UNIVERSITY OF NAIROBI

SCHOOL OF ENGINEERING

DEPARTMENT OF ENVIRONMENTAL AND BIOSYSTEMS ENGINEERING

OPTIMIZATION OF THE ANGLE OF CUT OF A FROG IN A MOULDBOARD PLOUGH: CASE OF A SANDY CLAY SOIL

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F56/69693/2013

A thesis submitted to the University of Nairobi in partial fulfilment of the requirements for the Degree of Master of Science in Environmental and Biosystems Engineering

2015

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DEDICATION

I thank God for the blessing of invaluable family, friends, mentors and teachers who have prodded me along this walk and inspired my thoughts. I dedicate this work to my family and to mankind.

ACKNOWLEDGEMENT

I would like to thank the Almighty Lord for His never ending favor and mercies. I wish to express my sincere gratitude to my supervisors; Eng. Dr. Duncan Mbuge and Eng. Prof. A. N. Gitau for the guidance and support offered throughout the entire MSc programme.

My sincere gratitude to the technical staff at the Department of Environmental and Biosystem Engineering. Special thanks to Mr. Wahome, Mr. Macharia, Mr. Muliro and Mr. Wamutito for their invaluable support and assistance in the field work and analyzing of data.

Finally I thank the University of Nairobi fraternity for awarding me a scholarship to enhance my studies and undertake an MSc degree in the Department of Environmental and Biosystem Engineering, University of Nairobi.

ABSTRACT

The Mouldboard plough is a common tillage implement used in Kenya. The draught characteristics and ability to maintain desired depths and speed of operation at different frog angles is unknown. This study aimed at optimizing the angle of cut of a frog of a mouldboard plough operating in sandy clay soil. This objective was achieved through the study of the soil-cut interactions. The measurable quantity in the study of soil- cut interactions was draught force. Draught force is an indicator of the power to be consumed hence the cost of tillage.

Tillage field experiments were carried out in University of Nairobi – Upper Kabete Campus. Data obtained from the field was evaluated in three different ways; Saunders equation, Dynamometer and Discrete Element Modelling (DEM). Saunders equation calculated draught force incorporating geometric parameters of the plough body components, ploughing speed and depth additionally the physical properties of the soil. The dynamometer used was digital and recorded the draught requirements in situ. DEM was used to simulate the field experiment using a software called EDEM that calculated the draught requirements.

The soil- cut interactions were studied at three different frogs angles of 30°, 40° and 50°.The speed of tillage was calculated to be an average of 1.5m/s for the low speed and 3.6m/s for the high speed. The depths of tillage were measured as an average of 8.0cm, 17.0cm and 24.0cm for the three frog angles used. Draught forces determined for the low speeds (1.5m/s) were at range of 0.7kN to 1.0kN for depths of 8.0cm. At depths of 17.0 cm the range of forces was 1.0kN to 1.4kN. At the depths of 24.0cm the draught forces calculated were a range of 1.4 kN to 1.9kN. For high speeds (3.6m/s) the draught forces were at ranges of 0.8kN to 1.3kN, 1.4kN to 2.2kN and 2.2kN to 3.2kN respectively for the depths aforementioned.

The results suggest that draught forces increase significantly with increase in the depth linearly. This relationship shows the importance of regulating the depth of tillage. Draught forces increased with increase in speed of tillage and the relationship was a second order polynomial equation. The study concluded that the 30° angle frog was the optimal frog to use in a mouldboard plough operating in sandy clay soil as it had minimum average draught force of 0.8 KN. Thus at this angle, we experience minimum draught at an optimum speed and at friable moisture content of the soil.

Key words: *Tillage, simulation, DEM, soil-cut interactions and draught force*

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NOMENCLATURE

AOR	Angle of Repose
API	Application Programming Interface
ARRD	Agrarian Reforms and Rural Development
ASDS	Agricultural Sector Development Strategy
ASALs	Arid and Semi-arid Land
ASTM	American Society for Testing and Materials
C_c	Coefficient of Gradation
CDF	Computational Fluid Dynamics
Cu	Uniformity of Coefficient
DEM	Discrete Element Model
GDP	Gross Domestic Product
GUI	Graphical User Interface
FAO	Food and Agricultural Organization
FAS	Future Agricultures Consortium
FEM	Finite Element Model
KARI	Kenya Agricultural Research Institute
KNBS	Kenya National Bureau of Statistics
MSI	Measuring Systems International
PCF	Particle Code Flow
SSA	Sub-Saharan Africa
USCS	Unified Soil Classification method
VBA	Visual Basic for Applications

CHAPTER 1: INTRODUCTION

1.1.Background

Agricultural production is a key aspect in development and a fundamental component of livelihood. Agriculture is the main source of food, raw materials in the agro industries and income. (KARI, 2012).It is key to rural development as well as rural poverty alleviation. Historically, very few countries have industrialized successfully without prior development of agriculture usually on minerals and ores. Kenya has continuously industrialized on the bulk of development in agriculture.

According to Kenya Agricultural Research Institute (KARI, 2012), agricultural contributes 24% directly to the country's gross domestic product (GDP), 27% indirectly through linkages to manufacturing, distribution and other related services, 75% to raw materials, 50% to export earnings, 80% to the livelihood avenues to a population that is largely rural based and it is the largest employer comprising of about 60% employment positions. This implies that growth in agricultural production is directly related to economic growth and if agriculture suffers so does the economy of the country.

Agricultural production (FAS, 2010) has been on the decline since independence as a result of myriad of reasons; oil price increase, privatization of some agricultural processes and these private institutions were seen as not fully equipped to the task, poor governance, international interference and high inflation rates.

It is imperative to the government to put effort to improve the agricultural sector in the country. With this in mind the Vision 2030 seeks to transform agriculture by turning it into a profitable economic activity capable of attracting private investors as well as providing attractive employment opportunities. The government has also put initiatives (KARI, 2012) to improve agriculture through; improved rural infrastructure, agricultural mechanization, provisions of subsidiaries especially in fertilizers and seeds, improving the quality of research and extension services, development of markets, control of importation of agricultural goods that pose a risk to the local agricultural manufacturing and also provision of rural credit the above measures seek to overcome the problem that farmers face of food insecurity, increase in cost of domesticated food production due to high costs of inputs as well as the low purchasing power attributed to by poverty.

The Agricultural Sector Development Strategy (ASDS, 2010) which was published to serve as a step to step process of improving the state of agriculture in Kenya for the years 2010 to 2020 has earmarked agriculture as the backbone of the economy and as the means of livelihood for most of our local population. It goes further on to emphasize the importance of sustained agriculture growth and the part that it plays in improving the standards of living of the Kenyan's citizens as well as the visualized as a necessary step in achieving efficiency and effectiveness in delivery of services to farmers.

Increase in Kenya population (KNBS, 2013) has seen the demand for food increase drastically. As of the last census in Kenya the population stood at 38.16 Million and as at 2012 the population stood at 43.18Million. This increase in demand for food has seen to the rise of innovative ways to increase food production and also ways of improving the yield. Irrigation and mechanization are some of the methods that have been developed to increase food production. Irrigation aims at increase the size of land that is arable without necessarily depending on the uncertain natural rains. Mechanization is aimed at improving productivity of farm labour and land.

1.2.Problem Statement

Agriculture is the main stay of many countries more so in Kenya where agriculture is the largest contributor to the economy (KARI, 2012). With other sources of revenue like tourism being under constant threat as well as minerals mining not being fully streamlined agriculture remains the largest source of revenue (KNBS, 2013). This goes a long way to emphasize the importance of agriculture to the Kenyan economy and why research should be increased in manifolds in this sector. According to World Bank the arable land in Kenya is 48.23% this was rated in the year 2011 this level has decreased significantly especially due to loss of arable land to the boom in the construction sector.

Mechanization was introduced to increase production in agriculture. Innovation of agricultural implements is encouraged to reduce the cost of operation and improve efficiency. Mechanization of tillage is important to the agricultural industry. If well managed and utilized it results to higher and better yields (FAO, 2009). Soil tilth creation continues to pose a challenge for most farmers, researchers, manufactures as well as developers (Shmulevich *et al*., 2007). Precision agriculture is vital to all farmers and is established through seedbed preparation, optimization of seedbed structures and the subsoil as well (Zhang *et al*., 2002). This can only be established through best management practices. Best management practices reduce the amount of energy used in soil tilth preparation as well as the cost involved (Tilman *et al.*, 2002)

Tillage contributes to roughly a half of the energy used in crop production (Kushwaha and Zhang, 1998). Due to rapid increase in fuel cost, power optimization of tillage is a necessity. Tillage tool design then becomes an important aspect to research on so as to allow developments that result in optimizing the design of the implements. Accurate modelling of soil implement interaction is the basic key of reducing these costs and increase of agricultural production (Zadeh, 2006).

Soil tillage by mouldboard ploughs is one of the fundamental phases of agricultural production although the most expensive in terms of energy cost (Formato *et al*., 2005). Efficiency of tillage is measured by the power consumption, tillage force/ draught force and the quality of soil (Bentaher *et al*., 2013). Draught force is measured through the study of soil-cut interaction. Tillage forces are functions of soil mechanical properties, working parameters of the tool and tool geometry. Previous studies (Formato *et al.*, 2005; Asaf, 2007 and Saunders, 2007) have concentrated in the optimization of the shape of mouldboard in order to increase energy efficiency.

Optimization of the performance of the mouldboard involves modification. This study focused on modification of the tool geometry and in particular the frog angle of the mouldboard. The frog is the housing unit of the mouldboard plough and any change on it affects the other soil engaging elements. Altering the frog angle affects how the implement cuts the soil, inverts it and consequently the draught requirements. Zadeh (2006) documented that accurate modelling of the soil- implement interaction allows the optimization of the implement without performing expensive and time consuming field tests that are undertaken at particular times of the year. The force required in pulling a tool through the soil is one of the criteria used to assess the suitability of a tool for soil manipulation (Moeenifar *et al*., 2014).

This study originates the relationship of the frog angle with respect to tillage speed and depth. The frog angle affects the draught requirements hence the tillage power and consequently the cost of ploughing. After analysis of the draught requirements required by the different frog angle the optimal angle was then recommended. The optimal angle of operation under sandy clay soil is of use to the farmers using the mouldboard plough to prepare land for planting.

1.3.Justification of the Study

With the erratic change in the size of arable land and increase in population, different measures have been adopted to increase the land size under cultivation by increasingly putting more land under irrigation and mechanizing the farming process (GoK, ASDS 2010).Irrigation, mechanization, pest control and fertilizer application result to increase in yield and output (FAO, 2009).

Mouldboard ploughs are used in tillage because they enrich and aerate the soil producing a fertile seed bed ideal for germination and growth of new crop (Godwin et al., 2007).The mouldboard plough has several parts namely; mouldboard, share, landslide and frog that affect the soil tilth. However, the cost of tillage is costly and time consuming. Studies have been conducted over time by researchers to reduce this cost of tillage (Mckyes, 1997, Sahu, 2006; and Saunders et al., 2007). Modification to improve the functionality of these parts is an important aspect to ensure use of the implements to their full capacity (Mustafa *et al*., 2014). Optimal performance of the tillage implements is measured by draught force. Draught force is measured by the study of soil-implement forces.

Draught force is a general indicator of the final cost that will be incurred in the soil preparation, the higher the force required the higher the cost. This cost is directly related to the power usage

(Mckyes, 1997) measured by the number of litres of oil used. This study aims at predicting the draught forces of a mouldboard operating at different ploughing depths and speed but on the same type of soil while altering the angle of the frog. This will result to a recommendation of the optimal angle of frog to farmers to use while tilling.

1.4.Objectives

1.4.1. Overall Objective

To establish the optimum angle of cut of a frog in mouldboard tillage operations in a sandy clay soil.

1.4.2. Specific Objectives

a) Identify the pertinent soil parameters that influence the angle of cut in sandy clay soil tillage.
b) Establish the draft force requirements for mouldboard tillage in sandy clay soil.
c) Establish the effect of speed and depth on tillage draught requirements

1.5.Scope of work

The study involved tillage of land using a mouldboard plough while varying the angle of the frog and determination of the draught forces for each angle eventually recommending the optimal angle of frog.

The experimental study was conducted in Upper Kabete, field station – University of Nairobi. The land tilled was fairly flat with a negligible gradient. The speed and depth of tillage was varied but the same type of soil was used. The soil in Upper Kabete is generally described as sandy clay which is soil with more than 30% of clay. The speed was divided into two; high and low speed typical of animal drawn implements. The low speed was below 2.5m/s and the high speed was above 2.5m/s but less than 5.0m/s. The depth of tillage was divided into three ranges with a band of 10cm from 0cm to 30cm. The different frogs of angle used were: 30^0, 40^0 and $50^{0.}$.

Data was collected for all the variables and the draught calculated using the Saunders equation. Also a dynamometer was used to record the draught forces while carrying out the experiment. The tillage process was later simulated using the discrete element model (DEM). The draught force calculated (Saunders Equation) was verified against that observed (dynamometer) and that modeled (DEM) The three draught forces obtained from the above methods were analyzed and the effect of both the tillage speed and depth investigated. The angle with the lowest draught forces was recommended as the optimal angle. The pertinent soil parameters influencing the angle of cut were obtained from various research materials.

CHAPTER 2: LITERATURE REVIEW

2.1. Agricultural Mechanization

Agricultural mechanization is the use of tools, implements and machinery applied to improving the productivity of farm labour and land. It aims at reduction of drudgery, increasing productivity and improving the quality of farm products. It is important to note that mechanization does not explicitly refer to the use of tractors only (FAO 2009).

Studies (Mrema *et al.*,2008; Sims *et al*,.2006) done show that since introduction of mechanization, there has been a decline in its implementation especially in the small scale farming and in the SSA this is highly attributed to the high cost of the implements and lack of sound policies governing mechanization resulting to a decline in food production and hence the current food insecurity in Kenya Mechanization has however grown in large scale production farms like the wheat and sugar production this is because large farms are able to enjoy the large bargaining purchasing power.

The most appropriate machinery and power source for any operation depends on the work to be done, the relative desirability, affordability and availability of the machines. Table 2.1 shows the key developments in agriculture and the impact on yield.

Table 2.1: Chronological developments in agriculture (Lal, 2007)

Era	Technology	Locale
11000–9000 BC	Mesopotamia	Beginning of settled agriculture
9500–8800 BC	Sumerians	Use of supplemental irrigation
5000–4000 BC	Mesopotamia	Use of simple tools such as an “ard” plough
3000–2000 BC	Indus Valley	Use of animal drivel plough
2500–2000 BC	Mesopotamia	The concept of fertility of cropland soils
900–700 BC	Greece	Use of manure
1604–1668 AD	Germany	Impact of saltpetre on plant growth
1100–1200 AD	Moorish	Spain soil quality

1803-1873 AD	Germany	Use of chemical fertilizers
1950- 1970 AD	U.S.	Corn Belt conservation tillage, no-till farming
1960s AD	Israel	Drip irrigation, fertigation
1980s AD		Biotechnology and genetically modified crops
2000 AD		Conservation tillage

The focus in this paper is the soil preparation process also known as tillage and the implement used is the mouldboard plough. The implements used in farming include but not limited to; ploughs sub-soilers and strip tiller for land preparation, sprayers, manure and liquid spreader for crop protection and balers, combine harvesters and tree shakers for harvesting.

Tillage is defined as the physical or mechanical manipulation of soil with tools and implements (Mannering *et al.*, 1983). It involves opening the upper crust of the soil and preparing the soil for planting. Its purpose is to increase soil aeration, destroy weeds and addition of soil fertility. It is a very intense process in farming in terms of labour and time requirement. Series of studies done by Food and Agricultural Organization (FAO: 2008; 2009) in SSA over various different times show that labour demand has its peaks during land preparation and weeding in farming. It is a prerequisite in farming and land preparation is vital in ensuring a good tilth for crops production.

