

**PARAMETRIC STUDIES AND ENERGY REQUIREMENT OF AN INCLINED
NARROW MODEL CHISEL BLADE IN A LABORATORY SOIL BIN**

BY

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APPROVAL

This Thesis has been read and approved as meeting the requirement of the Department of Agricultural and Biosystems Engineering in the Faculty of Engineering and Technology, University of Ilorin, Ilorin, Nigeria for the Award of Doctor of Philosophy (Ph.D.) Degree in Agricultural and Biosystems Engineering (Farm Power and Machinery Option).

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DEDICATION

This Thesis is dedicated to my entire family members.

DECLARATION

I, Iyanda, Muritala Olayode hereby declare that this thesis entitled Parametric Studies and Energy Requirement of an Inclined Narrow Model Chisel Blade in a Laboratory soil Bin is a record of my research work. It has neither been presented nor accepted in any previous application for a higher degree. All sources of information have been specifically acknowledged.

In addition, the research work has been ethically approved by the University Ethical Committee.

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ABSTRACT

Energy requirement of tillage operations depends on soil properties, tool and operating parameters. Effects of these factors on energy requirement to reduce cost of production, during tillage operations are yet to be thoroughly investigated. This study was aimed at determining parameters affecting energy requirement during tillage. The objectives of the study were to: (i) determine the engineering properties of the soil; (ii) determine soil draught of an inclined narrow model chisel blades in the laboratory soil bin; and (iii) develop empirical model equations for predicting draught and validate them with experimental data.

A modified soil bin measuring $8.00 \times 1.00 \times 0.56\text{ m}$ was used for the experiment. Soil samples collected from 36 representative locations in Kwara State were analyzed and mixed thoroughly before loading. Tool and soil processing carriages and model chisel blades were designed and constructed. The system was instrumented to log the draught in XYZ directions with respect to distance and time. Soil preparation for data collection involved soil pulverization, leveling and compaction. Soil penetration resistance and bulk density were determined at several locations along and across the soil bin. Effects of operating depth (20, 40, 60, 80, and 100 mm); forward speed (0.25, 0.50, 0.75, 1.00 and 1.25 m/s); tool cutting edge width (10, 20, 30, 40 and 50 mm); and tool angle of lift (20, 30, 40, 50 and 60°), on draught were studied. Soil moisture content range was maintained at 10 to 12% (dry basis) throughout the experiment. A 4^5 factorial statistical design in a completely randomized block was used. Regression equations were developed based on the contribution of each factor and combination of all factors to draught of tillage tool. The model equations developed were validated using parameters obtained from the soil bin experiment.

The findings of the study were that:

- (i) engineering properties of the soil were 1.50 g/cm^3 , 26.6° , 29.8° and 16.67 kPa for bulk density, angle of internal friction, soil-metal friction angle and cohesion, respectively;
- (ii) draught of inclined narrow model chisel was affected by width of cutting edge, depth, operating speed and angle of lift. The effects of interactions of these parameters were also significant ($p \leq 0.05$); and
- (iii) regression equations showed linear relationship between draught and speed ($R^2 = 0.85$), width of cutting edge ($R^2 = 0.99$), and depth of operation ($R^2 = 0.91$) while the relationship between draught and tool angle of lift was quadratic ($R^2 = 0.94$).

The study concluded that tool width, lift angle, depth, speed of operation and soil type are parameters that affect energy requirement of an inclined narrow model chisel blade. It is therefore recommended that the effects of these parameters must be considered in the design of an inclined narrow model chisel blade to enhance effective tillage operations and minimize energy requirement.

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CHAPTER ONE

INTRODUCTION

1.1 Background to the study

Soil tilling involves soil cutting, soil turning, and soil pulverization and thus demands high energy, not just due to the large amount of soil mass that must be moved, but also due to inefficient methods of energy transfer to the soil. The most widely used energy transfer method is to pull the tillage tool through the soil. Various methods have been attempted to improve efficiency such as vibratory tillage tools. However, development of more efficient methods effectively depends upon the necessity for improved understanding of tillage tool mechanics. Complete tillage tool mechanics is far from being realized, although generalized relations have been proposed (Fornstrom *et al.*, 1970).

The world has been facing crisis in the field of energy in the last decades. The crisis is very serious and many analysts believed that the root cause of many conflicts in the world indicates the crisis in the field of energy and resources of energy. In agriculture, although new machinery systems have facilitated production, they have also increased the demand for energy. Tillage as one preliminary and basic step for any agricultural production demands huge amount of energy. In a tillage operation, energy can be expressed in terms of energy per unit area or per volume of disturbed soil (Panwar and Siemens, 1972). Since energy requirement per unit volume has the same unit as draught per unit area, it can be shown as the draught requirement to cut a furrow in an exact cross section as expressed by McKyes (1985) and Chancellor (1994). Energy can also be expressed as the rate of energy per depth of operation (Darmora and Pandey 1995). The most important factors in the determination of energy requirement of a tillage tool are draught and the quantity of disturbed soil. In other words, if those two values are available, energy can easily be calculated as the product of draught and the length of disturbed soil. For any tillage operation,

the report of energy requirement must include the depth of operation as well. Gill and Vanden Berg (1968) reported two additional factors including tool shape and manner of tool movement as parts factors affecting energy requirement of a tillage tool. The report refers to the tool affecting factors such as tool speed, tool operating depth, tool shape, and tool rake angle.

Payne (1956) assumed two categories of tools as wide and narrow vertical tools. For wide tools (tool width is at least twice of its operating depth) and for narrow tool (operating depth is at least twice of the tool width).i .e.

For wide tool, $w/d \geq 2$ and

For narrow tool, $w/d \leq 2$

where,

w = tool width (m)

d = operating depth (m)

The amount of energy consumed during a tillage operation depends on three classes of parameters:

- (1) Soil properties
- (2) Tool parameters and
- (3) Operating parameters.

Draught and energy requirements, based on present soil and operating conditions, are considered important and necessary parameters for design and manufacture of efficient tillage implements. Thus quantification of these parameters with respect to different soil failure patterns necessitates having good knowledge of soil-tool interaction. During the 20th century, the appearance of new theories in the field of soil mechanics, mostly started by Terzaghi (1943), enabled new research

in both areas of civil and agricultural engineering. The improvements, brought on by these theories, continued in the second half of the century as use of computers increased. In the field of soil-tool interaction, experimental and analytical models appeared during the 1940's.

During operation, tillage tools apply forces to soil resulting in soil failure for enhanced agricultural production; e.g., by increasing seed emergence, improving plant rooting, increasing infiltration, and controlling erosion (Lindstrom *et al.*, 1990). The primary interest in tillage operations is the application of mechanical forces by machines to change the soil condition for agricultural production purposes that is the preparation of appropriate seeded for crop production (Schafer and Johnson, 1982). The force systems, applied by a tool, can cause the soil to yield by shear, compression, tension, and/or plastic flow. The amount of force required to shear the soil would change based upon soil conditions, tool specifications, and operational parameters employed during a tillage operation. Depth of cut, width of cut, tool shape (including cutting edges), tool arrangement, and travel speed are factors that may affect draught and the energy utilization efficiency for a specific soil condition. The effects of these parameters vary with different types of implements and with different soil conditions (Kepner and Bainer, 1972). Factors such as soil texture, soil moisture content, soil compaction, tool geometry, tool operating depth, tool forward speed, and tool rake angle obviously affect the energy requirement of a tillage operation. There has been much research that discusses the effect of these factors for different soil and tool conditions on tool energy requirement although each of them has some limitations in their applications (Koolen and Kuipers, 1983).

Blumel (1986) expressed that tillage energy can be divided into friction energy, deformation energy, cutting energy and acceleration energy. It was emphasized that it is very difficult to

measure these components separately, and even qualitative examinations are most often difficult. Kushwaha and Linke (1996) published a graph of tillage energy versus tool speed as a derived form literature that presents the influence of speed on the components of those energy components.

1.2 Statement of the Problem

Tillage as one preliminary, basic and very important step for any agricultural production requires large amount of energy, the knowledge of draught and energy requirements of a given tillage tool is important and necessary for the design and fabrication of such tool and the selection of appropriate prime mover for various tillage operations thereby reducing costs of Agricultural productions.

1.3 Aim and Objectives

The aim of this research work was to investigate energy requirement during a tillage operation.

The specific objectives were to:

- (i) determine the engineering properties of the soil used for the study (soil cohesion, soil angle of internal friction, soil metal friction angle, soil bulk density and soil moisture content).
- (ii) determine soil draught of an inclined narrow model chisel blades in the laboratory soil bin.
- (iii) develop model equations for predicting draught and validate it with experimental data from tests in the soil bin.

1.4 Justifications

Draught and of course energy requirements, based on soil and operating conditions, are considered very important parameters for design and manufacture of improved tillage implements. The focus of this study therefore is on the pattern of soil deformation and energy requirements for optimum tillage tool design and appropriate machine selection for available source of farm power. The knowledge of draught and energy requirements of any given tillage tool is essential for the design and fabrication of such tool and selection of appropriate prime mover for various tillage operations thereby reducing costs of agricultural productions and improving the timeliness of tillage operations.

Scope of the Project

The research work was carried out only on loamy sand in the laboratory soil bin. other soil types were also to be considered in future research to establish the draught and hence energy requirement for tillage operation in such soil types. The soil moisture content was also maintained at 10% - 12% dry basis. Therefore, soil moisture content should be varied in the future research works.

CHAPTER TWO

LITERATURE REVIEW

2.1 Soil Properties that affect Tillage Operations

Draught required during tillage is a function of soil properties, working depth, tool geometry, travel speed, and width of the implement. It is an important parameter for measuring and evaluating implement performance for energy requirements. Many studies have been carried out to determine draught and energy requirements of tillage implements under various soil conditions (Grisso *et al.*, 1996).

During tillage operations, factors that affect energy requirement of a working tool can be classified into three main groups: (1) soil properties (2) tool parameters and (3) operational parameters.

To evaluate energy requirement of a tillage tool, energy requirement resulting from each group of factors should be taken into account in order to have an estimation of total energy requirement.

Chandon and Kushwaha (2002), investigated the effect of rake angles, operating speeds, and tool cutting edges associated with deep tillage in sandy loam and clay loam fields at an operating depth of 18 cm, to select a tool that will reduce energy consumption. The magnitude of the draught and vertical forces for the elliptical cutting edge was the highest. Draught and vertical forces increased linearly with an increase in speed.

Soil mechanical, physical and soil dynamic properties have significant influence on the amount of energy requirement of a tillage operation. Soil properties that affect tillage energy are soil bulk

density, moisture content, cone index, friction angle, texture, compaction, soil cohesion, and soil strength.

Henderson *et al.* (1981) reported that several investigations have shown improvement in the physical properties of soil with the application of deep tillage. Improvements included increase in soil pore space, increased water uptake, and a reduction in the bulk density but there was little effect on other soil properties.

Some of the most important soil physical and soil dynamic properties which affect draught and energy requirements of tillage tools are as discussed below.

2.1.1 Soil Physical Properties

Soil moisture content and soil texture affect mechanical behaviour and strength of soil. Soils with the same mechanical and environmental conditions but different texture behave differently. Camp and Gill (1969) and Smith (1964) reported that shear strength parameters of fine grained soils decreased with increasing moisture content. However, the soil density was concurrently decreasing as the moisture content was increased. Presence of water in void space of fine-grained soils can have a major impact on the engineering behaviour of the soil. Therefore, it is important to know not only how much water is present, but also how it can affect engineering behaviour of soil. As moisture content of a soil increases, the soil changes from a brittle solid to a plastic solid and eventually to a viscous liquid. Mouazen and Ramon (2002) reported that draught force of subsoiler was increased with wet and dry bulk densities where it decreased with soil moisture content. Draught force was changed linearly with moisture content where it was a quadratic function of wet bulk density and a cubic function of dry bulk density respectively.

2.1.2 Soil Dynamic Properties

Dynamic properties of soil was defined as soil properties which become manifest through soil movement (Gill and Vanden Berg, 1968). According to this definition, if a block of soil starts moving on a flat surface, the resultant friction angle is a dynamic property of soil which does not appear unless soil starts moving. Also, when loose soil is compacted, its strength increases; therefore, soil strength is another dynamic property of soil. As the forward speed of a tillage tool increases, dynamic effects on the cutting force become more predominant because of two main effects: First, the need of continuous acceleration of new mass of soil as the tool travels, and second, variation of soil strength at high rate of shear.

Zhang and Kushwaha (1999) reported three mechanisms accounting for the draught increase with increase in operating depth: 1- soil inertial effect, 2- soil strength rate effect, and 3- wave propagation effect. The last effect comes from the research performed by Russians (Azyamova, 1963; Katsygin, 1969; Vetrov and Stanevski, 1972) who noticed when the speed of a tillage tool exceeds some limits; the draft requirement of the tillage tool inversely decreases. This was attributed to the fact that as the tool speed increased faster than the wave of soil stress propagation, theoretically, the plastic zone of soil in front of the tool decreased or even disappeared, thus the soil cutting resistance decreased. Based on this research, they claimed that there should be an optimum speed at which the draft requirement would be lower.

Measurement of dynamic properties of soil during tillage is very difficult because those physical measurements should be accomplished during the operation and are difficult to measure in dynamic state. There are concerns that mechanical devices cannot accurately measure those dynamic properties. The measuring device may react differently from the soil if for example it is

softer or harder than the soil. In addition, the measuring device may influence soil reaction if it is one of those inserting device such as soil penetrometer (Gill and Vanden Berg 1968).

2.1.3 Soil Cohesion Measurement during Soil Cutting Process

The nature of cohesion is presently not fully understood, it can be considered as the strength of the soil that is not dependent on the applied force. Koolen and Kuipers (1983) defined cohesion as bonding force among soil particles per unit area. They have considered it as a soil property which is affected by several factors including soil type, moisture content, and pore space. In soil mechanics, clay soils are classified as cohesive soils where sands are determined as non-cohesive or frictional soils, because sands may have no cohesion at all. The increase of soil cohesion with increasing soil bulk density has been reported by several researchers (Mulqueen *et al.* 1977 and Schmertmann, 1975.). They expressed that this relationship is dependent on soil type and moisture content. It was concluded that normally, coarse grained soils (high sand fraction) exhibited higher friction angle values and fine grained soils (highly clay content) exhibited higher cohesion values.

Payne (1956) measured cohesive and frictional properties of field soil using a torsional shear box. Approximate values of 33° and 3.5 kPa, and 33° and 21 kPa were determined for friction angle and cohesion of sandy loam and clay soils at depth of 10 cm respectively. McKyes (1978) employed draught measurements of Payne's tests (1956) to calculate same values by his own model. It was reported that the results of both methods were very close to each other.

2.1.4 Effects of Soil-Soil Friction on the Draught of Tillage Tools

During the tillage, part of energy requirement is expended to overcome the interlocking force of particles and their rolling and sliding on each other. Angle of internal friction (ϕ) exhibits the existence of friction force between soil particles. Its value is affected by soil porosity, moisture content, normal stress, and grain size distribution. Angle of internal friction is not affected by the rate of shear. Sandy soils are mostly named frictional soils because of their nature that usually have a larger angle of internal friction in comparison with clays. In general, well-graded sands with a larger relative density and sharp edge particles have a larger angle of internal friction when compared to the uniform sands with lower density and round edge particles. In an unsaturated agricultural soil, angle of internal friction varies from 25° for moist, loose, fine textured soils to about 45° for dry, dense, coarse textured soils (Koolen and Kuipers, 1983).

2.1.5 Soil Cone Index and Tillage Draught Requirement

Cone index of agricultural soils is a very important factor that is measured in most tillage studies, and it indicates the resistance of soil to penetration. Since for each tillage activity, a tillage tool should initially be able to penetrate the soil. Cone index values at different depths of different types of soils can help researchers to evaluate and compare soil mechanical strength and forces engaged in tillage operations. The ASAE Standards (2002) emphasizes that cone index does not provide specific soil values such as cohesion, angle of friction or coefficient of soil-metal friction. Ayers and Perumpral (1987) in their research work evaluated the effect of soil density, moisture content, and soil type on cone index. Their results showed that, moisture content level which produced maximum dry density did not include maximum cone index. Also, samples with 100% sand had a significant lower cone index than samples including some clay. An increase in

compaction level increased the maximum cone index attained for a soil mixed of 50% clay and 50% sand, and for all kinds of soils except for 100% sand, the effect of moisture content on relationship between dry density and cone index was consistent. Finally, in a soil mixture of 50% clay and 50% sand at low moisture contents of 2.2%, 4.4%, and 6.7%, cone index increased with dry density at a high rate. When moisture content reached higher amount of 8.8% and 11.8%, the relationship between cone index and dry density became more linear. As moisture content increased, the increasing rate of cone index with dry density significantly decreased.

2.1.6 Soil Shear Strength Determination during Tillage Operations

According to Gill and Vanden Berg (1968), soil strength is the ability or capacity of a particular soil in a particular condition to resist or endure an applied force. Tillage can cause soil failure by shear, compression, tension, or plastic flow. Shear is one of the most common methods of soil failure employed by many kinds of tillage implements. Many researchers have worked in this area investigating the characteristics of the shearing process. Johnson *et al.* (1978) evaluated methods and devices of shear measurements for agricultural soils. The most general envelope of shear strength was proposed by Coulomb as Equation 2.1:

$$\tau_{\max} = C + \sigma_n \tan \phi \quad (2.1)$$

where $\tau_{\max}$ is maximum shear stress (N), σ is normal stress (N), C is soil cohesion (N), ϕ is the soil-tool frictional angle ($^{\circ}$).

This envelope is referred to as the Mohr-Coulomb failure envelope. The authors indicated that although the envelope cannot represent shear failure at all soil conditions, it is still valid enough to be a law.

2.1.7 Soil Compaction and Tillage Draught Measurement

Compaction is defined as the compression of an unsaturated soil body due to a reduction in the free air volume (Hillel, 1980). Compaction is the densification of soils through the application of mechanical energy resulting in a reduction of air voids with little or no reduction in moisture content. Soil compaction is to some extent an unavoidable event that frequently occurs as a result of machinery traffic on agricultural soils. Although certain amount of soil compaction is required to ensure better contact between seeds and soil particles, any extra compaction increases soil strength and causes several problems. Many researchers have reported the harmful effects of soil compaction on soil structure including reduction of air filled void spaces, changes in soil matrix gaseous composition and increases in resistance to root growth (Soehne 1958; Gupta *et al.*, 1990; Janzen, 1990; Bicki and Siemens, 1991; Hakansson and Petelkau, 1991; Burt *et al.*, 1992). Laboratory tests are used to determine the optimum moisture content and maximum density to ensure that the desired design values for shear strength, compressibility, and permeability are met. Air is expelled from the soil rapidly whereas water, which has a viscosity 50-100 times greater than air, is expelled at a much slower rate. Proctor established that the compaction of a soil is a function of the following four variables:

1. Dry density
2. Water content
3. Compactive effort
4. Soil type (gradation, presence of clay minerals, etc.).

According to Gill and Vanden Berg (1968), compaction reduces soil permeability to water and aeration of the soil, increases the mechanical strength of the soil and therefore, reduces the

metabolic activities of roots. In addition, a compacted soil requires higher amount of energy during tillage operations to break down aggregates and clods into smaller particles in order to provide a suitable seed bed. All these effects may reduce the quality and quantity of food and fiber grown on the soil.

2.2 Tool Parameters that affect Draught and Energy Requirements

In a tillage operation different tool parameters influence energy requirement of the tool. Such parameters include tool type, tool shape and size, tilt angle, angle of attack, tool rake angle, tool sharpness, and tool material, all of which could affect draught and energy requirements.

2.2.1 Effect of Tool Parameters on Draught Requirement

In a comparison between power requirements of three subsoilers including a conventional, a triplex, and a parabolic subsoiler, the following results were reported by Ashrafi and Kushwaha (2006). In general, draught decreased for all three implements as speed increased except for the highest speed tested which showed a very definite increase in the draught. This increase in draught was most pronounced for the triplex and conventional subsoilers. No attempt was made to explain the soil dynamics of this response; however, the response was consistently observed for all three implements. Therefore, there appears to be an optimum ground speed for which less draught was required to operate the subsoilers for the soil conditions and operating depths used for the test. The researchers believed the shape of subsoiler could have a significant impact on power requirement. Oni *et al.*, (1992), revealed that soil depth and tool nose angle have significant effects on the draught, but added that at depths greater than 30 mm, the correlation between the draught and design factors were poor.

2.3 Operational Parameters and Draught Requirement

The operational parameters which influence draught and energy requirements of tillage implements are depth and speed.

2.3.1 Effects of Tillage Depth on Draught Requirement

Wolf *et al.* (1981) reported that draught increased sharply with depth of subsoiling on one soil condition. Increase in draught requirement with increase in subsoiling depth was also reported by Garner *et al.* (1987).

Summers *et al.* (1986) studied the effects of depth and speed on draught requirement of different tillage implements on three different Oklahoma soils. Results showed that draught was linearly proportional to depth for mould board plough, chisel plough, disk, and sweep plough. Girma (1989) measured applied forces on mould board plough during a tillage operation. At a constant speed of 0.8 m s^{-1} , it was reported that a polynomial including first and second order of depth between draught requirement and depth of operation for mould board plough existed.

The draught of geometrically similar models chisel furrowers in an artificial soil in an indoor soil bin increased with increases in tool travel speed at increasing levels of tillage depth, nose and slide angles, and cutting edge height (Mamman and Oni, 2005).

2.4 Draught prediction approach for tillage implements

The draught requirement of any tillage implement was found to be a function of soil properties, tool geometry, working depth, travel speed, and width of the implement (Glancey *et al.*, 1996). Soil properties that contribute to tillage energy are moisture content, bulk density, soil texture and soil strength. The relationship between the draught of plane tillage tools and speed, has been

defined as linear, second-order polynomial, parabolic and exponential (McKyes, 1985; Swick and Perumpral, 1988; Gupta *et al.*, 1989).

These differences in the findings are the result of inertia required to accelerate the soil, the effect of shear rate on shear strength and the effect of shear rate on soil–metal friction, all of which vary with soil type and condition. From the studies conducted in cohesive and frictional soils, Wheeler and Godwin (1996) confirmed that inertia effects on draught of tine are not significant below speeds of $\sqrt{5gw}$ and are limited up to speeds of $\sqrt{5g(w+0.6d)}$ where g is the acceleration due to gravity in m/s^2 , W is tool width in m and d is the depth of tillage operation in m , while Glancey *et al.* (1996) found the speed effects to be less significant as compared to the effect of depth. Many regression equations for the draught prediction of various tillage implements have been developed using the data collected from the field experiments to facilitate machinery selection, implement matching with tractor and estimation of fuel (ASAE, 2000; Kheiralla *et al.*, 2004). However, the applicability of such regression equations is limited to those soils and implements conditions for which these equations were developed. Therefore, new regression equations are required to be developed empirically for other soil and implement conditions. Alternative approaches to the use of regression equations for predicting the draught of tillage implement have also been developed using standard tillage tools (Glancey *et al.*, 1996; Desbiolles *et al.*, 1997). In these approaches, the standard tillage tools were tested in the field conditions with an instrumented mobile power source such as tractor to measure draught at the desired depth and speed of operation. However, field studies of draught measurement require enormous amounts of time, energy and cost for gathering agricultural machinery management data to select matching implements with tractors, to estimate fuel consumption, and to simulate and compare the performance of different farming systems.

2.5 Soil-Tool Modeling for Energy Requirement

Over the years, Different modelling tools have been implemented to model soil failure during tillage operations. Experimental, empirical, analytical, statistical and numerical modeling methods are different approaches to achieve this goal. Analytical methods have received much attention over last decades from many researchers. Because of the importance of this approach in calculating draught and energy requirements of particularly narrow tillage tools. On the other hand, numerical approaches such as Finite Element Method (FEM), Discrete Element Method (DEM), and Artificial Neural Networks (ANN) have been implemented in tillage science as the result of appearance of powerful computers. To date, there are only few reports on using DEM for tillage studies (Shikanai and Ueno, 2002; Khot *et al.* 2005). This method is one of the numerical analyses in which solid body is treated as aggregate particles.

The behaviour of the solid body is estimated from the solution to the equation of motion with respect to each of the particles in the DEM. With this technique, it is possible to treat the phenomenon of soil destruction by agricultural machines. In DEM, dynamic behaviour is described numerically using a time stepping algorithm. The time step is selected such that (a) velocities and acceleration can be assumed constant within the time step, and (b) the time step is indiscriminately small in manner that disturbances cannot propagate from one element further than its immediate neighbour during a single time step. The calculation cycle alternates between force displacement law at the contacts and Newton's second law of motion. The force displacement law is used to calculate the contact forces from relative displacements at contacts. Hryciw *et al.* (1997) used video tracking and digital image analysis method for experimental

validation of DEM simulation for large discontinuous deformation in sandy soil during plowing. Despite some powerful aspects of DEM in modeling soil-wheel interaction, the number of soil particles which can be handled in DEM simulation is much less than the actual number of particles considered in the laboratory experiments. Jayasuriya (1999) used bigger and narrow soil bins to validate the model for soil-tire interaction in lateritic soil. In addition, it is usually difficult to correlate the test results obtained from subsequent test runs due to the non uniformity involved during soil bin preparation. Literature further shows that DEM has not yet been used for soil tool interaction. This can be due to the difficulty of modeling soil failure by DEM during dynamic processes such as tillage operations. There has also been an attempt to apply Computational Fluid Dynamics (CFD) for soil failure modeling. This method was applied to simulate the soil flow around a simple tool. Simulations used a vertical blade in a rectangular flow domain (Karmakar and Kushwaha 2005a). Soil was treated as a Bingham viscoplastic material in respect to its non-Newtonian rheology. Free-surface simulation of an open channel visco-plastic soil flow indicated soil deformation patterns and the effect of speed on the failure front propagation. Soil deformations, as the flow of a visco-plastic material with yield stress, were observed to possess "plastic flow" and "plug flow" patterns. For a tool speed of 6 m s^{-1} , with a vertical tool of 20 mm thick and 50 mm wide, operating at 100 mm depth, the soil failure front was observed to be 160 mm at a depth of 10 mm below the top soil surface.

The critical speed range was found to be 5 to 6.5 m s^{-1} . Soil pressure on the tool surface increased with the tool operating speed. Pressure concentration was the highest at the tool tip; it decreased towards the soil surface and extended over greater area on the tool surface with increase in tool speed (Karmakar and Kushwaha, 2005b). Draught was related as a square

function of speed. Since this research is the only one found in literature, further investigation would be required to justify the ability of the method in modeling soil-tool interaction. Among the numerical approaches, FEM has received more attention and was implemented earlier than the other numerical methods. In addition, literature shows acceptable results obtained from FEM modeling research, however, the results emphasized on the limitations of this method. Therefore, in this section, results of some research pertinent to FEM modeling are presented. These reports will focus on draught and energy affecting factors data resulted from this modelling method.

2.6 Components of Energy Requirement Model for Tillage Tools

The total energy required by the tillage tool is divided into four main components, namely:

1. Energy requirements associated with soil-soil interaction;
2. Energy requirements associated with interaction between tilled soil and fixed soil masses;
3. Energy requirements associated with soil deformation and
4. Energy requirements associated with the acceleration of the tilled soil.

The above energy components was based on the studies by Blumel (1986) and Kushwaha and Linke, (1996). Energy is defined as the product of force and distance. It shows the amount of work done by the tool for soil manipulation during tillage operations.

Assumptions

Based on the theory proposed by Blumel, (1986) the following assumptions were made;

1. Deformation energy at depths up to 40mm inclusive is negligible (Grisso *et al.*, 1980)

2. Acceleration energy of soil at speeds up to 1kmh^{-1} inclusive is negligible (Godwin and Dogherty, 2003).

2.6.1 Validation of the Basic Assumptions

Validation of these basic assumptions was very important for reliability of the model. First assumption of the model was that deformation energy of soil at depths up to 40 mm was equal to zero. This can be discussed from different aspects. First of all, it should be noted that for such a vertical narrow tool, the amount of translocated soil due to the tool movement is very low. For vertical tools, it was observed (O'Callaghan and Farrelly, 1964) that at shallow depth, the tine displaced a chip of soil, slightly wider than the tine face width, immediately in front of it; while for deep operations, a fissure was developed in the soil some distance in front of the tine face and across the path of the tine. The fissure curved backwards on both sides of the tine forming a triangular wedge. In addition, since this is the first 40 mm depth of top soil, that is in contact with the free space, thus easy to be translocated. It should be noted that the cutting energy required to initially cut this top soil was provided by soil-tool energy component. The frictional energy requirement to separate this chip of soil at 40 mm depth was entirely provided by soil-soil energy component. The energy to accelerate this soil body was provided by soil acceleration energy. The only unaccounted part was the weight of this small soil body. Since the amount of the soil was very low, this assumption worked reasonably well for this energy model. The assumption of neglecting the weight of soil wedge in case of narrow tools is common in the literature (Grisso *et al.*, 1980).

