20.6

Upward vertical force using computer data acquisition (N)

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	40087.	20044.	4.00	
Rep.*Units* stratum					
Angle	6	3682716.	613786.	122.47	<.001
Depth	6	1132869.	188811.	37.67	<.001
Angle.Depth	35(1)	451275.	12894.	2.57	<.001
Residual	76(20)	380901.	5012.		
Total	125(21)	4752944.			

*** Standard errors of differences of means ***

Table	Angle	Depth	Angle Depth
rep.	21	21	3
d.f.	76	76	76
s.e.d.	21.85	21.85	57.80

*** Least significant differences of means ***

Table	Angle	Depth	Angle Depth
rep.	21	21	3
d.f.	76	76	76
l.s.d.	43.51	43.51	115.13

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	20.23	5.7
Rep.*Units*	76	70.79	20.0

Appendix 6.3.

Regression analysis (theoretical application rate)

Theoretical application rate m^3/ha , (0.2 m tine spacing).

Response variate: ap2
 Explanatory: depth
 Fitted Curve: $A + B \cdot R^{**}X$
 Constraints: $R > 1$

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	251371.	125685.3	142.77	<.001
Residual	141	124124.	880.3		
Total	143	375495.	2625.8		

Change	2	-251371.	-125685.3	-142.77	<.001
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*** Estimates of parameters ***

	estimate	s.e.
R	3.60E+10	2.67E+11
B	23.4	17.2
A	-18.7	26.6

***** Nonlinear regression analysis *****

Response variate: ap2
 Explanatory: depth
 Grouping factor: angle, constant parameters separate
 Fitted Curve: $A + B \cdot R^{**}X$
 Constraints: $R > 1$

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	8	266004.	33250.5	41.00	<.001
Residual	135	109491.	811.0		
Total	143	375495.	2625.8		

Change	6	-14633.	-2438.9	-3.01	<.001
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Percentage variance accounted for 69.1
 Standard error of observations is estimated to be 28.5

*** Estimates of parameters ***

	estimate
R	1.000E+09
B	33.53
A angle -15	-306.2
A angle -10	-310.6
A angle -5	-340.4
A angle 0	-322.8
A angle 5	-332.5
A angle 10	-334.5
A angle 15	-330.6

***** Nonlinear regression analysis *****

Response variate: ap2
 Explanatory: depth
 Grouping factor: angle, all linear parameters separate
 Fitted Curve: $A + B \cdot R^{**}X$
 Constraints: $R > 1$

Appendix 6.3

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	14	278814.	19915.3	26.57	<.001
Residual	129	96681.	749.5		
Total	143	375495.	2625.8		

Change 6 -12810. -2135.0 -2.85 <.001

Percentage variance accounted for 71.5
Standard error of observations is estimated to be 27.4

*** Estimates of parameters ***

	estimate
R	2.480E+18
B angle -15	5.841
A angle -15	15.65
B angle -10	4.963
A angle -10	21.47
B angle -5	5.338
A angle -5	14.90
B angle 0	5.050
A angle 0	21.51
B angle 5	3.607
A angle 5	15.31
B angle 10	4.233
A angle 10	5.990
B angle 15	2.631
A angle 15	28.57

***** Nonlinear regression analysis *****

Response variate: ap2
Explanatory: depth
Grouping factor: angle, all parameters separate
Fitted Curve: A + B*R**X
Constraints: R > 1

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.
Regression	20	288352.	14417.6	20.35
Residual	123	87143.	708.5	
Total	143	375495.	2625.8	

Change 6 -9538. -1589.7 -2.24

Percentage variance accounted for 73.0
Standard error of observations is estimated to be 26.6

*** Estimates of parameters ***

	estimate	s.e.
R angle -15	1.71E+19	2.69E+20
B angle -15	4.96	6.61
A angle -15	18.2	21.9
R angle -10	2.22E+17	3.95E+18
B angle -10	6.10	9.39
A angle -10	18.4	25.7
R angle -5	5.27E+11	8.86E+12
B angle -5	21.6	35.2
A angle -5	-20.0	61.6
R angle 0	17.	240.
B angle 0	780.	4383.
A angle 0	-822.	4420.
R angle 5	79339.	1571853.
B angle 5	85.	240.
A angle 5	-96.	268.
R angle 10	2.13E+13	4.13E+14
B angle 10	11.8	21.0
A angle 10	-10.7	40.0
R angle 15	9.98E+15	3.26E+17
B angle 15	4.2	12.2
A angle 15	24.5	29.3

***** Nonlinear regression analysis *****

Response variate: ap2
 Explanatory: depth
 Grouping factor: angle, all parameters separate
 Fitted Curve: A + B*R**X
 Constraints: R < 1

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	20	288352.	14417.6	20.35	<.001
Residual	123	87143.	708.5		
Total	143	375495.	2625.8		
Change	6	-9538.	-1589.7	-2.24	<.001

Percentage variance accounted for 73.0
 Standard error of observations is estimated to be 26.6

*** Estimates of parameters ***

	estimate	s.e.
R angle -15	1.71E+19	2.69E+20
B angle -15	4.96	6.61
A angle -15	18.2	21.9
R angle -10	2.22E+17	3.95E+18
B angle -10	6.10	9.39
A angle -10	18.4	25.7
R angle -5	5.27E+11	8.86E+12
B angle -5	21.6	35.2
A angle -5	-20.0	61.6
R angle 0	17.	240.
B angle 0	780.	4383.
A angle 0	-822.	4420.
R angle 5	79339.	1571853.
B angle 5	85.	240.
A angle 5	-96.	268.
R angle 10	2.13E+13	4.13E+14
B angle 10	11.8	21.0
A angle 10	-10.7	40.0
R angle 15	9.98E+15	3.26E+17
B angle 15	4.2	12.2
A angle 15	24.5	29.3

*** Accumulated analysis of variance ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Change					
+ depth	2	251370.5	125685.3	177.40	<.001
+ angle	6	14633.5	2438.9	3.44	0.004
+ depth.angle	6	12810.0	2135.0	3.01	0.009
+ Separate nonlinear	6	9538.0	1589.7	2.24	0.043
Residual	123	87142.9	708.5		
Total	143	375494.8	2625.8		

Theoretical application rate m^3/ha , (0.25 m tine spacing).

Response variate: ap25
 Explanatory: depth
 Fitted Curve: A + B*R**X
 Constraints: R > 1

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	160877.	80438.6	142.77	<.001
Residual	141	79440.	563.4		
Total	143	240317.	1680.5		
Change	2	-160877.	-80438.6	-142.77	<.001

Percentage variance accounted for 66.5
 Standard error of observations is estimated to be 23.7

*** Estimates of parameters ***

	estimate	s.e.
R	3.60E+10	2.67E+11
B	18.7	13.7
A	-14.9	21.3

***** Nonlinear regression analysis *****

Response variate: ap25
 Explanatory: depth
 Grouping factor: angle, constant parameters separate
 Fitted Curve: $A + B \cdot R^{**X}$
 Constraints: $R > 1$

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	8	170243.	21280.3	41.00	<.001
Residual	135	70074.	519.1		
Total	143	240317.	1680.5		
Change	6	-9365.	-1560.9	-3.01	<.001

Percentage variance accounted for 69.1
 Standard error of observations is estimated to be 22.8

*** Estimates of parameters ***

	estimate
R	1.000E+09
B	26.83
A angle -15	-245.0
A angle -10	-248.5
A angle -5	-272.3
A angle 0	-258.2
A angle 5	-266.0
A angle 10	-267.6
A angle 15	-264.5

***** Nonlinear regression analysis *****

Response variate: ap25
 Explanatory: depth
 Grouping factor: angle, all linear parameters separate
 Fitted Curve: $A + B \cdot R^{**X}$
 Constraints: $R > 1$

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	14	178441.	12745.8	26.57	<.001
Residual	129	61876.	479.7		
Total	143	240317.	1680.5		
Change	6	-8198.	-1366.4	-2.85	<.001

Percentage variance accounted for 71.5
 Standard error of observations is estimated to be 21.9

*** Estimates of parameters ***

	estimate
R	2.480E+18
B angle -15	4.673
A angle -15	12.52
B angle -10	3.970
A angle -10	17.18
B angle -5	4.270
A angle -5	11.92
B angle 0	4.040
A angle 0	17.21
B angle 5	2.885
A angle 5	12.25
B angle 10	3.387
A angle 10	4.792
B angle 15	2.105
A angle 15	22.85

***** Nonlinear regression analysis *****

Response variate: ap25
 Explanatory: depth
 Grouping factor: angle, all parameters separate
 Fitted Curve: $A + B \cdot R^{**X}$
 Constraints: $R > 1$

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.
Regression	20	184545.	9227.3	20.35
Residual	123	55771.	453.4	
Total	143	240317.	1680.5	

Change	6	-6104.	-1017.4	-2.24
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Percentage variance accounted for 73.0
 Standard error of observations is estimated to be 21.3

*** Estimates of parameters ***

	estimate	s.e.
R angle -15	1.71E+19	2.69E+20
B angle -15	3.97	5.29
A angle -15	14.6	17.5
R angle -10	2.22E+17	3.95E+18
B angle -10	4.88	7.51
A angle -10	14.7	20.6
R angle -5	5.27E+11	8.86E+12
B angle -5	17.3	28.2
A angle -5	-16.0	49.2
R angle 0	17.	240.
B angle 0	624.	3506.
A angle 0	-658.	3536.
R angle 5	79339.	1571853.
B angle 5	68.	192.
A angle 5	-77.	214.
R angle 10	2.13E+13	4.13E+14
B angle 10	9.5	16.8
A angle 10	-8.5	32.0
R angle 15	9.98E+15	3.26E+17
B angle 15	3.39	9.74
A angle 15	19.6	23.4

***** Nonlinear regression analysis *****

Response variate: ap25
 Explanatory: depth
 Grouping factor: angle, all parameters separate
 Fitted Curve: $A + B \cdot R^{**X}$
 Constraints: $R < 1$

Appendix 6.3

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	20	184545.	9227.3	20.35	<.001
Residual	123	55771.	453.4		
Total	143	240317.	1680.5		
Change	6	-6104.	-1017.4	-2.24	<.001

Percentage variance accounted for 73.0
Standard error of observations is estimated to be 21.3

*** Estimates of parameters ***

	estimate	s.e.
R angle -15	1.71E+19	2.69E+20
B angle -15	3.97	5.29
A angle -15	14.6	17.5
R angle -10	2.22E+17	3.95E+18
B angle -10	4.88	7.51
A angle -10	14.7	20.6
R angle -5	5.27E+11	8.86E+12
B angle -5	17.3	28.2
A angle -5	-16.0	49.2
R angle 0	17.	240.
B angle 0	624.	3506.
A angle 0	-658.	3536.
R angle 5	79339.	1571853.
B angle 5	68.	192.
A angle 5	-77.	214.
R angle 10	2.13E+13	4.13E+14
B angle 10	9.5	16.8
A angle 10	-8.5	32.0
R angle 15	9.98E+15	3.26E+17
B angle 15	3.39	9.74
A angle 15	19.6	23.4

*** Accumulated analysis of variance ***

	d.f.	s.s.	m.s.	v.r.	F pr.
Change					
+ depth	2	160877.1	80438.6	177.40	<.001
+ angle	6	9365.4	1560.9	3.44	0.004
+ depth.angle	6	8198.4	1366.4	3.01	0.009
+ Separate nonlinear	6	6104.3	1017.4	2.24	0.043
Residual	123	55771.5	453.4		
Total	143	240316.7	1680.5		

Appendix 7

Appendix 7.1.



All Dimensions in mm

Parallel Linkage

Appendix 7.2.

Quasi-static model for the depth prediction of selected injector tines attached to the Greentrac parallel linkage under soil dynamics laboratory conditions.

To enable the solution of the parallel linkage force system, defined in *Section 8.3.3*, a computer based modelling program has been developed to predict the operating depth of a number of selected injector tines under soil dynamics laboratory conditions.

7.2.1 Model basis.

The implicit nature of the governing equation describing the resolution of forces within the parallel linkage and injector tine force system requires that an iterative solution be derived to predict the operating depth of an injector tine. Tine force prediction models currently available (Godwin, 1974), are only suitable for simple soil engaging tines, whereas, injector tines tend to be complex in nature, primarily as a result of their geometry, and the soil disturbance requirements that are implicit in the bio-solids application procedure.

The developed model is based on the rigorous derivation of the general solution to the force system described in *Section 8.3.3*, and utilises Microsoft Visual Basic programming in Microsoft Excel to provide rapid operating depth prediction. A number of parameters are variable allowing the user to define the conditions under which the force system is constrained.

7.2.2 Main interface.

The main user interface comprises 5 main sections (*Fig. Ap 7.2.1*):

1. Linkage properties.
2. Tine properties.
3. Input control.
4. Solution control.
5. Display control.

These sections allow the user to control the model by varying the linkage dimensions and mass, in addition to viewing the graphical representation of the force system and solving the iterative problem to within a desired degree of accuracy.

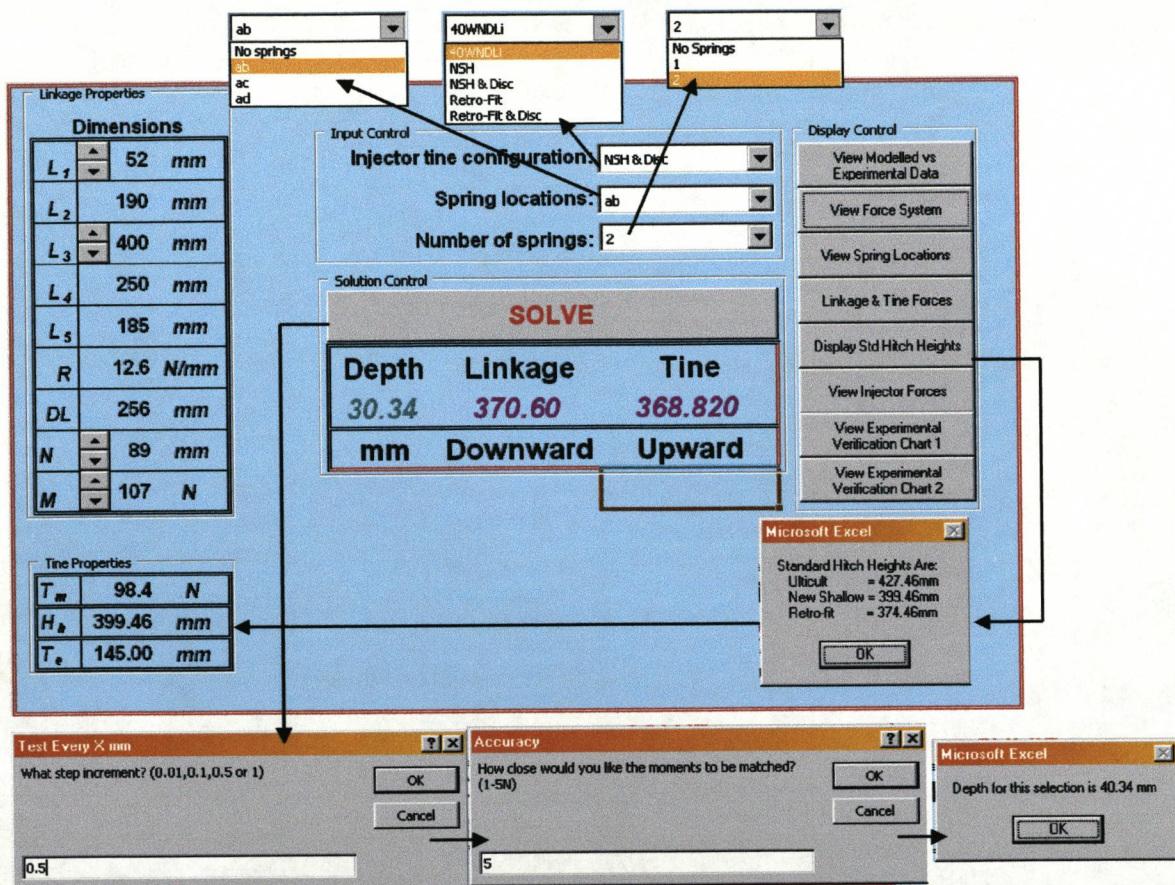


Fig. Ap 7.2.1 Main user interface of computer depth prediction model.

7.2.2.1 Linkage properties.

The linkage properties that may be varied, to allow the model to be used on any parallel linkage with an internal spring attachment, are contained within the “linkage properties” frame. In this instance, the model has been constrained to accept only minor variations by the user, although by slight modification, the variability of all linkage properties can be attained. Variables L_2 , and R are automatically altered depending on the users choices in the input control frame.

7.2.2.2 Tine properties.

The injector tine properties are also dictated by the users choice in the input control frame, the values of T_e , H_h and T_m are automatically updated depending on the choice of injector tine.

7.2.2.3 Input control.

The input control frame allows the user to select the injector tine configuration, spring locations and the number of springs attached to the system. Choice of injector tine will affect the values contained within the “tine properties” frame, choice of spring locations

will automatically update L_2 and choice of the number of springs will update R (spring rating). The user may ascertain the meaning of the spring location codes by depressing the "View Spring Locations" button in the display control frame.

7.2.2.4 Display control.

The display control frame allows the user to view the results of their inputs in a graphical form, and also provides information on the system. Much of the data contained within this section relates to the experimental verification of the linkage force system, presented in *Appendix 7.3*, and the graphical presentation of the force system in *Section 8.3.5*. This control section provides some help to the user on their selection of input for the solution of the problem.

7.2.2.5 Solution control.

This section utilises the conditions set by the user to establish the operating depth at which equilibrium between applied linkage forces and opposing tine forces are equal. Depressing the "Solve" button opens an input dialog box prompting the user for the step increment that the program uses to test for equilibrium. A selection of 0.5 in this instance will force the program to check for equilibrium every 0.5 mm between one extreme of linkage position and the other. Following this input, the user is prompted for an accuracy input. The value entered here sets the conditions under which the program will locate an answer. An accuracy of 5 N sets the program to stop once the linkage and injector forces are within 5 N of each other. Should the program be unable to find an answer, the cycle restarts, and the user should enter either a smaller step increment or a larger accuracy number. Once the program locates an answer, a dialog box appears indicating the operating depth at which force equilibrium within the system exists.

7.2.3 Model presentation.

The full working model is presented on 3.5" floppy disk attached to this thesis. Operation requires Microsoft Windows 95/98/NT and Microsoft Excel 97 or later.

Appendix 7.3.

Experimental verification of applied linkage force.

Following the analytical determination of the applied linkage force exerted as a result of changing linkage geometry and altering spring conditions, an experimental verification was carried out to confirm the analysis. Experimental verification was carried out using a load cell attached to the rear vertical arm of the parallel linkage, which was subsequently moved through its degree of travel. Calibrated load cell output was obtained using an auto-ranging digital multi-meter (Keithly 197). The results obtained using this method were converted from micro-volt output to load using a calibration equation, and compared to calculated applied force obtained using the equations presented in *Section 8.3.3.2*. Force testing was carried out under all possible standard spring conditions, over a simulated hitch point variation of 0.2 m. *Fig Ap 7.3.1* and *7.3.2* illustrate the correlation between predicted and experimental forces.

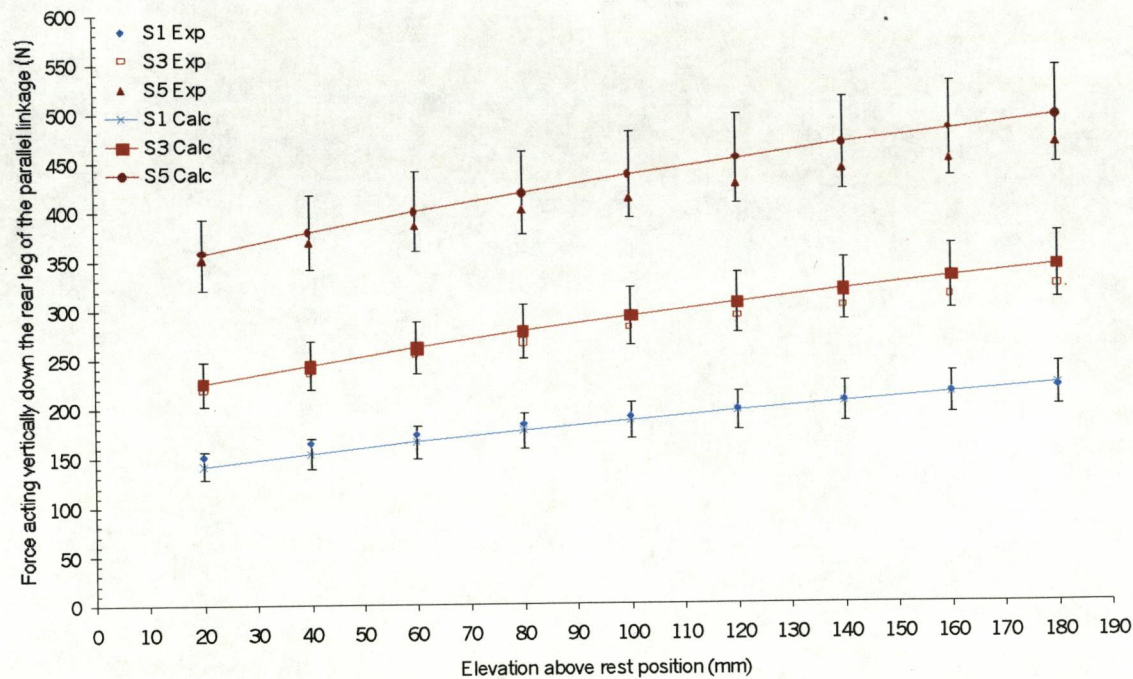


Fig Ap 7.3.1. Experimental and predicted forces acting down the rear vertical link of the Greentrac parallel linkage under applied spring force comprising 1 spring between pivots ab (S1), ac (S3) and ad (S5).

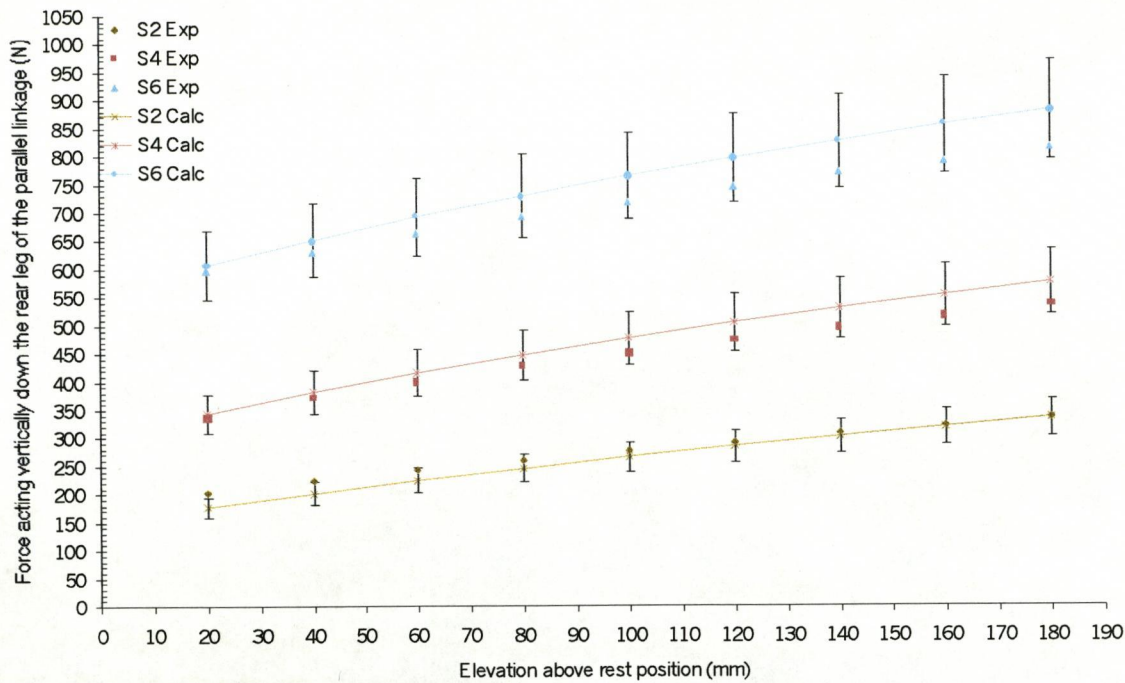


*Fig Ap 7.3.2. Experimental and predicted forces acting down the rear vertical link of the Greentrac parallel linkage under applied spring force comprising 2 springs between pivots *ab* (S2), *ac* (S4) and *ad* (S6).*

Experimental values were found to be consistently within 10% of calculated force values over all spring conditions. This suggests that the force system analysis presented in *Section 8.3.3.2* adequately represents experimental conditions.

Appendix 7.4.

Statistical analysis of soil properties relating to the evaluation of injector tines at
0.01 m depth increments

Variate: Bulk density (dry basis) kg/m³

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Prep_No_	16	46585.	2912.	0.73	0.745
Residual	34	135479.	3985.		
Total	50	182064.			

***** Tables of means *****

Grand mean 1443.2

Prep_No_	1.00	2.00	3.00	4.00	5.00	6.00	7.00
	1425.5	1423.8	1482.7	1427.6	1484.6	1430.2	1412.8
Prep_No_	8.00	9.00	10.00	11.00	12.00	13.00	14.00
	1479.2	1404.4	1475.1	1428.7	1448.8	1392.2	1482.2
Prep_No_	15.00	16.00	17.00				
	1411.5	1474.4	1451.1				

*** Standard errors of differences of means ***

Table	Prep_No_
rep.	3
d.f.	34
s.e.d.	51.54

*** Least significant differences of means ***

Table	Prep_No_
rep.	3
d.f.	34
l.s.d.	104.74

***** Stratum standard errors and coefficients of variation *****

d.f.	s.e.	cv%
34	63.12	4.4

Variate: Moisture content (dry basis) %

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Prep_No_	16	4.1291	0.2581	1.39	0.203
Residual	34	6.2940	0.1851		
Total	50	10.4231			

***** Tables of means *****

Grand mean 9.731

Prep_No_	1.00	2.00	3.00	4.00	5.00	6.00	7.00
	9.097	9.630	9.247	9.843	10.027	9.987	10.097
Prep_No_	8.00	9.00	10.00	11.00	12.00	13.00	14.00
	9.697	9.597	9.760	9.817	9.667	10.207	9.493
Prep_No_	15.00	16.00	17.00				
	9.873	9.477	9.907				

*** Standard errors of differences of means ***

Table	Prep_No_
rep.	3
d.f.	34
s.e.d.	0.3513

Appendix 7.4

*** Least significant differences of means ***

Table Prep_No_
rep. 3
d.f. 34
l.s.d. 0.7139

***** Stratum standard errors and coefficients of variation *****

Variate: Moisture

d.f. s.e. cv%
34 0.4303 4.4

Variate: Draught force (N)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.94231	0.47115	26.72	
Rep.*Units* stratum					
tine	4	7.23667	1.80917	102.59	<.001
depth	9	44.55862	4.95096	280.75	<.001
tine.depth	36	4.56858	0.12690	7.20	<.001
Residual	98	1.72821	0.01763		
Total	149	59.03439			

***** Tables of means *****

Grand mean 0.800

tine	40WNDLi	MT_D	MT_ND	NSH_D	NSH_ND		
	0.858	0.782	0.423	1.108	0.827		
depth	10.00	20.00	30.00	40.00	50.00	60.00	70.00
	0.147	0.225	0.351	0.430	0.548	0.722	0.984
depth	80.00	90.00	100.00				
	1.237	1.526	1.827				
tine	depth	10.00	20.00	30.00	40.00	50.00	60.00
40WNDLi		0.096	0.249	0.290	0.483	0.734	0.809
MT_D		0.120	0.157	0.261	0.300	0.447	0.698
MT_ND		0.085	0.110	0.132	0.169	0.216	0.328
NSH_D		0.193	0.277	0.520	0.643	0.649	0.919
NSH_ND		0.241	0.331	0.554	0.554	0.695	0.857
tine	depth	70.00	80.00	90.00	100.00		
40WNDLi		1.111	1.316	1.545	1.944		
MT_D		0.891	1.334	1.691	1.925		
MT_ND		0.553	0.642	0.885	1.111		
NSH_D		1.294	1.792	2.112	2.681		
NSH_ND		1.071	1.098	1.395	1.474		

*** Standard errors of differences of means ***

Table	tine	depth	tine depth
rep.	30	15	3
d.f.	98	98	98
s.e.d.	0.0343	0.0485	0.1084

*** Least significant differences of means ***

Table	tine	depth	tine depth
rep.	30	15	3
d.f.	98	98	98
l.s.d.	0.0680	0.0962	0.2152

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	0.0971	12.1
Rep.*Units*	98	0.1328	16.6

Variate: Vertical force (N)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.35793	0.17897	4.29	
Rep.*Units* stratum					
tine	4	17.93037	4.48259	107.50	<.001
depth	9	9.83110	1.09234	26.20	<.001
tine.depth	36	11.07219	0.30756	7.38	<.001
Residual	98	4.08647	0.04170		
Total	149	43.27805			

***** Tables of means *****

Grand mean -0.505

tine	40WNDLi	MT_D	MT_ND	NSH_D	NSH_ND		
	-0.371	-0.666	0.030	-1.022	-0.493		
depth	10.00	20.00	30.00	40.00	50.00	60.00	70.00
	-0.241	-0.279	-0.303	-0.343	-0.330	-0.389	-0.554
depth	80.00	90.00	100.00				
	-0.739	-0.946	-0.920				
tine	depth	10.00	20.00	30.00	40.00	50.00	60.00
40WNDLi		-0.106	-0.204	-0.176	-0.326	-0.401	-0.387
MT_D		-0.269	-0.104	-0.303	-0.376	-0.325	-0.341
MT_ND		-0.024	-0.012	0.132	-0.038	0.058	-0.061
NSH_D		-0.504	-0.430	-0.703	-0.560	-0.485	-0.655
NSH_ND		-0.303	-0.647	-0.467	-0.415	-0.499	-0.501
tine	depth	70.00	80.00	90.00	100.00		
40WNDLi		-0.383	-0.405	-0.722	-0.604		
MT_D		-0.847	-1.155	-1.567	-1.370		
MT_ND		0.070	0.058	0.070	0.047		
NSH_D		-1.072	-1.774	-1.811	-2.229		
NSH_ND		-0.539	-0.418	-0.701	-0.444		

*** Standard errors of differences of means ***

Table	tine	depth	tine depth
rep.	30	15	3
d.f.	98	98	98
s.e.d.	0.0527	0.0746	0.1667

*** Least significant differences of means ***

Table	tine	depth	tine depth
rep.	30	15	3
d.f.	98	98	98
l.s.d.	0.1046	0.1480	0.3309

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	0.0598	11.9
Rep.*Units*	98	0.2042	40.5

Appendix 7.5.

Calibration procedure and resulting equations for the initial dynamic performance study.

Four specific calibrations were carried out with regard to the initial dynamic performance study, designed to establish common factors influencing the response of injector tine combinations mounted on a parallel linkage system. Draught and vertical forces, and LVDT displacement for both the tine position and the land wheel were carried out.

7.4.1 Force calibration procedure.

Horizontal force was calibrated by applying known weights to the EORT in the plane of the draught force. Data was captured using the computer data logging equipment described in *Section 8.4.2.5*. The EORT amplified output was compared to the applied loads, enabling regression analysis and curve fitting. The loss of computer data 6 months after testing, due to a computer failure concurs that the calibration data cannot be presented in graphical form in an accurate manner. However, a paper copy of the calibration was recorded at the time of testing and the calibration equation for draught force can be confirmed as:

$$\text{Draught Force (N)} = \frac{\text{Output}}{0.0035}$$

$$R^2 = 0.9954$$

Vertical force calibration was carried out in a similar manner, suffering from the same computer failure problems, where the recorded vertical force calibration equation can be confirmed from paper copy as:

$$\text{Vertical Force (N)} = \frac{\text{Output}}{0.0004}$$

$$R^2 = 0.9874$$

7.4.2 Displacement calibration procedure.

The displacement of both the LVDT's was calibrated on the basis of actual displacement at the linkage rear vertical leg or the contact surface of the land-wheel.

7.4.2.1 Tine LVDT

The Linkage and tine combination was elevated at the rear vertical leg of the linkage in 0.01 m intervals, over the travel of the linkage. Output was once again recorded using the computer data capture equipment described in *Section 8.4.2.5*, and regression analysis was

applied to the data retrieved. Once again, computer failure does not permit the presentation of the final linear relationship, however a hard copy of the recorded and calculated equation can be confirmed as:

$$\text{Tine LVDT position above full extension} = \frac{\text{Output} + 6.7301}{0.0333}$$

$$R^2 = 0.9999$$

An intercept correction is necessary in considering the LVDT position, as the output range of the transducer is ± 10 Volts.

7.4.2.1 Land-wheel LVDT.

The land-wheel was elevated in 0.01 m intervals at the point of surface contact (under the wheel), and the output was recorded in the same manner as the Tine LVDT calibration. Similarly, the computer failure experienced after testing does not permit the graphical presentation of the calibration, however the equation describing the relationship between LVDT output and LVDT displacement is confirmed from hard copy as:

$$\text{Land - wheel LVDT position above full extension} = \frac{\text{Output} - 1.7879}{-0.0091}$$

$$R^2 = 0.9997$$

Once again, the intercept correction is required to account for the ± 10 V transducer output.

Appendix 7.6.

Statistical analysis of soil properties relating to the initial dynamic performance study.

Variate: Bulk density (dry basis) kg/m³

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Bin_Fit	67	181470.	2709.	1.35	0.074
Residual	136	273770.	2013.		
Total	203	455240.			