Alaverz *et al.*, 2009, divides soil cultivation is into two major types as shown below:

i. Primary tillage – it involves opening and loosening of the soil. It is done after harvesting and the initial step towards land preparation for the next farming cycle. The implements used in primary tillage include: mouldboard, disc and chisel ploughs. Disc ploughs are used to till lands that have more weeds. They are used to till depths above 30cm and not more than 60 cm. Chisel ploughs are used to break hard pans that occur due to compaction of soil and are hence used to till deep depths above 60cm Mouldboard ploughs are used to till land for depths below 30cm and since our depth of tillage is below 30cm this plough then becomes the implement of focus in this paper. Primary tillage is considered as the largest power consuming operation.

ii. Secondary tillage - it is meant for the preparations of a good tilth and breaking of any clods. The implements used include the harrowers and cultivators. A good tilth preparation involves breaking of clods to allow better germination and also enables irrigation and sowing.

2.2. Mouldboard plough

Mouldboard ploughs are the most widespread used tillage equipment in the world as well as the biggest consumer of energy in tillage (Bernacki, 1972; Ploufee *et al.*, 1999). During tillage mouldboard ploughs leave almost no untilled land and result to better pulverization. For this purpose, most researchers have endeavored to carry out numerous studies to optimize the performance of the mouldboard plough either through trial and error method or through semi-theoretical approaches. (Sahu, 2006; Mckyes, 1997)

Figure 2.1 shows a pictorial presentation of a traditional animal drawn mouldboard plough. The parts of a mouldboard plough broadly include: the plough body, hitch, wheel and handle beam assembly. The plough body which comprises of the plough, landside, share and the frog is our area of interest.

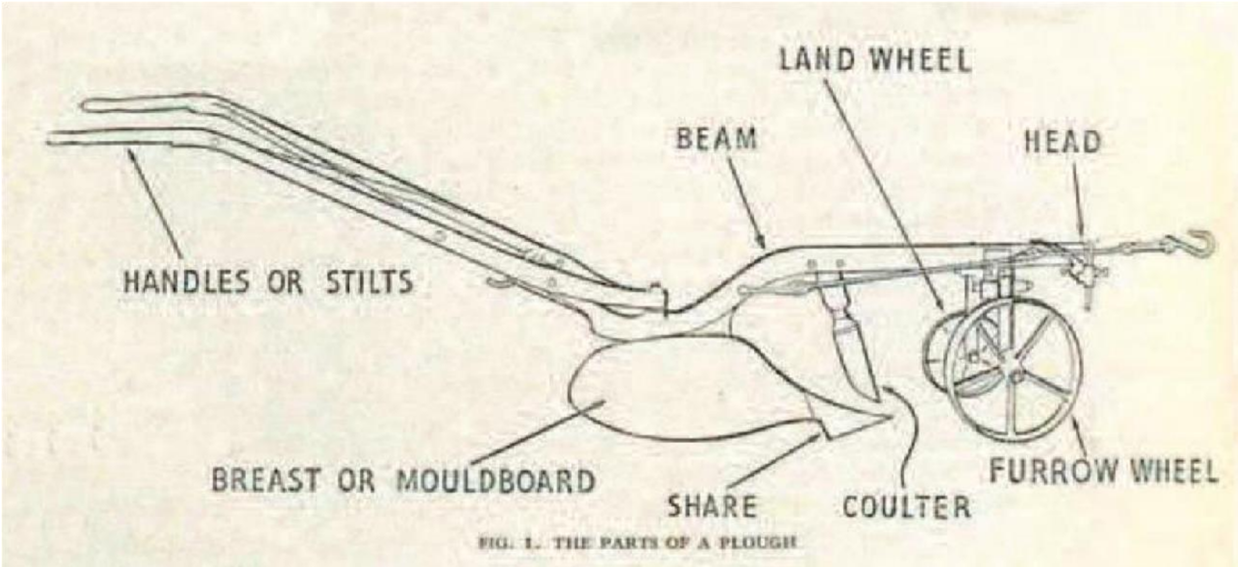

Figure 2.1: Traditional Plough *(adapted from National Ploughing Association- 2012)*

The depth of the furrow slice can be altered by adjusting the height of the furrow wheels. At the end of the furrow the ox-man lifts the share clear of the soil using the handles and guides the plough in the correct line. The area of focus in this study is the frog shown in Figure 2.2.

Figure 2.2: Frogs of different angles. *Photo, A.Hiuhu*

2.2.1. Mode of Operation of the Mouldboard Plough

Mouldboard ploughs are designed to slice the soil, loosen the soil, lift the furrow, fracture it and also invert. By doing so, they bury the plant residues and loosen the soil. The front edge of the mouldboard cuts the soil vertically and the curvature lifts the soil hence inverting the soil. The front edge is called the shin and it easily wears out. If the mouldboard is adjusted, it can flip a furrow slice to 180 degrees (Finner *et al*., 1985).

The share usually points downwards and must always be kept sharp to allow suction. They are attached to the frog by two bolts. Once it faces downwards it can then run in the ground hence suction. There two types of shares; the flat and the upset. In rough conditions the share type used is the upset. Shares can be sharpened if blunt or even replaced if they are worn out. The share cuts the furrow bottom and the shin in turn cuts the furrow wall.

The landside serves as a stabilizer and then holds the plough horizontally as it moves forward. Landsides are adjusted to alter the landside pressure on the furrow wall. They are also adjusted to the frog by bolts. There two types of landsides; plain and the heel type which is not commonly found. If the landside is not replaced after wearing out, it becomes increasing hard to control the plough. The working of the plough can be summarized as in Figure 2.3. Where; at position 1 no shearing is taking place but as the furrow slice is lifted shearing then occurs which is shown in position 2. At position 3 the furrow slice is now bending which then allows the mouldboard to break the soil and invert it (Finner *et al*., 1985).

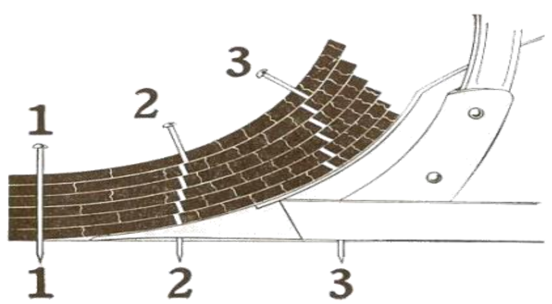

Figure 2.3: Working of the Mouldboard Plough. Image: adapted from Finner and Straub (1985)

The frog which is the area of interest is made of iron and is irregularly shaped. It acts as the support framework holding together the share, shin and landside. It is then attached to the beam which then forms the assembly. The frog is attached to the share through countersink bolts which makes the shares easily replaceable. Frogs are shaped in such ways that they allow the three soil engaging parts i.e. the share, mouldboard and landside to be correctly aligned hence performing their function correctly and effectively. Changing the measurements of the frog affects the width of cut, inversion of soil and the burial of weeds. This paper focuses on changing the angle of frog which in turn affects the working of the mouldboard plough and the draught forces required. Figure 2.4 show the soil engaging elements being dismantled

Figure 2.4: Dismantled soil engaging implements. *Photo, A.Hiuhu*

For tillage to be carried out, several factors are considered: soil moisture, root zone of the crop being planted, amount of weeds and the type of soil (Vilde, 2001). Dry and wet soil is not conducive for ploughing. If the soil is dry, more energy is used to open the soil resulting to the formation of large size clods as well as soil erosion. In wet conditions, soil sticks to the plough and the soil below the plough sole becomes compacted resulting to the formation of a hard pan. A hard pan destroys the soil structure and has to be broken before planting which means using more resources. Therefore before tillage is carried out each of these factors have to be evaluated.

The interaction of soil and farm implements is an important factor to consider as it affects the performance of machines (Saunders *et al*., 2007). This relationship is important in the design of machines resulting to a near perfect soil manipulation. A farmer will want the best tilth at the minimum costs so that he can make the most returns this is done by maximizing the field capacity of tillage equipment. Usually the method of tilling that prepares the land within the shortest time and keeps the power requirements at the minimum is selected.

2.3. Tillage systems

Soil Engineering 2nd edition (2010) describes various types of tillage systems being practiced across the globe as shown below:

2.3.1. Convectional Tillage

This method of tillage is also called intensive tillage and leaves less than 15% residues on the soil surface. The moldboard plough is one of the implement that is used in convectional tillage. Convectional tillage is a very expensive process because of the high fuel requirements. It also results to compaction of soil which is a huge problem and consequently deterioration in the soil structure.

2.3.2. Deep Tillage

Deep tillage method aims at breaking the hard pan also called plough pan that forms after continuous traffic and ploughing. Hard pan is usually formed under the plough layer. The chisel plough is usually used to break the hard pan.

2.3.3. Minimum Tillage

This method of tillage is also called reduced tillage. It aims at reducing the soil compaction problems and soil erosion. Minimum tillage is highly effective in soil and water conservation as compared to conventional tillage systems. Water conservation is achieved through improved infiltration and reduced evaporation. It leaves between 15-30% of residue cover after planting.

2.3.4. Conservation Tillage

This method of tillage leaves more than 30% of crop residue on the soil surface and it aimed at crop residue management. Conservation tillage is not one method but a collection of tillage practices (Mannering and Fenster, 1983).This tillage practices lead to beneficial changes in soil physical properties; improve soil aggregate stability

2.3.5. Ridge Tillage

Ridge tillage is a method of tillage where the soil is not disturbed from the planting stage to the harvesting period except during nutrient application. Crops are planted on ridges. This ridges are created using: disk openers or coulters while maintaining crop residues in between the ridges on the soil surface.

2.3.6. Zero Tillage

This method of tillage is also called no tillage. Just as the name suggests no tillage is done and the soil is left undisturbed except only when planting the seed and during nutrient application. Zero tillage results to reduced evaporation, increased soil infiltration and greater water recharge in soil profile (Allmaras et al., 1985). This method however results to heavy usage of pesticides this is because weeds are not removed. It is achieved by use of special implements like the coulters, row cleaners and tine openers.

2.4. Tillage systems and soil type

Soil is the medium of working in tillage and its characteristics affects its workability. The physical characteristics of the soil affect seed germination and crop yield. Tillage systems that are capable of optimizing these soil characteristics should therefore be practiced (Gitau 2000). Moisture content of the soil is an important determinant of the workability of soil. Texture of the soil also determines the workability of the soil.

Africa Conservation Tillage (ACT), Network (2002) documents that light soils are easy to work with at all moisture levels. These light soils are normally sandy soils that are characteristic of high water conduction and infiltration. However these soils have a low heat capacity which in turn reduces the organic matter content that supports little plant life.

Lal, 2007, proposes that medium texture soils which are mostly loamy soil are the most favored soil for crop production because they can hold enough water for plant growth, soil aeration and they have good drainage hence producing a higher crop yield. The nutrient content of the loamy soils is high and their workability also better.

Heavy texture soils which are commonly clay soil have a very low workability because when wet they hold a high moisture content that results to crumbling once tilled. When dry they become hard resulting to cracks and almost impossible to till. Tillage in heavy texture soils requires high draft forces.

2.5. Soil Structure and Properties

Soil is composed of solid, liquids and gases. Organic particles constitute the solid part while water and air fill up the liquid and gas phases of soil. This phase forms the pore spaces. Soil pores are important in soil structure because they permit water and air movements through the soil and root penetration. Any change in porosity affects the plant growth directly. An ideal soil should contain 50% solid particles and 50% pore spaces (Dexter, 2004).

Soil moisture is defined as the amount of water in the soil after it has been dried. Soils under zero tillage have greater soil moisture content and this is attributed to reduced evaporation because of the high residue cover characteristic of this method of tillage (Lal, 1993). Soil moisture determines the extent of crack propagation.

Bulk density is a measure of the compactness of soil and defined as the dry soil mass per unit volume (Dedousis *et al*., 2010). It increases as soil moisture increases to a certain limit. Soil strength is also a measure of the compactness of the soil and the relationship is direct the more the soil compactness the higher the soil strength. The greater the soil bulk density the lower the soil porosity is as well as biological activity.

Soil compaction increases the draught requirements marginally tillage (Lal, 1993). It is as a result of continuous traffic and cultivation practices resulting to reduction of pore spaces and re-arrangement of soil particles. It is a problem that affects the preparation of land for planting requiring one to plough deeper which in turn increases the draught requirements. Soil compaction is assessed through soil penetrability which is defined as the measure of ease with which an object may be driven into the soil.

When soil is under a loading system which in this case is the tillage implement, it fails in three ways all dependent on the soil moisture conditions: plastic flow, general shear failure and fracture (Dedousis *et al*., 2010). It is difficult to say that soil fails in one particular point when ploughing this is why soil tool interaction studies have evolved over time.

As the implement ploughs the soil, it provides energy that initiates the growth of cracks in soil as the energy increases more than that of the energy absorbed in the plastic deformation; the cracks deepen resulting to failure. In the initial stages of crack formation, the cracks extend in a horizontal direction creating a path for the blade edge. The blade of the implement penetrates the cracks like a wedge and the cracks continue to develop further. Hence the width, depth of operation and the angle of approach of the blade into the soil also determine the extent of the crack propagation.

The resistance to sliding of the soil-metal interface and soil-soil is a function of normal stress between the two surfaces. Adhesion is a function of the wettability of the implement surface and it is related to the soil moisture suction. Angle of soil-metal friction is a function of the roughness of the surfaces (Arvids *et al*., 2005).

2.6. Effects of tillage on Crops

One of the reasons of performing tillage is to produce a good tilth this involves making the soil viable for plant growth. The effect of tillage on crop yield is inconsistent and largely depends on the soil and climatic factors. Studies have been done on the type of crop that does best in particular seasons and under the particular tillage systems. Gregory (1994) reviewed the relationships between the roots, shoots and crop yield. However, the results were inconsistent and highly specific to the crop species and the soil collections.

Zero tillage results to greater strength of the surface soil that cause unfavorable soil conditions (John *et al.,* 2006). Under reduced tillage the soil has lower temperatures which reduces the yield of crops (Gitau *et al.,* 2000)

2.7. Equipment Management

Equipment management is defined as the art of managing and selecting proper equipment so as to perform a given task in good time and in the proper way without affecting the implement (Hunt 2001). Right time means that the land is prepared in good time, harvesting is done when the crops have the right moisture to avoid reduction in yield all this results to timely farming operations also called timeliness operations. This reduces wastage of resources. Ideal machinery is hard to put together and the perfect blend is not achieved at the first trial. A machine that works today is not guaranteed to work the next year. Changes in weather conditions or crop production systems demand that the machines used in farming must be flexible to cater for this variability.

Efficient usage of equipment is achieved if the field capacity level is 80% and above. Field capacity is a measure of the productivity in a given field and is defined as the ratio of effective field capacity to the theoretical field capacity. The effective field capacity is the actual rate of land processed in a known amount of time while theoretical field capacity is defined as the rate of performance obtained if a machine operates at 100% (ASAE, 2006). As a result of losses that occur operating a machine at 100% then becomes impossible. If a high field capacity is achieved, then this means that the soil is prepared for growing crops in the least possible time. A high field capacity is achieved if larger equipment is operated at low speeds and the smaller equipment is operated at higher speeds. Onwualu and Watts (1998) argue that the combination that enables land preparation in the shortest time with minimum operating cost and energy should be selected.

Farm managers use the draught and power requirements data of tillage equipment in the specific soil type to determine the size of the tractor required. The draught requirements are mainly a function of: soil properties, tool geometry, working depth and speed. (Saunders *et al.,* 2007)

Srivastave *et al*., (1993) argues that since the cost of machinery is very high, good care must be taken and this can only be achieved through efficient usage of equipment. Also, operations of these machines should be as per the manuals. Anderson (2004) conducted a study on the different costs involved in the farming process and he concluded that the cost of owning and operating the farm machinery represents about 35% to 50% of the cost of production excluding the repairs and maintenance cost this goes further to emphasis on the importance of efficient usage of equipment as a farmer is to cost.

Tractive efficiency is defined as the ratio of output to input power of a traction devise. Tractive efficiency is then used to calculate traction. Traction is defined as the effectiveness of power transfer between the tractive devise to another surface (ASAE, 2006).

