THE PERFORMANCE OF ANIMAL DRAWN MOULDBOARD PLOUGHS

BY

KENNETH KARIUKI NDUGO, B. Sc. University of Nairobi.

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DECLARATION

I declare that this thesis is my original work and has not been submitted for a degree in any other University.

Date 27.3.92

NDUGO K. KARIUKI

This thesis has been submitted for examination with our approval as the University supervisors.

Date 31/8/92

for Mr. L. Oudman

Date 31/8/92

Dr. P. G. Kaumbutho

DEDICATION

This Thesis is dedicated to the memory of my grandparents:

Mr. Pharis Ndugo Kanyiri
and
Mrs. Sophia Nyambura Ndugo.

CONTENTS

List of Figures

List of Tables

List of Plates

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To my mother, Margaret Wanjiku for all that she has done for me.

To the Almighty God, all this would not have been possible without YOU.

I am most grateful to all.

ABSTRACT

The geometry of four ploughs was characterised by taking various angular and linear measurements of the salient features of the plough body based on the method described by Boer (1966). Two of the ploughs were Kenyan manufactured, (Bukura Mk. II and Victory plough) while the other two ploughs were manufactured by a company in Holland, (Rumptstad: winding and cylindrical bottoms).

The specific resistances in sand of the four ploughs were evaluated as a measure of plough performance under three different soil conditions (blocks). The performance of these ploughs was evaluated between the speed range: 0.49 m/s to 1.04 m/s this is the speed that draught animals would be expected to operate at. The soil condition was characterised with respect to the following parameters: soil bulk density, soil moisture content, adhesion, coefficient of soil-metal friction, cohesion, internal angle of friction and the soil particle size distribution.

The performance of the ploughs was modeled using the technique attributed to Goryachkin (1927). The average modeling results from the three blocks compared well with the average results obtained experimentally.

1 INTRODUCTION

There are various types of animal drawn mouldboard ploughs available in Kenya. Some are manufactured locally and a number are imported. It has been established that ploughs suitable for some particular conditions are not necessarily suitable for other conditions. Some design requirements are unique to specific soils and working conditions. High speed ploughs have design requirements different from low speed ploughs. These differences range from geometry to strength requirements.

Various aspects could possibly be attributed to the poor state of design of ploughs in Kenya. They range from lack of stringent standards, lack of enough research or understanding of the soil-tool interaction to lack of appropriate materials for the fabrication of plough parts requiring special material like the share.

The performance of a plough is often used as a criterion to establish the suitability of such a plough for some particular conditions. The performance of the plough can also be used to compare different ploughs. The factors that affect the performance of ploughs have not been adequately investigated locally and as such have not been incorporated in the design of the ploughs. These factors include the shape characteristics of the plough, the characteristics of the soil, the speed of operation of the plough and the interaction between the soil and the plough. The criterion used to measure the performance of a tool depends on the requirements of the farmer, the researcher or the designer. The end use of the information on the tool performance influences the method that is used to obtain such information.

The ability to model the performance or the behaviour of a tool depends on the availability of data on the performance of such a tool. The ability to model the performance of a tool helps to predict its performance when it is subjected to some defined condition. Therefore, by measuring the characteristic parameters of a soil-tool system, it is possible to predict the performance of the tool in that system. This eliminates the need to physically evaluate the performance of the tool thereby saving scarce resources. The modeling of the performance of agricultural tools has not been specific to the Kenyan situation or conditions.

After weighing the facts highlighted in this introduction, it is evident that there is need to investigate what parameters affect the performance of animal drawn mouldboard ploughs and how they affect the performance. There is need to investigate the soil-tool interaction in order to obtain the ideal plough for specific soil conditions and avail this information to the manufacturers of ploughs.

2 OBJECTIVES

The objectives of this study are:

a) To characterise the geometry of four animal-drawn mouldboard ploughs.

b) To evaluate the performance of the animal drawn mouldboard ploughs with respect to their draught requirement (soil specific resistance) and soil inversion capability.

c) To model the performance of the animal drawn mouldboard ploughs.

In particular, the following aspects will be investigated: The differences in the plough geometry, the effect of the various soil parameters on their performance and the effect of speed on the performance of the ploughs.

3 LITERATURE REVIEW

3.1 The History of the Plough

Tillage implements first appeared probably in 6000 B.C. according to the Encyclopedia Brittanicca (1979) when man attempted to get involved in control of growth and yield of plants. Ploughs made an appearance in Mesopotamia around 3000 B.C. and 500 years later in Egypt. Figures 3.1 and 3.2 illustrate some of these early ploughs.

Figure 3.1 A plough deriving from the 40th Century B.C. according to a drawing on a Syracuse coin (Bernacki et al., 1972)

Figure 3.2 An Egyptian plough deriving from the 25th Century B.C. according to an Egyptian drawing (Bernacki et al., 1972)

According to the Encyclopedia Brittanicca (1979), the first iron ploughs were fabricated around 2000 years ago, in Northern Honan (China). They were flat, V-shaped and the iron piece was attached to wooden blades and handles. Initially they were hand-drawn but later they were adopted for animal traction (water buffalo) around the first century. Wheels, cutting coulters and mouldboards were included in the European ploughs around 1500 A.D.

Attempts to design ploughs based on technical calculations were first probably done by Lummis (1730). Hoffman (1752) investigated the effects of direction on the draught requirement of ploughs. Berch (1759) advocated the need of appropriate board bending in the construction of ploughs. Small (1784) and Bailey (1794), constructed ploughs on the basis of observations of movement of the furrow slice after it had been cut as cited by Bernacki et al., (1972).

In 1825 the Wawerka brothers from Czecholosvakia constructed an implement called the "Rukhadlo," where the mouldboard and the share were made from a single metal plate. By 1842 a new type of plough was made in the United States of America (U.S.A) where its working part consisted of a concave turning bowl called a disk, as cited by Bernacki et al. (1972).

Sack and Eberhard in Germany as cited by Bernacki et al., (1972) were designing ploughs entirely from iron, while in the U.S.A Oliver (1853) introduced a cast iron mouldboard. Morrison (1862) made the first double layered mouldboard from two hot rolled metal sheets.

3.2 Draught Animal Use in Agriculture

Draught animals are an important source of power in the developing countries and they will continue to play an important role into the future due to the high cost of machinery. About two billion people in the developing countries depend on animal power. Animals have been found to be ideal for hilly terrain, narrow fields and water logged fields. They have also been used extensively for transport within distances of twenty kilometres and transporting weights not exceeding 1000 Kgs.

Various types of draught animals have been known to provide between 0.4 to 0.8 hp for a period of 2 to 4 hours. According to F.A.O. as reported by Falvey () the following was the power utilization distribution in land cultivation as shown by Table 3.1.

Table 3.1 Area cultivated (10^6 ha) in the developed and less developed countries in 1975 (Falvey, ()).

Country	Area	Hand Labour	Animal power	Tractor power
L.D.Cs'	479	26%	52%	22%
D.Cs'	644	7%	11%	82%

These figures exclude China where animal power is used extensively hence in fact the role of draught animals is more important than actually what is given by the above data. The exclusion of figures from China in Table 3.1 was due to the unavailability of actual data from there during the survey by F.A.O.

3.3 Animal Drawn Mouldboard Ploughs in Kenya

3.3.1 Specification

The specification for the fixed type animal drawn mouldboard ploughs in Kenya is the KS06-252 of 1982. This specification is adapted from the Indian specification, IS:2192 (part 2) of 1976. The requirements of specification KS06-252 are quite general, they are as follows.

It classifies ploughs into four different sizes according to the length along the landside, from the share tip to the heel.

- Extra light up to 100 mm.
- Light ploughs from 100 mm to 150 mm.
- Medium ploughs from 150 mm to 200 mm.
- Heavy ploughs from 200 mm and above.

This classification assumes that the nominal size is proportional to the plough weight.

The standard specifies that the share and the share point should preferably be made of medium carbon steel of Brinell Hardness number greater or equal to 360. The plough should have adequate suction, but does not specify what is adequate.

All other parts of the plough should be made of mild steel except the gage wheel which should be made of cast iron. The beam should have a load bearing capacity of 8000 N. A safety device should be incorporated in the linkage to ensure that the maximum load is not exceeded.

The surface of the plough should be even and should be coated with anti-corrosive paint. The plough should have smooth inversion. Permanent markings on the plough include, the year of manufacture, the manufacturer's name or trade mark and the size of the plough.

These specifications are quite general and not specific enough on some aspects. They should be more explicit than they are at the moment and should be enforced more stringently. Presently the manufacturers do not have to abide by these specifications so long as they do not display the Kenya Bureau of Standard stamp on their products.

3.3.2 Plough Design

The designers of the ploughs have not really addressed themselves to the important aspects of the soil-tool interaction. Designers at the commercial level have not really been interested in the performance of the ploughs with respect to the final soil condition, the amount of pulverization or the degree of inversion. They have had an interest in the weight of the ploughs since they have found out that heavier ploughs do not sell as well as the lighter ones due to their presumable high draught requirement and cost. They have opted to manufacture lighter ploughs which has resulted in weaker ploughs which only work for a few seasons and then break down. The Local manufacturers have not seriously addressed themselves into finding ways of improving their products without compromising the strength. They have not attempted to use different materials to see how this would affect the performance of the ploughs.

3.3.3 Plough Testing

The testing done at the Government stations, the Rural Technology Development Centre (R.T.D.C.), formerly the Rural Technology Development Unit (R.T.D.U.) is not rigorous enough. A standard giving some guidelines to the performance requirements is lacking. The stations usually test the draught requirements, but they do not evaluate the physical properties of the soil. These parameters are important in evaluating the performance of the plough as they influence the draught requirement and the final soil condition.

The quality of the data taken during the testing is highly inadequate. The data are not accurate since the proper equipment for collecting them has been lacking or is not up to standard. Measurements of the draught should be taken continuously as it varies quite irregularly during the operation of the plough. Other parameters that have been used to evaluate the plough capacity include the ploughing speed. The ploughing speed is more a function of the animal strength than a plough design property.

3.4 The Plough Geometry

The shape of any tillage implement is very important as it influences the performance of the tool. It is an important parameter in determining the draught requirement and the final soil condition. The shape of the mouldboard plough depends on the soil type and the speed of operation. High speed ploughs are designed differently from low speed ploughs. The design is usually based on the projected path of the soil particles as they move along the plough body.

The shape of the mouldboard plough is difficult to describe precisely. Attempts have been made to try to identify the important points and features in the mouldboard plough body, a consensus is yet to be achieved on this aspect. Most of the existing descriptions depend on what the various researchers perceive to be the most important aspects of the plough body.

The mouldboard plough presents a special problem in attempting to describe its shape. The following is a general overview of various techniques and ways that various researchers have used to describe its shape. Though many techniques have been proposed to describe the shape, none has adequately related the performance of the ploughs to the shape.

The orthogonal section shape characterisation describes four basic plough types. Orthogonal sections for horizontal planes are generally called contour lines. Figure 3.3 illustrates the orthogonal section shape characterisation.

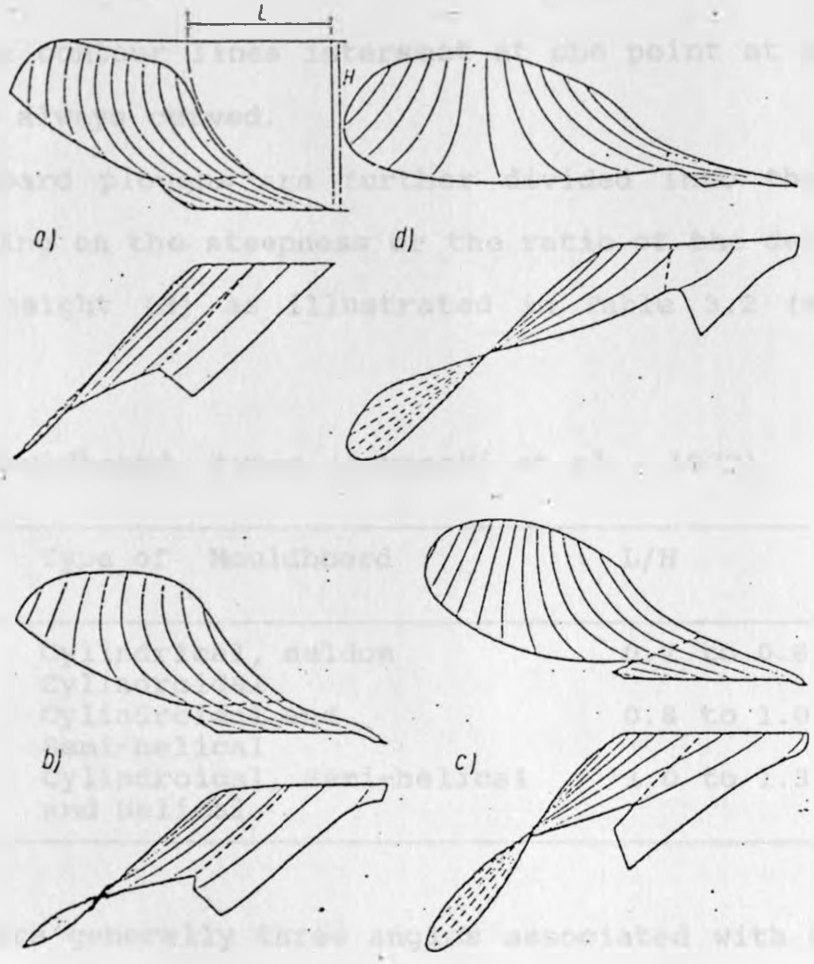


Figure 3.3 Profilograms of basic mouldboard types, a) Cylindrical; b) Cylindroidal; c) Semi-helical; d) Helical (Bernacki et al., 1972)

Cylindrical: Where the contour lines are parallel and run straight, the orthogonal sections in other planes run parallel.

Cylindroidal: The contour lines are straight but may curve at the wing of the mouldboard. The other orthogonal sections do not run parallel.

Semi-helical: The contour lines are more convergent, they intersect at the wing and they could either be straight or curved.

Helical: The contour lines intersect at one point at the wing and are always curved.

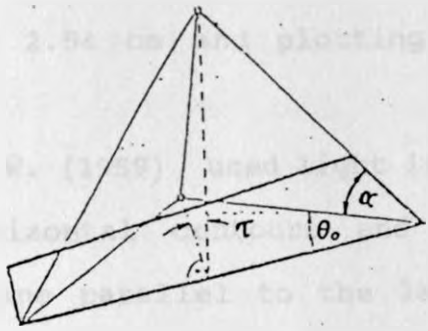
Mouldboard ploughs are further divided into three kinds depending on the steepness or the ratio of the depth (L) to the height (H) as illustrated in Table 3.2 (see Figure 3.3).

Table 3.2 Mouldboard types (Bernacki et al., 1972)

Kind of Mouldboard	Type of Mouldboard	L/H
Steep	Cylindrical, seldom Cylindroidal	0.7 to 0.8
Standard	Cylindroidal and Semi-helical	0.8 to 1.0
Inclined	Cylindroidal, Semi-helical and Helical	1.0 to 1.3

There are generally three angles associated with the share of the mouldboard ploughs as shown by the Figure 3.4. Angles α and τ are reciprocally proportional and they influence the quality of the furrow slice crushing and the value of the resistance.

White (1918), as cited by Gill and Vanden Berg (1969), reported that most plough bottoms have surfaces that could be fitted with equations representing hyperbolic paraboloids. Although he could not quantitatively relate these equations to the performance of the plough, he showed that the shapes could be represented mathematically.



α = load angle.
Θo = setting angle.
τ = cutting angle.

Figure 3.4 Share as a spatial wedge (Bernacki et al., 1972).

Ashby, W. (1931), proposed a set of nine standard parameters of plough bottom shape. Both Sohne (1959), and Ashby (1931), attempted to relate their shape parameters to the performance of the plough. None of their systems gave a complete description of the surface shape hence they were not very successful in their endeavour.

Nichols, M.L. and Kummer, T.H. (1932), studied the geometry of 22 typical ploughs of various shapes. They found out that the surfaces could be described by the use of arcs and circles moved and rotated about the line of travel of the share wing. They described their measurements in mathematical equations which expressed the entire surface. The complexity of their equations made them of little practical use.

Reed, I.F. (1941), described plough bottom shapes by measuring coordinates for horizontal contours at a vertical interval of 2.54 cm and plotting the plan view of the bottoms.

Sohne, W. (1959), used light interception technique to obtain horizontal contours and contour lines in the vertical plane parallel to the landside. He projected a narrow strip of light onto a white-painted plough surface and recorded the reflected light trace by using a camera on a line at right angles to the plane of the light beam. A family of horizontal and vertical contour lines was obtained by moving the plough bottom. He defined a number of shape parameters that he considered to be important.

The method described by Boer (1966), defines plough data that is both useful to the designer and the user. This method characterises the plough shape in linear and angular measurements. The method identifies angles, points and lengths that influence the performance of the plough in the following aspects:

- the way that the plough moves through the soil,
- the way that the furrow slice is received by the front end of the mouldboard,
- the way that the furrow slice is inverted by the mouldboard,
- the way that the furrow slice moves along the mouldboard and the plough carrying capacity.

This characterisation uses simple instruments and therefore it is cheap and can be easily used in the field.

It adequately identifies the important aspects of the plough geometry characteristics that influence the plough performance. These criteria were the consideration that was used to select this method for the shape characterisation over the other descibed methods which are expensive and complex.

Poesse, G. J. and Sprong, M. C. (1976), developed a technique which they called the C.P.C. (Characteristic Point Coordinate) method for description of mouldboard shapes. This method used a coordinate system on the three axes X, Y and Z. The X-Y plane represented the furrow bottom, the X-Z plane represented the furrow side and the Y-Z plane was perpendicular to the other two planes. They opted for this method after having used the pantograph which they found to be accurate but very tedious and difficult to comprehend.

The C.P.C. Method combines some principles from the pantograph and the method developed by Boer (1966). The characteristic points of a plough are:

- the points located on a gutter shaped mouldboard, where it has the greatest depth or,
- the points located on the surface of a convex shaped plough where it has the greatest height.

For a concave shaped plough, the soil movement is directed towards these characteristic points. On a convex plough the soil tends to break at these points. Soil handling by the plough depends on the position of these points and the shape of the mouldboard.

Poesse's (1976) idea was to characterise the shape as accurately as possible with the least amount of data. He was interested in the following:

- the horizontal cutting angle,
- the vertical cutting angle,
- the movement of the soil across the mouldboard,
- the turning of the soil,
- the shape of the mouldboard at certain points which he perceived to be important and the coordinates of these points.

The shape of the plough was represented in a graphical form where each different plough shape had a unique graph. By superimposing one graph on another, it was possible to compare different plough shapes. Despite the advantages of this method, it was not possible to use it in this study due to the unavailability of the apparatus required to make the necessary measurements.

3.5 The Performance of a Mouldboard Plough

Various criteria have been used by different people to evaluate the performance of mouldboard ploughs depending on their needs or requirements. These criteria include, the draught requirement of the plough, the degree of pulverisation of the soil, the amount of inversion of the soil and the efficiency of the plough in energy utilisation during soil cutting.

3.5.1 Draught Requirement of a Plough

E. V. Collins (1920) as cited by Bernacki et al. (1972) found that draught requirement was influenced by the following factors according to the given percentages.

weight - 18%
turning - 34%
cutting - 48%

He also found out that in sandy loam soils, the effects of the share sharpness on the draught were negligible, while on blue grass sod there was an increase of 14% due to share dullness.

Goryachkin (1927) found out that the specific resistance of furrow slice was more dependent on the depth than on the width of cut and that the resistance also depended on the type of plough bottom. He found that the friction between the furrow slice, the share and the mouldboard was important and contributed as much as 40% of the bottom resistance. He found out that the ploughing speed was proportional to the bottom resistance.

3.5.2 Energy Utilisation Efficiency

A significant amount of research has been carried out on soil engaging tools. Hadas, A. and Wolf, D. (1983) worked extensively to investigate energy efficiencies in tilling air dry soils using various types of ploughs. A clear cut relationship between the final soil condition and the energy efficiency could not be found. Some of the ploughs improved their efficiency with increasing ploughing speed. Some had no change in their efficiency with increasing operation speed while others actually showed a decline in their efficiency with increased ploughing speed.

These inconsistencies could be attributed to plough size and geometry differences. Gill and Vanden Berg (1967) found that the efficiency of ploughs decreased with increased ploughing speed. Both groups of researchers used the "Drop shatter" technique attributed to Marshall and Quirk (1950) to obtain energy required to reduce the soil clods to smaller sizes.

3.5.3 Soil Pulverisation and Mixing

The amount of soil loosening and the degree of pulverisation has been used as a measure of performance for soil cutting tools. Desir (1981) performed field tests on two soil types using tools of varying geometrical parameters. He observed that the degree of loosening was higher for the tools with a larger rake angle. The larger rake (attack) angle caused steeper rise of the soil along the advancing tool which resulted in higher tension and shear distortion in the soil. Desir (1981), found that the narrower tools caused more loosening than the wider tools. Gill and McCreery (1960) had earlier performed similar work and had shown that though the narrow tools showed better loosening ability, they required more energy per unit volume of loosened soil, hence their efficiency was lower than that of the wide tools.

Kouwenhoven and Terpstra (1973), performed some experiments to evaluate soil mixing. They used some glass beads as a granular medium to provide a uniform material to start with. The movement of the glass beads (sideways, upwards and downwards) was used as a way of quantifying the mixing. Glass markers of different colours were placed at different levels in the bead medium and their relative displacement after the passage of the tool was measured. From their observations during the experiments, Kouwenhoven and Terpstra concluded that the mixing of the glass beads (soil) decreased with increasing travel speed and also decreased with increasing rake angle in the range of 60° to 120°.

Some soil properties are important in the mixing and sorting action of the soil by the cutting tool. Soil particle size distribution is the most important. Smaller sized soil particles tend to percolate downwards while the larger ones tend to move upwards as the tool moves through the soil. This phenomenon is independent of the shape of the soil particle, surface roughness and the specific gravity of the soil particles according to Richards (1966) and Williams (1976).

