Investigation of the effect of rake angle on draft requirement for ripping in sandy clay

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Abstract: In this study, the effect of rake angle of a ripper plough on the draft requirement in a sandy-clay soil was investigated. The study was based on field experiments, laboratory tests and numerical simulation. Field experiments were conducted at the University of Nairobi field station in Upper Kabete, Kenya located at 1°15'S and 36°44'E at an altitude of about 1940 m above sea level. The soil at the location is a humic Nitisol belonging to the class of sandy-clay.

The numerical model was developed using the principles of the discrete element method embedded in a commercial code. EDEM Academic™ software was applied to model the draft requirement to ripping using ripper tines of rake angles; 30°, 45°, 60° and 75°. The model was calibrated using the results of soil physical tests that included of moisture content, bulk density, sieve analysis, shear strength, cone index and angle of repose. The integrity of the model was validated statistically using empirical data from field tests. The statistical methods utilized included of measures of central tendency, the One Sample Kolmogorov-Smirnov test, analysis of variance, the student t-test and multi-linear regression. The validated model was applied to predict the effect of the rake angle on the draft requirement; the forces arising due to particle and boundary contact during simulation were calculated using an inbuilt contact constitutive relation and displayed using the model's inbuilt query feature.

Statistical analysis indicated that the rake angle significantly influenced the value of the draft requirement in the sandy-clay soil at the 95% level of confidence. The draft requirement to ripping was found to decrease from the rake angle of 30° to a minimum at 45°. The draft requirement then increased through the rake angle of 60° to a maximum at 75°. The rake angle of 45° was found to give the minimum amount of the draft requirement while the rake angle of 75° was found to give the maximum amount of the draft requirement.

Keywords: ripper, rake angle, draft requirement, discrete element method, model, Kenya

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1 Introduction

1.1 Preamble

Compaction of agricultural soils is a great problem facing many farmers whose farms lie in cohesive soils worldwide. Research has shown that crop productivity in any agricultural system is adversely affected by soil compaction (Nawaz et al. 2012; Wiebe 2003). Soil compaction is caused by various factors including machinery wheel traffic, prolonged use of the mouldboard plough, eluviation of fine soil particles from the soil surface to a fine textured soil layer in the subsoil and the trampling by livestock during grazing prior to cultivation.

The commonly used technique to break-up a compacted soil is deep tilling using a subsoiler or chisel plough. However, the application of these techniques in a dry cohesive soil leads to the formation of clods creating an uneven seedbed unfavorable to planting and seed germination (Gitau and Gumbe 2004). On the other hand, such interventions in a wet soil may be counterproductive due to smearing eventual forming a hardpan. Less than

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optimal tillage depth with soil cutting equipment can result into soil compaction; this causes the un-intentional uplift of the clayey textured subsoil which typically happens when chisel shanks are set too deep. On the other hand, setting the ripper tines too shallow does not achieve the desired goal of breaking up the compacted soil layer. The traditional approach to preparing a good seedbed tilth by harrowing is not only expensive but still leads to soil compaction by tractor wheels. Furthermore, harrowing is not an option in conservation agriculture systems which lay a lot of importance on minimum soil disturbance.

According to Linde (2007), climate change, escalation of agricultural input prices and the reducing size of landholdings in the recent years has forced researchers to develop conservation agriculture to mitigate the negative environmental effects of conventional agriculture particularly soil erosion and the emission of carbon dioxide held in the soil to the environment. In spite of the major strides being taken towards conservation agriculture, soil compaction is still a dominant problem and thus breaking-up the compacted soil is still a major contributor to the input costs (Linde 2007). Moreover, conventional agriculture is still practiced in many parts of the world; ripping is still one of the operations performed to alleviate soil compaction and loosen the soil before planting.

There is a genuine need to make soil tillage more energy efficient in order to sustain significant profit margins. Soil tillage now presents a challenge to farmers and equipment manufacturers more than ever; farmers are being forced to work within constrained budgets while machine manufacturers are working towards optimizing the energy efficiency and the capital cost of their equipment to remain competitive in the market.