2.8. Types of Models Used in Soil-Implement Interactions

According to Zadeh, (2006), accurate modelling of the soil-implement interaction allows the optimization of implements design which then reduces the cost of tillage and well as time used. Soil-implement interaction is a complex process because of the spatial variability of soil, dynamic effects, the flow and the mixing that occurs within the soil. The dynamic effects means the soil keeps changing which then makes the interactions difficult to study.

Different modelling methods have been used over time to model the soil-implement interaction. At the start, the models were simple but with time they have improved by application of numerical procedures (Formato *et al*., 2005). Mustafa *et al* (2014) classifies this methods into the below categories:

- Analytical methods- they examine the soil failure by studying the quasi-static or dynamic conditions. These methods are not commonly used because they do not consider the soil movement.

- Empirical methods- they were invented to overcome the challenges of the analytical methods but they involve rigorous measurements, calculations and extrapolation of field conditions which is not easy to achieve.

- Numerical methods – they solve the problems of the two above methods. Numerical methods are divided into two groups; continuum and discontinuum methods. Finite element method (FEM) and computational fluid dynamics (CDF) are continuum methods while discrete element method falls under the later method.

Continuum methods assume continuity which is not always valid. Discrete element method (DEM) considers among many things in its modelling: soil failure, soil deformation and translocation. These considerations make DEM the most preferred method for soil –implement interaction study. According to Dexter (2004), models used in soil tillage need to consider the friability and workability effects.

2.9. Discrete Element Model (DEM)

DEM was developed by Cundall and Strack (1971) and was initially used in the study of rock mechanics. DEM aims at describing mechanical behavior of granular materials. It was developed on the basis of the study of the contact forces between finite number particles and their interactions are calculated by using contact models e.g. electrostatic. Particle motion is a result of the forces and moments acting at the center of mass. Newton’s Second Law of motion relates the translational motion to the resultant force while rotational motion is described by a system of Eulers equation. Contact constitutive law governs the determination of forces arising due to two or more interacting particles. DEM allows for the study of the relationship between the micro and macro behavior of the soil as well as the study of developments of cracks. DEM modeling is a copy paste in numerical terms of what happens in reality and particles on macroscopic properties can be simulated. DEM also allows for numerous what if scenarios on a desktop consequently providing a solution to design problems. This is done through modelling of continuum bulk materials which are examined at macroscopic scale.

DEM is suitable for modelling soils, the interaction between soils and other bodies (Owen *et al*., 2002) making it a suitable method for soil-implement interaction prediction. Carrillo *et al*., (1996) in his research presented a 3D model for soil ploughing while Clearly (1998) introduced 2D model for excavation. This shows that DEM removes the limitation of 2D. Tanaka *et al*., (2000) introduced a model that predicted the interaction between a vibrating a sub-soiler and the soil. Horner *et al*., (2001) developed a simulation model that allowed for the study of interaction between the soil and the plough. Hofstetter (2002) developed a model that studies the interaction between a bulldozer blade and the soil. The above extracts are just a few to illustrate the potential of using DEM as a tool for the study of soil- implement interaction.

DEM must be calibrated before it is used to take into account the irregular shapes and properties of the particles being used, soil in this case. Micro and macro mechanical parameters are used to calibrate the model. A stable iteration time step is also chosen to reduce the computational time. This iteration time is a function of the particle radius, poisson's ratio, shear modulus and particle velocity. Figure 2.5 shows the iteration steps of the simulation process.

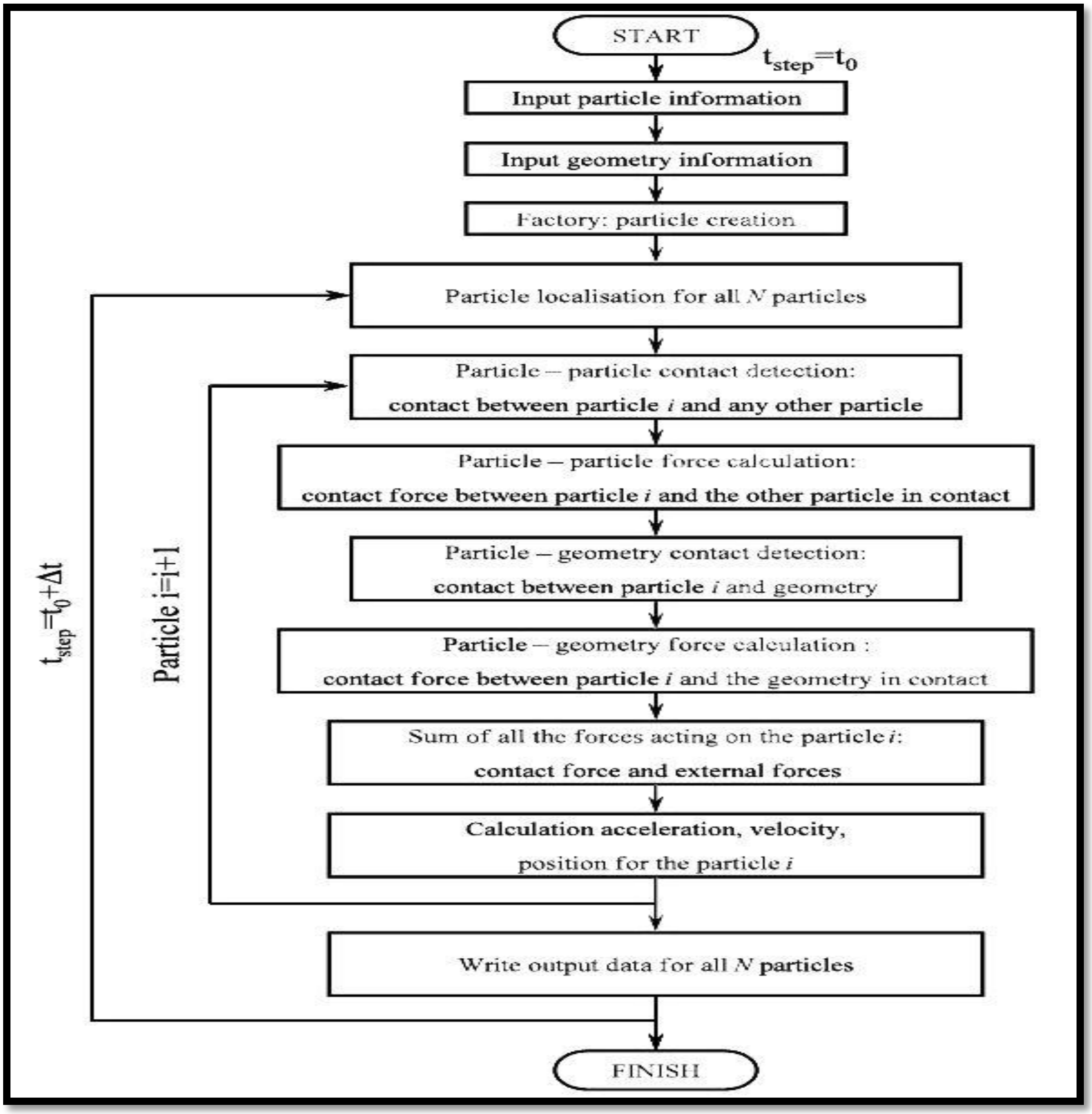

Figure 2.5: DEM Iteration process (EDEM 2010)

DEM has been integrated in various modelling platforms including EDEM, PFC and Yade among others.EDEM Academic^{TM} is a DEM software developed and distributed by DEM Solutions Ltd to assist students and researchers develop models to simulate the behavior of particle systems under a variety of loading conditions. EDEM Academic^{TM} is the superior platform as it provides an easy to use GUI, parallel processing capabilities, extensive customization through an Application Programming Interface (API) and built-in contact models.

EDEM Academic^{TM} software allows for the three types of interactions: Particle- particle contact models, particle – geometry contact models and particle- body forces models. EDEM Academic^{TM} components include: the creator, simulator and the analyst .The creator component is used to develop the layout of the equipment that will be used; in this study we shall use Auto Cad drawings of the mouldboard plough. The simulator component then simulates the process; tillage for this study EDEM 2010). The tillage is simulated with the different variables then the analyst component shall then calculate the draught requirements of the tillage process.

2.9.1. EDEM Calibration Parameters

EDEM Academic^{TM} is also calibrated to account for the different characteristics of the particles. The model parameters are simulated until they give a similar angle of repose (AOR) to that measured in the laboratory. AOR is a function of surface energy value, coefficient of restitution, coefficient of rolling, coefficient of static friction and coefficient of poisson ratio. Angle of repose is defined as the angle of inclination of the free surface to the horizontal of a bulk solid pile. After calibration, EDEM is run following the below steps:

- Use of the real material as observed on site. In this case we are using soil.
- Recreate the typical flow regime on the site.
- Provide comparative measurements between the experiment and simulation process.
- Develop a fit for all model with reference to particle size and shape that best matches the simulations with the experiment values

The high cost of tillage has necessitated the need for tillage power optimization. Tillage power is determined by the draught requirements. The study of soil-implement cut relationship allows the determination of draught requirements. Different methods have been studied and proposed to reduce this force in an attempt to improve the functionality of the implements: strip tillage (Temesgen *et al*., 2012), altering the shape of the mouldboard (Shrestha *et al*., 2001; Bentaher *et al*., 2013). While the mouldboard surface has been remodeled in an effort to optimize the design parameters (Shrestha *et a*l, 2001), this study aimed at determining the optimal frog angle at varying operating parameters of speed and depth of tillage. Altering the frog angle affects the width of cut and soil inversion of the plough.

Different methods are used to determine this force and with the advancement in nuclear science, numerical simulation is used to predict the forces varying different elements of the implement to determine the best operating level. In this study DEM was used to predict the draught requirements. The draught values were verified against those calculated (Saunders Equation) and observed (Dynamometer).

CHAPTER 3: THEORETICAL FRAMEWORK

3.1. Draught Force Prediction Models

Draught force from literature is expressed as function of tillage speed and depth and for these relationships, quadratic equations have been developed. Further research shows that draught force also depends on the physical properties of the soil being tilled, geometry of the plough point, that of the share and the mouldboard design parameters (Saunders *et al.*, 2007). Also, the operating factors like the speed of tillage as well as the depth of working influence the draught force as well.

Different models have been developed to predict the tillage draught forces. For these models most of them are based on two theories; Mohr –coulomb soil mechanics and Newtonian dynamics theory. Experimental evidence show that draught forces increase with speed according to a square law as shown by Gill and Vanden Berg (1968) and Kepner *et al*., (1982). This square law concept was further validated to show that there exists quadratic relationship between draught forces and speed this was researched on by Sohne (1959). Oskuoi and Witney (1982) improved the quadratic relationship and incorporated soil properties to the equation like the soil cone index. Later on, Qiong *et al*. (1986), Voorhees and Walker (1977) improved this relationship by incorporating moisture content to the equation. In the same year, Qiong *et al*., (1986) developed a rigorous mathematical analysis of soil movement over a mouldboard to predict its draught forces components. Wheeler and Godwin (1996) developed the tine theory that was used to predict forces as a result of soil inertia. This equation was then modified by Seig (1982) by incorporating the soil mechanics equation enabling prediction of forces acting on the plough tip and share. Saunders *et al*., (2000) and Godwin (2007) included the effect of speed in the force prediction model. The above summary shows the different variables that must be considered while trying to predict the draught forces and the evolution of the equations used to determine draught forces.

Equation 3.1 is quadratic equation that shows the relation between draught, speed, plough design characteristics and the soil conditions according to Saunders *et al*., (2000)

$$H_t = H_p + H_S + H_{mc} + H_e + H_{cs} + H_{ms} + H_{fs} \tag{3.1}$$

Where:

H_t - is the total draught force in KN.

H_p - is the draught force due to plough point.

H_s - is the draught force due to plough share.

H_{mc} - is the draught force due to mouldboard soil momentum change and draught force friction along the mouldboard.

H_e - is the draught force due to the increase in soil potential energy and the mouldboard

H_{cs} *and* H_{ms} - is the draught force arising from friction forces due to lateral forces at the share and at the mouldboard.

H_{fs} - is the draught force arising from lateral forces at the mouldboard because of the lateral soil movements.

The above model aims at predicting the plough draught forces in a semi rigorous manner and it incorporates the below data:

i. Soil parameters:
   - Bulk unit weight (γ) in KN/m^3
   - Cohesion of soil (C) in KN/m^2
   - Shearing resistance angle (Φ)
   - Soil metal friction angle(σ)
   - Soil –soil friction angle (φ_s)

ii. Plough geometric factors:

- Plough and share rake angles $(\propto_p \ and \ \propto_s)$
- Mouldboard angle to the direction of motion (θ)
- Effective length of the mouldboard (l) in M
- Working depth and width of the plough$(d_p and w_p)$ in M
- Working depth and width of the share$(d_s and w_s)$in M
- Speed of ploughing (V) in m/s
- Angle of share edge to direction of plough motion ($\beta)$

$$H_p = \left(\gamma d^2{}_p\, N_r + C d_p N_{ca}\right) w_p + 0.55 d_p \left(m - \left(m - \frac{1}{3}\right)\right) + \left(\frac{\gamma v^2 N_a d_p}{g}\right)\left(w_p + 0.33 d_p\right)\sin\left(\propto_p + \sigma\right) \tag{3.2}$$

The components in equation one are calculated as follows:

$$H_s = (\gamma d^2{}_s\, N_r + C d_s N_{ca}) + \left(\frac{\gamma v^2 N_a d_p}{g}\right)(w_s)\sin\left(\propto_p + \sigma\right)\sin\beta \tag{3.3}$$

$$H_{mc} = \left(\frac{\gamma}{g}\right)\left(w_p d_p + w_s d_s\right) v^2 [1 - \{1 - \sin\theta\tan\sigma\}\cos\theta] \tag{3.4}$$

$$H_e = (2\gamma)(w_p d_p + w_s d_s) d_s\text{-}] \tag{3.5}$$

$$H_{cs} = \left(\gamma d^2{}_s\, N_r + C d_s N_{ca} + \frac{\gamma v^2 N_a d_s}{g}\right) w_s \sin(\propto_s + \sigma)\cos\beta\tan\sigma \tag{3.6}$$

$$H_{ms} = \left(\frac{\gamma}{g}\right)\left(w_p d_p + w_s d_s\right) v^2 [\sin\theta - \{1 - \sin\theta\tan\sigma\}\tan\theta] \tag{3.7}$$

$$H_{fs} = (w_p d_p + w_s d_s)\tan\varphi_s \tan\sigma \tag{3.8}$$

Where:

M is the soil rupture distance ratio

G is the acceleration due to gravity (m/s)

N_{ca}, N_{γ}, N_a are dimensionless parameters

The other symbols have the same meaning as above.

This can be explained diagrammatically in Figure3.1.

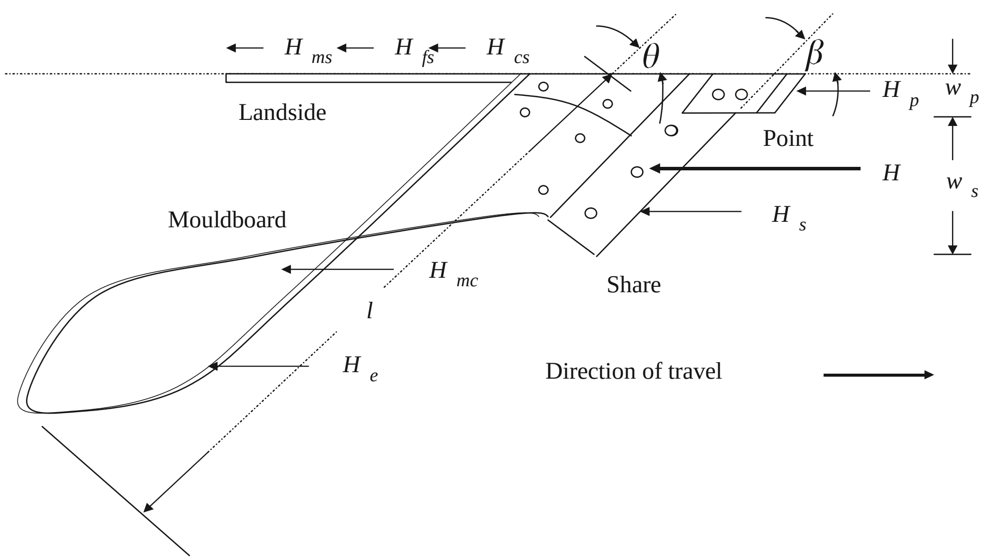

Figure 3.1.Components of the draught forces acting on the plough (Source: Saunders, C. 2007)

N_{ca}, N_{γ}, and N_a are soil parameters and are defined as soil adhesion cutting coefficient, soil frictional cutting coefficient and soil overburdening cutting coefficient respectively.