The second assumption was that acceleration energy at speeds up to 1 km h^{-1} was equal to zero. First of all, visual aspects of experiments supported the validity of this assumption. It was

noticed that the mode of tool movement was periodic. This means that soil at low speeds of tool was compressed ahead of the tool for a while then it was released. This process was very slow and possible to observe at 1 km h⁻¹ speed and did not throw much soil around. This assumption has been supported by previous research as well. Experiments conducted by on draft requirement of mouldboard plow, chisel plow, subsoiler, standard chisel, and standard lister showed that the effect of speed for all the implements was small, below 7.2 km h⁻¹. In addition, based on research reported by Schuring and Emori (1964), which was validated later by Godwin and Dogherty (2003), inertia forces for narrow tools below a speed of $\sqrt{5gw}$ in which g and w represent gravitational acceleration and width of tool respectively were insignificant

2.6.2 Components of Soil-Tool Interaction Energy for Tillage Tools

This energy component supposed to capture all interactions that occur between tool surface and the soil. Soil-tool adhesion and soil-tool friction, the two main components of soil strength against tool movement, are included in soil-tool interaction energy. Soil moisture affects soil-tool energy component as it would affect adhesion and soil-tool friction angle. In addition, surface area of the tool engaged with the soil, or in other words, depth of operation for a constant tool width, will affect this energy component. Tool speed would not change this energy component because the effect of speed on cutting energy would be part of soil acceleration energy. According to the modified Coulomb's law (Equation 2.2), adhesion and soil-tool friction would contribute to this component of energy.

$$S_{cutting} = C_a A_{tool} + N \tan \delta \quad (2.2)$$

Where;

S_{cutting} = soil-cutting force, N

C_a = soil – tool adhesion, Pa

A_{tool} = tool surface area engaged with soil, m²

N = normal force applied on the tool surface, N

δ = soil – tool friction angle.

2.6.3 Components of Soil-Soil Interaction Energy for Tillage Tools

Soil-soil energy component accounts for interactions that take place in the interface of soil particles. Therefore, it includes cohesion and soil internal friction. Since moisture content affects these two parameters, soil-soil energy component is correspondingly affected by soil moisture content. Soil-soil interaction energy is assumed as not affected by change in depth of operation because of three reasons.

First, undisturbed soil body adjacent to the wedge of soil in front of the tool is not necessarily in contact with the tool. Therefore, it is not necessarily affected by the tool depth. For such a vertical narrow tool as employed in this research, a wedge of soil is the only soil in contact with the tool surface (Gill and Vanden Berg 1968; McKyes 1985). To clarify this point, it is noticeable that when a vertical tool having a plane surface moves within a moist soil, soil particles are compressed to each other by the tool, and they do not slide on each other. From time to time, a block of compacted soil slides up on the tool surface at its interface with the tool, and after passing edges of tool surface, it left both sides of the tool or returned into the tool furrow.

Therefore, no sensible movement between soil particles is manifested in such tool and soil conditions, and consequently no extra soil-soil energy is consumed as a result of an increased depth. Considering the concept of critical depth of soil for vertical narrow tools (McKyes 1985), soil in front of the tool can be divided into two sections as above and below critical depth. Above the critical depth, soil at appreciable soil moisture content is compressed up to a certain point then sled on the tool surface upward and released. Therefore, this part of soil displacement is directly related to the soil-tool interaction energy (Godwin and Spoor 1977). Below the critical depth, the soil moves in horizontal and sideways directions and builds up a wall of compressed soil both sides of the moving tool. Therefore, it changes the force only on tool surface which is taken into account as part of soil-tool interaction energy (Godwin and Spoor 1977), but has nothing related to the soil-soil interaction energy.

The second reason explaining that why soil-soil interaction energy is not affected by tool depth returns to the reality that two main forces are concerned with regard to the adjacent soil body to the wedge of soil in front of the tool. These two are frictional and gravitational forces. Frictional forces are accounted as cohesion and internal friction, and this is why soil-soil energy value changes at different moisture contents. On the other hand, Gravitational forces are taken into account as part of deformation energy, and this is why deformation energy component is affected by depth of operation, but soil-soil component is not.

The third reason comes from the effectiveness of the soil gravitational forces on total force. It should be noted that even if the surface area of the soil wedge is entered as part of the value of soil-soil energy, its value when is multiplied by cohesion value (based on Coulomb's equation)

will contribute minor effect of total value of this energy component. In addition, since friction force between soil wedge and undisturbed adjacent soil body builds the main part of soil-soil energy, it is considerable that the friction force between these two soil bodies is neither affected by apparent contact area of the bodies nor by the normal force (Gill and Vanden Berg 1968). Since depth of operation represent contact area thus, soil-soil energy component is not affected by depth of operation. Similar to soil-tool interaction energy, this energy component is also assumed not to change by tool forward speed.

Soil shear force (based upon Coulomb's equation) includes two terms of soil cohesion and soil-soil friction force. To measure soil-soil friction force, applied force on soil rupture plane and angle of internal friction should be measured. A series of direct shear tests would provide cohesion values to be used in the equation. Measurement of normal force applied on the soil rupture plane needed knowing the shape and the features of the rupture plane, which was practically impossible (Hettiaratchi 1993). Therefore, an indirect method should be employed to calculate soil-soil interaction force and consequently soil-soil energy component.

Considering the basic assumptions, for each level of moisture content, where operating depth and forward speed were very low (1 km h^{-1} speed and 40 mm depth), the only energies contributing in total energy of the tool were soil-tool and soil-soil interaction energies. Soil-tool interaction energy shall be measured based on Equation 2.2 as discussed above. To measure soil-soil interaction energy, the difference between total energy of the tool in each experiment, obtained from soil bin instrumentation, and the amount of soil-tool interaction energy is the amount of soil-soil interaction energy. Same values of soil-soil interaction energy were exactly accounted to

the different levels of operating depth and forward speed, but not for different moisture contents. Soil-soil interaction energy is supposed to change only at different levels of moisture content, but maintained a constant value when the depth or speed is changed.

2.6.4 Components of Soil Deformation Energy for Tillage Tools

When a tool moves within the soil, cut soil will be translocated by the moving tool. Deformation energy component is standing to show the energy consumed for this soil translocation. Based upon the soil conditions and tool features, translocated soil may be taken to the soil surface then released, piled up on undisturbed soil, turned down and manipulated, or thrown away from the tool moving line. Deformation energy will present the energy which has been consumed to translocate the soil from its origin of the rest. The weight of the translocated soil is one important factor affecting soil deformation energy. Also, this is one major difference between soil deformation and soil-soil interaction energies. It is assumed that moisture content variations would change the value of this component. The reason is that any change in moisture would change cohesion and angle of internal friction which both affect the interlocking forces between particles. Consequently, it would affect the amount of soil that undergoes deformation and thereby energy consumption. The value of deformation component is also affected by depth of operation since at deeper depths of operation tool engages more amount of soil ahead to be translocated and thus, demands more energy. In contrast, tool forward speed would not influence this energy component. Deformation energy component keeps a constant value at different forward speeds. The reason is the energy required to throw extra soil at higher speeds compared to lower speeds is assumed as part of soil acceleration energy (Godwin and Spoor, 1977.).

To measure soil deformation energy, after measuring soil-tool and soil-soil interaction energies at lowest depth and speed levels, deformation energy is measured as follows; when the depth of operation is increased, more energy would be required. Since at low speeds there is no acceleration energy involved yet, the difference between the total tool energy and the summation of soil-tool and soil-soil interaction energies gave the soil deformation energy value. When the depth of operation is increased again, soil deformation energy is accordingly increased. This energy component will achieve new values at different moisture contents and different depths, but not at different forward speeds. Therefore, same values of deformation energy were used at different levels of forward speed (Godwin and Spur, 1977.).

2.6.5 Components of Soil Acceleration Energy for Tillage Tools

The soil acceleration energy component is the only component responsible for any resistive energy consuming event manifested due to the increase in tool forward speed.

Soil moisture content affects acceleration energy by changing soil compressibility level and the compressing energy required to press soil particles to each other before they can be released. The change in rate of soil shearing due to increased speed is also affected by soil moisture content. The effect of speed on soil cohesion, adhesion, and friction angles is also affected by soil moisture content. Acceleration energy is also affected by tool operating depth, which determines whether the soil should come up to the ground surface, or be compressed in the direction of movement (based on the critical depth level). In this way, Depth of operation affects the energy requirement to accelerate the soil. Evidently, this component of energy is dominantly influenced by tool forward speed. The basic assumption of having zero acceleration energy at low speeds up to 1 km h⁻¹ provided an opportunity to calculate soil deformation energy at different operating

depths. When tool forward speed is increased up to its second level, new acceleration effects became significant. However, at this level of speed, same deformation energy value was applied as for the first level of speed. Therefore, the value of soil acceleration energy is calculated as the difference between the total energy of the tool and the summation of soil-tool interaction, soil-soil interaction, and soil deformation energies. Acceleration energy component is changed with changing moisture content, depth of operation, and tool forward speed (Godwin and Spoor, 1977.).

As a summary of entire energy model, the following equation shows the relationship between the total energy requirement of the tool and the four main components of tillage energy. In addition, the equation summarizes the affecting parameters of each energy component.

$$\text{Total energy} = \text{Soil - Tool Interaction energy } f(\text{moisture content, depth}) + \text{soil - Soil interaction energy } f(\text{moisture content}) + \text{Soil Deformation energy } f(\text{moisture content, depth}) + \text{Soil acceleration energy } f(\text{moisture content, depth and speed}) \quad 2.2$$

2.7 Tillage Energy

The world has been facing a crisis in the field of energy in the last decades. The crisis is as serious as many analysts believe that the origin of many conflicts in the world reflects the crisis in the field of energy and resources of energy. In agriculture, although new machinery systems have facilitated production, they have increased the demand for energy. Tillage as one preliminary and basic step for any agricultural production demands huge amount of energy.

In a tillage operation, energy can be expressed in terms of energy per unit area or per volume of disturbed soil (Panwar and Siemens, 1972). Since energy requirement per unit volume has the

same unit as draught per unit area, it can be shown as the draft requirement to cut a furrow slice in an exact cross section as expressed by McKyes (1985) and Chancellor (1994). Energy can also be expressed as the rate of energy per depth of operation (Darmora and Pandey, 1995). The most important factors in determination of energy requirement of a tillage tool are draught and the amount of disturbed soil. In other words, if those two values are available, energy can easily be calculated as the product of draught and the length of disturbed soil. For a tillage operation, the report of energy requirement should as well include the depth of operation. It was also illustrated that energy consumed in a tillage operation was a function of both initial and final conditions of soil. This obviously includes soil physical properties such as soil moisture content, soil bulk density as well as soil texture. Gill and Vanden Berg (1968) reported two additional factors including tool shape and manner of tool movement as affecting factors on energy requirement of a tillage tool. The report refers to the factors affecting tool such as tool speed, tool operating depth, tool shape, and tool rake angle. Perdok and Werken (1982) studied energy requirement of different tillage implements at different soil textures.

2.8 Analytical Model Equation Development

Analytical approach is one of the first methods that have been used to predict the interaction between soil and a tillage tool. This approach has been employed by many researchers in the field of soil tillage for about five decades. The results of this approach are still valid to some extent and its governing rules are sometimes used in other approaches such as empirical and numerical approaches. Reece formed a basis in analytical approach and has been used by several investigators (Reece, 1965; Hettiaratchi and Reece 1967; Hettiaratchi and Reece. 1974). Two-dimensional cases are approximately valid for soil cutting tools with wide blades relative to their

depths of operations (width/depth greater than unity). When a cutting tool is not very wide, a large proportion of the cut soil moves sideways (Payne, 1956). Since more soil must be moved per unit width of the tool in the 3-D cases compared to the wide blades (2-D), a larger draught is expected for 3-D cases than that of wide blades. Payne (1956), O’callaghan and Farrelly (1964), Hittiaratchi and Reece (1967), Godwin and Spoor (1977), McKyes and Ali (1977), and Perumpral *et al.* (1983) are the researchers who have employed a static 3-D soil failure model to investigate soil-tool interaction. In all these models, the effect of travel speed on draught requirement has been ignored.

$$P = (\gamma g d^2 N_\gamma + C d N_c + C_a d N_a + q d N_q) w \quad (2.3)$$

Where:

P = total tool force, N

γ = total soil density, N m⁻³

g = acceleration due to gravity, 9.81 m s⁻²

d = total working depth below the soil surface, m

c = soil cohesion, N m⁻²

C_a = soil-tool adhesion, N m⁻²

q = surcharge pressure vertically acting on the soil surface, N m⁻²

w = tool width, m

N_γ, N_c, N_q = factors depend on soil frictional strength, soil geometry, and tool to soil Strength properties

2.8.1 Payne Model

By observing the upward displacement of soil in front of the tillage tool, Payne (1956) assumed a failure zone for tines with a width/depth ratio less than 1:1. Payne and Tanner (1959) discovered that apart from the complexity of the equations, tool geometry like rake angle, depth, and width can change the shape of the failure zone.

2.8.2 O'Callaghan-Farrelly model

Based on Payne model and experimental data, O'Callaghan-Farrelly (1964) developed a model. Several assumptions were made in this model; (1) A critical depth equal to $0.6 \times$ tine width was assumed; (2) Failure surface above the critical depth was described by a 2-D approach; (3) Two side crescents were neglected; (4) All tines were flat; (5) Rake angle was equal to 90° ; (6) Mass of the soil wedge was neglected; and (7) Adhesion and external friction between soil and tool surface were not counted.

Two equations to calculate draught requirements for shallow and deep tines were developed by the researchers that are not mentioned here. According to Shen and Kushwaha (1998), predictions from those equations are very close to the experimental data except for an underestimation when a very hard soil is encountered. Shen and Kushwaha (1998) discovered that part of shortcomings of this model returns to its assumptions particularly assumptions number 4, 5, and 7 above.

2.8.3 Hettiaratchi-Reece model

Hettiaratchi and Reece (1967) developed another model that was similar to the O'Callaghan-Farrelly model in some aspects. This model also assumed a critical depth for the operating tool and two traversal failure zones only below the critical depth. In the model, 2-D equations are

used to calculate the forward failure forces ahead of a soil-tool interface and 3-D equations for the transverse failure away from the center line of the interface. The equations were used in the same way as for the O'Callaghan-Farrelly model except that the mass of soil was counted in this model. According to Grisso and Perumpral (1985), this model overestimated forces for vertical tools ($\alpha = 90^\circ$), yet the model underestimated inclined tools.

2.8.4 Godwin-Spoor model

Godwin and Spoor (1977) suggested a circular shape for the soil failure

Cr scents on the surface and for the sides of a narrow tillage tool to predict the volume of displaced soil by the tool. In this model, r was defined as the total forward distance of soil failure on the surface from the tool face, and soil in front of the tool was analyzed by a 2-D failure region using the N-factors of Hettiaratchi and Reece (1974). According to Payne and Tanner (1956), the difficulty with such a model was that r changed when the aspect ratio of the blade (d/w) varied and soil strength changed. To solve the problem, Payne and Tanner performed some tests with narrow tillage tools in sandy soils in order to estimate r and s for various rake angles α , slenderness ratios d / w , and soil types. Results showed r changed as the rake angle changed, and a graph was developed to describe the relationship between r / d and the tool angle. According to Shen and Kushwaha (1998), the determination of the rupture distance r was still difficult.

2.8.5 Mckyes-Ali model

Mckyes and Ali (1977) developed an independent analytical model for narrow tools without the need to rely on experimental inputs of soil failure geometry. The model was similar to the

Godwin and Spoor model in the shape of the failure zone except that a flat bottom plane for the center wedge was assumed. The straight lines at the bottom of the crescents enabled to define the direction of forces at the bottom of the failure zone. This model is easier than the Godwin-Spoor model since it does not need prior knowledge of the rupture distance and N-factors are re-evaluated in this model. Moreover, the model uses a technique that increases the magnitude of N factors as the tool becomes narrower. In addition, by setting $w = \infty$, the researchers compared the N-factors with the N-factors used for 2-D models. It was found that for smooth blades, the results were very close, yet for the rough blades with $\alpha > 90^\circ - \phi$, rupture angle and the N-factors were much higher than those for the 2-D soil cutting cases. McKyes (1985) published a set of charts to determine the N-factors for some rake and rupture angles.

2.8.6 Grisso *et al.* model

With a similar shape of the failure zone to that of the Godwin and Spoor and the McKyes and Ali models, Grisso *et al.* (1980), Perumpral *et al.* (1983), developed a model in which side crescents were replaced by two forces acting on the center wedge. Soil weight of the two side crescents was neglected, and side planes of the center wedge were treated as slip planes; therefore, the failure zone of this model included only a center wedge. As in the McKyes and Ali model, the bottom slip surface was assumed to be straight. As well, the soil in front of the tool was assumed to move upward. This model produced equal values of $c N$ and $ca N$ as resulted from the previous two models, but γN value of the Grisso *et al.* model was less than one half of the same quantity resulting from the McKyes and Ali model.

2.9 Dynamic models

Based on the Mckyes-Ali model, two dynamic soil failure models have been developed in which the effect of tool speed have been accounted. The first model was introduced by Swick-Perumpral (1988) and the second model by Zeng-Yao (1992). The first model had some assumptions which overestimated the size of the side crescents (researchers). Therefore, a new angle of η based on the experimental data was proposed, which was a function of the rupture distance r and the rake angle α . In the Zeng-Yao dynamic model, the acceleration and strain-rate effects were included. Main difference between this model and the Mckyes-Ali model is that this model needs a prior knowledge of shear strain at failure to determine the position of shear failure boundary.

2.9.1 Finite Element Method (FEM) Models

Finite element method, which was used for the first time in aviation engineering in the middle of the 20th century, developed by extension in the other branches of science such as Physics, electro-magnetic, Mechanics, and civil engineering. Now, it has become a very powerful tool to solve the problems in those sciences. Any numerical method of soil failure modeling including FEM has to use a constitutive model to describe the relationship between applied stresses and resultant strains within the soil. Different constitutive models have been developed based on the way that researchers have looked at soil. Linear and nonlinear models have been categorized based on using a linear or nonlinear equation to relate stress and strain within the soil where by using theory of plasticity, soil can be viewed as only elastic, or purely plastic, or both elastic and plastic materials during the loading process. And finally, soil is viewed statically, if time is ignored in calculations, and dynamically if time is considered in modeling. Since many different

models for different views of soil have been developed, here only the most common models used in soil tillage studies will be briefly introduced. The hyperbolic model, which determines the hyperbolic relationship between stress and axial strain, was originally proposed by Kondner and Zelasko (1963) and later Duncan and Chang (1970) modified the model to use in a FEM analysis. Bailey's model was first proposed by Bailey *et al.* (1984) to predict volumetric strain v ϵ under hydrostatic compression. Later, the model was modified to include the effect of shear stress. The Cam clay model was originated at the University of Cambridge, England (Roscoe *et al.* 1958), and it is one of the simplest elastoplastic models which is very popular among the soil researchers. A modified version of the Cam clay model by Wroth and Houlsby (1980) shows the relationship between stress and strain at the normal consolidation line and the swelling line in terms of specific volume and mean normal pressure. The Cap model for the first time was proposed by Drucker *et al.* (1955) and then it was developed by Dimaggio and Sandler (1971) based on the work accomplished by a research group at MIT (Tang and Hoeg, 1968). Below, part of research in the area of tillage operations by implementing FEM method has been discussed.

2.9.2 Kushwaha and Shen model

Kushwaha and Shen (1995) employed FEM to solve the dynamic equation of interaction between the soil and a tool, which was previously used for the similar cases. By using a two-dimensional FEM, it became possible to predict the draft requirement of a vertical blade on soil. Comparison between the results of soil bin tests and the modeling showed that the predicted draft was very close to the experimental data. It was indicated that the method could work for predicting the forces acting between the soil and any other kinds of tillage tools by some modification.

2.9.3 Rosa and Wulfsohn model

Finite element method was implemented by Rosa and Wulfsohn (1999) to study a constitutive model for high speed tillage by using narrow tillage tools. Two different tools, including a flat and a triangular edged narrow tool, were used for soil bin experiments to test the effect of forward speeds between 0.5 to 10.0 m s⁻¹ over a distance of 1 to 3 m. The model's assumptions were: (1) Tool is narrow, rigid, and working in constant depth and velocity; (2) Failure is a 3-D case; (3) Tool deflection is negligible compared to the soil deflection; (4) Soil-tool interface is either totally smooth or totally rough in order to simulate the extreme cases; (5) Soil is assumed an isotropic and homogeneous medium; and (6) Soil particles are ideally assumed lumped masses and gravity effects are negligible compared to the inertial and strain rate effects or the contributed soil stiffness to draft. The results showed an overestimation of 1% at 2.8 m s⁻¹ and 25% at 8.4 ms⁻¹ for the triangular edged tool, yet the model predicted a correct trend of the draft requirement for the flat (reference) tool. The researchers reported that the soil model was not completely satisfactory in modeling soil cutting problems, particularly, at failure point. As well, they believed that remoulding the soil, which is common in laboratory tests, could lead to part of the problem during soil modeling in a FEM approach, and further development is needed to have more realistic soil conditions.

2.9.4 Chi and Kushwaha model

Chi and Kushwaha (1991) used a non-linear three-dimensional FEM to investigate soil-tool interaction. One of the main goals of this research was the evaluation of the effect of draft requirements of tillage tools on wear and friction losses. Actual tests in the soil bin were

conducted to compare with the results of the model. Draft was measured for different rake angles of the tool. Results of both theoretical and experimental methods obviously showed that the draft requirement decreased as the rake angle decreased, but stayed constant for the rake angles less than 45° . Results were very close, showing only about 0.8% error for a rake angle of 45° and 10.5% error for a rake angle of 90° when comparing the model with the actual test results of the soil bin. Stress on the edge of the tool was very large, and the maximum stress increased as depth was increased; therefore, the outer edges of the tool at the bottom suffered the greatest stress and wear. As well, this stress increased as the rake angle was increased. Since vertical position of the tool required the highest draft, it showed the highest level of the stress.

2.9.5 Mouazen and Nemenyi model

To date, only a few studies have focussed on real tillage implements using FEM to investigate the forces interacting between soil and tillage tools. Mouazen and Nemenyi (1999) developed FEM to analyze the reaction of a subsoiler in a nonhomogeneous sandy loam soil. In this research, the effect of tool geometry on subsoiler performance, by implementing a subsoiler shank attached to a chisel with different angles and effective cutting widths, was investigated by implementing a 3-dimensional FEM model. Simulation of soil-tool interaction was developed by adopting the Coulomb's law of friction. The FEM model overestimated the measured draft force in a range between 11 to 16.8% for a non-homogeneous and between 15 to 18.4% for a homogeneous soil for all four different chisel angles when the results were compared to the soil bin test results.

2.9.6 Fielke model

Fielke (1999) investigated the effect of cutting edge geometry of a 400 mm wide experimental sweep on horizontal and vertical components of forces. The study included soil failure patterns, and soil movement below the tillage depth using a 2-dimensional FEM. The results of the study showed that replacing a sharp cutting edge tool with a blunt one can increase draught requirement up to 80%. Also, the direction of the vertical force can change from one that acts to pull the tool into the soil to a force that provides tool lift. In this study, soil was represented by a linear elasto-plastic model, and the Mohr- Coulomb theory was employed as the soil failure criterion. Results of the modeling showed the power of FEM to model soil-tool interaction.

2.9.7 Plouffe et al. model

Plouffe *et al.* (1999) employed a 3-dimensional FEM to simulate forces applied on a moldboard plow during an operation. Three plowing depths of 100, 150, and 200 mm and three forward speeds of 0.25, 1, and 2 m s⁻¹ were implemented. A cylindrical plow bottom was fixed on a triaxial dynamometer and its movement in both vertical and lateral directions was controlled by two hydraulic cylinders. The type of soil used in the soil bin was a Sainte-Rosalie clay soil (53% clay, 27% silt, 20% sand, and 2.97% organic matter), which is a typical soil for moldboard plowing in Quebec, Canada. Results showed no significant difference between experimental data and the simulated data for the longitudinal forces (F_x), but for the vertical forces (F_z), simulated forces were significantly lower than measured forces for the forward speeds of 0.25 and 2 ms⁻¹. Both results showed an increase in F_y as depth and speed increased.

CHAPTER THREE

MATERIALS AND METHODS

Soil bin experiments were carried out using five speed levels of tillage tool, five levels of tool cutting widths, five levels of angle of lift and five levels of operating depths. The speed levels were 0.25, 0.50, 0.75, 1.00 and 1.25 m/s⁻¹. Tool cutting widths were 10, 20, 30, 40 and 50 mm. Tool lift angles were; 20°, 30°, 40°, 50° and 60° operating depths were 20, 40, 60, 80 and 100 mm. Other variables such as soil moisture contents, soil type and soil preparation method are the same for all experiments.

Therefore, a 4⁵ factorial experiment in a completely randomized block design (RCBD) was used and the data collected were analyzed statistically.

The existing soil bin facility at the Departmental soil tillage laboratory, constructed by Mamman (2002), was modified and used for this study. The following components were redesigned or constructed;

- i Soil processing and tools carriage
- ii Instrumentation system for data logging of draught in three dimensions
- iii Drive unit
- iv Control and safety features.

3.1 Soil Bin Dimensions

The dimensions of the existing soil bin are 5.60m long, 0.44m wide and 0.58m deep. The dimensions of modified soil bin are 8.00m long, 1.00m wide and 0.56m deep. A 3.73kW, single phase electric motor serves as the prime mover for the soil processing and tool carriages. The isometric view of the modified soil bin is shown in figure 3.1.

The soil processing equipment includes a rotary tiller, a soil leveler and a roller compactor. A tool bar frame and a tool bar constitute the tool carriage.

The soil in the test bin was collected at the back of Agricultural and Biosystems Engineering Department, University of Ilorin, Ilorin Nigeria. The soil is Sandy-loam which is fair representation of soil type that is predominant in the study area (Kwara state).

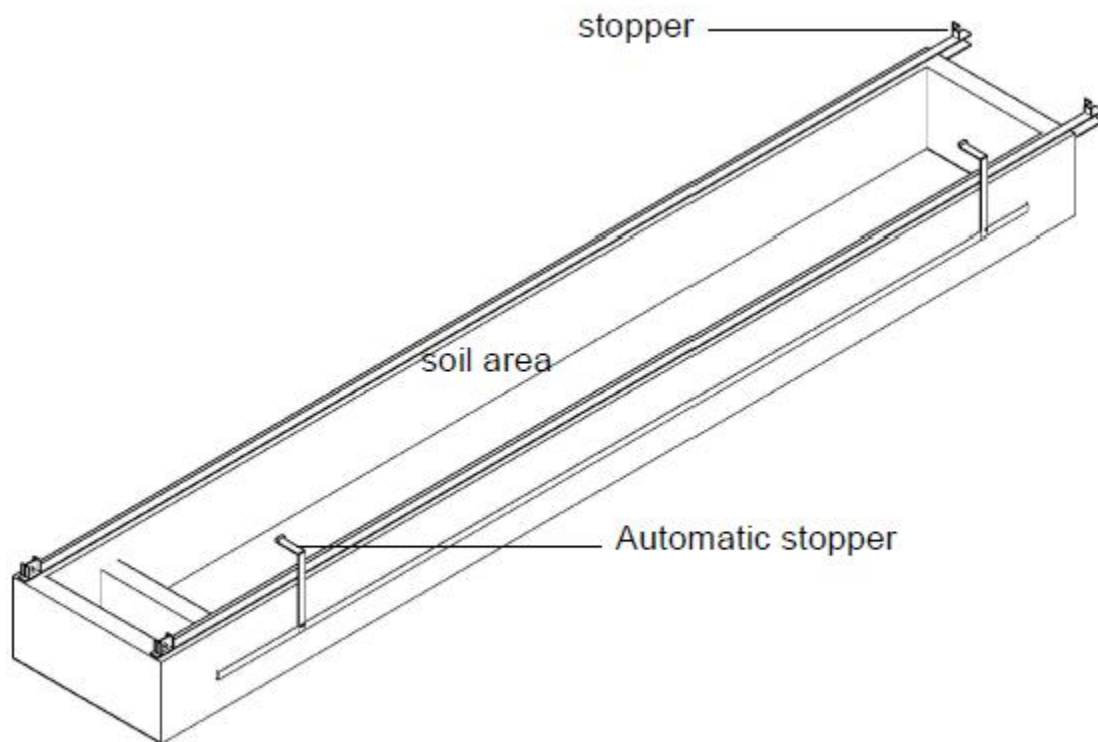


Figure 3.1 Isometric View of the Modified Soil Bin Constructed for the Study

3.2 Drive unit

A 3.73 kW electric motor was mounted to power the Soil processing and tool carriages and the rotary tiller. The speed of the electric motor can be varied using speed controller (Frequency

regulator). The carriage has both forward and reverse motions. The speed of the rotary tiller can be varied from the motor using speed controller and auto-reverse system.