The shape and the surface roughness mainly affect the flowability of the soil and its angle of repose. Irregular shaped particles have higher angle of repose than round ones. The shape of the furrow or the ridge formed by a cutting tool depends a lot on the angle of repose of the soil. Specific gravity of the soil has a minimal effect on the angle though the higher density particles of soil have a larger angle.

The specific gravity affects the sorting process during the manipulation of a soil. The soil moisture content is not very important in the sorting process especially in the moisture ranges occurring during cultivation. According to Winkelblech and Johnson (1964), at high moisture contents, percolation of the small particles is reduced due to cohesion.

3.6 Soil-Metal Sliding Resistance

3.6.1 Friction

Friction is a dynamic property of the soil involved in the rigid soil movement. The importance of friction between soil-tool relation depends on the reaction between the two. Vinogradov and Podskrebko, (1962); Vilde, (1973) as cited by Hendrick and Bailey, (1981) reported that overcoming resistance to sliding during tillage could amount to as much as 30 to 50% of the tillage energy requirement.

When two rigid bodies of soil move with respect to each other or when a tool moves with respect to the soil, forces act at the mutual contact surfaces.. One of the forces acting at this surface is friction. The exact nature of frictional forces is not yet well known. The acting forces are usually separated into forces acting normally and tangentially to the surface as shown by Figure 3.5.

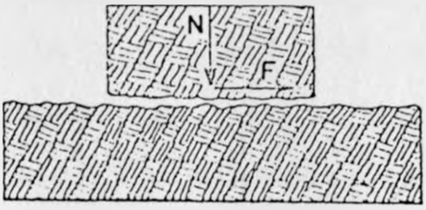


Figure 3.5 Normal force (N) and friction force (F) between two rigid bodies of soil (Gill, R.W. and Vanden Berg, G.E., 1968)

3.6.1.1 Coefficient of Friction (μ)

Several researchers, (Nichols, 1925 and 1931; Nagla, 1958; Vinogradov and Podskrebko, 1962; Slowinka and Jurkiewicz, 1977) have used the following conceptual model:

$$\mu = F/N \qquad \text{....[3.1]}$$

where F = frictional force tangential to the surface,
N = normal force perpendicular to the surface.
μ = coefficient of friction.

From experiments with other materials, it has been shown that the coefficient of friction is independent of the normal load, the area of contact surface and the speed of slipping. For soils, these observations are not quite true but they represent observed behaviour closely enough. They apply unless very large normal forces and high speeds are used. Nichols (1925) classified the general phases of friction as they are influenced by the moisture content of the soil. Figure 3.6 shows the variation of the coefficient of friction with moisture content.

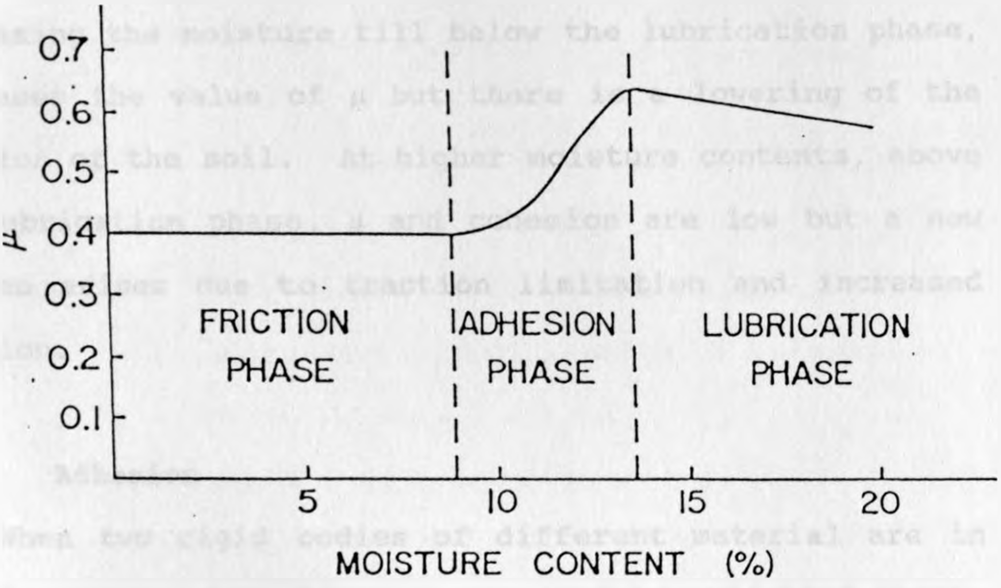


Figure 3.6 General phases of friction used to identify soil reactions at different moisture contents (Gill, R.W. and Vandern Berg, G. E., 1968)

Various attempts have been made to try and reduce the effect of this parameter. These attempts range from use of highly polished surfaces, coating of implements with plastic coatings to directing the exhaust gases to the soil-tool interface. The power increase resulting from directing the gases into the soil-tool interface does not compensate for the power drop due to the lowering of draught force hence it has not been a workable solution. The use of plastics has been more promising though they have a handicap due to their low strength and rigidity capacities.

Presently, the compromise appears to be the performance of tillage operations at optimal moisture content. This is achieved by operating at a condition where a trade-off between μ and cohesion can be achieved. Increasing the moisture till below the lubrication phase, increases the value of μ but there is a lowering of the cohesion of the soil. At higher moisture contents, above the lubrication phase, μ and cohesion are low but a new problem arises due to traction limitation and increased adhesion.

3.6.2 Adhesion

When two rigid bodies of different material are in mutual contact, some force is required to pull them apart. This force results from attraction between the two different materials and is known as adhesion. In soils, adhesive forces are exclusively due to the moisture content. Moisture tension and surface tension of the soil solution appear to explain the behaviour of adhesive forces.

Adhesion is a dynamic property of the soil that has been theoretically determined in terms of basic equations. However, it has not been expressed in terms that can be incorporated in some useful soil-machine relation. It has been related to physical properties but not appropriately by a quantitative equation describing behaviour. The importance of adhesion in the soil-machine relation results from its effect on sliding friction and stickiness. Söehne (1954); Payne and Fountaine (1954); Sitkei (1967); Vilde (1973) and Stafford and Tanner (1977) hypothesised that soil-metal sliding resistance consisted of both frictional and adhesive components. They formulated the following equation:

$$S = Ca + \sigma \tan\phi \qquad ....[3.2]$$

where S = interface tangential sliding stress,
Ca= interface tangential adhesive stress,
σ = interface normal stress,
ϕ = angle of soil-metal friction.

Attempts by Payne and Fountaine (1954); Vilde (1973) and Stafford and Tanner (1977) to separate the adhesive and frictional components were not very successful. They either moved a block of soil over steel or moved a steel slider over soil. Due to the fact that adhesion is affected by the length of the sliding path, the values obtained by this method averaged between the zero sliding-path length and the length of the sliding body.

3.6.3 Measurement of Friction and Adhesion

There are essentially two methods of measuring the coefficient of friction, the direct and the indirect method. The direct method entails the variation of the normal load on a soil block and the subsequent measurement of the force required to induce sliding. A plot of the normal load versus the frictional force is then used to evaluate the coefficient of friction. The indirect methods entail the use of torsional apparatus to induce shear failure in the soil.

The method used to measure adhesion is very important. Riek (1963), reported that adhesion measured by application of a tensile load was five times larger than that measured by sliding shear stress. It is therefore important to apply a method that is representative of the adhesive mechanism in the field condition. Hendrick and Bailey (1982), found that there existed a section on the Tangential Sliding Stress (TSS) versus the Initial Sliding Path Length (ISPL) plot where the TSS reduced at a constant rate. They found that in this section, the adhesive component of the sliding stress was constant. This section existed between two defined normal stresses, σ_1 and σ_2 and sliding paths SPL_1 and SPL_2. Hence the measurement of adhesion should be done within these boundary conditions

The simple slider apparatus technique is probably the easiest method for measuring the coefficient of friction. It consists of a slider which can be coated with different types of material, a spring balance and various different weights. To make a measurement, an axial load is gently applied to the slider through the spring balance until the slider begins to slide. The load at which this happens is noted and the procedure is repeated at different normal loads. A graph of the normal load versus the tangential load is plotted. The gradient of this graph gives the coefficient of friction for the soil-metal interface. Vetrov (1958), Mackson (1962), Dano (1961), Crowther and Haines (1921) are various researchers who used this technique. Payne (1956) used a vertical slider which could be used in situ. The apparatus is pulled through the soil by a mobile dynamometer unit. The variation of the normal load is achieved by either varying the orientation of the slider or by increasing the speed of operation.

The main advantage of the simple slider system is its simplicity in design and in use. Its drawback is the fact that it suffers from the "leading edge effect." This is where the soil tends to pile up in-front of the leading edge hence giving wrong readings of the frictional force. This method was rejected for this study due to the leading edge effects.

The torsional shear apparatus technique is more complex compared to the slider system. This method involves the placement of a circular disk or annulus on the soil surface and rotating it. This method evaluates both the coefficient of friction and adhesion. Söehne (1955), used the annulus while Rowe and Barnes (1961) used a circular disk. This technique has also been used to evaluate the coefficient of friction for grains by Lawton (1980) and Maina (1988). Complications in this system arise from the fact that the disk or the annulus operates continuously on the same soil surface. Structural changes in the soil present a continuously changing surface hence the coefficient of friction often changes. Travel distances vary greatly for the different parts of the disk. Use of a large narrow annulus limits the difference in the travel distance of the inner and outer edges of the slider.

The main advantage of the torsional apparatus is that it eliminates the problem of the leading edge present in the simple slider apparatus. The absence of the leading edge effects and the simplicity of the torsional apparatus made this technique the right choice for this study.

3.7 Shear

Shear is a form of failure or yield condition. Review on shear by Jaeger, J.C. (1956), attributed the first theory to predict Shear failure to Coulomb. He proposed that failure occurs when maximum shear stress reaches some critical value. Navier as reviewed by Jaeger (1955) modified the maximum shear theory. He proposed that shear failure occurs at a plane when the shear stress reaches some constant (T_o), that is increased by a constant factor μ multiplied with the normal stress (σ) acting on the plane. The criterion becomes:

$$T = T_o + \mu\sigma \qquad ....[3.3]$$

Mohr, according to Jaeger (1956), also proposed a shear failure theory. He argued that the normal and shear stress on the plane of failure are connected by some functional relationship. If a series of different stress states that cause failure are imposed on the same material and these stress states are plotted as Mohr circles, then the envelope that is tangent to the circles represents a failure criterion as shown on Figure 3.7. Angle ϕ is known as the angle of internal friction of the soil, while constant T_0 has been called Cohesion. It is represented in the following equation:

$$T = C + \sigma \tan\phi \qquad \text{....[3.4]}$$

Where, C = cohesion,

ϕ = angle of internal friction,

σ = normal stress,

T = shear stress.

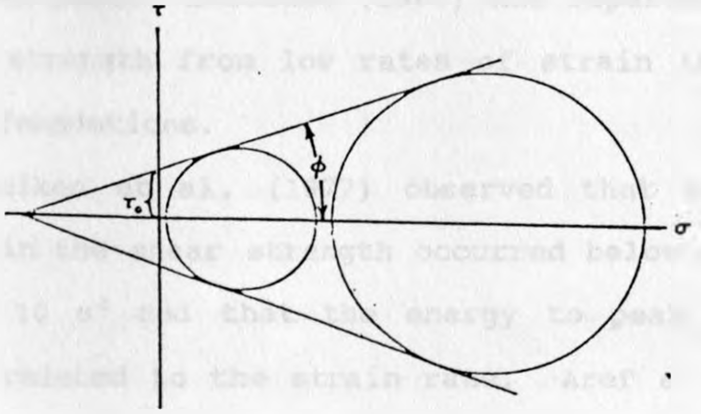


Figure 3.7 A Mohr envelope of stress (Gill, R.W. and Vandern Berg, G.E., 1968)

Cohesion has been rationalised as the shear stress at zero normal load. Cohesion and internal angle of friction are not real physical properties of the soil, but they are parameters of the assumed failure equation. The shear strength of the soil largely determines the forces resisting the soil engaging tools. Stafford (1979) reported that 85% of the draught forces on a rigid tine is due to cohesion.

3.7.1 Measurement of Cohesion and the Internal Angle of Friction of the soil

There are various techniques used for the measurement of the shear strength of the soil. The choice of the technique depends on how well it represents the actual failure condition in the field. It has been established that shear strength of the soil is a function of the deformation rate. Hvorslev (1960) has reported increases in shear strength from low rates of strain in long-term creep of foundations.

Flenniken et al. (1977) observed that most of the increase in the shear strength occurred below strain rate speed of 10 s^{-1} and that the energy to peak stress was linearly related to the strain rate. Aref et al. (1975) found that the energy to compress a soil sample was not affected by the strain rate, except for the peak. Hanson et al. (1967) measured the effect of strain rate in the range of 4-30 s^{-1} on the shear strength using centrifuge apparatus. Their conclusion was that the relationship between strain rate and the shear strength was dependent on the soil type, soil moisture, and the initial density. The value of the internal angle of friction has been reported to be independent of the strain rate by El-Domiaty and Chancellor (1970).

Different shear devices have been known to give non identical values of cohesion for nominally identical soil samples. Stafford and Tanner (1982) reported that the annular torsional device gave values of Cohesion which were seven times bigger than those given by the Triaxial test. This has been attributed to the high degree of soil confinement and the fact that the soil was being forced to fail at some defined plane.

3.7.1.1 The Torsional Shear Technique

The torsional shear technique has several different apparatus. A circular disk or an annulus with equally spaced grousers is rotated through the soil until shear failure occurs. Two types of loads are applied to this apparatus, a normal load and a turning moment. The normal load is varied in steps and the moment at which slip occurs is then noted. This apparatus can be mounted on a tractor, where the normal load is applied and varied hydraulically as reported by Girma (1989). Hvorslev (1952), Fountaine and Payne (1951) and Cohron (1963) are researchers who have utilised the torsional shear apparatus to evaluate the shear strength of soil.

The main advantage of this technique is that it can be used in-situ, its drawback is that it tends to give rather high values of cohesion than other methods. Evans and Sherratt (1948) used a Vane shear apparatus to evaluate cohesion. This apparatus is pushed through the soil and some turning moment is applied until shear failure occurs. Although this device can be used to great depths it has no way of varying the normal load on the soil hence its weakness. The advantage of this apparatus is its ability to measure cohesion in-situ and through some depth profile.

3.7.1.2 The Triaxial Test Technique

In this method, a cylindrical soil sample encased in some rubber membrane is subjected to a compressive axial load with a lateral confining pressure present. The soil sample is placed within a pressure chamber into which either air or water is pumped in. The soil under a chosen lateral pressure is then subjected to an increasing axial load until it fails. This procedure is repeated, each time the lateral pressure is varied and the sample loaded till it fails. The lateral confining pressure is called the Minor Principal Stress, while the axial stress plus the minor principal stress is known as the Major Principal Stress.

The results of this test are analysed by plotting Mohr circles for the stress conditions of each sample when failure occurs. The Triaxial test can be applied to both cohesive and cohesionless soils. There are three basic types of Triaxial procedures determined by the drainage condition of the soil sample. In the Unconsolidated Undrained (UU) test, the sample is not allowed to consolidate (drain under the confining pressure). In the Consolidated Undrained (CU) test, the sample is allowed to consolidate under the confining pressure by leaving the drain lines open. The drain lines are then closed and the axial load increased without further drainage. In the Consolidated Drained (CD) test the sample is allowed to consolidate and drain in such a way that excessive pore pressures are not allowed to build up. The CD test takes long to complete while the UU test takes a much shorter period. The Triaxial test takes a long period to complete and due to the existence of other faster and cheaper techniques, this technique was rejected for use in this study.

3.7.1.3 The Direct Shear Test Technique

This is probably the most common method for evaluating cohesion in the laboratory. Shear failure is effected by a shear force. The test can be applied to both cohesive and cohesionless soils. There are three procedures in this method just like in the Triaxial (UU, CU and CD) test. In the UU test, the shear force is applied before consolidation and drainage is allowed to take place. In the CU test, shear is not started until after settlement resulting from the normal load is complete. In the CD test, shear is not started until after settlement and it is applied very slowly to ensure that no pore pressure develops in the soil sample.

The sample is placed inside a square or a circular box which is split horizontally. The lower half is held in place while the upper half is pushed by some increasing force until failure occurs. The normal load is varied in various steps and the procedure is repeated each time noting the shear load at which the soil sample fails. A plot of the normal stress versus the shear stress is used to evaluate cohesion and the internal angle of friction. The advantages of this method over the others include, its simplicity, it is quick and cheaper to use. This method was chosen for use in this study due to these advantages over the other methods.

3.8 Measurement of Soil Bulk Density

Bulk density is an important soil physical property as it influences the conditions created by tillage. Dry bulk density is the mass of dry soil occupying a unit volume. It is another factor that influences the magnitude of the draught force. There are many methods that have been used to measure this parameter.

3.8.1 The Scattering Technique

The almost constant electron-to-mass ratio for the majority of elements is the basis for use of gamma-ray back scatter or attenuation for the measurement of soil bulk density (Freitag, 1971). Soil density can be related to the changes in attenuation of gamma rays in the soil as compared with attenuation in the air (Revut and Rode, 1969). Through suitable calibration, the measurement of transmission of scattering gamma radiation can be used to estimate soil bulk density.

The gamma-ray scattering method uses a source and a detector of gamma radiation located in a surface gauge. The instrument records reflected gamma radiation and must be calibrated for the condition to be measured (Rozhkov, 1970). The volume of soil needed for reading varies with the soil density, and roughly within a hemispherical area of diameter equal to the distance between the source and the detector (Freitag, 1971). A time span of 1 to 3 minutes is enough to take readings. Vomocil (1950), reported that the single probe measures density of a 20 to 25 cm layer and should not be closer than 15-20 cm to the surface. Rozhkov (1970), reported that bulk density readings were most accurate for a soil layer 0-5 cm. For measurements on the surface, the instrument must firmly lie on a flat surface and several orientations may be necesary. The health hazards and high cost associated with this technique make it unattractive for use in this study.

3.8.2 The Attenuation Technique

Van Bavel et al. (1957), reviewed the theoretical basis for gamma densitometry by transmission. They showed that the inverse square law applies only to primary radiation. They were able to separate primary and secondary radiation by scintillation counting and electronic discrimination. The gamma-ray attenuation uses two probes. The radiation source is on the tip of one of the probes and the detector is on the other probe. The transmission count measured is proportional to the mass of soil between the two probes.

Romkens and Whisler (1983), developed a method for inserting two parallel probes simultaneously into the soil. The drawback of their method is that the soil moisture content had to be known. Due to the dependence of the mass attenuation coefficient upon the soil condition, calibration for each soil type is necessary. Revut and Rode (1969) found gamma attenuation useful for measuring soil bulk density at depths of 0.2 to 3 m.

Henshall and Campbell (1983), evaluated gamma-ray attenuation using a scaler/ratemeter to select gamma photons with narrow energy range. This technique improves spatial resolution and allows measurements of soil bulk density within 100 mm of the soil surface. Corey et al. (1971), measured soil density and moisture content by measuring the attenuation of gamma-ray from two sources of different energy. They reported that this method was applicable for swelling soils. The need to calibrate this apparatus for specific soils, the cost and the possible health hazards assosiated with this technique disqualified it from being used in this study.

3.8.3 The Cone Index Technique

Attempts to relate the cone index to bulk density have been made. Ayers and Perumpral (1982), developed the following equation to predict soil bulk density.

$$DD = [(CI/C_1)C_2 + (MC - C_3)^2]^{1/C4} \quad \ldots.[3.5]$$

Where, DD = dry density (g/cc),

CI = cone index (kPa),

C_1,C_2,C_3 and C_4 are constants dependent on the soil type,

MC = moisture content (percentage dry weight).

From soils prepared in the laboratory, this relationship fitted data with a correlation coefficient (R^2) of 0.94 for sand and 0.98 for clay soils. Sands et al. (1979), found that in sandy soils the resistance to penetration was largely independent of the moisture content but directly related to the bulk density. At constant bulk density, the penetration resistance increased with depth because of increase in the overburden pressure and decrease in organic matter. Chesness et al. (1972), found out that remoulded soils did not exhibit the same characteristic as in-situ soils. They concluded that bulk density and moisture content are not sufficient to describe penetration resistance in sandy loam soils. The need to evaluate other soil parameters to obtain the "C" constants made this method unattractive for use in this study.

3.8.4 The Soil Core Technique

The core method uses a cylindrical metal sampler that is driven into the soil to the desired depth. The sampler is then carefully removed to preserve a known volume of the soil as it existed in-situ. Several types and sizes of samplers have been developed by researchers over time depending on their needs.

Van Groenewoud (1960), developed a sampler which had a cutting cylinder that can be forced into the ground by screwing it through a threaded guide cylinder. This sampler takes samples of size, 9.5 cm high and a diameter of 7.6 cm. The Sam Dimas soil sampler (Andrews and Broadfoot, 1958), is hand operated with a rotating cutter and a stationary tube. The sampler causes little disturbance to the core and the ground.

The Kachinskii method (Revut and Rode, 1969), uses cylindrical rings whose edges are chamfered. The rings are normally pressed into the soil. Distortion caused by friction between the cylinder walls and the inside of the cylinder is relieved above the cutting edge. When sampling dry, dense soils, the sampler is coated with grease.

Lutz (1947), used a device to press the cylinder into the ground to obtain samples of size, 4 cm high and 6 cm diameter. Jameson et al. (1950), found that this sampler worked well in loose arable soils but caused compression and fracturing in hard, dry or compact soils. The Lutz sampler was enlarged to a diameter of 9.5 cm and a height of 6.5 cm. A 0.3 cm diameter hole was drilled on the bottom of the can to allow air to escape. This was done to improve the performance of the sampler. Wells (1959), developed a sampler with a sampling tube and a trimming ring that can be driven into the ground with a heavy hammer. A hollow shafted borer slips over the sampling tube and by turning it by hand, the surrounding soil is removed. The sampler takes samples to a depth of 120 cm in steps of 15-30 cm. This sampler causes little disturbance to the soil though some compression has been reported.