Soil rupture distance is the distance ahead of the tine and a ratio between forward rupture distance and working depth.

Soil rupture distance is calculated as shown below in equation 3.9.

$$r = (\cot\alpha + \cot\beta) \quad (3.9)$$

3.2. Shear Strength Models

Shear strength of soil is defined as the resistance to shearing stresses. Failure of soil occurs when stresses between particles slide or roll past each other. Triaxial tests are carried out to determine the shear strength of soil. Shear strength is a function of cohesion and angle of internal friction. These values are obtained from Mohr's circle that is drawn in respect to the stresses of the particular soil. Stresses at a point in the ground can be represented by six stress components illustrated in Figure 3.2.

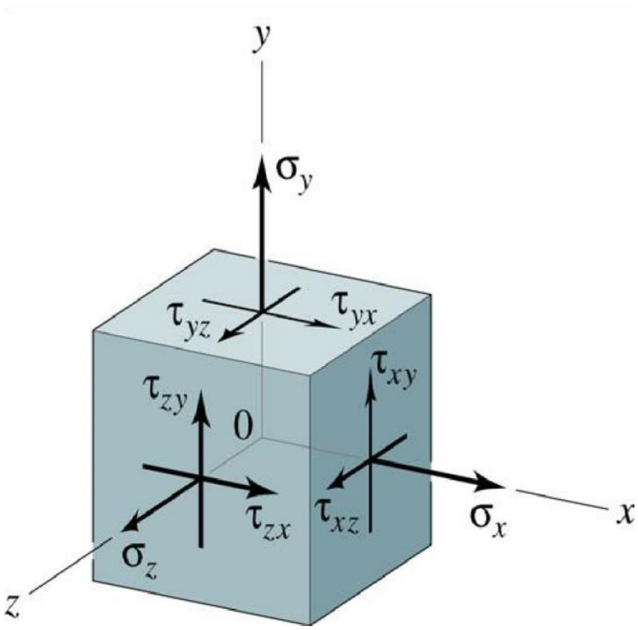

Figure 3.2: Normal and shear stress element in 3D

Normal stresses include: σ_x , σ_y and σ_z.The subscript denotes the face that the stress acts. Shear stresses include: τ_{xy}, τ_{yz} and τ_{xz} . The first subscript denotes the face and second denotes the direction of the stress. The stress tensor of the above cube is as equation 3.10.

$$\begin{matrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} \end{matrix} \tag{3.10}$$

The radius of mohr's circle is given by equation 3.11

$$R = \sqrt{\frac{(\sigma_x - \sigma_y)^2}{2} + {\tau_{xy}}^2} - \tag{3.11}$$

3.3. Discrete Element Model (DEM) Model

DEM describes the behavior of particles. Motion between these particles is a result of collision. In DEM simulation, after detecting the contacts, normal and tangential components of the relative displacement U_{abn}(m/s), U_{abt} (m/s) and the relative velocity between the two particles a (particle) and b (tillage implement) are calculated for the inter- particle contacts. This is illustrated in Figure 3.3.

The contact forces, normal force (F^s_n) and tangential force (F^s_t) between particles are computed using a suitable contact law. A damping force is added to the normal damping force (f^d_n) and the tangential damping force (f^d_t) to show the viscous behavior. The contact forces are defined as functions of the normal and tangential stiffness (K_n and K_t), normal and tangential relative displacements. While the damping forces are determined as functions of the damping coefficient and the relative velocity as per Raji (1999).

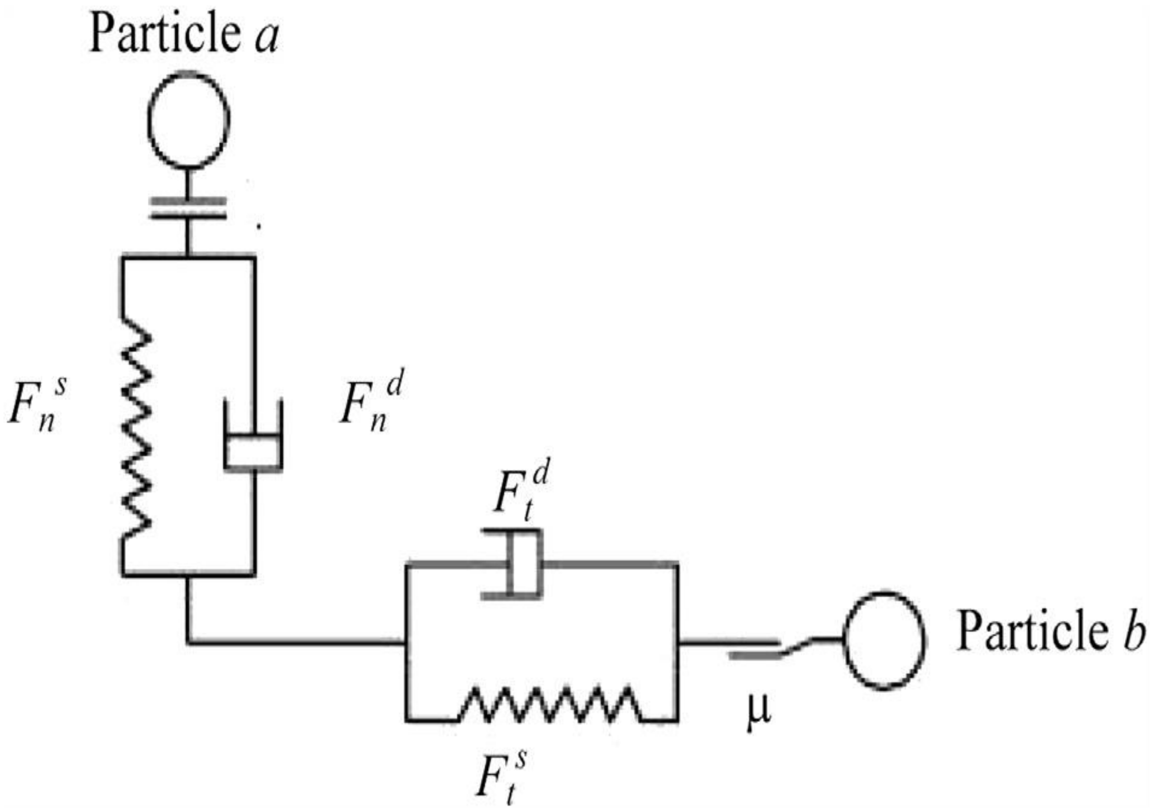

Figure 3.3: Schematic representation of the contacts (Tanaka 2000)

The normal and tangential contact forces as well as the damping forces are defined as functions of the equivalent radius, young's modulus, shear modulus and the mass of the particles. After calculations of F_n and F_t using equations 3.3.1 and 3.3.2 the gravitational force is added to the two forces and the resultant force is determined.

$$F_n = F_n^s + F_n^d \qquad 3.12$$

$$F_t = F_t^s + F_t^d \qquad 3.13$$

CHAPTER 4: MATERIALS AND METHODS

4.1. Research Study Area

The research study area was in Upper Kabete, University of Nairobi. The area was chosen because it has vast agricultural research lands. Figure 4.1 and 4.2 show the average temperature and rainfall values collected over a period of 12 years from 2000 respectively.

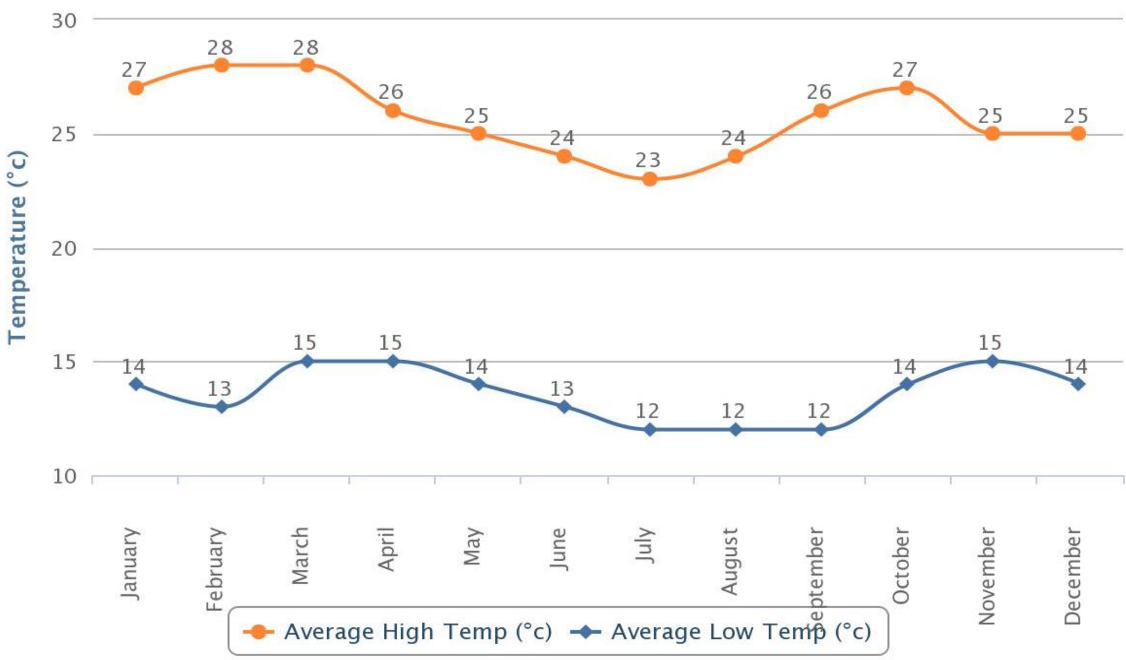

Figure 4.1: Average Temperature in Kabete (World Weather Online)

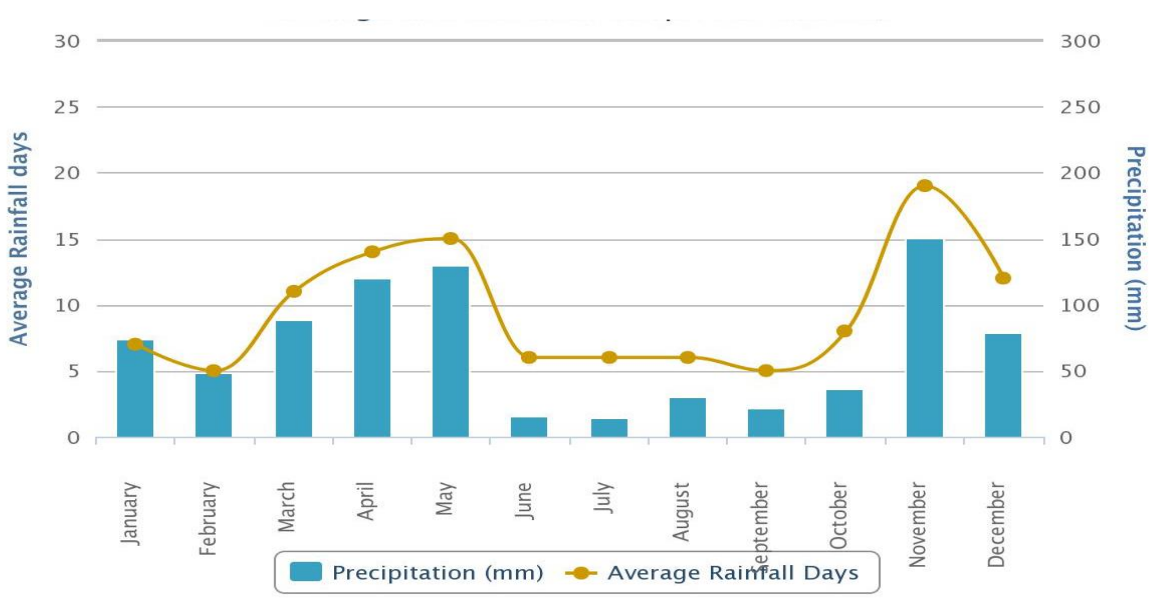

Figure 4.2: Average Rainfall in Kabete (World Weather Online)

4.2. Experimental Set-up

Calculations of the required size of the land were done on the basis of the variables of the experiment and replications performed. A 3 by 3 by 2 by 4 was used to determine the effects of the angle of frog on draught requirements. The numbers of variables were three; depth, speed and frog. Three various depths were used (D_1, D_2 and D_3), two speeds were used (S_1 and S_2) and three frog angles were used (F_{30} F_{40} and F_{50}). The depths used had a range of 10cm from 0cm to 30 cm. the speeds used were either less than 2.5m/s or higher than 2.5m/s but not higher than 5m/s. The replications were four for every set up. Given this factors the required size was found to be not less than 9.0 Acre.

The land was then divided into four blocks and pegs at the end and start of each block put to show the demarcation of the land. Soil samples were taken at random points. Length per block was 30m, width was 10m and space in between was 10 m to allow for turning space for the tractor.

The mouldboard plough was connected to a tractor to facilitate a constant speed operation at the various speed range values. The tractor was run in a continuous turn strip method. This design was chosen to avoid wastage of land (turning allowance) and reduce turning time as well. For each complete run, the same depth, speed and frog was used. The dynamometer was connected remotely to a display that was in turn connected to a PC to allow automatic saving of the data obtained as shown below. The operator of the PC was located at the mid-way of the land clear of any obstructions. Figure 4.3 shows the dynamometer used, the display unit and how it was connected to a computer.

Figure 4.3: Dyna – Link 2 Tension Dynamometer (Measuring Systems International 7300*)*

This digital dynamometer allowed for automatic reading of tension values as well as storage and printing at a later time. It uses rechargeable or disposable cells as the source of power. It has shackles above and below it that allow for easy mounting and are also reinforced with steel to reduce wear. The display section is well reinforced to prevent breakage while in use. Calibration was done to change: units of the tension values, the accuracy level, how the tension value was recorded and the period after which the value was recorded again.

The units inbuilt in the system are: pounds (lb), kilograms (kg), Kilo Newton (kN) and Tonnes (T). The units settled on were kN. The accuracy levels were given to two decimal places. The tension values recording inbuilt in the system were either as total or gross or net and the units settled on were the net tensions values. Net tension values were gross tension value less tare tension values. The dynamometer can record the readings either continuously or once if continuously the time of recording should also be calibrated. For this experiment the dynamometer was calibrated to continuous recording after every two seconds.

The manual provided different types of calibration. Each function is calibrated on its own. In addition there is a general calibration for the dynamometer before the specific feature or requirement calibration. The general calibration is divided into two major types: standard and initial calibration. The standard calibration is used if the weights to be measured are known but it is not a very accurate method. For this reasons the dynamometer was calibrated using the initial calibration method. This method uses a constant calibration number that is factory generated and is usually the seal number of the dynamometer. The calibration number varies the capacity of the dynamometer. Calibration was done using both methods, initial and standard. For each calibration a field test was done and it was discovered that the initial calibration was more accurate than the standard calibration. The field test carried out involved lifting a known weight in the laboratory.

After the initial calibration was done, the units were also calibrated to ensure the data was recorded in kN and finally the printer set up was also calibrated. At the end of the calibration, the values were saved in kN units to two decimal place and recorded after every two seconds.