3.3 Instrumentation system

The instrumentation system has three stages;

- a). sensor (transducer)
- b). signal processing, and
- c) Recording of output.

For this study, load cells were used as strain-sensitive transducer element calibrated in terms of force. The following advantages informed the choice of load cells

- a) High accuracy;
- b) Fast speed of response,
- c) Good linearity and stability, and
- d) Smallest possible size

Three load cells were mounted on the tool bar that carries the model tools. The load cells are mounted such that: one measure the force in horizontal direction (Draft force), another one measure force in vertical direction and the third measure force in lateral direction as shown in figure 3.2 below.

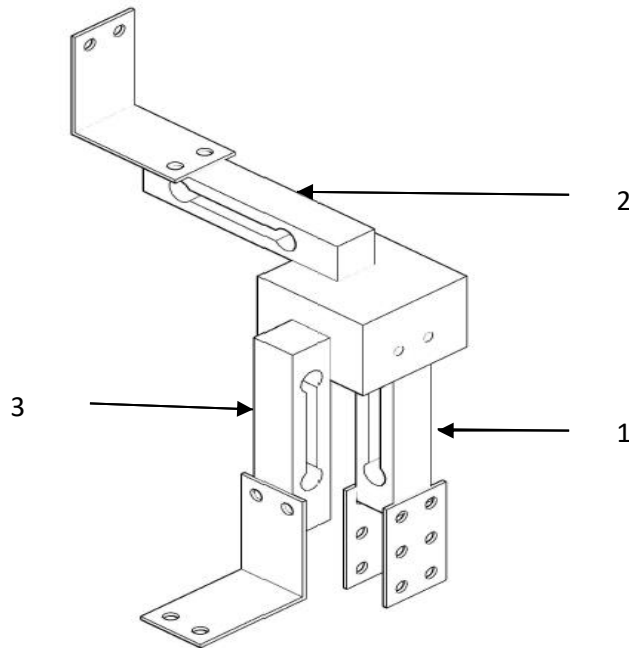


Figure 3.2 Arrangement of the three load cells;
 Load cell 1 measures Draught in horizontal direction while load cells 2
 and 3 measure Draught in vertical and lateral directions respectively.

3.4 Control and Safety Features

Speed controller (frequency regulator) was used to control the speed of the carriage on the rails and the rotational speed of the rotary tiller, respectively. Switching off the electric motor makes it to stop automatically. At both ends of the soil bin, iron bars was welded on the rails as stoppers (Bumps) to protect the carriage from derailing when there is any form of failure. The carriage can also be stopped by switching off the frequency regulator or the auto-reverse circuit. The auto-reverse circuit was designed and constructed to reverse the motion of electric motor, hence facilitate the to and fro movements of soil processing and tool carriages.

3.5 Collection and Analysis of Soil Samples

Soil sample were collected from 36 locations in Kwara state of Nigeria and analysed to establish the predominant soil type in the region. This is important so as to be able to select representative soil for the experiment. The particle size analysis was carried out on the samples collected using hydrometer method. The summary of the method is as follows;

The sample is treated with sodium hexametaphosphate ($\text{Na}_6(\text{PO}_3)_6$) to complex Ca^{++} , Al^{3+} , Fe^{3+} , and other cations that bind clay and silt particles into aggregates. Organic matter is suspended in this solution. The density of the soil suspension is determined with a hydrometer calibrated to read in grams of solids per liter after the sand settles out and again after the silt settles. Corrections were made for the density and temperature of the dispersing solution.

The soil used for the experiment proper was collected, sieved, thoroughly mixed and loaded into the soil bin. Preliminary tests were carried out on the soil which include; cone penetration resistance, soil moisture monitoring and Variation of bulk density with depth.

3.5.1 Collection and Analysis of Representative Soil for the Experiment

The representative soil used for the experiment is sandy-loam. The soil was collected at the back of the Department of Agricultural and Biosystems Engineering, University of Ilorin, Ilorin-Nigeria. The mechanical and physical properties of the soil were determined. The soil was screened and analyzed to determine its properties as explained in section 3.50 above. Engineering properties of the soil such as bulk density, angle of internal friction, soil-metal friction angle and cohesion were also determined.

3.5.2 Soil Preparation for Data Collection in the Soil Bin

Preparation of the soil for the experiments included four steps. In the first step, water is sprayed by attaching the sprinkler bar to the frame of tool carriage and running the frame on the soil along the bin. If more water is required, the number of passes of tool carriage and hence the sprinkler is increased.

In the second step, the roto-tiller was attached to the frame and by cultivating the top soil up to approximately 100 mm depth any soil hard pan will be broken as well as mixing dry and wet soil layers. If the initial soil is very dry and need much water, the water is added in several passes, and after each spraying, one roto-tilling will be carried out.

In the third step, the soil is leveled. Soil leveling is accomplished by a scraper blade almost as wide as the frame width.

In the fourth step, roller compactor is attached to the frame. The number of passes of roller compactor is based on the initial and final moisture contents of the soil and the level of required soil compaction. The criteria for obtaining the same compaction level were soil dry bulk density and soil cone penetration resistance.

3.5.3 Monitoring of Soil Conditions

The values of soil bulk density were determined at range of depth. 0-100 mm depth, two soil bulk density samples were taken immediately after each test from the undisturbed soil adjacent to the tool track with a core sampler. For each test, 6 moisture samples from different parts of the soil were taken, weighed, then dried for 24 hr at 105°C , then weighed again to determine soil moisture content and hence the soil bulk density.

To ensure uniform level of soil compaction, for each soil bin experiment, after compaction and before running the tool, soil cone index was measured by a digital cone penetrometer. Since the level of compaction by roller compactor is the same for all treatments, almost the same cone index values were achieved for different treatments. For each experiment, soil cone index were measured at 6 points of the bin.

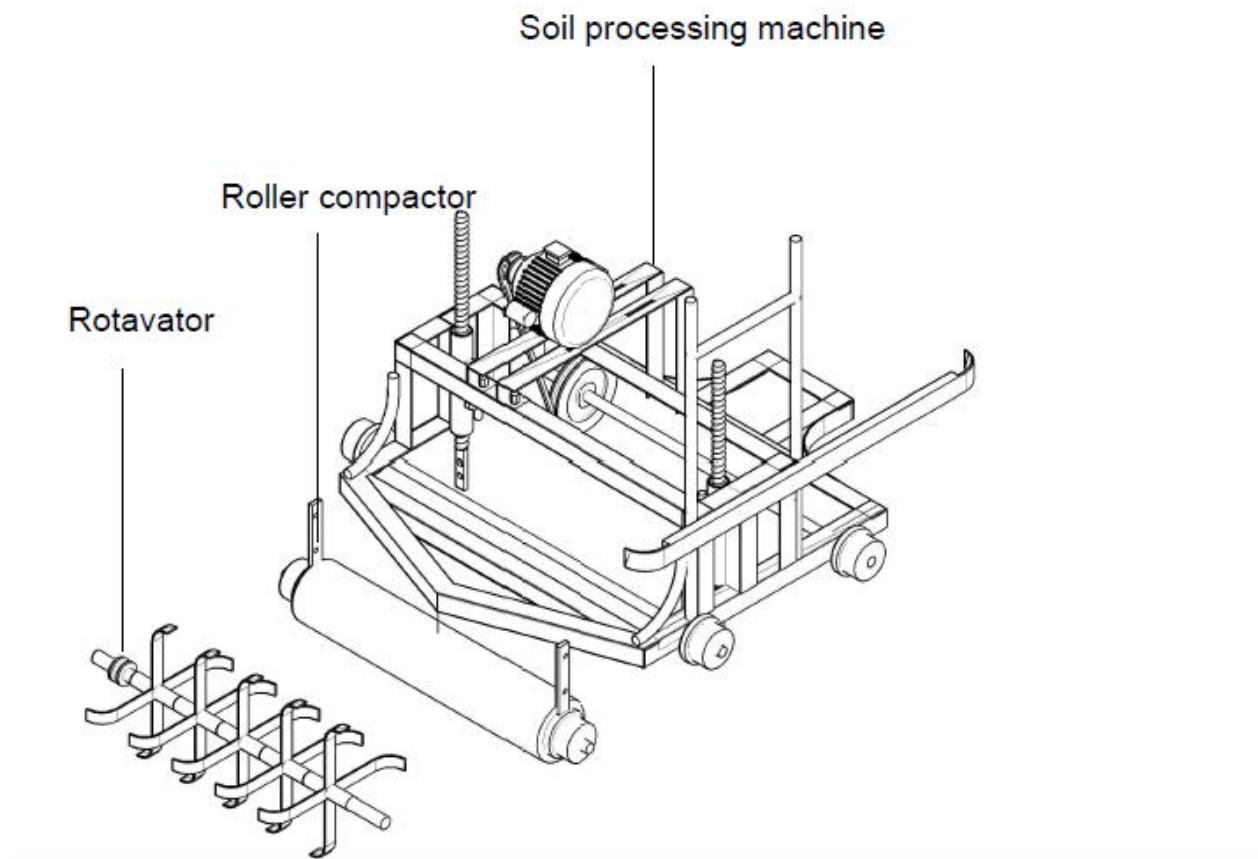
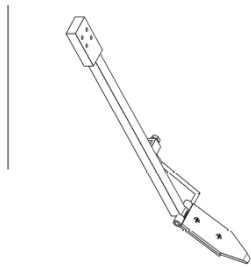


Figure 3.3 Soil Processing Carriage showing Roller Compactor and Rotary Tiller (Rotavator).



Narrow Model chisel blade

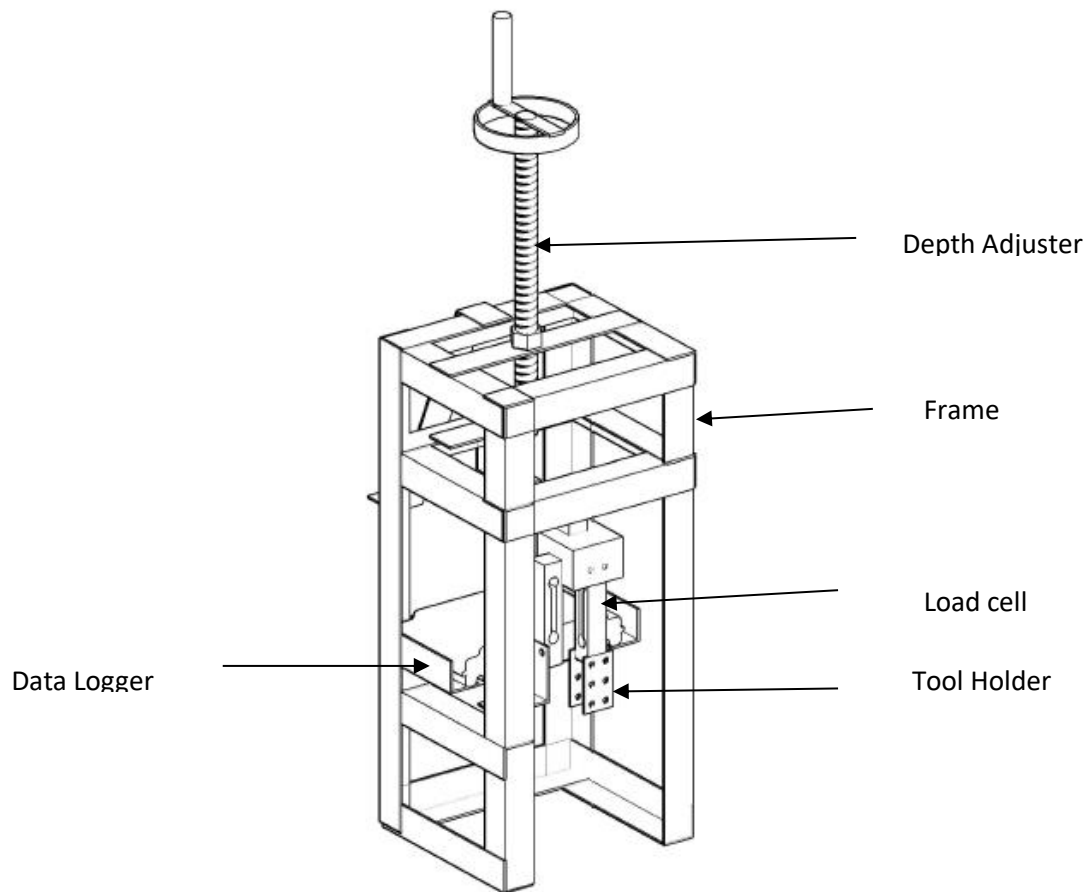


Figure 3.4 Assembly of Load cells and Data Logger

3.5.4 Direct Shear Test

Soil physical properties including cohesion, adhesion and internal friction angles were measured through the laboratory tests in order to be used later in the energy model. Direct shear test was employed to measure these values of soil shear strength under same moisture and density conditions as applied in the soil bin experiments.

3.5.5 Determination of Shear Strength of the Soil used.

There are three general ways to induce deformations in solids or semi-solids: tension, compression, and shear.

Soil is not capable of resisting tension; it is capable of resisting compression to some extent. In cases of excessive compression, failure usually occurs in the form of shearing along some internal surface within the soil. Failure plane is the plane on which the maximum shear stress acts, thus at failure shear stress along the failure surface reaches the shear strength.

Structural strength of soil is primarily a function of its shear strength, where shear strength refers to the soils ability to resist sliding along internal, 3-dimensional surfaces within a mass of soil.

Soil strength comes from internal friction and cohesion. It follows the formula

$$s = c + \sigma \tan (\Phi) \quad (3.1)$$

where s = shear strength, c = cohesion, σ = effective inter granular normal (to the shear plane) pressure, and Φ = angle of internal friction. The quantities s , c , and σ have units of pressure.

The shear strength of a heavy clay soil does not increase with increased load because $\Phi = 0$. The shear strength of a very sandy soil does increase with increasing load because Φ does not equal

0, but $c = 0$ for sand. Most soils are a mixture of sand and clay. Figure 3.5 illustrates the results of equation 3.1.

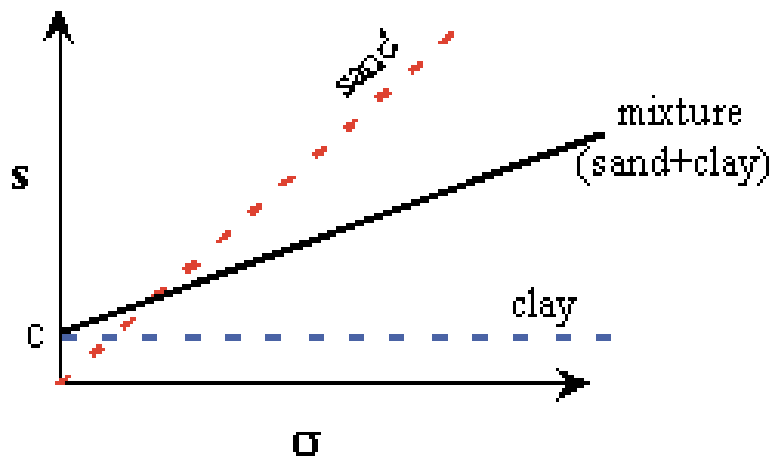


Figure 3.5 Shear strength of heavy clay, very sandy and a mixture of sand and clay soil. (Godwin and Spoor, 1977)

Three widely used laboratory tests are; Unconfined Compression Test, Direct Shear Test and Triaxial Compression Test.

Direct Shear Test - A shear stress is placed on the soil sample. The stress is increased until failure. Several of these tests will provide an experimental measurement for c and j for a given soil. (In the formula $s=c+\tan(j)$).

In a direct shear test, the failure of the soil sample in shear is caused along a predetermined plane. The normal load, strain and shearing force are measured directly during the test. It is also

used to estimate residual stress of soil. The apparatus utilizes a square box divided horizontally into two halves (figure 3.6). The box containing the sample is placed in a water jacket and subjected to constant normal load while a horizontal force is applied till the specimen fails along the plane of juncture of the two halves. A number of specimens are tested under different loads and from the data obtained the angle of internal friction and shearing strength of the soil can be evaluated.

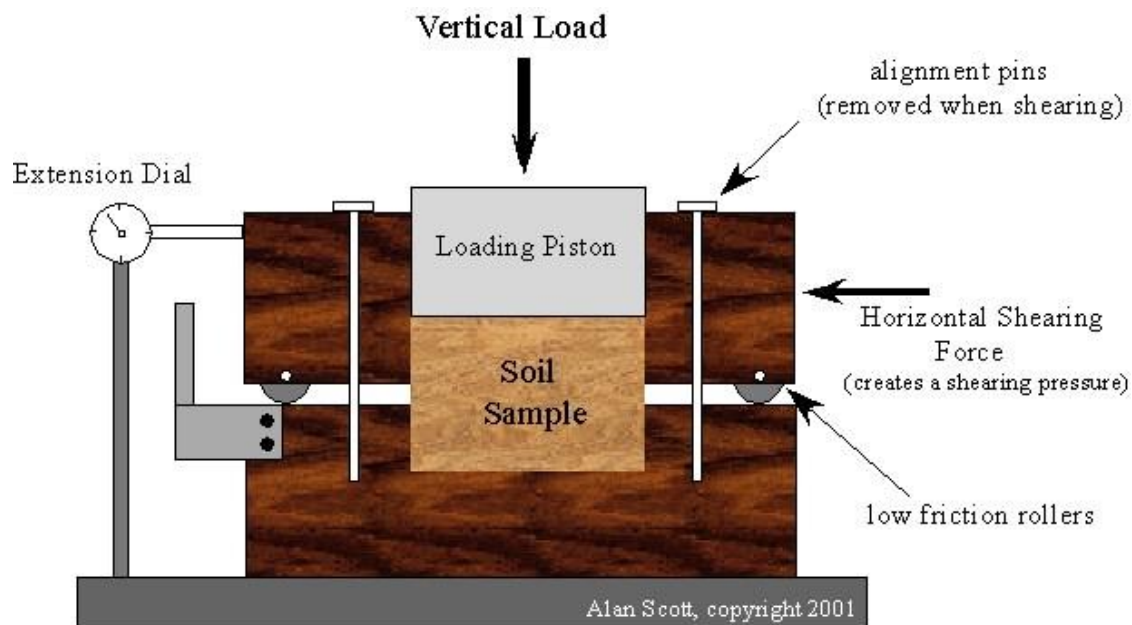


Figure 3.6 Direct Shear Box

The Direct Shear Test is used for determination of the consolidated drained (or undrained) shear strength of soils. The test is performed by deforming a specimen at a controlled rate on or near a single shear plane.

The direct shear test is a laboratory testing methods used to determine the shear strength parameters of soil. The test can be carried out at different moisture contents; however, it is common to saturate the sample before running the test.

To achieve reliable results, the test is often carried out on three or four samples of undisturbed soil. The soil sample is placed in a cubic shear box composed of an upper and lower box. The limit between the two parts of the box is approximately at the mid height of the sample. The sample is subjected to a controlled normal stress and the upper part of the sample is pulled laterally at a controlled strain rate or until the sample fails. The applied lateral load and the induced strain are recorded at given intervals. These measurements are then used to plot the stress-strain curve of the sample during the loading for the given normal stress.

Results of different tests for the same soil are presented in a chart with peak stress on vertical axis and normal (confining) stress on the horizontal axis. A linear curve fitting is often made on the test result points. The intercept of this line with the vertical axis gives the cohesion and its slope gives the peak friction angle.

3.6 Calculation of Draught Estimate on Narrow Tillage Tool

Data of draught are reported as the force required in horizontal direction of motion. Both functional draught (soil and crop resistance) and draught required to overcome rolling resistance of the implement are included with one exception: for manure injection, motion resistance of spreader transport wheels must be added to get total implement draught.

Draught required during tillage is a function of soil properties, working depth, tool geometry, travel speed, and width of the implement. It is an important parameter for measuring and evaluating implement performance for energy requirements. Several studies have been conducted to measure draft and energy requirements of tillage implements under various soil conditions (Grisso *et al.* 1996). Soil properties that contribute to tillage energy are moisture content, bulk density, cone index, soil texture, and soil strength.

Henderson *et al.* (1981) reported that several investigations have shown improvement in the physical properties of soil with the application of deep tillage. Improvements included increase

in soil pore space, increased water uptake, and a reduction in the bulk density but there was little effect on other soil properties.

Harrison and Reed (1961) investigated the effect of depth and speed on draft. They concluded that determining the relationship between draft and depth at a constant operating speed and the between draft and speed at a constant working depth were important to obtain linear regression with good correlation.

ASAE (1999) and Chandon and kushwaha (2002) stated that the typical draft requirements could be calculated using the following equation taking into account the soil texture, implement width, working depth, and travel speed.

$$D = F_i [A + B(S) + C(S)^2] W * T \quad (3.2)$$

where

D = implement draft, N

F = a dimensionless soil texture adjustment parameter

i = 1 for fine, 2 for medium and 3 for coarse textured soil

A, B & C = machine-specific parameters

S = field speed km/h

W = machine width (m), number of rows or tools

T = tillage depth (cm) for major tools, 1 (dimensionless) for minor tillage tools and seeding implements.

Soil and machine parameters are provided in the ASAE Standard ASAE D497.4 (ASAE, 1999).

This relationship is used to estimate the typical draft for a wide variety of tillage, and seeding implements and is a useful tool for machinery management (

Harrigan and Rotz 1995).

Typical, average draught requirement parameters are summarized in table 1 for most tillage and seeding machines. Each parameter is a function of tillage tool design. The constant parameter, A, is a function of soil strength while the coefficient of speed parameters, B or C, are related to soil bulk density. Soil is categorized as fine, medium, or coarse. Fine-textured soil is described as high in clay content, medium textured are loamy soils, and coarse textured are sandy soils. Typical of all parameters are listed along with an expected range or variation due to differences in machine design, machine adjustment, machine age, and site-specific conditions including soil moisture and residue cover. This range gives the expected variation of average or typical draught as machine and soil conditions vary.

For this research, the speed of operation ranges between 0.25 m/s and 1.25 m/s. The depth operation ranges between 20 mm and 100 mm, and Implement width of cut ranges between 10 mm and 50 mm.

For minor tool and medium textured soil; $A = 91$, $B = 5.4$, $C = 0.0$ and $F_i = 2$. Also

$T = \text{tillage depth} = 1$ (dimensionless) for minor tillage tools and seeding implements.

$W = \text{machine width (m), number of rows or tools (1) ASAE, 1999)}.$

Therefore, the typical, average draught requirement was calculated using equation 3.2 and the results are as presented in Table 3.1. The results of Table 3.1 were used in selecting the appropriate load cells for this research.

The typical, average draught requirement as estimated, are summarized in table 3.10 below;

Table 3.1: Average Draught Estimate

S/N0	Speed m/s (km/hr)	Estimated Draft (N)
1	0.20 (0.72)	189.780
2	0.80 (2.88)	213.104
3	1.20 (4.32)	228.656
4	1.60 (5.76)	244.208
5	2.00 (7.20)	259.760

3.6.1 Direct Shear Test

Soil physical properties including soil moisture content, cohesion, adhesion, internal friction angles were measured through the laboratory tests in order to be used later in the energy model. Direct shear test was employed to measure the values of soil shear strength under the same moisture content and density conditions as applied in the soil bin experiments.

3.7 Determination of Soil – Metal Friction Angle

The soil–metal frictional angle was determined using 200 mm square plate of thickness 4 mm, spring balance and standard weights.

The square plate was placed on leveled and well compacted soil, a known weight was placed on it and the plate was pulled horizontally using spring balance. The spring balance reading at the point when the plate was about to move was recorded. The value of known weight was then increased and the corresponding spring balance reading at the point when the plate was about to move was recorded. These procedures were repeated for several known weight and the spring

balance reading were recorded as shown in the table below. A graph of pull against known weight was plotted and the gradient determined.

3.8. Measurement of Penetration Resistace with Soil Depth

A roller compactor of mass 42 kg (412 N) was used to compact the soil in the soil bin. The number of passes to give certain penetration resistance was measured. The penetration resistance with depth were measured, with digital penetrometer, at 10, 20, and 30 passes of roller compactor. It was observed that variations in the values of bulk densities and penetration resistances with depth was least at 10 passes of roller compactor, hence 10 passes of roller compactor were used throughout the experiment

3.9 Development of Mode Equation for Narrow Chisel Tine

Consider a narrow tillage tool as shown in the Figure 3.7 below with free body diagram and vectorial representation of velocity component as shown in Figure 3.7.1.

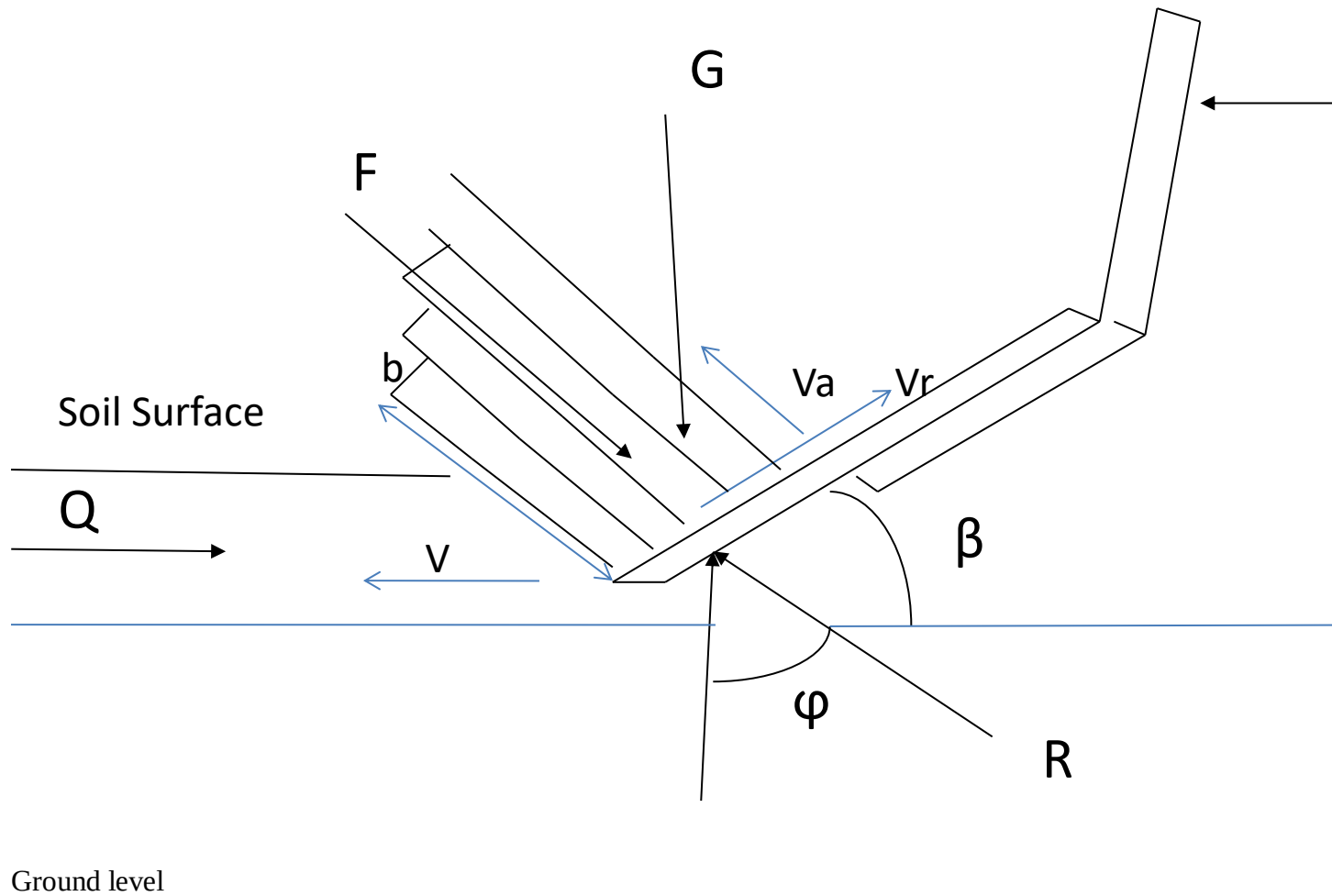


Figure 3.7 Free Body Diagram Showing Forces acting on Soil Segments at Instantaneous Motion of the Inclined Blade.