An energy efficient tillage tool is that which accomplishes a particular tillage operation with reduced draft requirement to overcome soil resistance; draft requirement is thus a reflection of the amount of soil resistance to a tillage tool. The prediction of draft requirement is an important undertaking in the design of tillage tools, particularly the selection of the optimal rake angle; it is however a “complex process due to the spatial variability of soil properties, the nonlinear and dynamic behaviour of soil, and the interaction between particles contact phenomenon such as slippage, particles re-arrangement due to stress and the flow that occurs at the interface zone between the soil and the tillage tool” (Asaf et al. 2007; Shmulevich 2010).

1.2 Soil compaction in agriculture

Soil compaction is a form of physical degradation depicted by an increase in the soil’s density and a corresponding decrease in the pore space as a result of applied loads. For engineering purposes such as the construction of a road, soil compaction increases the roadbed resistance to deformation and is thus desirable; however, soil compaction is undesirable in a farm setting as it reduces the infiltration capacity leading to increased surface runoff and the erosion of agricultural soils (Lull 1959; Payne 2008).

According to Payne (2008), soil compaction affects the physical, chemical and biological properties of the soil as well as hampering root growth. The initial effect on root growth is reduced nutrient uptake which in due course affects the entire plant (Lichtfouse 2011). Indeed, research by Penn College of Agricultural Sciences (2015) in tilled soils indicated yield losses in the first year due to severe compaction of about 15% due to residual effects of surface compaction. In the absence of recompaction, yield losses decreased to approximately 3% ten years after the compaction event.

Soil compaction is a problem in both conventional and conservation agriculture systems (Gitau and Gumbe 2004). McGarry (as cited in Benites et al. 2005) considers soil compaction to be the worst form of land degradation resulting from conventional agriculture practices caused by agricultural tires and implements working in moist to wet conditions at which the soil is susceptible to deformation. Conservation agriculture has been reported to generally improve the soil physical condition by reducing mechanical disturbance of the soil by Losada et al. (2005) and Gitau and Gumbe (2004); however, Blanco (2008) argues that soil compaction may actually increase with the conversion of conventional systems to conservation systems due to a lack of transient soil loosening by tillage operations particularly in no-till systems with poorly drained clay soils.

1.3 Ripping and ripper tines

A ripper is a chisel-shaped agricultural implement that can be animal or tractor powered. The ripper breaks up and opens the soil up to about 15 to 50 cm deep in both conventional and conservation agriculture systems to alleviate soil compaction. Figure 1 shows a gang of 3 rippers attached to a tool carriage.

Figure 1 A gang of rippers held by tool carriage (Schmeiser Farm Equipment 2014)

Recent research has seen the development of advanced ripping mechanisms such as the vibratory ripper which utilizes a chain-gear mechanism. Linde (2007), reports that the use of a vibrating tillage tool is an effective method of reducing the draft force. He utilized the vibratory mechanism to test and model the effect of the vibration on the draft force of a subsoiler. A different mechanism includes the use of an impact ripper that utilizes an hydraulic hammer to break even harder and rocky formations (Smith et al. 2001). These advanced ripping mechanisms, do however increase the overall energy consumption (Linde 2007).

In practical farm operations, it is the norm to connect several ripper tines on a common carriage in various gang arrangements or with other tools such as scrapers, seeders, discs among others. Kasisira (2004) discovered that deep tilling once every number of years at the same depth actually increased the problem of compaction as a result of operating below the critical depth as demonstrated in Figure 2. He proposed an arrangement in which the tools are arranged in a tandem configuration as shown in Figure 3.

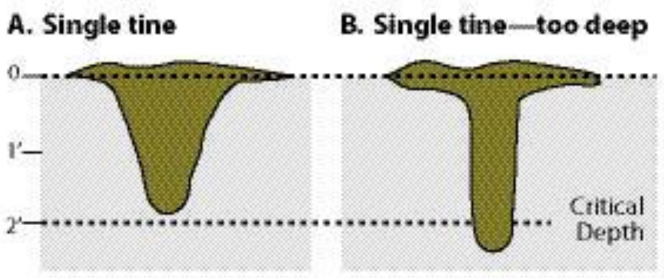


Figure 2 Critical depth: Source (Armstrong, n.d.)