The dynamometer connected remotely to the remote display, MSI 8000 RF. The remote display is charged electronically and does not use batteries like the dynamometer. It is connected to a display unit e.g. a computer to allow saving of the data because all the RF does is display the same values that the dynamometer is recording but from a distance. The computer then initiated the saving function of the dynamometer.

The RF display connects to the computer either through the internet or through a cable. We connected the RF using a cable for easier portability and to prevent internet downtime scenarios. However, an interface was required to allow compatibility of the RF display to the computer. The manufactures of the dynamometer provided the interface software called Tera Term as shown in Figure 4.4.

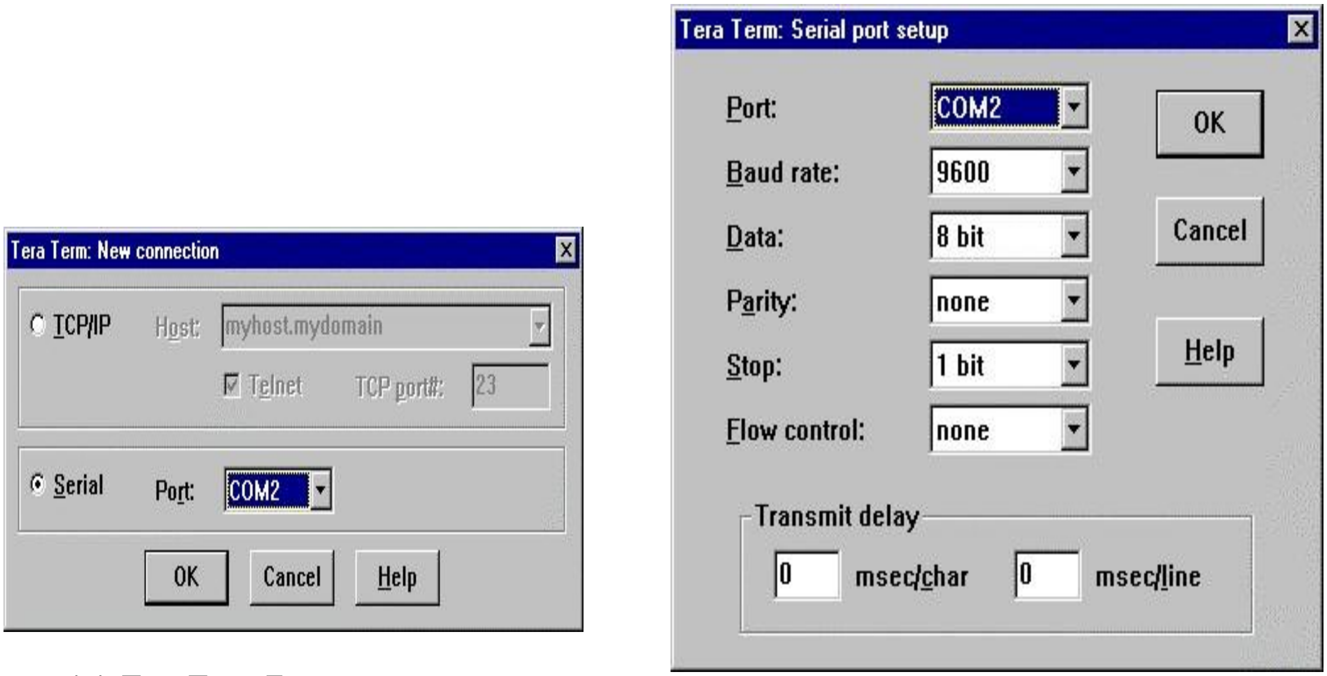

Figure 4.4: Tera Term Extract

Once tera term was installed in the computer the values recorded by the dynamometer were then saved in a tera term window in a version of a note pad and then saved to a word document in the computer's memory.

4.3. Characterization of Soil at the experimental site

Soil samples were collected at random to depths of 30cm with each block having not les that four soil samples. The soil collected was put in polythene papers that were clearly labeled with reference to the block the samples were collected from. The soil was collected using augers from three depths; 0-10 cm, 10-20 cm and 20-30 cm. At each point of soil sample collection, three samples were taken and analyzed for moisture content, bulk density, particle size, particle shape and shear strength parameters.

4.3.1. Dry Sieving

For classification of soil for engineering purposes, we ought to know the distribution of the grain sizes in any given soil mass. Particle size distribution test, also known as sieve analysis (usually dry sieving) test is a method used to determine the grain (granular) size distribution of soil samples (Holtz *et al.*, 1981).

The sieves used are normally made of woven wires with square openings and steel body frame and have different numbers which respect to the opening sizes. British Standards (BS) Sieve Aperture and American Society for Testing and Materials (ASTM) Sieve Aperture sizes are mostly the same especially from 4.75 mm to 63 μm, and slightly different from 75 mm to 6.3 mm and also the most widely used standards in construction.

In this research the soil tested is classified using the Unified Soil Classification method (USCS) In the USCS, all soils are placed into one of three major categories. They are: coarse, fine or highly grained soils.

4.3.1.1. *Dry Sieving Procedure*

i. The air dried soil samples were crushed using a rubber pestle and mortar to remove the large boulders but the soil was not crushed to fine particles. The soil sample was then weighed.

ii. A stack of sieves was arranged in the order described above; the sieves were cleaned using a soft bristle brush to ensure that no soil particles is lodged in between the mesh.

iii. The sieves were then weighed when empty and their respective weight recorded against their number. They were then arranged in the same order with the pan being at the bottom.

iv. The soil was then poured in to the stack of sieves and the stack was placed on the mechanical shaker and properly clamped. The mechanical shaker provided in the Kabete Laboratory is automatically set for 10 minutes.

v. Switch the mechanical shaker on and the vibrating starts. When the shaker timed out, the stack of sieves was removed carefully to ensure that the soil does not spill.

vi. The mass of each sieve was recorded with the weight including that of the soil remaining on the sieve and the sieve weight, this values were recorded. The soil was emptied in the labeled tin and the sieves cleaned the above process was then repeated for the other soil samples.

vii. From the weight values obtained, the weight of soil retained in each sieves was obtained as well as that passing as a percentage,

viii. A curve known as the grading curve was drawn of percentage passing/ fines against the log no of sieves. The diameters corresponding to 10%, 30% and 60% finer are recorded. From this figures Coefficient of Gradation (Cc) and Uniformity of Coefficient (C_u) were calculated.

ix. The above values combined with the amount passing or retained in No 200, 40 and size 75ɥm sieve were used to classify the soil using the USCS.

4.3.2. Triaxial Testing

This test was carried out to determine the shear strength of soils which is the maximum shear stress that can be applied to the soil or the resistance of soil to shearing stresses (Holtz *et al.*, 1981). When this maximum shear stress is reached the soil is regarded as having failed. At failure the shear stress along the failure surface (τ) reaches the shear strength (T_f).

The shear stress (σ_1) at failure and the corresponding normal stress are used to plot the Mohr circles. This circles were drawn on the basis of the Mohr- Coulomb theory that states that a material fails because of a critical combination of normal shear stress and not from either maximum normal or shear stress alone These circles or envelopes were used to obtain the shear strength parameters which are the cohesion factor (c), a measure of shear strength of soils due to friction and the angle of shear resistance or angle on internal friction (Ө), a measure of the forces that cement particles of soil. The higher these values are the higher the shear strength. The Mohr's circle was drawn with a radius. As much as this test is used in classification of soil, its importance to this research is in obtaining the cohesion and internal angle of friction. These values were then input into the Saunders equation.

Triaxial tests were carried out by subjecting cylindrical soil samples to a vertical or axial load. The soil sample was enclosed in rubber membranes with confining lateral pressures present. These pressures are adjustable by making use of the knob in the pressure chamber that varies pressure.

Pressure was applied either through use of water or air but in particular to this study air was used. The soil sample was hence subjected to an increasing axial load until it failed. This test can be performed on both cohesive and cohesion-less soils. The three basic types of triaxial compression test procedures as determined by the sample drainage conditions include:

- Unconsolidated undrained test (UU)
- Consolidated undrained test (CU)
- Consolidated drained test. (CD)

Unconsolidated undrained test is run rather quickly because the sample is not required to drain during application of the axial load.

Consolidated undrained test is performed by placing the sample in the chamber and introducing the confined pressures. The sample is then allowed to consolidate under the all-around confining pressures by leaving the drain lines open. The drain lines are then closed and the axial stress is increased without allowing further drainage.

Consolidated drained (CD), test is run in a similar manner as that of the consolidated undrained test but the difference is that under the CD, the sample is allowed to drain as the axial load is applied so that the high pore pressures do not develop. This test could take a considerable amount of time to run because of the time required to consolidate the soil sample under the confining pressure as well as time for drainage during the application of the axial load.

Minimal principal stress is defined as the lateral pressure or chamber pressure that is applied to the ends of the soil sample as well as to its side. Unit axial load is defined as the externally applied axial load divided by the cross sectional area of the test sample. Major Principal Stress is defined as the unit axial load plus the minor principal stresses in the soil sample.

4.3.2.1. *Triaxial Procedure*

i. The soil to be tested was put on a tray and pre moistened to a certain level such that it was not wet and when one clamps some soil in their hand, the soil does not stick.

ii. All the uneven particles of the soil were removed and the resulting mixture was then moulded by putting a small quantity of the soil into the mold then the soil was compacted with a rod until the specimen mold was full.

iii. The excess soil was removed using a scalpel and the mould removed by sliding it outwards on both sides that hold the specimen together. The mold was first oiled prior to putting the soil sample to ease its removal.

iv. The molded soil sample was shaped until its height was 76mm and placed on the base of the triaxial chamber. It was then put inside a rubber membrane. The soil sample was also placed in between two porous stones at the top and at the bottom. The soil sample was then enclosed by glass housing and placed in position of axial loading device. The pressure was readjusted to the desired chamber level. After this the pressure valve was opened. The pressures used in this practical ranged between 100 kpa to 400 kpa.

v. A lateral /all- around pressure were applied by means of air. With the application of the chamber pressure an axial load was consequently applied so as to produce an axial strain at a given rate of 0.5mm/min at this point the recording of time starts.

vi. The data sheet was filled with data of, initial height and weight, final height and weight after deformation, diameter of the sample, the proving ring readings, time taken to apply an axial load and the rest of the computations were done later. This process continued until the soil sample failed and this was demonstrated by the decline of the proving ring reading.

vii. The soil sample was removed after failure its final weight and height measured and recorded.

viii. This process was repeated for other soil samples of the same soil constituent at different chamber pressures.

ix. The Mohr's circles were drawn for each soil sample tested and attached in the appendices.

4.3.3. Bulk Density

This test was carried out to determine the compaction of the soil. Bulk density is defined as the weight of dry soil per unit volume (Dedousis *et al*., 2010). Soil compaction affects infiltration, rooting depth, available water capacity, soil porosity and soil micro-organism. It is dependent on soil organic matter and soil texture. As the depth increases the bulk density values also increases. The bulk density value will be input into the Saunders equation in calculation of draught requirements.

4.3.3.1. Bulk Density Procedure

i. The sample in the ring was weighed and the weight recorded.

ii. It was then put in the oven for drying.

iii. The weight of the dry samples was also weighed and recorded.

iv. The dry soil sample was then removed and the weight of the ring measured.

v. The moisture content of the soil was then calculated.

vi. The height and diameter of each ring was also measured and recorded and the respective volume calculated.

vii. This was repeated for all samples and bulk density calculated.

4.3.4. Angle of Repose

This test was carried out to determine the maximum slope which the grains are stable (Van, 1945). The value of AOR was used in the calibration of EDEM software. The values of surface energy, coefficient of restitution, static friction and rolling were varied until the resultant AOR value obtained was close to that obtained in the laboratory.

4.3.4.1. Angle of Repose Procedure

i. A stream of soil was slowly poured into the center of the pan without disturbing the pile.

ii. The steepest slope of the soil was measured using a protractor.

iii. This was repeated thrice to get an average angle of repose.

CHAPTER 5: RESULTS and DISCUSSIONS

5.1. Pertinent Parameters Influencing the Angle of Cut

From literature materials the components affecting draught requirements against which optimization was performed are shown in Table 5.1. These components can be broadly described as soil and plough parameters.

Table 5.1: Components affecting draught requirements

Soil Property	**Author of study**
Moisture content	P.M. Owende (2006), S.M. Edward (2006), R.K.Sahu (2006)
Cohesion and angle of internal friction	P.M. Owende(2006), S.M. Edward(2006), R.K.Sahu (2006), C.I. Ijioma (1995), J. Tong (2006).
Bulk Density	J.Tong(2006), R.K. Sahu (2006)
Speed of ploughing	R.K Sahu(2006), P.M. Owende (2006), S.M. Edward (2006), Chris Saunders(2007)
Depth of ploughing	R.K.Sahu(2006), P.M. Owende (2006), S.M. Edward (2006), Chris Saunders(2007)
Angle of repose	Z. Asaf(2007), D.Rubinstein(2007), Mustafa Ugul(2014), Chris Saunders(2007)
Width of cut	R.J. Godwin(2007), M.J O'Dogherty(2007)

5.2. Classification of Soil

The soil was classified using the dry sieving method and the results are as shown in Table 5.2. The work sheet is arranged as per the sieves used from the largest to the smallest sieve and the weight of the soil that passes each sieve and consequently weight of the soil that is retained in each sieve.

Table 5.2: Dry sieving results of sample A

A Sieve No	B Log Sieve No	C Weight of sieve (grams)	D Weight of sieve+ soil (grams)	E Retained Mass (grams) (D-C)	F Cumulative Weight (Sum of E)	G Weight Passing =(624.26-F)	H Percentage Passing (100%) =(G/624.26)
4mm	0.60206	548.50	879.09	330.59	330.59	293.67	47.04
1.70mm	0.230449	407.29	497.63	90.34	420.93	203.33	32.57
1mm	0	508.54	595.54	87.00	507.93	116.33	18.63
850um	-0.07058	391.05	413.21	22.16	530.09	94.17	15.09
500um	-0.30103	343.21	399.80	56.59	586.68	37.58	6.02
212um	-0.67366	319.82	345.79	25.97	612.65	11.61	1.86
106um	-0.97469	442.41	449.3	6.89	619.54	4.72	0.76
63um	-1.20066	271.06	275.16	4.10	623.64	0.62	0.10
53um	-1.27572	264.05	264.37	0.32	623.96	0.30	0.05
45um	-1.34679	265.15	265.31	0.16	624.12	0.14	0.02
Tin		240.93	241.07	0.14	624.26	0.00	0.00

A graph of the percentage Soil passing Vs the Log No sieve was plotted for the values obtained Table 5.2:

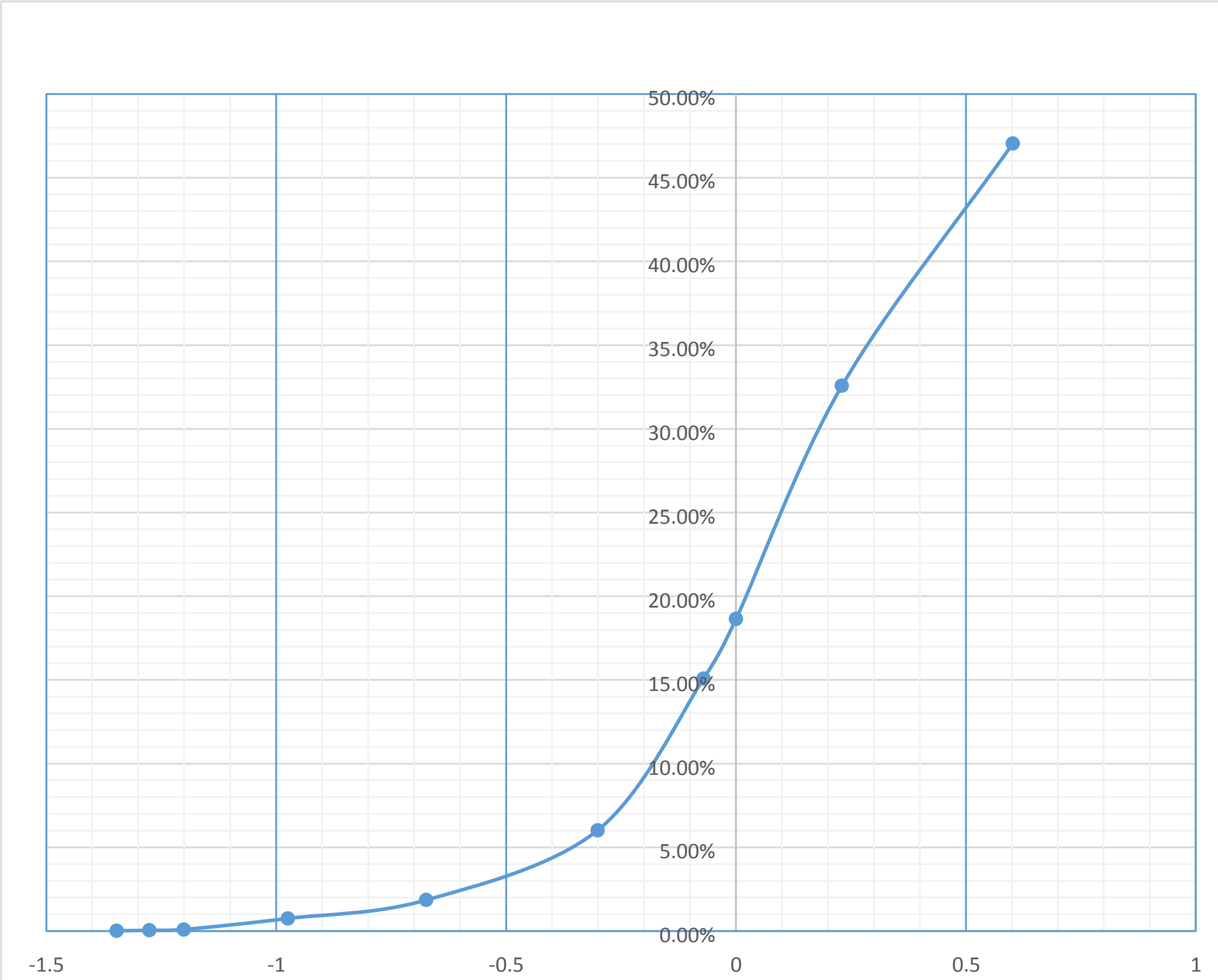

Figure 5.1: Graph of Percentage of Soil Passing Vs Log No Sieve

Using the Unified Soil Classification Manual (USCS) we are able to conclusively determine that the soil is of *sandy clay* type.

5.3. Bulk density

Bulk density was calculated as a ratio of dry weight of bulk sample to the volume of soil core. Bulk density values were calculated for each range of 10cm depth from 0-30cm the results are shown in Table 5.3.

Table 5.3: Bulk Density values

Depth (cm)	**Bulk Density (KN/M^3)**
0-10	3.06
10-20	3.12
20-30	3.36

5.4. Cohesion of soil

This was obtained from the triaxial test. Mohr`s circle were drawn as per the data obtained from the test hence determination of the cohesion and internal angle values.. The cohesion of the soil was found to be an average of 78kN/m^2.

Table5.4: Values of Angles Calculated

Type of Angles	**Value of Angle (°)**
Shearing resistance angle	38.00
Soil-metal friction angle	20.00
Soil-soil friction angle	0.78*
Plough angle	25.00
Share Rake angle	20.00
Mouldboard angle to the direction of motion	155.00
Angle of share edge to the direction of plough motion	26.00

*Soil-soil friction angle was determined as Tan 38° (shearing resistance angle)

5.5. Plough Geometric Parameters

The plough geometric parameters were inputs into the Saunders equation and were measured as shown in Table 5.5.

Table 5.5: Plough parameters measurements

Plough Parameter	Length (cm)
Length of mouldboard	72.00
Working depth of plough	8.00*
Width of plough	26.00
Working depth of share	11.00
Working width of share	31.00

*Working depth was measured between three different ranges of 10cm from 0cm to 30cm. 8.00cm was the average working depth between 0cm to 10cm range.

5.6. Determination of Draught Requirements

Draught was determined in three different ways, calculated, measured and predicted. Draught force was calculated using the Saunders equation. A data logger in this case an MS 7300 digital dynamometer was used to measure the draught forces. Draught forces were predicted using the DEM model and the EDEM software. A basic programme was written in Visual basic for applications (VBA) to assist with the calculations of draught using equations 3.1 to 3.11 for the Saunders equation. Table 5.6 shows the draught force obtained using the three different methods of determining the draught requirements.

Table 5.6: Draught forces values for the three frogs used

Frog (°)	Code	Speed (m/s)	Depth (cm)	Dynamometer (kN)	Saunders (kN)	Simulation (kN)
30	S1D1	1.60	7.75	0.66	0.76	0.99
	S2D1	2.66	8.00	0.81	1.06	0.86
	S1D2	1.45	16.25	1.32	1.03	1.28
	S2D2	3.56	17.00	1.55	2.16	1.47
	S1D3	1.39	24.75	1.86	1.42	2.19
	S2D3	3.89	24.50	2.04	3.15	1.91
40	S1D1	1.60	7.25	0.92	0.75	1.69
	S2D1	3.17	8.25	0.95	1.27	0.88
	S1D2	1.75	16.25	1.37	1.16	1.44
	S2D2	3.95	18.25	1.59	2.21	1.59
	S1D3	1.57	24.00	1.88	1.52	1.97
	S2D3	4.17	24.25	2.03	3.30	2.51
50	S1D1	1.34	7.00	0.82	0.70	0.91
	S2D1	3.36	7.25	0.84	1.26	1.23
	S1D2	1.33	15.25	1.11	0.95	0.99
	S2D2	3.95	16.25	1.27	2.11	1.23
	S1D3	1.44	23.25	1.35	1.39	1.31
	S3D3	4.02	24.25	1.53	2.99	1.57

The draught forces were analyzed using qlik view and R software. R software is statistical software while qlik view is used in modelling. Figures 5.2 to 5.7 show graphs of the draught forces calculated against speed and depth for the three frog angles used.

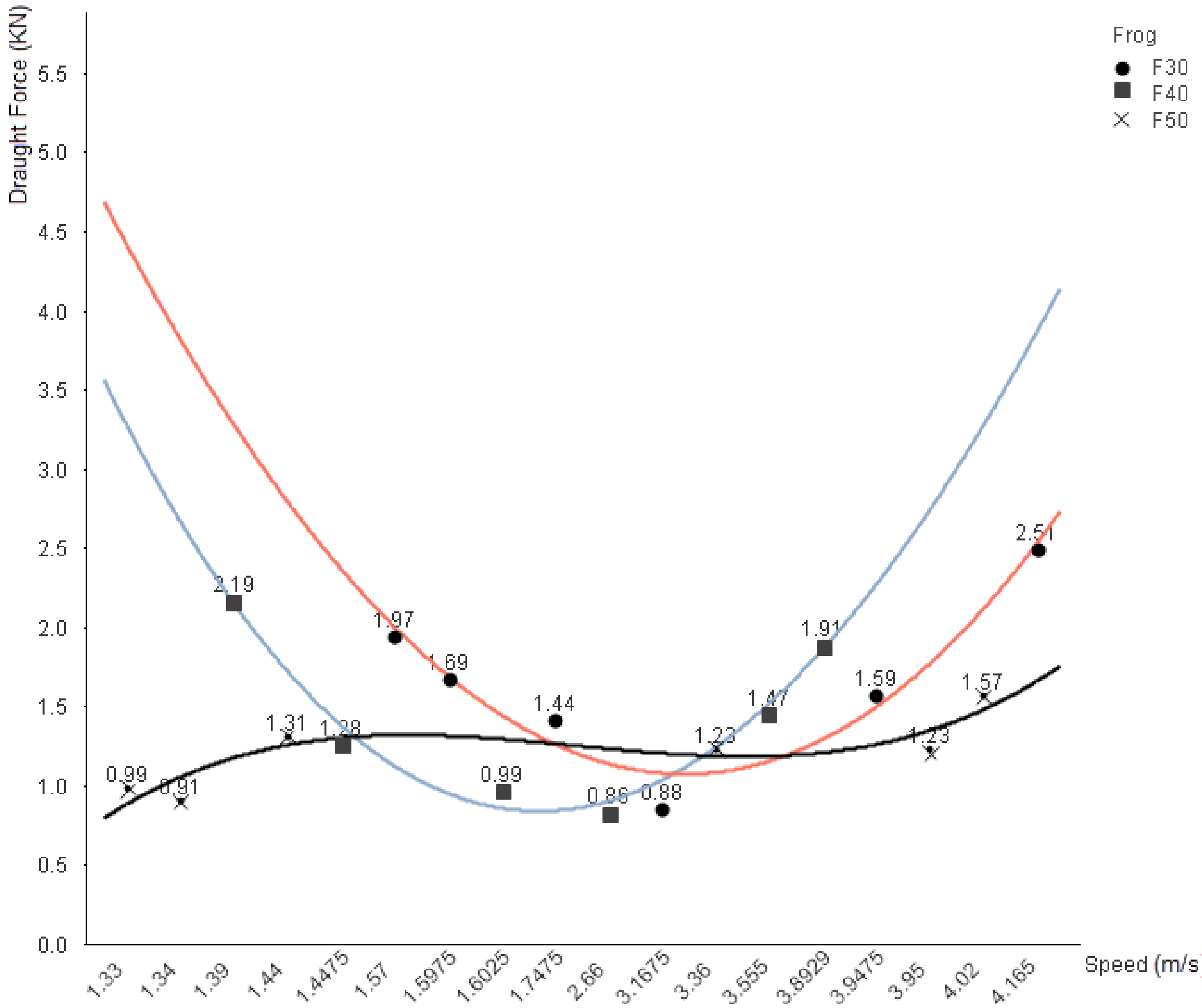

Figure 5.2: Simulation Draught Force Vs Speed

This is a graph of draught force Vs speed. The draught force was determined through the simulation method using the EDEM software. It portrays the least draught force as 0.9kN at a speed of 1.6m/s for the frog at an angle of 30°. The graph shows the relationship between draught force and speed as a quadratic equation with a value of 0.96 as the coefficient of determination.

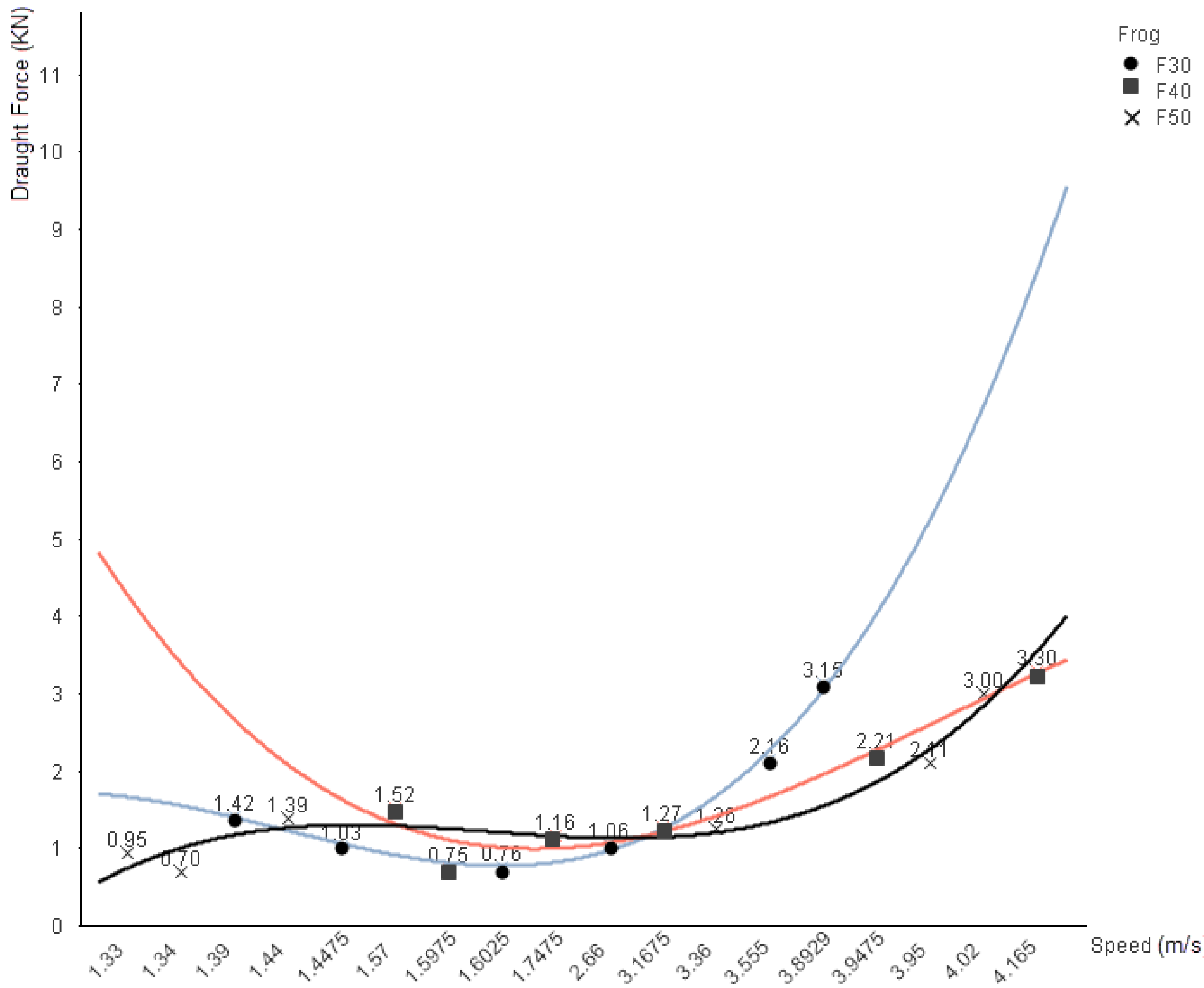

Figure 5.3: Saunders Draught Force Vs Speed

This is a graph of draught force Vs speed. The draught force was determined through Saunders equation method. It portrays the least draught force as 0.8kN at a speed of 1.6m/s for the frog at an angle of 30°. The graph shows the relationship between draught force and speed as a quadratic equation with a value of 0.98 as the coefficient of determination.