Foale and Upchurch (1982), reported a hand operated device for taking cores of 20 to 50 cm diameter to a depth of 2 m. This system uses an electric jack hammer or a drop hammer for driving the corer. Srivastava (1982), designed a sampler for extracting large samples of undisturbed soil for root mass observation. The sampler uses a fence post driver, while a hydraulic cylinder is used for the removal of the undisturbed samples. The sampler works to depths of up to 60 cm.

Mielke and Wilhelm (1983), developed a mast anchor for taking samples where the weight of the vehicle carrying the sampler could not develop enough force to drive the sampler into the ground. Mielke (1973), described a sampler which encases soil samples in heat shrinkable tubes. Gin et al. (1978), mounted a hydraulic sampler on a tractor that could take samples to a depth of 125 cm and at a distance 125 cm from the centre of the machine. This sampler is ideal for sampling soils in cropped areas with minimal disturbance. Though the soil core technique is tedious, it was used in this study due its low cost, lack of potential health hazards and high level of accuracy in the measurement of bulk density compared to the other methods.

3.8.5 The Excavation Technique

In this method, some quantity of soil is excavated and its volume determined (Blake, 1965). The drawback with this method, is lack of accurate measurement of the excavated soil volume. Sand funnel, balloon or high viscosity fluid methods are used to determine the volume. In the sand funnel method, the excavated hole is filled with sand of known volume per unit mass. The mass of sand in the funnel is weighed before and after filling the hole. In the balloon method, the balloon is placed in the hole and filled with a fluid till it covers the hole. The high viscosity method pours a highly viscous fluid into the hole and the volume needed to fill the hole is noted. The high viscosity of the fluid reduces seepage from the hole. The low accuracy of this method disqualified it from being used in this study.

3.9 Measurement of Soil Moisture Content

Soil moisture content is one of the most important elements that influences the soil physical properties. Most soil properties are affected to a large extent by the moisture content. The soil moisture content has been known to influence the following properties; the coefficient of friction, soil shear strength, soil bearing capacity, adhesion, bulk density and the Atterberg limits. The soil moisture content is important in tillage operations. Various techniques have been developed to evaluate the soil moisture content.

3.9.1 The Tensiometer Technique

This technique is based upon the attractive forces between water and the soil. The Tensiometer is made up of a porous ceramic cup that is connected to a closed container filled with water. Negative pressure is built up in the container as the soil dries up, the Tensiometer is sensitive to the soil moisture surrounding the ceramic cup. At equilibrium, the moisture potential of the soil is equal to the tension in the container.

The maximum tension that can be measured by this method is -100 kPa though -80 kPa is the practical limit. Above this value air enters the cup and starts to disturb the readings. The soil moisture content is obtained through a relationship between moisture content and moisture tension of that particular soil. Tensiometer readings are affected by temperature and hysteresis due to the wetting and drying (Richards and Gardner, 1930). Response time constant could vary from 0.5 seconds in loam soil to 10 minutes in heavy clay soil (Towner, 1981). The limitation in the moisture content range that this method can measure and due to problems assosiated with hysterisis, made this method unattractive for use in this study.

3.9.2 The Neutron Scattering Technique

This technique is based on the fact that Hydrogen atoms affect the movement of neutrons and hence they can be used to measure soil water content (Revut and Rode, 1969). A neutron moisture gauge is made up of fast moving neutron source and slow moving neutron detector (International Atomic Energy Agency, 1970). The technique measures moisture content in a 15 cm diameter sphere for wet soils and up to 50 cm for dry soils (Thien, 1983). Silt, clay content and bulk density are the most important factors influencing the measurement of the water content using this technique (Hanus et al., 1972). Conversion of slow neutron counts to volumetric soil water content requires calibration for specific soils.

Natural non-homogeneity of soils causes calibration problems, yet theoretical methods assume uniform soil properties and moisture content (Vachaud et al., 1977). Sinclair and Williams (1979) and Williamson and Turner (1980), found variation in site heterogeneity to be the main source of random errors. The advantages of the neutron method include the ability to measure the moisture content regardless of its physical state and the ability to monitor temporal moisture changes and repeated readings at the same site (Schmugge et al., 1980). Other than the high cost of the apparatus, other disadvantages include health risk, poor depth resolution, inaccurate readings near the surface and the dependency on other physical and chemical properties of the soil. These disadvantages made it impossible to utilise this method in this study.

3.9.3 The Gamma-ray Attenuation Technique

This technique uses the principle that the scattering and absorption of Gamma-rays depends on the density of the matter on their path. Assuming that soil density remains constant, moisture changes can be determined from the changes in Gamma-ray measurement of wet density. De Vriers (1969), found that collimation is necessary for measurements within 1 cm of the soil surface. Keng and Topp (1983), compared Gamma-ray attenuation with Time Domain Reflectomery (TDR) and attributed the variation in attenuation to the variation in soil density.

The advantages of this technique include, the fact that readings can be taken over small vertical and horizontal distances. The measurements are independent of the physical state of water and they are non destructive (Schmugge et al., 1980). The drawbacks include high cost, potential health risks and the variation in readings in stratified soils. The drawbacks of this method made it unacceptable for use in this study.

3.9.4 The Electrical Resistance Technique

This technique is based on the ability of porous material to transmit electrical current which can be related to its water and electrolyte content. When the effects of soluble salt content are small, the relationship between electrical resistance and water content can be determined (Thien, 1964). Two electrodes are buried in the soil and the resistance between them is read. Due to the possibility of high contact resistance between the electrode and the soil, the electrodes are usually enclosed in an absorbent material.

Electrical resistance is suitable for undisturbed samples and for soils compacted to known density (Croney et al., 1951). The accuracy of this method is affected by moisture hysteresis, uniformity of the blocks and the sensitivity of the blocks. At moisture tension above 30 kPa, gypsum blocks are preferred due to their high sensitivity, uniformity and low hysteresis errors (Bouget et al., 1958). At lower moisture tensions, nylon-gypsum blocks are used. Fibre glass-gypsum blocks operate over a zero to 1500 kPa range moisture tension. The drawbacks of this method heavily outweigh the advantages of using it.

3.9.5 The Thermocouple Psychrometer Technique

Rawlins (1966), developed the theoretical analysis for this method. Rawlins showed that it was possible to eliminate major temperature effects on water potential measurements. Rawlins and Dalton (1967), reported from Greenhouses' tests accuracies of ± 50 kPa within 5°c temperature fluctuations. In wet or coarse textured soils, temperature had little effect on the water potential (Campbell and Gardner, 1971). The complexity and cost of this method reduces its practical applications.

3.9.6 The Thermoelectric Technique

Heat dissipation in porous material depends upon its water content. In this method, the water content is determined by heating the soil and monitoring the temperature rise (Thein, 1983). Phene et al.,(1971a), described a matric potential sensor that measures heat dissipation from a porous block in equilibrium with the soil. It consists of a P-N junction diode that is surrounded by a heating coil embedded in a porous medium. The range and the sensitivity of the sensor can be varied by changing the composition of the porous medium. This method is used within a matric potential of 0 to 200 kPa. This method is complex and not very accurate hence not widely used for soil moisture content determination.

3.9.7 The Nuclear Magnetic Resonance Technique (NMR) and Time Domain Reflectometry Technique (TDR)

NMR is associated with a resonant interaction between nuclear magnetic moments and applied static radio frequency magnetic fields. NMR signal from the hydrogen in the water is used for water content measurement. Soil water content is nearly a linear function of the NMR signal.

TDR provides a measure of dielectric constant of the soil between two parallel transmission lines. Water content has the greatest effect on the dielectric constant whilst temperature, soil type, density and the salt content have small effects. The high cost of these two techniques make them prohibitive to use.

3.9.8 The Gravimetric Technique

This is the most commonly used method for determining soil moisture content. Soil samples are dried in an oven at temperature ranging between 105°c and 110°c. Samples of 100 to 200g require about 24 - 36 hours in the oven (Thein, 1983). Moisture content is the weight reduction expressed as a percentage of the dry weight of the soil. This method is used to calibrate the other methods of moisture content determination.

Errors in this method arise from the type of devices used to obtain the samples, the containers in which the samples are placed, time lapse before weighing the sample, temperature and the time of drying the sample and the equipment used for weighing the sample. Loss of organic matter at high temperature and water remaining in the sample could also introduce errors (Reynolds, 1970a).

The procedure is tedious and at times it is not possible to obtain representative soil samples in stratified soils. The method is also destructive. The main advantage of this method is that it requires simple and inexpensive equipment and accurate if carefully applied. The advantages of this method over the others made it the best choice to use in this study.

3.10 Soil Bins

Field studies of traction and tillage devices are usually hampered by non-uniformity in the field conditions and erratic weather. It is of paramount importance that uniform and reproducable conditions exist during tillage studies, otherwise the results would not only be inconclusive but also difficult to analyse. Non-uniformity in the field conditions arise from differences in:

- soil type,
- soil moisture content,
- soil bulk density,
- soil porosity,
- soil frictional properties,
- soil strength properties.

Development of concepts in soil dynamics depends on the control of experiments. In tillage some degree of control must therefore be achieved. To do this, researchers have developed the concept of the soil bin (Wismer,1984; Söehne, 1985). A soil bin is made up of the following facilities.

- the tool processing carriageway,
- the soil processing carriageway,
- the drive system,
- the instrumentation controls,
- safety devices,
- and any other soil testing equipment.

There are essentially two types of soil bin testing facilities depending on which component is in motion. The bin can be stationary while the soil processing and tool carriages are in motion and vice versa. For either option, the bin can be circular or straight depending on the availability of space, energy and the type of study.

Circular soil bins are used where continuous tool movement is needed, in most cases the bin moves relative to the tool. The main drawback of this system, is that the outer part of the tool travels farther than the inner part. The straight movable type consists of a soil box mounted on rails with the soil processing and tool carriage stationary (Larson et al., 1968). The drawbacks of this system are the high energy and large space requirements. Cracks could also develop in the soil due to vibration in the system.

The stationary bin is the most common type. It eliminates the problems of the movable type and has greater flexibility in the speeds that can be achieved (Wegscheid and Myers, 1966 and Durant et al., 1981). The drawback of this type is the design requirement. The carriages must be rigid and perpendicular to the direction of travel. The two rails supporting the carriages can either be on one side of the bin (Siemens and Weber, 1964 and Hettiaratchi, 1968) or one rail on each side of the bin (Durant et al., 1981). The carriages are moved using a towing system positioned at one end of the bin. A steel rope and sheave or chain and sprocket systems are used.

Power can be obtained from an electric motor (Kuczewski, 1981) or a stationary tractor engine (Godwin et al., 1981). Hydraulic power systems are usually used to achieve better speed and power control. Instrumentation and control systems consist of transducers for force, displacement and speed measurements. For symmetrical tools, the extended octagonal ring transducer is used

(Siemens and Weber, 1964; Godwin, 1975 and Owen et al., 1987). For curved tools, dynamometers that can measure forces and moments in three directions are used (Perumpral et al., 1980; Lisko and Harrison, 1988). Potentiometers and encoders are used for the measurement of displacements.

Microcomputers based data acquisition and control systems have enhanced data collection and processing. They have also ensured better monitoring of varying soil parameters in experiments (Schaffer and Bailey, 1980; Young et al., 1986; Liskso and Harrison, 1988).

The following are research centres that have made great use of soil bin facilities.

- The National Tillage Machinery Laboratory. Auburn, Alabama in USA.
- The Army Mobility Research Centre. Vicksburg, Mississippi in USA.
- The Land Locomotion Laboratory. Warren, Michigan in USA.
- The National Institute of Agricultural Engineering. Silsoe, England.
- Institute of Fundamental Research in Agricultural Engineering. Volkenrode, Germany.
- Institute of Agricultural Mechanisation. Konosu, Japan.

The following is an illustration of some soil bin components.

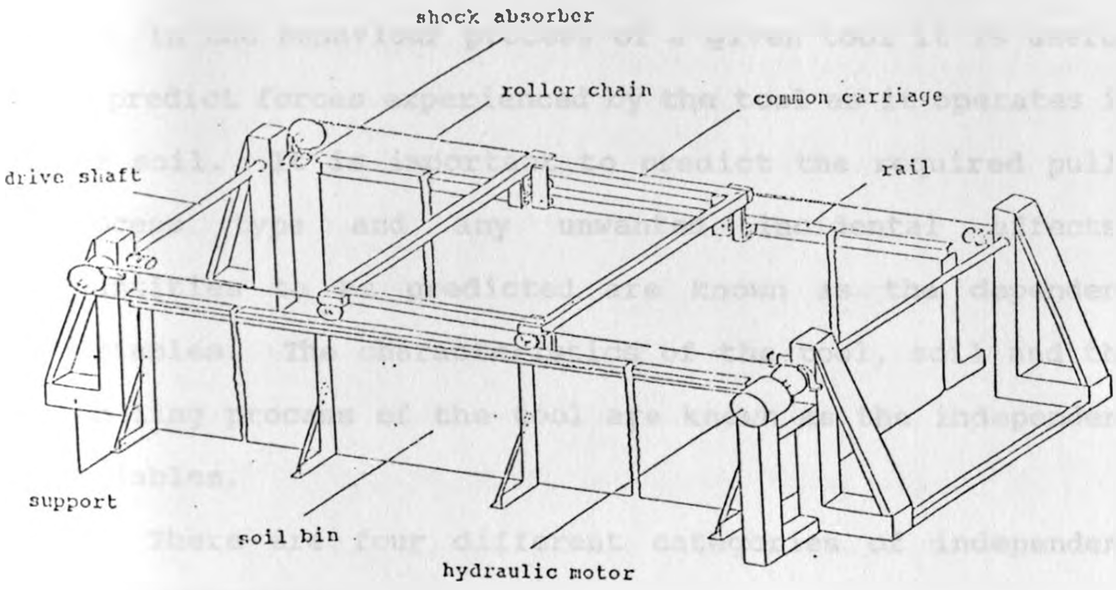


Figure 3.8 Soil bin, drive system and common carriage (Onwaulu, A. P. and Watts, K. C., 1989).

4 SIMILITUDE AND MATHEMATICAL MODELING OF SOIL-TOOL INTERACTION

There are basically two groups of methods used for the prediction of a process (behaviour of a tool). They are similitude and mathematical modeling.

In the behaviour process of a given tool it is useful to predict forces experienced by the tool as it operates in the soil. It is important to predict the required pull, process type and any unwanted incidental effects. Quantities to be predicted are known as the dependent variables. The characteristics of the tool, soil and the handling process of the tool are known as the independent variables.

There are four different categories of independent soil variables:

Elemental mechanical properties: These includes properties like cohesion, internal angle of friction, bearing capacity, tensile strength and soil frictional properties.

Strength determining factors: These includes properties like the bulk density, moisture content, bonds between particles, the distribution of the bonds and the spatial distribution of particles.

Relationships between treatment and the behaviour of the soil: The behaviour of soil in any process depends on the treatment that the soil had been subjected to before the process. The treatment could range from tillage operation, wheel passes, wetting or drying. The draught force needed in a process is a measure of soil behaviour.

Results of the characterisation of the process: These include tests like Penetrometer test, Plate penetration test, Atterberg Consistency Limits and the Drop Shatter test.

4.1 Similitude Modeling

This a method that is based on observations of relationships between independent variables and the dependent variables. In this method the mechanism of the process is not known hence it is also known as the black box approach.

Similitude modeling assumes that any dependent variable y, is dependent on independent variables $x_1, \ldots x_n$ of the soil-tool system. This can be formulated in the following way.

$$y = f(x_1 \ldots x_n) \qquad \ldots.[4.1]$$

Where f is the prediction function defined in the range x_i known as the domain of the function.

Variables x_i should satisfy the following conditions:

- the function should be unique,
- the sensitivity of y to any x_i should be appropriate,
- no values of x_i are superfluous.

The development of a prediction method is easier when there are few independent variables. Two methods are used to reduce these variables. The two methods used to achieve this include reducing the domain of the function and the use of Buckingham's Pi theorem. Reducing the domain of the problem occurs when one or more of the independent variables are assumed constant. This method is only applicable when the x_i in question is equal to those constant values. Quantities that can be held constant include;

- the working depth,
- the working speed,
- shape of the tool,
- the soil type.

The second method for reducing the number of independent variables, Buckingham Pi theorem states that equation [4.1] can be reduced to

$$Y = F(X_1 \ldots X_{n-b}) \qquad \ldots.[4.2]$$

with the restrictions that the number of dimensions in which y and x_i can be measured equals b and that Y and X_i are dimensionless and independent (Murphy, 1950).

Similitude modeling is a technique that is gaining widespread use in Agricultural Engineering research. Models of the soil engaging tools have been tested in soil bins and the results used to predict forces in the prototypes.

The theory of similitude considers situations under which the behaviour of two systems will be similar. According to Murphy (1950), and Freitag et al. (1970), this situation arises if the two systems are geometrically, kinematically and dynamically similar. In modeling where soils are involved it has not been possible to obtain perfect models, but distorted models have been obtained.

In choosing the pertinent variables that describe a system it has not been possible to do it in such a way as to satisfy all the conditions of similitude theory. Soil particle size, soil cohesion and soil internal angle of friction are variables that cannot be scaled down to represent a model. In order to use the theory of similitude, distortion factors have had to be obtained so that the mathematical models obtained can be corrected. This has been achieved by the use of at least two models, one is the model of the prototype and the other one is a model of the model.

Various models have been developed through similitude modeling relating the various factors that influence the soil cutting and the force necessary to do so. Reece (1965) developed the Universal Earth Moving Equation which was based on the similarity between earth moving and soil bearing capacity of a shallow foundation.

$$P = (\tau g d 2 N_{\tau} + c d N_c + q d N_q) W \qquad \ldots.[4.3]$$

Where, P = total tool force

τ = total soil density,

c = soil cohesion strength,

q = surcharge pressure acting vertically,

g = acceleration due to gravity,

d = tool working depth

W = tool width.

N_γ, N_c and N_q are factors dependent on soil frictional strength, tool geometry and tool to the soil strength properties.

The dependency of the N factors on the tool geometry makes it difficult to compute the N factors accurately especially when dealing with complex shapes like those of mouldboard ploughs. This limits the use of this model to predict the draught force on the mouldboard plough.

Luth and Wismer (1971) and Wismer and Luth (1972) developed the following predictive equations for plane horizontal cutting force components using the technique of similitude modeling. The limitation of these two models was that they were developed for plane horizontal cutting tools and therefore cannot be used for the mouldboard plough.

For sandy soils,

$$F_x/\tau g b z^{.5} L^{1.5} = \theta^{1.73}[z/L\sin\theta]^{.77}[1.05(z/b)^{1.1} + 1.26v^2/gL + 3.91] \quad ....[4.4]$$

and for clay soils

$$F_x/\tau g b z^{.5} L^{1.5} = \theta^{1.15}[z/L\sin\theta]^{1.21}[(CIs\Phi/\tau g z)^{1.21} (.055\{z/b\}^{.78} + .065) + 0.64v^2/gL] \quad ....[4.5]$$

Where, F_x = horizontal component of total cutting force,

γ = soil total density,

g = acceleration due to gravity,

b = blade width,

z = blade operating depth,

L = blade length,

θ = blade rake angle (radians),

v = operating velocity,

CIs = cone index of a standard cone,

Φ = dimensionless shear factor = (vd_s/bv_s).

Similitude modeling could not be used in this study due to the lack of appropriate facilities and equipment, the best option was then to use mathematical modeling.

4.2 Mathematical modeling

The other group of methods used for the prediction of processes is mathematical modeling. It is based on the knowledge of the mechanism of the process under consideration. This group of methods assumes some hypothetical mechanism under which a particular process occurs. Such mechanisms range from failure patterns, compaction patterns, deformation patterns and displacement patterns. The equilibrium of forces is used to calculate the dependent variable quantities. The rationale of using this method is based on the following features;

- the effectiveness of the method,

- the compatibility of the mechanism,
- the degree to which the hypothetical mechanism resembles the process being simulated.

Goryachikin (1927) developed the following equation for trailing mouldboard ploughs.

$$P_x = fG + k_o ab + \epsilon abv^2 \qquad \text{....[4.6]}$$

where, P_x = total plough resistance,
f = coefficient of idle resistance,
G = plough weight,
k_o = coefficient of static resistance,
ϵ = coefficient of dynamic resistance,
v = forward speed,
a = thickness of the furrow slice,
b = width of the furrow slice.

This model has been criticised for not being accurate especially for heavier soils, (Poesse and Van Ouwerkerk, 1967). The following are some researchers who have used the same model to describe the performance of ploughs. Söhne (1960), Söhne and Möller (1962), Bernacki (1963), Poesse and Van Ouwerkerk (1967) and Zoz (1974). Goryachkin's (1927) modeling method is used to model the performance of the four selected animal drawn mouldboard ploughs in this study.

The development of Goryachkin's model is based on the following relationship:

$$P_x = d(mv/dt) = m(dv/dt) + v(dm/dt) \qquad ....[4.7]$$

The first component in this equation, m(dv/dt); determines the force necessary to produce acceleration of the furrow slice. The second component of the equation, v(dm/dt); determines the force necessary to produce constant velocity of the varying soil slice mass on the mouldboard surface.

The first component is expressed as resistance in the following equation.

$$m(dv/dt) = fG + K_0ab \qquad ....[4.8]$$

In the second component, the derivative dm/dt represents the mass of the furrow slices passing over the mouldboard in unit time.

dm/dt can be expressed as $(\tau/g)(abv_1)$.

where, τ = bulk density of the furrow slice.

g = acceleration due to gravity.

Goryachkin accepted that velocity v_1 of a furrow slice on the mouldboard is proportional to the forward plough speed v, so that

$$v_1 = \epsilon_1 v \qquad ....[4.9]$$

Therefore, in [4.7]

$$v(dm/dt) = \epsilon_1(\tau/g)abv^2 \qquad ....[4.10]$$

Letting $\epsilon_1(\tau/g)$ be ϵ, then the third term in equation [4.6] is obtained.

$$v(dm/dt) = \epsilon abv^2 \qquad ....[4.11]$$

The resistance of the bottom K_x can be defined by the last two components of Goryachkin's formula [4.6]. The specific resistance of the bottom will amount to,

$$k = k_o + \epsilon v^2 \qquad ....[4.12]$$

The coefficient of resistance, k_o represents the specific resistance of the bottom at ploughing speed $v = 0$. It is known as the specific resistance of the soil and it characterises the soil firmness. The coefficient ϵ depends to a smaller degree on the soil type and to a more considerable degree on the type of plough bottom.