***** Tables of means *****

Grand mean 1347.4

Bin_Fit	1.00	2.00	3.00	4.00	5.00	6.00	7.00
	1345.4	1396.6	1361.9	1376.6	1312.8	1369.2	1334.1
Bin_Fit	8.00	9.00	10.00	11.00	12.00	13.00	14.00
	1328.7	1303.3	1326.7	1378.9	1367.7	1419.8	1331.1
Bin_Fit	15.00	16.00	17.00	18.00	19.00	20.00	21.00
	1350.8	1334.8	1319.4	1342.5	1304.2	1340.7	1323.3
Bin_Fit	22.00	23.00	24.00	25.00	26.00	27.00	28.00
	1331.0	1348.0	1391.0	1346.3	1421.6	1293.5	1329.4
Bin_Fit	29.00	30.00	31.00	32.00	33.00	34.00	35.00
	1368.3	1353.2	1330.6	1312.2	1397.1	1321.4	1330.3
Bin_Fit	36.00	37.00	38.00	39.00	40.00	41.00	42.00
	1309.3	1318.5	1311.8	1351.1	1350.2	1344.8	1322.9
Bin_Fit	43.00	44.00	45.00	46.00	47.00	48.00	49.00
	1353.3	1370.0	1348.1	1335.7	1394.6	1381.5	1393.3
Bin_Fit	50.00	51.00	52.00	53.00	54.00	55.00	56.00
	1367.4	1320.5	1384.3	1323.5	1349.4	1393.1	1350.6
Bin_Fit	57.00	58.00	59.00	60.00	61.00	62.00	63.00
	1357.3	1351.9	1332.1	1369.9	1334.4	1279.8	1354.1
Bin_Fit	64.00	65.00	66.00	67.00	68.00		
	1290.9	1347.7	1343.7	1369.0	1377.0		

*** Standard errors of differences of means ***

Table	Bin_Fit
rep.	3
d.f.	136
s.e.d.	36.63

*** Least significant differences of means ***

Table	Bin_Fit
rep.	3
d.f.	136
l.s.d.	72.44

***** Stratum standard errors and coefficients of variation *****

Variate: Bulk_Den

d.f.	s.e.	cv%
136	44.87	3.3

Appendix 7.6

Variate: Moisture content (dry basis) %

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Bin_Fit	67	30.8099	0.4598	2.28	<.001
Residual	136	27.4388	0.2018		
Total	203	58.2487			

***** Tables of means *****

Grand mean 9.951

Bin_Fit	1.00	2.00	3.00	4.00	5.00	6.00	7.00
	9.217	10.540	9.583	9.923	9.353	9.580	9.780
Bin_Fit	8.00	9.00	10.00	11.00	12.00	13.00	14.00
	10.130	10.043	10.367	10.293	10.200	10.573	9.657
Bin_Fit	15.00	16.00	17.00	18.00	19.00	20.00	21.00
	9.990	10.080	10.023	8.533	9.317	9.603	9.437
Bin_Fit	22.00	23.00	24.00	25.00	26.00	27.00	28.00
	10.003	9.853	10.253	10.380	10.413	10.543	10.237
Bin_Fit	29.00	30.00	31.00	32.00	33.00	34.00	35.00
	9.920	9.967	10.013	10.030	10.620	9.870	10.293
Bin_Fit	36.00	37.00	38.00	39.00	40.00	41.00	42.00
	9.773	9.530	9.910	9.733	9.683	9.623	9.707
Bin_Fit	43.00	44.00	45.00	46.00	47.00	48.00	49.00
	9.930	10.267	10.400	10.453	10.413	10.250	10.093
Bin_Fit	50.00	51.00	52.00	53.00	54.00	55.00	56.00
	9.967	9.753	10.000	10.107	10.273	10.300	9.333
Bin_Fit	57.00	58.00	59.00	60.00	61.00	62.00	63.00
	9.573	10.083	9.817	10.653	9.843	10.063	9.447
Bin_Fit	64.00	65.00	66.00	67.00	68.00		
	9.830	10.010	9.620	10.213	9.380		

*** Standard errors of differences of means ***

Table	Bin_Fit
rep.	3
d.f.	136
s.e.d.	0.3667

*** Least significant differences of means ***

Table	Bin_Fit
rep.	3
d.f.	136
l.s.d.	0.7253

***** Stratum standard errors and coefficients of variation *****

Variate: Moisture

d.f.	s.e.	cv%
136	0.4492	4.5

Appendix 7.7.

Operating depth profiles for model verification (Flat soil surface, constant hitch height).

7.7.1 40WNDLi injector tine profiles

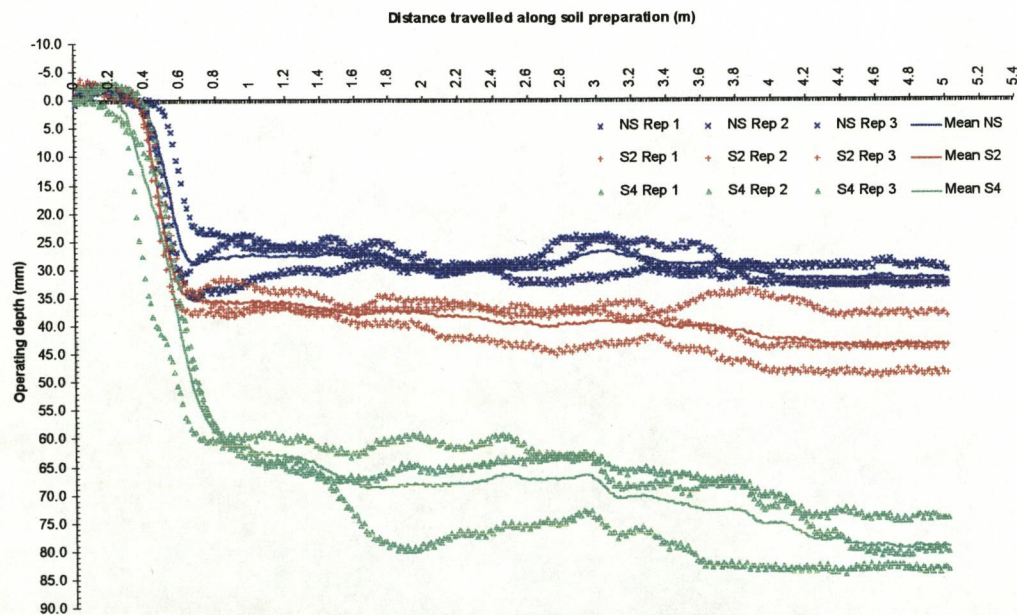


Fig. Ap 7.1. Mean and replicates of the 40WNDLi injector operating with no springs (NS), 2 springs between pivots ab (S2) and ac (S4).

7.7.2 NSH and disc-injector tine profiles

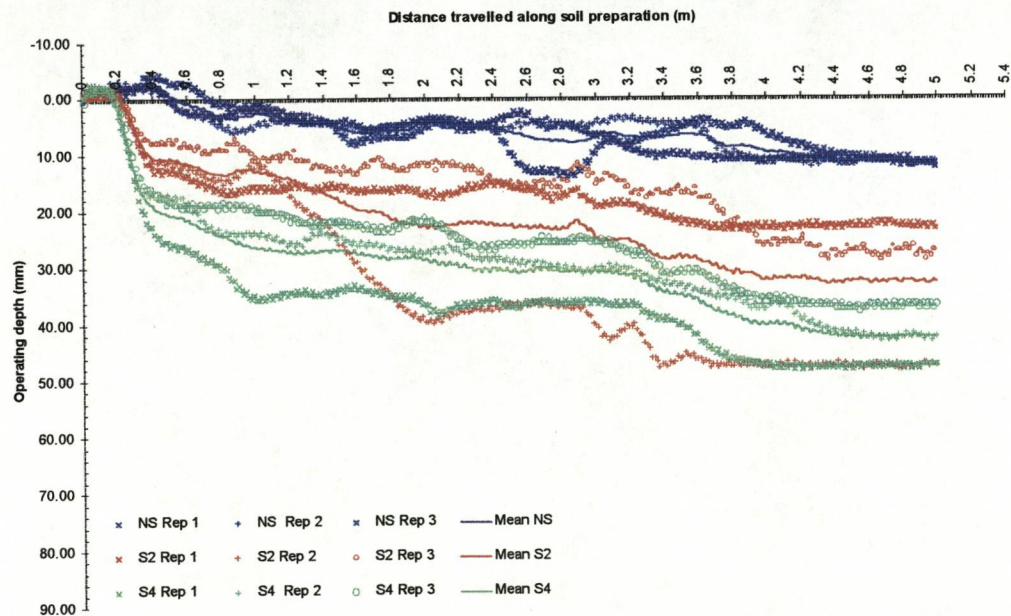


Fig. Ap 7.2. Mean and replicates of the NSH injector tine and disc operating with no springs (NS), 2 springs between pivots ab (S2) and ac (S4).

7.7.3 NSH injector tine profiles without disc

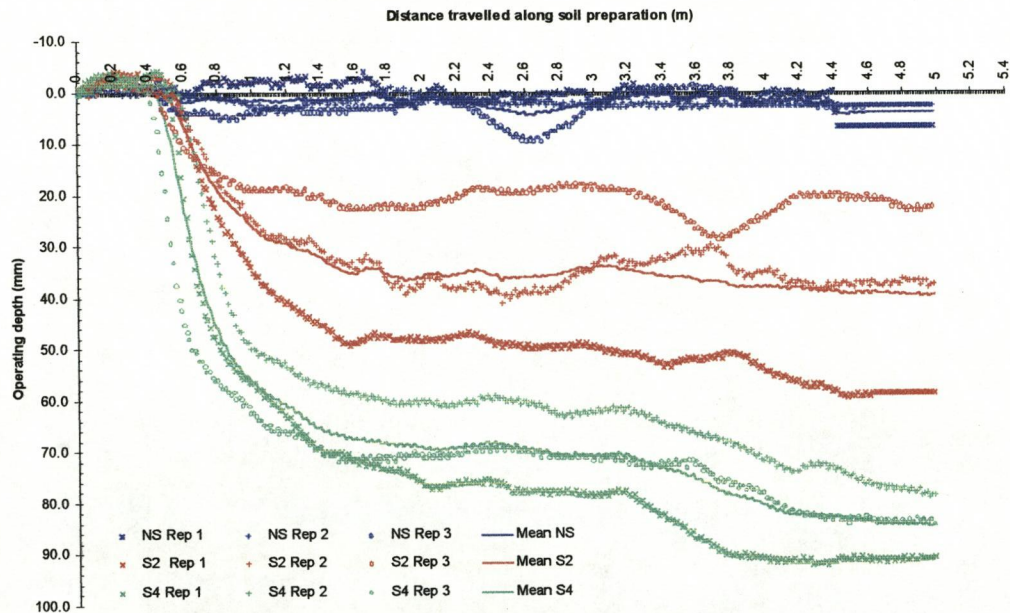


Fig. Ap 7.3. Mean and replicates of the NSH injector tine without disc operating with no springs (NS), 2 springs between pivots ab (S2) and ac (S4).

7.7.4 Retrofit injector tine profiles with disc

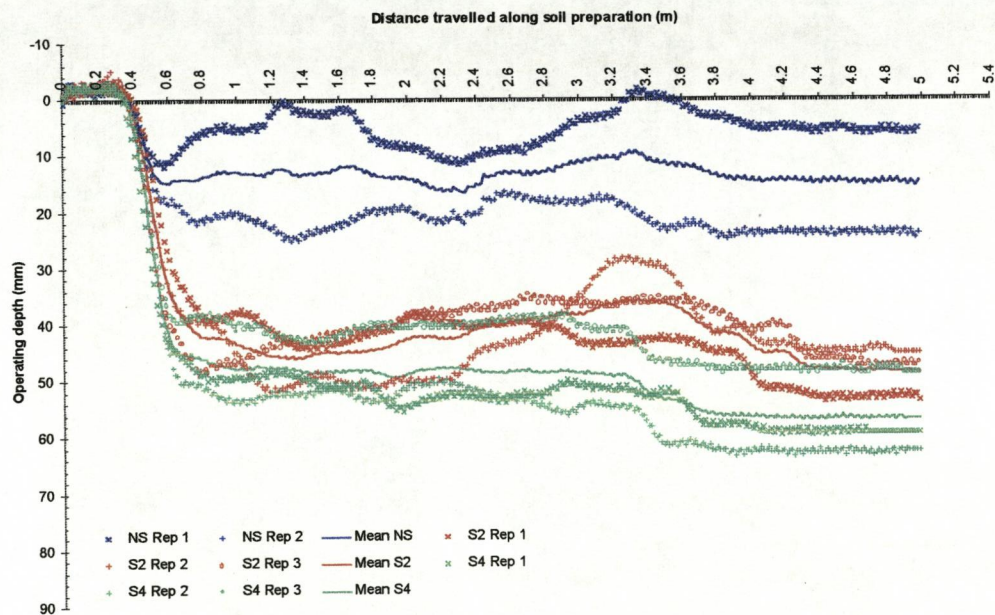


Fig. Ap 7.4. Mean and replicates of the Retrofit injector tine with disc operating with no springs (NS), 2 springs between pivots ab (S2) and ac (S4).

7.7.5 Retrofit injector tine profiles without disc

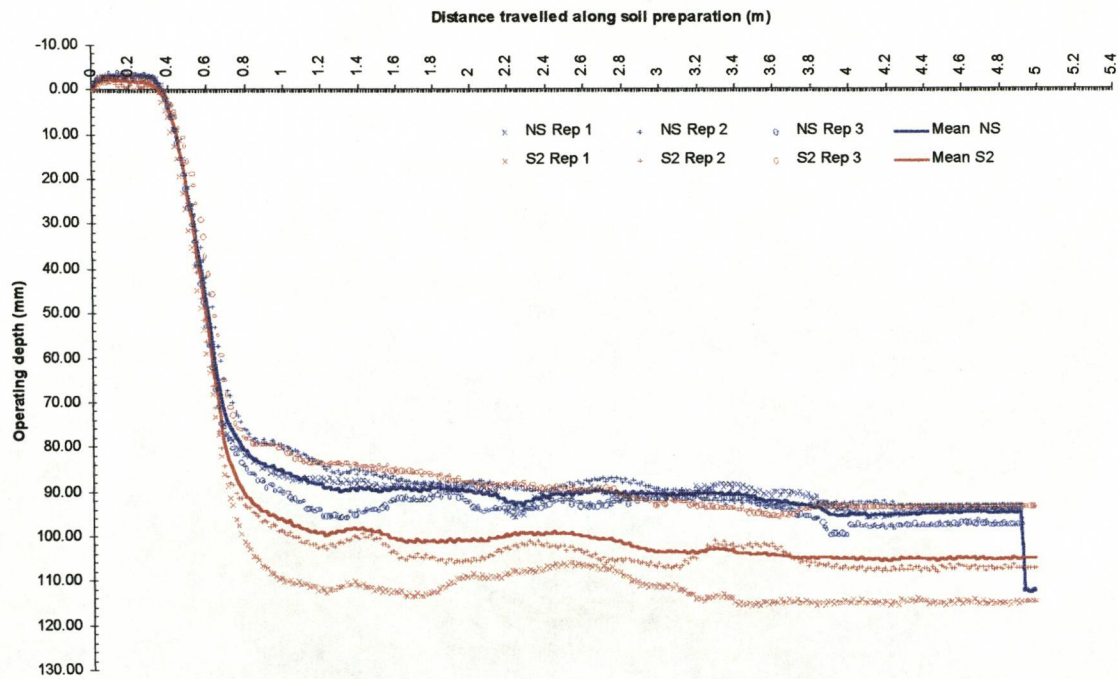


Fig. Ap 7.5. Mean and replicates of the Retrofit injector tine without disc operating with no springs (NS), and 2 springs between pivots ab (S2).

Appendix 7.8.

Graphical presentation of dynamic soil profiles following 5 selected injector tine configurations over a sinusoidal soil surface change.

7.8.1 40WNDLi injector tine profiles

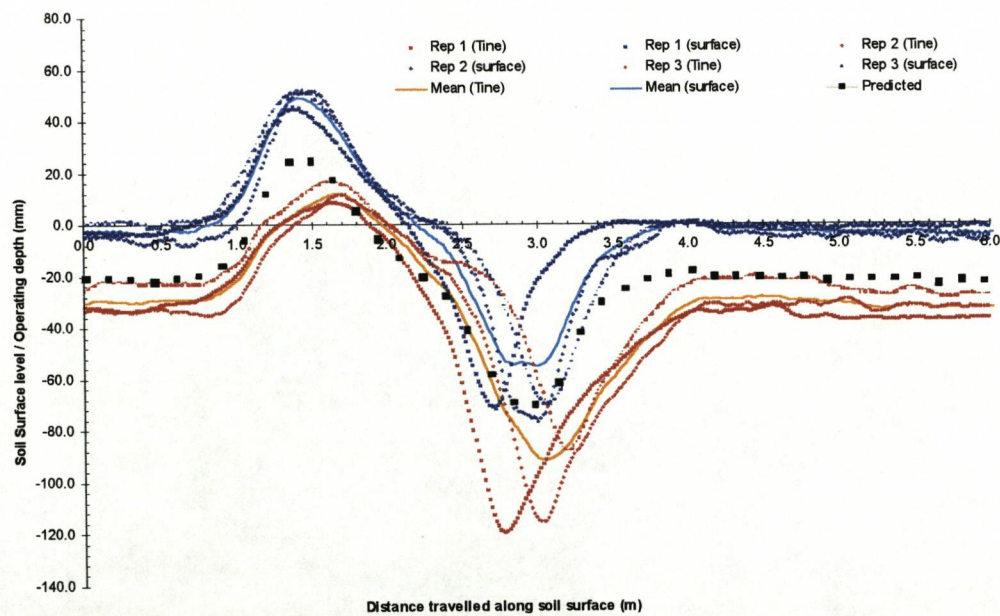


Fig. Ap 7.8.1. Dynamic performance of the 40WNDLi injector tine on the Greentrac parallel linkage with no spring assistance.

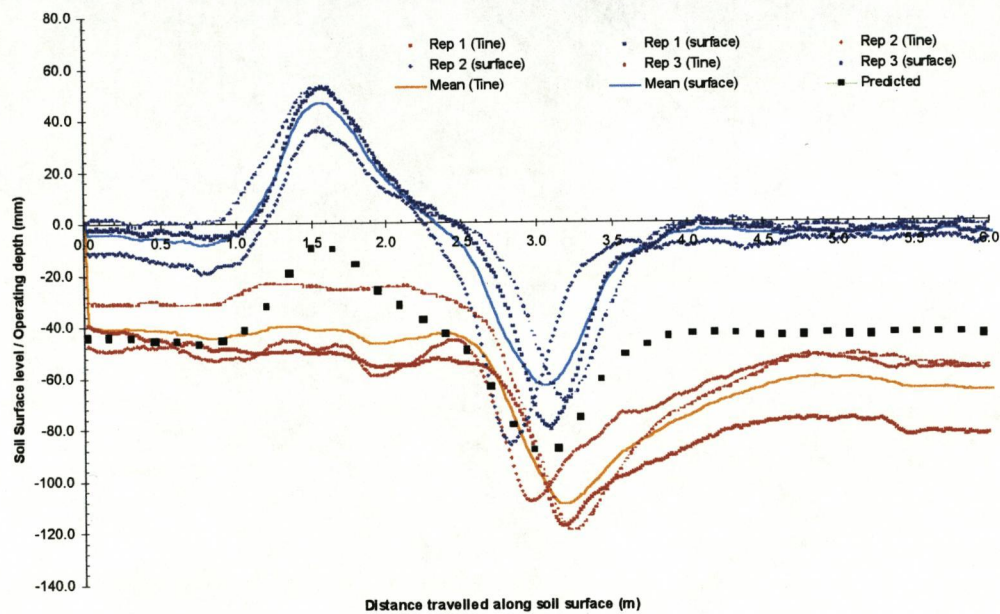


Fig. Ap 7.8.2. Dynamic performance of the 40WNDLi injector tine on the Greentrac parallel linkage with 2 springs between pivots ab.

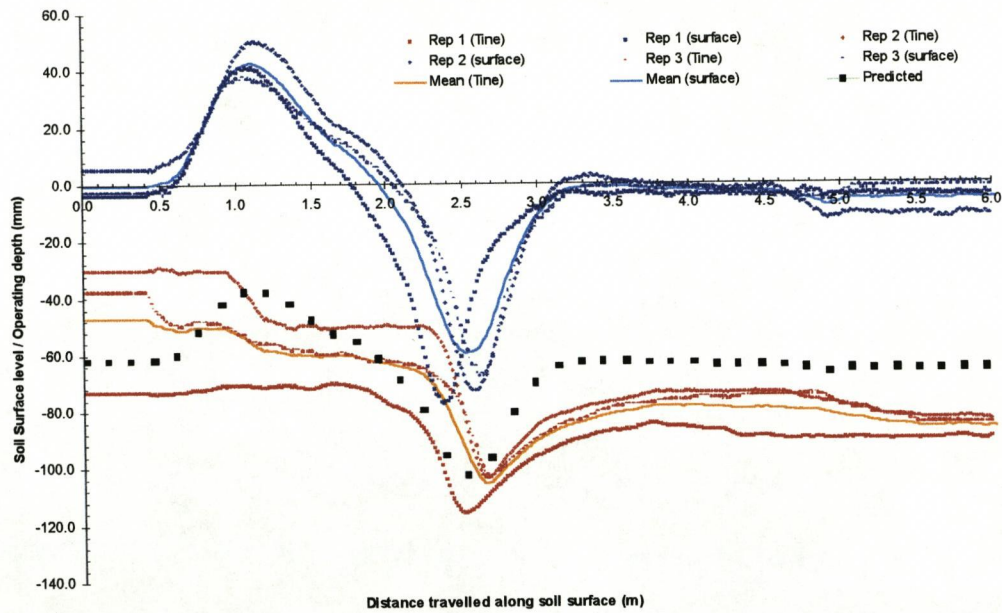


Fig. Ap 7.8.3. Dynamic performance of the 40WNDLi injector tine on the Greentrac parallel linkage with 2 springs between pivots ac.

7.8.2 NSH injector tine with disc.

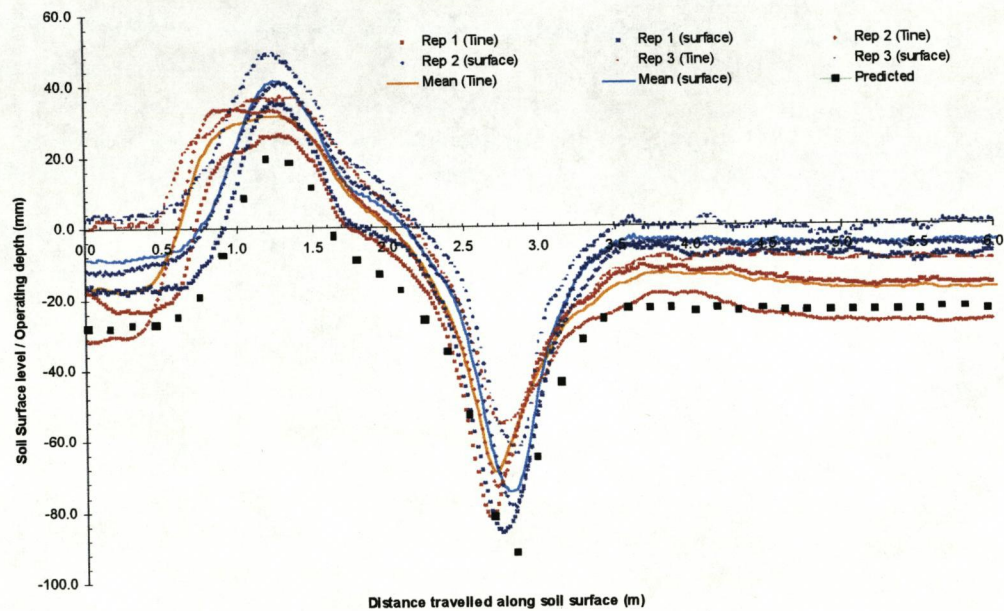


Fig. Ap 7.8.4. Dynamic performance of the NSH injector tine and disc on the Greentrac parallel linkage with no spring assistance.

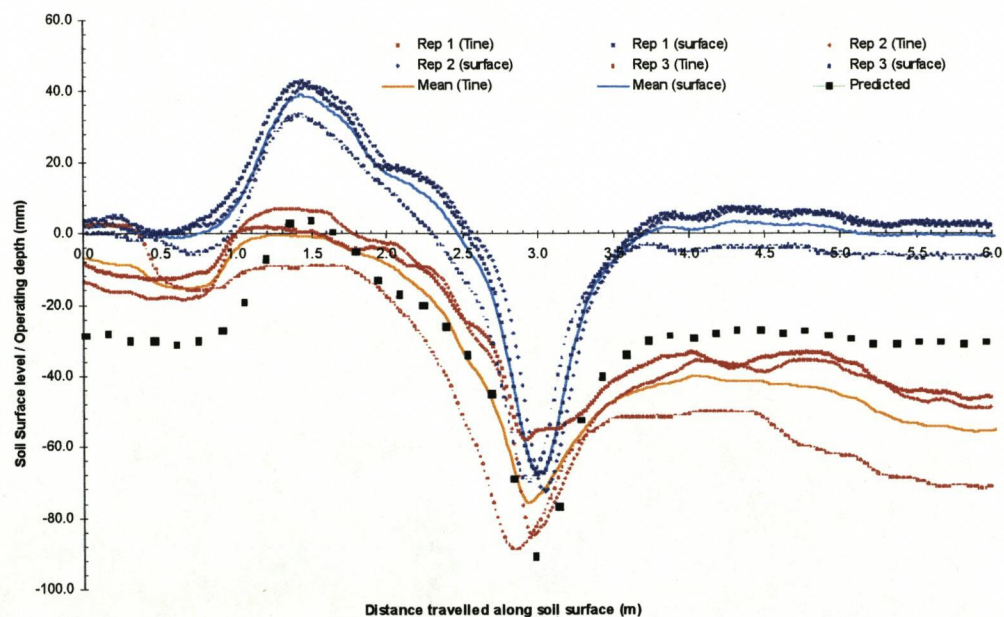


Fig. Ap 7.8.5. Dynamic performance of the NSH injector tine and disc on the Greentrac parallel linkage with 2 springs between pivots *ab*.

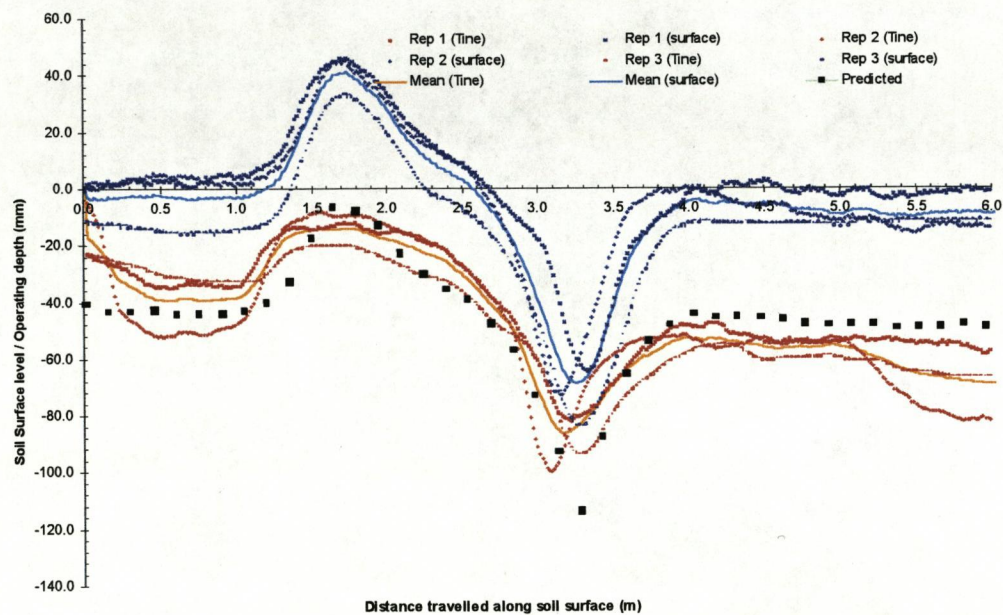


Fig. Ap 7.8.6. Dynamic performance of the NSH injector tine and disc on the Greentrac parallel linkage with 2 springs between pivots *ac*.

7.8.3 NSH injector tine without disc.

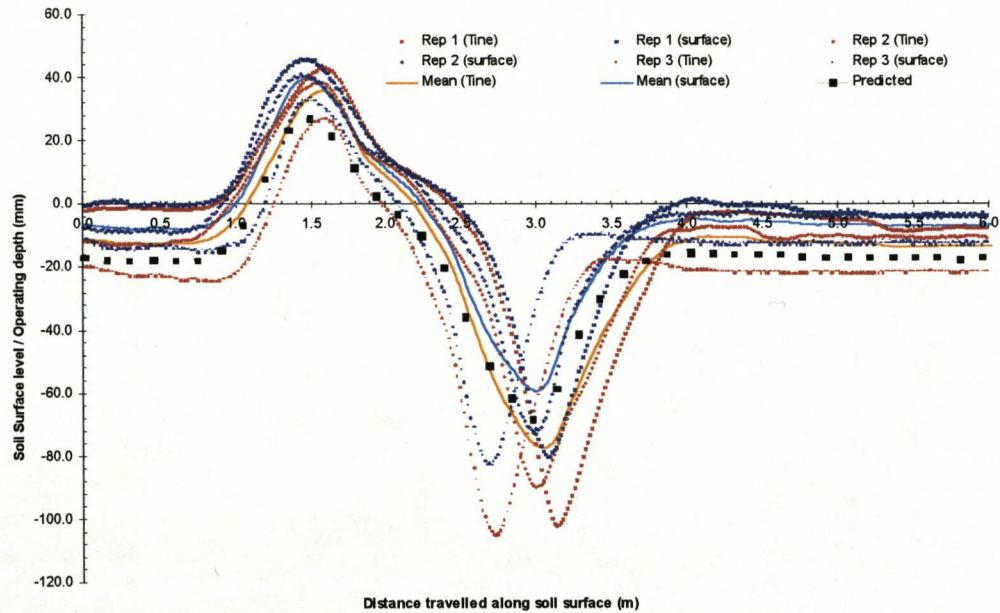


Fig. Ap 7.8.7. Dynamic performance of the NSH injector tine without disc on the Greentrac parallel linkage with no spring assistance.

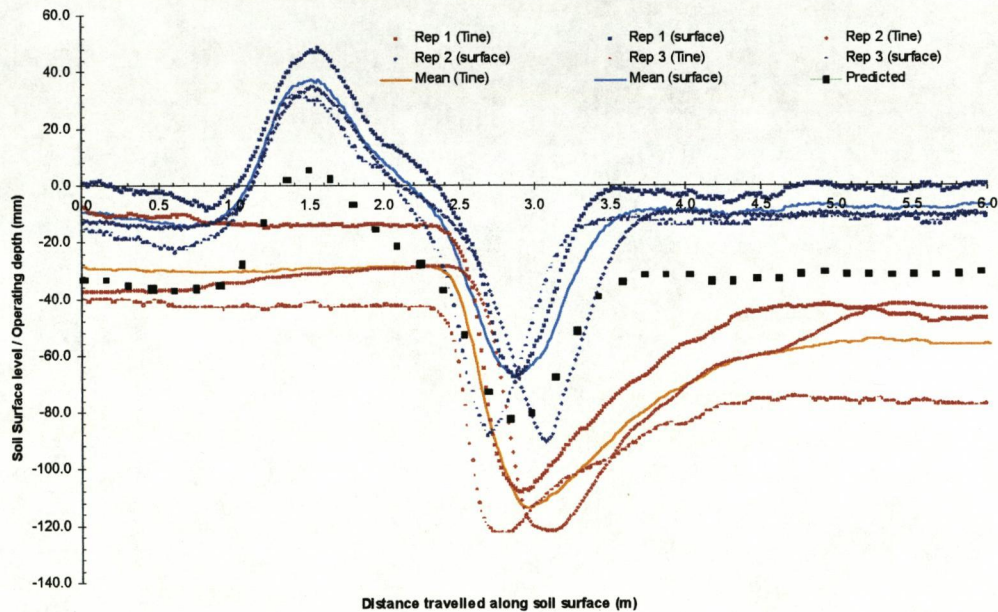


Fig. Ap 7.8.8. Dynamic performance of the NSH injector tine without disc on the Greentrac parallel linkage with 2 springs between pivots ab.

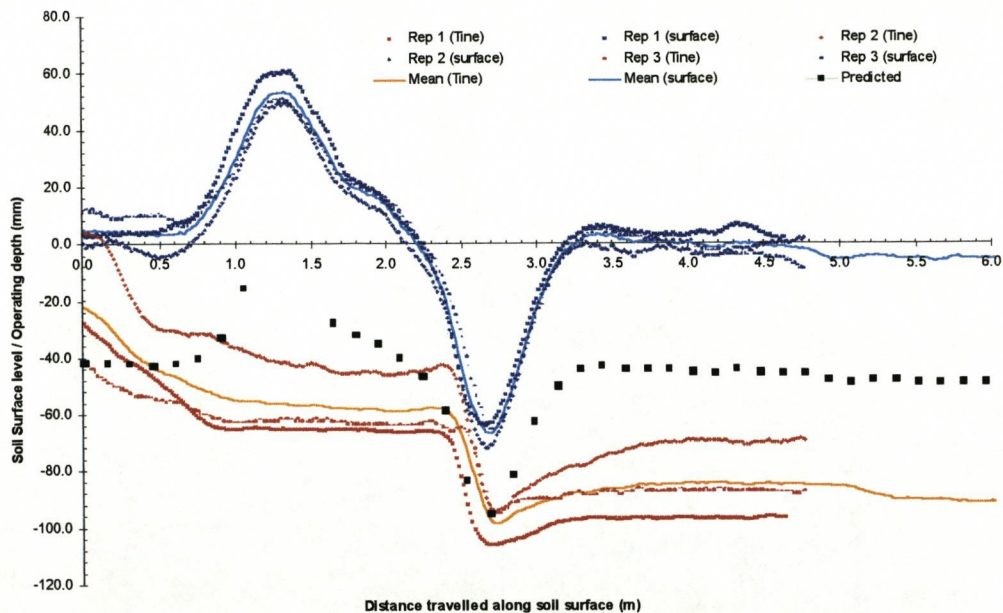


Fig. Ap 7.8.9. Dynamic performance of the NSH injector tine without disc on the Greentrac parallel linkage with 2 springs between pivots ac.

7.8.4 Retro-fit injector tine with disc.

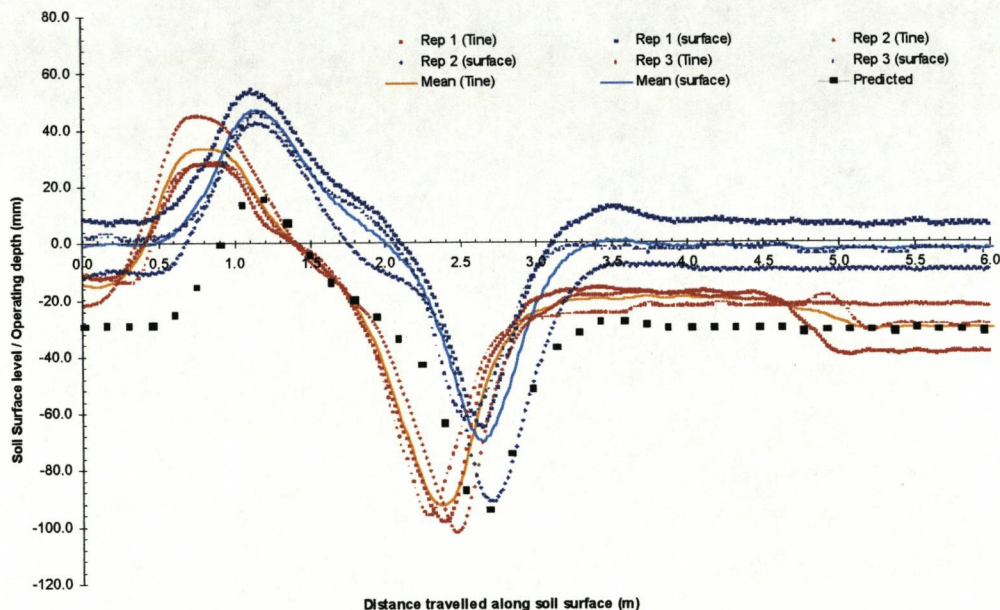


Fig. Ap 7.8.10. Dynamic performance of the Retro-fit injector tine with disc on the Greentrac parallel linkage with no spring assistance.