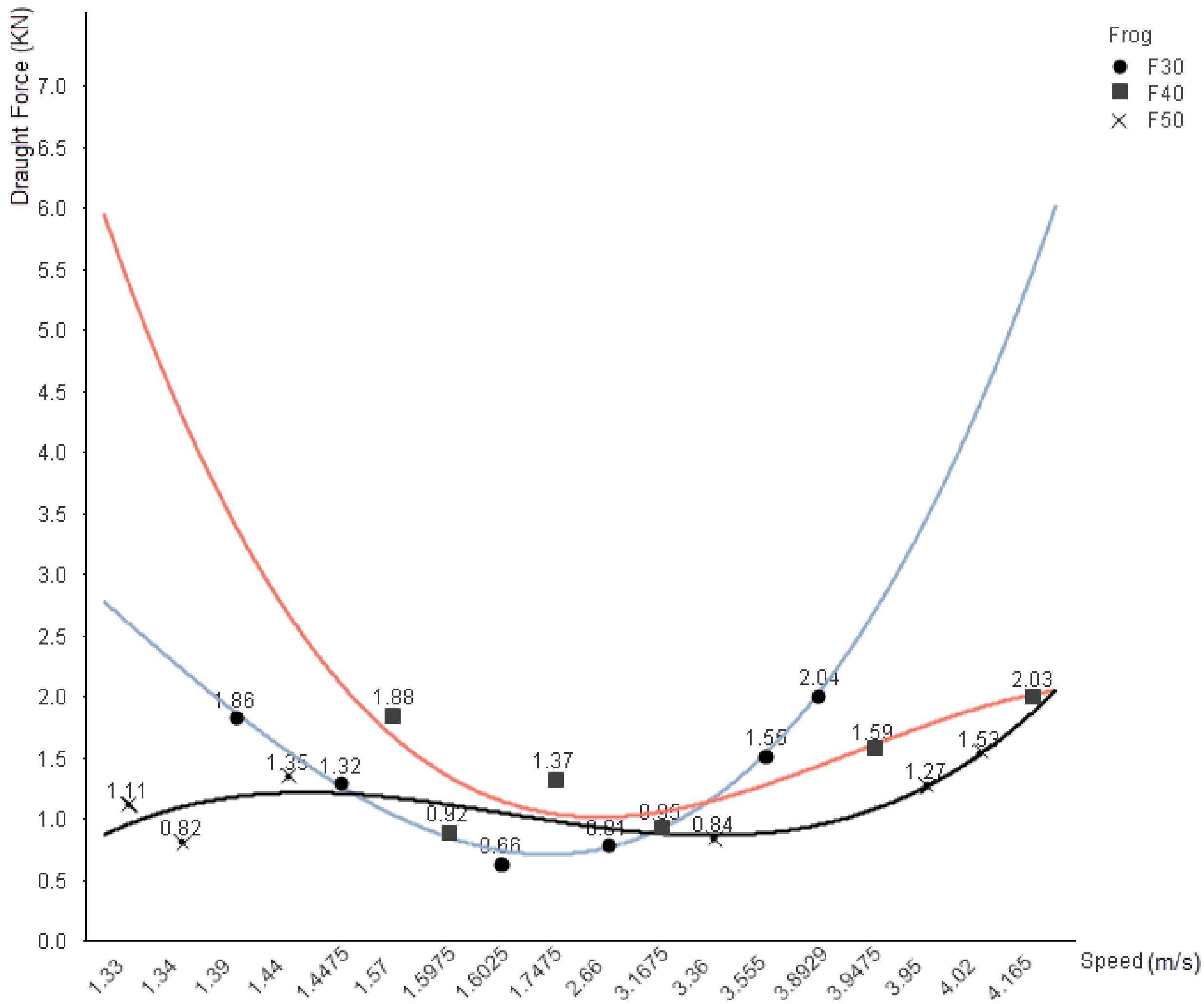

Figure 5.4: Dynamometer Draught Force Vs Speed

This is a graph of draught force Vs speed. The draught force was determined from data obtained from the data logger station which was the dynamometer. It portrays the least draught force as 0.7kN at a speed of 1.6m/s for the frog at an angle of 30°. The graph shows the relationship between draught force and speed as a quadratic equation with a value of 0.92 as the coefficient of determination.

Figure. 5.2. 5.3 and 5.4 show that Frog 50° behaves in contrary to frog 30° and frog 40° this is because, draught forces increases as the cutting angle increases sometimes in multiples of 5 if the soil is saturated (Palmer, 1999). In this study, the soil was not saturated

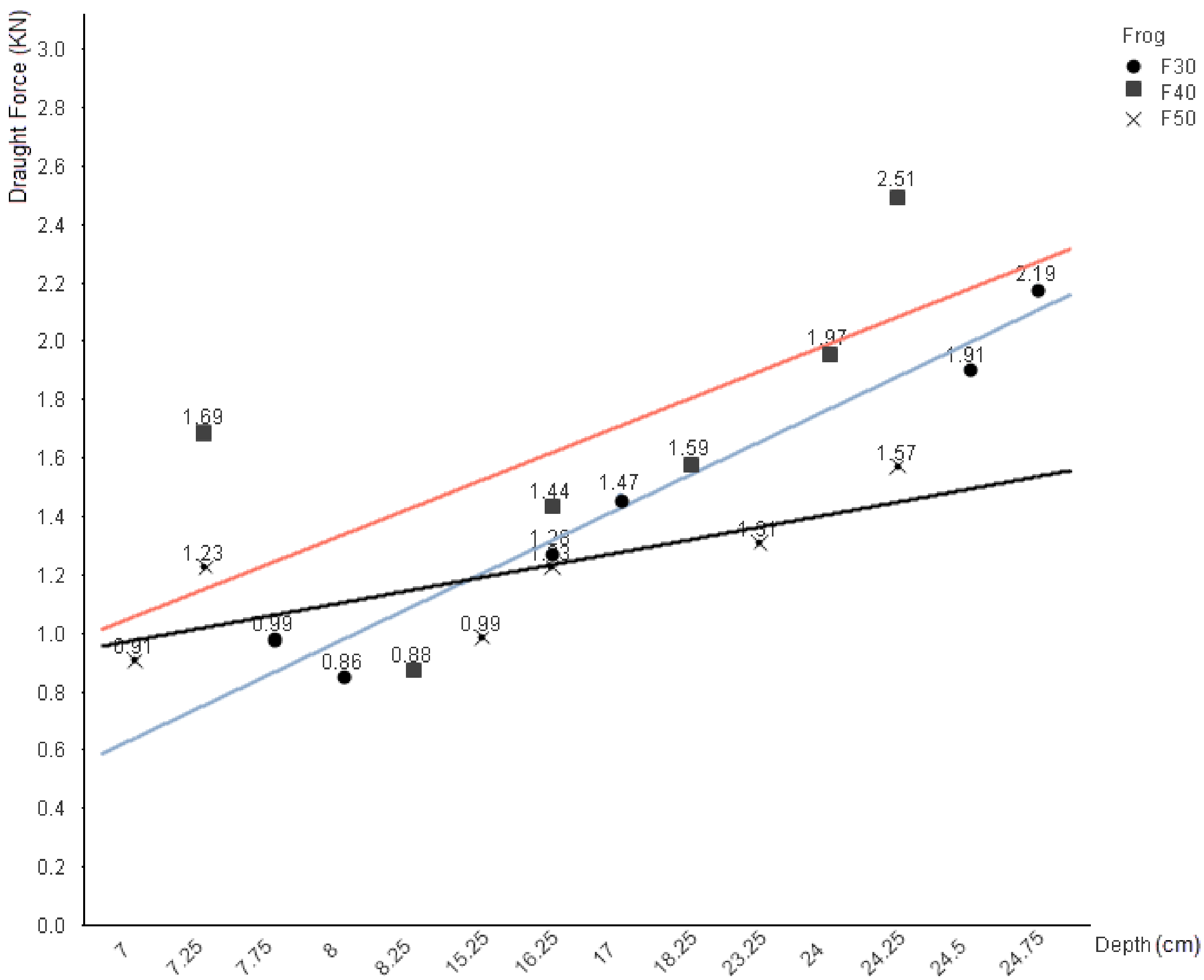

Figure 5.5: Simulation Draught Force Vs Depth

This is a graph of draught force Vs depth. The draught force has been determined through simulation method using the EDEM software. The graph shows the relationship between draught force and speed as liner equation.

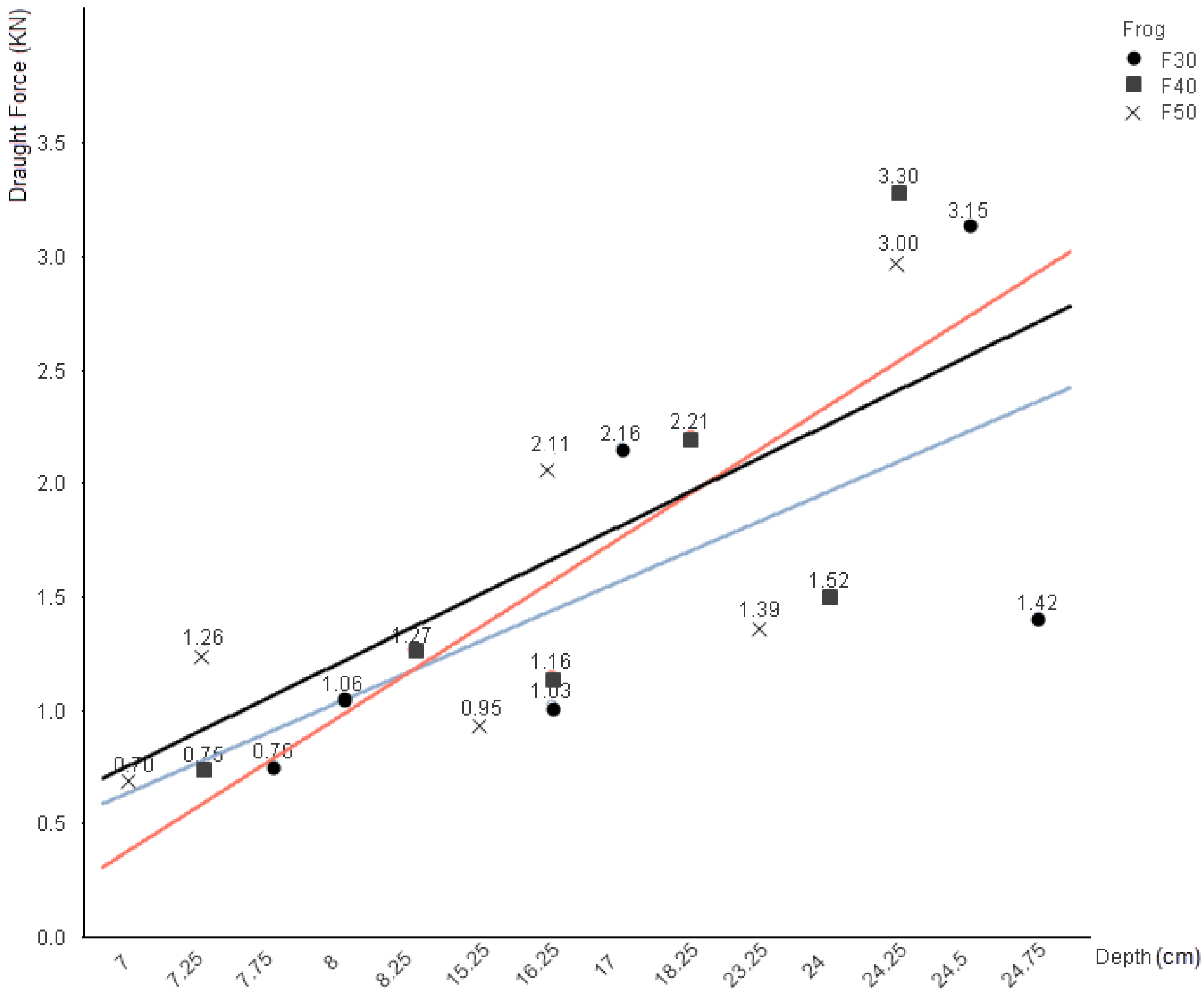

Figure 5.6: Saunders Draught Force Vs Depth

This is a graph of draught force Vs depth. The draught force has been determined from the Saunders equation .The graph shows the relationship between draught force and depth is linear.

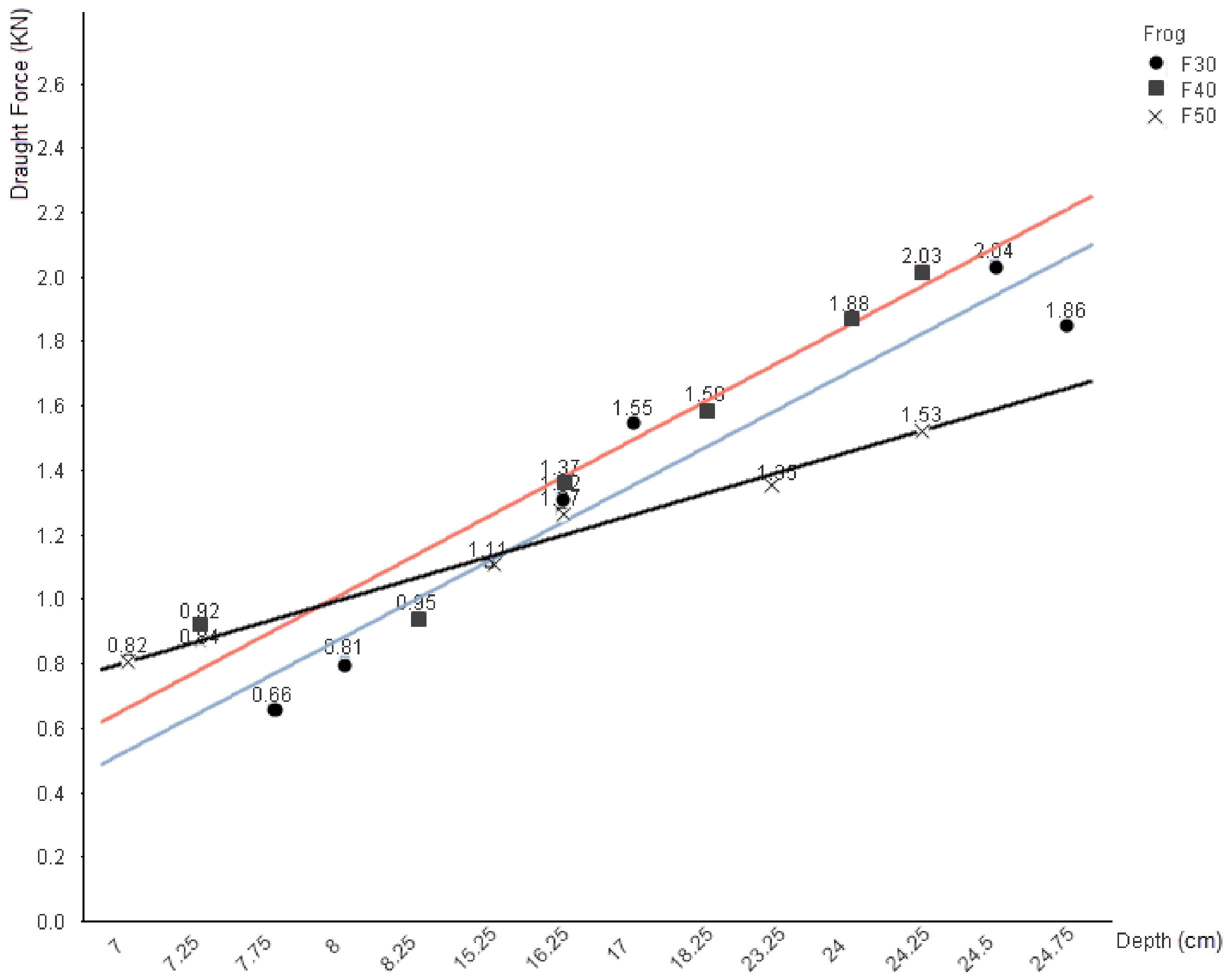

Figure 5.7: Dynamometer Draught Force Vs Depth

This is a graph of draught force Vs depth. The draught force has been determined from data obtained from the data logger station which was the dynamometer. The graph shows the relationship between draught force and depth as liner.

In low speeds (below 2.5m/s) frog 30° had the lowest draught forces while in high speeds (above 2.5m/s) frog 50° had the lowest draught forces. Saunders equation resulted to very high draught forces values when speeds above 2.5m/s were used. The Dynamometer recorded minimal draught forces at speeds above 2.5m/s because it was not stable hindering its ability to measure the force. C Saunders et al., (2007), determined the draught forces using Saunders equation in a sandy clay soil for depths between 12.5 cm and 22.5 cm the study established the draught force as a range of 1.0kN to 2.0kN. These results assimilated those determined in this study.

The difference between the modeled and experimental predicted forces was a positive at low speeds at an average and negative at low speeds. This is because Saunders equation works best for speeds below 2.5m/s. The difference between the draught forces obtained from the dynamometer and that obtained experimentally also exhibited the same behavior. The difference between modeled forces and those obtained from the dynamometer was about 4%.

For an increase in ploughing speed over a range of 1.6m/s to 2.5m/s for example, the draught force increased by a mean value of 20.55% at a depth of 8cm. However the effect of depth over the same depth of 8cm to 17cm at a speed of 2.5m/s the draught force increased by a mean value of 38.6% showing that the change in draught force is greater for an increase in depth than for the increase in speed over typical practical ranges.

R software was used to run statistical analysis on the data. The effect of speed, depth, frog angle on the draught force was investigated .Regression equations were created and models run to test the relationship. At a 95% confidence level the p-values were found to be less than 0.05 and the null hypothesis was accepted indicating the significance of speed, depth and frog angle to the draught force.