The dynamic resistance of the bottom $K_b = \epsilon abv^2$ is composed of resistance K_1 resulting from the acceleration of the soil mass moving over the mouldboard and the energy necessary to throw the soil mass forward and aside. Speed changes of the furrow slice develop forces K_2 which increases the pressure of the mouldboard on the furrow bottom. This is expressed in the following formula.

$$K_b = K_1 + K_2 \qquad ....[4.13]$$

$$K_1 = \int_0^{V_x} \frac{d}{dt}(V-V_x)\,dm \qquad ....[4.14]$$

Assuming that friction is only in the y plane then:

$$K_2 = \int_0^{V_y} \mu \frac{d}{dt} V_y dm + \int_0^{V_z} \frac{d}{dt} V_z dm \qquad ....[4.15]$$

Where μ is the coefficient of friction between soil and the plough bottom. Subscripts x, y and z refer to parameters along the X, Y and Z planes.

Assuming average acceleration,

$$d/dt(V - V_x) = (V - V_x)/t \qquad ....[4.16]$$

where, t = time that the furrow slice takes to pass from the share edge to the wing end,

V_x = average component of speed at the end of the mouldboard.

Since t = s/v, then

$$K_1 = (V - V_x)Vm/s \qquad ....[4.17]$$

where, s = the furrow slice length,

m = the mass of the furrow slice.

Assuming that,

$m = sab(\tau/g)$.

Then,

$$K_1 = \tau/g(abV)(V - V_x) \qquad ....[4.18]$$

Assuming that K_2 is proportional to K_1 that is $k_2 = \Gamma k_1$ then $k_b = k_1(1+\Gamma)$

Let $1+\Gamma = \cap$ then,

$$K_b = \cap K_1 \qquad ....[4.19]$$

Where $\cap$ and Γ are factors of proportionality.

To solve for the coefficient ϵ, the dynamic resistance calculated is compared with the third term in Goryachkin's formula as follows.

$$K_b = \cap(ab\tau)(V^2 - VV_x)/g = \epsilon abV^2 \qquad ....[4.20]$$

from $V_x = V\ \text{Cos}\theta_s$,

$$\epsilon = (\cap\tau/g)(1 - \text{Cos}\theta_s)$$

then,

$$k = k_o + (\cap\tau/g)(1-\text{Cos}\theta_s)v^2 \qquad ....[4.21]$$

Where θ_s = the setting angle of the mouldboard wing,

From equation [4.12] the values of k_o and ϵ can be obtained. The measured specific resistances are burdened with errors amounting to β_n as shown by the following summation of equations.

$$k_1 - (k_0 + \epsilon V_1^2) = \beta_1$$

$$k_2 - (k_0 + \epsilon V_2^2) = \beta_2$$

$$. \quad . \quad . \quad .$$

$$k_n - (k_0 + \epsilon V_n^2) = \beta_n \qquad ....[4.22]$$

By squaring both sides of the equation and summing up the following is obtained.

$$\Sigma[k_n - (k_0 + \epsilon V_n^2)]^2 = \beta_n^2 \qquad ....[4.23]$$

The least error is obtained when the following partial derivatives are equal to zero.

$$(\delta\Sigma\beta_n^2)/(\delta k_0) = 0 \qquad ....[4.24]$$

$$(\delta\Sigma\beta_n^2)/(\delta\epsilon) = 0 \qquad ....[4.25]$$

Differentiating both equations, the following is obtained.

$$2\Sigma(k_0 + \epsilon V_n^2 - k_n) = 0 \qquad ....[4.26]$$

$$2\Sigma(k_0 + \epsilon V_n^2 - k_n)V_n^2 = 0 \qquad ....[4.27]$$

Factorising these two equations, the following two equations with the two unknowns k_0 and ϵ are obtained.

$$nk_0 + \epsilon\Sigma V_n^2 - \Sigma k_n = 0 \qquad ....[4.28]$$

$$k_0\Sigma V_n^2 + \epsilon\Sigma V_n^2 - \Sigma k_n V_n^2 = 0 \qquad ....[4.29]$$

From where,

$$k_0 = [\Sigma k_n \Sigma V_n^4 - \Sigma V_n^2 \Sigma k_n V_n^2] / [n\Sigma V_n^4 - (\Sigma V_n^2)^2] \quad ....[4.30]$$

$$\epsilon = [n\Sigma k_n V_n^2 - \Sigma k_n \Sigma V_n^2] / [n\Sigma V_n^4 - (\Sigma V_n^2)^2] \quad ....[4.31]$$

Equations [4.30] and [4.31] were used to calculate the values k_o and ϵ (see the appendix).

5 MATERIALS AND METHODOLOGY

5.1 The Soil Bin Facility

A shed was built using corrugated iron sheets both on the roof and on the sides. The dimensions of the shed were 20 metres long, 4 metres wide and 3 metres high at the pitch. A pit 20 metres long, 2.5 metres wide and 0.5 metres deep was dug inside the shed and filled with 35 tonnes of sand. The pit was lined with polythene paper on the sides and on the bottom to reduce seepage of water from the sand and to reduce infiltration of water from the surrounding ground.

Due to the problems associated with working under field conditions, as discussed in section 3.10, a soil bin facility was constructed inside the shed to conduct this study. Instead of using "natural soil," sand was used in the shed since it is a much easier medium to condition to some required properties. The ability to vary the soil condition and hold it at that state was a prerequisite for this study hence the choice of using sand.

5.2 The Four Selected Animal-Drawn Mouldboard Ploughs

Four Animal-drawn mouldboard ploughs were selected for this study. Two of these ploughs were local while the other two were imported from the Netherlands. The criteria for selecting these ploughs were, their availability and extent of use locally. The local ploughs were the Bukura Mk. II and the Victory, while the imported ploughs were the Rumptstad cylindrical and winding bottomed ploughs.

Plate 5.1 The local ploughs, Victory plough on the left hand side and the Bukura Mk. II on the right hand side.

The Bukura Mk. II was developed by the Rural Technology Development Centre, Bukura in Western Kenya. This plough was an improvement of its predecessor the Bukura Mk. I plough. The Bukura Mk. II weighs about 32.5 kg and is specially adapted for use in a multi-purpose tool bar frame. The frame of this plough is 1.7 m long, 1 m high and 0.5 m wide at the handles. Except for the gauge wheel which is made from cast iron the rest of the plough is made from mild steel.

The Victory plough has a characteristic green colour and weighs about 33.6 kg. This plough is manufactured by Steel Structures limited who call it by the name "Oxen plough, Light Duty". Except for the gage wheel which is made from cast iron, the rest of the plough is made from mild steel. The overall length, height and width of this plough is 2.0, 0.9, and 0.6 m respectively.

The two imported ploughs are manufactured by a Dutch company known as "Rumptstad".

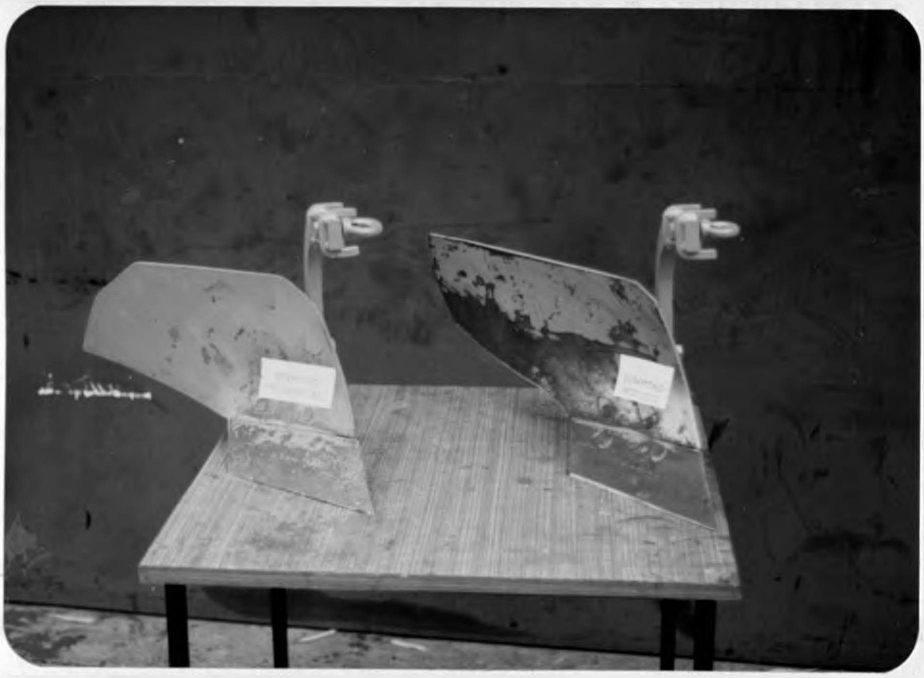


Plate 5.2 The imported ploughs, Rumptstad (cylindrical bottom) on the left hand side and the Rumptstad (winding bottom) on the right hand side.

The Rumptstad Animal traction implements are predominantly yellow in colour. The two Dutch ploughs, Rumptstad (winding bottom) and Rumptstad (cylindrical bottom) use the same tool frame. The bottom is attached to the frame through a bolt that is welded on the frame and a locking nut is used to hold the bottom firmly onto the frame. The Rumptstad (winding bottom) is the larger of the two ploughs weighing about 38.2 kg while the Rumptstad (cylindrical bottom) is the smaller of the two weighing about 36.5 kg. The frame of these ploughs is made from mild steel while the bottom is made from alloy steel.

The overall length, height and width of these two ploughs is the same at 1.7, 0.8 and 0.6 m respectively.

5.3 The Conditioning of the Soil-Bin Sand

The variation of the physical and mechanical properties of sand can be achieved by some mechanical manipulation. Sand is an easy medium to work with because it exhibits little or no cohesion. Sand exhibits little variation in its physical and mechanical properties and it can be easily reconstituted to its original state after a tillage operation.

Sand conditioning was necessary to ensure soil uniformity (bulk density and moisture content) at some specified condition, and to enable the alteration of the sand condition. To ensure uniformity in the sand, a ten disc offset harrow was passed through the sand by a tractor for six to eight passes. Half the passes were in the ploughing direction, while the other half were in the opposite direction. This was necessary to ensure that the sand was thoroughly mixed as there was a tendency for a moisture gradient to exist along the vertical and lateral directions.

The final harrow passes were in the ploughing direction to ensure that the compaction by the tractor tyres was eliminated. The sand was then levelled manually using a rake and spades after which a 70 Kg roller was passed over the sand surface to ensure that the sand was evenly compacted to some specified bulk density. This roller had to be pulled by two people.

The alteration of the sand condition was achieved by artificially varying the moisture content and the number of roller passes. For the first condition, the sand was allowed to dry to a moisture content of about 0.7% (w.b). This was achieved through evaporation and continuous turning of the sand using the harrow. The roller was then passed twice over the sand surface. This resulted in a bulk density of 1.64 g/cm^3. Each plough was then ran five times. Four runs were used for data collection while the first run was used to check on the plough depth adjustment since a ploughing depth of 15 cm was desired. After each plough made the five runs, the sand was re-constituted to its previous condition and the next plough was run through the sand and its data were collected. This procedure was repeated for all the four ploughs. The bulk density was measured before each treatment to verify that the sand had been re-constituted to its previous condition.

For the second condition, some water was poured into the sand. The sand was then harrowed to ensure that it was uniformly wetted. The roller was then passed four times (twice the number under the first condition) on the sand surface. An average moisture content of 3.49 % (w.b) and bulk density of 1.73 g/cm^3 was achieved. The performance of the four ploughs was then evaluated under this second condition. For the third condition, more water was added to the sand which was again thoroughly mixed with the harrow to ensure uniform water distribution in the sand. The number of roller passes was increased to six. An average moisture content of 8.52 % (w.b) and a bulk density of 1.89 g/cm^3 was achieved. Hence the performance of the four ploughs was evaluated at three different conditions.

5.4 Draught Measurement

The specific resistance of soil can be evaluated as one criterion to compare the performance of various ploughs. The evaluation of specific resistance requires the draught force, the width and depth ploughed be measured. It is important to operate the various ploughs at the same depth and width. The specific resistance has some dependency on the depth as there exists some critical depth of operations for ploughs. The specific resistance decreases with increasing depth till the critical depth is achieved after which it starts to increase with increasing depth. Attempts were made to operate the ploughs at the same depth of 15 cm but it was not always possible especially for the victory plough.

The draught was measured using a recording Hydraulic Dynamometer from which a Dynamogram was obtained. The dynamometer was placed on the tractor and the hydraulic sensor was between the tractor and the plough. A 20m rope was used to attach the plough to the tractor. The long length of the rope ensured that the tractor stayed out of the shed during the runs. This was done to avoid compaction of the sand by the tractor.

The dynamogram chart was started immediately the tractor started to move and was stopped at the end of the run. Though the shed was 20 metres long, data was collected over a distance of 12.15 metres. This ensured that the plough-tractor system had stabilised before data collection started. The system had to accelerate from rest to the required speed at the beginning of the run.

5.5 Width Measurement

Ten pegs were placed on each side of the soil bin directly opposite each other in a line parallel to the ploughing direction. These pegs were used as reference points while measuring the width ploughed. After opening the first furrow, a tape measure was placed between the two opposing pegs across the bin and the distance between the furrow edge and the pegs on one side was noted. After each consecutive plough run, this distance was recorded. Plate 5.3 illustrates this procedure.

Plate 5.3 Taking the width measurements.

The width ploughed was obtained by subtracting two consecutive readings.

5.6 Depth Measurement

Measurement of depth presented a special problem. This was because as soon as the plough opened a furrow, some sand fell back into the furrow. To overcome this problem, some special pegs were made for depth measurement. These pegs were made from 15 cm long, 0.5 cm diameter iron rods and a base plate (8 x 4 x 0.5 cm) welded on them to enable them remain in a standing position in the sand. These pegs were placed in the furrow bottom as soon as the plough opened the furrow by somebody following closely behind the plough. The falling sand then covered the base plate of the pegs and helped to keep the pegs upright. Plate 5.4. illustrates the depth measurement.

Plate 5.4 Taking the depth measurements.

The depth was measured by pushing a steel rule through the sand till it touched the base plate. By adding the thickness of the base plate to the steel rule reading, the actual depth was obtained.

Due to the low cohesion present in the sand, the sand surface could not support the furrow wheel of the ploughs. The furrow wheels tended to sink into the ground making it difficult to control the working depth. This problem was solved by attaching some skids of dimension 12 cm wide and 45 cm long on the furrow wheel. The skids helped in the depth control as the sinking of the furrow wheels was reduced considerably due to the increase in the surface area in contact with the sand.

5.7 Bulk Density and Moisture Content Measurement

It is difficult to obtain undisturbed samples of sand due to its low cohesion, which makes it hard to retain the sand samples in the sampler while retrieving them from the ground. The consequence of this is that a high level of accuracy in the measurement of bulk density is difficult to attain. To improve on the accuracy many samples of sand were collected (36 samples).

The evaluation of bulk density presented another unique problem due to the difficulty involved in obtaining core samples of the sand. The gravimetric method was applied with some adjustment to the size of the cylindrical containers. Four cylindrical samplers of size 5 centimetre diameter and 5 centimetre height were joined together using some insulating tape to obtain cylinders of height 20 cm. These cylinders were then pushed slowly through the sand surface until they were wholly embedded in the sand. The top of the cylinders was then covered by fitting a lid.

The sand around the sampler was excavated and a spade was pushed below the sampler and the whole set-up was then withdrawn from the sand surface. The whole set-up was then turned upside down ensuring that none of the sand in the cylinder spilled out. The purpose of the spade was to support the cylinder while it was being withdrawn from the

Plate 5.5 The soil sampling cylinder in position with the sand excavated on one side.

sand surface and to ensure that no sand spilled out of the cylinder. After turning the cylinder upside down, a lid was fitted on the remaining open side of the cylinder (the cylinders were open on both sides).

The samples were then taken to the laboratory where each cylinder was carefully sheared off into the four original small cylinders. During the shearing procedure, the cylinder was placed in a big container to ensure that any sand that might spill out was trapped in the container. The content of each small sample was then weighed using an electronic balance. The weight of the empty container was then subtracted from the gross weight of the sample to obtain the weight of the sand alone which was then used for calculation of the bulk density.

The samples were then placed in an oven at 105° c for a period ranging from 24 to 36 hours depending on whether the sample had dried completely. Complete drying was attained when no further sample weight loss was detected after re-weighing. The samples were then removed from the oven and weighed again, the weight loss of the samples was used to calculate the moisture content of the sand. The idea behind joining the four cylinders was to enable the evaluation of the bulk density and moisture content along the depth profile. Bigger cylinders were easier to use than the smaller ones. The ability to obtain bigger samples reduced errors in the calculation of these two parameters. Three sets of the 5 cm diameter by 20 cm height cylinders were used three times to obtain samples at any one condition, hence a total of thirty-six samples were used for the evaluation of these two parameters at each soil condition.

5.8 Soil Inversion by the Plough

Soil inversion by a plough depends on the shape of mouldboard, the width, the height of the furrow slice and the ploughing speed. Due to the deformation that a furrow slice undergoes during the inversion and crushing process, it is difficult in theory to describe the real process of inversion.

During the inversion process, the furrow slice undergoes some twisting and bending deflection resulting in the loosening of soil particles in the upper parts and compression in the lower parts. As the furrow slice moves over the mouldboard, the speed of the soil particles varies and it becomes difficult to assign the speed distribution of these particles for a particular soil cross section. It is assumed that the plough speed is equal to the furrow slice speed. This is not always true as investigations have shown that the average furrow slice speed, V_s is usually lower than the ploughing speed, V. The difference in speed has been attributed to the swelling of the furrow slice as it moves over the mouldboard. For simplicity, the movement of a furrow slice over the mouldboard is treated as a continuous flow.

The dependency of inversion on the lateral dimensions of the furrow slice was eliminated since the sand did not produce furrow slices. This enabled the soil particles to be displaced independently of each other. The effects of speed were taken care of as all the measurements were done at the same speeds for all the ploughs.

The evaluation of this parameter was achieved by the use of marked marbles which were placed in the sand. Two sets of twelve marbles were placed inside the sand matrix at two different locations at defined coordinates. The marbles were placed in three layers at depths of 2, 7 and 12 centimetres. At each layer parallel to the ground surface, four marbles were placed in a 5 centimetre square grid. The plough was then moved through the sand and the subsequent displacement (lateral and axial) of the marbles was measured using a tape measure. This procedure was repeated for all the four ploughs and at the four working speeds. The displacement was measured at sand moisture condition of 0.7% (w.b.). Figure 5.1 shows how these marbles were placed in the sand matrix.

Lateral placement (cm).

Depth (cm)	*00*	*05*	*10*	*15*
02	A	B	C	D
07	E	F	G	H
12	I	J	K	L

Figure 5.1 Marble placement in the sand matrix

5.9 Soil Particle Size Distribution

This was obtained using the Sieve Analysis method. Four samples, approximately 1000 grammes each were passed through American standard testing sieves (ASTME 11 specification). The samples were shaken using a mechanical shaker at a frequency of 90 Hz for 30 minutes. The amount of sand retained in each sieve was then weighed using an electronic balance. From these measurements, the percentages of sand retained and passing through the sieves were calculated.

5.10 Coefficient of Soil-Metal Friction and Adhesion

The value of the coefficient of friction (μ) for soil-metal surfaces, depends on the moisture content of the soil, the level of compaction of the soil and the surface finish of the metal. For steel-sand interface, values of the coefficient of friction (μ) reported ranged from, 0.38 to 0.82 with the higher values occurring at higher moisture contents. As was discussed in chapter three, soils do not adhere completely to the laws of friction as it has been reported that the sliding velocity affects the value of the coefficient of friction (μ).

It is possible to obtain different values of the coefficient of friction (μ) for the same soil-metal combination. The values of the coefficient of friction (μ) obtained could only be indicative of the actual values and yet this is an important parameter in tillage operations and studies. It was explained in section 3.6.2 that no quantitative equation describing behaviour for adhesion has been developed. The normal procedure is to try to separate the effects of the friction component and the effects of the adhesion component from the measured sliding resistances which is difficult. The method that was used was the rotating annulus. Some important aspects of this technique are that the Initial Sliding Path Length (ISPL) and the sliding velocity have some effect on the tangential adhesive stress component (Hendrick and Bailey, 1982). It was not possible to control the sliding velocity in this work as the required torque was applied manually.

The method of the rotating an annulus (see section 3.6.3.) was used to comparatively evaluate the coefficient of soil-metal friction. The annulus is not a standard laboratory instrument but it gave results useable in comparing or characterising the soil condition. The annulus was made of mild steel of dimensions 0.45 metres and 0.25 metres for the outer and inner diameters respectively. The annulus was placed on the sand surface and some turning moment was applied manually through a 20 centimetre long arm. The rotating arm had a dial for showing the applied torque.

The torque was applied slowly until slip occurred between the sand surface and the annulus, the torque at which this occurred was noted. The torque was applied in the anti-clockwise direction until slip occurred, the procedure was then repeated in the clockwise direction. The average of the two torque readings was then taken as the torque at which the slip occurred. The normal load on the annulus was varied in five steps by placing additional weights on the upper side of the annulus. The load was varied from 162 N to 238 N, this load range was used because the annuls weighed 16.5 Kgs (162 N) and the available weights were in the 1 Kg range. Increment in the load was achieved by the consequent addition of two weights. The procedure was done at three different spots on the sand surface. Plate 5.6 illustrates this procedure.

The equipment that was used could have been a source of error. The pointer of the dial on the torque arm was missing hence a sliding pointer was improvised. This pointer could not give the torque readings with a high level of precision.

Plate 5.6 Rotating an annulus on the sand surface for the measurement of adhesion and the coefficient of soil-metal friction.