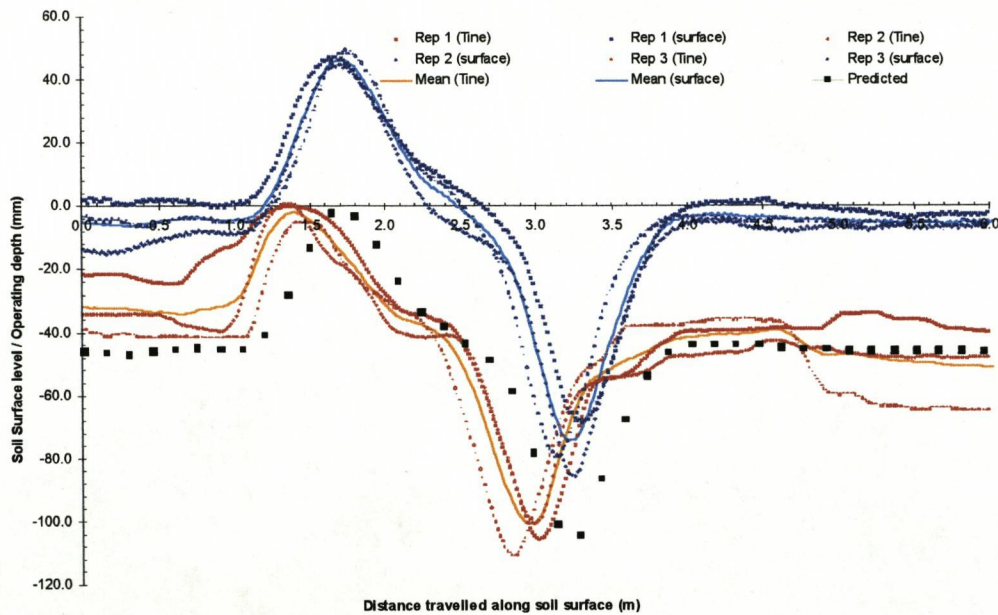


Fig. Ap 7.8.11. Dynamic performance of the Retro-fit injector tine with disc on the Greentrac parallel linkage with 2 springs between pivots *ab*.

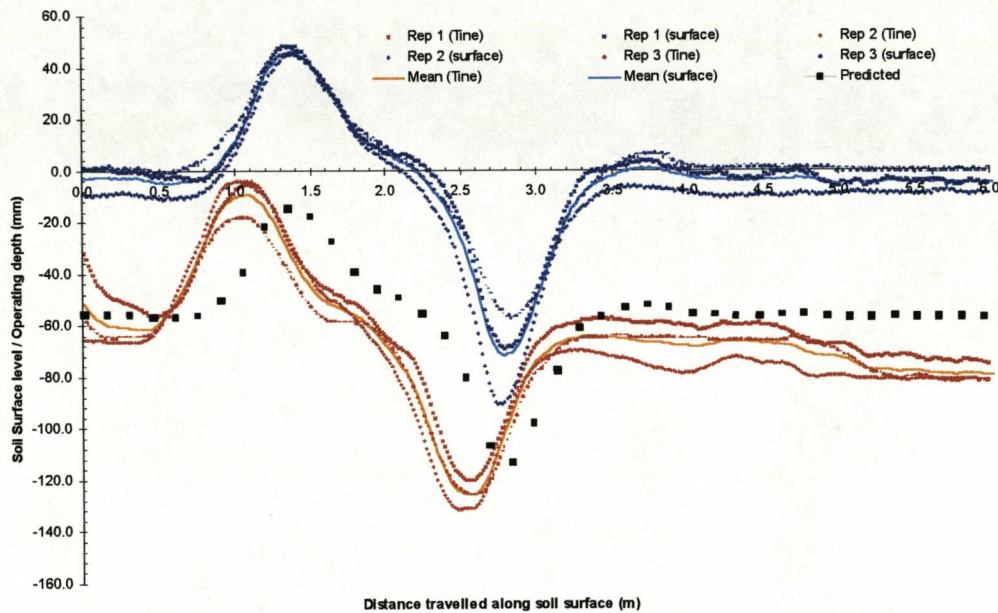


Fig. Ap 7.8.12. Dynamic performance of the Retro-fit injector tine with disc on the Greentrac parallel linkage with 2 springs between pivots *ac*.

7.8.5 Retro-fit injector tine without disc.

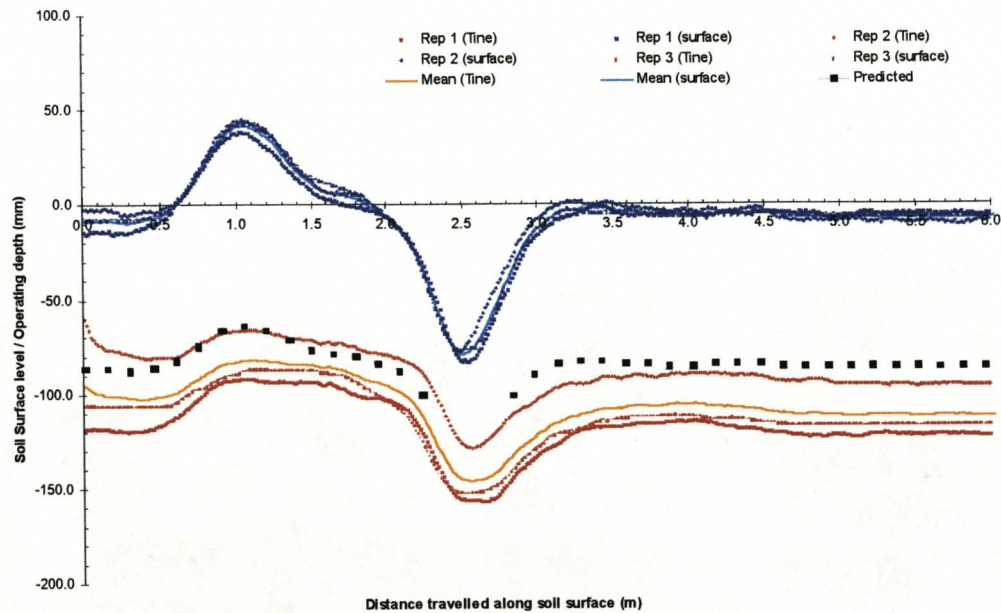


Fig. Ap 7.8.13. Dynamic performance of the Retro-fit injector tine without disc on the Greentrac parallel linkage with no spring assistance.

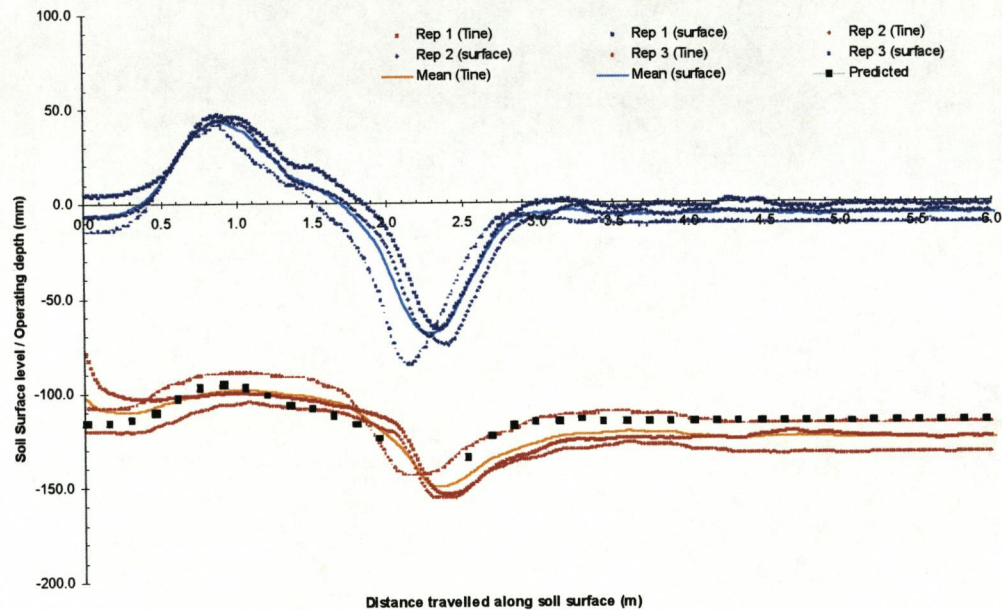


Fig. Ap 7.8.14. Dynamic performance of the Retro-fit injector tine without disc on the Greentrac parallel linkage with 2 springs between pivots ab.

Appendix 7.9.

Graphical presentation of dynamic soil profiles following 5 selected injector tine configurations following a sinusoidal change in implement toolbar height at 50 mm/s.

7.9.1 40WNDLi injector tine profiles

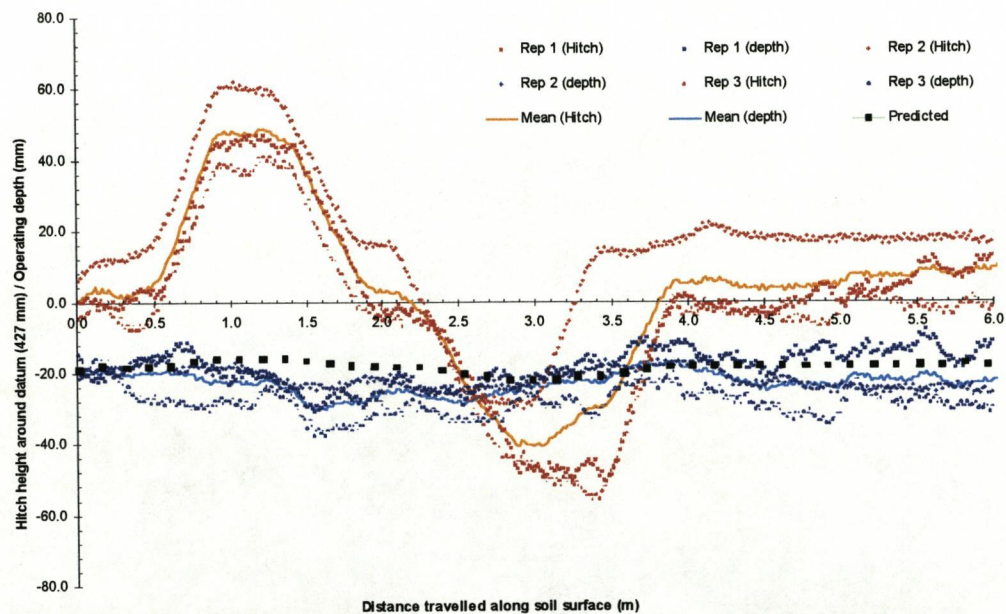


Fig. Ap 7.9.1. Dynamic performance of the 40WNDLi injector tine on the Greentrac parallel linkage with no spring assistance.

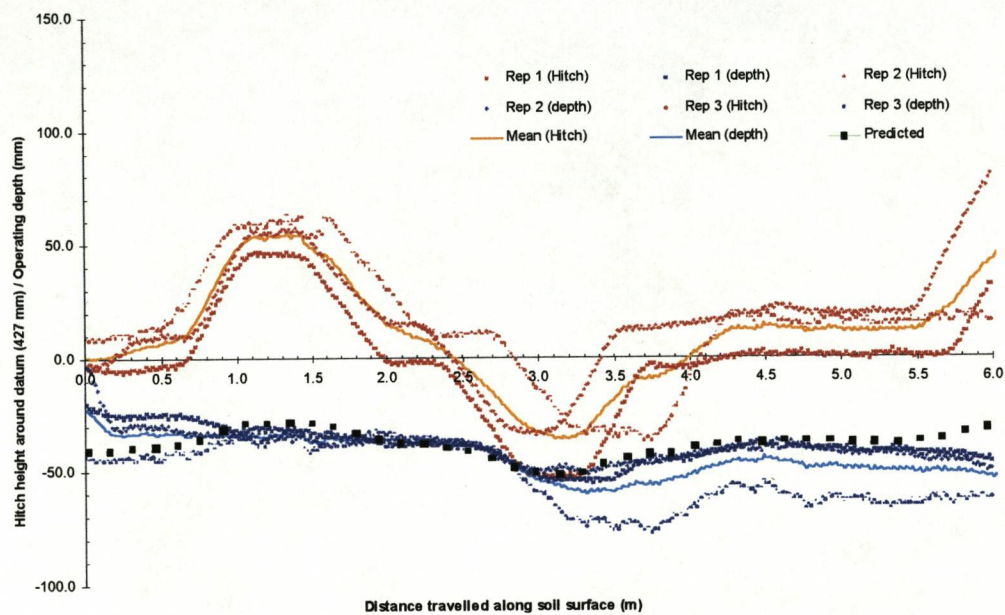


Fig. Ap 7.9.2. Dynamic performance of the 40WNDLi injector tine on the Greentrac parallel linkage with 2 springs between pivots ab.

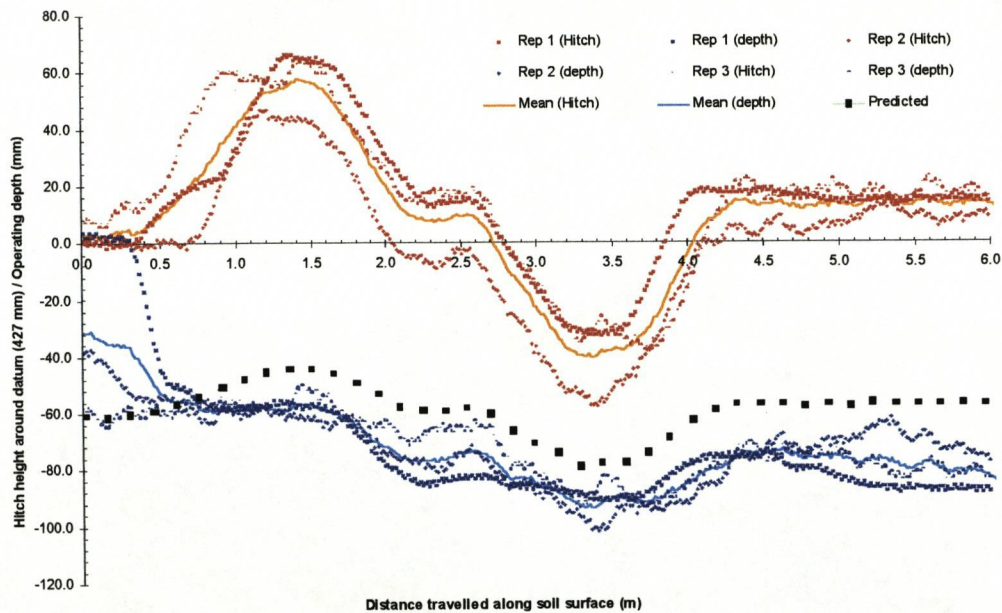


Fig. Ap 7.9.3. Dynamic performance of the 40WNDLi injector tine on the Greentrac parallel linkage with 2 springs between pivots ac.

7.9.2 NSH injector tine with disc.

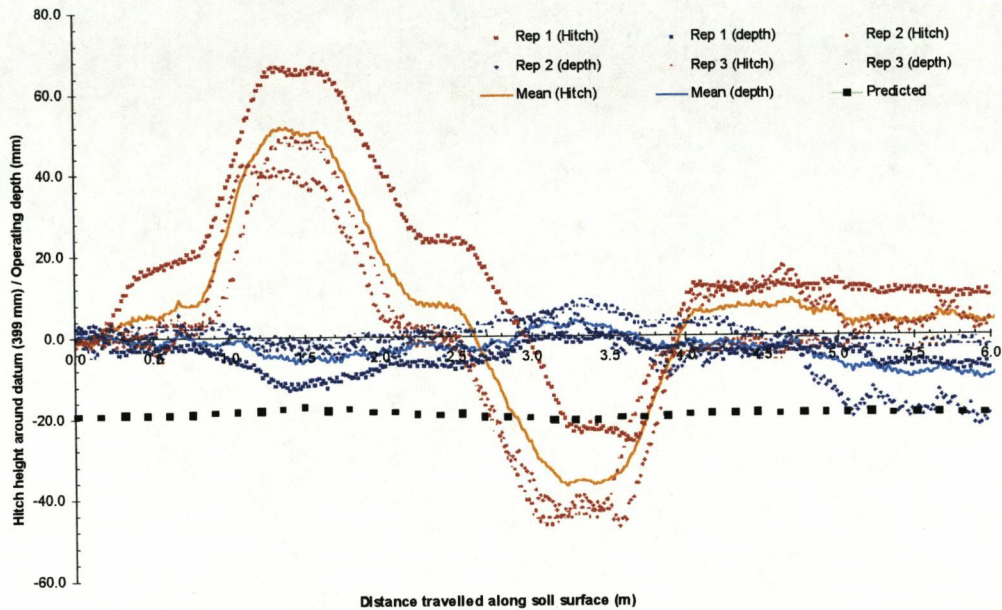


Fig. Ap 7.9.4. Dynamic performance of the NSH injector tine and disc on the Greentrac parallel linkage with no spring assistance.

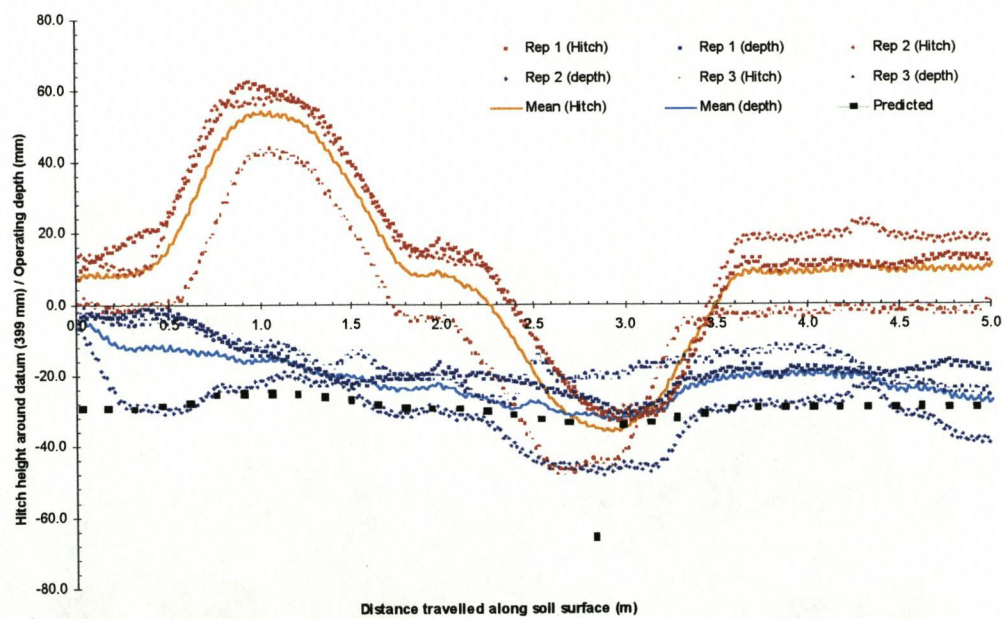


Fig. Ap 7.9.5. Dynamic performance of the NSH injector tine and disc on the Greentrac parallel linkage with 2 springs between pivots ab.

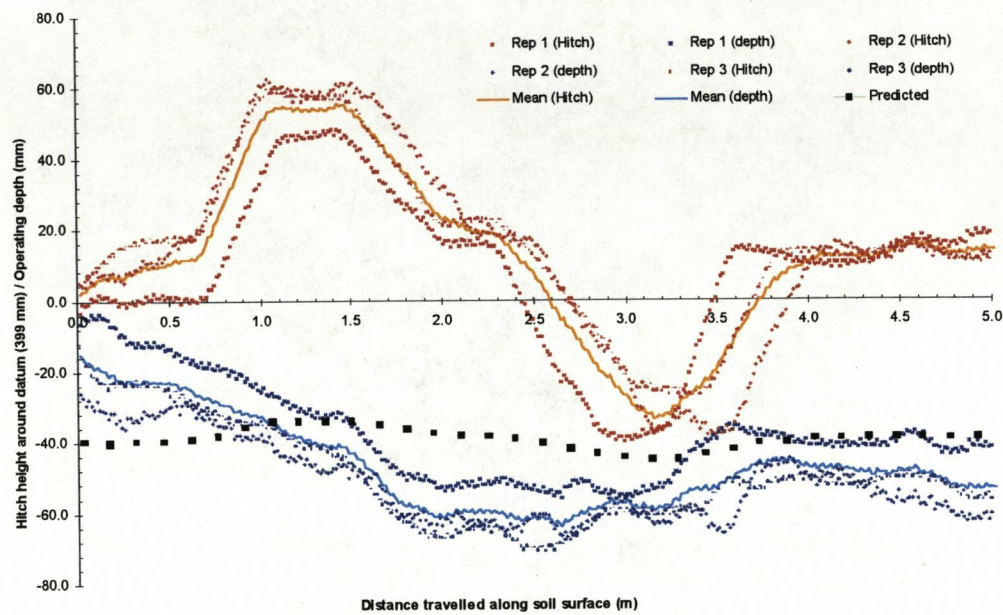


Fig. Ap 7.9.6. Dynamic performance of the NSH injector tine and disc on the Greentrac parallel linkage with 2 springs between pivots ac.

7.9.3 NSH injector tine without disc.

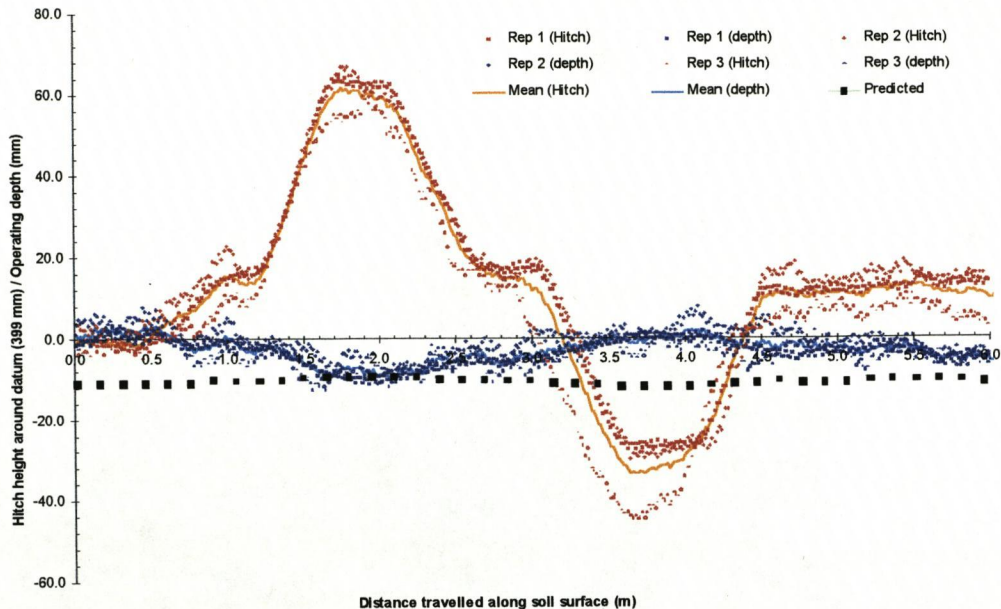


Fig. Ap 7.9.7. Dynamic performance of the NSH injector tine without disc on the Greentrac parallel linkage with no spring assistance.

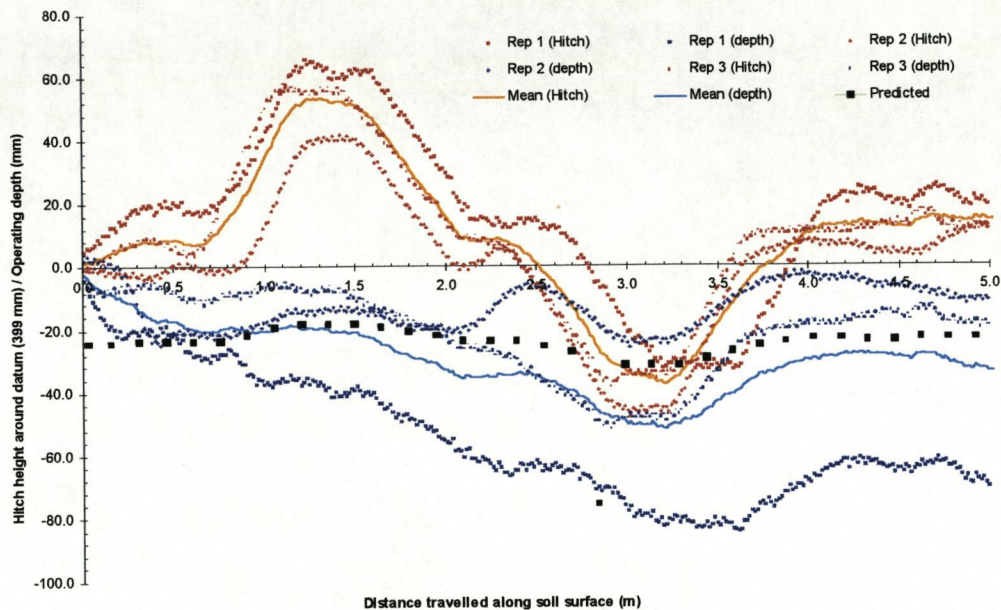


Fig. Ap 7.9.8. Dynamic performance of the NSH injector tine without disc on the Greentrac parallel linkage with 2 springs between pivots ab.

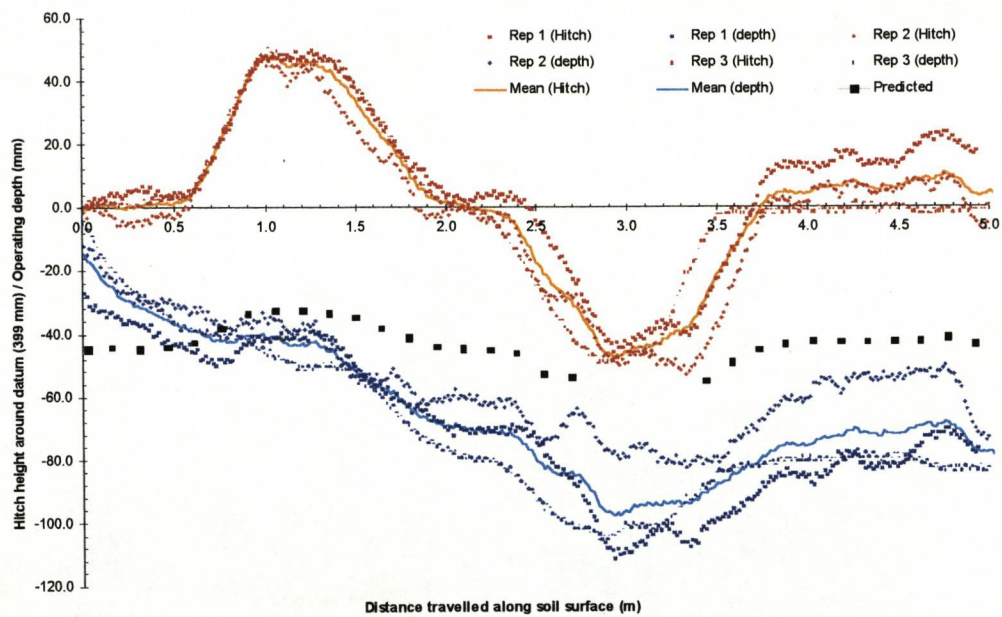


Fig. Ap 7.9.9. Dynamic performance of the NSH injector tine without disc on the Greentrac parallel linkage with 2 springs between pivots ac.

7.9.4 Retro-fit injector tine with disc.

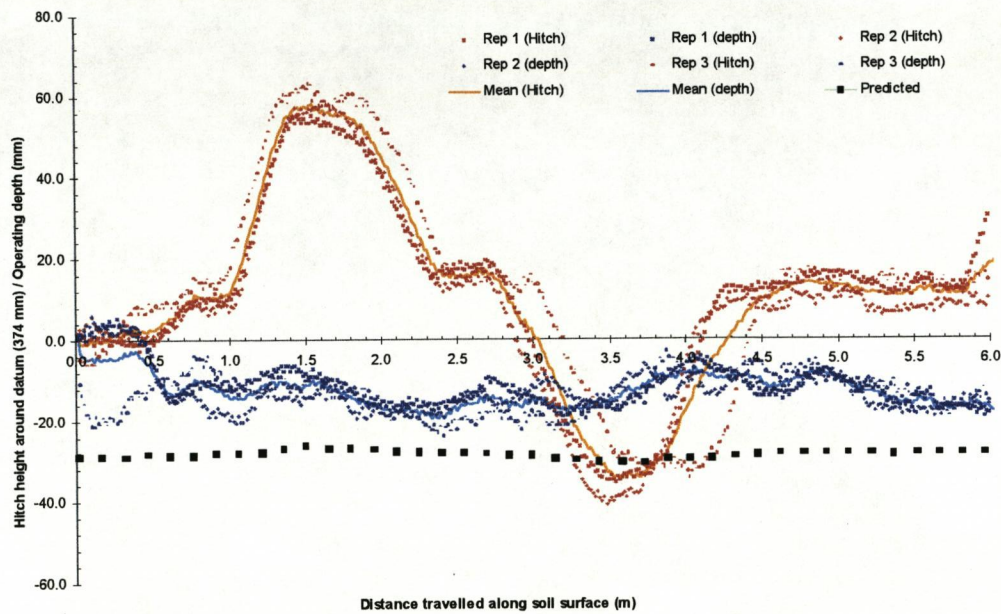


Fig. Ap 7.9.10. Dynamic performance of the Retro-fit injector tine with disc on the Greentrac parallel linkage with no spring assistance.

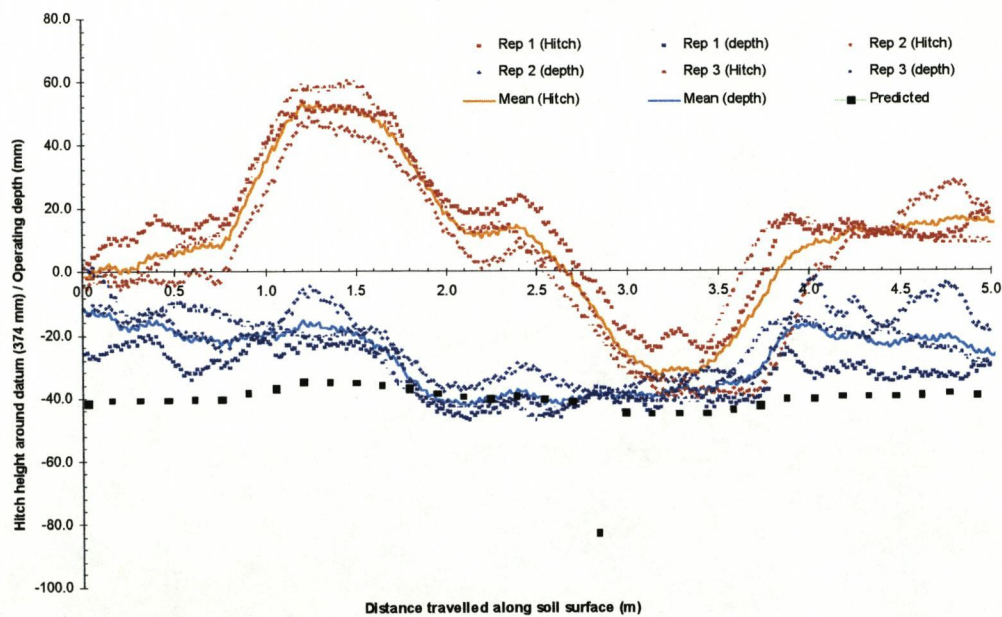


Fig. Ap 7.9.11. Dynamic performance of the Retro-fit injector tine with disc on the Greentrac parallel linkage with 2 springs between pivots ab.

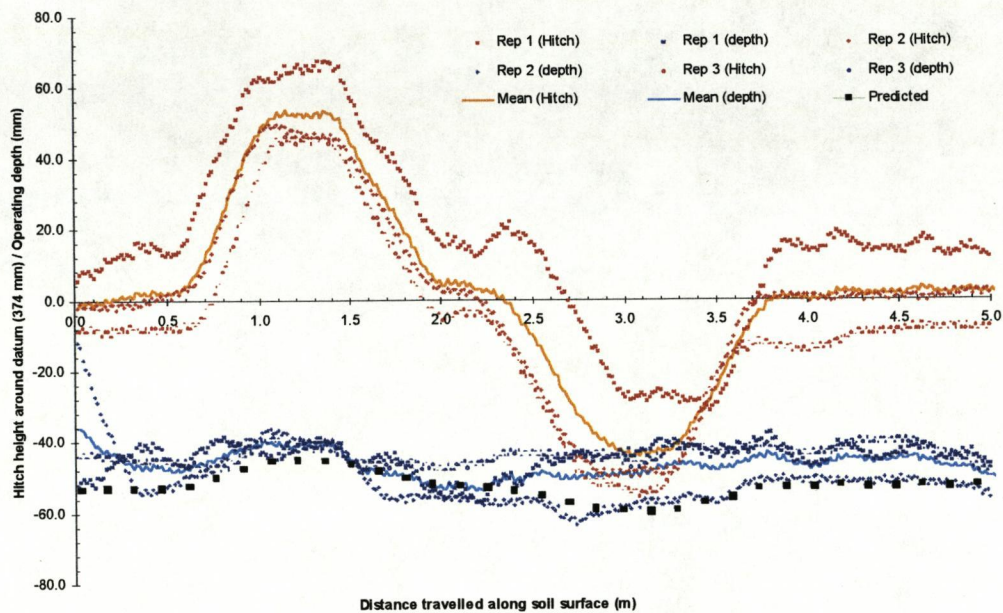


Fig. Ap 7.9.12. Dynamic performance of the Retro-fit injector tine with disc on the Greentrac parallel linkage with 2 springs between pivots ac.