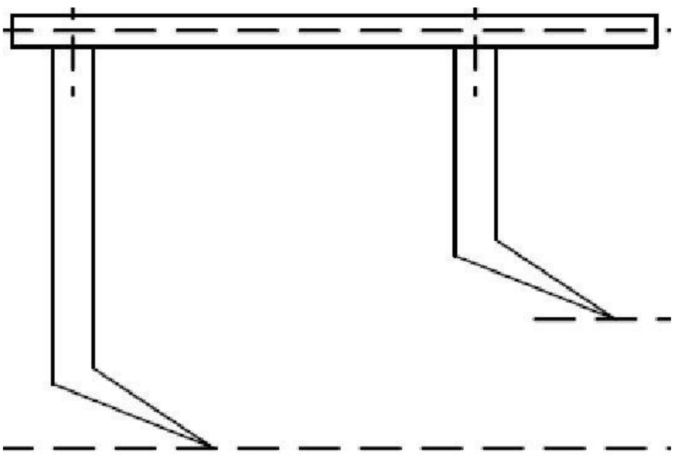


Figure 3 Tools in tandem configuration: Source (Kasisira 2004)

The problem presented by the tandem arrangement is that, bigger and more powerful tractors might be required to draw the tools through the soil resulting into more energy consumption and a greater deal of soil compaction as a result of the heavier tractor. On the contrary, lighter tractors are being introduced by CIMMYT in partnership with ACIAR, KENDAT and the University of Nairobi to serve small-scale farmers in various Counties of Kenya, these tractors, most of them two-wheeled, are technically unable to draw rippers in a tandem arrangement.

1.4 Influence of soil, tool and operational parameters on soil resistance

Tillage in an agricultural soil involves loading the soil until cracking patterns develop. According to O'Callaghan et al. (as cited in Kasisira 2004), the soil deforms both elastically and plastically when a force is applied to the tillage tool; the stress in the soil increases in the zone ahead of the surface of the soil-engaging element reaching a critical stress value where the soil fails. This has been confirmed by the Mohr-Coulomb failure criterion which contends that a soil mass fails at the point where the shear stress reaches the shear strength of the soil (Raj 2008).

The Mohr-Coulomb criterion postulates that the soil shear strength is a function of the soil cohesion and the soil-to-soil friction. The soil cohesion is dependent on the strength of the bonds between adjacent soil particles only and represents the maximum value of the shear stress when the normal stress is set to zero. However, soil-to-soil friction results from the interlocking of rough soil particles and is thus a function of the applied normal stress (Marenya 2009).

The geometry of a tillage tool and the soil shear strength parameters control the shape of the failure plane that results. Kasisira (2004) reports that the average soil resistance to a tillage tool is approximated by the force needed to develop the initial failure plane. The failure of an agricultural soil is influenced by various factors including soil parameters, tool and operating parameters that have a direct bearing on the soil resistance experienced during passive tillage.

1.4.1 Effect of soil parameters on soil resistance

The soil physical properties contributing to soil resistance include the moisture content, bulk density, texture, temperature, color and porosity (Marenya 2009). According to Gill (1968), soil physical properties particularly the moisture content, bulk density and texture affect the mechanical behavior and shear strength of a soil.

According to Rose (2004), soil strength is generally reduced as it absorbs water due to a concurrent decrease in the cohesion and the friction angle. The moisture content affects the ability of a particular soil in a particular condition to resist or endure an applied force and hence directly influences the amount of soil resistance to tillage (Gill 1968; Gitau et al. 2006). Various techniques exist for establishing the moisture content in a soil, the simplest method being the gravimetric method where the water content is expressed as the ratio of the weight of water contained in a weight of dry soil.