The torque readings were read both on the clockwise and anticlockwise directions in an attempt to reduce errors and the average of the two was taken to be the applied torque. It was noticed that the dial did not give the same reading on the clockwise and anticlockwise directions as it should have, hence indicating a probable calibration error.

Due to the fact that the torque was applied manually, it was not possible to ascertain that the torque was applied perpendicularly to the stem of the annulus. The implication of this is that there exists the possibility that the effective torque was lower than the indicated torque on the dial.

5.11 Cohesion and Internal Angle of Friction

The direct shear test was used to evaluate cohesion and the internal angle of friction. The Unconfined Undrained procedure was used. The test was carried out in the Soil Mechanics Laboratory of the Department of Civil Engineering (University of Nairobi) on Ring Number 2030. The shearing rig had a proving ring of calibration factor of 0.75 Kg per division. A gear ratio of 5 was used. The shearing box was of dimensions, 6 cm by 6 cm by 4 cm.

Two samples of sand at each condition were used for the evaluation of these two parameters. The normal stress on the sand was varied from 33425 N/M^2 to 74120 N/M^2 in four steps. The sand was compacted to the same density as it was in the soil bin. This was done by placing a pre-determined mass of sand into the shearing box such that the mass-volume ratio in the shear box was then same as that in the sand bin. The shearing load was gradually increased until the sample failed, the shear load at failure was noted. The horizontal shear displacement was also noted during the shearing process.

Although the same shearing rig was used to conduct the tests, the tests were not carried out on the same day but over a period of over ten weeks. The possibility that the calibration of the ring in the rig was interfered with by other users cannot be ruled out. The rig was in constant use and hence some permanent deformation could have occurred over that period of time. The UU test was used as it was felt that the effects of sand pore pressure were insignificant since the samples had low water content. Stafford and Tanner (1983), showed that the strain rate was important as it affected the values of cohesion obtained. A constant gear ratio of 5 to 1 was therefore maintained for all the tests.

It is very important to evaluate the cohesion of a soil while it is in the same condition as in the field. Disturbed samples were used in this study hence it was necessary to reconstitute the sand. This was achieved by compacting the sand inside the shearing box to the density it had while in the field. The compaction was done in three layers but it was not possible to verify that the levels of compaction were the same. This aspect could have influenced the results though not significantly.

The use of cohesion and the internal angle of friction in explaining the failure mechanism assumes that the soil fails under shear failure mechanism. Soil does not always fail under this mechanism. Elijah and Weber (1971), reported soil failing under a flow failure mechanism at increased tillage speeds. This failure pattern has been observed to give good pulverisation. Shear failure pattern was assumed in this work since it was carried out at low speeds not exceeding 1.04 m/s.

Due to the effects of the strain rate, it is important to measure cohesion at the same strain rate that the soil in the field is subjected to otherwise the results obtained might not reflect the actual situation. The method chosen to evaluate cohesion is very important as it has been shown that different methods give different values of cohesion for the same soil condition. The reason attributed to the differences obtained while measuring cohesion is because the failure patterns in these methods are different. It is therefore important to choose a method that approaches the failure pattern in the field as closest as possible.

5.12 The Plough Geometry

The method used to describe the shape is influenced by the objective of the shape characterisation. The method described by Boer (1966), was used to describe the shape of the ploughs. Figure 5.2 illustrates some of the plough measurements that were taken. These measurements were taken using the following equipment; two tape measures, a protractor, a pair of spring dividers and an Engineer's square.

The following linear measurements as shown in figure 5.2 were taken.

length of line 1, 2, AB, BG, BC, CG, AC, CF and BF,

length of the plough diagonal (line AF) and the length of the cutting edge of the share,

length and height of the landside,

height of the mouldboard at the front end,

distance from the share point to point A,

distance from point H to the upper side of the mouldboard, distance from point H to the lower side of the mouldboard,

distance from point F to the landside,

distance from the point of maximum concavity under line 2 to point A.

The following concavities were measured,

maximum concavity under line 2, at point C and at point H

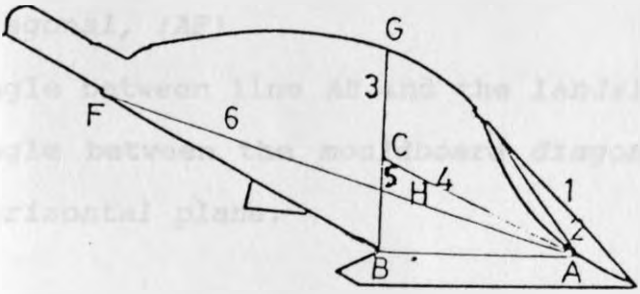


Figure 5.2 Side view of mouldboard showing the lines that are necessary for its description (Boer, 1966).

The following angular measurements were taken,

The active vertical angle at the front end of the share: This is the angle in a vertical plane between the cutting edge of the share and the bottom of the landside.

The active vertical angle at the heel of the share: This is the angle in a vertical plane between the heel of the share and the perpendicular to the cutting edge of the share.

Rise angle mouldboard: This is the angle in a vertical plane between line 2 and the landside.

Rise angle mouldboard and the share: This is the angle in a vertical plane between line 1 and the landside.

Horizontal cutting angle: This is the angle in the horizontal plane between the cutting edge of the share and the landside.

Angle between the *landside* and the *border line* between the landside and the share *(line AB)*.

Angle between *line AC* and the *landside*.

Angle between the *landside* and the *mouldboard diagonal, (AF)*.

Angle between line *AH* and the *landside*.

Angle between the *mouldboard diagonal, (AF)* and the *horizontal plane*.

5.13 Dynamometer Calibration.

This was done every week that the dynamometer was used. A dial scale dynamometer was used to calibrate the hydraulic dynamometer. The sensor of the hydraulic dynamometer was connected in series with the dial dynamometer. The dynamometer set-up was then connected between a stationary tractor and a hoist. The tractor weight provided resistance to the tensile load applied through the hoist. The load was varied by pulling on one of the chains of the hoist. The readings on both the dynamometers were taken at each load, the load was varied between zero to 1950 N in about 14 steps. The dial dynamometer readings were then plotted against the readings of the hydraulic dynamometer. The regression equation of this graph was then used to calibrate the hydraulic dynamometer. The dynamometer was calibrated during the loading process only as it was noticed that the unloading and loading curves were similar hence no hysterisis.

The calibration curves of the hydraulic dynamometer are presented in Figures 5.3, 5.4, 5.5, 5.6 and 5.7. The plotting paper in the dynamometer that was used to collect data corrected by calibration curves 1 and 2 had a different scale from the plotting paper used in the dynamometer for collecting data corrected by curves 3,4 and 5.

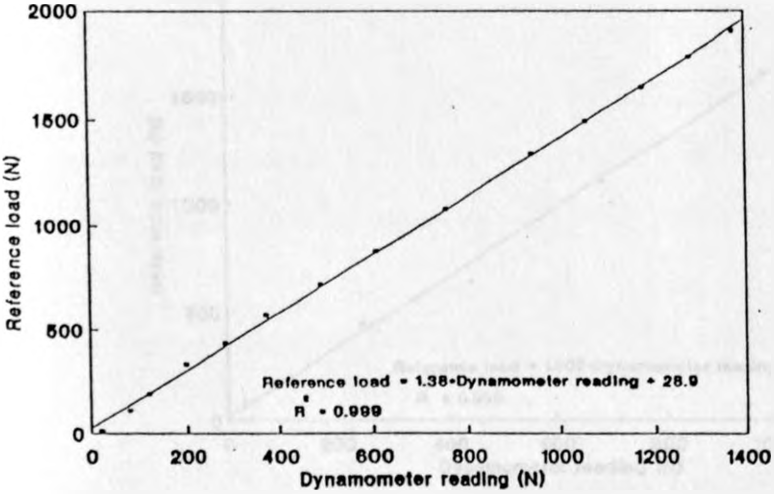


Figure 5.3 Calibration curve one.

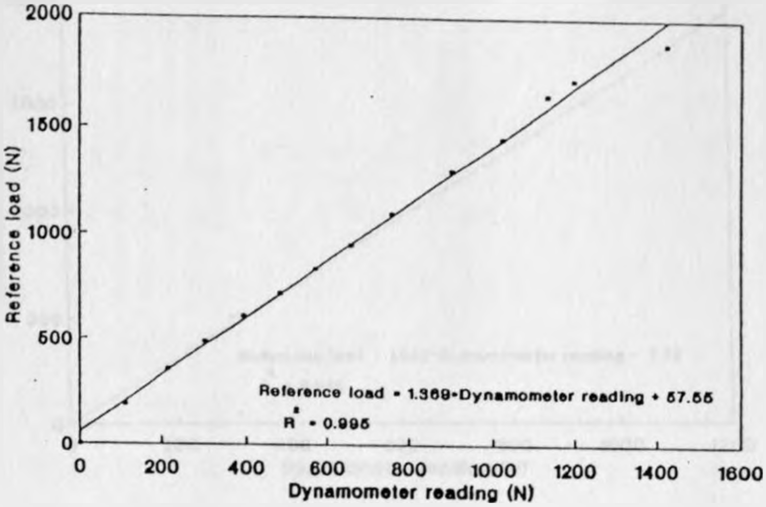


Figure 5.4 Calibration curve two

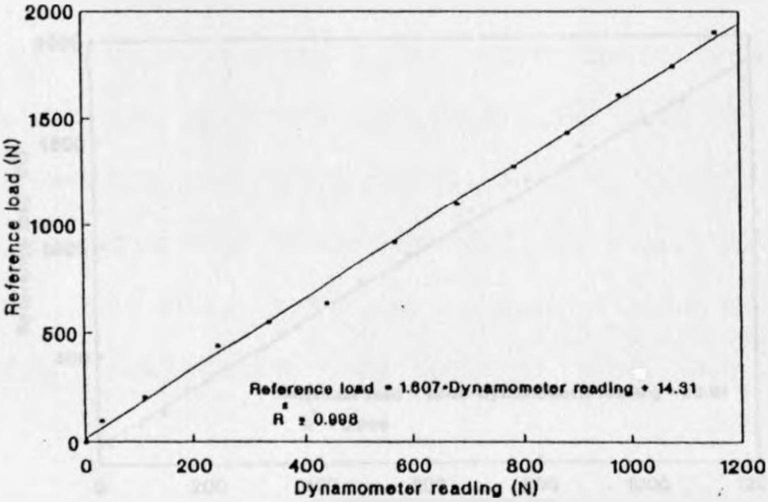


Figure 5.5 Calibration curve three

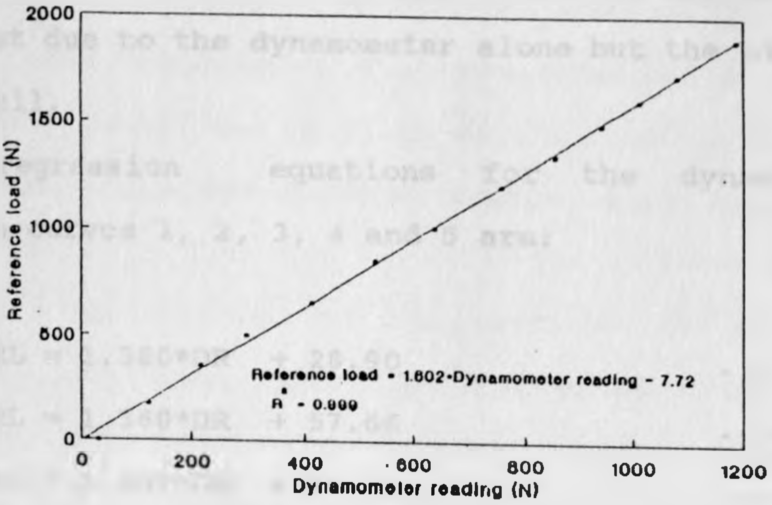


Figure 5.6 Calibration curve four

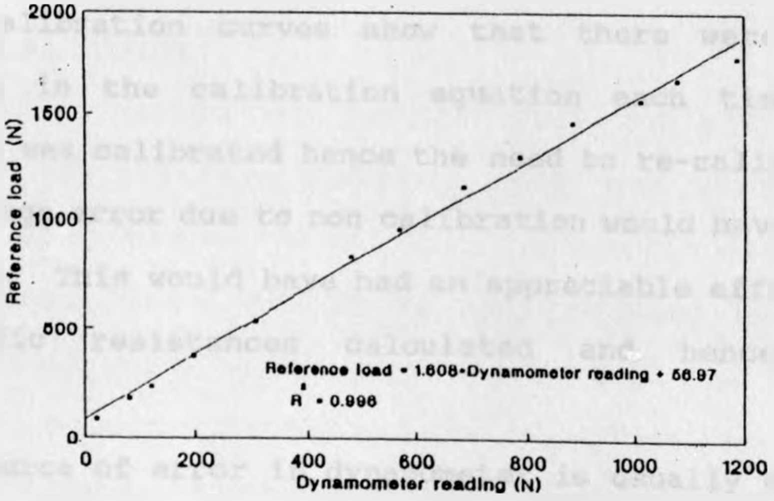


Figure 5.7 Calibration curve five

This explains the difference between the gradient of curves (1,2) and (3,4,5) which had an average gradient of 1.37 and 1.606 respectively. Hence the difference in the gradient was not just due to the dynamometer alone but the plotting paper as well.

The regression equations for the dynamometer calibration curves 1, 2, 3, 4 and 5 are:

$$RL = 1.380*DR + 28.90 \quad ....[5.1]$$

$$RL = 1.360*DR + 57.66 \quad ....[5.2]$$

$$RL = 1.607*DR + 14.31 \quad ....[5.3]$$

$$RL = 1.602*DR - 7.72 \quad ....[5.4]$$

$$RL = 1.608*DR + 56.97 \quad ....[5.5]$$

respectively.

where, RL = Reference load

DR = Dynamometer reading

The calibration curves show that there were some differences in the calibration equation each time the dynamometer was calibrated hence the need to re-calibrate. The percentage error due to non calibration would have been significant. This would have had an appreciable effect on the specific resistances calculated and hence the conclusion.

The source of error in dynamometer is usually due to hysteresis. This is especially so if the dynamometer is not allowed sufficient time to relax and if it measures loads near its limit. Permanent deformations could occur in the dynamometer parts necessitating continuous calibration and re-calibration. The dynamometer that was used had a hydraulic sensor. Some small quantities of fluid were noticed to be leaking out of the sensor, this was another reason which necessitated continuous dynamometer calibration. Ideally the calibration should have been done on a daily basis, but the practicability of this was not possible due to the time limit. The compromise of calibrating once a week was observed. The calibration data (regression equations) were used to convert the dynamometer readings to the actual force.

5.14 Ploughing Velocity

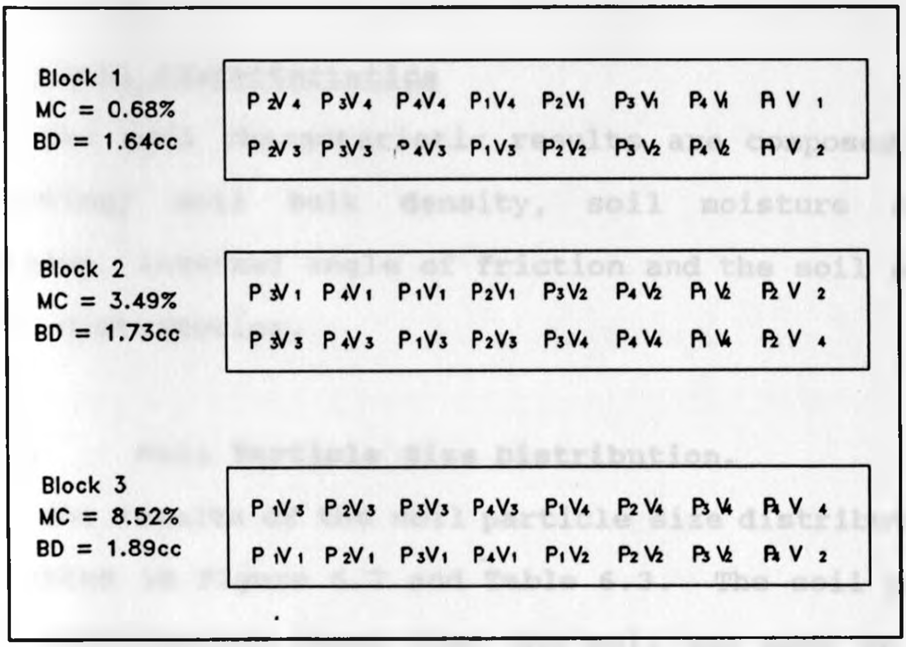
The ploughing velocity was evaluated by measuring the time taken to travel over a distance of 12.15 metres using a stop watch.

5.15 Experimental Design

The Experimental design used for this study was a Split-Plot design. The two factors were ploughing speed and plough type, where the ploughing speed was the main plot factor and plough type the sub-plot factor. The four ploughs are described in section 5.2. The velocities were; 0.49 m/s, 0.6 m/s, 0.82 m/s and 1.04 m/s, the combination of the ploughs and the velocities gave a total of sixteen treatments. The experiment was conducted within three blocks, with the criteria for blocking being the bulk density and moisture content. The location of the experiment site was the Field Station of the College of

Agriculture and Veterinary Sciences at the Kabete Campus of the University of Nairobi.

The following was the experimental layout.



Block 1 MC = 0.68% BD = 1.64cc	P_2V_4	P_3V_4	P_4V_4	P_1V_4	P_2V_1	P_3V_1	P_4V_1	P_1V_1
	P_2V_3	P_3V_3	P_4V_3	P_1V_3	P_2V_2	P_3V_2	P_4V_2	P_1V_2
Block 2 MC = 3.49% BD = 1.73cc	P_3V_1	P_4V_1	P_1V_1	P_2V_1	P_3V_2	P_4V_2	P_1V_2	P_2V_2
	P_3V_3	P_4V_3	P_1V_3	P_2V_3	P_3V_4	P_4V_4	P_1V_4	P_2V_4
Block 3 MC = 8.52% BD = 1.89cc	P_1V_3	P_2V_3	P_3V_3	P_4V_3	P_1V_4	P_2V_4	P_3V_4	P_4V_4
	P_1V_1	P_2V_1	P_3V_1	P_4V_1	P_1V_2	P_2V_2	P_3V_2	P_4V_2

P_1 = Rumptstad (winding bottom) plough
P_2 = Rumptstad (cylindrical bottom) plough
P_3 = Bukura Mk. II plough
P_4 = Victory plough
V_1 = A speed of 0.49 m/s
V_2 = A speed of 0.60 m/s
V_3 = A speed of 0.82 m/s
V_4 = A speed of 1.04 m/s
MC = Moisture content (% w.b)
BD = Bulk density (cc)
P_iV_j = The various treatments.

Figure 5.8 The schematic experimental layout of the Split-Plot Design.

6 RESULTS AND DISCUSSION

The results and discussions of the experiments in the study are presented under various sections. These sections include the soil characteristics, plough characteristics, soil-tool interaction characteristics and the statistical analysis.

6.1 Soil Characteristics

The soil characteristic results are composed of the following; soil bulk density, soil moisture content, cohesion, internal angle of friction and the soil particle size distribution.

6.1.1 Soil Particle Size Distribution.

The results of the soil particle size distribution are presented in Figure 6.7 and Table 6.3. The soil particle size distribution shows that the soil was made up of the following composition, 1.0 % silt, 92.8 % sand and 6.1 % gravel.

Table 6.1 Soil particle size distribution.

Soil type	Particle size (mm)	Composition (%)
Gravel	2 - 20	6.1
Coarse sand	0.6 - 2	30.9
Medium sand	0.2 - 0.6	46.3
Fine sand	0.06 - 0.2	15.6
Silt	0.02 - 0.06	1.0

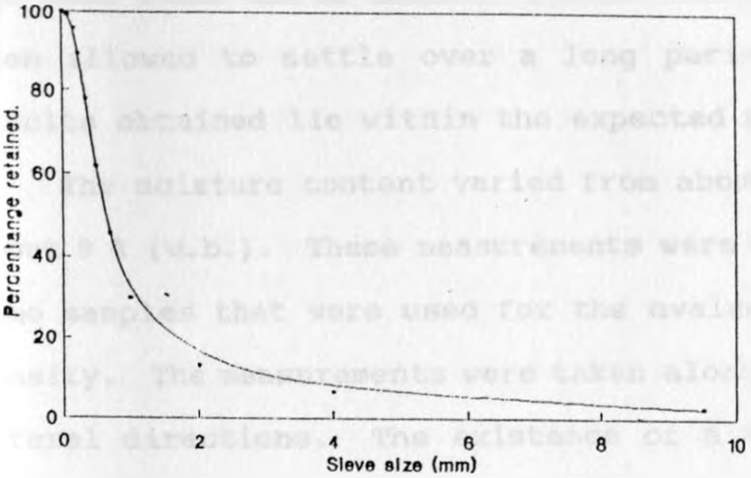


Figure 6.1 Soil particle size distribution.

6.1.2 Bulk Density and Moisture Content.

Table 6.2 presents the results of bulk density and the moisture content.

Table 6.2 Soil characteristics.

Block	Average moisture content (% w.b)	Average bulk density (g/cm^3)
One	0.68	1.64
Two	3.49	1.73
Three	8.52	1.89

The bulk density of sand varied from an average minimum of 1.64 g/cm^3 to a maximum average of 1.89 g/cm^3 as presented in Table 6.1. Loose sand has been observed to have a bulk density as low as 1.3 g/cm^3. The minimum value of 1.64 g/cm^3

obtained was due to the compaction that the sand had been subjected to by the roller during the conditioning. Sand has been observed to exhibit a bulk density above 2 g/cm^3 when allowed to settle over a long period of time. The results obtained lie within the expected range.

The moisture content varied from about 0.7 % (w.b.) to about 9 % (w.b.). These measurements were obtained from the same samples that were used for the evaluation of the bulk density. The measurements were taken along the vertical and lateral directions. The existence of a moisture gradient is explained by the fact that the sand in the top surface lost moisture due to evaporation and also the moisture percolated downwards, leaving the lower layers wetter than the upper ones. The attempt to alleviate this problem by passing a harrow through the sand proved to be relatively successful.