7.9.5 Retro-fit injector tine without disc.

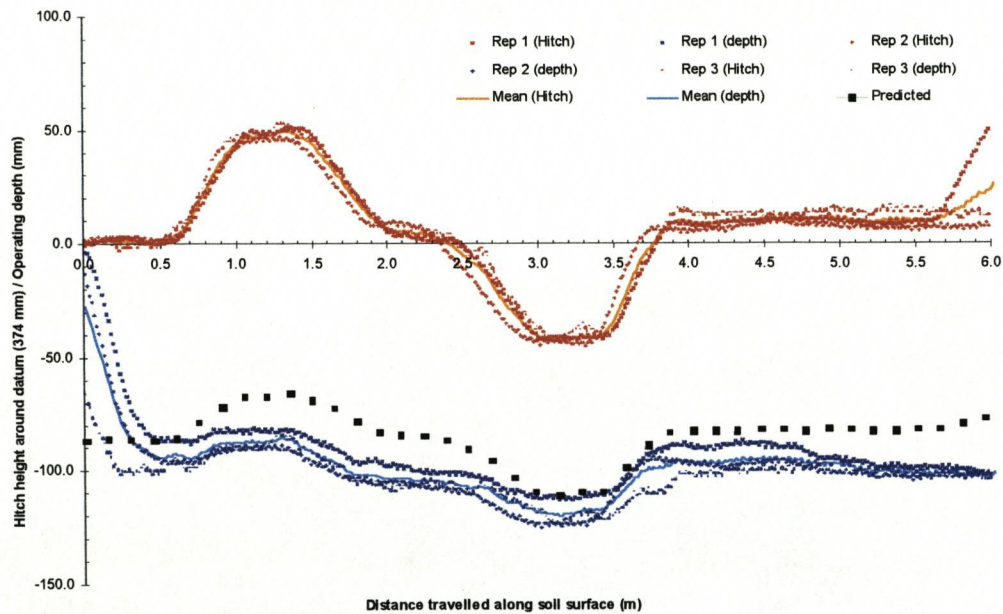


Fig. Ap 7.9.13. Dynamic performance of the Retro-fit injector tine without disc on the Greentrac parallel linkage with no spring assistance.

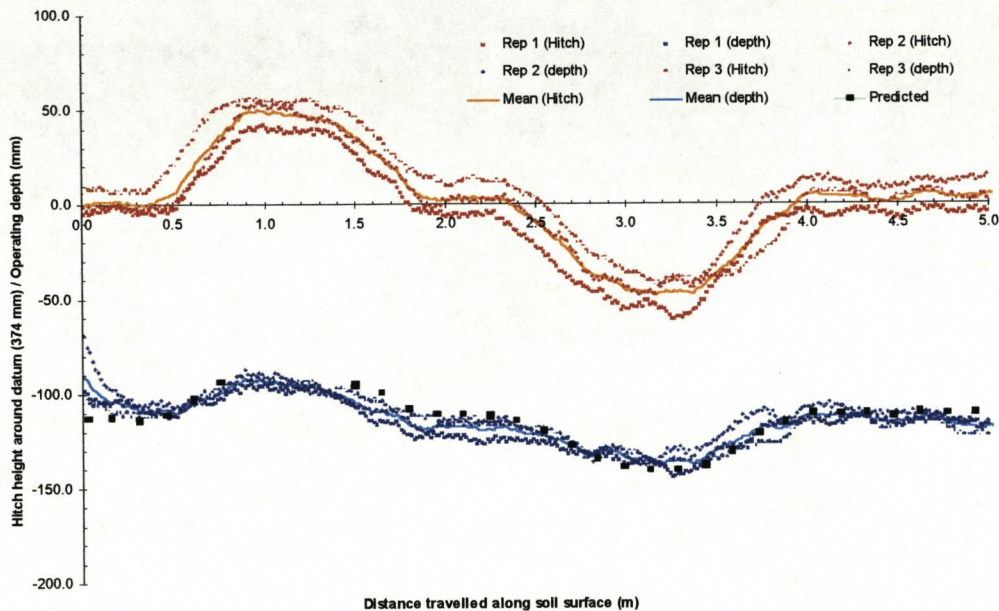


Fig. Ap 7.9.14. Dynamic performance of the Retro-fit injector tine without disc on the Greentrac parallel linkage with 2 springs between pivots ab.

Appendix 7.10.

Graphical presentation of dynamic soil profiles following 5 selected injector tine configurations following a sinusoidal change in implement toolbar height at 100 mm/s.

7.10.1 40WNDLi injector tine profiles

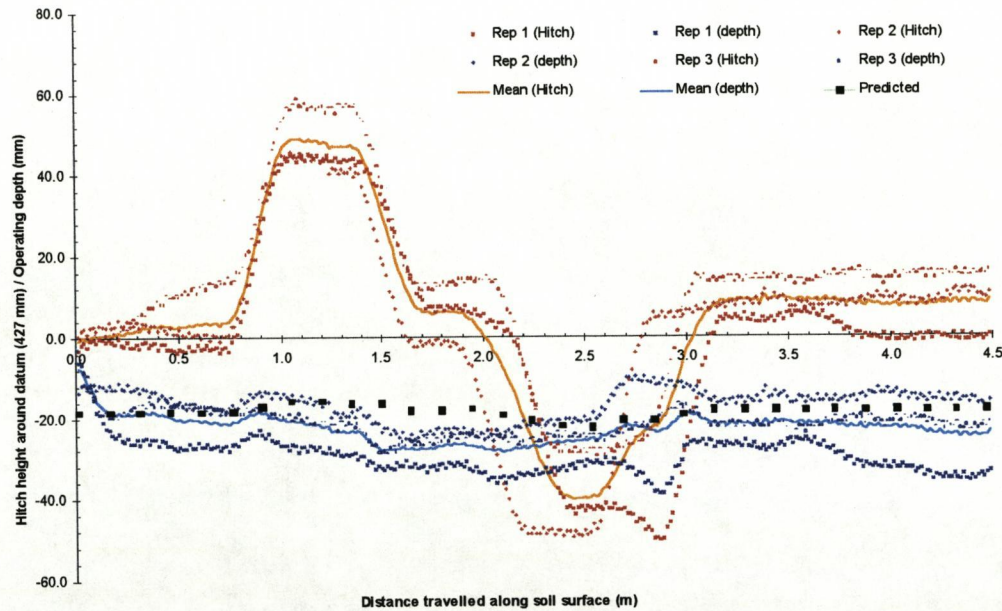


Fig. Ap 7.10.1. Dynamic performance of the 40WNDLi injector tine on the Greentrac parallel linkage with no spring assistance.

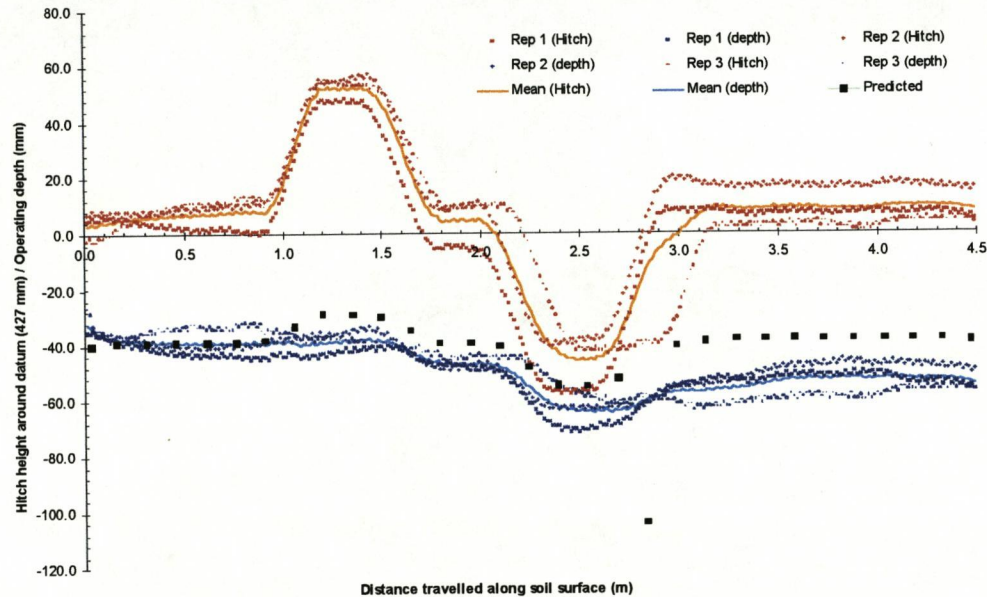


Fig. Ap 7.10.2. Dynamic performance of the 40WNDLi injector tine on the Greentrac parallel linkage with 2 springs between pivots ab.

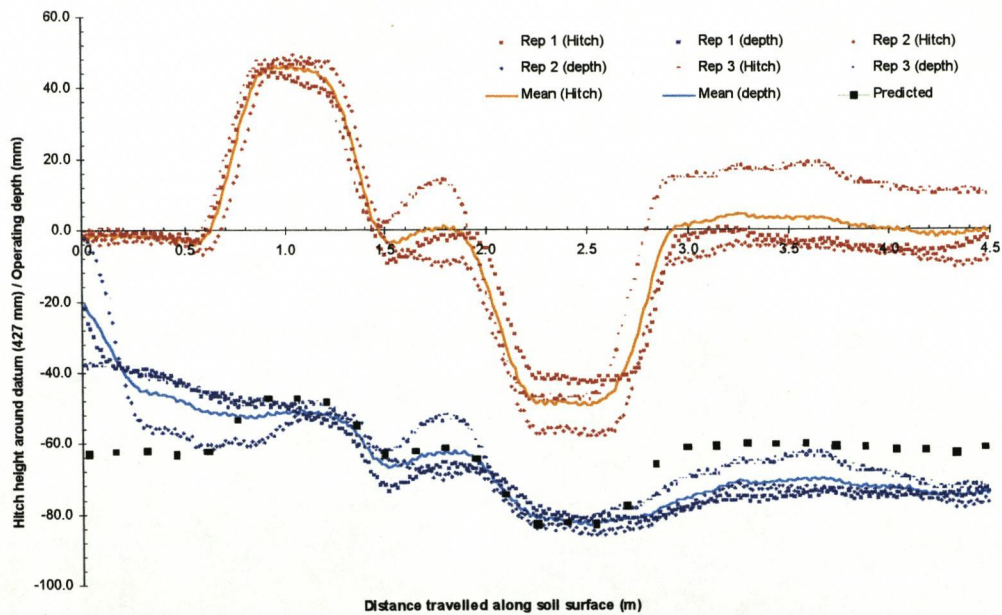


Fig. Ap 7.10.3. Dynamic performance of the 40WNDLi injector tine on the Greentrac parallel linkage with 2 springs between pivots ac.

7.10.2 NSH injector tine with disc.

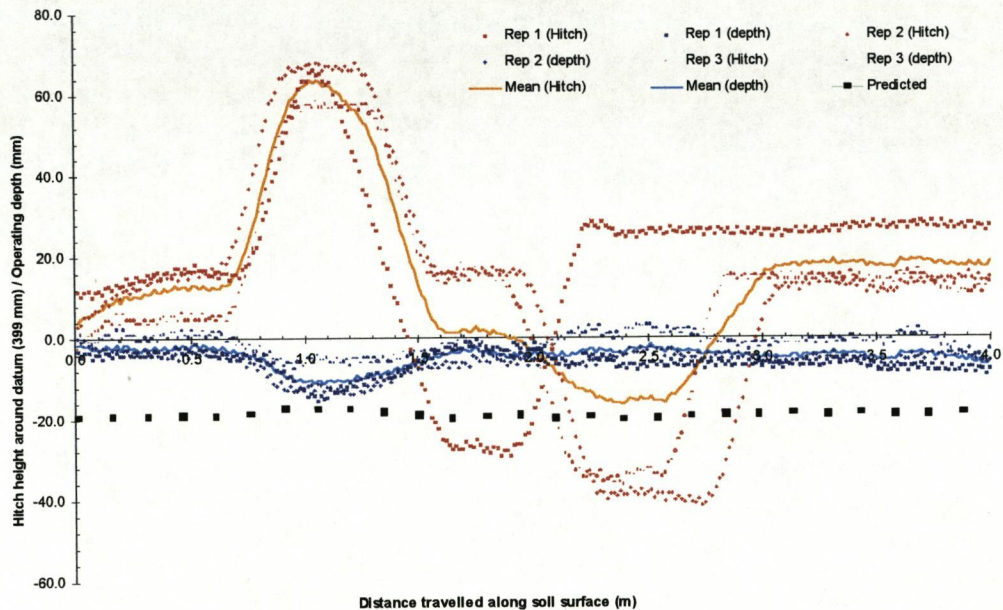


Fig. Ap 7.10.4. Dynamic performance of the NSH injector tine and disc on the Greentrac parallel linkage with no spring assistance.

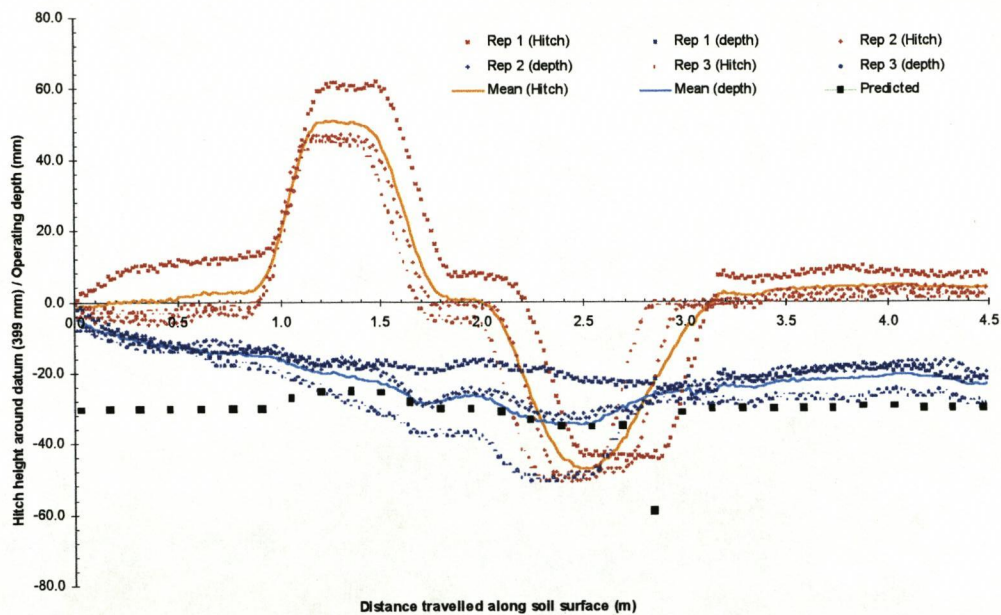


Fig. Ap 7.10.5. Dynamic performance of the NSH injector tine and disc on the Greentrac parallel linkage with 2 springs between pivots *ab*.

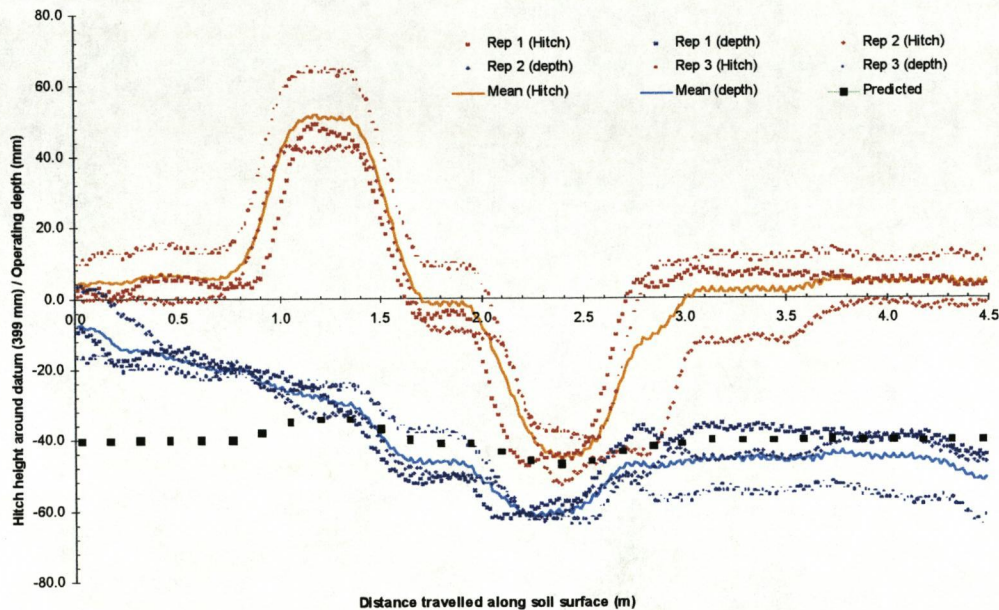


Fig. Ap 7.10.6. Dynamic performance of the NSH injector tine and disc on the Greentrac parallel linkage with 2 springs between pivots *ac*.

7.10.3 NSH injector tine without disc.

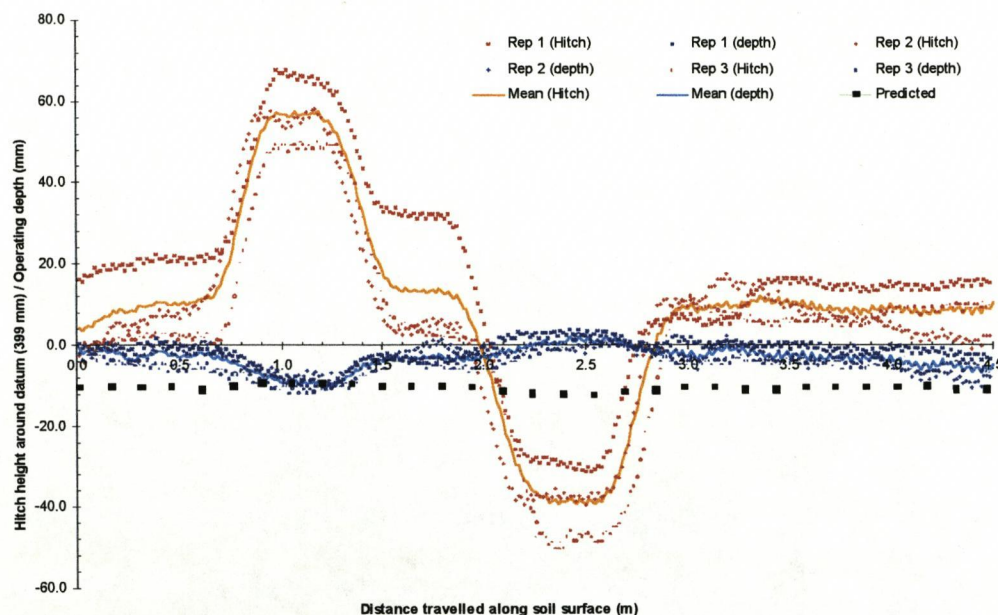


Fig. Ap 7.10.7. Dynamic performance of the NSH injector tine without disc on the Greentrac parallel linkage with no spring assistance.

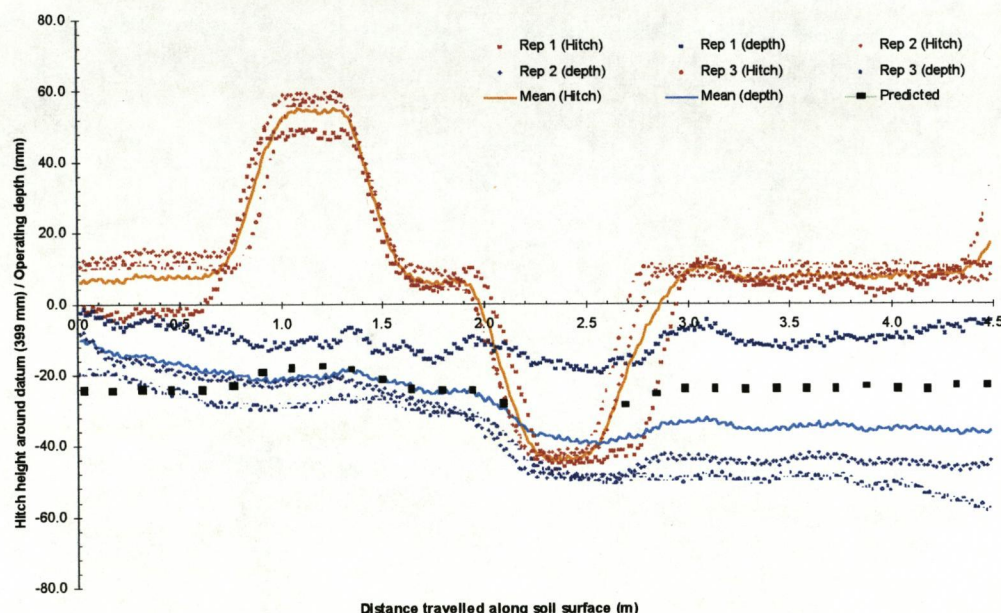


Fig. Ap 7.10.8. Dynamic performance of the NSH injector tine without disc on the Greentrac parallel linkage with 2 springs between pivots ab.

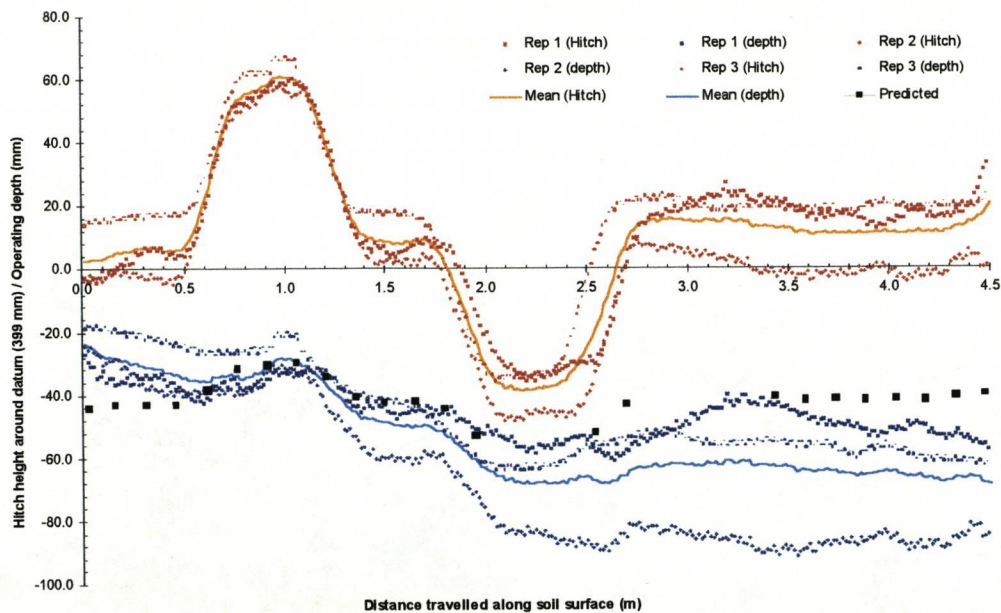


Fig. Ap 7.10.9. Dynamic performance of the NSH injector tine without disc on the Greentrac parallel linkage with 2 springs between pivots ac.

7.10.4 Retro-fit injector tine with disc.

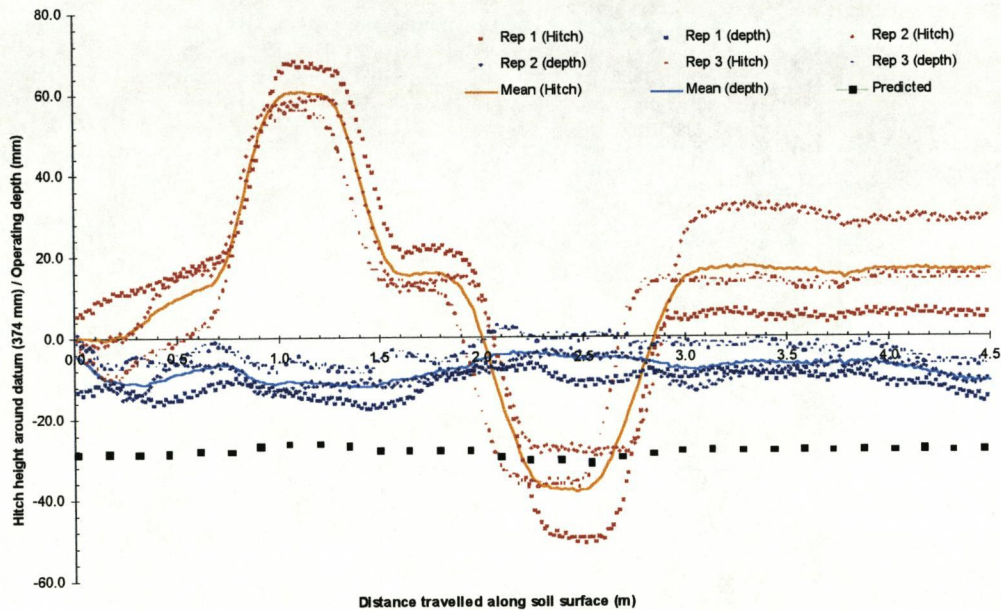


Fig. Ap 7.10.10. Dynamic performance of the Retro-fit injector tine with disc on the Greentrac parallel linkage with no spring assistance.

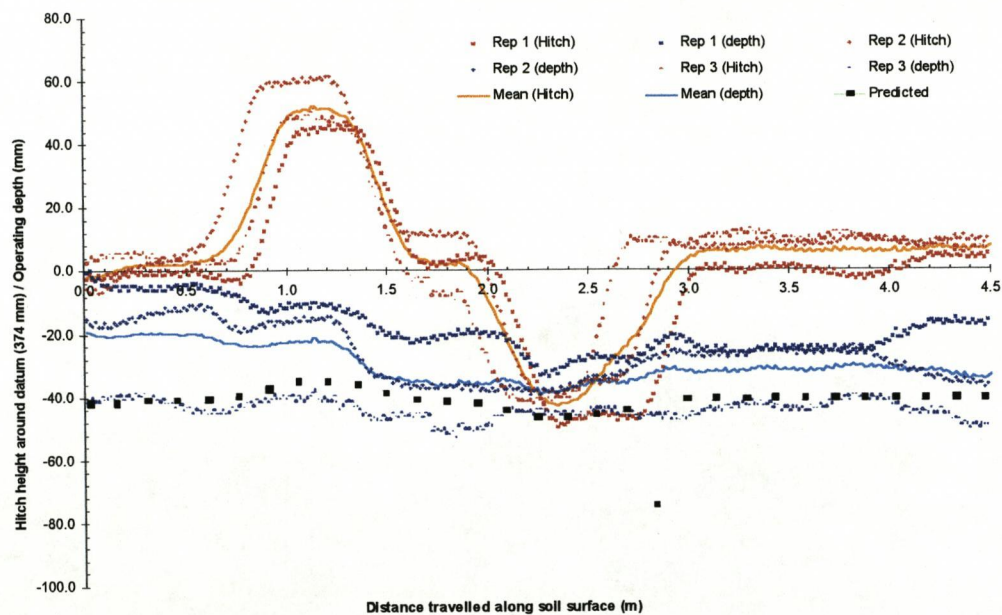


Fig. Ap 7.10.11. Dynamic performance of the Retro-fit injector tine with disc on the Greentrac parallel linkage with 2 springs between pivots ab.

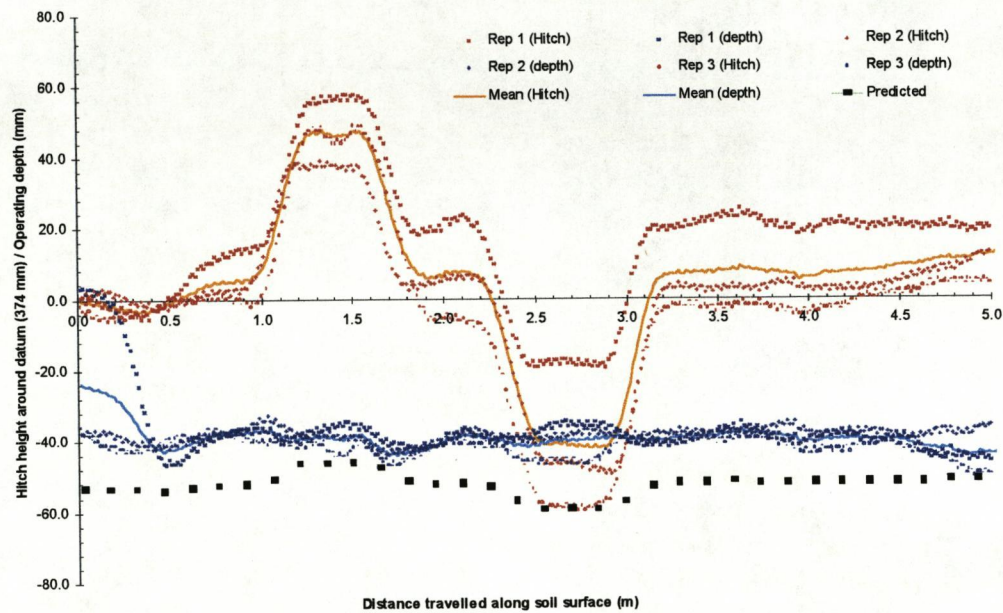


Fig. Ap 7.10.12. Dynamic performance of the Retro-fit injector tine with disc on the Greentrac parallel linkage with 2 springs between pivots ac.

7.10.5 Retro-fit injector tine without disc.

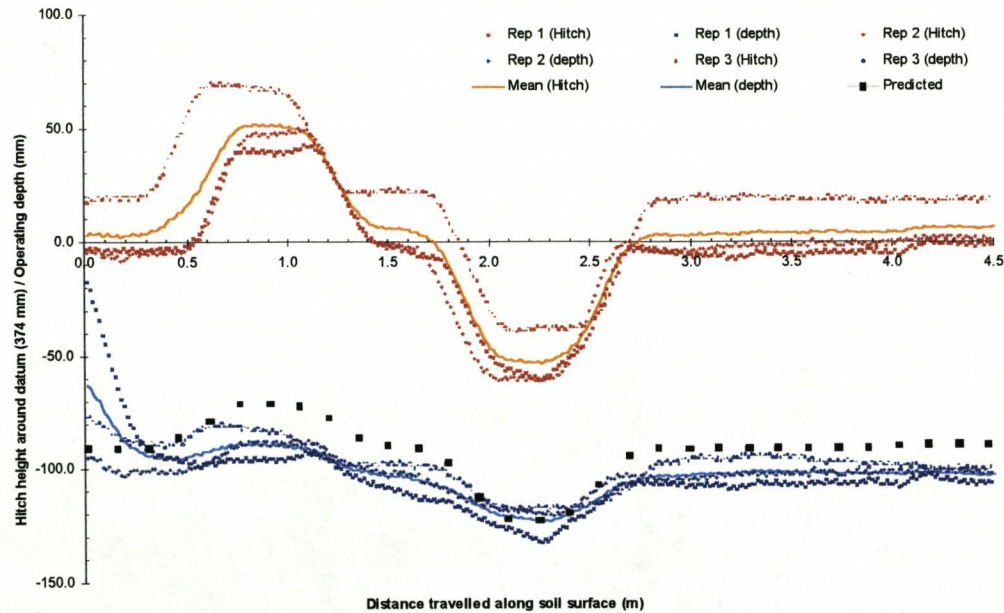


Fig. Ap 7.10.13. Dynamic performance of the Retro-fit injector tine without disc on the Greentrac parallel linkage with no spring assistance.

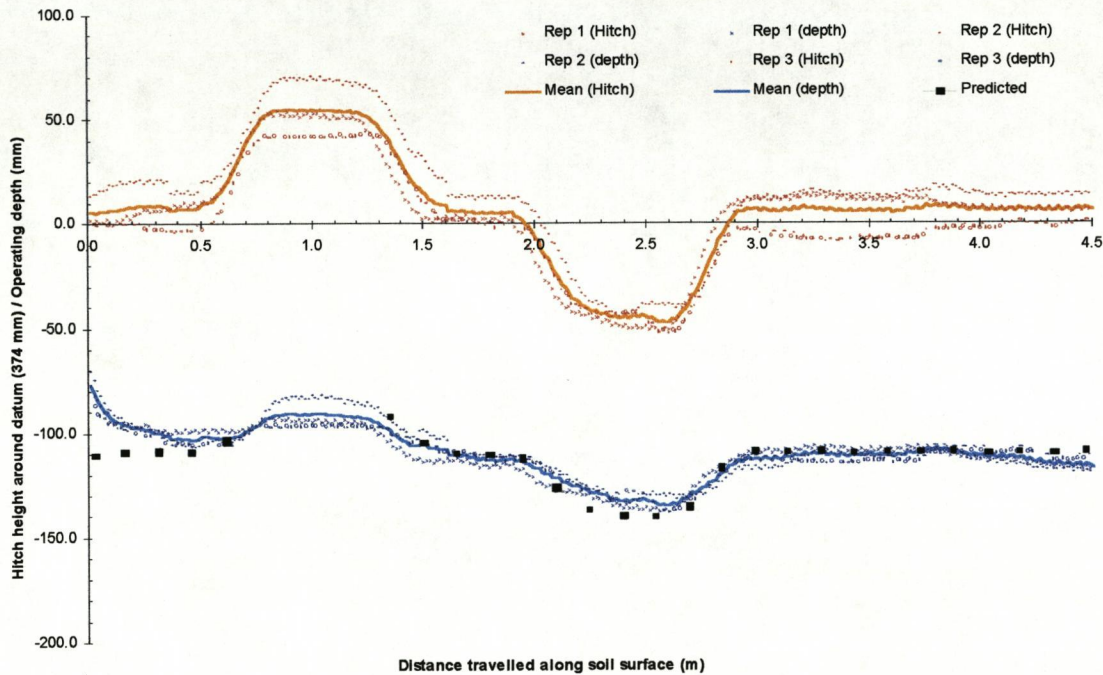


Fig. Ap 7.10.14. Dynamic performance of the Retro-fit injector tine without disc on the Greentrac parallel linkage with 2 springs between pivots ab.

Appendix 8

Appendix 8.1.