The soil bulk density has been shown to be almost linearly related to the soil resistance measured by the penetrometric technique (Dedousis and Bartzanas 2010). Soil bulk density is known to be a function of moisture content and the compactive effort, Chancellor (as cited in Marenya 2009) observed that the changes in the amount of moisture within different soil depths influenced the soil bulk densities within such depths. Marenya (2009) therefore recommends that studies geared towards the quantification of soil resistance to tillage be conducted at a constant bulk density throughout the test layer.

1.4.2 Effect of tool and operating parameters on soil resistance

Godwin and O'Dogherty (2007) defined a narrow tine as the one having a depth to width ratio of between one and six; very narrow tines have a depth to width ratio beyond six. Soil failure under the action of narrow tines is three dimensional in nature depicting two modes of failure at a certain critical tine depth (d_c) as postulated by Godwin and O'Dogherty (2007);

- Crescent failure near the soil surface and above the critical depth with soil moving forwards, sideways and upwards
- Lateral failure below the critical depth with the soil moving forwards and sideways only

The slenderness of a tillage tine has been reported to influence the location of the critical tine depth (d_c) which in turn dictates the maximum useful cutting depth of the tine. According to Kasisira (2004), operating the tine below the critical depth reduces soil pulverization, causes soil compaction while increasing the soil resistance to the tine. This was confirmed by McKyes et al. (as cited in Zadeh 2006) who observed that the soil resistance and the degree of soil pulverization increased with the relative narrowness of the tillage tines.

Ghaly and Al-Suhaibani (2010) studied the effect of the cutting depth and operating speed on the performance of a medium sized ripper in a sandy soil. Their findings revealed that increasing the cutting depth and/or the operating speed increased the soil resistance to ripping. Owen (as cited in Ghaly and Al-Suhaibani 2010) investigated the force to depth relationship of a ripper tine with three different wing types in a compacted clay loam soil and found the vertical force on the tine to increase linearly with the cutting depth; the horizontal force, moment and total force increased quadratically with the cutting depth.

In their research to establish the effect of the rake angle of a ripper on the power requirements while working in a clay loam soil, Tong and Moayad (2006) found out that the soil resistance on a tool decreased with increase of the rake angle from 15^o to 45^o where it attained a minimum value and then increased to a maximum value at a rake angle of 75^o. To achieve less soil resistance, high cutting efficiency and excellent soil pulverization during ripping, Zadeh (2006), recommends that the tool should have a rake angle of about 30^o and should be fairly narrow with a depth to width ratio of at least two.

1.5 Modeling soil resistance to ripping

The global demand for energy has of-late risen to considerably high levels due to accelerated industrialization and population growth. The high demand for energy is believed to be one of the causes of the widespread conflicts and wars currently being waged in various parts of the world. With industrial development, more sophisticated machinery requiring higher amounts of energy have been developed for various agricultural functions.

Much of the energy required for agricultural activities is consumed by tillage to provide sufficient draft to overcome the soil resistance and power soil pulverization processes. Newton’s third law of motion states that “to each action there is always an equal and opposite reaction”; the interpretation of this is that the soil resistance to a tillage tool will be of an equivalent magnitude to the measured or predicted draft on the tool after subtracting any rolling resistance of the prime mover.

Zadeh (2006) observed that the energy consumed in a tillage operation is a function of the soil type and condition, tool parameters and operating parameters. Over the years, a number of researchers have developed analytical, empirical and numerical models to predict the draft required by various tillage tools; these models combine the factors above into a mathematical equation or a computer model to predict the draft.

1.5.1 Analytical models

A lot of research has been done on the prediction of the forces acting on a simple tool and the soil failure developed in the process (Kasisira 2004; Zadeh 2006; Marenya 2009). Limit equilibrium analysis has been analytically employed to describe soil failure under tillage and force prediction models based on Terzaghi’s (as cited in Kasisira 2004) passive earth pressure theory. Two dimensional models have been developed for wide tillage tines (depth to width ratio less than 0.5) while three dimensional models have been developed for narrow (depth to width ratio between 1 and 6) to very narrow tines (depth to width ratio greater than 6).