Sources of error in these measurements could be attributed to, the sampling technique, compaction of the samples and loss of moisture while transferring the sand from the sampling cylinders into the bowls. Some moisture films were noticed in the inside lining of the samplers. The same electronic balance was used in all the weighing processes to minimise errors.

6.1.3 Cohesion and Internal Angle of Friction

The results on cohesion and the internal angle of friction are presented on Figures 6.3, 6.5 and 6.7 which were derived from results presented on Figures 6.2, 6.4 and

6.6 respectively. Figures 6.2, 6.4 and 6.6 are plots of the shear displacement versus shear load at defined normal stresses as indicated in the graphs. The results of the plots from Figures 6.3, 6.5 and 6.7 recorded values of the coefficient of determination, (R^2) of 0.99, 0.96 and 0.91 respectively. Figures 6.2, 6.4 and 6.6 represent the conditions in blocks 1, 2 and 3 respectively.

Table 6.3 Cohesion and internal angle of friction.

Block	Cohesion (Pa)	Internal angle of friction (Degrees)
One	6985	34
Two	52	44
Three	23594	36

The trend of the results obtained on cohesion across the three blocks was consistent with the results obtained on the soil specific resistances. Block two had the lowest cohesion and soil specific resistances, block three had the highest cohesion and soil specific resistances with respect to the four ploughs. The value of cohesion and soil specific resistances in block one were in the range between the values in block two and three. The consistency in the trend between cohesion and the soil specific resistance is observed by the fact that an increase in the soil cohesion was followed by a subsequent increase in soil specific resistance

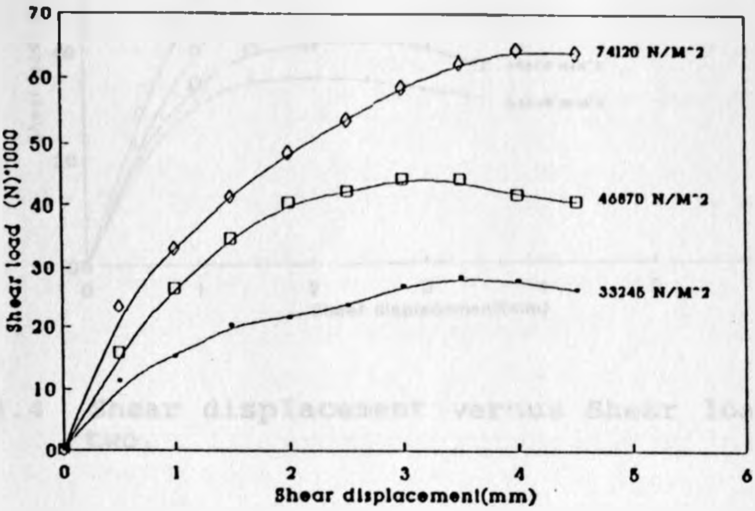


Figure 6.2 Shear displacement versus Shear load in block one.

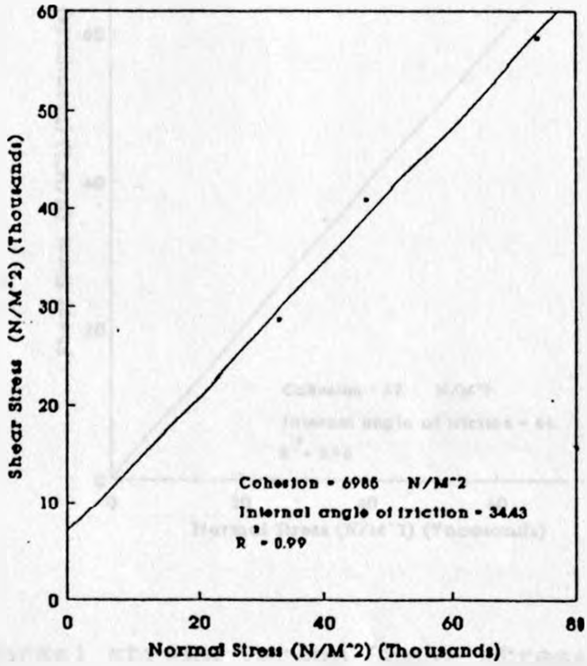


Figure 6.3 Normal stress versus Shear stress in block one.

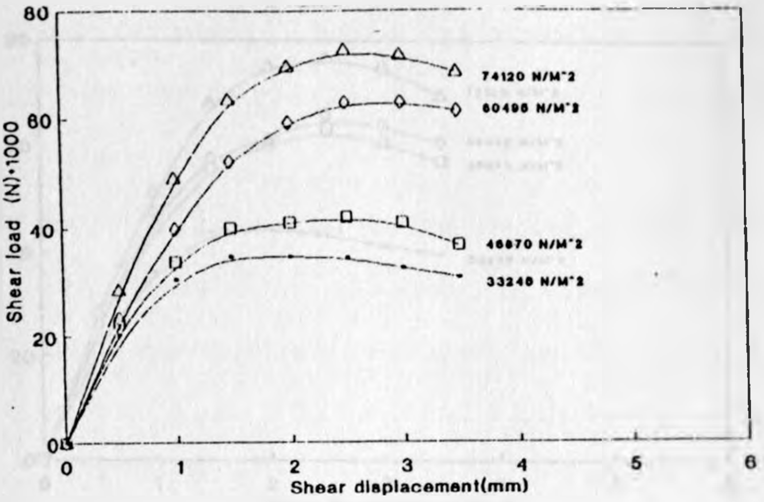


Figure 6.4 Shear displacement versus Shear load in block two.

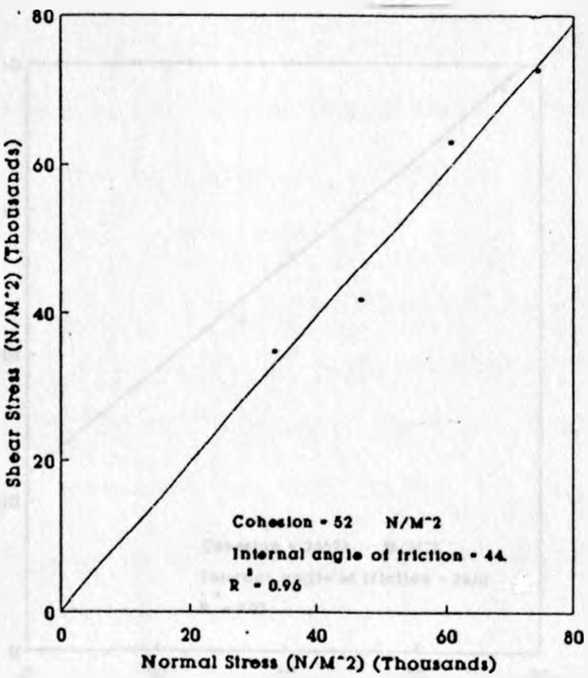


Figure 6.5 Normal stress versus Shear stress in block two.

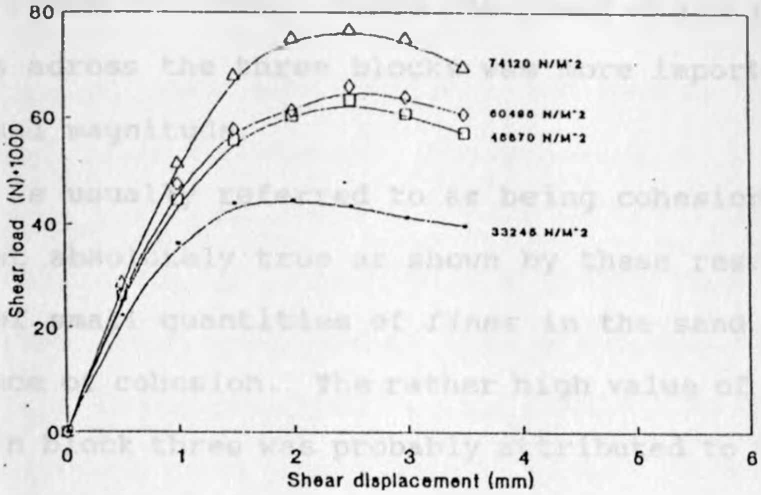


Figure 6.6 Shear displacement versus Shear load in block three.

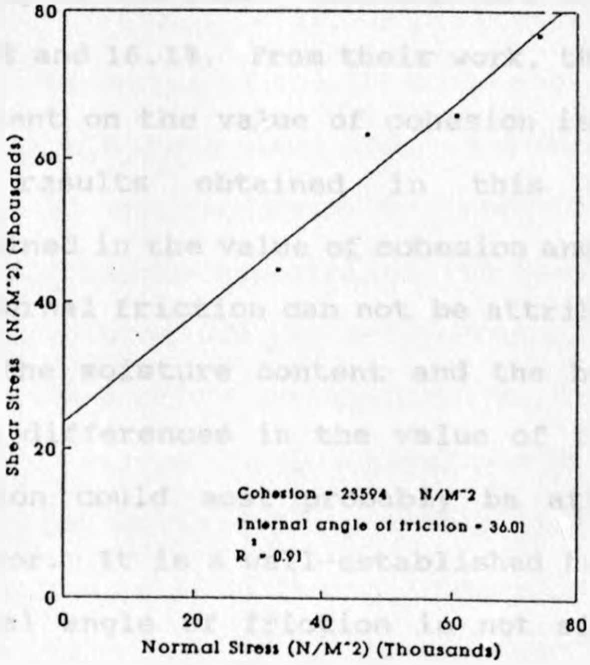


Figure 6.7 Normal stress versus Shear stress in block three.

Cohesion and the internal angle of friction are not real soil parameters but parameters describing a failure mechanism (Shear failure). Hence the trend of the these two parameters across the three blocks was more important than their actual magnitude.

Sand is usually referred to as being cohesionless but this is not absolutely true as shown by these results. The presence of small quantities of *fines* in the sand explains the presence of cohesion. The rather high value of cohesion obtained in block three was probably attributed to the water that was used to wet the sand. The water was obtained from a dam which has an appreciable amount of silt. Stafford and Tanner (1983), reported peak values as high as 208 kPa and residual values of up to 20.2 kPa for cohesion in a sandy clay loam, made up of 60% sand. The moisture content range was between 11.7% and 16.1%. From their work, the influence of moisture content on the value of cohesion is apparent.

From the results obtained in this study, the differences obtained in the value of cohesion and especially the angle of internal friction can not be attributed to the differences in the moisture content and the bulk density only. The high differences in the value of the internal angle of friction could most probably be attributed to experimental error. It is a well-established fact that the value of internal angle of friction is not significantly affected by the moisture content of the soil.

The results on cohesion and internal angle of friction in block two are of special interest. Although this block had the lowest value of cohesion, it had the highest value of the internal angle of friction. The values of these two parameters were obtained from the same Normal-Shear stress graph. An error in the evaluation of any of the two parameters would have most probably resulted in an error in the evaluation of the other. The gradient of the Normal-Shear stress graph gave the internal angle of friction of the soil while the intercept on the Y-axis gave the value of cohesion. The gradient of this graph was steep (see Figure 6.5), which resulted in the Y-axis intercept being near the origin and therefore giving a low value of cohesion.

Though sand has low cohesion, the value of 52 Pa. measured in this block was outside the scale of the values in the other two blocks. The value of 44 degrees obtained for the internal angle of friction was certainly outside the expected range. The value of the internal angle of friction is this block should have been about the same as in the other two blocks as this parameter is constant for the same soil. The most probable explanation for these results is that a calibration error was present in the proving ring of the shearing rig when this test was carried out. The actual value of cohesion measured in this block was probably higher than the 52 Pa. but certainly lower than in the other two blocks following the trend of the soil specific resistances.

6.2 Plough Characteristics

The results on plough characteristics consists of the plough geometry and the soil inversion measurements.

6.2.1 Plough geometry

The results on the plough geometry are presented in Table 6.4 where Rd-1, Rd-2, Bk-2 and Vi represent the Rumptstad (cylindrical bottom), Rumptstad (winding bottom), Bukura Mk. II and Victory ploughs respectively. The plough geometry measurements are based on figure 5.2

The vertical cutting angle (1) refers to the angle at the front end of the share while the vertical cutting angle (2) refers to the angle at the end of the share while unit deg. represents degrees (see Table 6.4).

It was not possible to avoid drawing comparison of the various shape parameters between the local ploughs and the imported ploughs. The two local ploughs tended to display some common similarities between them while the two imported ploughs had some characteristics common to them.

The Rumptstad ploughs had no noticeable horizontal suction while the local ploughs had suction ranging from, 12 mm for the Bukura Mk. II to 20 mm for the Victory plough. The horizontal suction provides suction onto the furrow wall for the plough.

Table 6.4 Linear and angular measurements of the ploughs.

Description of Measurement	Units	Plough			
		Rd-1	Rd-2	Bk-2	Vi
Horizontal suction	mm	0	0	12	20
Vertical suction	mm	18	20	20	23
Length: line 1	mm	370	390	340	335
Length: line 2	mm	220	245	205	200
Length: line AB	mm	260	260	220	240
Length: line BG	mm	248	254	222	233
Length: line BC	mm	103	123	90	105
Length: line CG	mm	145	136	135	127
Length: line AC	mm	280	287	245	300
Length: line AH	mm	262	230	230	236
Length: line CF	mm	321	393	275	248
Length: line BF	mm	333	434	308	297
Length: Mouldboard diagonal (line AF)	mm	586	678	515	510
Length: Cutting edge of the share	mm	305	300	315	330
Length: Landside	mm	600	600	510	515
Height: Landside	mm	60	60	51	50
Height: Mouldboard front end	mm	298	310	260	300
Distance: Share point to point A	mm	170	165	140	140
Distance: Point of maximum concavity under line 2 to point A	mm	124	125	130	132
Distance: Point H to upper side of the mouldboard	mm	190	177	145	156
Distance: Point H to lower side of the mouldboard	mm	38	73	78	75
Concavity: Point C	mm	18	31	15	12
Concavity: Point H	mm	32	7	43	38
Concavity: Under line 2	mm	2	6	11	10
Vertical cutting angle(1)	deg.	24	24	25	29
Vertical cutting angle(2)	deg.	35	35	34	44
Rise angle mouldboard	deg.	56	62	44	44
Rise angle mouldboard and share	deg.	42	47	37	39
Horizontal cutting angle	deg.	40	40	46	44
Angle: Landside and AB	deg.	44	44	46	46
Angle: Landside and AC	deg.	35	32	34	31
Angle: Landside and AF	deg.	45	36	41	41
Angle: Landside and AH	deg.	40	36	31	32
Angle: Landside and the horizontal plane	deg.	7	14	16	20

The vertical suction helps the plough to penetrate into the ground. The vertical suction varied from 18 mm in the Rumptstad (cylindrical) bottom to 23 mm in the Victory plough. This high value of the vertical suction of the Victory plough explains the tendency of this plough to dig deep into the soil making depth control difficult to achieve.

Except for the Victory plough, the other three ploughs had about the same active vertical cutting angles both at the front and the rear ends of the share. The Victory plough as shown on Table 6.4 had the larger active vertical cutting angles. These angles are important as they influence the way that the plough moves through the soil. The high values of these angles on the Victory plough is one the reasons of the bulldozing action displayed by this plough. Values reported for the active vertical angle (1) range from about 20 to 25 degrees. High values for the active vertical cutting angle (2) are ideal for working in harder soils.

The two imported ploughs had a larger rise angle mouldboard and Rise angle mouldboard-share and longer lines *1* and *2* compared to the local ploughs. The imported ploughs had lower concavities at the front end of the mouldboard under line *2* compared to the local ploughs. The rise angles, lengths of lines *1* and *2* and the concavity under line *2* influence the manner that the furrow slice is received by the front end of the mouldboard. These parameters influence the turning and the deformation of the furrow slice. The difference in the Rise angles mouldboard and mouldboard-share gives an indication of the role of the share in this action.

The horizontal cutting angle varied from 40 degrees for the imported ploughs to 45 degrees for the local ploughs. This angle exhibits a big range among different mouldboard ploughs, varying from 30 to 50 degrees. This angle influences the turning especially for relatively dry coherent soils. High speed ploughs working in sodded soils display lower values for this angle due to improved undercutting of the furrow slice while ploughs working in fields with rhizomes require that this angle be large. Hence the local ploughs would then be suitable for working in rhizome fields while the imported ploughs would be more apt for higher speed application.

The local ploughs had shorter distances between their upper and lower points on the mouldboard (line *BG*) behind the share compared to the imported ploughs. The imported ploughs had higher concavity at point *C* (under line *BG*) compared to the local ploughs. The Rumptstad (winding bottom) had the highest concavity while the Victory plough had the lowest. The angle between the landside and line *AC* was about the same for all the four ploughs; ranging from 31 to 35 degrees.

The angle between the landside and the plough body (line *AB*) was about the same for all the four ploughs. The local ploughs measured 46 degrees while the imported ploughs measured 44 degrees. The angle between the landside and the plough body gives some insight to the turning of the furrow slice and the openness of the furrow made by the mouldboard.

The local ploughs had shorter mouldboard diagonals (line *AF*) compared to the imported ploughs. The angle between this diagonal and the landside gives an indication of how traverse (inclination of the plough to the furrow wall on the horizontal plane) the plough body is compared to its direction of travel. High traversity is desirable for sticky soils, hence making Rumptstad (cylindrical bottom) most suitable for such soils and the Rumptstad (winding) bottom the least suitable. The local ploughs displayed higher concavities under this diagonal compared to the imported ploughs. The local ploughs also displayed a larger angle between this diagonal and the horizontal plane.

High correlation has been observed between the length of the plough diagonal and the working depth, the working width and the turning of the furrow slice. Poor turning of the furrow slice occurs if the length of this diagonal is smaller than the summation of the operating width and depth while working in heavy soils. From this observation, one draws the conclusion of the unsuitability of the local ploughs in heavier soils unless they work shallow depths and small widths. The turning of the local ploughs could be improved by the addition of tails on the mouldboard wings.

The shape of the plough behind point *B* influences the turning of the furrow slice at certain depths. Angle *BCF* gives an indication of the shape at point *B*. The larger this angle is, the higher the tendency of the furrow slice to pass below the end of the mouldboard. The consequence of this is that the mouldboard ceases to influence the turning action. From calculations, the Victory plough had the largest angle at this point (108 degrees) which is another explanation of its bulldozing effect.

From this discussion it is obvious that various parameters influence the performance of ploughs. These parameters influence the performance of the ploughs differently. The way that these parameters are combined in the geometry of the plough determines the way that the plough performs. The shape of the mouldboard should be designed bearing in mind the requirements of the user. These requirements are largely influenced by the Agro-ecological zone of user. Soil inversion is not always desirable, in the drier regions soil pulverisation without inversion is important for the preservation of the soil moisture. In the wetter regions soil inversion is very important for the destruction of weeds.

6.2.2 Soil Inversion by the Ploughs

The results on inversion are presented in Figures 6.8, 6.9, 6.10 and 6.11. They are presented in terms of the lateral and axial displacement of the marbles. The results indicate that the Rumptstad (cylindrical bottom) plough had the most displacement of the marbles hence the sand. It recorded an average of 58 cm and 24 cm for axial and lateral displacements respectively. The lateral displacement gives an indication of the inversion capability of the plough while the axial displacement gives an indication of how much the plough pushed the soil forward. The Rumptstad (Cylindrical bottom) plough appeared to displace the lower layers of the sand more than the upper ones both in the lateral and axial directions as shown in Figure 6.8.

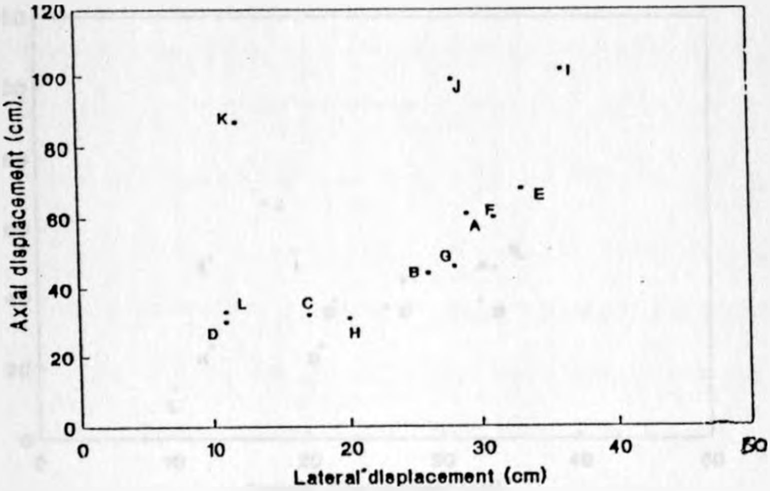


Figure 6.8 Soil inversion by the Rumptstad (cylindrical) plough.

Marbles in column *AEI* (along the vertical profile) had the highest average lateral displacement as was expected since this was the first line of marbles to make contact with the plough. Due to the limited knowledge of the inversion process, it is not very certain whether marbles *A* or *I* should have the most lateral displacement.

The Rumptstad (winding bottom) plough had an average displacement of the marbles of 41 cm and 23 cm in the axial and lateral directions respectively. The displacement by this plough was less than that of the cylindrical bottom plough. This plough displayed an increase in axial displacement down the depth profile, that is the lower layers of the marbles got more axial displacement than the upper layers as shown in figure 6.9.

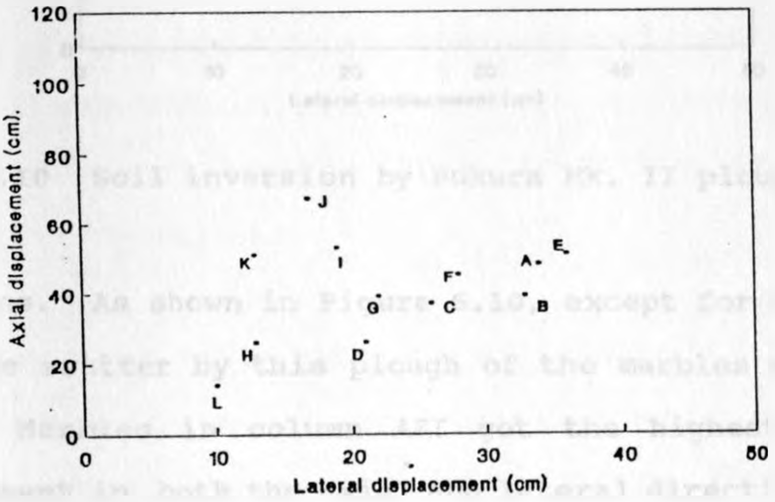


Figure 6.9 Soil inversion by the Rumptstad (winding) plough.