Second order partial differential equation representing the sensitivity of β to L_1 .

$$\frac{\partial}{\partial L_1} \left(\frac{\partial F}{\partial \beta} \right) = - \left[\begin{aligned} & \frac{1}{4} \frac{N \alpha R [AF] L_2 \sin[AD] [AF]}{[AE]^{\frac{3}{2}}} + \frac{1}{2} \frac{N \alpha R \left(2 \frac{(L_2 - L_1)N}{L_3^2} + 2 \frac{[AB]}{L_3} \right) L_2 \sin[AD]}{\sqrt{[AE]}} + \frac{1}{2} \frac{N \alpha R [AF] L_2 \cos[AD] [AC]}{\sqrt{[AE]}} + \frac{1}{2} \frac{N \alpha R [AF] L_2 \cos[AD] [AH]}{\sqrt{[AE]}} \\ & - \frac{N \alpha R (\sqrt{[AE]} + 10 - DL) L_2 \sin[AD] [AC] [AH]}{1 + \frac{[AB]^2}{(L_2 - L_1)^2 [AA]}} \\ & + N \alpha R (\sqrt{[AE]} + 10 - DL) L_2 \cos[AD] \left[\frac{\frac{N^2}{L_3^3 (L_2 - L_1) [AA]^{\frac{3}{2}}} + \frac{[AB]N}{(L_2 - L_1)^2 [AA]^{\frac{3}{2}} L_3^2}}{1 + \frac{[AB]^2}{(L_2 - L_1)^2 [AA]}} - \frac{[AG] \left(2 \frac{[AB]N}{(L_2 - L_1)^2 [AA] L_3} + 2 \frac{[AB]^2}{(L_2 - L_1)^2 [AA]} \right)}{\left(1 + \frac{[AB]^2}{(L_2 - L_1)^2 [AA]} \right)} \right] \\ & + \frac{1}{4} \frac{N \alpha R [AF] L_2 \sin[AD] [AF]}{[AE]^{\frac{3}{2}}} - \frac{1}{2} \frac{N \alpha R \left(2 \frac{(L_2 - L_1)N}{L_3^2} + 2 \frac{[AB]}{L_3} \right) L_1 \sin[AD]}{\sqrt{[AE]}} - \frac{1}{2} \frac{N \alpha R [AF] \sin[AD]}{\sqrt{[AE]}} - \frac{1}{2} \frac{N \alpha R [AF] L_1 \cos[AD] [AH]}{\sqrt{[AE]}} \\ & - N \alpha R (\sqrt{[AE]} + 10 - DL) \cos[AD] [AH] + \frac{N \alpha R (\sqrt{[AE]} + 10 - DL) L_1 \sin[AD] [AC] [AH]}{1 + \frac{[AB]^2}{(L_2 - L_1)^2 [AA]}} \\ & - N \alpha R (\sqrt{[AE]} + 10 - DL) L_1 \cos[AD] \left[\frac{\frac{N^2}{L_3^3 (L_2 - L_1) [AA]^{\frac{3}{2}}} + \frac{[AB]N}{(L_2 - L_1)^2 [AA]^{\frac{3}{2}} L_3^2}}{1 + \frac{[AB]^2}{(L_2 - L_1)^2 [AA]}} - \frac{[AG] \left(2 \frac{[AB]N}{(L_2 - L_1)^2 [AA] L_3} + 2 \frac{[AB]^2}{(L_2 - L_1)^2 [AA]} \right)}{\left(1 + \frac{[AB]^2}{(L_2 - L_1)^2 [AA]} \right)} \right] \end{aligned} \right] \frac{1}{L_3 \sqrt{[AA]}} \\ - \left[\begin{aligned} & \frac{1}{2} \frac{N \alpha R [AF] L_1 \sin[AD]}{\sqrt{[AE]}} + \frac{N \alpha R (\sqrt{[AE]} + 10 - DL) L_1 \cos[AD] [AC]}{1 + \frac{[AB]^2}{(L_2 - L_1)^2 [AA]}} - \frac{1}{2} \frac{N \alpha R [AF] L_1 \sin[AD]}{\sqrt{[AE]}} - N \alpha R (\sqrt{[AE]} + 10 - DL) \sin[AD] - \frac{N \alpha R (\sqrt{[AE]} + 10 - DL) L_1 \cos[AD] [AC]}{1 + \frac{[AB]^2}{(L_2 - L_1)^2 [AA]}} \end{aligned} \right] \frac{1}{L_3^2 [AA]^{\frac{3}{2}}} \quad [35]$$

Where:

$$[AA] = 1 - \frac{N^2}{L_3^2} \quad [36]$$

$$[AB] = L_4 - \frac{(L_2 - L_1)N}{L_3} \quad [37]$$

$$[AC] = \frac{N}{L_3 (L_2 - L_1) [AA]} + \frac{[AB]}{(L_2 - L_1)^2 \sqrt{[AA]}} \quad [38]$$

$$[AD] = \tan^{-1} \left(\frac{[AB]}{(L_2 - L_1)^2 \sqrt{[AA]}} \right) + \sin^{-1} \frac{N}{L_3} \quad [39]$$

$$[AE] = (L_2 - L_1)^2 [AA] + [AB]^2 \quad [40]$$

$$[AF] = -2(L_2 - L_1) [AA] + 2 \frac{[AB]N}{L_3} \quad [41]$$

$$[AG] = -\frac{1}{\sqrt{[AA]} L_3} + 2 \frac{[AB]N}{(L_2 - L_1) [AA]^{\frac{3}{2}} L_3^2} \quad [42]$$

$$[AH] = \frac{[AG]}{1 + \frac{[AB]^2}{(L_2 - L_1)[AA]}} + \frac{1}{\sqrt{[AA]}L_3} \quad [43]$$

$$[AI] = -2 \frac{(L_2 - L_1)^2 N}{L_3^2} - 2 \frac{[AB](L_2 - L_1)}{L_3} \quad [44]$$

Appendix 8.2.

Second order partial differential equation representing the sensitivity of β to L_2 .

$$\frac{\partial}{\partial L_2} \left(\frac{\delta F}{\delta d} \right) = - \frac{\left[\begin{aligned} & \frac{1}{4} \frac{N \alpha R [AF] L_2 \sin[AD] [AF]}{[AE]^{\frac{3}{2}}} + \frac{1}{2} \frac{N \alpha R \left(2 \frac{(L_2 - L_1) N}{L_3} + 2 \frac{[AB]}{L_3} \right) L_2 \sin[AD]}{\sqrt{[AE]}} + \frac{1}{2} \frac{N \alpha R [AF] L_2 \cos[AD] [AC]}{\sqrt{[AE] \left(1 + \frac{[AB]^2}{(L_2 - L_1)^2 [AA]} \right)}} + \frac{1}{2} \frac{N \alpha R [AF] L_2 \cos[AD] [AH]}{\sqrt{[AE]}} \\ & - \frac{N \alpha R (\sqrt{[AE]} + 10 - DL) L_2 \sin[AD] [AC] [AH]}{1 + \frac{[AB]^2}{(L_2 - L_1)^2 [AA]}} \\ & + N \alpha R (\sqrt{[AE]} + 10 - DL) L_2 \cos[AD] \left(\frac{\frac{N^2}{L_3^2 (L_2 - L_1)^2 [AA]^{\frac{3}{2}}} + \frac{[AB] N}{(L_2 - L_1)^2 [AA]^{\frac{3}{2}} L_3^2} - \frac{[AG] \left(2 \frac{[AB] N}{(L_2 - L_1)^2 [AA] L_2} + 2 \frac{[AB]^2}{(L_2 - L_1)^2 [AA]} \right)}{1 + \frac{[AB]^2}{(L_2 - L_1)^2 [AA]}} \right) \\ & + \frac{1}{4} \frac{N \alpha R [AF] L_2 \sin[AD] [AF]}{[AE]^{\frac{3}{2}}} - \frac{1}{2} \frac{N \alpha R \left(2 \frac{(L_2 - L_1) N}{L_3} + 2 \frac{[AB]}{L_3} \right) L_2 \sin[AD]}{\sqrt{[AE]}} - \frac{1}{2} \frac{N \alpha R [AF] \sin[AD]}{\sqrt{[AE]}} - \frac{1}{2} \frac{N \alpha R [AF] L_2 \cos[AD] [AH]}{\sqrt{[AE]}} \\ & - N \alpha R (\sqrt{[AE]} + 10 - DL) \cos[AD] [AH] + \frac{N \alpha R (\sqrt{[AE]} + 10 - DL) L_2 \sin[AD] [AC] [AH]}{1 + \frac{[AB]^2}{(L_2 - L_1)^2 [AA]}} \\ & - N \alpha R (\sqrt{[AE]} + 10 - DL) L_2 \cos[AD] \left(\frac{\frac{N^2}{L_3^2 (L_2 - L_1)^2 [AA]^{\frac{3}{2}}} + \frac{[AB] N}{(L_2 - L_1)^2 [AA]^{\frac{3}{2}} L_3^2} - \frac{[AG] \left(2 \frac{[AB] N}{(L_2 - L_1)^2 [AA] L_2} + 2 \frac{[AB]^2}{(L_2 - L_1)^2 [AA]} \right)}{1 + \frac{[AB]^2}{(L_2 - L_1)^2 [AA]}} \right) \end{aligned} \right]}{L_2 \sqrt{[AA]}} \left(\begin{aligned} & \frac{1}{2} \frac{N \alpha R [AF] L_2 \sin[AD]}{\sqrt{[AE]}} + \frac{N \alpha R (\sqrt{[AE]} + 10 - DL) L_2 \cos[AD] [AC]}{1 + \frac{[AB]^2}{(L_2 - L_1)^2 [AA]}} - \frac{1}{2} \frac{N \alpha R [AF] L_2 \sin[AD]}{\sqrt{[AE]}} - N \alpha R (\sqrt{[AE]} + 10 - DL) \sin[AD] - \frac{N \alpha R (\sqrt{[AE]} + 10 - DL) L_2 \cos[AD] [AC]}{1 + \frac{[AB]^2}{(L_2 - L_1)^2 [AA]}} \end{aligned} \right) N$$

$$[45]$$

Where:

$$[AA] = 1 - \frac{N^2}{L_3^2} \quad [46]$$

$$[AB] = L_4 - \frac{(L_2 - L_1) N}{L_3} \quad [47]$$

$$[AC] = \frac{N}{L_3 (L_2 - L_1) [AA]} + \frac{[AB]}{(L_2 - L_1)^2 \sqrt{[AA]}} \quad [48]$$

$$[AD] = \tan^{-1} \left(\frac{[AB]}{(L_2 - L_1)^2 \sqrt{[AA]}} \right) + \sin^{-1} \frac{N}{L_3} \quad [49]$$

$$[AE] = (L_2 - L_1)^2 [AA] + [AB]^2 \quad [50]$$

$$[AF] = -2(L_2 - L_1) [AA] + 2 \frac{[AB] N}{L_3} \quad [51]$$

$$[AG] = -\frac{1}{\sqrt{[AA]} L_3} + 2 \frac{[AB] N}{(L_2 - L_1) [AA]^{\frac{3}{2}} L_3^2} \quad [52]$$

$$[AH] = \frac{[AG]}{1 + \frac{[AB]^2}{(L_2 - L_1)[AA]}} + \frac{1}{\sqrt{[AA]}L_3} \quad [53]$$

$$[AI] = -2 \frac{(L_2 - L_1)^2 N}{L_3^2} - 2 \frac{[AB](L_2 - L_1)}{L_3} \quad [54]$$

Appendix 8.3.

Second order partial differential equation representing the sensitivity of β to L_3 .

$$\begin{aligned}
 \frac{\partial}{\partial L_3} \left(\frac{\delta F}{\delta t} \right) = & -\frac{1}{2} \frac{[BO]N(2Df(0.2254d + 7.6567) + 2Vf(-0.0284d + 7.6411))}{(\sqrt{Df^2 + Vf^2}[BA]L_3^2)} - \frac{1}{2} \frac{[BN](2Df(0.2254d + 7.6567) + 2Vf(-0.0284d + 7.6411))N^2}{(\sqrt{Df^2 + Vf^2})} \\
 & + \frac{\sqrt{Df^2 + Vf^2}[BN]N \left(\frac{1}{\sqrt{[BA]L_3}} + \frac{-0.0284d + 7.6411}{Df} - \frac{Vf(0.2254d + 7.6567)}{Df^2} \right)}{1 + \frac{Vf^2}{Df^2}} + \frac{\sqrt{Df^2 + Vf^2}[BO] \left(-[BK] - \frac{1}{\sqrt{[BA]L_3^2}} \right)}{\sqrt{[BA]}} \\
 & - \frac{\sqrt{Df^2 + Vf^2}[BO]N^2 \left(\frac{1}{\sqrt{[BA]L_3}} + \frac{-0.0284d + 7.6411}{Df} - \frac{Vf(0.2254d + 7.6567)}{Df^2} \right)}{[BA]^{\frac{3}{2}}L_3^3} - \frac{\sqrt{Df^2 + Vf^2}[BO]N^2}{[BA]^{\frac{3}{2}}L_3^3} - 3 \frac{\sqrt{Df^2 + Vf^2}[BN]N^3}{[BA]^{\frac{3}{2}}L_3^3} - 2 \frac{\sqrt{Df^2 + Vf^2}[BN]N}{[BA]^{\frac{3}{2}}L_3^3} \\
 & \left(\begin{aligned}
 & \frac{1}{4} \frac{N\alpha R[B]L_3 \sin[BD][BG]}{[BE]^{\frac{3}{2}}} + \frac{1}{2} \frac{N\alpha R \left(2 \frac{(L_2 - L_1)^2 N}{L_3^3} + 2 \frac{[BC](L_2 - L_1)}{L_3^2} \right) L_3 \sin[BD]}{\sqrt{[BE]}} + \frac{1}{2} \frac{N\alpha R[B]L_3 \cos[BD][BF]}{\sqrt{[BE]}} + \frac{1}{2} \frac{N\alpha R[BG]L_3 \cos[BD][BI]}{\sqrt{[BE]}} \\
 & - N\alpha R(\sqrt{[BE]} + 10 - DL)L_3 \sin[BD][BF][BI] \\
 & + N\alpha R(\sqrt{[BE]} + 10 - DL)L_3 \cos[BD] \left(\frac{2[BK] + \frac{1}{\sqrt{[BA]L_3^2}} - 3 \frac{[BC]N}{(L_2 - L_1)[BA]^{\frac{3}{2}}L_3^2} - 2 \frac{[BC]N}{(L_2 - L_1)[BA]^{\frac{3}{2}}L_3^2}}{\left(1 + \frac{[BC]^2}{(L_2 - L_1)^2[BA]} \right)} - \frac{[BH] \left(2 \frac{[BC]N}{(L_2 - L_1)[BA]L_3^2} - 2 \frac{[BC]^2 N}{(L_2 - L_1)^2[BA]^2 L_3^3} \right)}{\left(1 + \frac{[BC]^2}{(L_2 - L_1)^2[BA]} \right)} - [BK] - \frac{1}{\sqrt{[BA]L_3^2}} \right) \\
 & + \frac{1}{4} \frac{N\alpha R[B]L_3 \sin[BD][BG]}{[BE]^{\frac{3}{2}}} - \frac{1}{2} \frac{N\alpha R \left(2 \frac{(L_2 - L_1)^2 N}{L_3^3} + 2 \frac{[BC](L_2 - L_1)}{L_3^2} \right) L_3 \sin[BD]}{\sqrt{[BE]}} - \frac{1}{2} \frac{N\alpha R[B]L_3 \cos[BD][BF]}{\sqrt{[BE]}} - \frac{1}{2} \frac{N\alpha R[BG]L_3 \cos[BD][BI]}{\sqrt{[BE]}} \\
 & + N\alpha R(\sqrt{[BE]} + 10 - DL)L_3 \sin[BD][BF][BI] \\
 & - N\alpha R(\sqrt{[BE]} + 10 - DL)L_3 \cos[BD] \left(\frac{2[BK] + \frac{1}{\sqrt{[BA]L_3^2}} - 3 \frac{[BC]N}{(L_2 - L_1)[BA]^{\frac{3}{2}}L_3^2} - 2 \frac{[BC]N}{(L_2 - L_1)[BA]^{\frac{3}{2}}L_3^2}}{\left(1 + \frac{[BC]^2}{(L_2 - L_1)^2[BA]} \right)} - \frac{[BH] \left(2 \frac{[BC]N}{(L_2 - L_1)[BA]L_3^2} - 2 \frac{[BC]^2 N}{(L_2 - L_1)^2[BA]^2 L_3^3} \right)}{\left(1 + \frac{[BC]^2}{(L_2 - L_1)^2[BA]} \right)} - [BK] - \frac{1}{\sqrt{[BA]L_3^2}} \right)
 \end{aligned} \right) \\
 & + \frac{L_3 \sqrt{[BA]}}{L_3^2 \sqrt{[BA]}} \left(\frac{1}{2} \frac{N\alpha R[B]L_3 \sin[BD]}{\sqrt{[BE]}} + N\alpha R(\sqrt{[BE]} + 10 - DL)L_3 \cos[BD][BI] - \frac{1}{2} \frac{N\alpha R[B]L_3 \sin[BD]}{\sqrt{[BE]}} - N\alpha R(\sqrt{[BE]} + 10 - DL)L_3 \cos[BD][BI] \right) \\
 & + \frac{\left(\frac{1}{2} \frac{N\alpha R[B]L_3 \sin[BD]}{\sqrt{[BE]}} + N\alpha R(\sqrt{[BE]} + 10 - DL)L_3 \cos[BD][BI] - \frac{1}{2} \frac{N\alpha R[B]L_3 \sin[BD]}{\sqrt{[BE]}} - N\alpha R(\sqrt{[BE]} + 10 - DL)L_3 \cos[BD][BI] \right) N^2}{L_3^4 [BA]^{\frac{3}{2}}} \\
 & - \frac{\left(\frac{1}{2} \frac{N\alpha R[BG]L_3 \sin[BD]}{\sqrt{[BE]}} + N\alpha R(\sqrt{[BE]} + 10 - DL)L_3 \cos[BD][BF] - \frac{1}{2} \frac{N\alpha R[BG]L_3 \sin[BD]}{\sqrt{[BE]}} - N\alpha R(\sqrt{[BE]} + 10 - DL)L_3 \cos[BD][BF] \right) N}{L_3^4 [BA]^{\frac{3}{2}}} \\
 & + \frac{3(N\alpha R(\sqrt{[BE]} + 10 - DL)L_3 \sin[BD] - N\alpha R(\sqrt{[BE]} + 10 - DL)L_3 \sin[BD])N}{L_3^4 [BA]^{\frac{3}{2}}} + \frac{3(N\alpha R(\sqrt{[BE]} + 10 - DL)L_3 \sin[BD] - N\alpha R(\sqrt{[BE]} + 10 - DL)L_3 \sin[BD])N^3}{L_3^4 [BA]^{\frac{3}{2}}}
 \end{aligned} \tag{55}$$

Where:

$$BA = 1 - \frac{N^2}{L_3^2} \tag{56}$$

$$BB = \sin^{-1} \left(\frac{N}{L_3} \right) \tag{57}$$

$$BC = L_4 - \frac{(L_2 - L_1)N}{L_3} \tag{58}$$

$$BD = \tan^{-1} \frac{[BC]}{(L_2 - L_1)\sqrt{[BA]}} \tag{59}$$

$$BE = (L_2 - L_1)^2 [BA] + [BC]^2 \tag{60}$$

$$BF = \frac{\frac{N}{\sqrt{[BA]}L_3^2} - \frac{[BC]N^2}{(L_2 - L_1)[BA]^{3/2}L_3^3}}{1 + \frac{[BC]^2}{(L_2 - L_1)^2[BA]}} - \frac{N}{\sqrt{[BA]}L_3^2} \quad [61]$$

$$BG = 2 \frac{(L^2 - L^1)^2 N^2}{L_3^3} + 2 \frac{[BC](L_2 - L_1)N}{L_3^2} \quad [62]$$

$$BH = -\frac{1}{\sqrt{[BA]}L_3} + \frac{[BC]N}{(L_2 - L_1)[BA]^{3/2}L_3^2} \quad [63]$$

$$BI = \frac{[BH]}{1 + \frac{[BC]^2}{(L_2 - L_1)^2[BA]}} + \frac{1}{\sqrt{[BA]}L_3} \quad [64]$$

$$BJ = -2 \frac{(L_2 - L_1)^2 N}{L_3^2} - 2 \frac{[BC](L_2 - L_1)}{L_3} \quad [65]$$

$$BK = \frac{N^2}{[BA]^{3/2}L_3^4} \quad [66]$$

$$BN = \sin \left([BB] + \tan^{-1} \left(\frac{Vf}{Df} \right) \right) \quad [67]$$

$$BN = \cos \left([BB] + \tan^{-1} \left(\frac{Vf}{Df} \right) \right) \quad [68]$$

Appendix 8.4.

Second order partial differential equation representing the sensitivity of β to L_4 .

$$\begin{aligned}
 \frac{\partial}{\partial L_3} \left(\frac{\partial F}{\partial d} \right) = & - \left(\frac{1}{4} \frac{NsR[CG]L_2 \sin[CC][2L_4 - 2[CB]]}{[CD]^{\frac{3}{2}}} - \frac{NsR(L_2 - L_1)L_2 \sin[CC]}{\sqrt{[CD]}L_3} + \frac{1}{2} \frac{NsR[CG]L_2 \cos[CC]}{\sqrt{[CD]}(L_2 - L_1)\sqrt{[CA]} \left(1 + \frac{(L_4 - [CB])^2}{(L_2 - L_1)^2[CA]} \right)} + \frac{1}{2} \frac{NsR(2L_4 - 2[CB])L_2 \cos[CC][CF]}{\sqrt{[CD]}} \right. \\
 & - \frac{NsR(\sqrt{[CD]} + 10 - DL)L_2 \sin[CC][CF]}{(L_2 - L_1)\sqrt{[CA]} \left(1 + \frac{(L_4 - [CB])^2}{(L_2 - L_1)^2[CA]} \right)} + NsR(\sqrt{[CD]} + 10 - DL)L_2 \cos[CC] \left\{ \frac{N}{(L_2 - L_1)[CA]^{\frac{3}{2}}L_3^2 \left(1 + \frac{(L_4 - [CB])^2}{(L_2 - L_1)^2[CA]} \right)} - 2 \frac{[CE](L_4 - [CB])}{\left(1 + \frac{(L_4 - [CB])^2}{(L_2 - L_1)^2[CA]} \right)(L_2 - L_1)^2[CA]} \right\} \\
 & + \frac{1}{4} \frac{NsR[CG]L_1 \sin[CC][2L_4 - 2[CB]]}{[CD]^{\frac{3}{2}}} + \frac{NsR(L_2 - L_1)L_1 \sin[CC]}{\sqrt{[CD]}L_3} - \frac{1}{2} \frac{NsR[CG]L_1 \cos[CC]}{\sqrt{[CD]}(L_2 - L_1)\sqrt{[CA]} \left(1 + \frac{(L_4 - [CB])^2}{(L_2 - L_1)^2[CA]} \right)} - \frac{1}{2} \frac{NsR(2L_4 - 2[CB])L_1 \cos[CC][CF]}{\sqrt{[CD]}} \\
 & + \frac{NsR(\sqrt{[CD]} + 10 - DL)L_1 \sin[CC][CF]}{(L_2 - L_1)\sqrt{[CA]} \left(1 + \frac{(L_4 - [CB])^2}{(L_2 - L_1)^2[CA]} \right)} - NsR(\sqrt{[CD]} + 10 - DL)L_1 \cos[CC] \left\{ \frac{N}{(L_2 - L_1)[CA]^{\frac{3}{2}}L_3^2 \left(1 + \frac{(L_4 - [CB])^2}{(L_2 - L_1)^2[CA]} \right)} - 2 \frac{[CE](L_4 - [CB])}{\left(1 + \frac{(L_4 - [CB])^2}{(L_2 - L_1)^2[CA]} \right)(L_2 - L_1)^2[CA]} \right\} \Bigg) \\
 & - \frac{\left(\frac{1}{2} \frac{NsR(2L_4 - 2[CB])L_2 \sin[CC]}{\sqrt{[CD]}} + \frac{NsR(\sqrt{[CD]} + 10 - DL)L_2 \cos[CC]}{(L_2 - L_1)\sqrt{[CA]} \left(1 + \frac{(L_4 - [CB])^2}{(L_2 - L_1)^2[CA]} \right)} - \frac{1}{2} \frac{NsR(2L_4 - 2[CB])L_1 \sin[CC]}{\sqrt{[CD]}} + \frac{NsR(\sqrt{[CD]} + 10 - DL)L_1 \cos[CC]}{(L_2 - L_1)\sqrt{[CA]} \left(1 + \frac{(L_4 - [CB])^2}{(L_2 - L_1)^2[CA]} \right)} \right) N}{(L_3^3[CA]^{\frac{3}{2}})}
 \end{aligned}
 \tag{69}$$

Where:

$$CA = 1 - \frac{N^2}{L_3^2} \tag{70}$$

$$CB = \frac{(L_2 - L_1)N}{L_3} \tag{71}$$

$$CC = \tan^{-1} \left(\frac{L_4 - [CB]}{(L_2 - L_1)\sqrt{[CA]}} \right) + \sin^{-1} \left(\frac{N}{L_3} \right) \tag{72}$$

$$CD = (L_2 - L_1)^2[CA] + (L_4 - [CB])^2 \tag{73}$$

$$CE = -\frac{1}{\sqrt{[CA]}L_3} + \frac{(L_4 - [CB])N}{(L_2 - L_1)[CA]^{\frac{3}{2}}L_3^2} \tag{74}$$

$$CF = \frac{[CE]}{1 + \frac{(L_4 - [CB])^2}{(L_2 - L_1)^2[CA]}} + \frac{1}{\sqrt{[CA]}L_3} \tag{75}$$

$$CG = -2 \frac{(L_2 - L_1)^2 N}{L_3^2} - 2 \frac{(L_4 - [CB])(L_2 - L_1)}{L_3} \tag{76}$$

Appendix 8.5.

Second order partial differential equation representing the sensitivity of β to L_5 .

$$\begin{aligned}
 \frac{\partial}{\partial L_5} \left(\frac{\delta F}{\delta d} \right) = & \frac{1}{2} \frac{\cos \left([EB] + \tan^{-1} \left(\frac{VF}{Df} \right) \right) \left(2Df(0.2254d + 7.6567) + 2VF(-0.0284d + 7.6411) \right)}{\sqrt{Df^2 + VF^2} [EA] L_3} - \frac{1}{2} \frac{[EN] \left(2Df(0.2254d + 7.6567) + 2VF(-0.0284d + 7.6411) \right) N}{\left(\sqrt{Df^2 + VF^2} [EA]^{\frac{1}{2}} L_3^2 \right)} \\
 & + \frac{\sqrt{Df^2 + VF^2} [EN] \left\{ \frac{1}{\sqrt{[EA]} L_3} + \frac{-0.0284d + 7.6411}{Df} - \frac{VF(0.2254d + 7.6567)}{Df^2} \right\}}{[EA] L_3} - \frac{\sqrt{Df^2 + VF^2} \cos \left([EB] + \tan^{-1} \left(\frac{VF}{Df} \right) \right) N}{[EA] 2L_3^3} \\
 & - \frac{\sqrt{Df^2 + VF^2} \cos \left([EB] + \tan^{-1} \left(\frac{VF}{Df} \right) \right) \left\{ \frac{1}{\sqrt{[EA]} L_3} + \frac{Df}{1 + \frac{VF^2}{Df^2}} \right\} N}{\left([EA]^{\frac{1}{2}} L_3^2 \right)} - \frac{3 \sqrt{Df^2 + VF^2} [EN] N^2}{[EA]^{\frac{1}{2}} L_3^4} - \frac{\sqrt{Df^2 + VF^2} [EN]}{[EA]^{\frac{1}{2}} L_3^2} \\
 & \left(\frac{1}{4} \frac{NsR[EK] L_2 \sin[ED][EI]}{[EB]^{\frac{1}{2}}} + \frac{1}{2} \frac{NsR[EK] L_2 \cos[ED][EG]}{\sqrt{[EB]}} + \frac{1}{2} \frac{NsR[EI] L_2 \cos[ED][EJ]}{\sqrt{[EB]}} - NsR(\sqrt{[EE]} + 10 - DL) L_2 \sin[ED][EG][EJ] \right. \\
 & \left. + NsR(\sqrt{[EE]} + 10 - DL) L_2 \cos[ED] \left(\frac{2 \frac{N}{[EA]^{\frac{1}{2}} L_3^3} - 3 \frac{[EC] N^2}{(L_2 - L_1) [EA]^{\frac{1}{2}} L_3^4} - \frac{[EC]}{(L_2 - L_1) [EA]^{\frac{1}{2}} L_3^2} - \left(-\frac{1}{\sqrt{[EA]} L_3} + [EF] \right) \left(2 \frac{[EC]}{(L_2 - L_1) [EA] L_3} - 2 \frac{[EC]^2 N}{(L_2 - L_1)^2 [EA]^{\frac{1}{2}} L_3^2} \right)}{1 + \frac{[EC]^2}{(L_2 - L_1)^2 [EA]}} - \frac{N}{[EA]^{\frac{1}{2}} L_3^3} \right) \right. \\
 & \left. + \frac{1}{4} \frac{NsR[EK] L_2 \sin[ED][EI]}{[EB]^{\frac{1}{2}}} - \frac{1}{2} \frac{NsR[EK] L_2 \cos[ED][EG]}{\sqrt{[EB]}} - \frac{1}{2} \frac{NsR[EI] L_2 \cos[ED][EJ]}{\sqrt{[EB]}} + NsR(\sqrt{[EE]} + 10 - DL) L_2 \sin[ED][EG][EJ] \right. \\
 & \left. - NsR(\sqrt{[EE]} + 10 - DL) L_2 \cos[ED] \left(\frac{2 \frac{N}{[EA]^{\frac{1}{2}} L_3^3} - 3 \frac{[EC] N^2}{(L_2 - L_1) [EA]^{\frac{1}{2}} L_3^4} - \frac{[EC]}{(L_2 - L_1) [EA]^{\frac{1}{2}} L_3^2} - \left(-\frac{1}{\sqrt{[EA]} L_3} + [EF] \right) \left(2 \frac{[EC]}{(L_2 - L_1) [EA] L_3} - 2 \frac{[EC]^2 N}{(L_2 - L_1)^2 [EA]^{\frac{1}{2}} L_3^2} \right)}{1 + \frac{[EC]^2}{(L_2 - L_1)^2 [EA]}} - \frac{N}{[EA]^{\frac{1}{2}} L_3^3} \right) \right) \\
 & \left(L_3 \sqrt{[EA]} \right) \\
 & + \frac{\left(\frac{1}{2} \frac{NsR[EK] L_2 \sin[ED]}{\sqrt{[EB]}} + NsR(\sqrt{[EE]} + 10 - DL) L_2 \cos[ED][EJ] - \frac{1}{2} \frac{NsR[EK] L_2 \sin[ED]}{\sqrt{[EB]}} - NsR(\sqrt{[EE]} + 10 - DL) L_2 \cos[ED][EJ] \right) N}{\left(L_3^3 [EA]^{\frac{1}{2}} \right)} \\
 & - \frac{\left(\frac{1}{2} \frac{NsR[EI] L_2 \sin[ED]}{\sqrt{[EB]}} + NsR(\sqrt{[EE]} + 10 - DL) L_2 \cos[ED][EG] - \frac{1}{2} \frac{NsR[EI] L_2 \sin[ED]}{\sqrt{[EB]}} - NsR(\sqrt{[EE]} + 10 - DL) L_2 \cos[ED][EG] \right) N}{\left(L_3^3 [EA]^{\frac{1}{2}} \right)} \\
 & + 3 \frac{\left(NsR(\sqrt{[EE]} + 10 - DL) L_2 \sin[ED] - NsR(\sqrt{[EE]} + 10 - DL) L_2 \sin[ED] \right) N^2}{\left(L_3^3 [EA]^{\frac{1}{2}} \right)} + \frac{NsR(\sqrt{[EE]} + 10 - DL) L_2 \sin[ED] - NsR(\sqrt{[EE]} + 10 - DL) L_2 \sin[ED]}{L_3^3 [EA]^{\frac{1}{2}}}
 \end{aligned}$$

[77]

Where:

$$[EA] = 1 - \frac{N^2}{L_3^2} \quad [78]$$

$$[EB] = \sin^{-1} \left(\frac{N}{L_3} \right) \quad [79]$$

$$[EC] = L_4 - \frac{(L_2 - L_1) N}{L_3} \quad [80]$$

$$[ED] = \tan^{-1} \left(\frac{[EC]}{(L_2 - L_1) \sqrt{[EA]}} \right) + [EB] \quad [81]$$

$$[EE] = (L_2 - L_1)^2 [EA] + [EC]^2 \quad [82]$$

$$[EF] = \frac{[EC]N}{(L_2 - L_1)[EA]^{3/2} L_3^2} \quad [83]$$

$$[EG] = \frac{\frac{1}{\sqrt{[EA]}L_3} - [EF]}{1 + \frac{[EC]^2}{(L_2 - L_1)^2 [EA]}} - \frac{1}{\sqrt{[EA]}L_3} \quad [84]$$

$$[EH] = \frac{(L_2 - L_1)^2 N}{L_3^2} \quad [85]$$

$$[EI] = 2[EH] + 2 \frac{[EC](L_2 - L_1)}{L_3} \quad [86]$$

$$[EJ] = \frac{-\frac{1}{\sqrt{[EA]}L_3} + [EF]}{1 + \frac{[EC]^2}{(L_2 - L_1)^2 [EA]}} + \frac{1}{\sqrt{[EA]}L_3} \quad [87]$$

$$[EK] = -2[EH] - 2 \frac{[EC](L_2 - L_1)}{L_3} \quad [88]$$

$$[EN] = \sin \left([EB] + \tan^{-1} \left(\frac{Vf}{Df} \right) \right) \quad [89]$$

Appendix 8.6.