Payne (1956) was the pioneer of three-dimensional force prediction for inclined tillage tools. He made an assumption of the failure zone for tines with a width/depth ratio less than one by observing the upward displacement of the soil ahead of the tillage tine (Zadeh 2006). This model was improved by Osman (1964) by introducing soil properties, tool rake angle and tool surface roughness to the force expression by employing dimensional analysis.

A force prediction model was developed by O'Callaghan and Farrelly (1964) as an extension to Payne's (1956) work. It is reported by Marenya (2009) that the influence of the side crescents for soil failure above the critical depth and the forces resulting from adhesion and soil interface friction were not taken into account in developing the model, further, Zadeh (2006) notes that the model underestimated the draft force when a very hard soil was encountered; he attributed this weakness to the nature of the assumptions made while developing the model.

Hettiaratchi and Reece (1967) developed a three dimensional model for soil failure based on the passive earth pressure theory. They assumed that the failure configuration involved forward and transverse failure regimes (Grisso and Perumpral 1985). The total force on the tools was reported to be the sum of the forces for the forward and transverse failure. Even though this model captures the soil properties, soil-metal frictional properties and the tool geometry (Marenya 2009), Grisso and Perumpral (1985) indicate that it tends to predict the draft force above the expected range.

Godwin and Spoor (1977) studied the soil failure mechanism under the action of narrow tines with various degrees of slenderness. A circular shape was proposed for the soil failure crescents on the soil surface and the sides of the tines to establish the volume of soil displaced by the tine (Zadeh 2006). The soil failure in front of the tool was hypothesized to be a wedge and the equation developed by Hettiaratchi and Reece (1967) for wide tines was utilized to obtain the draft from the centroid of the wedge.

Studies by McKyes and Ali (1977) on the cutting of soil by narrow blades produced a three-dimensional force model similar to that of Godwin and Spoor (1977). They however developed an equation to establish the rapture distance in terms of a failure angle and the soil and tool parameters; this eliminated the need of having prior knowledge on the rapture distance for establishing the forces on the tine. The draft prediction equation developed was the sum of the forces from the center wedge and the side crescents. However, Grisso and Perumpral (1985) report that the McKyes-Ali model doesn't predict the lift force on the tool accurately.

Perumpral et al. (1983) developed a soil-tool equation based on limit equilibrium analysis. This model was based on the Godwin and Spoor (1977) and McKyes and Ali (1977) models but the side crescents adjoining the center wedge were substituted with two sets of forces acting on the faces of the center wedge (Grisso and Perumpral 1985). The prediction equation was given as a sum of the forces acting on the horizontal and vertical directions of the center wedge. Swick and Perumpral (1988) improved the work done by Perumpral et al. (1983); they formulated a three dimensional soil cutting model that took into account the tool dynamic effects. Even though this model utilized some assumptions that overestimated side crescent dimensions (Zadeh 2006), it gave a sufficient prediction of the forces acting on a narrow tine (Kasisira 2004).

A dynamic soil cutting model was developed by Zeng and Yao (1992) taking into account the acceleration and strain rate effects to predict the forces on both wide and narrow tines. Apart from a prior knowledge of shear strain at soil failure to establish the shear failure boundary, this model was otherwise similar to that developed by McKyes and Ali (1977).

1.5.2 Numerical models

Various numerical models have been developed to predict the forces acting on tillage tools. These models have been introduced into the field of tillage science due to the recent advances in computing power (Zadeh 2006). Most of the numerical models developed in tillage research have been formulated using the Finite Element Method (FEM), Smoothed Particle Hydrodynamics (SPH), Computational Fluid Dynamics (CFD) and the Discrete Element Method (DEM).

FEM can be used without a prior assumption of the soil failure pattern presenting the possibility of modeling tillage activities that use tools of various shapes (Kasisira 2004). Furthermore, FEM presents an advantage over the analytical methods discussed above if a constitutive relation for the soil is provided. However, Marenya (2009) reports that the constitutive relation for agricultural soils is not yet fully understood and thus FEM has limited applicability in precision modeling and optimization of tillage tools.