This plough displayed less scatter for the marbles as compared to the other Rumptstad plough. Marbles in column *AEI* had the highest average lateral displacement as expected with marble *E* having the highest lateral displacement.

The inversion by the Bukura Mk. II plough is presented in Figure 6.10. The plough recorded an average displacement of 45 cm and 21 cm in the axial and lateral directions respectively. There was a marked decrease in displacement down the vertical profile both in the axial and lateral

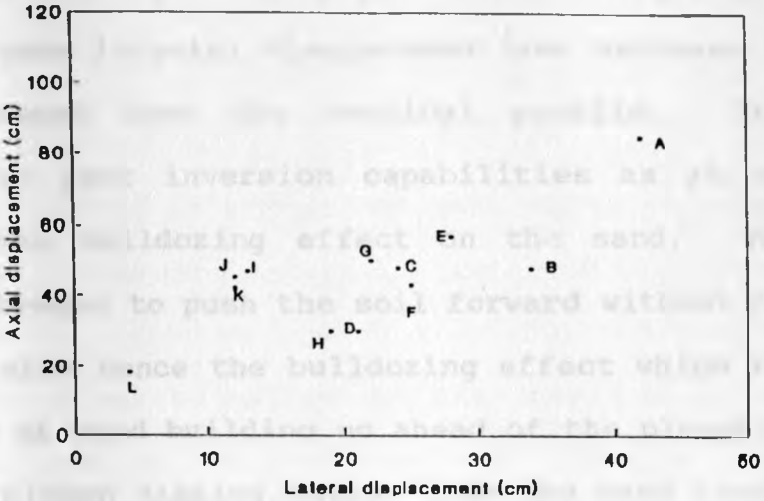


Figure 6.10 Soil inversion by Bukura Mk. II plough.

directions. As shown in Figure 6.10, except for marbles *A* and *L* the scatter by this plough of the marbles was quite small. Marbles in column *AEI* got the highest average displacement in both the axial and lateral directions, with *A* getting the highest displacement.

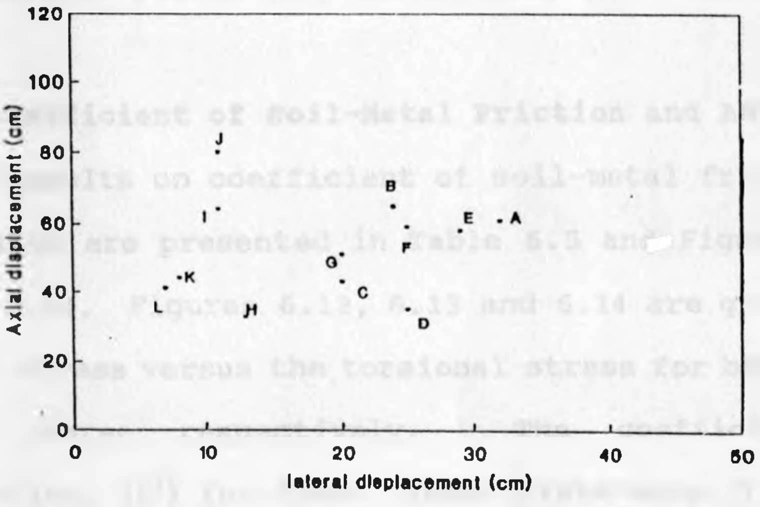


Figure 6.11 Soil inversion by the Victory plough.

The Victory plough had the least lateral displacement averaging 19 cm and a rather high 53 cm for the axial displacement as shown in Figure 6.11. This plough displayed an increase in axial displacement and decrease in lateral displacement down the vertical profile. This plough displayed poor inversion capabilities as it had a very noticeable bulldozing effect on the sand. The Victory plough tended to push the soil forward without throwing it to the side hence the bulldozing effect which resulted in a surge of sand building up ahead of the plough. This led to the plough sinking deeper into the sand resulting into high draught requirement. This plough displayed a small scatter of the marbles.

6.3 Soil-Tool Interaction Characteristics

The results on soil-tool characteristics include the coefficient of soil-metal [mild steel] friction (μ), adhesion, the specific resistances of the ploughs and the coefficients of static (k_o) and dynamic (ϵ) resistances.

6.3.1 Coefficient of Soil-Metal Friction and Adhesion

The results on coefficient of soil-metal friction (μ) and adhesion are presented in Table 6.5 and Figures 6.12, 6.13 and 6.14. Figures 6.12, 6.13 and 6.14 are graph plots of normal stress versus the torsional stress for blocks one, two and three respectively. The coefficients of determination, (R^2) for these linear plots were, 1.00, 0.97 and 0.99 for blocks one, two and three respectively.

Table 6.5 Soil-Tool interaction characteristics.

Block	μ	Adhesion (Pa)
One	0.54	-129
Two	0.51	30
Three	0.62	-160

The values of μ reported here, 0.51 to 0.62 are quite well within the expected range (refer to section 5.10). The results on adhesion and the coefficient of soil-metal friction appear to follow the same trend as the results on cohesion and the internal angle of friction. Block three had the highest value of the coefficient of soil-metal friction but the lowest value of adhesion, while block two had the lowest value of the coefficient of soil-metal friction but the highest value of adhesion.

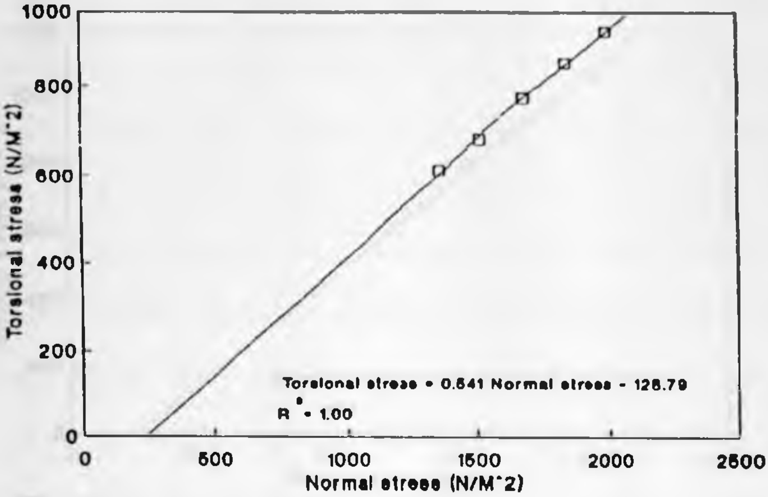


Figure 6.12 Normal stress versus torsional stress in block one.

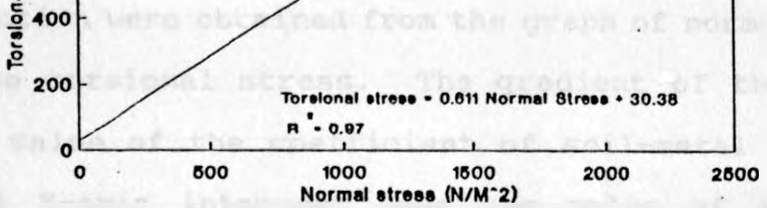


Figure 6.13 Normal stress versus torsional stress in block two.

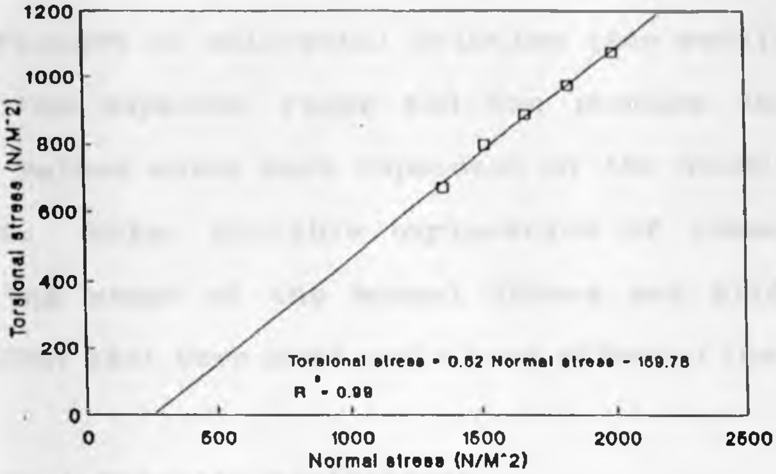


Figure 6.14 Normal stress versus torsional stress in block three.

The values obtained for these two parameters in block one were in the range between the values in blocks two and three. This trend of behaviour of these two parameters was similar to the trend of behaviour of cohesion and the internal angle of friction.

The results of adhesion and the coefficient of soil-metal friction were obtained from the graph of normal stress versus the torsional stress. The gradient of this graph gave the value of the coefficient of soil-metal friction while the Y-axis intercept gave the value of adhesion. Adhesion varied from negative 160 Pa to 30 Pa. It is difficult to accurately explain the negative values.

A shift to the left by graphs given by Figures 6.12 and 6.14 would have given more plausible results. Calibration error in the torque measuring device could have resulted in this anomaly. A calibration error (the torque metre was not calibrated) was suspected because the values obtained for the coefficient of soil-metal friction (see section 5.10) were in the expected range and the problem was in the adhesion values which were dependent of the graph's Y-axis intercept. Other possible explanation of these results include the range of the normal stress and Sliding Path Length (SPL) that were used could have affected the results.

6.3.2 Soil Specific Resistances

The results on the soil specific resistances are presented in Table 6.6 and Figures 6.15, 6.16, 6.17 and 6.18. Figures 6.15, 6.16 and 6.17 are plots of the specific resistance versus the velocity for all the four ploughs in blocks one, two and three respectively. Figure 6.18 is the plot of the average specific resistances from all the three blocks versus the velocity.

Results from block one show that Bukura Mk II plough had the highest specific resistance varying from 0.35 Kg/cm^2 at 0.49 m/s to 0.40 Kg/cm^2 at 1.04 m/s. The victory plough had the next highest specific resistance followed by the Rumptstad (cylindrical bottom) plough. The Rumptstad (winding bottom) had the least specific resistance. In block two the trend was generally similar to that in block one. The specific resistances in this block were generally similar to those in block one though this block had a higher bulk density and lower cohesion than block one. The effects cohesion and bulk density could have cancelled each hence the similarity in the specific resistances in these two blocks.

Table 6.6 Soil specific Resistances.

Plough	Speed (m/s)	Specific Resistances (Kg/cm^2) Block			
		One	Two	Three	Average
Rumptstad (Cylindrical)	0.49	0.31	0.31	0.38	0.33
	0.60	0.33	0.32	0.40	0.35
	0.82	0.34	0.35	0.41	0.36
	1.04	0.36	0.38	0.41	0.38
Rumptstad (Winding)	0.49	0.28	0.27	0.31	0.29
	0.60	0.28	0.30	0.34	0.31
	0.82	0.33	0.31	0.36	0.33
	1.04	0.35	0.34	0.38	0.36
Bukura Mk. II	0.49	0.35	0.34	0.35	0.35
	0.60	0.35	0.36	0.36	0.36
	0.82	0.37	0.36	0.37	0.37
	1.04	0.40	0.41	0.41	0.41
Victory	0.49	0.32	0.34	0.36	0.34
	0.60	0.35	0.35	0.36	0.35
	0.82	0.36	0.35	0.39	0.37
	1.04	0.36	0.38	0.43	0.39

At lower speeds, the victory plough and Bukura Mk II had approximately the same specific resistance. The rate of increase of the specific resistance of Bukura Mk. II plough was higher than that of the Victory plough. At higher speeds, the Victory plough had approximately the same specific resistance as the Rumptstad (cylindrical bottom) plough which displayed a rapid increase in specific resistance with increasing speed. The Rumptstad (winding bottom) plough showed a decrease in the specific resistance compared to that in block one.

Block three had the toughest soil conditions, it had the highest bulk density, the highest cohesion and the highest coefficient of friction (μ). The trend in performance in this block was different from that in the other two blocks. The Rumptstad (cylindrical bottom) had the highest specific resistance in this block. The Victory plough had the next highest resistance reaching a record 0.43 Kg/cm^2 at 1.04 m/s.

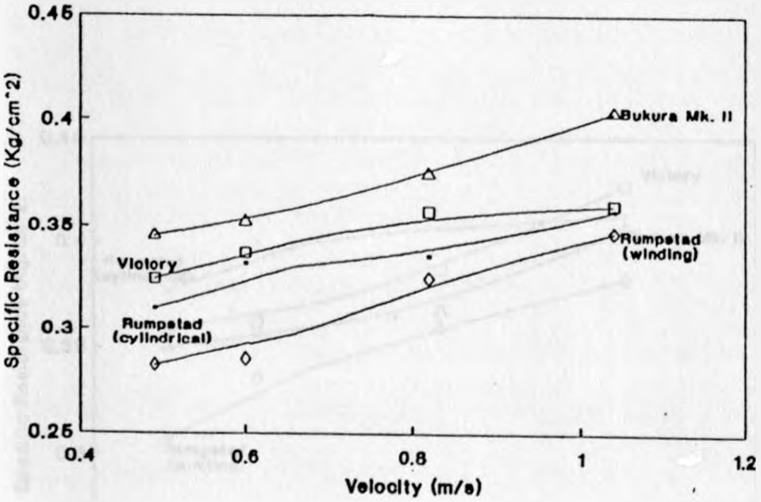


Figure 6.15 Plough performance in block one.

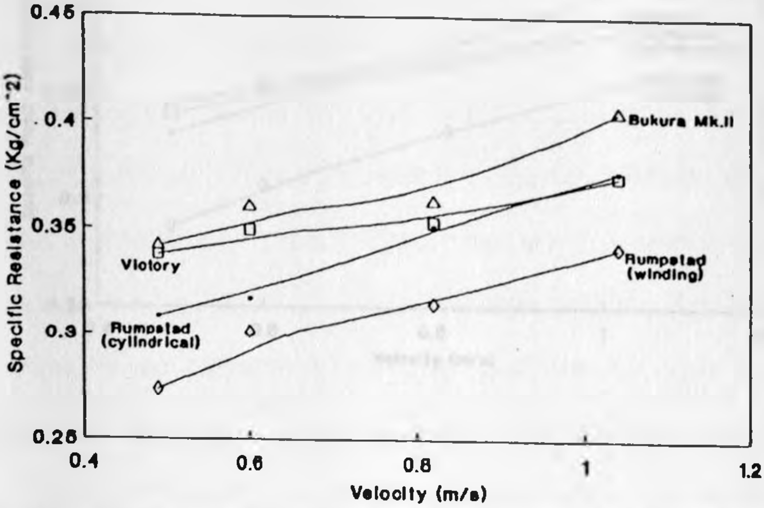


Figure 6.16 Plough performance in block two.

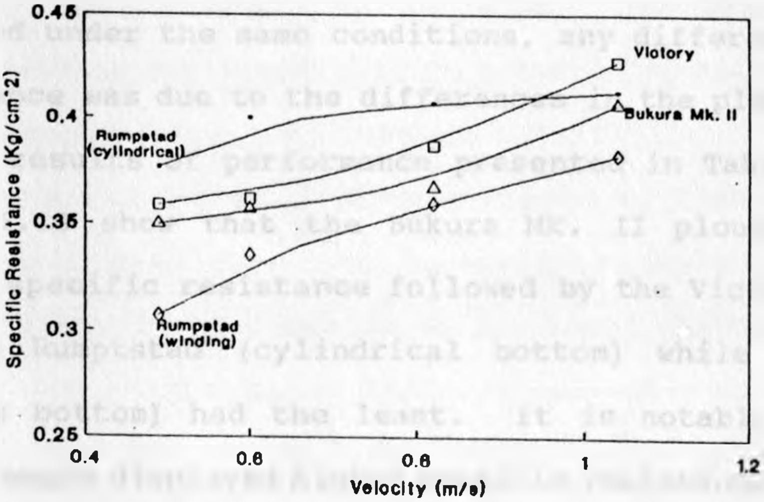


Figure 6.17 Plough performance in block three.

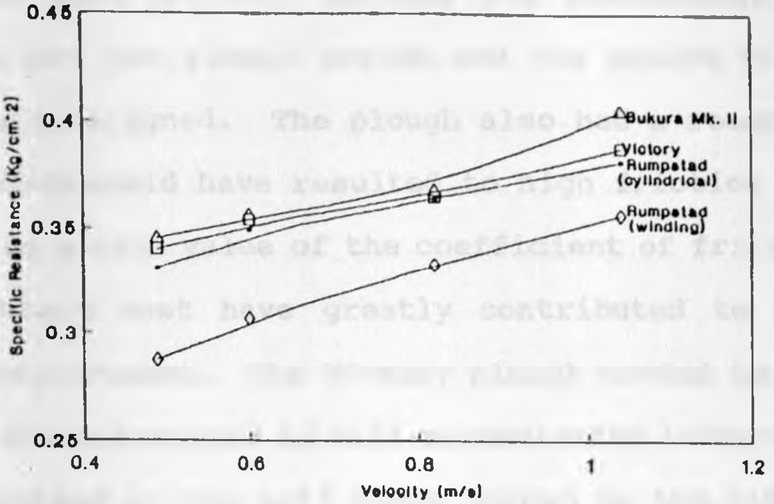


Figure 6.18 Average plough performance in the three blocks.

Bukura Mk II had the next highest resistance while Rumptstad (winding bottom) again had the least specific resistance. It is interesting to note that the specific resistance of Bukura Mk. II plough was fairly consistent in all the three blocks. Since the performance of these ploughs was evaluated under the same conditions, any difference in the performance was due to the differences in the ploughs. The average results of performance presented in Table 6.6 and Figure 6.18 show that the Bukura Mk. II plough had the highest specific resistance followed by the Victory plough then by Rumptstad (cylindrical bottom) while Rumptstad (winding bottom) had the least. It is notable that the local ploughs displayed higher specific resistances compared to the imported ploughs.

The Bukura Mk. II plough showed the highest specific resistance most probably because its workmanship was not only poor but the plough bottom and the plough frame were not properly aligned. The plough also had a rough surface finish which could have resulted to high friction with the sand due to a high value of the coefficient of friction (μ). These factors must have greatly contributed to its high draught requirement. The Victory plough tended to bulldoze the soil which resulted in soil accumulating infront of this plough instead of the soil being thrown to the side as the plough moved forward. This plough displayed a tendency to dig deeper into the soil. These two factors contributed a lot in increasing the draught requirement of this plough. Though the imported ploughs were heavier than the local ploughs, they displayed lower specific resistances because of the following reasons. These ploughs had a very smooth surface finish hence had little friction with the soil and their inversion capability was good as the soil was able to flow over them smoothly to the side. The shape of the plough plays an important role in determining the magnitude of the draught force (see section 6.2.1).

Though the imported ploughs displayed lower specific resistances, this does not necessarily imply that they require less draught compared to the local ploughs. Lower specific resistance means that the plough requires less force per unit area of soil, but if the furrow slice is big, then the draught force would be high. The imported ploughs are bigger than the local ones hence if not wisely used, they would require high draught forces to operate them making it difficult to work with them using animal power. It is therefore important to control the size of the furrow slice otherwise the advantage of these ploughs would not be realised. While using specific resistance as a criterion of performance comparison, careful thought is necessary. The same plough could give different values for specific resistance of the same soil just by varying the dimensions of the furrow slice as was noticed in this study.

Table 6.7 Static and Dynamic coefficients of resistances.

Plough	k_o (Kg/cm^2)			ϵ (Kgs^2/cm^2m^2)		
	Block					
	1	2	3	1	2	3
Rumptstad (Cylind.)	0.31	0.29	0.38	0.041	0.090	0.042
Rumptstad (Winding)	0.26	0.26	0.29	0.074	0.079	0.093
Bukura Mk II	0.33	0.33	0.33	0.071	0.074	0.056
Victory	0.33	0.33	0.33	0.026	0.043	0.079

Table 6.7 presents the results of the Static (k_o) and Dynamic (ϵ) coefficients of resistances of the soil and the ploughs in the three blocks. The results show that k_o varied from 0.26 Kg/cm^2 for the Rumptstad (winding bottom) plough in block two to 0.38 Kg/cm^2 for the Rumptstad (cylindrical) bottom plough in block three. Table 6.8 presents typical values of k_o for the described soil conditions.

Table 6.8 Static coefficients of resistance for typical soil conditions (Bernacki et al.,1972)

Soil condition	k_o (Kg/cm^2)
Light soil	0.2 - 0.3
Medium firm soil	0.3 - 0.5
Firm heavy soil	0.5 - 0.7
Very heavy soil	Over 0.7

The results on the k_o values show that they lie in the region of a medium firm soil. The values of ϵ ranged from 0.026 Kgs^2/cm^{2}m^2 for the victory plough in block one to 0.093 Kgs^2/cm^{2}m^2 for the Rumptstad (winding bottom) plough in block three. The value of ϵ largely depends on the plough shape characteristics, but it has been observed that the velocity range has some influence on it. Research has shown that different values of ϵ can be obtained for the same plough bottom on the same soil condition for different speed ranges. The following results from a "Polish *Pc1*" plough bottom illustrates this phenomenon.

Velocity range: 1 - 2.4 m/s, $\epsilon = 0.026$ Kgs^2/m^2,

Velocity range: 1 - 3.3 m/s, $\epsilon = 0.032$ Kgs^2/m^2.

The setting angle of the mouldboard wihg, θ_1 and the angle at which the furrow slice leaves the mouldboard, θ_2 are important in determining the value of ϵ. The differences obtained in the value of ϵ for different speed ranges is attributed to the differences in the trajectory of the furrow slice as it leaves the mouldboard.

6.3.3 Modeling

The results presented in Table 6.9 and Figures 6.19, 6.20, 6.21 and 6.22 show that the results obtained from the field and those obtained from the model compare well. The calculations of k_o, ϵ and the model specific resistances are presented in the appendix. The values of the Static (k_o) and Dynamic (ϵ) coefficients of resistances presented in Table 6.9 were obtained using equations [4.30] and [4.31].