Where;

Q = the reaction of undeformed soil in front of the cutting tool

F = the dynamic pressure on the tool surface

G = weight of the furrow slice

R = resultant force normal to the tool with the inclined angle φ

φ = soil-metal friction angle (angle of friction between the soil and steel)

β = soil shear stress cutting angle

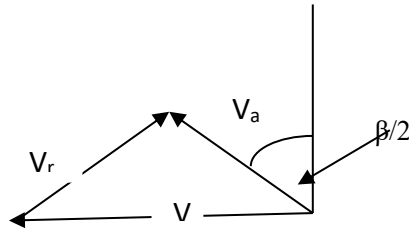


Figure 3.7.1 Vectorial Representation of Velocity Components during Soil Cutting

The general expression for soil deformation in front and ahead of the tool is given by;

$$K_r = f(a, b, \delta, \beta, \varphi) \quad (3.31)$$

Where;

a = thickness/height of a furrow slice

b = width of the share edge or furrow slice

β = soil shear stress cutting angle

φ = soil – metal friction angle (angle of friction between the soil and steel)

σ = Shear strength of the soil

3.9.1 Process of Soil Cutting

The process of soil cutting is similar to planning of metal or plastic materials. The following steps illustrate the activities of tillage tools;

Step1. A crack forms in front of the tool as it penetrates the soil.

2. The crack will progress and elongate until its curvature touches the surface of

uncut soil as the tool penetrates further.

3. The cracks widen simultaneously thus forming a family of slices to form trapezoidal shape 0, 1, 2, 3, called furrow slices

4. when the cutting angle, β , is large enough, the soil ceases to slide up the working surface of the blade but starts to build up or collect in front of the blade.

It should be noted that width of furrow slice (b) and σ give linear relationship with respect to tractive resistance. Hence increasing the depth of penetration of the tool and the cutting angles β and ϕ will increase the tractive resistance.

Trapezoidal soil slice 0,1,2,3 which move along the surface of the tool with velocity V_r

and with forward or translatory velocity V .

The movement of the soil slice of trapezoidal 0, 1, 2, 3 along the shape of the share of the tool with velocity V_r and velocity of soil cutting V . Then the sliding velocity along the share plane 2 – 3 is (V_a) such that vectorial representation of the velocity equation are as given below;

$$V_a = \frac{V \sin \beta}{\sin(\beta + \phi)} \quad (3.32)$$

$$V_r = \frac{V \sin \varphi}{\sin(\beta + \varphi)} \quad (3.33)$$

It should be noted that during deformation of soil by share, the relative velocity of the furrow slice along the surface of the tool will be $V_r < V_a$, $a_1 > a$.

Hence the shrinkage of the furrow slice is given by;

$$\frac{a}{a_1} = \frac{\sin \varphi}{\sin(\beta + \varphi)} \quad (3.34)$$

In essence with increase in β the relative displacement of furrow slice increases. This is based on the theory of chips formation during cutting or planning of steel or other plastic materials. This type of chip formation is not stepped shearing of chips. It must, however, be noted that all loamy and clay loam agricultural soil are deformed during cutting by fracturing and not necessarily by cutting, hence application of shearing formation of steel cutting or other plastic materials is a matter of mathematical convenience.

Note that the thickness equals the depth of penetration of the tool, also the relative velocity V_r equals translatory velocity V . So from vectorial triangular velocity representation;

$$V_a = 2V \cos(90 - \beta/2) \quad (3.35)$$

3.9.2 Soil Resistance during the Operation of Narrow Tillage Tools

There are soil resistances to be overcome during soil cutting by chisel tine. The resistances of the soil to be overcome are in four (4) components;

1. Soil resistance to tool penetration R_T
2. Soil resistance to deformation R_K
3. The weight of the furrow slice R_G
4. Inertial force on the furrow slice R_F

Figure 3.9.3 Resistances to be overcome by Tillage Tool

So the longitudinal component P_x of the tractive force of the narrow tillage tool at a constant forward velocity along an idealized soil furrow slice is;

$$P_x = R_{tx} + R_{kx} + R_{Gx} + R_{Fx} \quad (3.36)$$

Generally soil resistance to deformation depends on the thickness and width of furrow slice. The ultimate tractive strength (σ) and the angle of cutting β and ϕ such that;

$$R_{KX} = f(a, b, \delta, \beta, \phi) \quad (3.37)$$

Note that the value of the width of furrow slice, b , shear strength σ and R_k are linear. Increasing the depth of penetration of the tool means increasing β and ϕ and it will increase the tractive resistance to deformation K_r

Let Q be the reaction of undeformed soil in front of the cutting tool,

Let F = the dynamic pressure,

Let G = weight of the furrow slice

Let R = Resultant force normal to tool with the inclined angle, Θ .

Assuming that Q is parallel to X – axis

Assuming that F is opposite Va of furrow slice making an angle of $\beta/2$ such that solving all the components in X – direction and equate it to zero gives;

$$\text{I) } \Sigma X = 0, -Q - F \sin \beta/2 + R \sin(\beta + \varphi) = 0$$

$$\text{II) } \Sigma Z = 0, F \cos \beta/2 + G - R \cos(\beta + \varphi) = 0$$

And,

$$R = \frac{G}{\cos(\beta + \varphi)} + F \frac{\cos \frac{\beta}{2}}{\cos(\beta + \varphi)} \quad (3.38)$$

Substitute R in (I)

$$Q = G \tan(\beta + \varphi) + F [\cos \frac{\beta}{2} \tan(\beta + \varphi) - \sin \frac{\beta}{2}] \quad (3.39)$$

And,

$$R_x = G \tan(\beta + \varphi) + F \cos \frac{\beta}{2} \tan(\beta + \varphi) \quad (3.4)$$

$$R_z = G + F \cos \frac{\beta}{2} \quad (3.41)$$

Such that; weight of furrow slice, G

$$G = a.b.L.\gamma_v \quad (3.42)$$

Where; a = thickness/height of a furrow slice

b = width of cutting surface

L = length of cutting tool or blade

γ_v = volumetric weight of the soil (Bulk density)

$$M = \frac{a.b.L.\gamma_v}{g} \quad (3.43)$$

M = mass of furrow slice.

$$F = \frac{2a.b.L.\gamma_v}{g} V^2 \sin \frac{\beta}{2} \quad (3.44)$$

But $V_a = 2V \sin \frac{\beta}{2}$ (Relative velocity of furrow slice)

$$R_{kx} = \frac{a.b.L.\gamma_v \tan(\beta + \varphi)}{V^2 \sin \beta \tan(\beta + \varphi)} + \frac{a.b.L.\gamma_v}{g} \quad (3.45)$$

Hence,

$$R_{GX} = a.b.L.\gamma_v \tan(\beta + \varphi) \quad (3.46)$$

The equation above characterizes the force required to overcome the resistance due to the weight of the soil, G.

$$R_{FX} = \frac{1}{V^2 \sin \beta \tan(\beta + \varphi)} + \frac{a.b.L.\gamma_v}{g} \quad (3.47)$$

The equation above characterizes the force required to overcome the dynamic pressure of the furrow slice due to the force of inertial, F.

$$P_x = R_{TX} + R_{KX} + R_{GX} + R_{FX} \quad (3.48)$$

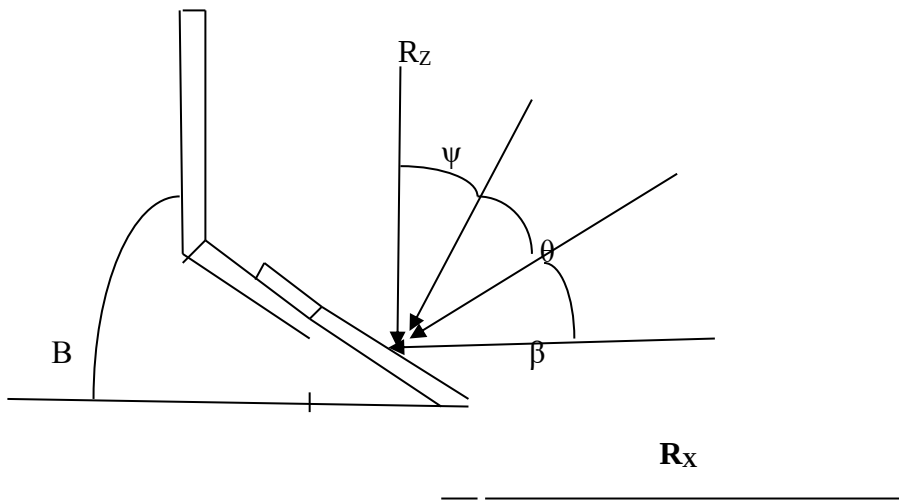
From investigation or experimentation $R_{TX} \leq 0.4R_{GX}$

$$K = f(\sigma_c, \sigma\Phi) = K_c, k\Phi$$

K is the dynamic property (shearing strength of the soil)

Note that

1. R helps the penetration of the working tool into the soil
2. The value of $\varphi(\sigma)$ for soil without rocks or plant roots can be determined from $\varphi(\sigma)$ and cutting angle such that $\varphi = \psi$ and $\psi = 90 - (\beta + \varphi)$



3. For $\psi = \text{constant}$, an increase in β lead to decrease in penetrability
4. β is the predetermining angle $0 \leq \beta \leq 90^\circ$
5. $h = L \sin \beta$

$$R_{GX} = a.b.L.\gamma_v \frac{\tan(\beta + \varphi)}{\sin \beta} \quad (3.49)$$

6. The optimum value of β of which the resistance R_{GX} is minimum depends on friction angle $\varphi = (\sigma)$.

7. Note also that effect of β on R_{FX} is govern by

$$R_{FX} = \frac{a.b.\gamma_v}{g} V^2 \sin \beta \tan(\beta + \varphi) \quad (3.5)$$

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Results

The properties of the soil used for the experiment are as stated in Table 4.1 below;

Table 4.1 Properties of the soil used for the research.

Soil Properties	Values
Percentage sand	84.96
Percentage silt	8.00
Percentage clay	7.04
Cohesion	16.67 kPa
Angle of internal friction	26.6°
Soil-metal friction angle	29.8°
Moisture content	11 – 12%
Bulk density	1.50g/cm ³

Appendix 2. Shows draught of an inclined model chisel blade at various tool widths, tool depth, tool lift angle and speed of operation.

Table 4.2 and Figure 4.1 respectively show the result and graph of soil – metal friction angle determination experiment. The value of soil metal friction angle was found to be 29.8°.

Table 4.2 Spring balance readings when the plate was about to move.

S/No.	Load (kgf)	Pull (kgf)
1	0.5	1.00
2	1.0	1.30
3	1.5	1.75
4	2.0	1.90
5	2.5	2.00
6	3.0	2.15
7	3.5	2.50
8	4.0	2.75
9	4.5	3.00
10	5.0	3.50
11	5.5	3.90
12	6.0	4.00

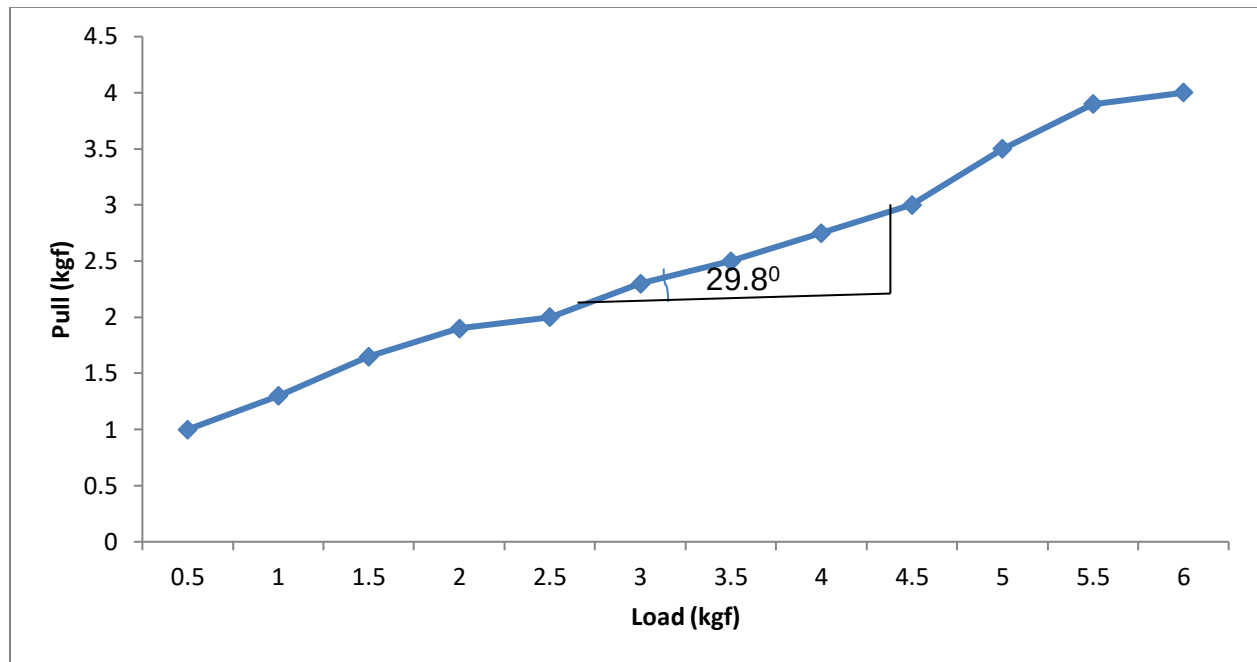


Figure 4.1 Graph of pull against load for the Determination of soil-metal friction angle.

Table 4.3 and Figure 4.2 respectively show the result and graph of soil cone penetration resistance with depth after 10, 20 and 30 passes of roller compactor.

Table 4.3 Cone penetration resistance with depth after 10, 20 and 30 passes of roller compactor.

Depth (mm)	Pressure (MPa) (after 10 passes)	Pressure (MPa) (after 20 passes)	Pressure (MPa) (after 30 passes)
10	0.10	0.10	0.16
20	0.15	0.15	0.19
30	0.16	0.16	0.21
40	0.17	0.16	0.22
50	0.18	0.15	0.21

60	0.17	0.15	0.22
70	0.16	0.19	0.22
80	0.16	0.20	0.24
90	0.16	0.24	0.25
100	0.16	0.26	0.26
110	0.16	0.26	0.27
120	0.17	0.27	0.28
130	0.18	0.29	0.31
140	0.23	0.29	0.36
150	0.24	0.30	0.49

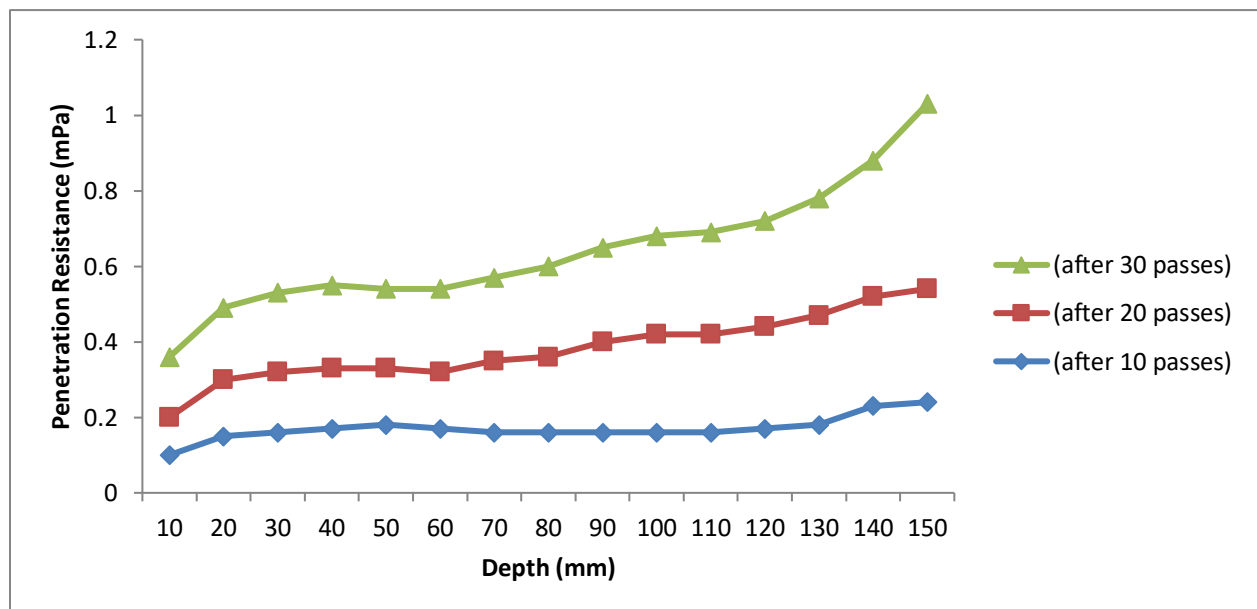


Figure 4.2 Graphs of penetration resistance after 10, 20, and 30 passes of

Roller compactor

Table 4.4 and Figure 4.3 respectively show the result and graph of direct shear test on the soil sample used for the Experiment. The soil- soil angle internal friction was determined to be 26.6° .

Table 4.4 Results of Direct Shear Stress measurements for the Soil Samples used.

Normal Stress (kPa)	Shear Stress (kPa)
100	45
200	89
300	138
400	185
500	260

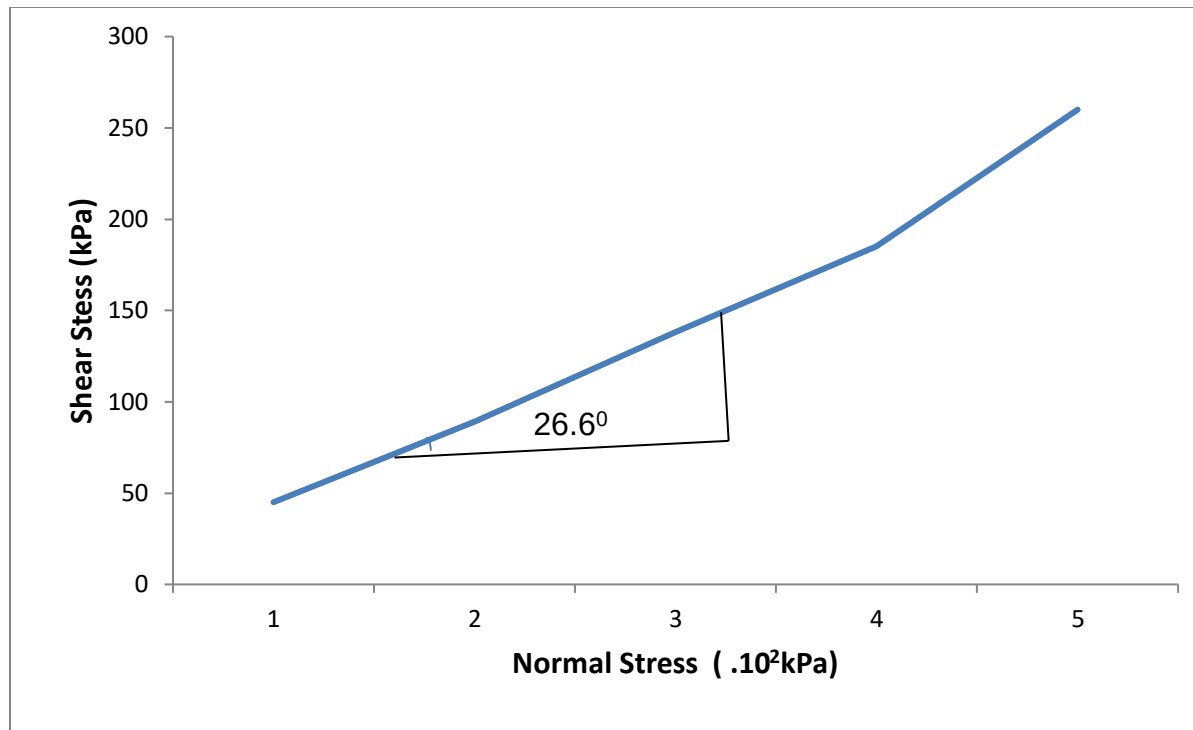


Figure 4.3 Shear stress Vs Normal Stress Curve for Soil Used.

Table 4.5 and Figure 4.4 respectively show the result and curves of soil bulk density variation with depth after 10, 20 and 30 passes of roller compactor.

Table 4.5 Bulk Density of the Soil in the Soil Bin after 10, 20 and 30 passes of Roller Compactor

Depth (mm)	Soil density after 10 Roller passes (g/cm ³)	Soil density after 20 Roller passes (g/cm ³)	Soil density after 30 Roller passes (g/cm ³)
20	1.494	1.510	1.520
40	1.495	1.510	1.520
60	1.491	1.500	1.515
80	1.491	1.500	1.510
100	1.490	1.492	1.510
120	1.485	1.490	1.500

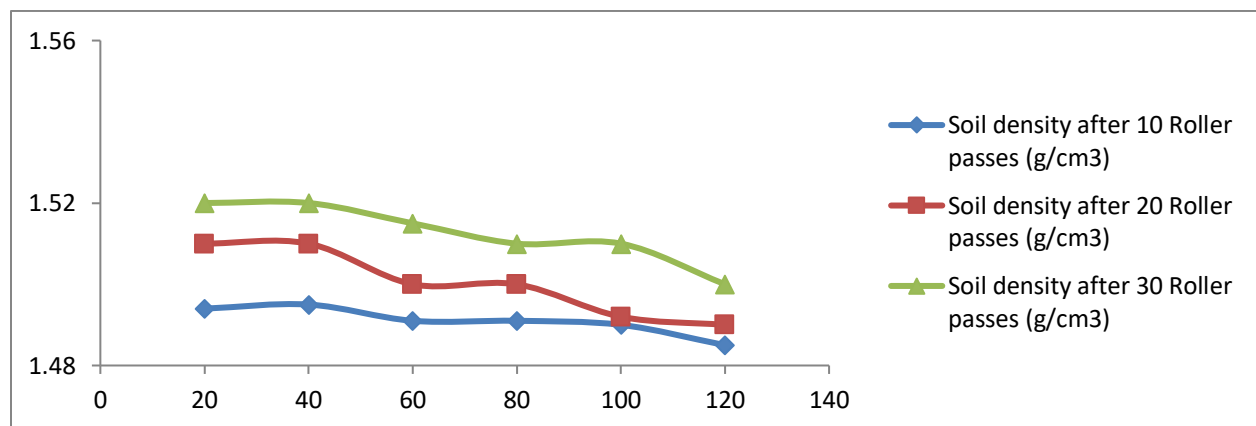


Figure 4.4 Bulk Densities at 10, 20 and 30 Passes of Roller Compactor against Soil Depth.

Table 4.6 shows the result of analysis carried out on the soil sample collected from the three senatorial districts of Kwara state and Table 4.7 shows the result of analysis of a well mixed soil.

Table 4.6 Soil Textural Classification for Kwara State.

S/N	Sample Code	Place of collection	L.G.A.	Senatorial District	Sand %	Silt %	Clay %	Texture
1	A ₁	Malete	Moro	Kwara-North	74.96	16.00	9.04	Sandy Loam
2	A ₂	Bode-Saadu	Moro	Kwara-North	75.68	10.00	14.32	Sandy Loam
3	A ₃	Shao	Moro	Kwara-North	87.68	6.00	6.32	Loamy Sand
4	B ₁	Oke-Oyi	Ilorin-East	Kwara-Central	78.96	16.00	5.04	Loamy Sand
5	B ₂	Mandala	Asa	Kwara-Central	85.68	8.00	6.32	Loamy Sand
6	B ₃	Alapa	Asa	Kwara-Central	89.68	6.00	4.32	Loamy Sand
7	C ₁	Omupo	Ifelodun	Kwara-South	82.96	12.00	5.04	Loamy Sand
8	C ₂	Ajase-Ipo	Irepodun	Kwara-South	81.68	10.00	8.32	Loamy Sand
9	C ₃	Koko	Ifelodun	Kwara-South	85.68	8.00	6.32	Loamy Sand

Table 4.7 Textural Classification of Mixed Soil from Kwara State

S/No	SAMPLE	SAND	SILT	CLAY	TEXTURE
1	A	82.96	10.00	7.04	Loamy Sand
2	B	84.96	10.00	5.04	Loamy Sand
3	C	84.96	10.00	5.04	Loamy Sand
4	D	84.96	8.00	7.04	Loamy Sand

NOTE: Samples A, B, and C is mixed soil from Kwara North, Central and South.

Sample D is the soil collected at the back of Department of Agricultural and Biosystems

Engineering, University of Ilorin, Ilorin-Nigeria.

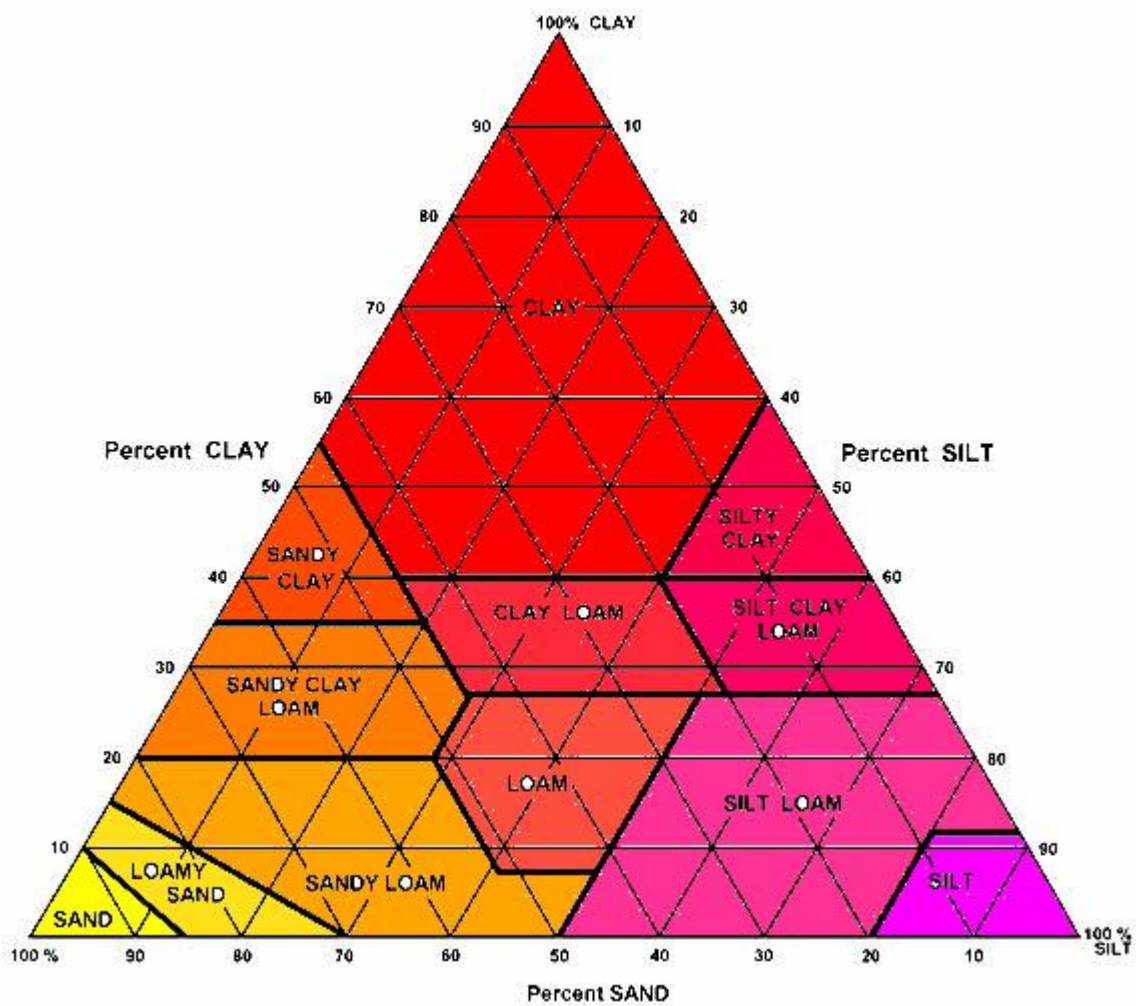


Figure 4.5 USDA Soil Textural Classification Chart

Table 4.8 and Figures 4.61 – 4.63 respectively show the result and curves of soil moisture loss within a period of ten days.