Second order partial differential equation representing the sensitivity of β to R.

$$\frac{\partial}{\partial R} \left(\frac{\partial F}{\partial d} \right) = \frac{\left[\frac{1}{2} \frac{N_s \left(-2 \frac{(L_2 - L_1) 2N}{L_3^2} - 2 \frac{[FB](L_2 - L_1)}{L_3} \right) L_2 \sin[FC]}{\sqrt{[FD]}} + N_s(\sqrt{[FD]} + 10 - DL) L_2 \cos[FC] \left(\frac{-\frac{1}{\sqrt{[FA]} L_3} + \frac{[FB]N}{(L_2 - L_1)[FA]^{3/2} L_3^2} + \frac{1}{\sqrt{[FA]} L_3}}{1 + \frac{[FB]^2}{(L_2 - L_1)^2 [FA]}} \right) \right.}{\left(L_3 \sqrt{[FA]} \right)} - \frac{\left[\frac{1}{2} \frac{N_s \left(-2 \frac{(L_2 - L_1) 2N}{L_3^2} - 2 \frac{[FB](L_2 - L_1)}{L_3} \right) L_1 \sin[FC]}{\sqrt{[FD]}} - N_s(\sqrt{[FD]} + 10 - DL) L_1 \cos[FC] \left(\frac{-\frac{1}{\sqrt{[FA]} L_3} + \frac{[FB]N}{(L_2 - L_1)[FA]^{3/2} L_3^2} + \frac{1}{\sqrt{[FA]} L_3}}{1 + \frac{[FB]^2}{(L_2 - L_1)^2 [FA]}} \right) \right]}{\left(L_3 \sqrt{[FA]} \right)} - \frac{(N_s(\sqrt{[FD]} + 10 - DL) L_2 \sin[FC] - N_s(\sqrt{[FD]} + 10 - DL) L_1 \sin[FC]) N}{(L_3^3 [FA]^{3/2})}$$

[90]

Where:

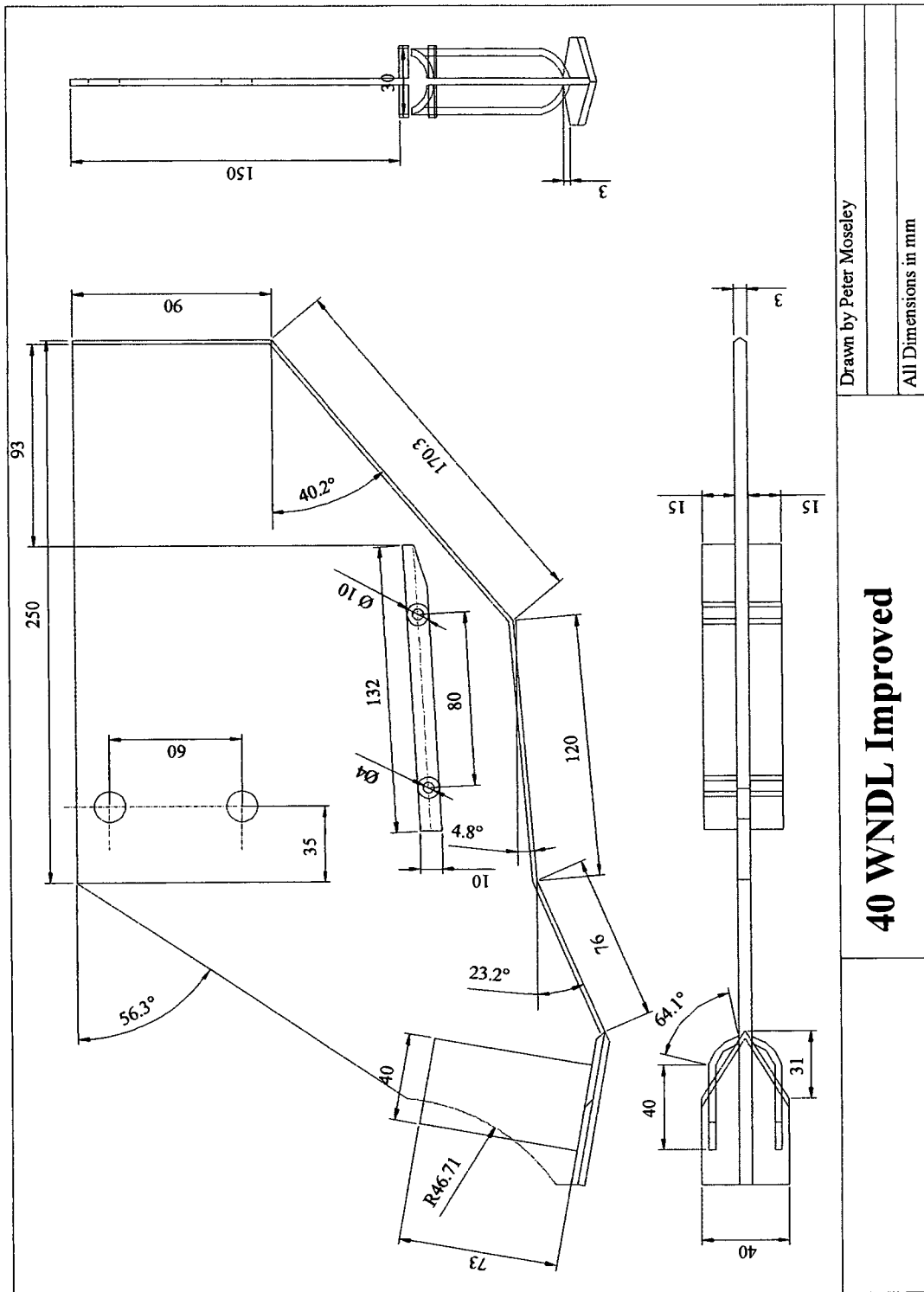
$$[FA] = 1 - \frac{N^2}{L_3^2} \quad [91]$$

$$[FB] = L_4 - \frac{(L_2 - L_1)N}{L_3} \quad [92]$$

$$[FC] = \tan^{-1} \left(\frac{[FB]}{(L_2 - L_1) \sqrt{[FA]}} \right) + \sin^{-1} \left(\frac{N}{L_3} \right) \quad [93]$$

$$[FD] = (L_2 - L_1)^2 [FA] + [FB]^2 \quad [94]$$

Amended 40WNDLi injector tine with depth control skids.



Appendix 9

Appendix 9.1.

Statistical analysis of soil properties relating to the evaluation of the 40WNDLi injector tine with skids at 0.01 m depth increments

Variate: Bulk density (dry basis) kg/m³

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	733.	367.	0.28	
Rep.*Units* stratum					
Bin_Fit	4	4664.	1166.	0.90	0.505
Residual	8	10315.	1289.		
Total	14	15712.			

***** Tables of means *****

Grand mean 1450.6

Bin_Fit	1.00	2.00	3.00	4.00	5.00
	1443.5	1475.1	1435.9	1430.6	1467.7

*** Standard errors of differences of means ***

Table	Bin_Fit
rep.	3
d.f.	8
s.e.d.	29.32

*** Least significant differences of means ***

Table	Bin_Fit
rep.	3
d.f.	8
l.s.d.	67.61

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	8.56	0.6
Rep.*Units*	8	35.91	2.5

Variate: Moisture content (dry basis) %

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.06588	0.03294	0.61	
Rep.*Units* stratum					
Bin_Fit	4	0.25278	0.06319	1.16	0.395
Residual	8	0.43462	0.05433		
Total	14	0.75328			

***** Tables of means *****

Grand mean 9.633

Bin_Fit	1.00	2.00	3.00	4.00	5.00
	9.655	9.708	9.817	9.541	9.443

*** Standard errors of differences of means ***

Table	Bin_Fit
rep.	3
d.f.	8
s.e.d.	0.1903

*** Least significant differences of means ***

Table	Bin_Fit
rep.	3
d.f.	8
l.s.d.	0.4389

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	0.0812	0.8
Rep.*Units*	8	0.2331	2.4

Appendix 9.2.

Statistical analysis of soil properties relating to the dynamic performance assessment
considering joint type and depth control device.

Variate: Bulk density (dry basis) Preps 1 to 12 UP/DP bearing linkage kg/m³

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Prep_No_	11	33339.	3031.	1.10	0.384
Position	1	1650.	1650.	0.60	0.443
Prep_No_.Position	11	13487.	1226.	0.44	0.928
Residual	48	132634.	2763.		
Total	71	181111.			

***** Tables of means *****

Grand mean 1417.8

Prep_No_	1.00	2.00	3.00	4.00	5.00	6.00	7.00
	1412.0	1401.9	1380.5	1401.4	1403.4	1406.8	1418.3

Prep_No_	8.00	9.00	10.00	11.00	12.00
	1444.9	1461.8	1418.2	1442.1	1422.2

Position	Lower	Upper
	1413.0	1422.6

Prep_No_ Position	Lower	Upper
1.00	1424.9	1399.2
2.00	1415.4	1388.4
3.00	1363.0	1398.0
4.00	1408.2	1394.7
5.00	1392.9	1413.9
6.00	1412.0	1401.7
7.00	1419.1	1417.5
8.00	1425.7	1464.1
9.00	1468.9	1454.8
10.00	1392.1	1444.2
11.00	1435.2	1449.1
12.00	1398.9	1445.5

*** Standard errors of differences of means ***

Table	Prep_No_	Position	Prep_No_ Position
rep.	6	36	3
d.f.	48	48	48
s.e.d.	30.35	12.39	42.92

*** Least significant differences of means ***

Table	Prep_No_	Position	Prep_No_ Position
rep.	6	36	3
d.f.	48	48	48
l.s.d.	61.02	24.91	86.30

***** Stratum standard errors and coefficients of variation *****

d.f.	s.e.	cv%
48	52.57	3.7

Variate: Moisture content (dry basis) Preps 1 to 12 UP/DP bearing linkage %

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Prep_No_	11	6.6288	0.6026	1.48	0.170
Position	1	0.2080	0.2080	0.51	0.478
Prep_No_.Position	11	2.6092	0.2372	0.58	0.833
Residual	48	19.5455	0.4072		
Total	71	28.9916			

***** Tables of means *****

Grand mean 8.912

Prep_No_	1.00	2.00	3.00	4.00	5.00	6.00	7.00
	9.170	8.230	9.167	8.600	8.728	8.928	8.712

Prep_No_	8.00	9.00	10.00	11.00	12.00
	8.782	8.932	9.153	9.237	9.307

Position	Lower	Upper
	8.966	8.858

Prep_No_ Position	Lower	Upper
1.00	9.287	9.053
2.00	8.327	8.133
3.00	9.190	9.143
4.00	8.650	8.550
5.00	9.053	8.403
6.00	9.167	8.690
7.00	8.473	8.950
8.00	8.803	8.760
9.00	9.213	8.650
10.00	9.053	9.253
11.00	9.397	9.077
12.00	8.977	9.637

*** Standard errors of differences of means ***

Table	Prep_No_	Position	Prep_No_ Position
rep.	6	36	3
d.f.	48	48	48
s.e.d.	0.3684	0.1504	0.5210

*** Least significant differences of means ***

Table	Prep_No_	Position	Prep_No_ Position
rep.	6	36	3
d.f.	48	48	48
l.s.d.	0.7408	0.3024	1.0476

***** Stratum standard errors and coefficients of variation *****

d.f.	s.e.	cv%
48	0.6381	7.2

Variate: Bulk density (dry basis) Preps 13 to 26 FP bearing linkage kg/m³

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Prep_No_	13	21462.	1651.	0.72	0.734
Residual	28	64634.	2308.		
Total	41	86096.			

***** Tables of means *****

Grand mean 1396.3

Prep_No_	13.00	14.00	15.00	16.00	17.00	18.00	19.00
	1384.8	1375.3	1402.2	1378.5	1407.6	1361.7	1375.9
Prep_No_	20.00	21.00	22.00	23.00	24.00	25.00	26.00
	1394.7	1419.6	1432.8	1420.3	1432.0	1394.1	1368.7

*** Standard errors of differences of means ***

Table	Prep_No_
rep.	3
d.f.	28
s.e.d.	39.23

*** Least significant differences of means ***

Table	Prep_No_
rep.	3
d.f.	28
l.s.d.	80.36

***** Stratum standard errors and coefficients of variation *****

d.f.	s.e.	cv%
28	48.05	3.4

Variate: Moisture content (dry basis) Preps 13 to 26 FP bearing linkage %

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Prep_No_	13	15.8916	1.2224	1.80	0.094
Residual	28	19.0287	0.6796		
Total	41	34.9203			

***** Tables of means *****

Grand mean 9.78

Prep_No_	13.00	14.00	15.00	16.00	17.00	18.00	19.00
	9.46	8.60	9.33	10.21	9.06	9.07	9.47
Prep_No_	20.00	21.00	22.00	23.00	24.00	25.00	26.00
	10.00	10.79	9.99	10.20	10.74	10.00	9.97

*** Standard errors of differences of means ***

Table	Prep_No_
rep.	3
d.f.	28
s.e.d.	0.673

*** Least significant differences of means ***

Table	Prep_No_
rep.	3
d.f.	28
l.s.d.	1.379

***** Stratum standard errors and coefficients of variation *****

d.f.	s.e.	cv%
28	0.824	8.4

Variate: Bulk density (dry basis) Preps 1 to 14 UP/DP pin jointed linkage kg/m³

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Prep_No_	13	42914.	3301.	1.53	0.137
Position	1	7472.	7472.	3.45	0.068
Prep_No_.Position	13	115691.	8899.	4.11	<.001
Residual	56	121180.	2164.		
Total	83	287258.			

***** Tables of means *****

Grand mean 1438.3

Prep_No_	1.00	2.00	3.00	4.00	5.00	6.00	7.00
	1387.4	1438.2	1411.0	1442.0	1419.7	1457.7	1454.0

Prep_No_	8.00	9.00	10.00	11.00	12.00	13.00	14.00
	1447.6	1423.3	1419.0	1453.0	1452.0	1453.8	1477.2

Position	Lower	Upper
	1447.7	1428.9

Prep_No_ Position	Lower	Upper
1.00	1380.8	1394.1
2.00	1449.2	1427.3
3.00	1444.2	1377.9
4.00	1406.7	1477.2
5.00	1389.3	1450.1
6.00	1454.6	1460.8
7.00	1464.6	1443.5
8.00	1515.9	1379.2
9.00	1410.8	1435.8
10.00	1453.0	1385.0
11.00	1509.1	1396.9
12.00	1512.8	1391.2
13.00	1463.4	1444.2
14.00	1413.5	1540.8

*** Standard errors of differences of means ***

Table	Prep_No_	Position	Prep_No_ Position
rep.	6	42	3
d.f.	56	56	56
s.e.d.	26.86	10.15	37.98

*** Least significant differences of means ***

Table	Prep_No_	Position	Prep_No_ Position
rep.	6	42	3
d.f.	56	56	56
l.s.d.	53.80	20.34	76.09

***** Stratum standard errors and coefficients of variation *****

d.f.	s.e.	cv%
56	46.52	3.2

Variate: Moisture content (dry basis) Preps 1 to 14 UP/DP pin jointed linkage %

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Prep_No_	13	13.275	1.021	0.45	0.942
Position	1	0.014	0.014	0.01	0.937
Prep_No_.Position	13	0.917	0.071	0.03	1.000
Residual	56	126.545	2.260		
Total	83	140.751			

***** Tables of means *****

Grand mean	10.00						
Prep_No_	1.00	2.00	3.00	4.00	5.00	6.00	7.00
	10.79	10.69	10.36	10.00	9.99	9.90	10.11
Prep_No_	8.00	9.00	10.00	11.00	12.00	13.00	14.00
	10.20	9.76	9.55	9.43	9.47	9.79	10.00
Position	Lower	Upper					
	10.01	9.99					
Prep_No_ Position	Lower		Upper				
1.00	10.88		10.71				
2.00	10.91		10.46				
3.00	10.26		10.46				
4.00	9.85		10.15				
5.00	9.94		10.05				
6.00	9.92		9.87				
7.00	10.05		10.17				
8.00	10.38		10.03				
9.00	9.72		9.80				
10.00	9.56		9.54				
11.00	9.39		9.46				
12.00	9.41		9.52				
13.00	9.79		9.79				
14.00	10.15		9.84				

*** Standard errors of differences of means ***

Table	Prep_No_	Position	Prep_No_ Position
rep.	6	42	3
d.f.	56	56	56
s.e.d.	0.868	0.328	1.227

*** Least significant differences of means ***

Table	Prep_No_	Position	Prep_No_ Position
rep.	6	42	3
d.f.	56	56	56
l.s.d.	1.739	0.657	2.459

***** Stratum standard errors and coefficients of variation *****

d.f.	s.e.	cv%
56	1.503	15.0

Variate: Bulk density (dry basis) Preps 15 to 28 FP pin jointed linkage kg/m³

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Prep_No_	13	35243.	2711.	1.04	0.448
Residual	28	73282.	2617.		
Total	41	108525.			

***** Tables of means *****

Grand mean	1424.8						
Prep_No_	15.00	16.00	17.00	18.00	19.00	20.00	21.00
	1394.3	1374.8	1430.1	1432.0	1424.3	1426.6	1458.0
Prep_No_	22.00	23.00	24.00	25.00	26.00	27.00	28.00
	1459.9	1388.2	1433.5	1413.7	1416.6	1407.3	1487.9

*** Standard errors of differences of means ***

Table	Prep_No_
rep.	3
d.f.	28
s.e.d.	41.77

*** Least significant differences of means ***

Table	Prep_No_
rep.	3
d.f.	28
l.s.d.	85.56

***** Stratum standard errors and coefficients of variation *****

d.f.	s.e.	cv%
28	51.16	3.6

Variate: Moisture content (dry basis) Preps 15 to 28 FP pin jointed linkage %

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Prep_No_	13	12.7064	0.9774	1.72	0.111
Residual	28	15.8781	0.5671		
Total	41	28.5845			

***** Tables of means *****

Grand mean 9.87

Prep_No_	15.00	16.00	17.00	18.00	19.00	20.00	21.00
	9.87	10.77	10.13	10.04	8.74	9.10	9.48
Prep_No_	22.00	23.00	24.00	25.00	26.00	27.00	28.00
	10.52	9.92	10.00	9.37	10.65	9.83	9.76

*** Standard errors of differences of means ***

Table	Prep_No_
rep.	3
d.f.	28
s.e.d.	0.615

*** Least significant differences of means ***

Table	Prep_No_
rep.	3
d.f.	28
l.s.d.	1.259

***** Stratum standard errors and coefficients of variation *****

d.f.	s.e.	cv%
28	0.753	7.6

Variate: Bulk density (dry basis) Preps 1 to 14 UP/DP 40WNDLi skid tine kg/m³

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Prep_No_	13	26062.	2005.	0.94	0.523
Position	1	2595.	2595.	1.21	0.276
Prep_No_.Position	13	35796.	2754.	1.29	0.249
Residual	56	119906.	2141.		
Total	83	184359.			

***** Tables of means *****

Grand mean 1445.8

Prep_No_	1.00	2.00	3.00	4.00	5.00	6.00	7.00
	1431.3	1418.7	1425.8	1454.6	1440.8	1448.4	1473.6
Prep_No_	8.00	9.00	10.00	11.00	12.00	13.00	14.00
	1418.8	1457.8	1447.9	1441.7	1443.9	1460.9	1477.3
Position	Lower	Upper					
	1451.4	1440.3					

Prep_No_	Position	Lower	Upper
1.00		1441.1	1421.6
2.00		1388.4	1449.0
3.00		1461.2	1390.4
4.00		1438.7	1470.5
5.00		1443.3	1438.3
6.00		1486.9	1409.8
7.00		1503.5	1443.7
8.00		1443.5	1394.1
9.00		1451.5	1464.1
10.00		1463.4	1432.5
11.00		1418.1	1465.4
12.00		1442.2	1445.5
13.00		1456.3	1465.6
14.00		1481.4	1473.2

*** Standard errors of differences of means ***

Table	Prep_No_	Position	Prep_No_ Position
rep.	6	42	3
d.f.	56	56	56
s.e.d.	26.72	10.10	37.78

*** Least significant differences of means ***

Table	Prep_No_	Position	Prep_No_ Position
rep.	6	42	3
d.f.	56	56	56
l.s.d.	53.52	20.23	75.69

***** Stratum standard errors and coefficients of variation *****

d.f.	s.e.	cv%
56	46.27	3.2

Variate: Moisture content (dry basis) Preps 1 to 14 UP/DP 40WNDLi skid tine %

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Prep_No_	13	5.6313	0.4332	1.87	0.055
Position	1	0.6590	0.6590	2.84	0.098
Prep_No_.Position	13	4.0367	0.3105	1.34	0.220
Residual	56	13.0058	0.2322		
Total	83	23.3328			

***** Tables of means *****

Grand mean 9.476							
Prep_No_	1.00	2.00	3.00	4.00	5.00	6.00	7.00
	9.340	9.778	9.550	9.227	9.175	9.392	9.073
Prep_No_	8.00	9.00	10.00	11.00	12.00	13.00	14.00
	9.260	9.667	9.665	9.917	9.493	9.858	9.272
Position	Lower	Upper					
	9.565	9.388					
Prep_No_ Position	Lower	Upper					
1.00	9.427	9.253					
2.00	9.820	9.737					
3.00	9.277	9.823					
4.00	9.293	9.160					
5.00	9.167	9.183					
6.00	9.650	9.133					
7.00	8.837	9.310					
8.00	9.273	9.247					
9.00	9.673	9.660					
10.00	9.780	9.550					
11.00	10.410	9.423					
12.00	9.857	9.130					
13.00	9.757	9.960					
14.00	9.687	8.857					

*** Standard errors of differences of means ***

Table	Prep_No_	Position	Prep_No_ Position
rep.	6	42	3
d.f.	56	56	56
s.e.d.	0.2782	0.1052	0.3935

*** Least significant differences of means ***

Table	Prep_No_	Position	Prep_No_ Position
rep.	6	42	3
d.f.	56	56	56
l.s.d.	0.5574	0.2107	0.7882

***** Stratum standard errors and coefficients of variation *****

d.f.	s.e.	cv%
56	0.4819	5.1

Variate: Bulk density (dry basis) Preps 15 to 28 FP 40WNDLi skid tine kg/m³

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Prep_No_	13	15391.	1184.	1.15	0.365
Residual	28	28920.	1033.		
Total	41	44311.			

***** Tables of means *****

Grand mean	1448.3						
Prep_No_	15.00	16.00	17.00	18.00	19.00	20.00	21.00
	1444.1	1412.4	1427.7	1489.5	1436.8	1454.8	1430.0
Prep_No_	22.00	23.00	24.00	25.00	26.00	27.00	28.00
	1435.7	1456.5	1466.7	1450.6	1472.3	1454.0	1444.7

*** Standard errors of differences of means ***

Table	Prep_No_
rep.	3
d.f.	28
s.e.d.	26.24

*** Least significant differences of means ***

Table	Prep_No_
rep.	3
d.f.	28
l.s.d.	53.75

***** Stratum standard errors and coefficients of variation *****

d.f.	s.e.	cv%
28	32.14	2.2

Variate: Moisture content (dry basis) Preps 15 to 28 FP 40WNDLi skid tine %

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Prep_No_	13	0.53258	0.04097	1.36	0.237
Residual	28	0.84120	0.03004		
Total	41	1.37378			

***** Tables of means *****

Grand mean	9.652						
Prep_No_	15.00	16.00	17.00	18.00	19.00	20.00	21.00
	9.910	9.487	9.663	9.560	9.593	9.810	9.543
Prep_No_	22.00	23.00	24.00	25.00	26.00	27.00	28.00
	9.603	9.597	9.640	9.557	9.657	9.740	9.763

*** Standard errors of differences of means ***

Table	Prep_No_
rep.	3
d.f.	28
s.e.d.	0.1415

*** Least significant differences of means ***

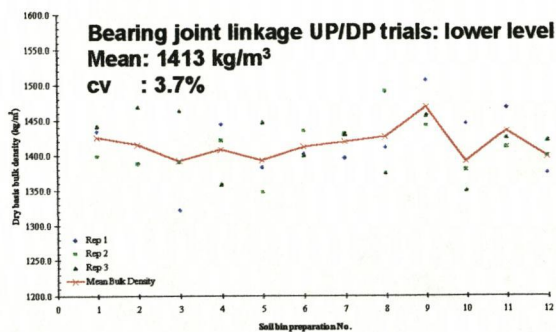
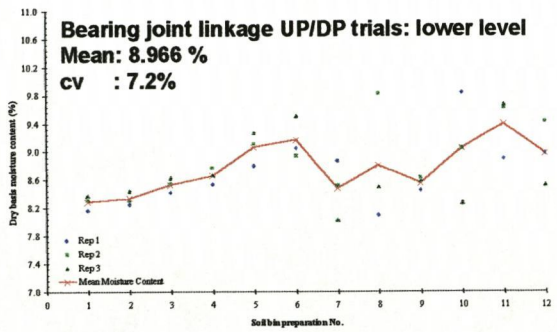
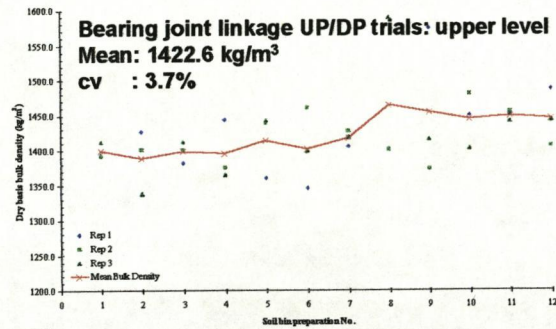
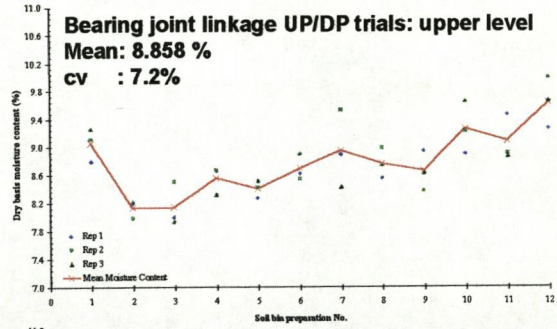
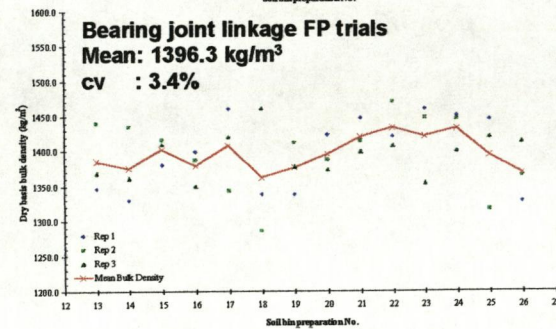
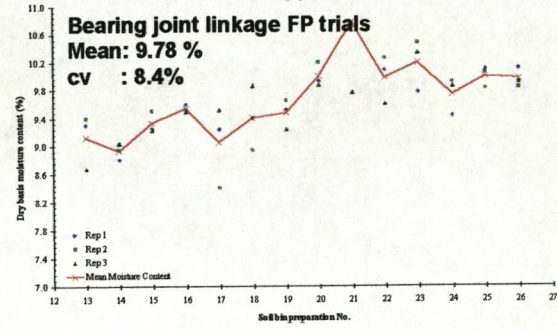
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d.f.	28
l.s.d.	0.2899

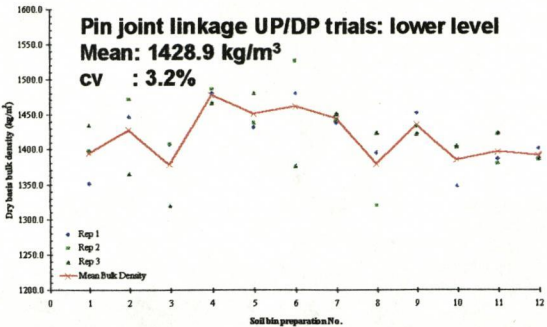
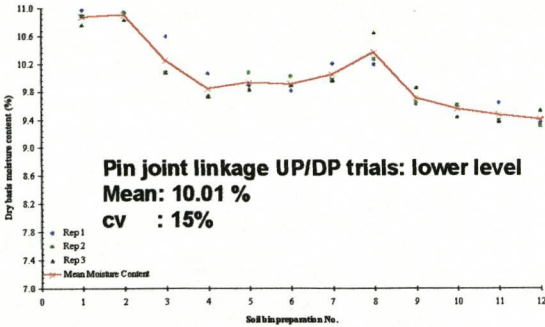
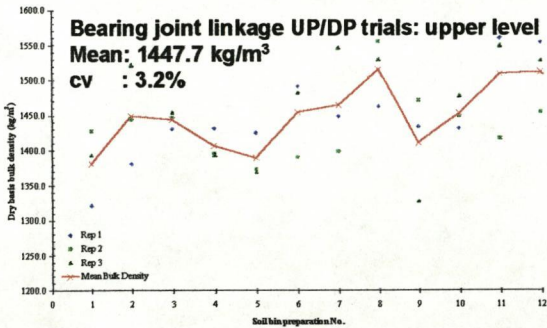
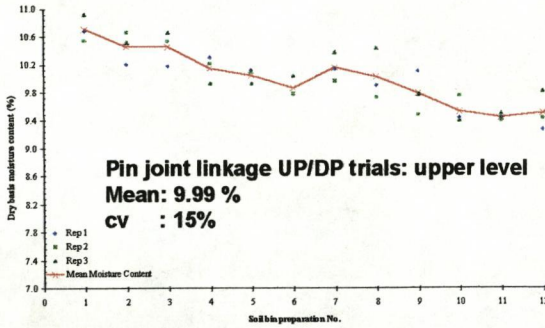
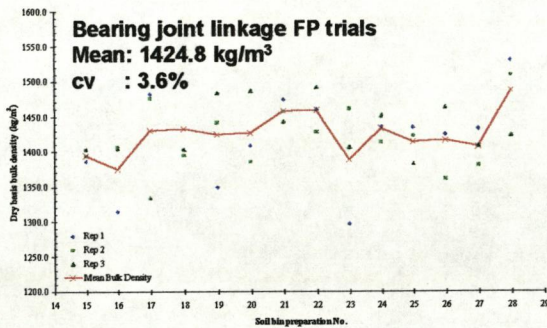
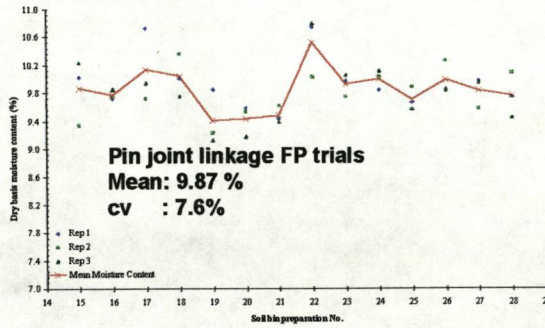
***** Stratum standard errors and coefficients of variation *****

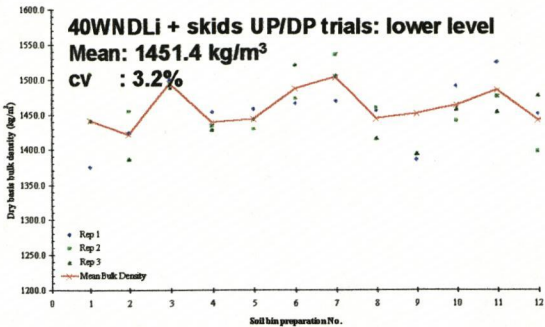
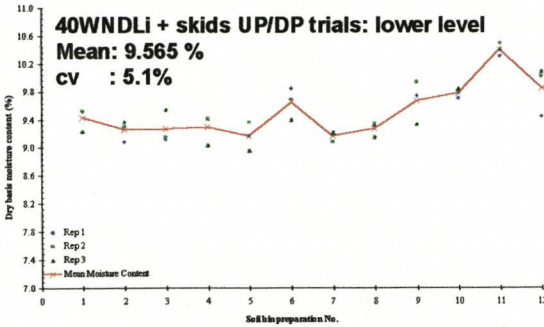
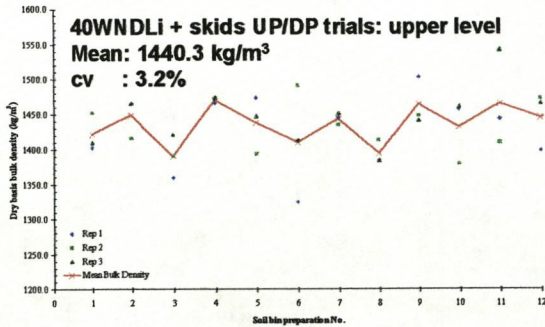
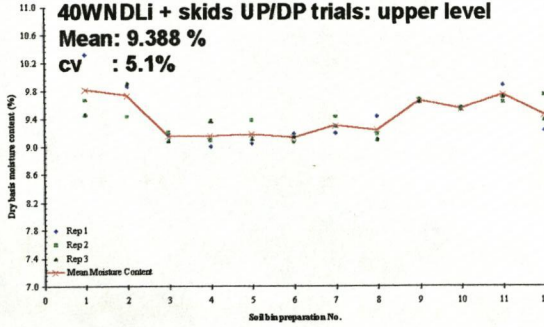
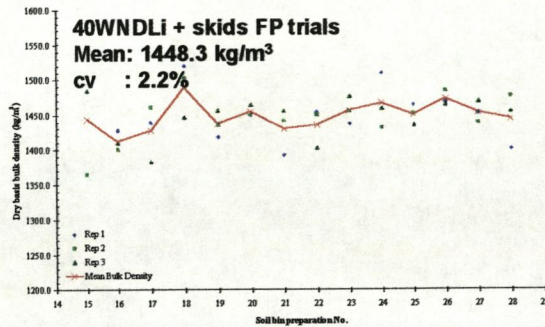
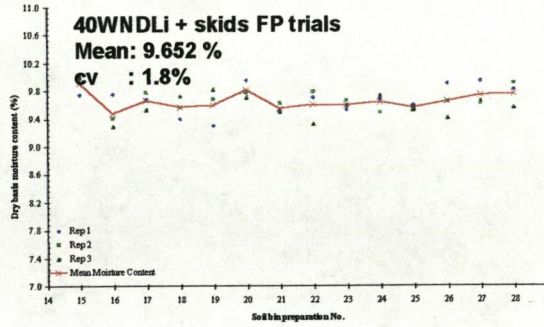
d.f.	s.e.	cv%
28	0.1733	1.8

Appendix 9.3.

Soil properties throughout the final dynamic study in the soil bin.







Appendix 9.4.

Statistical analysis of joint type on depth and dynamic performance.

Variate: Difference between experimental and predicted depths prior to step change

Source of variation	d.f. (m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	932.23	466.12	17.40	
Rep.*Units* stratum					
Link	1	3769.31	3769.31	140.72	<.001
Springs	5	4122.83	824.57	30.78	<.001
Prep	3	1351.67	450.56	16.82	<.001
Link.Springs	5	1226.25	245.25	9.16	<.001
Link.Prep	3	333.74	111.25	4.15	0.008
Springs.Prep	15	990.65	66.04	2.47	0.005
Link.Springs.Prep	15	674.77	44.98	1.68	0.069
Residual	90(4)	2410.78	26.79		
Total	139(4)	15657.26			

***** Tables of means *****

Grand mean 14.85

Link	b	nb					
	9.73	19.96					
Springs	1.00	2.00	3.00	4.00	5.00	6.00	
	6.29	11.44	15.02	22.07	20.62	13.65	
Prep	DP	HD	HU	Up			
	18.20	12.08	17.60	11.51			
Link Springs	1.00	2.00	3.00	4.00	5.00	6.00	
b	4.33	9.68	11.54	12.40	13.64	6.79	
nb	8.24	13.20	18.50	31.73	27.59	20.52	
Link Prep	DP	HD	HU	Up			
b	12.81	8.30	10.10	7.71			
nb	23.59	15.86	25.09	15.31			
Springs Prep	DP	HD	HU	Up			
1.00	6.81	3.67	11.45	3.22			
2.00	18.54	8.11	14.16	4.95			
3.00	17.67	8.59	23.58	10.25			
4.00	24.25	21.57	24.18	18.27			
5.00	25.59	21.20	18.18	17.51			
6.00	16.35	9.37	14.02	14.88			
Link Springs Prep	DP	HD	HU	Up			
b 1.00	5.34	1.74	7.15	3.09			
2.00	16.91	6.77	10.69	4.35			
3.00	13.32	4.50	21.64	6.70			
4.00	10.02	17.45	8.51	13.63			
5.00	22.20	15.74	7.35	9.28			
6.00	9.08	3.62	5.23	9.23			
nb 1.00	8.28	5.59	15.75	3.35			
2.00	20.17	9.45	17.62	5.54			
3.00	22.01	12.68	25.52	13.81			
4.00	38.47	25.68	39.85	22.91			
5.00	28.97	26.65	29.01	25.73			
6.00	23.62	15.13	22.80	20.53			

*** Standard errors of differences of means ***

Table	Link	Springs	Prep	Link Springs
rep.	72	24	36	12
d.f.	90	90	90	90
s.e.d.	0.863	1.494	1.220	2.113

Table	Link Prep	Springs Prep	Link Springs Prep
rep.	18	6	3
d.f.	90	90	90
s.e.d.	1.725	2.988	4.226
*** Least significant differences of means ***			

Table	Link	Springs	Prep	Link Springs
rep.	72	24	36	12
d.f.	90	90	90	90
l.s.d.	1.714	2.968	2.424	4.198

Table	Link Prep	Springs Prep	Link Springs Prep
rep.	18	6	3
d.f.	90	90	90
l.s.d.	3.427	5.936	8.395

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	3.116	21.0
Rep.*Units*	90	5.176	34.9

Variate: Difference between experimental and predicted depths after a step change

Source of variation	d.f. (m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	1406.02	703.01	9.34	
Rep.*Units* stratum					
Link	1	1.20	1.20	0.02	0.900
Springs	5	889.28	177.86	2.36	0.046
Prep	3	76.57	25.52	0.34	0.797
Link.Springs	5	635.49	127.10	1.69	0.145
Link.Prepare	3	739.70	246.57	3.28	0.025
Springs.Prepare	15	1452.06	96.80	1.29	0.227
Link.Springs.Prepare	15	631.62	42.11	0.56	0.898
Residual	90(4)	6771.41	75.24		
Total	139(4)	12446.72			

***** Tables of means *****

Grand mean 12.01							
Link		b	nb				
		11.91	12.10				
Springs		1.00	2.00	3.00	4.00	5.00	6.00
		8.41	10.86	15.31	14.26	13.39	9.80
Prep		DP	HD	HU	Up		
		12.20	10.81	12.80	12.21		
Link Springs		1.00	2.00	3.00	4.00	5.00	6.00
b		7.14	14.69	15.14	15.46	11.01	8.05
nb		9.69	7.03	15.48	13.06	15.77	11.55
Link Prep		DP	HD	HU	Up		
b		10.08	8.65	13.39	15.53		
nb		14.32	12.98	12.21	8.88		
Springs Prep		DP	HD	HU	Up		
1.00		4.78	10.01	9.57	9.29		
2.00		8.16	13.55	8.03	13.70		
3.00		13.23	14.33	17.35	16.35		
4.00		16.09	8.54	22.29	10.11		
5.00		15.03	10.10	14.59	13.83		
6.00		15.90	8.36	4.96	9.96		

Link	Springs	Prep	DP	HD	HU	Up
b	1.00		2.90	7.04	10.82	7.79
	2.00		9.68	16.04	11.14	21.92
	3.00		10.21	8.47	20.91	21.00
	4.00		13.04	8.78	23.62	16.40
	5.00		15.23	5.22	8.94	14.63
	6.00		9.44	6.36	4.93	11.45
nb	1.00		6.66	12.98	8.33	10.78
	2.00		6.64	11.07	4.92	5.48
	3.00		16.26	20.19	13.80	11.70
	4.00		19.15	8.30	20.97	3.82
	5.00		14.84	14.98	20.25	13.03
	6.00		22.36	10.37	4.98	8.47

*** Standard errors of differences of means ***

Table	Link	Springs	Prep	Link Springs
rep.	72	24	36	12
d.f.	90	90	90	90
s.e.d.	1.446	2.504	2.044	3.541

Table	Link Prep	Springs Prep	Link Springs Prep
rep.	18	6	3
d.f.	90	90	90
s.e.d.	2.891	5.008	7.082

*** Least significant differences of means ***

Table	Link	Springs	Prep	Link Springs
rep.	72	24	36	12
d.f.	90	90	90	90
l.s.d.	2.872	4.975	4.062	7.035

Table	Link Prep	Springs Prep	Link Springs Prep
rep.	18	6	3
d.f.	90	90	90
l.s.d.	5.744	9.949	14.070

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	3.827	31.9
Rep.*Units*	90	8.674	72.3

Variate: Actual performance: distance to return to 85% of final experimental operating depth.