Table 6.9 Combined results from the three blocks.

Plough	Velocity (m/s)	k_o (Kg/cm^2)	ϵ (Kgs^2/cm^{2m2})	Specific Resistance (Kg/cm^2) Expt.	Model	% diff.
Rumptstad (cylind)	0.49	0.323	0.057	0.331	0.337	-1.81
	0.60			0.349	0.344	1.43
	0.82			0.364	0.361	0.82
	1.04			0.382	0.385	-0.79
Rumptstad (winding)	0.49	0.273	0.082	0.287	0.293	-2.09
	0.60			0.307	0.303	1.30
	0.82			0.333	0.328	1.50
	1.04			0.357	0.362	-1.40
Bukura Mk.II	0.49	0.328	0.069	0.345	0.345	0.00
	0.60			0.356	0.353	0.84
	0.82			0.368	0.374	-1.63
	1.04			0.405	0.403	0.49
Victory	0.49	0.331	0.052	0.340	0.343	-0.88
	0.60			0.354	0.350	1.13
	0.82			0.365	0.366	-0.27
	1.04			0.388	0.387	0.26

Ideally, the k_o values obtained for the four ploughs should have been the same since they characterise the soil's firmness. The performance of the ploughs was evaluated under the same soil conditions hence the value of k_o should

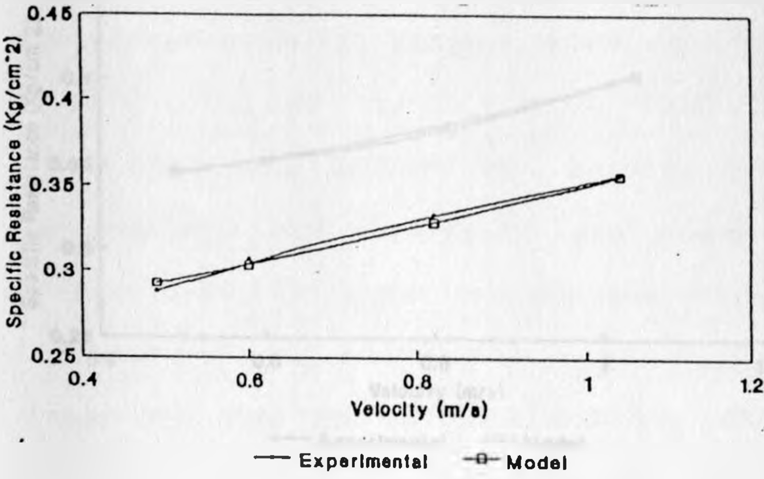


Figure 6.19 Experimental-Modeled performance comparison for the Rumptstad (winding) plough.

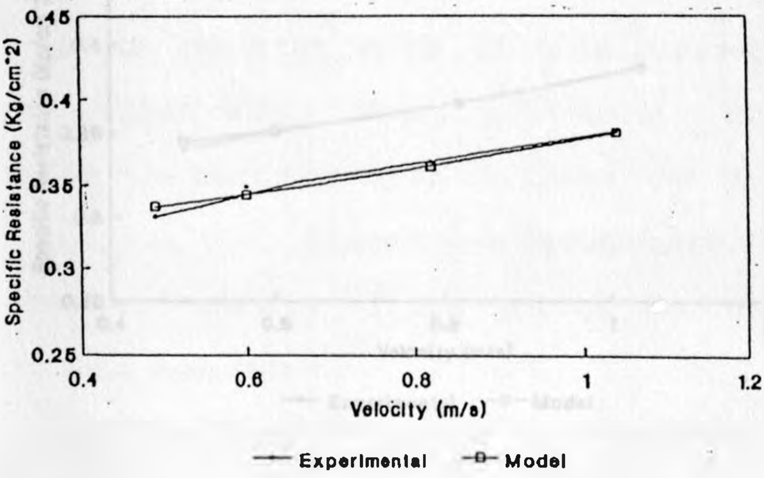


Figure 6.20 Experimental-Modeled performance comparison for the Rumptstad (cylindrical) plough.

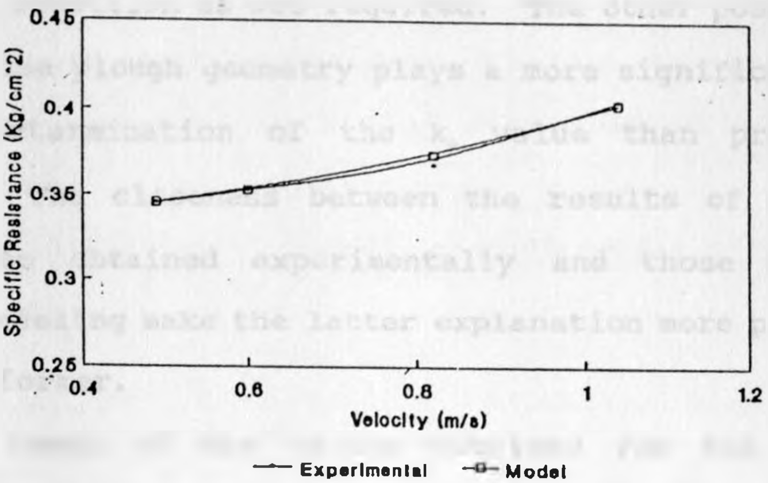


Figure 6.21 Experimental-Modeled performance comparison for the Bukura Mk. II plough.

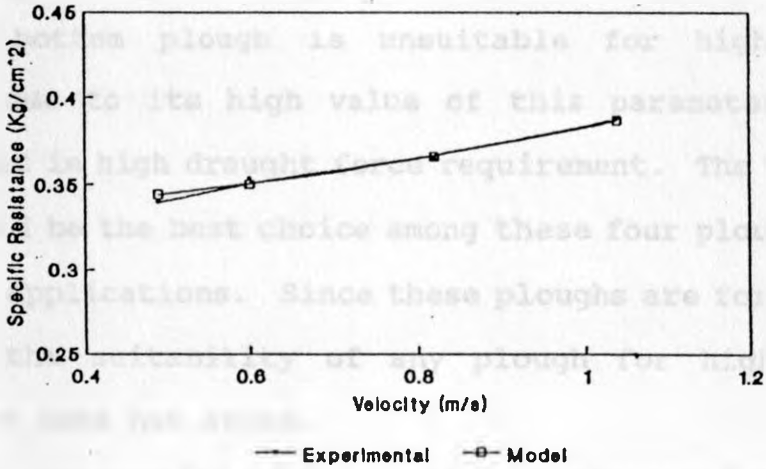


Figure 6.22 Experimental-Modeled performance comparison for the Victory plough.

have been the same for all.

Differences in the value of k_0 could have resulted from the plough performance not being evaluated under the same soil condition as was required. The other possibility was that the plough geometry plays a more significant role in the determination of the k_0 value than previously thought. The closeness between the results of specific resistances obtained experimentally and those obtained through modeling make the latter explanation more plausible than the former.

The range of the values obtained for the dynamic resistance (ϵ) was large. This was expected as it is known that the value of this parameter is largely influenced by the plough geometry. The Rumptstad (winding) bottom had a value out of range from the values of the other three ploughs. This is not surprising as this plough had a distinctly different shape from the rest. The Rumptstad (winding) bottom plough is unsuitable for high speed operation due to its high value of this parameter which would result in high draught force requirement. The Victory plough would be the best choice among these four ploughs for high speed applications. Since these ploughs are for animal traction, the suitability of any plough for high speed application does not arise.

Though the results on the specific resistances from the field compared well with the results obtained through modeling, the following observations were made. The model tended to over-estimate the specific resistances at the lower speeds and under-estimate the specific resistances at the higher speeds compared to the experimental results. The models can only be used accurately to predict the performance of the plough within the speed range that was used to evaluate their performance. However, these over and under-estimations were small and only observable at the third decimal level of significance.

The following are the models of performance of the four ploughs as shown in Table 6.9.

Rumptstad plough (cylindrical bottom),

$$k = 0.323 + 0.057V^2 \qquad \text{....[6.1]}$$

Rumptstad plough (winding bottom),

$$k = 0.273 + 0.082V^2 \qquad \text{....[6.2]}$$

Bukura Mk. II plough,

$$k = 0.328 + 0.069V^2 \qquad \text{....[6.3]}$$

Victory plough,

$$k = 0.331 + 0.052V^2 \qquad \text{....[6.4]}$$

The results from the three blocks were averaged to obtain the models because it was felt that the range of the static coefficient of resistance (k_0) for a specific soil condition is quite large. The results presented in Table 6.9 and Figures 6.19, 6.20, 6.21 and 6.22 show that the combining of the results gives a good representation of the plough performance.

6.4 Statistical Analysis

The results from the statistical analysis are presented in the ANOVA table, (Table 6.10). Except for the interaction of the plough and the speed (P*V) all the other effects were found to be significant at 1 % level of significance. These effects are, the replication, the treatment, the plough type and the velocity.

The statistical analysis results show that the performance of the ploughs was evaluated under different conditions. This is shown by the ANOVA table since the replications (Blocks) were found to be significantly different. The differences in the blocks were caused by differences in the soil bulk density, cohesion, adhesion and the coefficient of soil-metal friction. The combined effect of these parameters led to the significant difference across the blocks.

The results indicate that the ploughs were also significantly different. The differences in the ploughs included the plough weight, the plough geometry and the material used for the design of the ploughs. The speed range that was used to evaluate the performance of the ploughs ensured that the speeds were significantly different. Speed plays an important role in determining the draught force on a plough. A small increase in the speed of operation results in a considerable increase in the draught force. The lowest speed that was used in this study was 0.49 m/s while the highest was 1.04 m/s. The highest speed was more than two times faster than the slowest speed, this speed range ensured that each operational speed was different from the other one.

The Statistical analysis showed that there was no interaction between the plough type and the speed. This was not surprising as there should be no reason for any interaction between the two since they are independent factors. The independence between the plough type and the speed meant that a change in any one of these two parameters had no effect on the other.

The experiments recorded low values of the coefficient of variation (C.V.); C.V.$_{(v)}$ was 1.13 % and C.V.$_{(p)}$ was 4.83% for the velocity and plough respectively.

Table 6.10 ANOVA of the Split-Plot Design of the specific resistance of the soil.

Source of Variation	Dof	SS ($x10^{-2}$)	MS ($x10^{-2}$)	Computed F	Tabular F 5 %	Tabular F 1 %
Blocks	2	1.33	0.665	105.06	5.14	10.92
Velocity(V)	3	2.18	0.727	114.85	4.76	9.78
Error(V)	6	0.038	0.006			
Ploughs(P)	3	1.69	0.563	19.40	3.01	4.72
PV	9	0.113	0.013	0.43	2.3	3.26
Error(P)	24	0.697	0.029			
Total	47	6.05				

$CV_{(v)} = 1.13\%$

$CV_{(p)} = 4.83\%$

7 CONCLUSION

Soil specific resistance was used to evaluate the performance of the four selected animal drawn mouldboard ploughs. The local ploughs generally showed inferior performance compared to the imported ploughs. Bukura Mk. II had the highest soil specific resistance ranging from 0.35 kg/cm^2 to 0.41 kg/cm^2, the Victory plough had the next highest ranging from 0.34 kg/cm^2 to 0.39 kg/cm^2. The Rumptstad (cylindrical bottom) plough had soil specific resistance ranging from 0.33 kg/cm^2 to 0.38 kg/cm^2, the Rumptstad (winding bottom) plough had the lowest soil specific resistance ranging from 0.29 kg/cm^2 to 0.36 kg/cm^2. The soil specific resistances were evaluated between a speed range of 0.49 m/s to 1.04 m/s. Therefore the Rumptstad (winding bottom) had the best performance with respect to the draught requirement.

The Rumptstad (cylindrical bottom) plough had the best inversion capabilities. It had an average soil displacement in the lateral and axial directions of 24 and 58 cm respectively. The Rumptstad (winding bottom) had an average soil displacement of 23 and 41 cm in the lateral and axial directions respectively. The Bukura Mk. II had an average soil displacement of 21 and 45 cm in the lateral and axial directions respectively. The Victory plough had the lowest inversion capabilities. It had an average soil displacement of 19 and 53 cm in the lateral and axial directions respectively. The lateral soil displacement was the criterion used to measure plough soil inversion capabilities.

The imported ploughs were larger than the local ploughs. In the shape characterisation, some features were the same in all the ploughs. Some features were common in the local ploughs while the imported ploughs also had some features common to them. The Victory plough had the largest vertical cutting angle at the front end of the share measuring 44 degrees, the other three ploughs had the same angle measuring 35 degrees. The large vertical cutting angle of the Victory plough made this plough ideal for hard soils. The angle between the share and the landside varied from 44 to 46 degrees for all the ploughs.

The Rumptstad (winding bottom) plough had the largest rise angle which measured 62 degrees, it was followed by the other Rumptstad plough which measured 56 degrees. The Bukura Mk. II and Victory ploughs both had this angle measuring 44 degrees. The Rumptstad (winding bottom) had the longest lines 1 and 2 which measured 390 and 245 mm respectively, the Rumptstad (cylindrical bottom) plough measured 370 and 220 mm. The Victory and Bukura Mk. II ploughs had the same measurements for lines 1 and 2 which measured 340 and 200 mm respectively.

The Rumptstad ploughs had horizontal cutting angles measuring 40 degrees while Bukura Mk. II plough measured 44 degrees. The Victory plough had the largest horizontal cutting angle which measured 46 degrees. The smaller horizontal cutting angle on the Rumptstad ploughs made them ideal for high speed application.

The Bukura Mk. II plough had shortest mouldboard diagonal which measured 510 mm followed by the Victory plough which measured 515 mm. The Rumptstad (winding bottom) plough had the longest moulboard diagonal which measured 678 mm, the Rumptstad (cylindrical bottom) measured 586 mm. Long mouldboard diagonal is desirable for good furrow turning. After considering all the aspects of plough performance, the Rumptstad (winding bottom) was found to be the better of all four ploughs.

A mathematical model was developed for each of the four ploughs to describe their performance (soil specific resistance) with respect to speed. The four mathematical models predicted the performance of each of the plough accurately. The largest percentage difference between the values of soil specific resistance obtained experimentally and those obtained from the models was 2.09%. These models tended to give higher values by about 1.20% at the lower speed (0.49 m/s) and higher values by about 0.36% at the higher speed (1.04 m/s) for the soil specific resistance compared to the values obtained in the experiment. The results from these models should only be used within the speed range that was used in this study hence their limitation.

8 RECOMMENDATIONS AND FUTURE WORK

The following are recommendations and proposals for future work based on the findings and problems encountered in this study.

The development of a soil bin facility and acquisition of the instrumentation for the facility locally is a matter of top priority. The development and testing of agricultural tools would be highly enhanced by the acquisition of such a facility. The soil bin facility would make it possible to evaluate and compare the performances of various implements under controlled conditions.

The following need to be considered:

- The performance of the four ploughs needs to be evaluated under field conditions and the findings be compared with results obtained in this study. This would entail an elaborate statistical design so as to minimise errors associated with conducting tillage studies in the field.
- Mathematical modeling was used to model the performance of these four ploughs. There is the need to model the performance using a more detailed and revealing modeling technique like similitude modeling and compare the results with those obtained in this study. Similitude modeling would only be possible if a soil bin facility existed hence the recommendation for the acquisition of one.
- There is need to develop and standardise a method for plough shape description. Presently, many methods exist making it difficult to compare different plough shapes

described using different methods.

The Victory plough requires the following geometrical design improvements to reduce its bulldozing effect:

- Reduction on the size of the following; the two vertical cutting angles and angle BCF (see Figure 5.2).

The workmanship and the surface finish on the Bukura Mk. II needs improvement so as to reduce its draught requirement. A jig should be used during the manufacture of this plough so that proper alignment between the plough body and the frame is achieved.

APPENDIX

The calculation of the coefficients of static (k_o) and dynamic (ϵ) resistances and model soil specific resistances as shown on Table 6.8.

Plough: Rumptstad (cylindrical bottom)
Weight: 36.5 Kg.

Average specific Resistance $[k_n]$ Kg/cm^2	Velocity $[V_n]$ m/s	V_n^2 $(m/s)^2$	V_n^4 $(m/s)^4$	$k_n{*}V_n^2$ Kgm^2/cm^{2}s^2
0.331	0.492	0.242	0.0586	0.0801
0.349	0.598	0.358	0.1279	0.1248
0.364	0.825	0.681	0.4633	0.2477
0.382	1.037	1.075	1.1564	0.4108
Σ = 1.426	2.952	2.356	1.8061	0.8635

$$\Sigma k_n \Sigma V_n^4 = 2.5756$$

$$\Sigma V_n^2 \Sigma k_n V_n^2 = 2.0340$$

$$n\Sigma V_n^4 = 7.2246$$

$$[\Sigma V_n^2]^2 = 5.5491$$

$$k_o = [2.5756 - 2.0340] / [\ 7.2246 - 5.5491] = 0.3232$$

$$n\Sigma k_n V_n^2 = 3.4539$$

$$\Sigma k_n \Sigma V_n^2 = 3.3592$$

$$\epsilon = [3.4539 - 3.392] / [\ 7.2246 - 5.5491] = 0.0565$$

Therefore, $k = 0.323 + 0.057V^2$

Model soil specific resistances,

Velocity (m/s)	k_o (Kg/cm^2)	ϵV^2 (Kg/cm^2)	k (Kg/cm^2)
0.49	0.323	0.014	0.337
0.60	0.323	0.021	0.344
0.82	0.323	0.038	0.361
1.04	0.323	0.062	0.385

Plough: Rumptstad (winding bottom)
Weight: 38.2 Kg.

Average specific Resistance [k_n] Kg/cm^2	Velocity [V_n] m/s	V_n^2 (m/s)^2	V_n^4 (m/s)^4	$k_n*V_n^2$ Kgm^2/cm^{2}s^2
0.287	0.488	0.238	0.0567	0.0683
0.307	0.600	0.360	0.1296	0.1105
0.333	0.829	0.687	0.4723	0.2289
0.357	1.030	1.061	1.1255	0.3787
Σ = 1.426	2.947	2.346	1.7841	0.7865

$\Sigma k_n \Sigma V_n^4 = 2.2908$

$\Sigma V_n^2 \Sigma k_n V_n^2 = 1.8452$

$n \Sigma V_n^4 = 7.1365$

$[\Sigma V_n^2]^2 = 5.5051$

$k_o = [2.2908 - 1.8452] / [\ 7.1365 - 5.5051] = 0.2731$

$n \Sigma k_n V_n^2 = 3.1458$

$\Sigma k_n \Sigma V_n^2 = 3.0126$

$\epsilon = [3.1458 - 3.0126] / [\ 7.1356 - 5.5051] = 0.0816$

Therefore, $k = 0.273 + 0.082V^2$

Model soil specific resistances,

Velocity (m/s)	k_o (Kg/cm^2)	ϵV^2 (Kg/cm^2)	k (Kg/cm^2)
0.49	0.273	0.020	0.293
0.60	0.273	0.030	0.303
0.82	0.273	0.055	0.328
1.04	0.273	0.089	0.362

Plough: Bukura Mk II
Weight: 32.5 Kg.

Average specific Resistance [k_n] Kg/cm^2	Velocity [V_n] m/s	V_n^2 (m/s)^2	V_n^4 (m/s)^4	$k_n*V_n^2$ Kgm^2/cm^{2}s^2
0.345	0.492	0.242	0.0586	0.0835
0.356	0.609	0.371	0.1376	0.1320
0.368	0.817	0.667	0.4455	0.2456
0.405	1.041	1.084	1.1744	0.4389
Σ = 1.474	2.959	2.364	1.8161	0.9001

$\Sigma k_n \Sigma V_n^4$ = 2.6769

$\Sigma V_n^2 \Sigma k_n V_n^2$ = 2.1279

$n \Sigma V_n^4$ = 7.2642

$[\Sigma V_n^2]^2$ = 5.5890

k_o = [2.6769 - 2.1279] / [7.2642 - 5.5890] = 0.3277

$n \Sigma k_n V_n^2$ = 3.6003

$\Sigma k_n \Sigma V_n^2$ = 3.4847

ϵ = [3.6003 - 3.4847 / [7.2642 - 5.5890] = 0.0690

Therefore, $k = 0.328 + 0.069V^2$

Model soil specific resistances,

Velocity (m/s)	k_o (Kg/cm^2)	ϵV^2 (Kg/cm^2)	k (Kg/cm^2)
0.49	0.328	0.017	0.345
0.60	0.328	0.025	0.353
0.82	0.328	0.046	0.374
1.04	0.328	0.075	0.403

Plough: Victory
Weight: 33.6 Kg.

Average specific Resistance [k_n] Kg/cm^2	Velocity [V_n] m/s	V_n^2 $(m/s)^2$	V_n^4 $(m/s)^4$	$k_n*V_n^2$ Kgm^2/cm^2s^2
0.340	0.491	0.241	0.0581	0.0820
0.354	0.603	0.364	0.1322	0.1287
0.365	0.820	0.672	0.4521	0.2454
0.388	1.049	1.100	1.2109	0.4270
Σ = 1.447	2.963	2.377	1.8533	0.8831

$\Sigma k_n \Sigma V_n^4$ = 2.6818

$\Sigma V_n^2 \Sigma k_n V_n^2$ = 2.0995

$n \Sigma V_n^4$ = 7.4133

$[\Sigma V_n^2]^2$ = 5.6525

$k_o = [2.6818 - 2.0995] / [7.4133 - 5.6525] = 0.3307$

$n \Sigma k_n V_n^2$ = 3.5323

$\Sigma k_n \Sigma V_n^2$ = 3.4402

$\epsilon = [3.5323 - 3.4402] / [7.4133 - 5.6525] = 0.0522$

Therefore, $k = 0.331 + 0.052V^2$

Model soil specific resistances,

Velocity (m/s)	k_o (Kg/cm^2)	ϵV^2 (Kg/cm^2)	k (Kg/cm^2)
0.49	0.331	0.012	0.343
0.60	0.331	0.019	0.350
0.82	0.331	0.035	0.366
1.04	0.331	0.056	0.387

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