Table 4.8 Progressive Soil Moisture Loss

S/W	W ₁ (g)	W ₂ (g)	W ₃ (g)	W ₄ (g)	W ₅ (g)	W ₃ -W ₂ (g)	Moisture Content (%)						
A	61.30	482.80	442.50	442.20	442.20		10.65						
B	54.00	486.20	450.00	445.40	445.40		10.42						
C	60.30	420.80	383.70	383.70	383.70		11.47						
			29°C	28°C	27°C	29°C	29°C	29°C	29°C	29°C	29°C	27°C	28°C
S/W	W ₁	W ₂	W _{d1}	W _{d2}	W _{d3}	W _{d4}	W _{d5}	W _{d6}	W _{d7}	W _{d8}	W _{d9}	W _{d10}	W _{d11}
A1	61.40	450.00	445.50	440.10	435.40	432.00	428.60	426.40	424.20	422.50	419.70	418.60	418.20
A2	56.10	456.40	451.20	447.40	442.60	439.40	436.00	433.30	431.30	429.70	425.90	424.30	423.70
A3	68.00	457.50	452.70	449.70	445.50	442.70	440.00	437.90	435.60	434.20	429.80	427.60	426.20
B1	60.40	462.30	456.70	450.80	445.20	441.00	437.70	435.20	432.80	431.10	429.80	428.60	428.60
B2	51.20	447.70	442.30	435.90	430.80	427.30	424.10	421.30	419.80	417.90	415.70	415.10	414.70
B3	57.10	462.30	457.70	451.70	446.30	442.40	438.90	436.30	433.60	432.00	429.40	428.40	427.70
C1	55.60	438.70	438.70	438.60	438.30	438.10	438.10	437.40	437.30	437.20	437.40	436.50	430.00
C2	71.90	424.70	424.70	424.60	424.40	424.00	423.50	423.40	423.30	423.20	422.70	422.20	415.70
C3	55.00	463.70	463.30	463.30	462.90	463.40	462.00	462.00	462.00	461.50	461.40	461.30	455.40

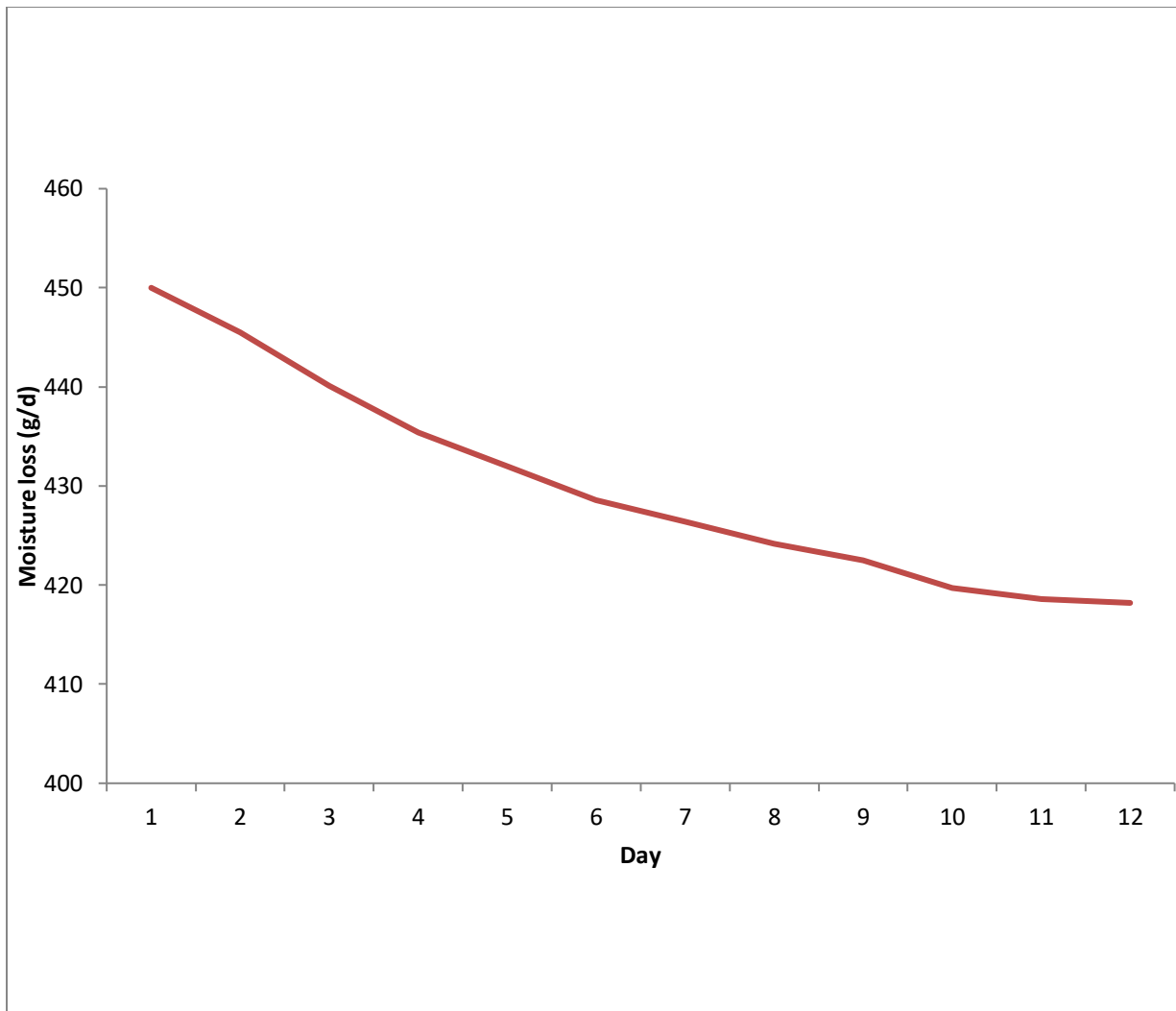


Figure 4.6 Progressive Soil Moisture Losses for Sample A

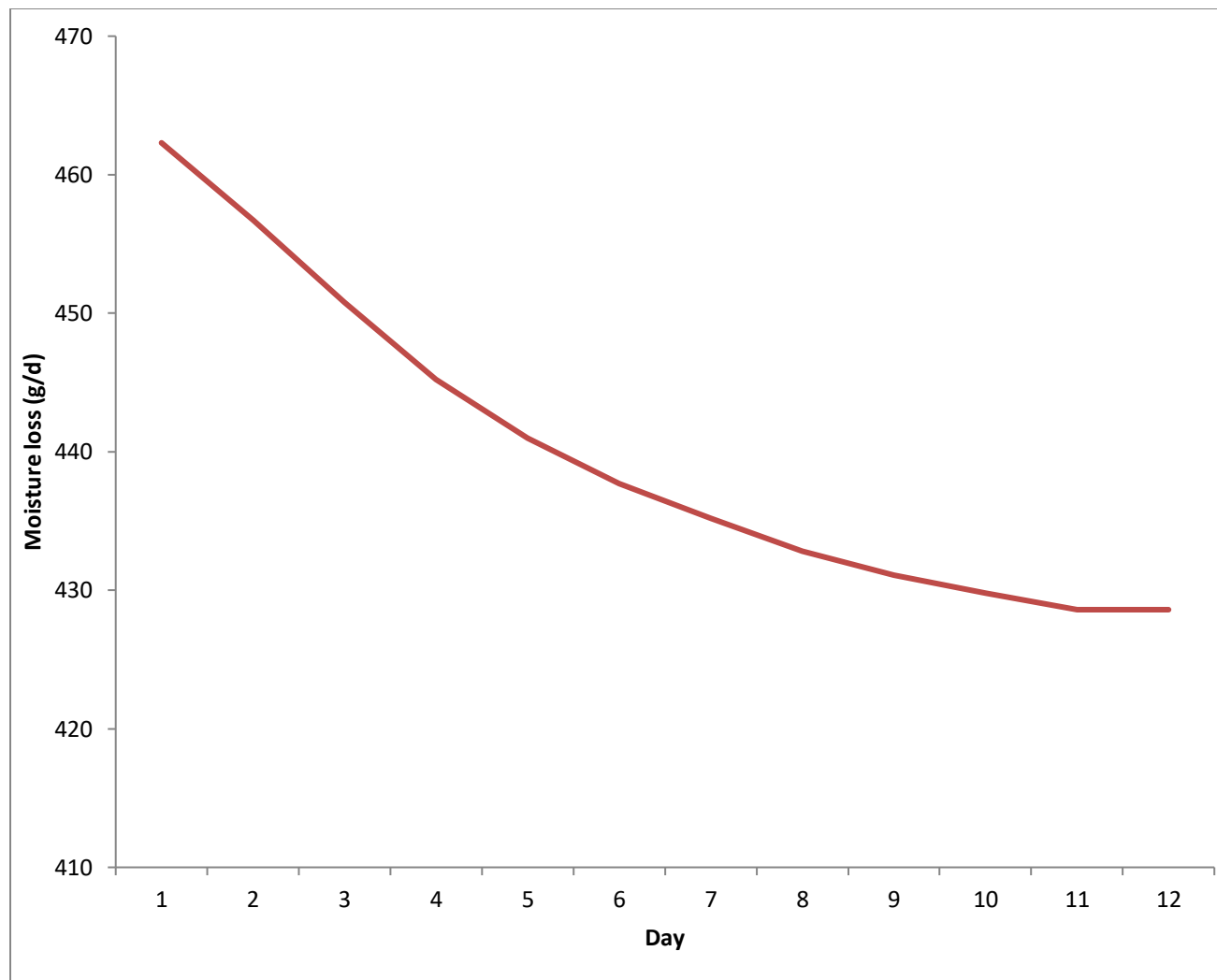


Figure 4.7 Progressive Soil Moisture Losses for Sample B

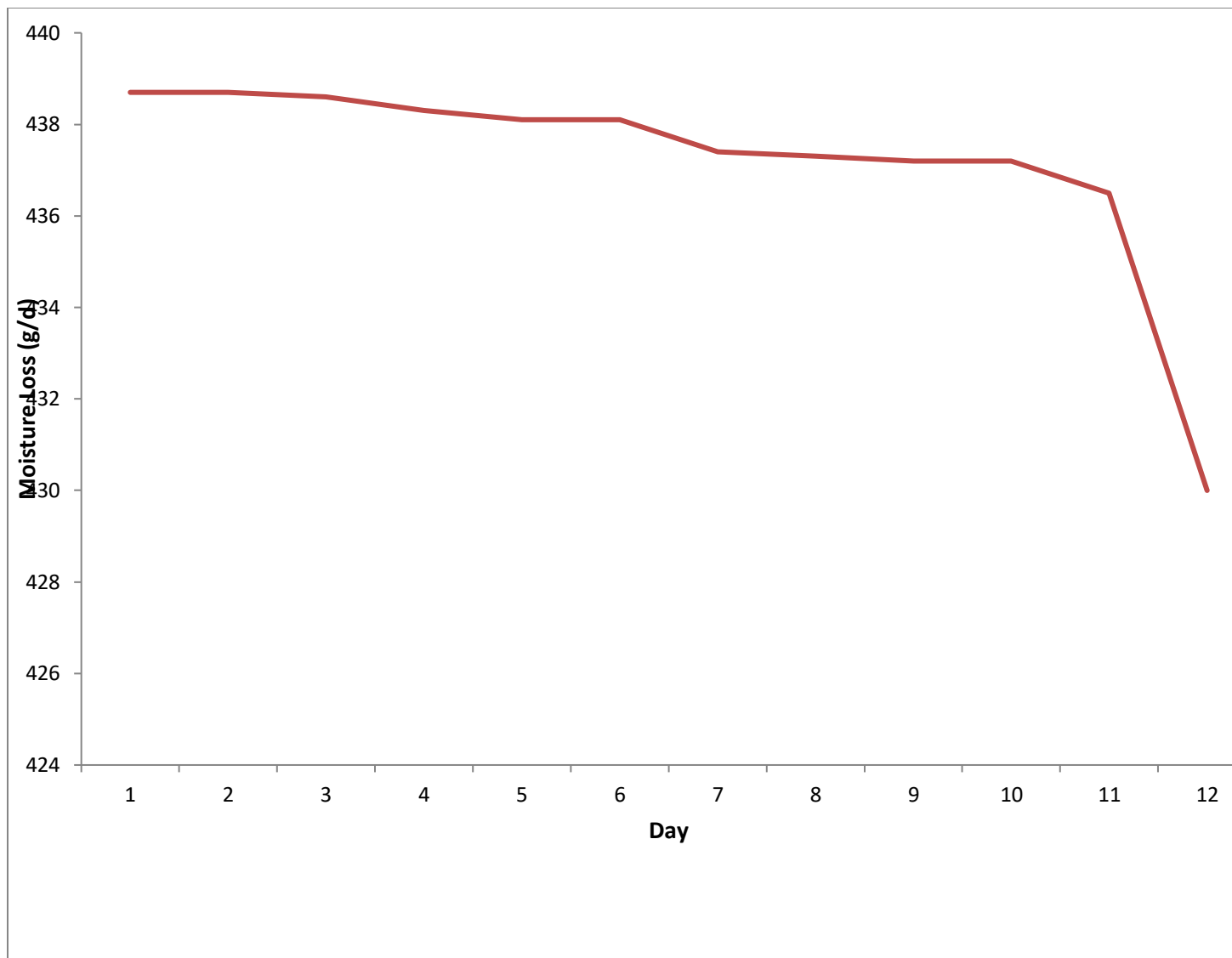


Figure 4.8 Progressive Soil Moisture Loss for Sample C

Table 4.9 Tillage Draught for Inclined Tool at various Width of cutting edge, Lift angle, Depth and Speed of Operation.

S/N	Width of cutting edge (mm)	Lift angle (degree)	Depth of cut (mm)	Speed of operation (m/s)	Draught (N) 1	Draught (N) 2	Average Draught (N)
1	10	20	20	0.25	21	20	20.50
2				0.50	26	26	26.00
3				0.75	35	36	35.50
4				1.00	47	46	46.50
5				1.25	53	55	54.00
6			40	0.25	55	56	55.50
7				0.50	67	66	66.50
8				0.75	81	83	82.00
9				1.00	89	90	89.50
10				1.25	95	95	95.00
11			60	0.25	105	107	106.00
12				0.50	116	118	117.00
13				0.75	123	122	122.50
14				1.00	132	133	132.50
15				1.25	138	139	138.50
16			80	0.25	142	141	141.50
17				0.50	148	149	148.50
18				0.75	154	153	153.50
19				1.00	161	160	160.50
20				1.25	166	167	166.50
21			100	0.25	172	172	172.00
22				0.50	176	177	176.50
23				0.75	183	182	182.50
24				1.00	186	185	185.50
25				1.25	190	189	189.50

Tale 4.10 is the ANOVA table showing the significant contribution of each factor to Draught of an inclined narrow model chisel blade.

Table 4.10 ANOVA TABLE

Dependent Variable: DRAUGHT

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	3.208E6 ^a	624	5140.741	581.269	.000
Intercept	1.746E7	1	1.746E7	1.975E6	.000
WIDTH	97181.877	4	24295.469	2.747E3	.000
ANGLE	19636.845	4	4909.211	555.089	.000
DEPTH	2915847.349	4	728961.837	8.242E4	.000
SPEED	137933.509	4	34483.377	3.899E3	.000
WIDTH * ANGLE	1207.451	16	75.466	8.533	.000
WIDTH * DEPTH	6330.427	16	395.652	44.737	.000
WIDTH * SPEED	626.787	16	39.174	4.429	.000
ANGLE * DEPTH	13764.219	16	860.264	97.271	.000
ANGLE * SPEED	460.099	16	28.756	3.251	.000
DEPTH * SPEED	3668.275	16	229.267	25.923	.000
WIDTH * ANGLE * DEPTH	3677.925	64	57.468	6.498	.000
WIDTH * ANGLE * SPEED	653.725	64	10.214	1.155	.200
WIDTH * DEPTH * SPEED	1137.669	64	17.776	2.010	.000
ANGLE * DEPTH * SPEED	2023.997	64	31.625	3.576	.000
WIDTH * ANGLE * DEPTH * SPEED	3672.539	256	14.346	1.622	.000
Error	5527.500	625	8.844		
Total	2.068E7	1250			
Corrected Total	3213350.193	1249			

a. R Squared = .998 (Adjusted R Squared = .997)

Tales 4.11, 4.12, 5.13 ad 4.14 shows the estimated mean of draught and the corresponding values of speed of operation, tool lift angle, operating depth and speed of operation respectively, while

figures 4.9, 4.10, 4.11 and 4.12 respectively shows the graph of estimated mean of Draught against speed of operation, tool lift angle, operating depth and speed of operation.

Table 4.11 Estimated mean draught for various widths

DRAUGHT						
Duncan						
WIDTH	N	Subset				
		1	2	3	4	5
10	250	106.64				
20	250		111.26			
30	250			118.11		
40	250				123.36	
50	250					131.62
Sig.		1.000	1.000	1.000	1.000	1.000

Table 4.12 Estimated mean draught for various angles of lift

DRAUGHT					
Duncan					
ANGLE	N	Subset			
		1	2	3	4
40	250	114.63			
30	250		115.67		
50	250		115.90		
60	250			119.32	
20	250				125.47
Sig.		1.000	.383	1.000	1.000

Table 4.13 Estimated mean draught for various depths

DRAUGHT

Duncan

DEPTH	N	Subset				
		1	2	3	4	5
20	250	47.54				
40	250		84.96			
60	250			120.71		
80	250				154.39	
100	250					183.39
Sig.		1.000	1.000	1.000	1.000	1.000

Table 4.14 Estimated mean draught for various speeds

DRAUGHT

Duncan

SPEED	N	Subset				
		1	2	3	4	5
0.25	250	103.61				
0.5	250		110.44			
0.75	250			118.09		
1	250				125.79	
1.25	250					133.06
Sig.		1.000	1.000	1.000	1.000	1.000

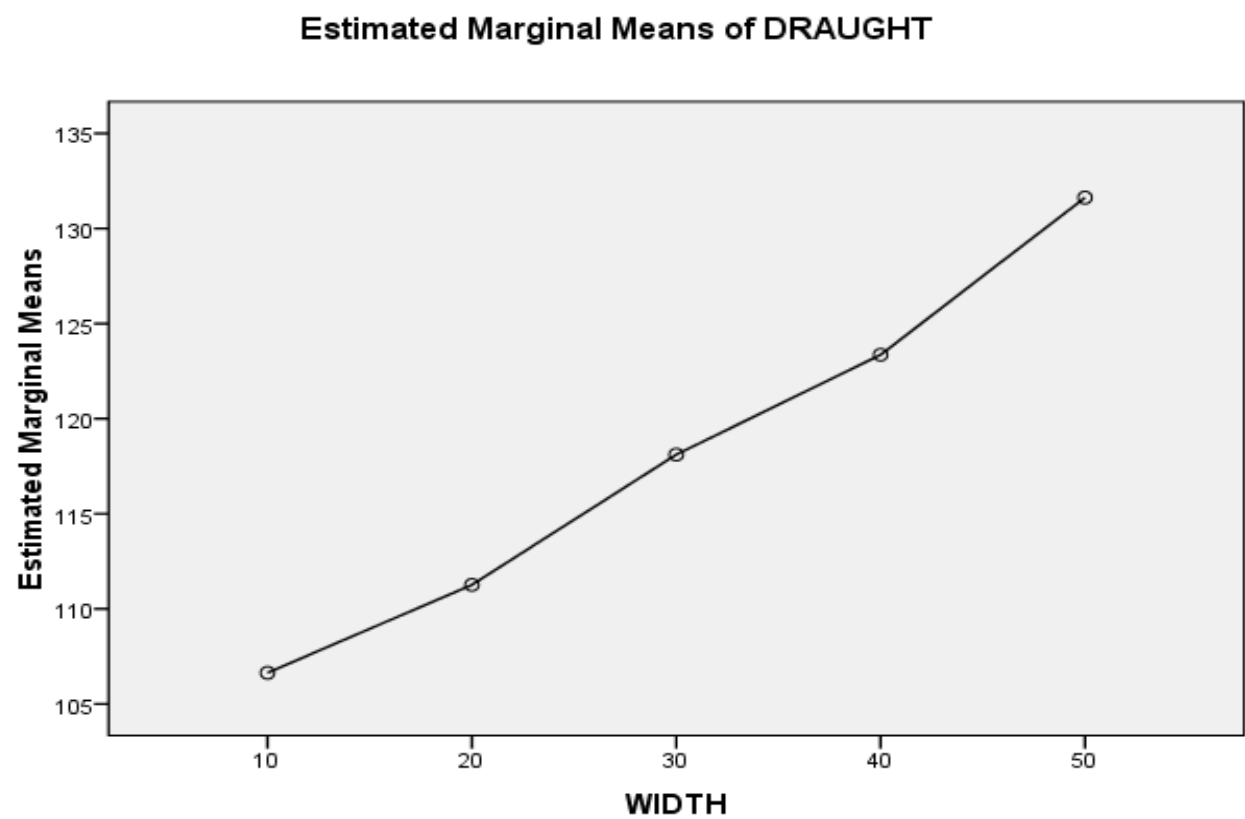


Figure 4.9 Estimated Marginal Means of Draught against Width of cutting edges

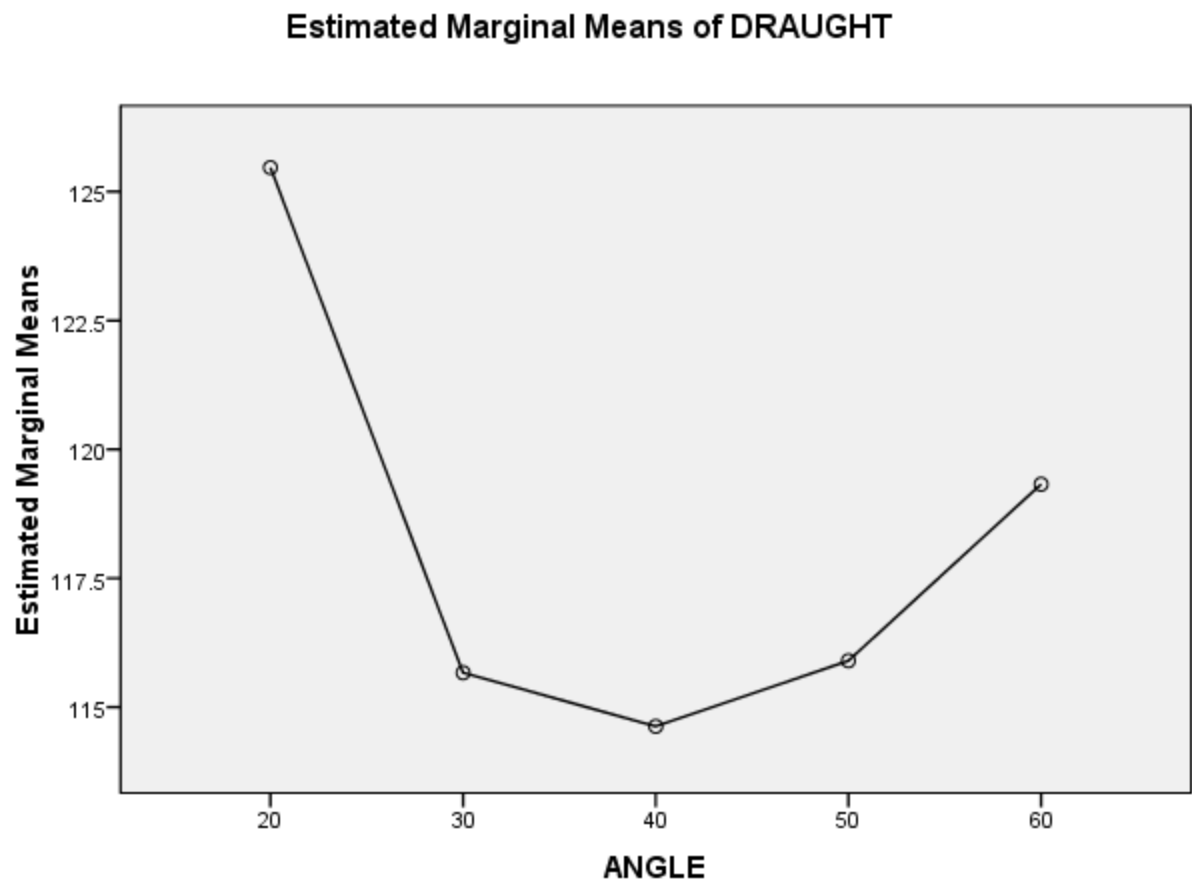


Figure 4.10 Estimated Marginal Means of Draught against Lift Angles

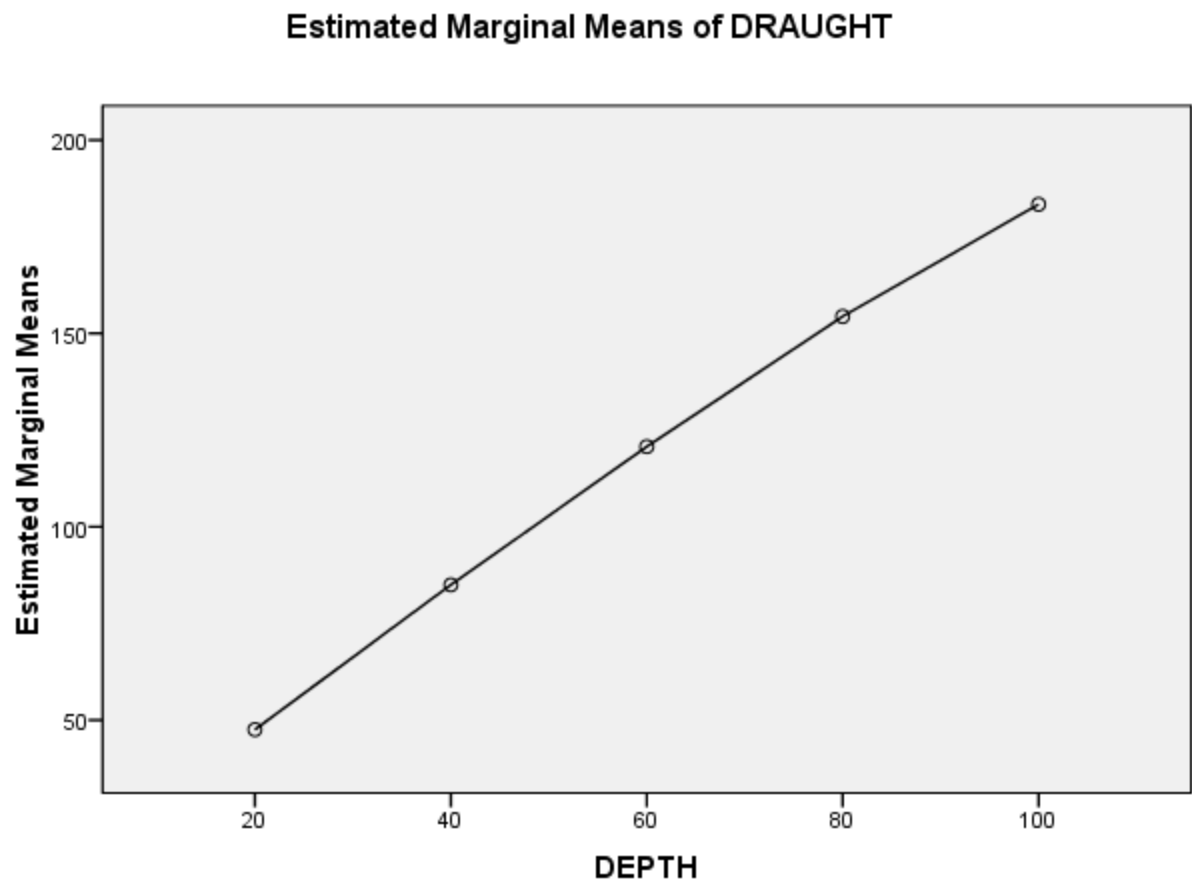


Figure 4.11 Estimated Marginal Means of Draught against Depths of operation

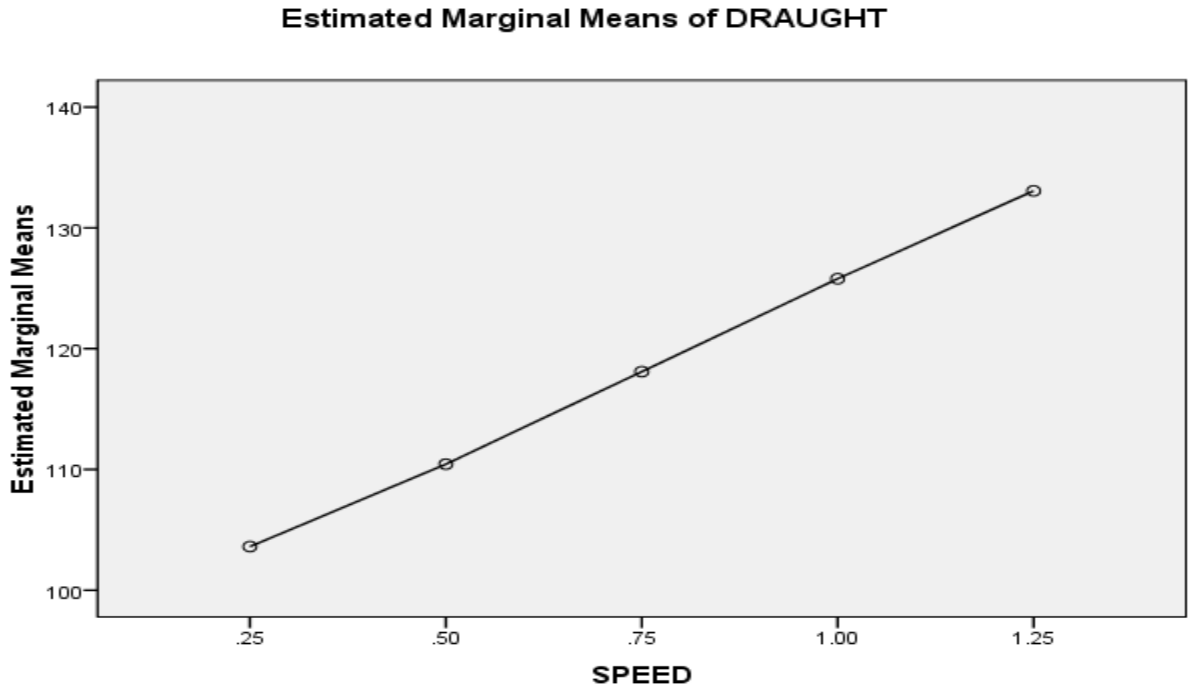


Figure 4.12 Estimated Marginal Means of Draught against Speed of operation

Figures 4.13, 4.14, 4.15, 4.16 and 4.17 shows the Estimated Marginal Means of Draught against Width at various depth of operation at 0.25, 0.50, 0.75, 1.00 and 1.25 m/s speed of operation

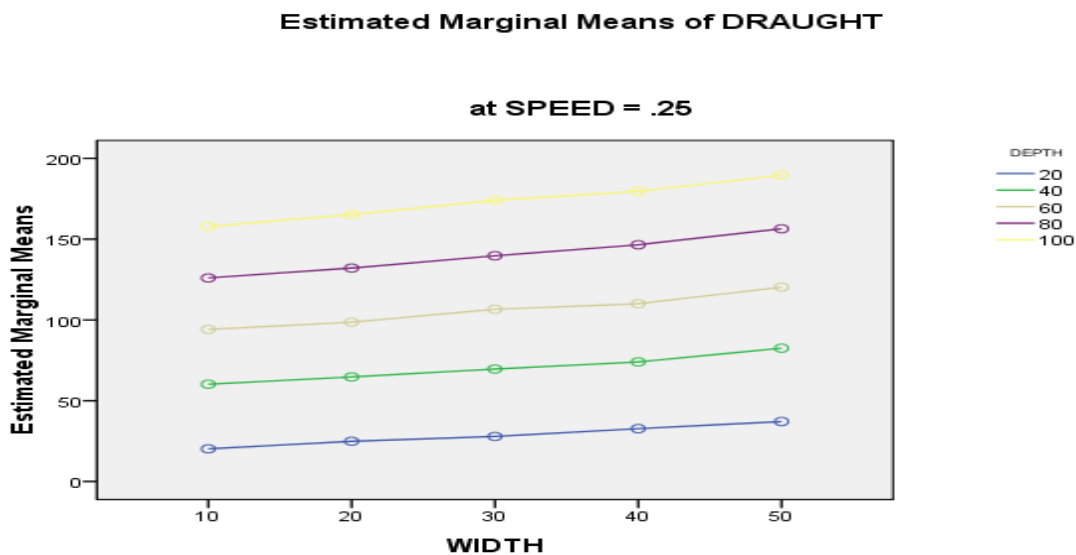


Figure 4.13 Estimated Marginal Means of Draught against Width at various depth of Operation.