Table 5.7 Effect of parameters on the Draught Force

Source	DF	Sig
Speed	1	0.003
Depth	2	0.002
Frog angle	2	0.003
Speed and Depth	4	0.001
Depth and Frog Angle	5	0.002
Speed and Frog Angle	4	0.002

A liner regression was applied to investigate the degree of correlation of EDEM and experimental draft force. Figure 5.8 shows a datasets of both the draft and an R2 (Coefficient of determination) value of 0.9399 indicating that the model used accurately modelled the tillage process.

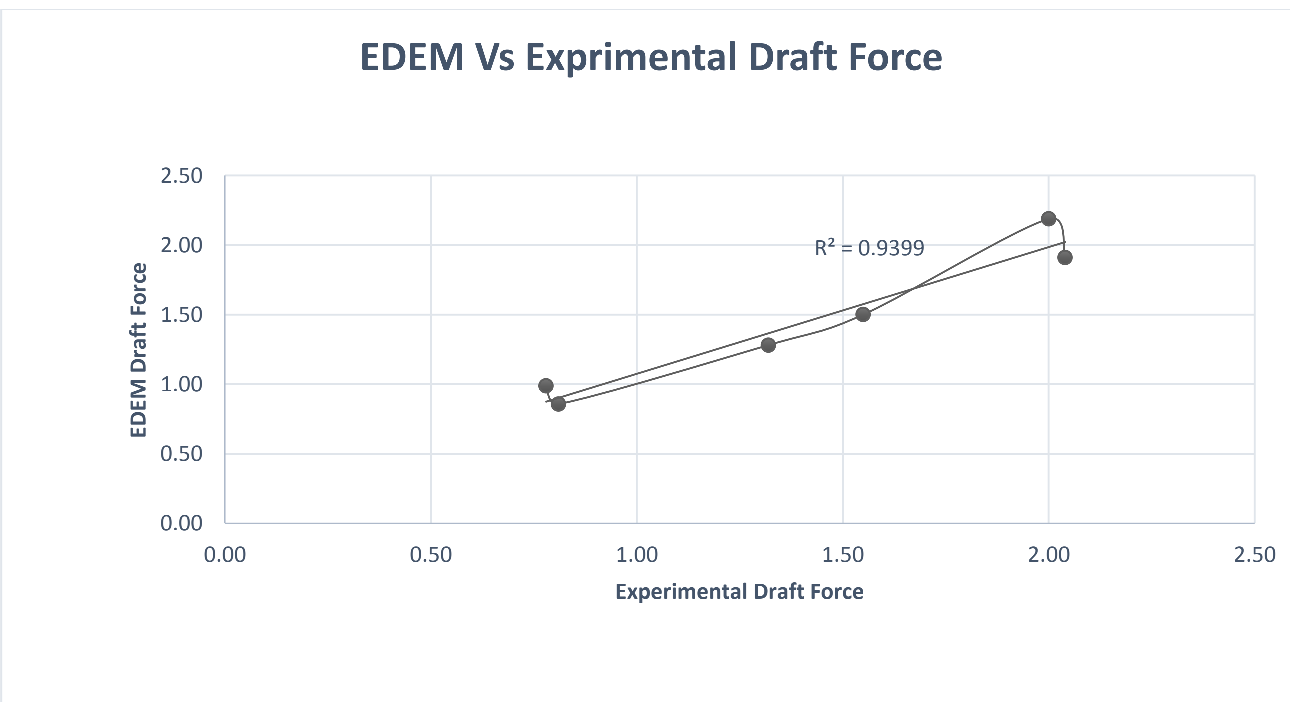

Figure 5.8: Graph of EDEM Vs Experimental Draught Force

*the values were taken for all the frogs at a speed of 2.5m/s and depth of 8.0cm

CHAPTER 6: CONCLUSION AND RECOMMENDATION

6.1.CONCLUSION

The pertinent parameters that affected draught force were divided into soil parameters, working parameters of the tool and plough parameters. From literature materials the pertinent soil parameters affecting draught included: cohesion of soil, angle of internal friction, moisture content, bulk density, soil metal friction angle and soil soil friction angle. These parameters were determined by carrying out various tests on the soil samples collected from the field site.

A numerical simulation method was used to predict the draught forces acting on a mouldboard plough. This was done based on the knowledge of the critical physical properties of the soil, the tillage speed, tillage depth and the defining geometric parameters of the plough. The model used was DEM and the software used was EDEM. Field experiments were carried out to verify the draught force predictions at tillage depths of ranges of 10cm from 0-30 cm and the speeds ranged from 1.33 m/s to 4.2m/s. The field experiments were conducted in two ways; using data obtained from an automated data logger and also inputting the variables of the parameters in an equation. The data logger used was the dynamometer and the equation used was Saunders equation. A VBA was developed to calculate the total draught force requirements using the Saunders equation.

A comparison of the measured and predicted draught forces showed that the model is able to accurately predict the draught force with good accuracy. This was supported by a coefficient of determination value of 0.9399. A statistical analysis of all the variables at 95% confidence interval showed a significance level less than 0.05 indicating that the frog angle, speed and depth of tillage had a great significance on the draught forces.

The graphs developed showed that draught force increased as speed and depth of tillage increased for all the frog angles. Draught force increased with increase in depth of tillage linearly. The liner relationship between draught force and depth shows the importance of regulating the depth Draught force increased with speed of tillage and the relationship was quadratic equation. The optimal speed was observed to be 1.60m/s across all frogs.

The frog at angle 30° was the optimal angle. This frog had minimal draught requirements hence the objective of the study was achieved.

6.2.RECOMMENDATION

1. This study should be replicated for various types of soil to establish if the outputs of this study and its conclusion still hold.
2. This study should be replicated for a mouldboard plough that has more than one ploughs to determine if the conclusions of this study will hold.
3. Studies should be done to improve Saunders equation when the velocity of tilling is higher than 4.0m/s.
4. Studies should also be done to investigate the effect of change of the frog angle of the specific parts of the plough according to the Saunders equation.

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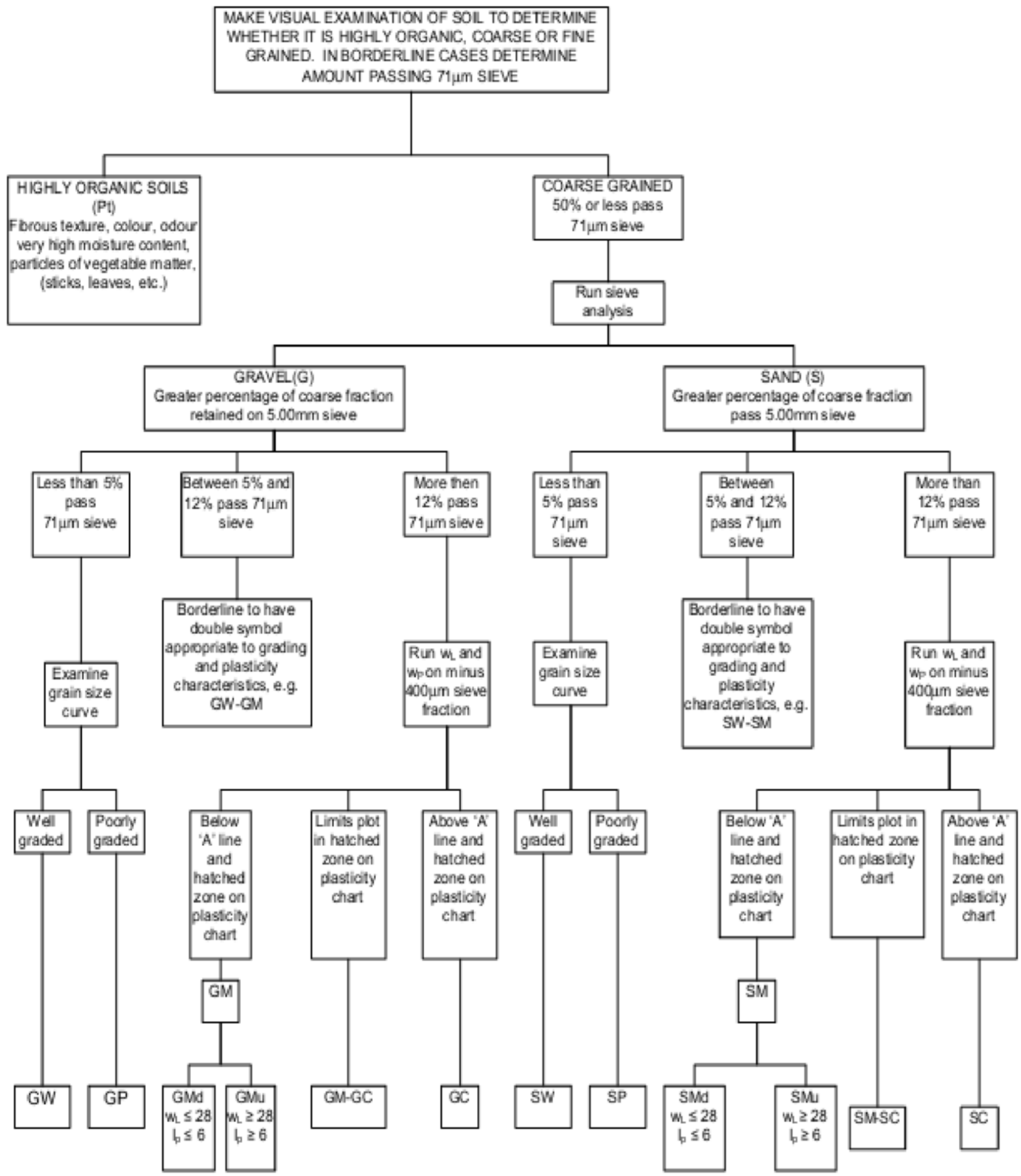
APPENDICES

APPENDIX A: SOIL CLASSIFICATION

A.1: BULK DENSITY CALCULATIONS

Depth	Wet Sample Weight + Container (g)	Dry Sample Weight + Container (g)	Weight of Container(g)	Dry Sample Weight (Kg)	Volume of Container (M^3)	Bulk Density (KN/m^3)
0-10	57.5	52.28	30.17	0.02211	0.00007541	2.876
10-20	66.57	59.04	24.92	0.03412	0.00010016	3.343
20-30	66.22	57.95	25.79	0.03216	0.00010016	3.15
0-10	83.97	73.25	32.32	0.04093	0.00010016	4.009
10-20	68.57	59.39	25.29	0.0341	0.00010016	3.34
20-30	45.58	39.99	11.39	0.0286	0.00007541	3.721
0-10	57.46	52.27	25.28	0.02699	0.00009901	2.674
10-20	61.04	53.88	25.21	0.02867	0.00010016	2.808
20-30	59.75	51.96	23.58	0.02838	0.00009901	2.812
0-10	61.21	56.03	32.42	0.02361	0.00010016	2.313
10-20	54.67	50.14	25.77	0.02437	0.00007541	3.171
20-30	60.94	55.24	29.15	0.02609	0.00010016	2.556
0-10	66.48	60.25	24.91	0.03534	0.00010016	3.461
10-20	57.35	51.54	23.94	0.0276	0.00009901	2.735
20-30	89.44	80.03	32.7	0.04733	0.00010016	4.636
0-10	62.38	56.49	25.52	0.03097	0.00010016	3.033
10-20	57.83	53.03	25.52	0.02751	0.00009901	2.726
20-30	66.62	59.3	25.79	0.03351	0.00010016	3.282

A.2: USCS MANUAL



APPENDIX B SOIL PARAMETERS CALCULATIONS

B.1: Soil Coefficient Parameters

Reference	Computations	Output
	Soil friction cutting Coefficient $$N_\gamma = \frac{0.5\cot\alpha + \cot\beta\left(1 + \frac{2d}{3w}\sqrt{\cot * \cot\beta + 2\cot \propto \cot\beta \sin[\beta+\phi]}\right)}{\sin[\alpha+\beta+\delta+\phi]}$$ Where: α = 25° β = 26° w = 0.26M δ = 20° ϕ = 38° taking depth as 0.08m $$\frac{0.5\cot 25 + \cot 26\left(1 + \frac{2 * 0.08}{3 * .26}\sqrt{\cot * \cot 26 + 2\cot \propto \cot 26 \sin[26+38]}\right.}{\sin[25+26+20+38]}$$ Taking depth as 0.17m Taking depth as 0.25m	$N_\gamma = 3.407109$ $N_\gamma = 3.524816$ $N_\gamma = 3.629444$

Soil Parameters computations		
Reference	Computations	Output
	Soil Overburdening Cutting Coefficient $N_q = \frac{\cot\alpha + \cot\beta\left(1 + \frac{d}{w}\sqrt{\cot * \cot\beta + 2\cot \propto \cot\beta\sin[\beta + \phi]}\right)}{\sin[\alpha + \beta + \delta + \phi]}$ Where: α = 25° β = 26° w = 0.26M δ = 20° ϕ = 38° taking depth as 0.08m $\frac{\cot 25 + \cot 26\left(1 + \frac{0.08}{0.26}\sqrt{\cot * \cot 26 + 2\cot \propto \cot 26\sin[26 + 38]}\right)}{\sin[25 + 26 + 20 + 38]}$ Taking depth as 0.17m Taking depth as 0.25m	$N_q = 5.568853$ $N_q = 6.842729$ $N_q = 7.975063$

Soil Parameters computations		
Reference	Computations	Output
	Soil Adhesion Cutting Coefficient $$N_{ca} = \frac{-\cos[\alpha+\beta+\delta+\phi]}{\sin\alpha\sin[\alpha+\beta+\delta+\phi]}$$ Where: α = 25° β = 26° δ = 20° ϕ = 38° taking depth as 0.08m $$N_{ca} = \frac{\cos(25+26+20+38)}{\sin 25 * \sin[25+26+20+38]}$$	$N_{ca} = 0.04368$
	Soil Rupture Distance Ratio $$m = \frac{d(\cot\alpha+\cot\beta)}{d}$$ $$m = \cot 25 + \cot 26$$	$m = 4.194811$

APPENDIX C: TERMINOLOGIES

Agricultural Mechanization

This is defined as the process of using agricultural machinery to mechanize the work of agriculture increasing productivity and reducing drudgery.

Angle of Repose

It is the steepest angle of the slope of the material at rest measured relative to the horizontal plane and it's of importance as it helps in qualitative comparison of the soil furrow profile after tillage.

Arable Land

This is land capable of producing crops and suitable for tillage. FAO defines is as land that is temporary under crops.

Damping Forces

These are forces that are used to dissipate energy from a vibrating structure. The force is usually equal in magnitude but opposite in direction to that of the motion of the vibrating body.

Discrete Element Modeling

Discrete element modeling also known as DEM is one of the numerical modeling methods and aims at describing the mechanical behavior of granular materials.

EDEM

EDEM is one of the softwares that is integrated with DEM capabilities.

Effective Field Capacity

This is the actual rate of the land processed in a known amount of time.

Field Capacity

It is defined as the ratio of effective field capacity to theoretical field capacity hence a measure of the productivity in a given field.

Modeling

Modeling is done to investigate the behavior of something without testing it in the real life. This is aimed at saving resources.

Mohr coulomb theory

This theory states that material fails because of a critical combination of normal shear stress and not from either maximum stress or shear stress alone.

Newton's Second Law of Motion

This theory states that acceleration of an object as produced by a net force is directly proportional to the magnitude of the net force.

Precision Agriculture

Precision Agriculture aims at revolutionizing agriculture and making it a more computerized function allowing the farmers to control most of the farm operations.

Soil-cut Interaction

This is defined as the process in which the response of the soil influences the motion of the tool and tool influences the response of the soil.

Soil Rupture Distance

This distance is defined as the ratio between forward rupture distance and working depth.

Theoretical Field Capacity

This is defined as the rate of performance obtained if a machine operates at 100%.however it is unlikely for a machine to perform at a 100% because of the operational losses

Tillage

Tillage is defined as the physical or mechanical manipulation of soil with tools.