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.3234	0.1617	0.32	
Rep.*Units* stratum					
Link	1	1.3402	1.3402	2.63	0.108
Prep	3	7.1426	2.3809	4.67	0.004
Springs	5	3.5501	0.7100	1.39	0.234
Link.Pre	3	0.2231	0.0744	0.15	0.932
Link.Springs	5	1.3971	0.2794	0.55	0.739
Prep.Springs	15	11.8712	0.7914	1.55	0.104
Link.Pre.Springs	15	6.7498	0.4500	0.88	0.585
Residual	90(4)	45.8719	0.5097		
Total	139(4)	77.1552			

***** Tables of means *****

Grand mean 0.853

Link	b	nb					
	0.757	0.950					
Prep	DP	HD	HU	Up			
	0.867	0.635	0.701	1.210			
Springs	1.00	2.00	3.00	4.00	5.00	6.00	
	0.639	0.977	0.686	0.808	1.077	0.933	
Link	Prep	DP	HD	HU	Up		
b		0.779	0.595	0.592	1.061		
nb		0.955	0.675	0.809	1.359		
Link	Springs	1.00	2.00	3.00	4.00	5.00	6.00
b		0.539	0.792	0.794	0.710	0.891	0.815
nb		0.739	1.162	0.577	0.906	1.264	1.051
Prep	Springs	1.00	2.00	3.00	4.00	5.00	6.00
DP		0.944	0.757	0.506	0.907	0.877	1.211
HD		0.298	0.812	0.391	0.429	1.073	0.805
HU		0.210	0.432	0.354	0.929	1.387	0.892
Up		1.103	1.906	1.490	0.966	0.971	0.823
Link	Prep	Springs	1.00	2.00	3.00	4.00	5.00
b		DP	0.659	0.317	0.511	0.862	0.808
		HD	0.357	0.847	0.515	0.546	0.733
		HU	0.297	0.614	0.401	0.327	1.239
		Up	0.843	1.390	1.747	1.105	0.783
nb		DP	1.229	1.197	0.502	0.952	0.947
		HD	0.239	0.778	0.267	0.312	1.413
		HU	0.124	0.249	0.307	1.531	1.536
		Up	1.363	2.423	1.234	0.828	1.159
Link	Prep	Springs	6.00				
b		DP	1.519				
		HD	0.570				
		HU	0.674				
		Up	0.496				
nb		DP	0.902				
		HD	1.041				
		HU	1.110				
		Up	1.150				

*** Standard errors of differences of means ***

Table	Link	Prep	Springs	Link Prep
rep.	72	36	24	18
d.f.	90	90	90	90
s.e.d.	0.1190	0.1683	0.2061	0.2380

Table	Link Springs	Prep Springs	Link Prep Springs
rep.	12	6	3
d.f.	90	90	90
s.e.d.	0.2915	0.4122	0.5829

*** Least significant differences of means ***

Table	Link	Prep	Springs	Link Prep
rep.	72	36	24	18
d.f.	90	90	90	90
l.s.d.	0.2364	0.3343	0.4094	0.4728

Table	Link Springs	Prep Springs	Link Prep Springs
rep.	12	6	3
d.f.	90	90	90
l.s.d.	0.5790	0.8189	1.1581

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	0.0580	6.8
Rep.*Units*	90	0.7139	83.7

Variate: Combined performance: distance to return to 85% of final modelled operating depth.

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.3009	0.1504	0.63	
Rep.*Units* stratum					
Link	1	11.1697	11.1697	46.82	<.001
Prep	3	20.8117	6.9372	29.08	<.001
Springs	5	14.3368	2.8674	12.02	<.001
Link.Prep	3	5.1726	1.7242	7.23	<.001
Link.Springs	5	11.5964	2.3193	9.72	<.001
Prep.Springs	15	38.5209	2.5681	10.76	<.001
Link.Prep.Springs	14(1)	28.6311	2.0451	8.57	<.001
Residual	61(33)	14.5536	0.2386		
Total	109(34)	80.8644			

***** Tables of means *****

Grand mean 0.829

Link	b	nb					
	0.551	1.108					
Prep	DP	HD	HU	Up			
	1.035	0.188	0.925	1.168			
Springs	1.00	2.00	3.00	4.00	5.00	6.00	
	0.602	0.824	1.264	1.231	0.451	0.601	
Link	Prep	DP	HD	HU	Up		
b		0.768	0.206	0.431	0.797		
nb		1.302	0.169	1.419	1.540		
Link	Springs	1.00	2.00	3.00	4.00	5.00	6.00
b		0.593	0.649	0.813	0.399	0.326	0.523
nb		0.611	0.999	1.716	2.063	0.577	0.679
Prep	Springs	1.00	2.00	3.00	4.00	5.00	6.00
DP		0.396	0.763	2.288	0.829	1.348	0.586
HD		0.187	0.165	0.160	0.302	0.068	0.244
HU		0.708	0.304	1.919	2.231	0.197	0.191
Up		1.117	2.064	0.690	1.563	0.192	1.384
Link	Prep	Springs	1.00	2.00	3.00	4.00	5.00
b	DP		0.400	1.075	1.284	0.501	0.869
	HD		0.208	0.169	0.134	0.288	0.064
	HU		0.995	0.337	0.773	0.168	0.154
	Up		0.768	1.016	1.060	0.639	0.217
nb	DP		0.391	0.451	3.292	1.156	1.827
	HD		0.166	0.162	0.186	0.316	0.071
	HU		0.421	0.272	3.066	4.293	0.241
	Up		1.467	3.111	0.321	2.487	0.167
Link	Prep	Springs	6.00				
b	DP		0.477				
	HD		0.377				
	HU		0.159				
	Up		1.081				
nb	DP		0.695				
	HD		0.112				
	HU		0.223				
	Up		1.686				

*** Standard errors of differences of means ***

Table	Link	Prep	Springs	Link Prep
rep.	72	36	24	18
d.f.	61	61	61	61
s.e.d.	0.0814	0.1151	0.1410	0.1628

Table	Link Springs	Prep Springs	Link Prep Springs
rep.	12	6	3
d.f.	61	61	61
s.e.d.	0.1994	0.2820	0.3988

*** Least significant differences of means ***

Table	Link	Prep	Springs	Link Prep
rep.	72	36	24	18
d.f.	61	61	61	61
l.s.d.	0.1628	0.2302	0.2820	0.3256

Table	Link Springs	Prep Springs	Link Prep Springs
rep.	12	6	3
d.f.	61	61	61
l.s.d.	0.3987	0.5639	0.7975

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	0.0560	6.8
Rep.*Units*	61	0.4885	58.9

Appendix 9.5.

Statistical analysis of Depth control device comparison on depth and dynamic performance.

Variate: Distance to attain 85% of final operating depth.

Source of variation	d.f. (m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.1712	0.0856	0.42	
Rep.*Units* stratum					
Tine	1	0.6026	0.6026	2.96	0.089
Springs	5	1.8595	0.3719	1.82	0.116
Prep	3	12.4461	4.1487	20.35	<.001
Tine.Springs	5	0.5924	0.1185	0.58	0.714
Tine.Prepare	3	1.2278	0.4093	2.01	0.118
Springs.Prepare	15	9.0679	0.6045	2.96	<.001
Tine.Springs.Prepare	15	3.2337	0.2156	1.06	0.407
Residual	91(3)	18.5546	0.2039		
Total	140(3)	47.0043			

***** Tables of means *****

Grand mean 0.753

Tine	NS	S					
	0.817	0.688					
Springs	1.00	2.00	3.00	4.00	5.00	6.00	
	0.645	0.670	0.847	0.608	0.873	0.872	
Prep	DP	HD	HU	UP			
	0.675	0.467	0.624	1.244			
Tine Springs	1.00	2.00	3.00	4.00	5.00	6.00	
NS	0.769	0.792	0.794	0.710	0.891	0.948	
S	0.520	0.547	0.901	0.505	0.856	0.797	
Tine Prep	DP	HD	HU	UP			
NS	0.779	0.595	0.745	1.149			
S	0.571	0.339	0.503	1.339			
Springs Prep	DP	HD	HU	UP			
1.00	0.649	0.281	0.860	0.788			
2.00	0.421	0.545	0.453	1.260			
3.00	0.476	0.366	0.450	2.097			
4.00	0.726	0.494	0.317	0.894			
5.00	0.676	0.654	1.028	1.135			
6.00	1.101	0.461	0.638	1.290			
Tine Springs Prep	DP	HD	HU	UP			
NS 1.00	0.659	0.357	1.216	0.843			
2.00	0.317	0.847	0.614	1.390			
3.00	0.511	0.515	0.401	1.747			
4.00	0.862	0.546	0.327	1.105			
5.00	0.808	0.733	1.239	0.783			
6.00	1.519	0.570	0.674	1.029			
S 1.00	0.639	0.206	0.503	0.733			
2.00	0.525	0.242	0.291	1.130			
3.00	0.441	0.218	0.498	2.448			
4.00	0.590	0.441	0.307	0.684			
5.00	0.545	0.575	0.817	1.487			
6.00	0.684	0.352	0.602	1.551			

*** Standard errors of differences of means ***

Table	Tine	Springs	Prep	Tine Springs
rep.	72	24	36	12
d.f.	91	91	91	91

s.e.d.	0.0753	0.1304	0.1064	0.1843
Table	Tine Prep	Springs Prep	Tine Springs Prep	
rep.	18	6	3	
d.f.	91	91	91	
s.e.d.	0.1505	0.2607	0.3687	

*** Least significant differences of means ***

Table	Tine	Springs	Prep	Tine Springs
rep.	72	24	36	12
d.f.	91	91	91	91
l.s.d.	0.1495	0.2589	0.2114	0.3662

Table	Tine Prep	Springs Prep	Tine Springs Prep	
rep.	18	6	3	
d.f.	91	91	91	
l.s.d.	0.2990	0.5179	0.7324	

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	0.0422	5.6
Rep.*Units*	91	0.4515	60.0

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Variate: Difference between experimental and modelled operating depth prior to step change.

Source of variation	d.f. (m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	330.57	165.28	6.39	
Rep.*Units* stratum					
Tine	1	182.77	182.77	7.07	0.009
Springs	5	2695.85	539.17	20.86	<.001
Prep	3	425.04	141.68	5.48	0.002
Tine.Springs	5	478.47	95.69	3.70	0.004
Tine.Pre	3	211.94	70.65	2.73	0.048
Springs.Pre	15	789.85	52.66	2.04	0.021
Tine.Springs.Pre	15	985.86	65.72	2.54	0.003
Residual	91 (3)	2352.26	25.85		
Total	140 (3)	8396.65			

***** Tables of means *****

Grand mean	8.54						
Tine	NS	S					
	9.66	7.41					
Springs	1.00	2.00	3.00	4.00	5.00	6.00	
	2.69	7.00	7.86	13.88	14.53	5.25	
Prep	DP	HD	HU	UP			
	10.08	6.71	10.42	6.93			
Tine Springs	1.00	2.00	3.00	4.00	5.00	6.00	
NS	3.91	9.68	11.54	12.40	13.64	6.79	
S	1.47	4.31	4.19	15.35	15.43	3.70	
Tine Prep	DP	HD	HU	UP			
NS	12.81	8.30	9.82	7.71			
S	7.35	5.12	11.01	6.15			
Springs Prep	DP	HD	HU	UP			

1.00	3.18	1.78	2.97	2.83
2.00	10.06	3.78	10.68	3.47
3.00	10.65	3.57	13.30	3.94
4.00	9.21	14.91	17.38	14.01
5.00	19.82	13.16	13.43	11.72
6.00	7.55	3.07	4.74	5.62

Tine	Springs	Prep	DP	HD	HU	UP
NS	1.00		5.34	1.74	5.48	3.09
	2.00		16.91	6.77	10.69	4.35
	3.00		13.32	4.50	21.64	6.70
	4.00		10.02	17.45	8.51	13.63
	5.00		22.20	15.74	7.35	9.28
	6.00		9.08	3.62	5.23	9.23
S	1.00		1.02	1.82	0.46	2.57
	2.00		3.21	0.79	10.66	2.59
	3.00		7.97	2.65	4.96	1.18
	4.00		8.40	12.37	26.24	14.39
	5.00		17.45	10.59	19.51	14.16
	6.00		6.03	2.53	4.25	2.01

*** Standard errors of differences of means ***

Table	Tine	Springs	Prep	Tine Springs
rep.	72	24	36	12
d.f.	91	91	91	91
s.e.d.	0.847	1.468	1.198	2.076

Table	Tine Prep	Springs Prep	Tine Springs Prep
rep.	18	6	3
d.f.	91	91	91
s.e.d.	1.695	2.935	4.151

*** Least significant differences of means ***

Table	Tine	Springs	Prep	Tine Springs
rep.	72	24	36	12
d.f.	91	91	91	91
l.s.d.	1.683	2.915	2.380	4.123

Table	Tine Prep	Springs Prep	Tine Springs Prep
rep.	18	6	3
d.f.	91	91	91
l.s.d.	3.366	5.831	8.246

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	1.856	21.7
Rep.*Units*	91	5.084	59.6

Variate: Difference between experimental and modelled operating depth after a step change.

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	271.68	135.84	3.23	
Rep.*Units* stratum					
Tine	1	1198.55	1198.55	28.48	<.001
Springs	5	969.05	193.81	4.61	<.001
Prep	3	267.78	89.26	2.12	0.103
Tine.Springs	5	654.00	130.80	3.11	0.012
Tine.Pre	3	397.93	132.64	3.15	0.029
Springs.Pre	15	797.58	53.17	1.26	0.242
Tine.Springs.Pre	15	413.36	27.56	0.65	0.821
Residual	91(3)	3829.21	42.08		

Total 140(3) 8765.53

***** Tables of means *****

Grand mean 8.94

Time		NS	S				
		11.83	6.06				
Springs		1.00	2.00	3.00	4.00	5.00	6.00
		5.04	8.69	9.53	13.17	10.43	6.79
Prep		DP	HD	HU	UP		
		8.95	6.71	10.11	9.99		
Time	Springs	1.00	2.00	3.00	4.00	5.00	6.00
	NS	6.61	14.69	15.14	15.46	11.01	8.05
	S	3.46	2.69	3.91	10.88	9.85	5.54
Time	Prep	DP	HD	HU	UP		
	NS	10.08	8.65	13.04	15.53		
	S	7.82	4.77	7.19	4.44		
Springs	Prep	DP	HD	HU	UP		
	1.00	4.18	4.77	5.81	5.38		
	2.00	6.20	8.84	7.81	11.91		
	3.00	6.81	6.43	12.57	12.30		
	4.00	14.64	6.97	19.49	11.58		
	5.00	13.91	6.59	11.21	10.01		
	6.00	7.99	6.66	3.80	8.72		
Time	Springs	Prep	DP	HD	HU	UP	
	NS	1.00	2.90	7.04	8.71	7.79	
		2.00	9.68	16.04	11.14	21.92	
		3.00	10.21	8.47	20.91	21.00	
		4.00	13.04	8.78	23.62	16.40	
		5.00	15.23	5.22	8.94	14.63	
		6.00	9.44	6.36	4.93	11.45	
	S	1.00	5.46	2.50	2.91	2.98	
		2.00	2.72	1.65	4.48	1.91	
		3.00	3.41	4.39	4.22	3.60	
		4.00	16.23	5.17	15.36	6.77	
		5.00	12.58	7.96	13.48	5.39	
		6.00	6.53	6.97	2.66	6.00	

*** Standard errors of differences of means ***

Table	Time	Springs	Prep	Time Springs
rep.	72	24	36	12
d.f.	91	91	91	91
s.e.d.	1.081	1.873	1.529	2.648

Table	Time Prep	Springs Prep	Time Springs Prep
rep.	18	6	3
d.f.	91	91	91
s.e.d.	2.162	3.745	5.296

*** Least significant differences of means ***

Table	Time	Springs	Prep	Time Springs
rep.	72	24	36	12
d.f.	91	91	91	91
l.s.d.	2.148	3.720	3.037	5.260

Table	Time Prep	Springs Prep	Time Springs Prep
rep.	18	6	3
d.f.	91	91	91
l.s.d.	4.295	7.439	10.521

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	1.682	18.8
Rep.*Units*	91	6.487	72.6

Variate: Experimental distance taken to attain 85% of modelled operating depth

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.5673	0.2836	1.18	
Rep.*Units* stratum					
Tine	1	0.0465	0.0465	0.19	0.662
Springs	5	1.9462	0.3892	1.61	0.166
Prep	3	18.7319	6.2440	25.89	<.001
Tine.Springs	5	0.6898	0.1380	0.57	0.721
Tine.Prepare	3	5.0274	1.6758	6.95	<.001
Springs.Prepare	15	3.9577	0.2638	1.09	0.376
Tine.Springs.Prepare	15	2.9790	0.1986	0.82	0.649
Residual	79(15)	19.0555	0.2412		
Total	128(15)	47.4483			

***** Tables of means *****

Grand mean 0.602

Tine		NS	S				
		0.584	0.620				
Springs		1	2	3	4	5	6
		0.527	0.592	0.832	0.526	0.483	0.652
Prep		DP	HD	HU	UP		
		0.736	0.216	0.326	1.129		
Tine Springs		1	2	3	4	5	6
NS		0.586	0.649	0.813	0.537	0.374	0.545
S		0.467	0.535	0.851	0.514	0.592	0.759
Tine Prep		DP	HD	HU	UP		
NS		0.895	0.211	0.426	0.804		
S		0.577	0.222	0.227	1.454		
Springs Prep		DP	HD	HU	UP		
1		0.481	0.206	0.602	0.817		
2		0.696	0.223	0.276	1.174		
3		1.028	0.200	0.500	1.598		
4		0.853	0.289	0.167	0.794		
5		0.781	0.075	0.151	0.925		
6		0.574	0.305	0.263	1.467		
Tine Springs Prep		DP	HD	HU	UP		
NS 1		0.400	0.208	0.967	0.768		
2		1.075	0.169	0.337	1.016		
3		1.284	0.134	0.773	1.060		
4		1.028	0.301	0.168	0.653		
5		0.992	0.077	0.154	0.272		
6		0.588	0.377	0.159	1.055		
S 1		0.561	0.205	0.237	0.867		
2		0.317	0.277	0.215	1.332		
3		0.773	0.267	0.228	2.136		
4		0.679	0.277	0.165	0.935		
5		0.570	0.073	0.148	1.577		
6		0.560	0.233	0.367	1.879		

*** Standard errors of differences of means ***

Table	Tine	Springs	Prep	Tine Springs
rep.	72	24	36	12
d.f.	79	79	79	79
s.e.d.	0.0819	0.1418	0.1158	0.2005
Table	Tine Prep	Springs Prep	Tine Springs	

			Prep
rep.	18	6	3
d.f.	79	79	79
s.e.d.	0.1637	0.2836	0.4010

*** Least significant differences of means ***

Table	Tine	Springs	Prep	Tine Springs
rep.	72	24	36	12
d.f.	79	79	79	79
l.s.d.	0.1629	0.2822	0.2304	0.3991

Table	Tine Prep	Springs Prep	Tine Springs Prep
rep.	18	6	3
d.f.	79	79	79
l.s.d.	0.3259	0.5644	0.7982

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	0.0769	12.8
Rep.*Units*	79	0.4911	81.6

Variate: Experimental operating depth attained prior to step change.

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	1337.27	668.64	8.45	
Rep.*Units* stratum					
Tine	1	8098.68	8098.68	102.40	<.001
Springs	5	47344.34	9468.87	119.72	<.001
Prep	3	6799.69	2266.56	28.66	<.001
Tine.Springs	5	2395.02	479.00	6.06	<.001
Tine.Pre	3	2238.84	746.28	9.44	<.001
Springs.Pre	15	2828.78	188.59	2.38	0.006
Tine.Springs.Pre	15	1826.90	121.79	1.54	0.108
Residual	91(3)	7197.41	79.09		
Total	140(3)	78779.77			

***** Tables of means *****

Grand mean		50.18					
Tine	NS	S					
	57.68	42.68					
Springs	1.00	2.00	3.00	4.00	5.00	6.00	
	30.74	35.96	38.68	57.73	53.25	84.73	
Prep	DP	HD	HU	UP			
	55.73	41.95	58.11	44.94			
Tine	Springs	1.00	2.00	3.00	4.00	5.00	6.00
NS		34.05	38.65	43.12	68.78	65.64	95.87
S		27.43	33.28	34.24	46.69	40.87	73.60
Tine	Prep	DP	HD	HU	UP		
NS		63.31	44.40	71.59	51.43		
S		48.15	39.50	44.64	38.45		
Springs	Prep	DP	HD	HU	UP		
1.00		32.48	26.13	34.30	30.04		
2.00		36.98	31.31	42.01	33.56		
3.00		41.80	34.09	44.05	34.77		
4.00		73.35	41.67	72.10	43.82		
5.00		56.71	41.50	65.71	49.10		
6.00		93.05	77.01	90.52	78.36		

Tine	Springs	Prep	DP	HD	HU	UP
NS	1.00		35.94	27.98	38.48	33.79
	2.00		39.24	31.70	46.33	37.31
	3.00		45.02	38.81	52.23	36.41
	4.00		81.77	42.84	98.64	51.88
	5.00		68.45	44.69	87.64	61.77
	6.00		109.43	80.40	106.19	87.44
S	1.00		29.02	24.28	30.12	26.30
	2.00		34.72	30.92	37.68	29.81
	3.00		38.59	29.37	35.87	33.13
	4.00		64.93	40.51	45.56	35.75
	5.00		44.97	38.30	43.77	36.43
	6.00		76.67	73.61	74.84	69.27

*** Standard errors of differences of means ***

Table	Tine	Springs	Prep	Tine Springs
rep.	72	24	36	12
d.f.	91	91	91	91
s.e.d.	1.482	2.567	2.096	3.631

Table	Tine Prep	Springs Prep	Tine Springs Prep
rep.	18	6	3
d.f.	91	91	91
s.e.d.	2.964	5.135	7.261

*** Least significant differences of means ***

Table	Tine	Springs	Prep	Tine Springs
rep.	72	24	36	12
d.f.	91	91	91	91
l.s.d.	2.944	5.100	4.164	7.212

Table	Tine Prep	Springs Prep	Tine Springs Prep
rep.	18	6	3
d.f.	91	91	91
l.s.d.	5.889	10.199	14.424

***** Stratum standard errors and coefficients of variation *****

Stratum	d.f.	s.e.	cv%
Rep	2	3.732	7.4
Rep.*Units*	91	8.893	17.7

Variate: Experimental operating depth attained after a step change.

Source of variation	d.f. (m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	2770.62	1385.31	13.96	
Rep.*Units* stratum					
Tine	1	5589.05	5589.05	56.30	<.001
Springs	5	59825.26	11965.05	120.54	<.001
Prep	3	7074.35	2358.12	23.76	<.001
Tine.Springs	5	1376.95	275.39	2.77	0.022
Tine.Prep	3	1026.40	342.13	3.45	0.020
Springs.Prep	15	4421.30	294.75	2.97	<.001
Tine.Springs.Prep	15	2852.40	190.16	1.92	0.031
Residual	91(3)	9033.16	99.27		
Total	140(3)	92472.73			

***** Tables of means *****

Grand mean 53.42							
Tine		NS	S				
		59.65	47.19				
Springs	1.00	2.00	3.00	4.00	5.00	6.00	
	31.67	33.99	39.09	67.18	60.60	88.00	
Prep		DP	HD	HU	UP		
		45.38	60.43	47.52	60.34		
Tine	Springs	1.00	2.00	3.00	4.00	5.00	6.00
	NS	35.12	35.31	45.09	75.44	68.35	98.60
	S	28.22	32.66	33.10	58.92	52.84	77.40
Tine	Prep	DP	HD	HU	UP		
	NS	50.41	66.96	57.85	63.38		
	S	40.36	53.91	37.19	57.31		
Springs	Prep	DP	HD	HU	UP		
	1.00	29.49	32.11	30.73	34.34		
	2.00	33.90	36.88	29.14	36.03		
	3.00	34.48	41.94	37.53	42.43		
	4.00	55.60	78.42	61.95	72.74		
	5.00	41.92	76.79	45.65	78.04		
	6.00	76.91	96.47	80.13	98.49		
Tine	Springs	Prep	DP	HD	HU	UP	
	NS	1.00	32.11	34.20	38.49	35.67	
		2.00	34.52	37.84	31.07	37.81	
		3.00	40.42	51.28	47.41	41.25	
		4.00	59.11	84.77	87.79	70.06	
		5.00	54.46	83.45	52.50	83.00	
		6.00	81.86	110.20	89.83	112.51	
	S	1.00	26.87	30.01	22.97	33.02	
		2.00	33.28	35.91	27.21	34.26	
		3.00	28.55	32.59	27.64	43.60	
		4.00	52.10	72.07	36.11	75.41	
		5.00	29.38	70.12	38.79	73.08	
		6.00	71.97	82.75	70.43	84.46	

*** Standard errors of differences of means ***

Table	Tine	Springs	Prep	Tine Springs
rep.	72	24	36	12
d.f.	91	91	91	91
s.e.d.	1.661	2.876	2.348	4.067
Table	Tine Prep	Springs Prep	Tine Springs Prep	
rep.	18	6	3	
d.f.	91	91	91	
s.e.d.	3.321	5.752	8.135	

*** Least significant differences of means ***

Table	Tine	Springs	Prep	Tine Springs
rep.	72	24	36	12
d.f.	91	91	91	91
l.s.d.	3.298	5.713	4.665	8.080
Table	Tine Prep	Springs Prep	Tine Springs Prep	
rep.	18	6	3	
d.f.	91	91	91	
l.s.d.	6.597	11.426	16.159	

***** Stratum standard errors and coefficients of variation *****

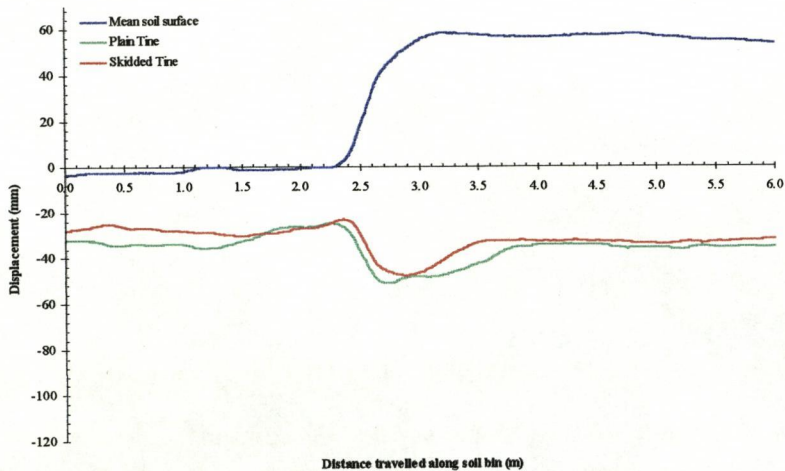
Stratum	d.f.	s.e.	cv%
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Rep	2	5.372	10.1
Rep.*Units*	91	9.963	18.7

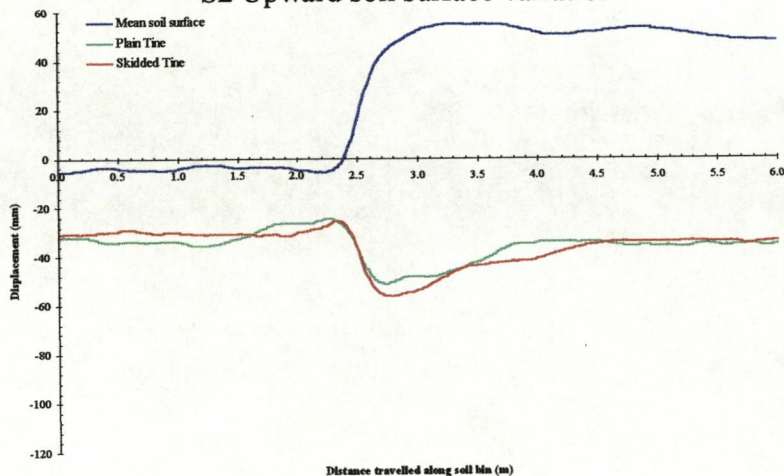
Appendix 9.6.

Mean soil profiles: Plain tine vs. tine & skids on a bearing jointed parallel linkage.