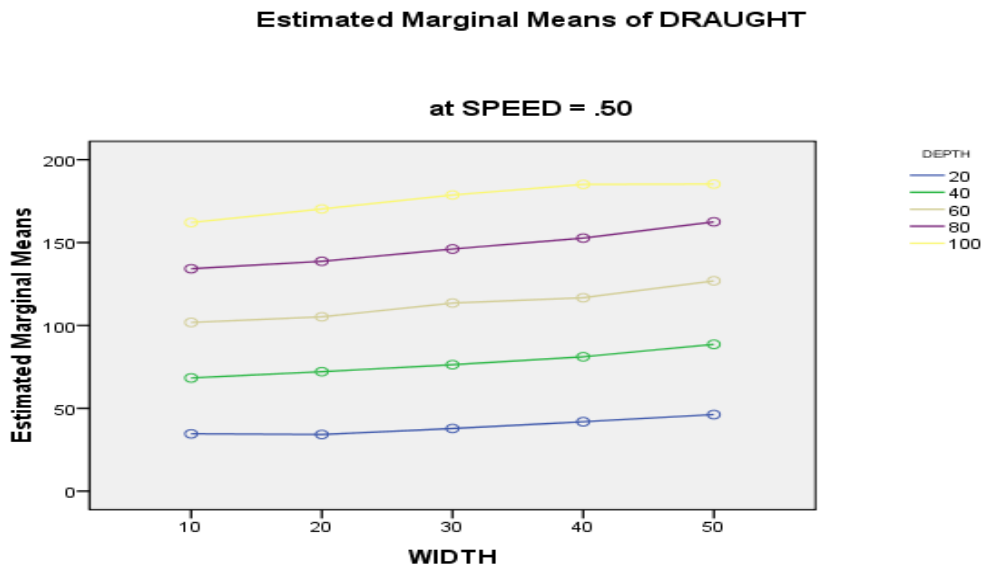


Figure 4.14 Estimated Marginal Means of Draught against Width at various depth of Operation.

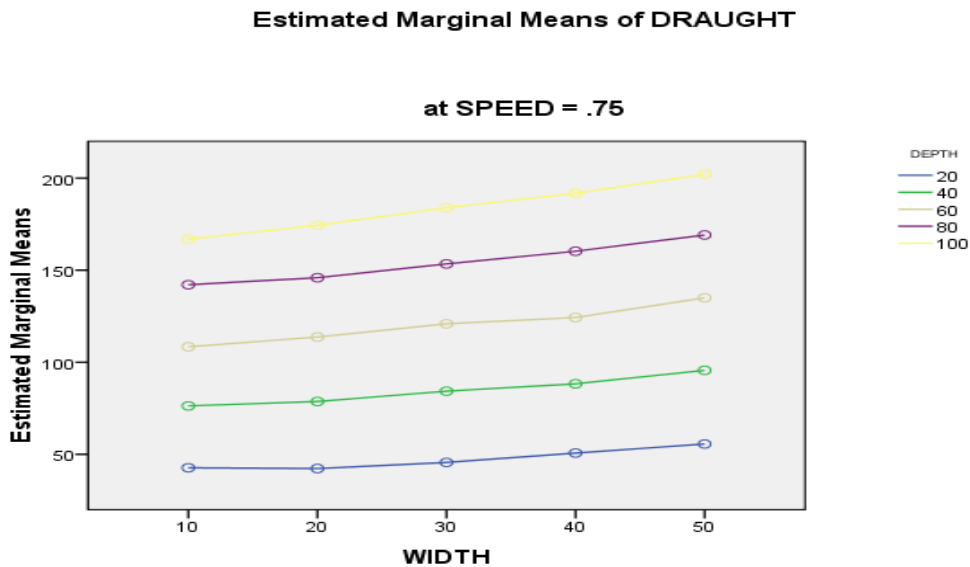


Figure 4.15 Estimated Marginal Means of Draught against Width at various depth of Operation.

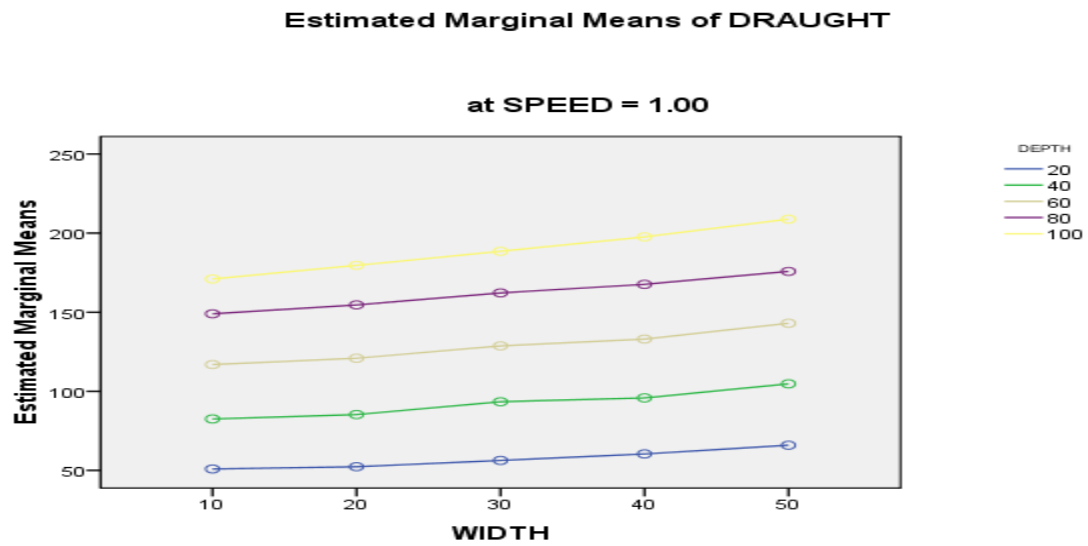


Figure 4.16 Estimated Marginal Means of Draught against Width at various depth of Operation.

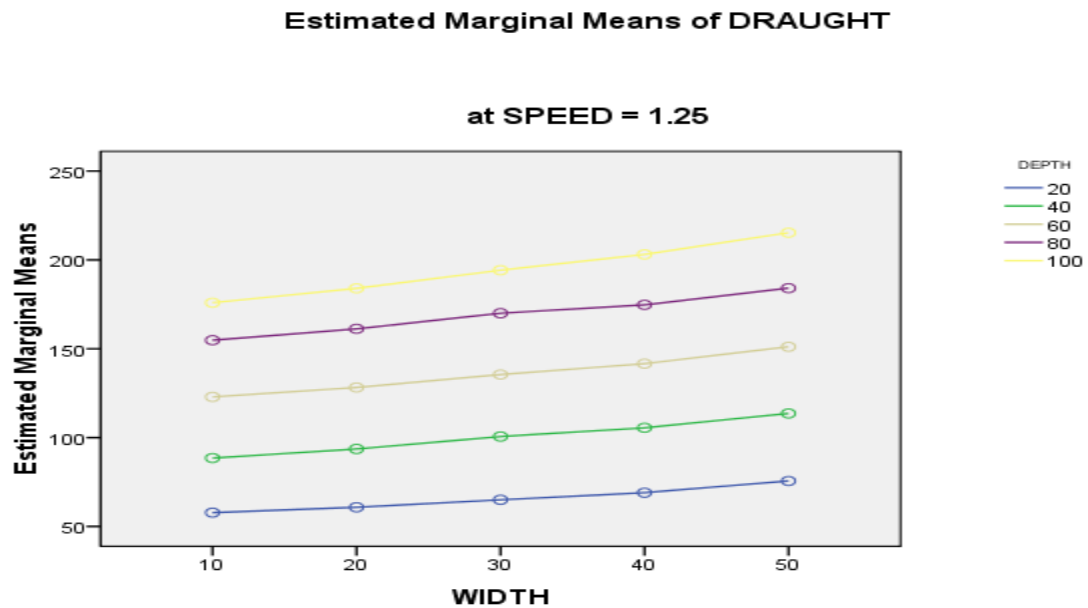


Figure 4.17 Estimated Marginal Means of Draught against Width at various depth of Operation.

Table 4.15 shows the regression analysis and equation for all the four factors considered in this research while tables 4.16 to 4.19 show the regression equation for individual factor.

Table 4.15 REGRESSION ANALYSIS

Coefficients ^a					
Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	-20.220	.979		-20.654	.000
ANGLE	-.121	.015	-.034	-8.261	.000
WIDTH	.621	.015	.173	42.534	.000
DEPTH	1.706	.007	.951	233.740	.000
SPEED	29.706	.584	.207	50.886	.000

a. Dependent Variable: DRAUGHT

The regression equation for all the four factors are as shown in equation 4.1

$$P = -20.220 - 0.121\beta + 0.621b + 1.706d + 29.706s \quad (4.1)$$

Regression equation is given by:

Table 4.16 Regression Equation for Draught and lift angle

Model Summary and Parameter Estimates								
Dependent Variable: DRAUGHT								
Equation	Model Summary					Parameter Estimates		
	R Square	F	df1	df2	Sig.	Constant	b1	b2
Linear	.001	1.413	1	1248	.235	123.020	-.121	
Quadratic	.006	3.592	2	1247	.028	151.780	-1.764	.621

The independent variable is ANGLE.

Regression equation is given by;

$$P = 151.780 - 1.764\beta + 0.621\beta^2 \quad (4.2)$$

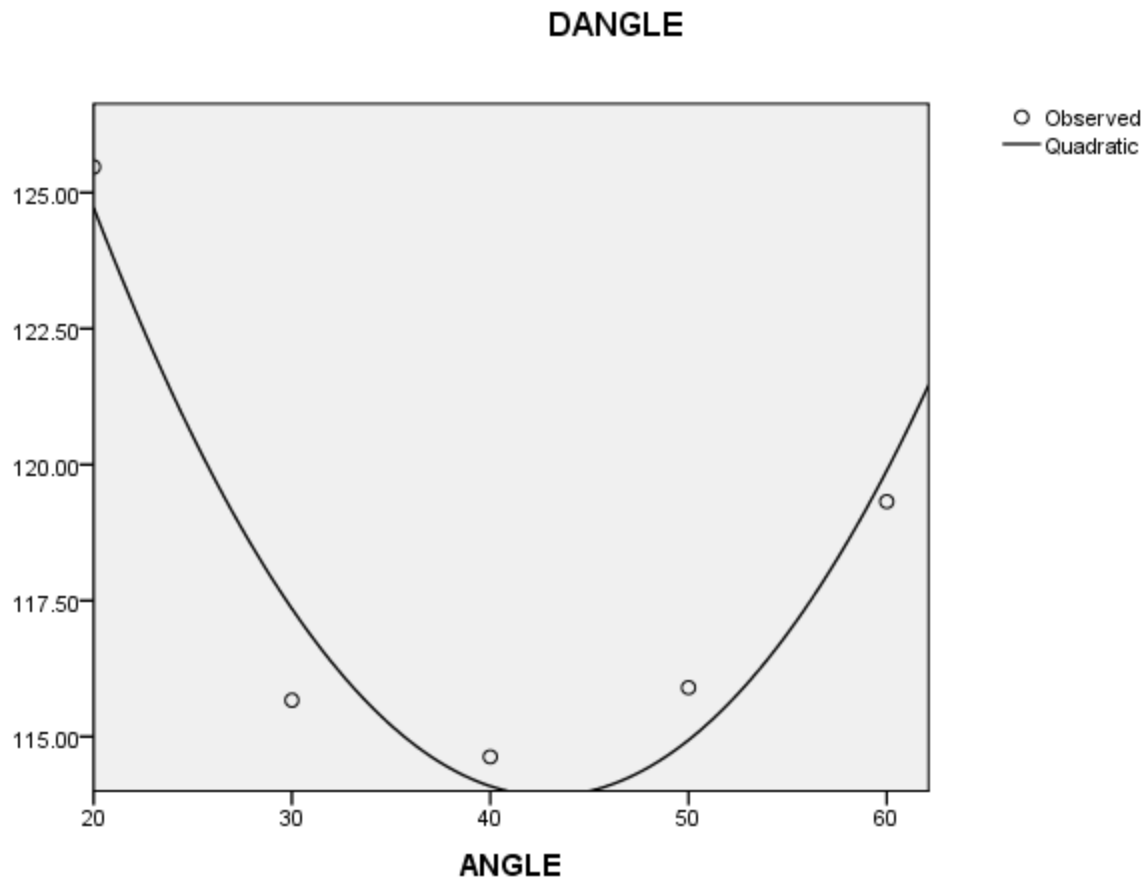


Figure 4.18 Graph of Estimated Mean of Draught against Lift Angle.

Table 4.17 Regression Equation for Draught and Depth of Operation

Coefficients ^a					
Model		Unstandardized Coefficients		Standardized Coefficients	
		B	Std. Error	Beta	
1	(Constant)	15.859	1.036		15.315
	DEPTH	1.706	.016	.951	109.259
					Sig.

a. Dependent Variable: DRAUGHT

Regression equation is given by;

$$P = 15.859 + 1.706d \quad (4.3)$$

Table 4.18 Regression Equation for Draught and Speed of Operation

Coefficients ^a					
Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
1 (Constant)	95.918	3.293		29.129	.000
SPEED	29.706	3.971	.207	7.480	.000

a. Dependent Variable: DRAUGHT

Regression equation is given by;

$$P = 95.918 + 29.706s \quad (4.4)$$

Table 4.19 Regression Equation for Draught and Width of Cutting edge

Coefficients ^a					
Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
1 (Constant)	99.575	3.315		30.037	.000
WIDTH	.621	.100	.173	6.211	.000

a. Dependent Variable: DRAUGHT

Regression equation is given by;

$$P = 99.575 + 0.621b \quad (4.5)$$

Figures 4.19 to 4.23 show the graphs of Draught against Speed at $\beta = 30^\circ$, $b = 10$ mm at $d = 20$ mm, $d = 40$ mm, $d = 60$ mm, $d = 80$ mm and $d = 100$ mm respectively

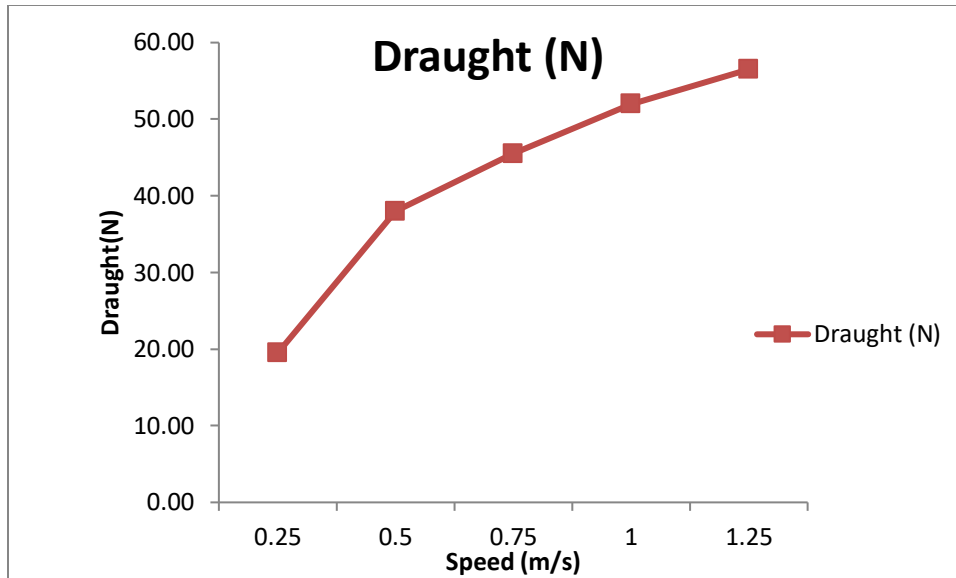


Figure 4.19 Graph of Draught against Speed at $\beta = 30^\circ$, $b = 10$ mm $d = 20$ mm

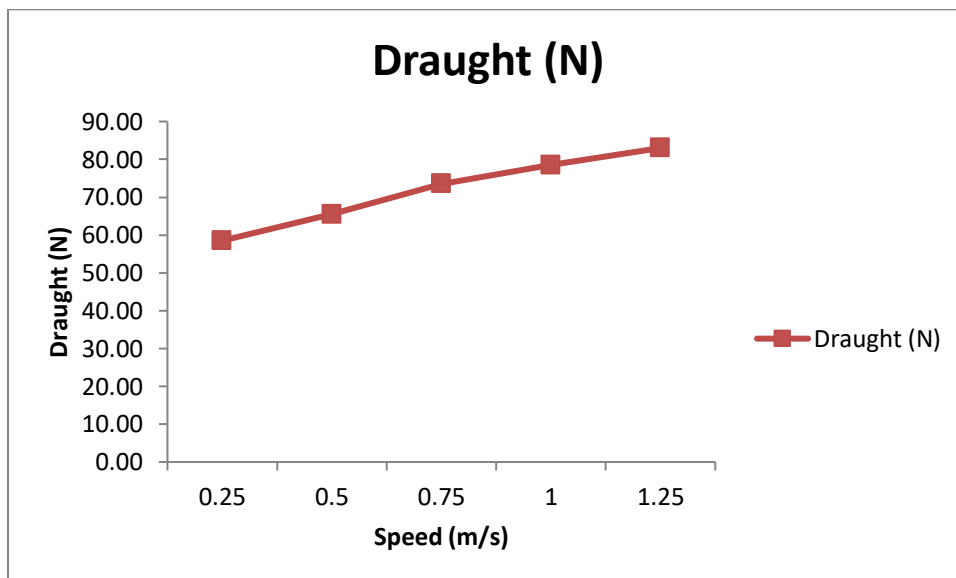


Figure 4.20 Graph of Draught against Speed at $\beta = 30^\circ$, $b = 10$ mm $d = 40$ mm

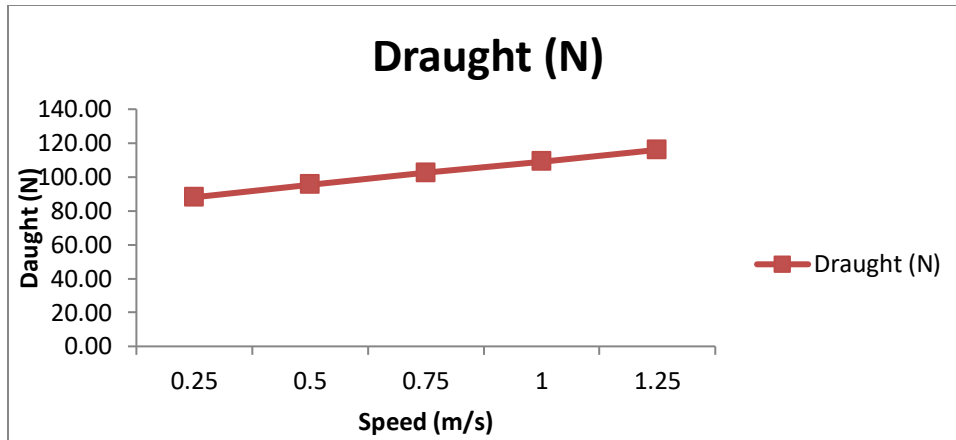


Figure 4.21 Graph of Draught against Speed at $\beta = 30^\circ$, $b = 10$ mm $d = 60$ mm

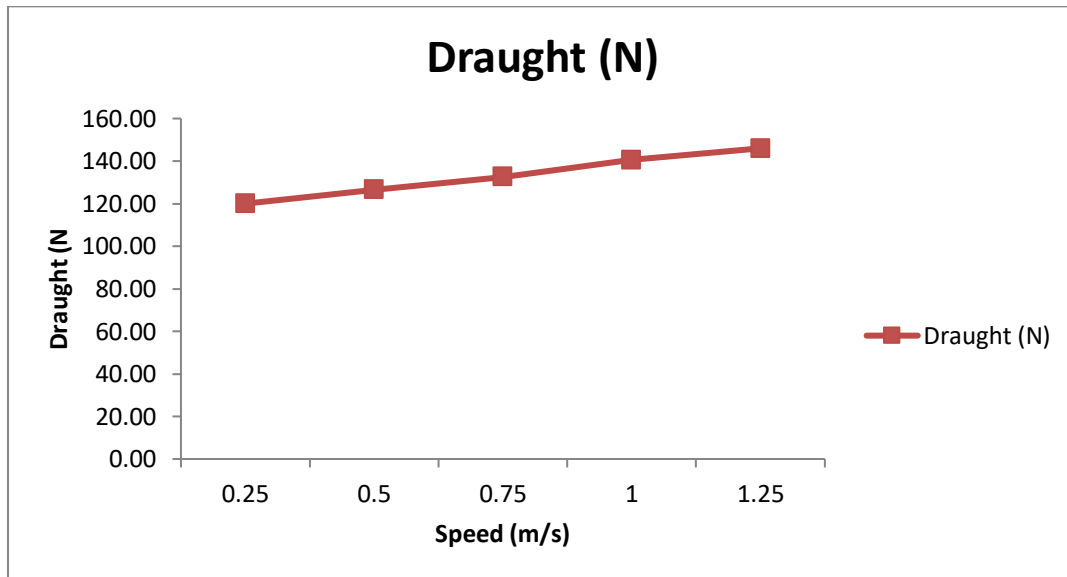


Figure 4.22 Graph of Draught against Speed at $\beta = 30^\circ$, $b = 10$ mm $d = 80$ mm

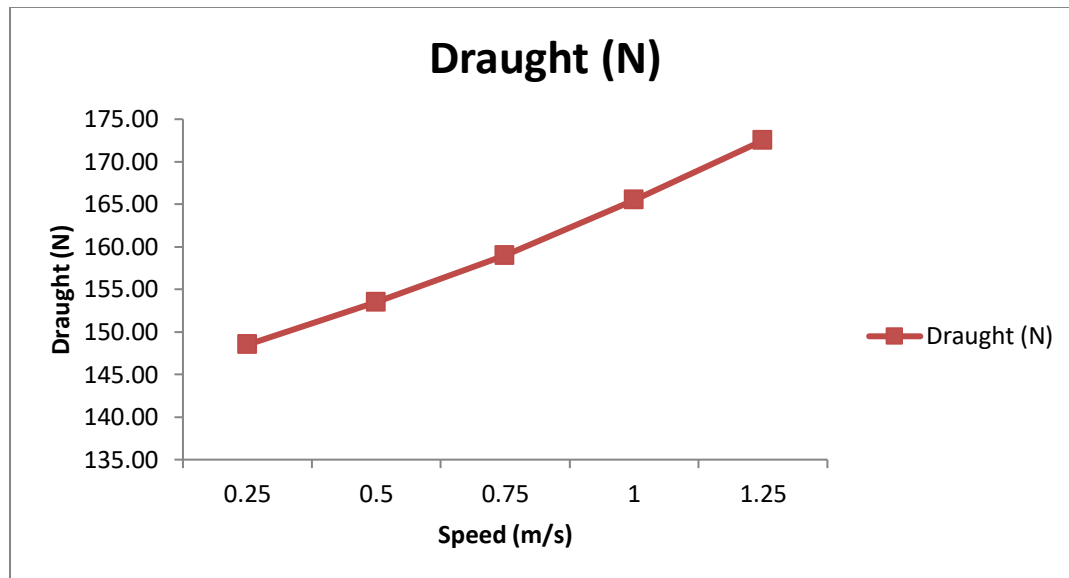


Figure 4.23 Graph of Draught against Speed at $\beta = 30^\circ$, $b = 10 \text{ mm}$ $d = 100 \text{ mm}$
 β = Lift angle, b = width of cutting edge, d = Depth of operation, s = Speed of operation.

4.2 Discussion of Results

The results of tables 4.6 and 4.7 showed that the type of soil that is predominant in the study area (Kwara state) is Loamy sand. The properties of the soil used as determined were;

Percentage sand	84.96
Percentage silt	8.00
Percentage clay	7.04
Cohesion	16.67 kPa
Angle of internal friction	26.6°
Soil-metal friction angle	29.8°
Moisture content	11 – 12%
Bulk density	1.50 g/cm^3

Table 4.10 is the ANOVA (Analysis of variance) for the four factors considered, namely; depth of operation, speed of operation, width of cutting edge and tool lift angle. The table showed that

contribution of individual factor and combination of factors to the draught of the tillage tool was significant at 5% confidence level. Regression equation 4.1 showed the relationship between the draught and four factors considered.

4.2.1 Effects of Depth of Operation on the Draught of Narrow Tillage Tool

The results of appendix II and figure 4.11 showed that draught of an inclined narrow model chisel blade increases with increase in depth of operation. This is so because as the depth of operation increases the tool come in contact with more soil masses and hence additional effort was required to cut the soil, lift, pulverize and displace the soil to enhance good seed bed. Figure 4.11 also indicated that the relationship between the draught and depth of operation is almost linear. The linearity of the relationship between draught and depth of operation was further amplified by equation 4.3 which is the regression equation for draught and operating depth. The results of table 4.10 showed that the draught of the tillage tool was significantly affected by tool operating depth. This result agreed with the one obtained by Ashrafi and Kushwaha, 2006, Mamman and Oni, 2005, Garner *et al.*, 1987 and Oni *et al.*, 1992.

4.2.2 Effects of Speed of Operation on the Draught of Narrow Tillage Tool

The results of appendix II and figure 4.12 showed that draught of an inclined narrow model chisel blade increases with increase in speed of operation. Figures 4.19 to 4.23 revealed that the rate of increment was slow but table 4.10 showed that the effect of operating speed on draught was still significant. The relationship between the draught and speed of operation is almost linear. The regression equation (equation 4.4) also indicated the nature of relationship between the draught and speed of operation. This result was in line with the one obtained by Ashrafi and

Kushwaha, 2006, Chandon and Kushwaha (2002), Girma, 1989, Mamman and Oni, 2005 and Oni *et al.*, 1992.