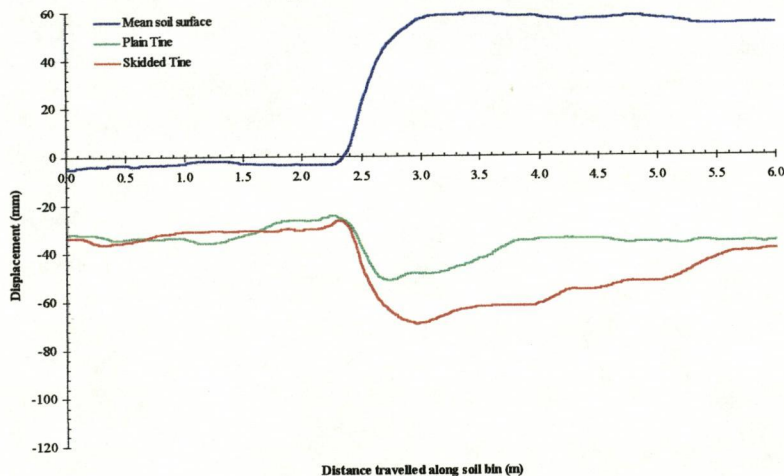
S1 Upward soil surface variation



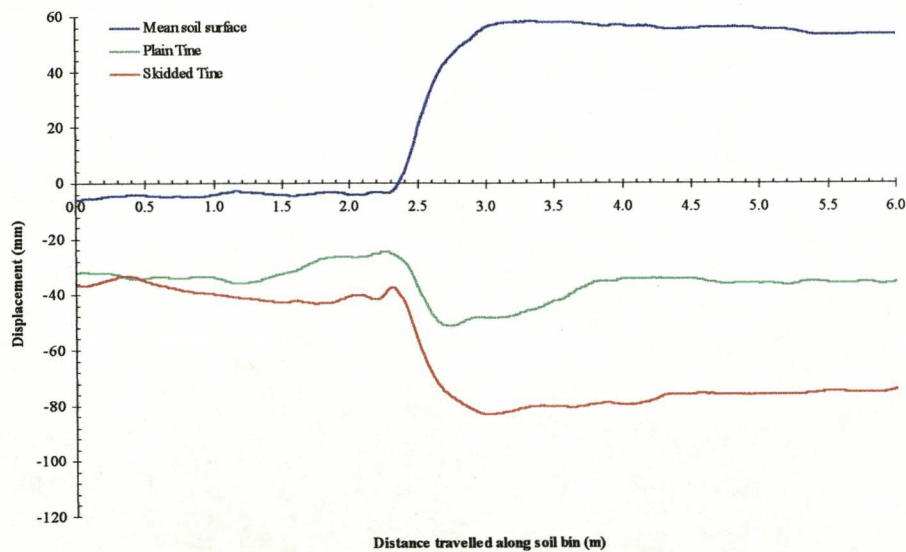
S2 Upward soil surface variation



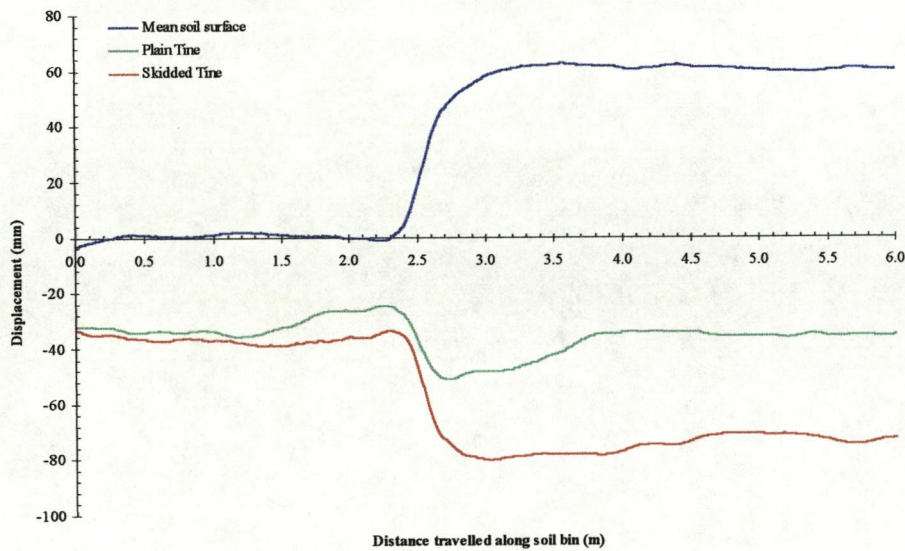
S3 Upward soil surface variation



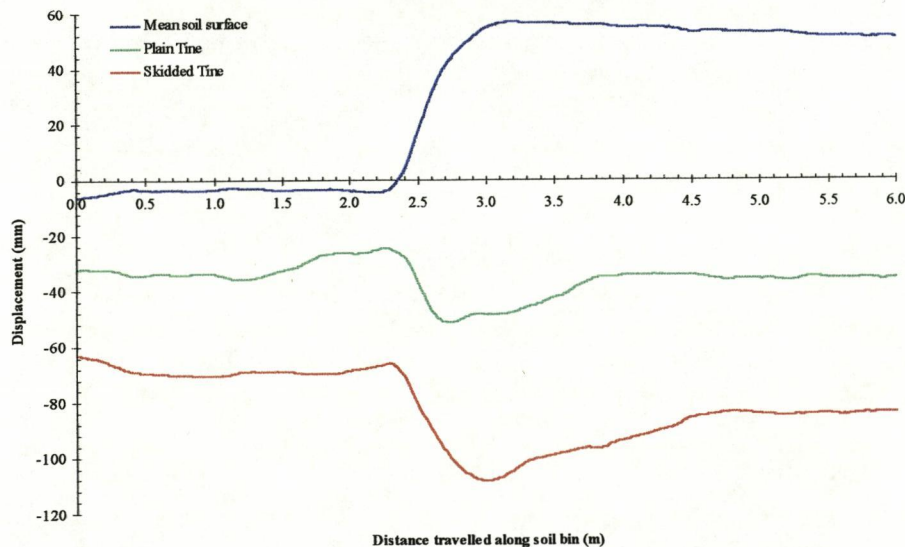
S4 Upward soil surface variation



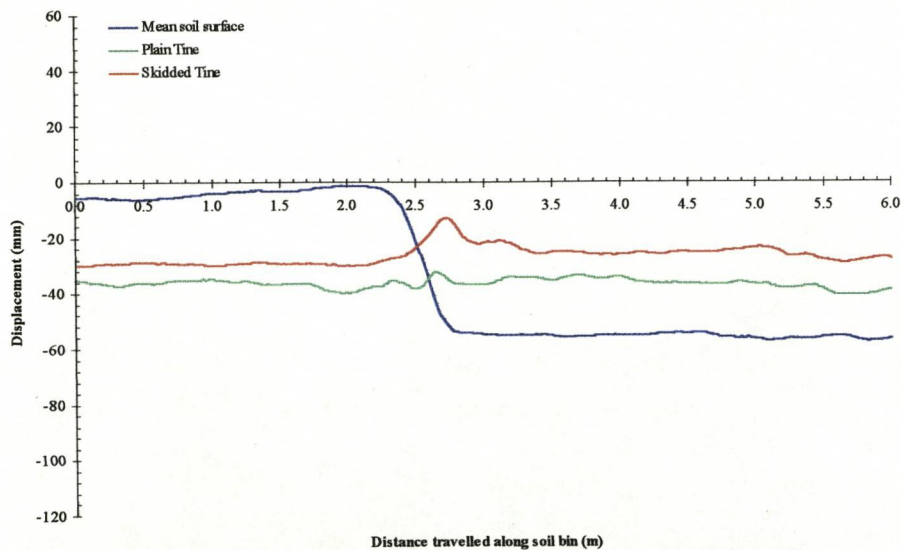
S5 Upward soil surface variation



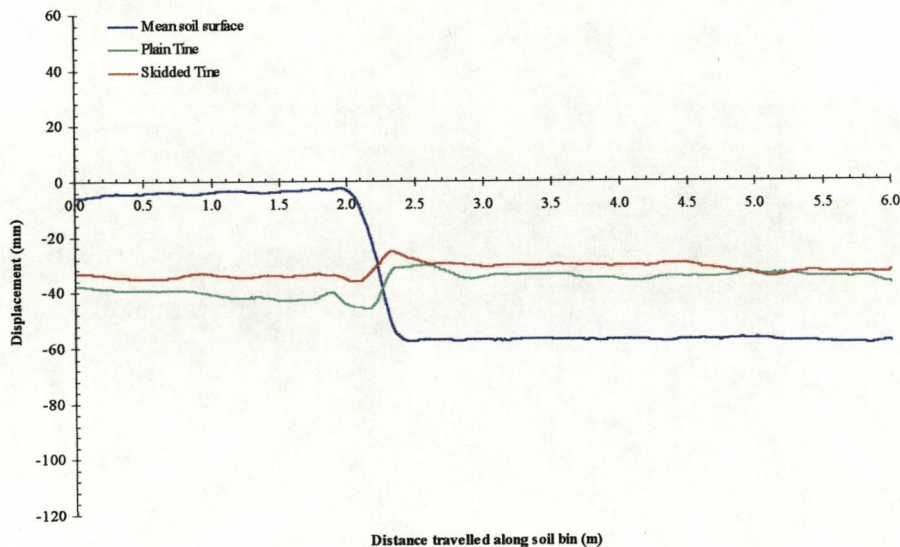
S6 Upward soil surface variation



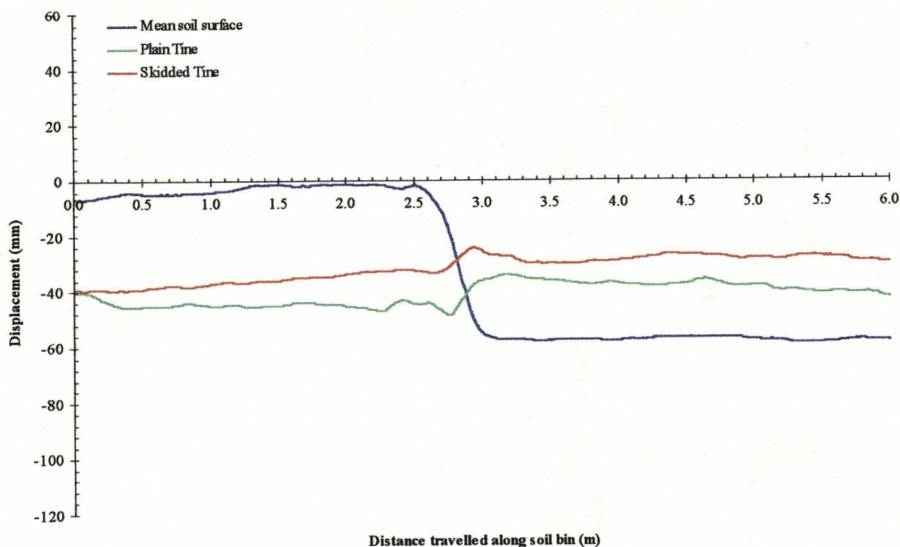
S1 Downward soil surface variation



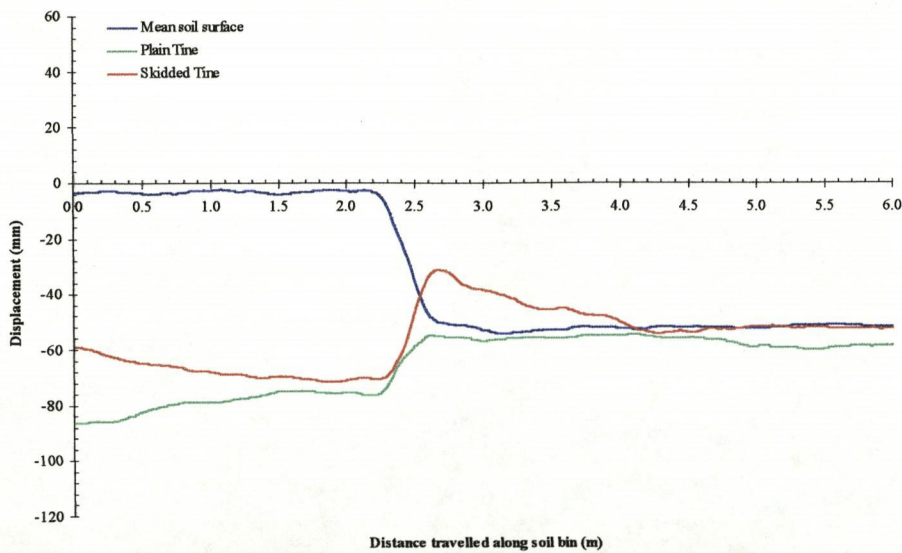
S2 Downward soil surface variation



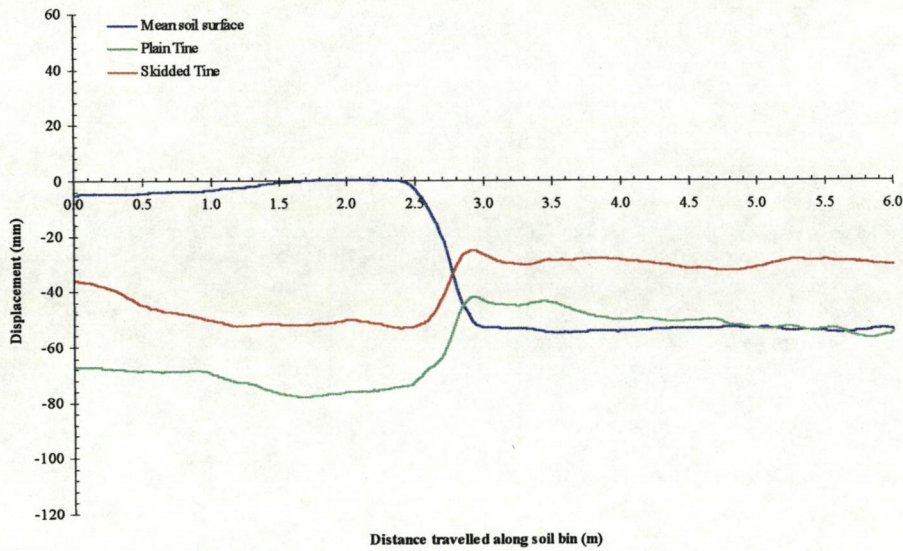
S3 Downward soil surface variation



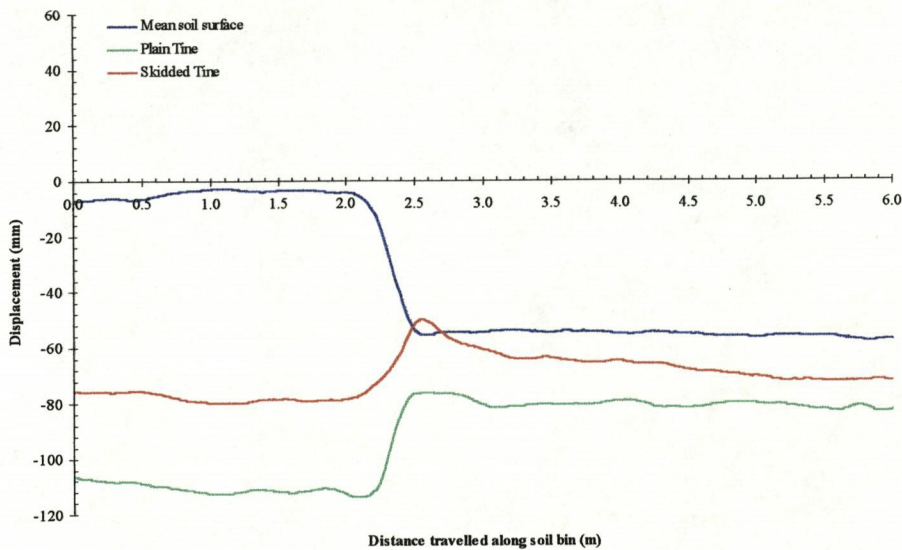
S4 Downward soil surface variation



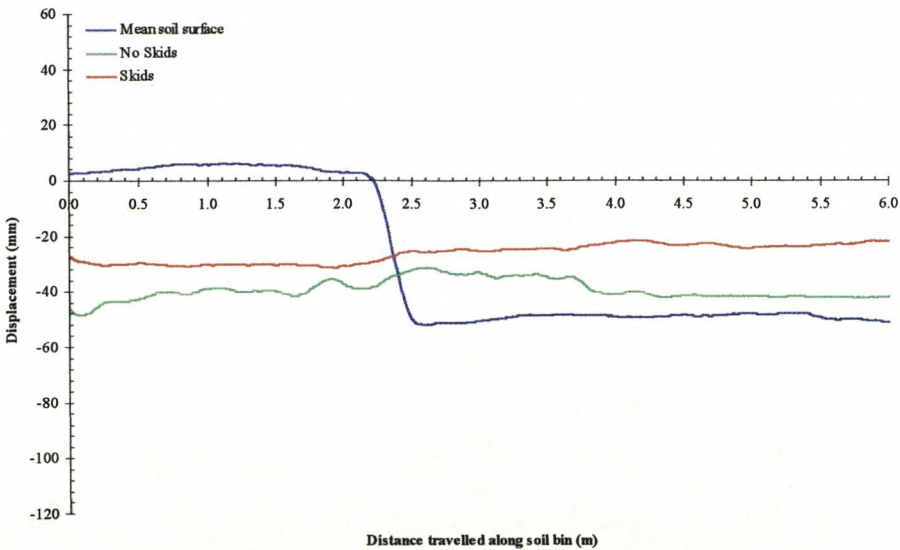
S5 Downward soil surface variation



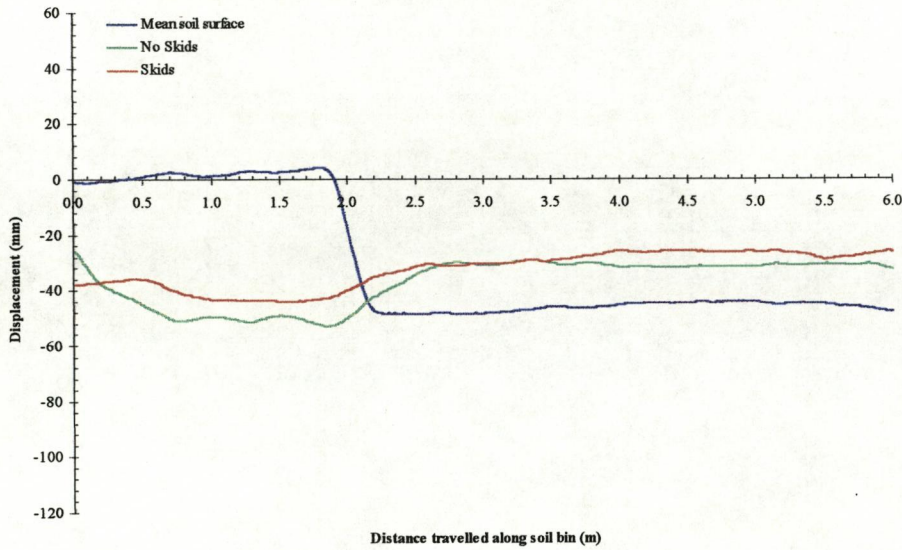
S6 Downward soil surface variation



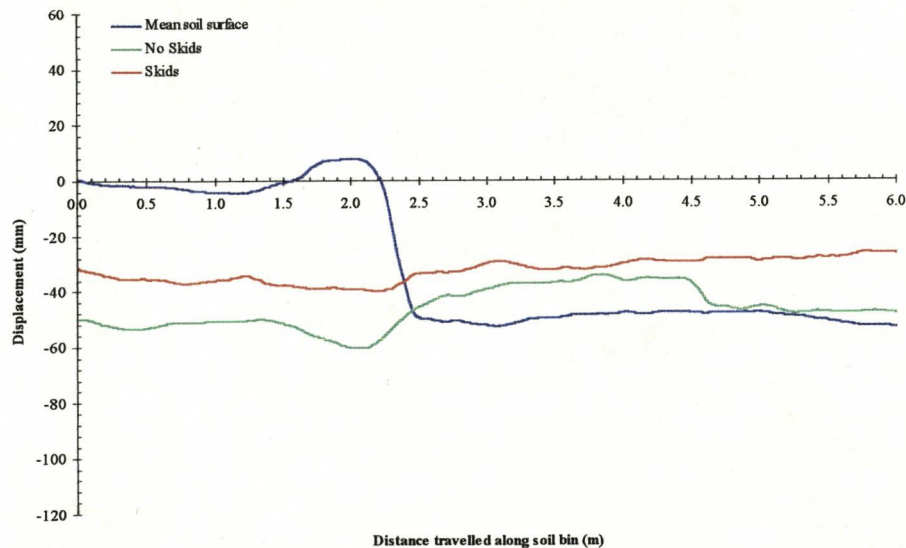
S1 Upward hitch height variation



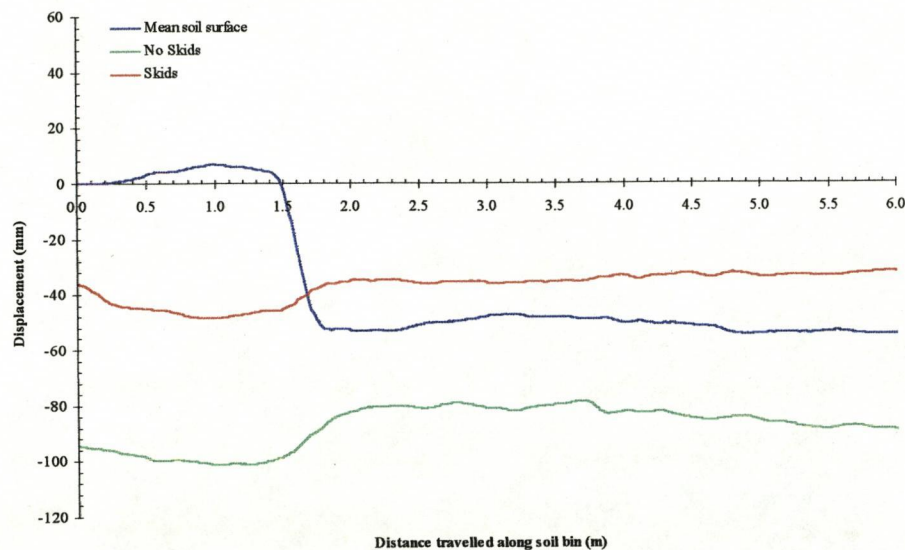
S2 Upward hitch height variation



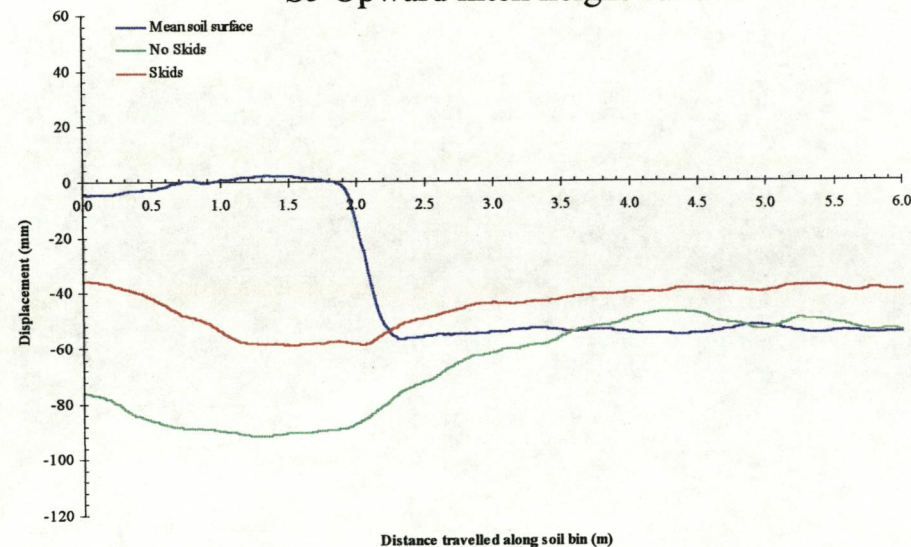
S3 Upward hitch height variation



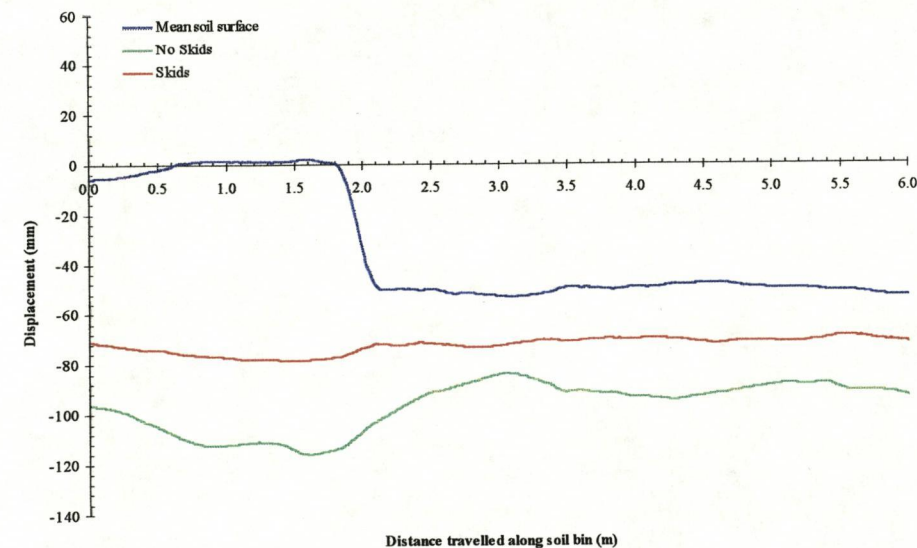
S4 Upward hitch height variation



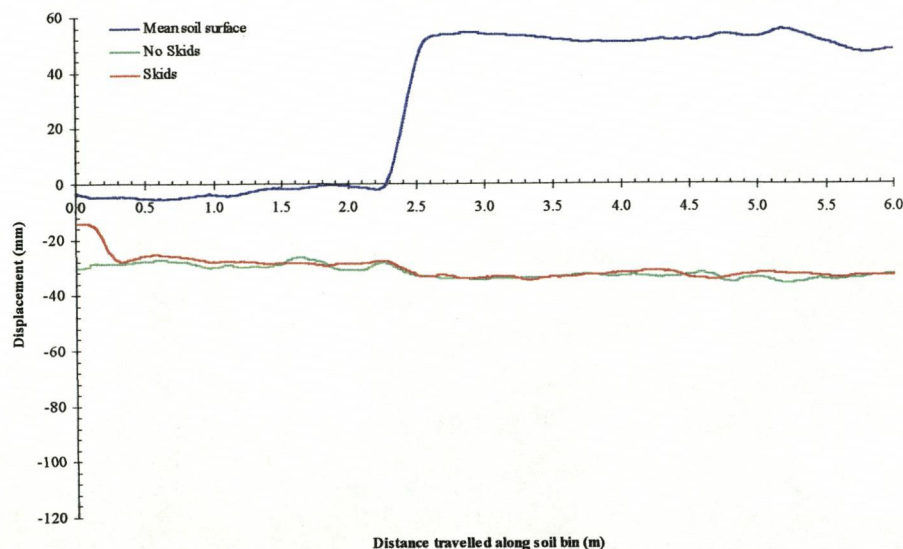
S5 Upward hitch height variation



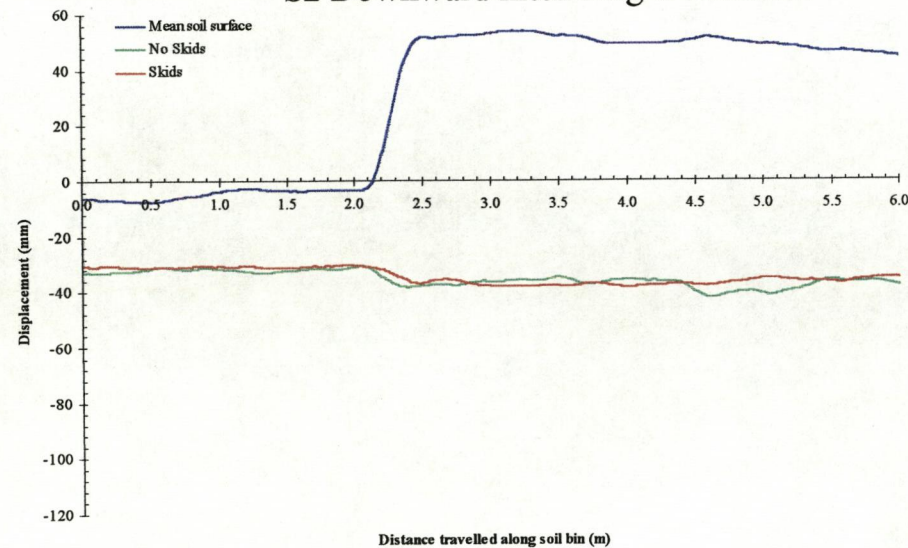
S6 Upward hitch height variation



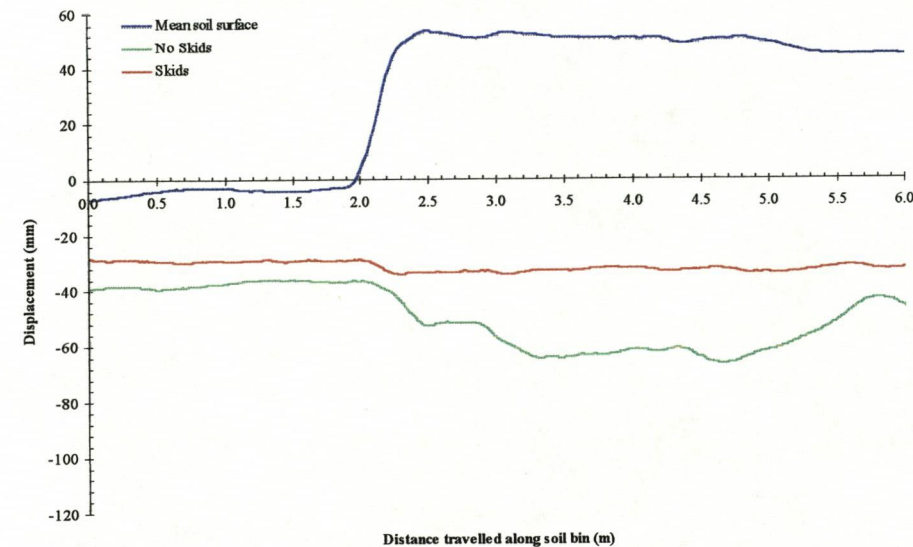
S1 Downward hitch height variation



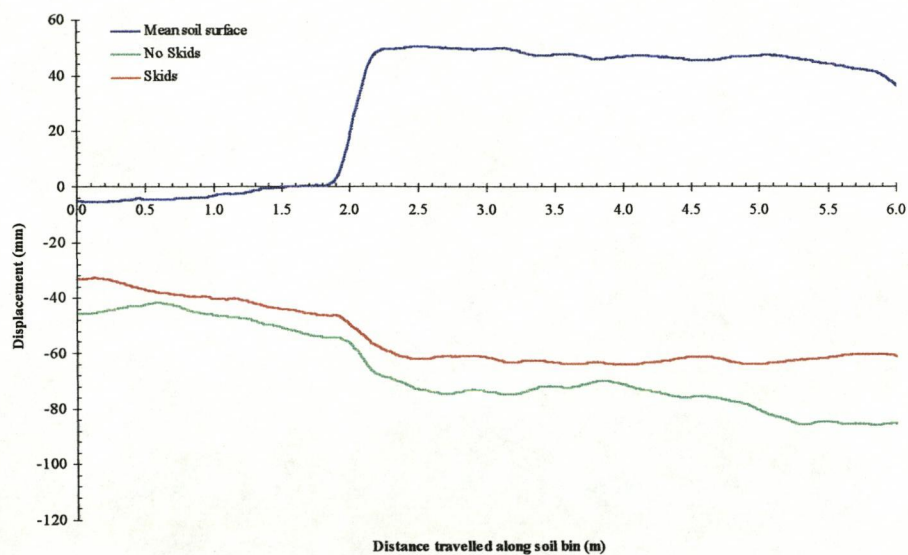
S2 Downward hitch height variation



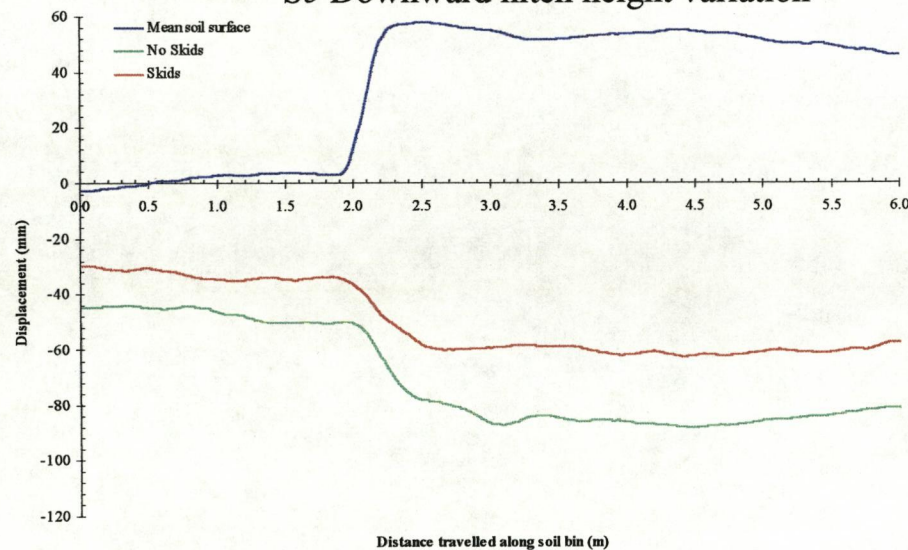
S3 Downward hitch height variation



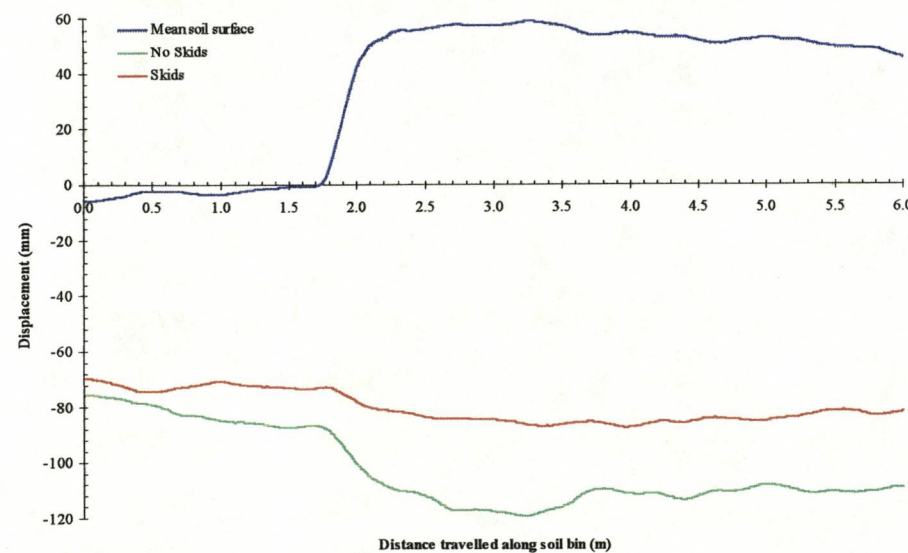
S4 Downward hitch height variation



S5 Downward hitch height variation



S6 Downward hitch height variation



Appendix 9.7.

Guidelines to the video footage presented on the CD.

The CD attached to this thesis document contains a number of video files representing the tests carried out in the Cranfield University soil dynamics laboratory at Silsoe. The files represent the 40WNDLi injector tine working with and without depth control skids and on a bearing jointed linkage. The video files contained on the CD are presented in *Table 9.7.1*.

Table 9.7.1
Video files on CD

 Downward Soil S1 Bearings &Skids	21,406KB	Video Clip	05/02/99 20:49
 Downward Soil S1 Bearings No Skids	22,356KB	Video Clip	30/01/99 17:17
 Downward Soil S2 Bearings &Skids	20,874KB	Video Clip	05/02/99 21:03
 Downward Soil S2 Bearings No Skids	28,515KB	Video Clip	30/01/99 17:30
 Downward Soil S3 Bearings &Skids	20,684KB	Video Clip	05/02/99 20:46
 Downward Soil S3 Bearings No Skids	16,806KB	Video Clip	30/01/99 17:15
 Downward Soil S4 Bearings &Skids	22,622KB	Video Clip	05/02/99 07:57
 Downward Soil S4 Bearings No Skids	18,745KB	Video Clip	30/01/99 17:17
 Downward Soil S5 Bearings &Skids	20,607KB	Video Clip	05/02/99 07:53
 Downward Soil S5 Bearings No Skids	21,102KB	Video Clip	30/01/99 17:13
 Downward Soil S6 Bearings &Skids	17,490KB	Video Clip	05/02/99 07:52
 Downward Soil S6 Bearings No Skids	20,607KB	Video Clip	30/01/99 17:24
 Upward Soil S1 Bearings &Skids	25,245KB	Video Clip	05/02/99 07:41
 Upward Soil S1 Bearings No Skids	19,999KB	Video Clip	30/01/99 17:00
 Upward Soil S2 Bearings &Skids	18,859KB	Video Clip	04/02/99 21:45
 Upward Soil S2 Bearings No Skids	23,193KB	Video Clip	30/01/99 16:51
 Upward Soil S3 Bearings &Skids	21,672KB	Video Clip	05/02/99 07:44
 Upward Soil S3 Bearings No Skids	21,672KB	Video Clip	30/01/99 17:02
 Upward Soil S4 Bearings &Skids	22,432KB	Video Clip	04/02/99 21:54
 Upward Soil S4 Bearings No Skids	19,239KB	Video Clip	30/01/99 16:57
 Upward Soil S5 Bearings &Skids	22,622KB	Video Clip	04/02/99 21:49
 Upward Soil S5 Bearings No Skids	19,391KB	Video Clip	30/01/99 16:54
 Upward Soil S6 Bearings &Skids	24,523KB	Video Clip	05/02/99 07:48
 Upward Soil S6 Bearings No Skids	21,938KB	Video Clip	30/01/99 17:05

In order to view the video footage, Windows 98 is required. If Windows 98 is unavailable, Microsoft Media Player is also included on the CD for installation to enable viewing. To install Microsoft Media Player, access the CD by Windows Explorer (or My Computer) and enter the directory "Media Player". Execute the file called "mpie4ful" and the media player will install. Following successful installation, run the program called "Setup" in the media player directory on the CD. This will upgrade the media player to allow successful viewing.