4.2.3 Effects of Width of Cutting edge on the Draught of Narrow Tillage Tool

Figure 4.12 and results of appendix II and showed that draught of an inclined narrow model chisel blade increases with increase in width of cutting edge. Figure 4.9 and regression equation 4.5 showed that the relationship between the draught and width of cutting edge was linear. The increase in draught was as a result of more soil masses that was been cut as the implement width was increased. This result agreed with the one obtained by Ashrafi and Kushwaha, 2006, Mamman and Oni, 2005, Garner *et al.*, 1987 and Oni *et al.*, 1992.

4.2.4 Effects of Angle of Lift on the Draught of Narrow Tillage Tool

Figure 4.10 showed that the draught of an inclined narrow model chisel blade progressively decreases with increase in lift angle up to certain value and then increase with increase in lift angle. This figure showed that the relationship between the draught and lift angle was quadratic. This result was further established by the regression equation 4.2. Solving equation 4.2 gives 42° as the angle that required minimum amount of draught to till the soil at all conditions. The reason for this result can be explained by the fact that at lower angle of lift, large amount of soil masses actually rest on the tillage tool and was not easily displaced resulting in high draught value, but as the lift angle increases up to 42° it was easier for the tool to displace the soil to the side and reduce the quantity of soil carried by the tool and hence reduce the tillage tool draught. Beyond 42° the draught increases with increase in lift angle because the tillage tool tends to push the soil ahead of it instead of actually tilling the soil.

In summary, appendix 2 showed the draught values as obtained from the soil bin at various tool width of cutting edge, tool depth, tool angle of lift and operating speed. The table showed that the draught of an inclined tillage tool used for this experiment increase with increase in tool width of cutting edge, tool depth and speed of operation, but the draught progressively decreases as the tool lift angle increases up to 42° and then increases as the lift angle increases. It implied that the relationship between draught and lift angle is quadratic.

Tables 4.8 and Figures 4.61 to 4.63 showed that moisture loss from the soil surface can be retarded by covering it with black nylon. This was essential for this experiment to facilitate speedy data acquisition by limiting the amount of water needed by the soil in the soil bin. Figures 4.71 to 4.74 indicated that speed of operation has effects on the draught of tillage tools. It showed that as the speed of operation increases, the draughts also increase and that the relationship between the speed of operation and draught is not linear but parabolic in nature.

Figures 4.10 show the analysis of variance (ANOVA). The Table indicated that the four factors considered in this research work (width of cutting edge b , tool lift angle β , depth of operation d and speed of operation s) significantly affected the draught of an inclined narrow model chisel blade. The interactions of these factors are also significant except for the interaction of width of cutting edge b , tool lift angle β , depth and speed of operation s that is not significant at 5% confidence level. The draught of inclined narrow chisel model increases with increase in width of cutting edge, depth of operation and speed of operation. The tool lift angle has a quadratic relationship with draught.

Figures 4.9, 4.10, 4.11 and 4.12 show the graph of draught against width of cutting edge, tool lift angle, depth of operation and speed of operation respectively. While the plots for width of cutting edge, depth of operation and speed of operation exhibit direct relationship, tool angle of lift shows quadratic relationship.

Table 4.15 shows the regression analysis for combined effect of the four factors considered; width of cutting edge, tool lift angle, depth of operation and speed of operation. The coefficient of regression equation for each factors are; 0.621, -0.121, 1.706 and 29.706 respectively. The equation is as presented in equation (4.1). The equation showed that linear relationship is significant for the combination of all the four factors. Equations 4.2, 4.3, 4.4 and 4.5 are the individual regression equations for tool lift angle, depth of operation, speed of operation and width of cutting edge respectively.

Figures 4.16, 4.17, 4.18 ad 4.19 shows the regression analysis and coefficients of regression equation for tool lift angle, depth of operation, speed of operation and width of cutting edge respectively. All the factors show direct relationship except for tool lift angle which shows quadratic relationship.

Figures 4.19, 4.20, 4.21, 4.22 ad 4.23 show the graphs of Graph of Draught against Speed at $\beta = 30^\circ$, $b = 10$ mm $d = 20, 40, 60, 80$ ad 100 mm respectively. All the plots show linear relationship.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions.

The following conclusions could be drawn from the results obtained;

- i) The soil type that is predominant in Kwara state for agricultural practices is Loamy sand with 84.96% sand, 8.00% silt and 7.04% clay.
- ii) The engineering properties of the soil relevant to this research were; soil bulk density, soil angle of internal friction, soil-metal friction angle and soil cohesion and their corresponding values were; 1.50 g/cm³, 26.6⁰, 29.8⁰ and 16.67kPa respectively.
- iii) The draught an inclined tillage tool is significantly affected by tool width of cutting edge, tool depth, tool angle of lift and operating speed. The effects of interactions of tool width of cutting edge, tool depth, tool angle of lift and operating speed are also significant. The draught increase with increase in tool width of cutting edge, tool depth and operating speed, but the relationship between the draught and tool angle of lift is quadratic. It was also observed that at higher depth of operation, the rate of increment of the draught tends to reduce. This is not unconnected to moisture migration from upper layer of the soil to lower layer.
- iv) Regression equations were developed based on the contribution of each factor and combination of all four factors to Draught of an inclined narrow chisel model. The model equations developed were validated using extra data from soil bin experiments

at the same soil and tool but different operational conditions. The regression equation formed showed linear relationship between Draught and speed, Draught and width of cutting edge, and Draught and depth of operation but the relationship between Draught and tool angle is quadratic, 42° was obtained as the best angle of lift for minimum energy requirement at all conditions.

5.2 Recommendations

It is recommended that results of this research be adopted for effective tillage tools design, minimum energy requirement and low production costs. This research was carried out only on loamy sand soil, it is therefore, recommended that the research be repeated using other agricultural soil types.

5.3 Contributions to Knowledge

- ❖ Measurement of Draught in 3 directions (XYZ Directions).
- ❖ Measurement of Draught with respect to Time and Distance.
- ❖ Available data base for Farm tools manufacturers and Farmers for machinery selection.
- ❖ Complete instrumentation of soil bin.

REFERENCES

ASAE Standard, 2000. ASAE D497.4. Agricultural Machinery Management Data.

ASAE, St. Joseph, MI, USA

ASAE. 1999. ASAE Standard D497.4. Agricultural machinery management data. St.

Joseph, Mich.: ASAE

Ashrafi Zandeh S. R. and R. L. Kushwaha, 2006. Development of a Tillage Energy

Model Using a Simple Tool. The Canadian society for engineering in agricultural,

Food, environmental, and biological systems. Paper No. 06-130.

Ayers, P.D. 1987. Moisture and density effects on soil shear strength parameters for

coarse grained soils. *Transactions of the ASAE* 30(5): 1282-1287.

Ayers, P.D., J.V. Perumpral. 1982. Moisture and density effect on cone index. *Transactions of*

the ASAE 25(5): 1169-1172.

Azyamova, E.N. 1963. Studies of dynamics of deformation of soil. Trudy (TSNIIMESKH)

Minsk 1:131-139. (Translated by W.R. Gill, National Tillage Machinery Laboratory,

USDA-ARS, Auburn, AL).

Baily, A.C., C.E. Johnson and R.L. Schafer. 1984. Hydrostatic compaction of agricultural soils.

Transactions of the ASAE 27(4): 925-955. 129

Bicki, T.J. and J.C. Siemens. 1991. Crop response to wheel traffic soil compaction. *Transactions*

of the ASAE 34 (3): 909-913.

Blumel, K. 1986. Messungen an Einer Ackerfrase in der Bodenrinne unter besonderer

Berucksichtigung der auftretenden Krafte (Measurements on a rotary tiller in the soil bin

in special consideration of the acting forces). Research Report Agricultural Engineering

No. 129 of Max-Eyth Society, University of Hohenheim, Germany.

- Burt, E.C., R.K. Wood, and A.C. Baily. 1992. Some comparisons of average to peak soil-tire contact pressures. *Transactions of the ASAE* 35 (2): 401-405.
- Camp, D.R. and W.R. Gill. 1969. The effect of drying on soil strength parameters. *Soil Science Society of America Proceedings*, 13(5): 641-644.
- Chandon, K., and R. L. Kushwaha. 2002. Soil Forces on Deep Tillage Tools. Paper Presented at the AIC 2002 meeting, CSAE/SCGR Programme, Saskatoon, Sasatchewan, Canada. July 14 = 17, 2002.
- Chancellor, W.J. 1994. Soil physical properties. In *Advances in Soil Dynamics*. Ed. P.D. Hansen ASAE Monograph, 12, 21-254. St. Joseph, MI: ASAE.
- Chi, L. and R.L. Kushwaha. 1991. Three-dimensional, finite element interaction between soil and simple tillage tool. *Transactions of the ASAE* 34(2): 361-366. 130
- Darmora, D.P. and K.P. Pandey. 1995. Evaluation of performance of furrow openers of combined seed and fertilizer drills. *Soil & Tillage Research* 34: 127-139.
- Desbiolles J M A; Godwin R J; Kilgour J; Blackmore B. S. 1997. A novel approach to the prediction of tillage tool draught using a standard tine. *Journal of Agricultural Engineering Research*, 66, 295–309
- Dimaggio, F.L. and I.S. Sandler. 1971. Material model for granular soil. *Journal of the Engineering Mechanics Division, American Society of Civil Engineers* 93(3): 935-950.
- Drucker, D.C., R.E. Gibson and D.J. Hankwe. 1955. Soil mechanics and work-hardening theory of plasticity. In *Proceedings of the American Society of Civil Engineers* Vol. 81, Paper 798, 1-14.
- Duncan, J.M. and C.Y. chang. 1970. Nonlinear analysis of stress and strain in soils. *Journal of Soil Mechanics and Foundations Division, American Society of Civil*

Engineers 89 (SM5):1629-1653.

- Fielke, J.M. 1999. Finite element modelling of the interaction of the cutting edge of tillage implements with soil. *Journal of Agricultural Engineering Research* 74: 91-101
- Fornstrom, K.J., R.D. Brazee and W.H. Johnson. 1970. Tillage-tool interaction with a bounded, artificial soil. *Transactions of the ASAE*: 409-416.
- Garner, T.H., W.R. Raynolds, H.H. Miles, J.W. Davis, D. Wolf and U.M. Peiper. 1987. Energy requirement for subsoiling coastal plain soils. *Transactions of the ASAE* 30(2): 343-349.
- Gill, W.R. and G.E. Vanden Berg. 1968. *Soil Dynamics in Tillage and Traction*. USDAARS Agricultural Handbook No. 316. U.S., Washington DC 20402: Government Printing Office.
- Girma, G. 1989. Measurement and prediction of forces on plough bodies-1. Measurement of forces and soil dynamic parameters. Land and Water Use, eds., Dodd & Grace, ISBN, 1539-1546. 906191 980 0, Balkema, Rotherdam. 132
- Glancey, J.L., S.K. Upadhyaya, W.J. Chancellor and J.W. Rumsey. 1996. Prediction of agricultural implement draft using an instrumented analog tillage tool. *Soil & Tillage Research* 37: 47-65.
- Godwin, R.J. and M.J. O'Dogherty. 2003. Integrated soil tillage force prediction models. In Proceedings of the 9th European Conference of the ISTVS, 2-21. Har2-21.per Adams, UK, September 8th to 11th, 2003,
- Godwin, R.J. and G. Spoor. 1977. Soil failure with narrow tines. *Journal of Agricultural Engineering Research* 22(4): 213-228.
- Grisso, R.D., J.V. Perumpral and C.S. Desai. 1980. A soil-tool interaction model for narrow tillage tools. ASAE Paper 80-1518, ASAE, St. Joseph, MI 49085.

- Grisso, R.D., M.Yasin and M.F.Kocher. 1996. Tillage implement force operating in silty clay loam. *Trans of ASAE* 39(6): 1977 – 1983.
- Grisso, R.D. and J.V. Perumpral. 1985. Review of models for predicting performance of narrow tillage tool. *Transactions of the ASAE* 28(4): 1062-1067.
- Gupta, S.C., A. Hadas, W.B. Voorhees, D. Wolf, W.E. Larson and P.P. Sharma. 1990. Development of guides on the susceptibility of soils to excessive compaction. University of Minnesota BARD Report. St. Paul. t133
- Gupta C P; Pandey K. P. 1989. An analytical model for predicting draft forces on convex-type cutting blades. *Soil and Tillage Research*, 14, 131–144
- Hakansson, I. and H. Petelkau. 1991. Benefits of reduced vehicles weight. In *Soil Compaction in Crop Production*, ed. B.D. Soane and C. Vanouwerkerk, Amsterdam, Netherland: Elsevier. *Soil & Tillage Research* 28(1993): 159-177.
- Harrigan, T.M. and C.A. Rotz. 1995. Draft relationships for tillage and seeding equipment. *Applied Engineering in Agriculture* 11(6): 773 – 783.
- Henderson, H.D., M. Almassi, A.A. Malik, and Z. Mojaddadi. 1981. Deep tillage in the Beqa'a Valley, Lebanon Effect on soil properties and yield of wheat and potatoes. *Trans of ASAE* 24(6): 1466–1470
- Hettiaratchi, D.R.P. and A.R. Reece. 1967. Symmetrical three-dimensional soil failure. *Journal of Terramechanics* 4(3): 45-67.
- Hettiaratchi D.R.B. 1993. The development of a powered low draught tine cultivator. *Soil & Tillage Research* 28(1993): 159-177.
- Hettiaratchi, D.R.P. and A.R. Reece. 1974. The calculation of passive soil resistance. *Geotechnique* 24(3): 289-310.

- Hillel, D. 1980. *Fundamentals of Soil Physics, 1st edition*. New York, NY: Academic Press, Inc.
- Hryciw, R. D., S. A. Raschke, A. M. Ghalib, D. A. Horner and J. F. Peters. 1997. Videotracking for experimental validation of discrete element simulations of large discontinuous deformations. *Computer and Geotechnique* . 21(3): 235-253. 134
- Janzen, D.C. 1990. An industry response to concerns in agriculture. ASAE paper No. 90-1074. St. Joseph, MI: ASAE.
- Jayasuriya, H.P.W. 1999. Modeling soil-tire interactions in lateritic soil. Unpublished PhD diss. (AE-99-1) Bangkok, Thailand.: Asian Institute of Technology, Department of Agricultural Systems and Engineering.
- Johnson, C.E., L.L. Jensen, R.L. Schafer and A.C. Baily. 1978. Some soil tool analogs. ASAE Paper No. 77-1054, ASAE, St. Joseph, MI 49085.
- Karmakar, S. and R. L. Kushwaha. 2005a. Simulation of soil deformation around a tillage tool using computational fluid dynamics. *Transactions of the ASAE* 48(3): 923- 932.
- Karmakar, S. and R. L. Kushwaha. 2005b. CFD Simulation of soil forces on a flat tillage tool. ASABE paper No. 051160. St Joseph, ASABE.
- Katsygin, V.V. 1964. Relation of draft of agricultural machines to operation speeds. *Voprosy Sel'skohozyaistvennoi Mekhaniki*, Section 2, 96-119, Vol. XII. (Translated by W.R. Gill, National Tillage Machinery Laboratory, USDA-ARS, Auburn, AL).
- Katsygin, V.V. 1969. Relation of draft of agricultural machines to operation speeds. *Voprosy Sel'skohozyaistvennoi Mekhaniki*, Section 2, 96-119, Vol. XII. (Translated by
- Kepner, R.A., R. Bainer and E.L. Barger. 1972. *Principles of Farm Machinery*. Westport, CT: The Avi Publishing Co. 135

- Kheiralla A F; Yahya A; Zohadie M; Ishak W. 2004. Modelling of power and energy requirements for tillage implements operating in Serdang sandy clay loam, Malaysia. *Soil and Tillage Research*, 78, 21–34
- Khot, L.R., V.M. Salokhe and H. Jayasuriva. 2005. Experimental validation of distinct element simulation for dynamic wheel-soil interaction. ASAE Paper No. 053120. Presented in Annual International Meeting, 17-20 July, 2005, Tampa Convocation Center, Tampa, Florida, USA.
- Kondner, R.L. and J.S. Zelasko. 1963. A hyperbolic stress-strain response: cohesive soils. *Journal of Soil Mechanics and Foundations Division, American Society of Civil Engineers* 89 (SM1):115-143
- Koolen, A.J. and H. Kuipers. 1983. *Agricultural soil mechanics*. Berlin, Germany. Library of Congress Cataloging in Publication Data.
- Kushwaha, R.L. and C. Linke. 1996. Draft-speed relationship of simple tillage tools at high operating speeds. *Soil & Tillage Research* 39: 61-73. 136
- Kushwaha, R.L. and J. Shen. 1995. Finite element analysis of the dynamic interaction between soil and tillage tool. *Transactions of the ASAE* 37(5): 1315-1319.
- Lindstrom, M.J., W.W. Nelson, T.E. Schumacher and G.D. Lemme. 1990. Soil movement by tillage as affected by slope. *Soil & Tillage Research* 17:225-264
- Mamman E. and Oni K. 2005. Draught Performance of a Range of Model Chisel Furrowers. *Agricultural Engineering International: the CIGR Ejournal*. Manuscript PM 05 003. Vol. VII.
- McKyes, E. 1985. *Soil Cutting and Tillage*. Amsterdam, The Netherlands. Elsevier Science Publishers. 137

- McKyes, E. 1978. The calculation of draft forces and soil failure boundaries of narrow cutting blades. *Transactions of the ASAE* 21(1): 20-24.
- McKyes, E. and O .S. Ali. 1977. The cutting of soil by narrow blades. *Journal of Terramechanics* 14(2): 43-58.
- Mouazen, A.M. and H. Ramon. 2002. A numerical hybrid modelling scheme for evaluation of draught requirements of a subsoiler cutting a sandy loam soil, as affected by moisture content, bulk density, and depth. *Soil & Tillage Research* 63: 155-165.
- Mouazen, A.M. and M. Nemenyi. 1999. Finite element analysis of subsoiler cutting in non-homogeneous sandy loam soil. *Soil & Tillage Research* 51: 1-15.
- Mulqueen, J., J.V. Stafford and D.W. Tanner. 1977. Evaluation of penetrometers for measuring soil shear strength. *Journal of Terramechanics* 14(3): 137-151. Nichols, M.L. 1931. The dynamic properties of soil II. Soil and metal friction. *Journal of Agricultural Engineering* 12:321-324. 138
- O'Callaghan, J.R. and K.M. Farrelly. 1964. Cleavage of soil by tined implements. *Journal of Agricultural Engineering Research* 9(3): 259-270.
- Oni K. C., S. J. Clark and W. H. Johnson. 1992. The effects of design on the draught of Undercutter-sweep tillage tools. *Soil & Tillage Research*, 22 (1992) 117-130. Elsevier Science Publishers B. v., Amsterdam.
- Panwar, J.S. and J.C. Siemens. 1972. Shear strength and energy of soil failure related to density and moisture. *Transactions of the ASAE* 15: 423-427.
- Payne, P.C.J. and D.W. Tanner. 1959. The relationship between rake angle and the performance of simple cultivation implements. *Journal of Agricultural Engineering Research* 4(4): 312-

325.

- Payne, P.C.J. 1956. The relationship between the mechanical properties of soil and the performance of simple cultivation implements. *Journal of Agricultural Engineering Research* 1(1): 23-50.
- Perdok UD, van de Werken G. 1982. Power and labour requirements in soil tillage. *International Congress 12th of Agricultural Machinery Exhibition*, Landbouw RAI, Amsterdam, 55-70.
- Perumpral, J.V., R.D. Grisso and C.S. Desai. 1983. A soil tool model based on limit equilibrium analysis. *Transactions of the ASAE* 26(4): 991-995.
- Plouffe, C., C. Lague, S. Tessier, M.J. Richard and N.B. McLaughlin. 1999. Moldboard plow performance in a clay soil: simulation and experiment. *Transactions of the ASAE* 42(6): 1531-1539.
- Reece, A.R. 1965. The fundamental equation of earthmoving machines. Symposium of Earthmoving Machines. *Institute of Mechanical Engineering*. 179(3F).
- Rosa, U.A. and D. Wulfsohn. 1999. Constitutive model for high speed tillage using narrow tools. *Journal of Terramechanics* 36: 221-234.
- Roscoe, K.H., A.N. Schofield and C.P. Wroth. 1958. On the yielding of soils. *Geotechnique* 8(1): 22-53.
- Schafer, R.L., and C.E. Johnson. 1982. Changing soil condition-The soil dynamics of tillage. In *Tillage Effects on Soil Physical Properties and Processes*. American Society of Agronomy Special Publication Number 44, 14-15. Madison.
- Schmertmann, J.H. 1975. Measurement of insitu shear strength. In *Proceedings of the Conference on insitu measurement of soil properties*, 2: 57-138.

- Schuring, D.J. and I.R. Emori. 1964. Soil deforming processes and dimensional analysis. Paper 897c. *Society of Agricultural Engineering*, New York.
- Shen, J. and R.L. Kushwaha. 1998. *Soil-Machine Interactions: A Finite Element Perspective*. Saskatoon, Saskatchewan: Marcel Dekker Inc.
- Shikanai, T. and M. Ueno. 2002. Simulation of soil resistance at plate penetration by the distinct element method. ASAE Paper No. 023046. Presented in Annual International Meeting, July 28-July 31, 2002, Hyatt Regency Chicago, Chicago, Illinois, USA.
- Siemens, J.C.,
- Shikanai, T. and M. Ueno. 2002. Simulation of soil resistance at plate penetration by the distinct element method. ASAE Paper No. 023046. Presented in Annual International Meeting, July 28-July 31, 2002, Hyatt Regency Chicago, Chicago, Illinois, USA.
- Siemens, J.C.,
- Smith, J.L. 1964. Strength-moisture-density relations of fine grained soils in vehicle mobility research. Technical report No. 3-369. U.S. Army Engineer Waterways Experimental Station. Vicksburg, MS.
- Soehne, W. 1958. Fundamentals of pressure distribution and soil compaction under tractor tires. *Journal of Agricultural Engineering* 39: 276-281, 290.
- Summers, J.D., A. Khalilian and D.G. Batchelder. 1986. Draft relationships for primary tillage in Oklahoma soils. *Transactions of the ASAE* 29(1): 37-39.
- Swick W C; Perumpral J V (1988). A model for predicting soil tool interaction. *Journal of Terramechanics*, 25, 43–56
- Tang, W.H. and K. Hoeg. 1968. Plane strain loading of a strain hardening soil. Contact Report No. 3-129, Report 5, Contract DA-22-079-eng-471. Cambridge, MA:

Department of Civil Engineering, MIT.

Terzaghi, K. 1943. *Theoretical Soil Mechanics*. New York, NY: John Wiley & Sons.

Vetrov, Y.A. and V.P. Stanevski. 1972. The investigation of the factors of the speed of cutting soils. *Mining Construction and Highway Machines* 8: 21-26. Translated by W.R. Gill, National Tillage Machinery Laboratory, Auburn, AL.

Wheeler P N; Godwin R J. 1996. Soil dynamics of single and multiple tines at speeds up to 20 km/h. *Journal of Agricultural Engineering Research*, 63(3), 243–250

Wroth, C.P. and G.T. Houlsby. 1980. A critical state model for predicting the behavior Of Clays. In *Proceedings of the Workshop on Limit Equilibrium, Plasticity and Generaralized Stress-Strain in Geotechnical Engineering*: 592-627, New York, NY: ASAE.

Zhang, Z.X. and R.L. Kushwaha. 1999. Operating speed effect on the advancing soil failure zone in tillage operation. *Canadian Agricultural Engineering* 41(2): 87-92. 145

Zeng, D. and Y. Yao. 1992. A dynamic model for soil cutting by blade and tine. *Journal of Terramechanics* 29(3): 317-327.144

Appendix I: Design of transmission system for soil bin tool carriage

Soil bin dimensions

Length = 5840mm (5.84m)

Width = 430mm (0.43m)

Depth = 570mm (0.57m)

Thickness of the wall = 110mm (0.11m)

The carriage shall be powered by 5hp (3.7285kW) electric motor. The power transmission system shall be belt – pulley (V – belt and pulley).

Selection of cross – section of belt

For power, $P = 1.5 - 15\text{kW}$, cross – section B of V – belt is suitable

Top width of belt, $w = 17\text{mm}$

Nominal thickness, $t = 13\text{mm}$

Mass per metre = 0.189kg/m

If;

Motor speed (N_1) = 1400 rpm

Diameter of driving pulley (d_1) = 60mm

Diameter of driven pulley (d_2) = 300mm

The speed of the driven pulley can be calculated using the equation below;

$$N_1 d_1 = N_2 d_2 \quad (3.10)$$

$$N_2 = \frac{N_1 d_1}{d_2} = \frac{1400 \times 60}{300} = 280\text{rpm}$$

Belt speed, V_b

$$V_b = \frac{\pi \times N_1 d_1}{60 \times 1000} = \frac{3.142 \times 1400 \times 60}{60 \times 1000} = 4.40\text{ m/s} \quad (3.11)$$

If the diameter of the roller on the driven shaft (d_3) = 100mm

The linear speed of the machine (V) is given by

$$V = \frac{\pi d_3 N_2}{60 \times 1000} \quad (3.12)$$

$$V = \frac{3.142 \times 100 \times 280}{60 \times 1000} = 1.466 \text{m/s (5.28 km/hr)}$$

The speed can be varied by using pulleys of various diameters on the driven shaft.

The pitch length of the belt required is given by;

$$L = 2C + \frac{\pi}{2}(D_1 + D_2) + \frac{(D_2 - D_1)^2}{4C} \quad (3.13)$$

Where;

L = belt length

D₁ = diameter of small pulley

D₂ = diameter of big pulley

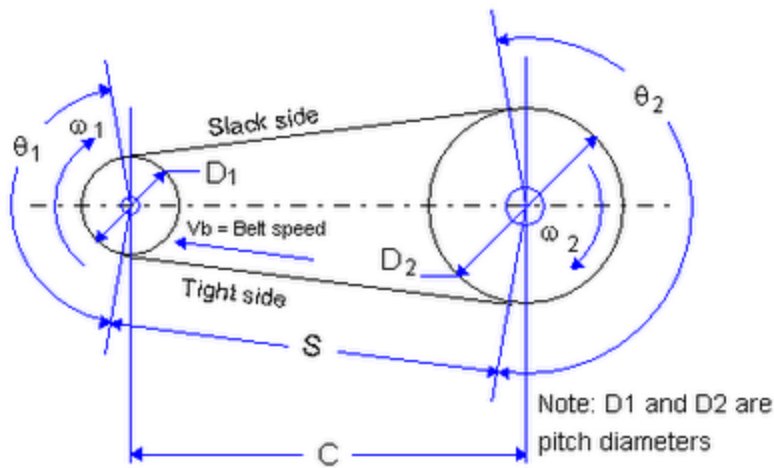
C = centre distance

If C = 46cm, D₁ = 60mm (6cm) and D₂ = 300mm (30cm)

Then;

$$L = 2 \times 46 + (6 + 30) + \frac{(30 - 6)^2}{4 \times 46} = 131.13 \text{cm}$$

Basic belt drive geometry



Angle of contact on each sheave is given by

$$\theta_1 = 180 - 2 \sin^{-1} \frac{(D_2 - D_1)}{2C} \quad (3.14)$$

$$\theta_2 = 180 + 2 \sin^{-1} \frac{(D_2 - D_1)}{2C} \quad (3.15)$$

$$\theta_1 = 149.75^\circ$$

$$\theta_2 = 210.25^\circ$$

Belt tension

The tension on the belt was calculated as stated below;

$$P = (T_1 - T_2)V \quad (3.16)$$

$$\frac{T_1}{T_2} = e^{f\theta} \quad (3.17)$$

$$V = \frac{\Pi Nd}{60} \quad (3.18)$$

Where

P = power transmitted = 3.728kW (3728W)

T_1 = tension on the tight side

T_2 = tension on the slack side

V = belt speed = 4.40m/s

f = coefficient of friction = 0.25

θ = angle of wrap on the small pulley = $150^\circ = 2.62\text{rad}$

From equation 3.22

$$T_1 - T_2 = \frac{3728}{4.4} = 847.3\text{W} \quad (3.19)$$

$$T_1 = T_2 + 847.3 \quad (3.20)$$

From equation 3.23

$$T_1 = T_2 e^{f\theta} \quad (3.21)$$

From equations 3.26 and 3.27

$$T_2 e^{f\theta} = T_2 + 847.3 \quad (3.22)$$

$$T_2 = \frac{847.3}{e^{f\theta} - 1} \quad (3.23)$$

$$T_2 = 1177\text{N} (1.177\text{kN})$$

$$T_1 = 2024\text{N} (2.024\text{kN})$$

Shaft design based on strength

Design is carried out so that the stress at any location on the shaft should not exceed yielding point of the material.

Stress due to Torsion is given by;

$$\tau_{xy} = \frac{T \times r}{J} = \frac{16T}{\pi d_0^3 (1 - C^4)} \quad (3.24)$$

Where;

τ_{xy} = shear stress due to torsion

T = torque on the shaft

d_o = outside diameter of the shaft

$$C = \frac{d_i}{d_o}$$

d_i = Internal diameter of the shaft (hollow)

$$T = \frac{7024 \times hP}{N(RPM)} = \frac{9549 \times kW}{N(RPM)} \quad (3.25)$$

For 5Hp electric motor and shaft speed of 280 rpm;

Then $T = 125.43 \text{ kN-m}$

For 30mm shaft

$$\tau_{xy} = 23666 \text{ kN/m}^2 \text{ (23.666 Mpa)}$$

APPENDIX II. Tillage Draught for Inclined Tool at various Width, Lift angle, Depth and Speed of Operation.

S/N	Width of cutting edge (mm)	Lift angle (degree)	Depth of cut (mm)	Speed of operation (m/s)	Draught (N) 1	Draught (N) 2	Average Draught (N)
1	10	20	20	0.25	21	20	20.50
2				0.50	26	26	26.00
3				0.75	35	36	35.50
4				1.00	47	46	46.50
5				1.25	53	55	54.00
6		40	40	0.25	55	56	55.50
7				0.50	67	66	66.50
8				0.75	81	83	82.00
9				1.00	89	90	89.50
10				1.25	95	95	95.00
11		60	60	0.25	105	107	106.00
12				0.50	116	118	117.00
13				0.75	123	122	122.50
14				1.00	132	133	132.50
15				1.25	138	139	138.50
16	10	80	80	0.25	142	141	141.50
17				0.50	148	149	148.50
18				0.75	154	153	153.50
19				1.00	161	160	160.50
20				1.25	166	167	166.50
21		100	100	0.25	172	172	172.00
22				0.50	176	177	176.50
23				0.75	183	182	182.50
24				1.00	186	185	185.50
25				1.25	190	189	189.50
26	10	30	20	0.25	20	19	19.50
27				0.50	37	39	38.00
28				0.75	45	46	45.50
29				1.00	52	53	52.50
30				1.25	56	57	56.50
31		40	40	0.25	59	58	58.50
32				0.50	66	65	65.50
33				0.75	73	74	73.50
34				1.00	79	78	78.50
35				1.25	84	82	83.00
36	10	60	60	0.25	89	87	88.00
37				0.50	96	95	95.50

S/N	Width of cutting edge (mm)	Lift angle (degree)	Depth of cut (mm)	Speed of operation (m/s)	Draught (N) 1	Draught (N) 2	Average Draught (N)
38				0.75	102	103	102.50
39				1.00	108	110	109.00
40				1.25	115	117	116.00
41			80	0.25	119	121	120.00
42				0.50	126	127	126.50
43				0.75	133	132	132.50
44				1.00	141	140	140.50
45				1.25	146	146	146.00
46			100	0.25	148	149	148.50
47				0.50	154	153	153.50
48				0.75	159	159	159.00
49				1.00	165	166	165.50
50				1.25	173	172	172.50
51		40	20	0.25	19	21	20.00
52				0.50	38	39	38.50
53				0.75	46	47	46.50
54				1.00	53	54	53.50
55				1.25	58	59	58.50
56			40	0.25	61	62	61.50
57				0.50	69	67	68.00
58				0.75	74	73	73.50
59				1.00	78	79	78.50
60				1.25	84	83	83.50
61			60	0.25	89	88	88.50
62				0.50	97	96	96.50
63				0.75	105	103	104.00
64				1.00	112	114	113.00
65				1.25	117	119	118.00
66			80	0.25	121	120	120.50
67				0.50	129	131	130.00
68				0.75	140	138	139.00
69				1.00	144	145	144.50
70				1.25	150	149	149.50
71			100	0.25	155	153	154.00
72				0.50	158	157	157.50
73				0.75	163	162	162.50
74				1.00	166	164	165.00
75				1.25	169	170	169.50
76		50	20	0.25	18	17	17.50
77				0.50	39	37	38.00

S/N	Width of cutting edge (mm)	Lift angle (degree)	Depth of cut (mm)	Speed of operation (m/s)	Draught (N) 1	Draught (N) 2	Average Draught (N)
78				0.75	44	44	44.00
79				1.00	49	48	48.50
80				1.25	59	60	59.50
81			40	0.25	62	62	62.00
82				0.50	67	69	68.00
83				0.75	73	75	74.00
84				1.00	82	82	82.00
85				1.25	89	90	89.50
86			60	0.25	93	92	92.50
87				0.50	99	98	98.50
88				0.75	105	105	105.00
89				1.00	114	112	113.00
90				1.25	118	120	119.00
91			80	0.25	123	122	122.50
92				0.50	133	134	133.50
93				0.75	144	143	143.50
94				1.00	148	149	148.50
95				1.25	152	155	153.50
96			100	0.25	153	155	154.00
97				0.50	158	159	158.50
98				0.75	163	162	162.50
99				1.00	167	166	166.50
100				1.25	170	172	171.00
101		60	20	0.25	23	24	23.50
102				0.50	33	32	32.50
103				0.75	41	43	42.00
104				1.00	54	53	53.50
105				1.25	61	60	60.50
106			40	0.25	64	63	63.50
107				0.50	73	74	73.50
108				0.75	78	79	78.50
109				1.00	84	84	84.00
110				1.25	92	91	91.50
111			60	0.25	95	96	95.50
112				0.50	102	101	101.50
113				0.75	109	107	108.00
114				1.00	116	118	117.00
115				1.25	122	124	123.00
116			80	0.25	126	125	125.50
117				0.50	133	132	132.50

S/N	Width of cutting edge (mm)	Lift angle (degree)	Depth of cut (mm)	Speed of operation (m/s)	Draught (N) 1	Draught (N) 2	Average Draught (N)
118				0.75	141	143	142.00
119				1.00	150	152	151.00
120				1.25	159	158	158.50
121			100	0.25	161	160	160.50
122				0.50	164	165	164.50
123				0.75	168	168	168.00
124				1.00	172	173	172.50
125				1.25	176	178	177.00
126	20	20	20	0.25	27	28	27.50
127				0.50	35	34	34.50
128				0.75	42	41	41.50
129				1.00	48	48	48.00
130				1.25	57	56	56.50
131			40	0.25	61	60	60.50
132				0.50	70	71	70.50
133				0.75	78	79	78.50
134				1.00	89	88	88.50
135				1.25	99	101	100.00
136			60	0.25	109	108	108.50
137				0.50	118	119	118.50
138				0.75	127	128	127.50
139				1.00	134	133	133.50
140				1.25	142	144	143.00
141			80	0.25	145	146	145.50
142				0.50	152	153	152.50
143				0.75	159	158	158.50
144				1.00	166	168	167.00
145				1.25	173	174	173.50
146			100	0.25	176	178	177.00
147				0.50	183	184	183.50
148				0.75	186	188	187.00
149				1.00	193	192	192.50
150				1.25	196	198	197.00
151		30	20	0.25	25	26	25.50
152				0.50	33	35	34.00
153				0.75	41	43	42.00
154				1.00	53	54	53.50
155				1.25	60	62	61.00

S/N	Width of cutting edge (mm)	Lift angle (degree)	Depth of cut (mm)	Speed of operation (m/s)	Draught (N) 1	Draught (N) 2	Average Draught (N)
156			40	0.25	64	65	64.50
157				0.50	73	72	72.50
158				0.75	79	78	78.50
159				1.00	84	85	84.50
160				1.25	90	90	90.00
161			60	0.25	95	94	94.50
162				0.50	99	101	100.00
163				0.75	115	115	115.00
164				1.00	119	120	119.50
165				1.25	124	125	124.50
166			80	0.25	129	128	128.50
167				0.50	135	133	134.00
168				0.75	142	141	141.50
169				1.00	148	149	148.50
170				1.25	153	154	153.50
171			100	0.25	158	157	157.50
172				0.50	163	162	162.50
173				0.75	168	166	167.00
174				1.00	175	176	175.50
175				1.25	179	180	179.50
176		40	20	0.25	23	24	23.50
177				0.50	31	32	31.50
178				0.75	39	42	40.50
179				1.00	49	51	50.00
180				1.25	61	62	61.50
181			40	0.25	65	64	64.50
182				0.50	71	72	71.50
183				0.75	77	78	77.50
184				1.00	83	82	82.50
185				1.25	88	89	88.50
186			60	0.25	94	93	93.50
187				0.50	99	98	98.50
188				0.75	106	108	107.00
189				1.00	114	115	114.50
190				1.25	123	122	122.50
191			80	0.25	127	126	126.50
192				0.50	133	132	132.50
193				0.75	139	140	139.50

S/N	Width of cutting edge (mm)	Lift angle (degree)	Depth of cut (mm)	Speed of operation (m/s)	Draught (N) 1	Draught (N) 2	Average Draught (N)
194				1.00	147	146	146.50
195				1.25	153	154	153.50
196			100	0.25	158	158	158.00
197				0.50	164	163	163.50
198				0.75	168	169	168.50
199				1.00	172	172	172.00
200				1.25	176	177	176.50
201		50	20	0.25	21	22	21.50
202				0.50	36	37	36.50
203				0.75	45	44	44.50
204				1.00	55	56	55.50
205				1.25	63	62	62.50
206			40	0.25	66	67	66.50
207				0.50	72	73	72.50
208				0.75	79	78	78.50
209				1.00	86	85	85.50
210				1.25	95	94	94.50
211			60	0.25	98	99	98.50
212				0.50	103	104	103.50
213				0.75	109	108	108.50
214				1.00	115	116	115.50
215				1.25	124	125	124.50
216			80	0.25	127	128	127.50
217				0.50	133	136	134.50
218				0.75	142	143	142.50
219				1.00	155	156	155.50
220				1.25	160	161	160.50
221			100	0.25	164	165	164.50
222				0.50	169	168	168.50
223				0.75	173	172	172.50
224				1.00	176	177	176.50
225				1.25	179	180	179.50
226		60	20	0.25	26	27	26.50
227				0.50	34	35	34.50
228				0.75	43	43	43.00
229				1.00	54	55	54.50
230				1.25	63	62	62.50
231			40	0.25	68	67	67.50

S/N	Width of cutting edge (mm)	Lift angle (degree)	Depth of cut (mm)	Speed of operation (m/s)	Draught (N) 1	Draught (N) 2	Average Draught (N)
232	30	20	60	0.50	73	74	73.50
233				0.75	81	80	80.50
234				1.00	85	86	85.50
235				1.25	94	96	95.00
236				0.25	98	98	98.00
237				0.50	105	106	105.50
238				0.75	111	110	110.50
239				1.00	121	122	121.50
240				1.25	125	128	126.50
241			80	0.25	132	133	132.50
242				0.50	139	141	140.00
243				0.75	148	147	147.50
244				1.00	156	155	155.50
245			100	1.25	164	166	165.00
246				0.25	168	170	169.00
247				0.50	173	174	173.50
248				0.75	177	177	177.00
249				1.00	182	181	181.50
250				1.25	187	188	187.50
251			40	0.25	31	30	30.50
252				0.50	38	39	38.50
253				0.75	44	43	43.50
254				1.00	56	57	56.50
255				1.25	64	65	64.50
256				0.25	69	68	68.50
257				0.50	75	73	74.00
258				0.75	87	88	87.50
259				1.00	96	97	96.50
260				1.25	106	105	105.50
261			60	0.25	114	116	115.00
262				0.50	123	122	122.50
263				0.75	136	137	136.50
264				1.00	144	145	144.50
265			80	1.25	155	154	154.50
266				0.25	158	157	157.50
267				0.50	164	165	164.50
268				0.75	172	171	171.50
269				1.00	177	176	176.50

S/N	Width of cutting edge (mm)	Lift angle (degree)	Depth of cut (mm)	Speed of operation (m/s)	Draught (N) 1	Draught (N) 2	Average Draught (N)
270				1.25	182	183	182.50
271			100	0.25	185	186	185.50
272				0.50	188	190	189.00
273				0.75	194	195	194.50
274				1.00	198	197	197.50
275				1.25	202	204	203.00
276		30	20	0.25	28	27	27.50
277				0.50	39	41	40.00
278				0.75	48	49	48.50
279				1.00	55	57	56.00
280				1.25	64	65	64.50
281			40	0.25	69	70	69.50
282				0.50	76	77	76.50
283				0.75	83	82	82.50
284				1.00	89	90	89.50
285				1.25	98	96	97.00
286			60	0.25	104	103	103.50
287				0.50	109	110	109.50
288				0.75	117	116	116.50
289				1.00	125	124	124.50
290				1.25	132	133	132.50
291			80	0.25	135	137	136.00
292				0.50	142	143	142.50
293				0.75	149	148	148.50
294				1.00	156	157	156.50
295				1.25	163	162	162.50
296			100	0.25	167	166	166.50
297				0.50	173	171	172.00
298				0.75	178	179	178.50
299				1.00	183	184	183.50
300				1.25	189	188	188.50
301		40	20	0.25	25	28	26.50
302				0.50	35	35	35.00
303				0.75	47	46	46.50
304				1.00	56	57	56.50
305				1.25	68	67	67.50
306			40	0.25	73	72	72.50
307				0.50	79	81	80.00

S/N	Width of cutting edge (mm)	Lift angle (degree)	Depth of cut (mm)	Speed of operation (m/s)	Draught (N) 1	Draught (N) 2	Average Draught (N)
308				0.75	87	88	87.50
309				1.00	94	93	93.50
310				1.25	98	99	98.50
311			60	0.25	104	103	103.50
312				0.50	109	110	109.50
313				0.75	116	115	115.50
314				1.00	121	122	121.50
315				1.25	125	126	125.50
316			80	0.25	129	130	129.50
317				0.50	135	137	136.00
318				0.75	142	141	141.50
319				1.00	156	158	157.00
320				1.25	163	165	164.00
321			100	0.25	169	169	169.00
322				0.50	173	174	173.50
323				0.75	179	177	178.00
324				1.00	183	182	182.50
325				1.25	188	189	188.50
326		50	20	0.25	24	25	24.50
327				0.50	37	39	38.00
328				0.75	44	46	45.00
329				1.00	56	55	55.50
330				1.25	63	64	63.50
331			40	0.25	67	69	68.00
332				0.50	74	75	74.50
333				0.75	79	81	80.00
334				1.00	96	95	95.50
335				1.25	102	103	102.50
336			60	0.25	107	106	106.50
337				0.50	113	114	113.50
338				0.75	119	118	118.50
339				1.00	126	125	125.50
340				1.25	133	132	132.50
341			80	0.25	138	136	137.00
342				0.50	144	142	143.00
343				0.75	149	151	150.00
344				1.00	158	157	157.50
345				1.25	166	168	167.00

S/N	Width of cutting edge (mm)	Lift angle (degree)	Depth of cut (mm)	Speed of operation (m/s)	Draught (N) 1	Draught (N) 2	Average Draught (N)
346			100	0.25	169	170	169.50
347				0.50	174	173	173.50
348				0.75	179	177	178.00
349				1.00	183	182	182.50
350				1.25	187	188	187.50
351		60	20	0.25	30	31	30.50
352				0.50	37	38	37.50
353				0.75	45	44	44.50
354				1.00	56	58	57.00
355				1.25	66	64	65.00
356			40	0.25	70	69	69.50
357				0.50	77	76	76.50
358				0.75	83	85	84.00
359				1.00	91	93	92.00
360				1.25	99	100	99.50
361			60	0.25	105	104	104.50
362				0.50	112	113	112.50
363				0.75	118	117	117.50
364				1.00	127	128	127.50
365				1.25	133	132	132.50
366			80	0.25	139	138	138.50
367				0.50	145	144	144.50
368				0.75	156	155	155.50
369				1.00	163	164	163.50
370				1.25	173	175	174.00
371			100	0.25	179	180	179.50
372				0.50	186	185	185.50
373				0.75	190	191	190.50
374				1.00	197	196	196.50
375				1.25	204	203	203.50
376	40	20	20	0.25	35	36	35.50
377				0.50	44	45	44.50
378				0.75	49	51	50.00
379				1.00	58	60	59.00
380				1.25	67	69	68.00
381			40	0.25	72	74	73.00
382				0.50	79	80	79.50
383				0.75	86	85	85.50

S/N	Width of cutting edge (mm)	Lift angle (degree)	Depth of cut (mm)	Speed of operation (m/s)	Draught (N) 1	Draught (N) 2	Average Draught (N)
384				1.00	95	96	95.50
385				1.25	109	108	108.50
386			60	0.25	114	115	114.50
387				0.50	121	120	120.50
388				0.75	132	133	132.50
389				1.00	147	145	146.00
390				1.25	158	160	159.00
391			80	0.25	163	165	164.00
392				0.50	169	170	169.50
393				0.75	176	177	176.50
394				1.00	182	181	181.50
395				1.25	189	190	189.50
396			100	0.25	192	193	192.50
397				0.50	197	196	196.50
398				0.75	204	205	204.50
399				1.00	209	208	208.50
400				1.25	213	214	213.50
401		30	20	0.25	32	33	32.50
402				0.50	41	42	41.50
403				0.75	50	51	50.50
404				1.00	62	61	61.50
405				1.25	70	69	69.50
406			40	0.25	74	75	74.50
407				0.50	82	83	82.50
408				0.75	90	89	89.50
409				1.00	97	97	97.00
410				1.25	104	105	104.50
411			60	0.25	110	109	109.50
412				0.50	117	116	116.50
413				0.75	122	124	123.00
414				1.00	131	133	132.00
415				1.25	140	141	140.50
416			80	0.25	146	145	145.50
417				0.50	152	154	153.00
418				0.75	159	160	159.50
419				1.00	165	164	164.50
420				1.25	171	170	170.50
421			100	0.25	176	176	176.00

S/N	Width of cutting edge (mm)	Lift angle (degree)	Depth of cut (mm)	Speed of operation (m/s)	Draught (N) 1	Draught (N) 2	Average Draught (N)
422				0.50	182	183	182.50
423				0.75	189	188	188.50
424				1.00	194	193	193.50
425				1.25	197	199	198.00
426		40	20	0.25	33	32	32.50
427				0.50	42	43	42.50
428				0.75	50	53	51.50
429				1.00	62	61	61.50
430				1.25	71	70	70.50
431			40	0.25	75	77	76.00
432				0.50	83	84	83.50
433				0.75	89	91	90.00
434				1.00	96	97	96.50
435				1.25	104	106	105.00
436			60	0.25	109	108	108.50
437				0.50	115	114	114.50
438				0.75	123	122	122.50
439				1.00	127	129	128.00
440				1.25	135	134	134.50
441			80	0.25	139	138	138.50
442				0.50	145	146	145.50
443				0.75	152	151	151.50
444				1.00	160	161	160.50
445				1.25	167	169	168.00
446			100	0.25	172	174	173.00
447				0.50	176	177	176.50
448				0.75	184	183	183.50
449				1.00	191	190	190.50
450				1.25	198	196	197.00
451		50	20	0.25	29	31	30.00
452				0.50	38	37	37.50
453				0.75	46	48	47.00
454				1.00	57	56	56.50
455				1.25	66	68	67.00
456			40	0.25	71	72	71.50
457				0.50	78	77	77.50
458				0.75	86	88	87.00
459				1.00	93	93	93.00

S/N	Width of cutting edge (mm)	Lift angle (degree)	Depth of cut (mm)	Speed of operation (m/s)	Draught (N) 1	Draught (N) 2	Average Draught (N)
460				1.25	104	106	105.00
461			60	0.25	108	110	109.00
462				0.50	115	116	115.50
463				0.75	121	123	122.00
464				1.00	128	129	128.50
465				1.25	135	136	135.50
466			80	0.25	140	141	140.50
467				0.50	145	146	145.50
468				0.75	154	155	154.50
469				1.00	162	163	162.50
470				1.25	169	170	169.50
471			100	0.25	175	175	175.00
472				0.50	181	180	180.50
473				0.75	186	185	185.50
474				1.00	192	190	191.00
475				1.25	197	196	196.50
476		60	20	0.25	34	32	33.00
477				0.50	43	44	43.50
478				0.75	55	54	54.50
479				1.00	63	64	63.50
480				1.25	69	71	70.00
481			40	0.25	75	75	75.00
482				0.50	82	83	82.50
483				0.75	89	90	89.50
484				1.00	98	96	97.00
485				1.25	104	105	104.50
486			60	0.25	109	108	108.50
487				0.50	116	117	116.50
488				0.75	121	122	121.50
489				1.00	130	131	130.50
490				1.25	139	138	138.50
491			80	0.25	143	145	144.00
492				0.50	149	151	150.00
493				0.75	159	160	159.50
494				1.00	168	170	169.00
495				1.25	175	177	176.00
496			100	0.25	181	182	181.50
497				0.50	189	190	189.50

S/N	Width of cutting edge (mm)	Lift angle (degree)	Depth of cut (mm)	Speed of operation (m/s)	Draught (N) 1	Draught (N) 2	Average Draught (N)
498				0.75	196	198	197.00
499				1.00	205	204	204.50
500				1.25	211	210	210.50
501	50	20	20	0.25	42	41	41.50
502				0.50	49	50	49.50
503				0.75	58	59	58.50
504				1.00	66	68	67.00
505				1.25	75	76	75.50
506			40	0.25	82	83	82.50
507				0.50	87	89	88.00
508				0.75	93	93	93.00
509				1.00	102	104	103.00
510				1.25	112	113	112.50
511			60	0.25	119	118	118.50
512				0.50	127	126	126.50
513				0.75	138	138	138.00
514				1.00	151	153	152.00
515				1.25	165	166	165.50
516			80	0.25	172	172	172.00
517				0.50	179	180	179.50
518				0.75	186	185	185.50
519				1.00	193	194	193.50
520				1.25	199	201	200.00
521			100	0.25	203	204	203.50
522				0.50	208	108	158.00
523				0.75	214	213	213.50
524				1.00	218	219	218.50
525				1.25	225	224	224.50
526		30	20	0.25	38	37	37.50
527				0.50	45	46	45.50
528				0.75	53	55	54.00
529				1.00	65	66	65.50
530				1.25	75	75	75.00
531			40	0.25	81	82	81.50
532				0.50	87	86	86.50
533				0.75	93	92	92.50
534				1.00	101	103	102.00
535				1.25	109	110	109.50

S/N	Width of cutting edge (mm)	Lift angle (degree)	Depth of cut (mm)	Speed of operation (m/s)	Draught (N) 1	Draught (N) 2	Average Draught (N)
536			60	0.25	117	118	117.50
537				0.50	124	123	123.50
538				0.75	132	134	133.00
539				1.00	139	141	140.00
540				1.25	148	146	147.00
541			80	0.25	153	152	152.50
542				0.50	159	159	159.00
543				0.75	167	168	167.50
544				1.00	173	174	173.50
545				1.25	189	188	188.50
546			100	0.25	194	193	193.50
547				0.50	198	197	197.50
548				0.75	205	204	204.50
549				1.00	211	212	211.50
550				1.25	217	216	216.50
551		40	20	0.25	35	36	35.50
552				0.50	47	48	47.50
553				0.75	55	56	55.50
554				1.00	68	67	67.50
555				1.25	76	77	76.50
556			40	0.25	83	82	82.50
557				0.50	89	90	89.50
558				0.75	96	97	96.50
559				1.00	103	102	102.50
560				1.25	110	112	111.00
561			60	0.25	119	118	118.50
562				0.50	125	124	124.50
563				0.75	131	131	131.00
564				1.00	139	138	138.50
565				1.25	144	145	144.50
566			80	0.25	149	150	149.50
567				0.50	156	156	156.00
568				0.75	162	163	162.50
569				1.00	168	169	168.50
570				1.25	176	175	175.50
571			100	0.25	181	182	181.50
572				0.50	188	190	189.00
573				0.75	196	195	195.50

S/N	Width of cutting edge (mm)	Lift angle (degree)	Depth of cut (mm)	Speed of operation (m/s)	Draught (N) 1	Draught (N) 2	Average Draught (N)
574				1.00	201	203	202.00
575				1.25	208	207	207.50
576		50	20	0.25	33	34	33.50
577				0.50	42	44	43.00
578				0.75	51	53	52.00
579				1.00	60	63	61.50
580				1.25	76	75	75.50
581			40	0.25	83	82	82.50
582				0.50	90	89	89.50
583				0.75	98	99	98.50
584				1.00	108	107	107.50
585				1.25	116	118	117.00
586			60	0.25	124	125	124.50
587				0.50	131	132	131.50
588				0.75	137	136	136.50
589				1.00	142	144	143.00
590				1.25	149	149	149.00
591			80	0.25	154	153	153.50
592				0.50	159	158	158.50
593				0.75	165	164	164.50
594				1.00	170	170	170.00
595				1.25	176	175	175.50
596			100	0.25	181	182	181.50
597				0.50	188	187	187.50
598				0.75	196	194	195.00
599				1.00	202	200	201.00
600				1.25	208	207	207.50
601		60	20	0.25	38	37	37.50
602				0.50	45	46	45.50
603				0.75	58	58	58.00
604				1.00	69	67	68.00
605				1.25	76	75	75.50
606			40	0.25	83	84	83.50
607				0.50	89	90	89.50
608				0.75	97	98	97.50
609				1.00	108	109	108.50
610				1.25	117	119	118.00
611			60	0.25	123	122	122.50

S/N	Width of cutting edge (mm)	Lift angle (degree)	Depth of cut (mm)	Speed of operation (m/s)	Draught (N) 1	Draught (N) 2	Average Draught (N)
612				0.50	128	129	128.50
613				0.75	136	137	136.50
614				1.00	142	141	141.50
615				1.25	149	150	149.50
616			80	0.25	154	155	154.50
617				0.50	159	160	159.50
618				0.75	166	165	165.50
619				1.00	173	174	173.50
620				1.25	180	182	181.00
621			100	0.25	187	188	187.50
622				0.50	195	194	194.50
623				0.75	201	203	202.00
624				1.00	210	212	211.00
625				1.25	221	220	220.50

Appendix III: Calculation of Draught Estimate on Narrow Tillage Tool

For s = 0.2m/s (0.72km/hr) using

$$D = F_i [A + B(S) + C(S)^2] W * T$$

$$D = 2[91 + 5.4(0.72) + 0(0.72)^2] 1 * 1$$

$$= 2[91 + 5.4(0.72)^2] 1 * 1$$

$$= 2[91 + 3.89 + 0] 1$$

$$= 2(94.89)$$

$$= 189.78N$$

For s = 0.8m/s (2.88km/hr)

$$D = 2[91 + 5.4(2.88) + 0(2.88)^2] 1 * 1$$

$$= 2[91 + 15.552] 1$$

$$= 2(106.552) 1$$

$$= 213.104N$$

For s = 1.2m/s (4.32km/hr)

$$\begin{aligned}
 D &= 2[91+5.4(4.32)+0(4.32)^2] 1*1 \\
 &= 2[91+23.328] 1 \\
 &= 2(114.328) 1 \\
 &= 228.656\text{N}
 \end{aligned}$$

For $s = 1.6\text{m/s}$ (5.76km/hr)

$$\begin{aligned}
 D &= 2[91+5.4(5.76)+0(5.76)^2] 1*1 \\
 &= 2[91+31.104] 1 \\
 &= 2(122.104) 1 \\
 &= 244.208\text{N}
 \end{aligned}$$

For $s = 2.0\text{m/s}$ (7.2km/hr)

$$\begin{aligned}
 D &= 2[91+5.4(7.20)+0(7.20)^2] 1*1 \\
 &= 2[91+28.88] 1 \\
 &= 2(129.88) 1 \\
 &= 259.76\text{N}
 \end{aligned}$$



APPENDIX IV: Picture of Soil Processing Carriage on the Soil Bin



APPENDIX V: Picture of the Researcher Setting the Depth of Tillage Tool during Data Acquisition



APPENDIX VI: Picture of Prepared Soil, Soil Bin and Tool Carriage Ready for Data Acquisition



APPENDIX VII: Picture of Instrumentation Expert during the Calibration of Distance Sensor



APPENDIX VIII: Picture of Soil Bin after the action of Tillage Tool



APPENDIX IX: Picture of Tool and Soil Processing Carriage



APPENDIX X: Picture of the Soil Bin after the action of Tillage Tool



APPENDIX XI: Picture of Tool Carriage in action during Data Acquisition



APPENDIX XII: Picture of Tool and Soil Processing Carriage



APPENDIX XIII: Picture of Soil Processing Carriage with Soil Leveller on the Soil Bin



APPENDIX XIV: Picture of Soil Mixing Operation



APPENDIX XV: Picture of Tool and Soil Processing Carriage with Soil Leveller