SPH is one of the continuum simulation approaches which use a mesh free based algorithm unlike FEM. Urbán et al. (2002) used the SPH method to assess its applicability in soil-tool interaction simulation. They reported that SPH requires less computational resources and time to configure and run a simulation. SPH however always overestimated tillage forces and thus more research is required to provide accurate material models for calibration.

Karmakar (2005) reported that the study of soil mechanical behavior from a Viscoplastic fluid flow perspective using CFD is useful to tillage dynamics. He successfully modeled soil failure using a Bingham model in CFD to depict soil plastic failure with respect to the yield stress. However, Karmakar et al. (2009) experimentally validated a CFD model for a narrow tillage tool and discovered that it over predicted the draft force. CFD predictions for higher operating speeds and depths were found to be significantly different from the experimental values.

According to Shmulevich et al. (2007), the complexity of modeling the actual soil-tillage interaction behavior becomes more profound when dynamic effects are taken into account; a better understanding of soil translocation during tillage is thus required to forecast the redistribution among soil particles (Shmulevich, Asaf and Rubinstein 2007). DEM provides an adept alternative for modeling soils and their interaction with both rigid and flexible bodies thus depicting the non-linearity in soil behavior; with good computing resources, DEM provides an easy way to set-up, calibrate and run simulations; DEM is thus a promising way to model the actual soil behavior particularly in tillage without the limitation of the other numerical methods and may serve as a tool for optimization of the design process (Asaf et al. 2007).

Over the past few years, several researchers have reported the ability of DEM in simulating the micro-mechanics of the dynamic behavior of particles that form the material in various engineering and science applications. Sitharam (2000) presented the theory of DEM and some of its applications in engineering; he reported that DEM simulated deformation mechanisms in particulate media more reasonably than the continuum methods, it was detailed enough to develop and validate constitutive relations of particular materials using their appropriate particle properties, sizes, shapes and gradation.

Shmulevich et al. (2007) investigated the interaction between soil and a wide cutting blade using DEM and obtained a good correlation between the model results and experimental results. Linde (2007) developed a DEM model to optimize a vibratory subsoiler and quantify the draft reduction caused by the vibrating mechanism; he concluded that DEM was able to model the vibratory subsoiler mechanism for its design and optimization. Obermayr et al. (2011) developed a discrete element model that successfully reproduced the variations of the draft force for various cutting widths and depths for the calculation of soil-cutting forces in cohesionless granular material. (Okayasu et al. 2012) established that the soil cutting behavior by a plow was controlled by soil conditions, tillage depth and tillage speed. It is thus evident that DEM is capable of reliably modeling the soil-tool interaction during tillage; this underscores its applicability in modeling the draft requirement during ripping.

2 Materials and methods

2.1 Description of the study area

The study was carried out in the University of Nairobi Field Station at Upper Kabete campus which lies at 1°15'S and 36°44'E at an altitude of about 1940 m above sea level. The soils and the climate of the area are reported by Karuku et al. (2012) to be representative of the Central Kenya Highlands. Gachene et al. (2000) also mentions that the soil at the site is a humic Nitisol with no surface crusting. The study plot was bare (i.e. without any crop or weed residue) after a cassava crop had been harvested. The plot is oriented along contour lines within a gentle main-slope and a negligible cross-slope.

2.2 Data collection approach

2.2.1 Experimental set-up

Field experiments were conducted to collect draft force datasets for validating the numerical model. The datasets were recorded using a data acquisition system consisting of an MSI7300 digital dynamometer connected wirelessly to a MSI8000 remote display to stream the draft force data instantaneously into a laptop computer through the serial port.

The design of the dynamometer could not allow direct connection to the three point hitch of the towed tool carriage; it was attached as shown in Figure 4. The tillage tines under investigation were attached to the towed tool carriage which was attached to the three point hitch of the towed tractor (i.e. with gear lever in neutral position); the dynamometer was attached between the rear towed tractor and the front towing tractor via carbon steel shackles. The tractors used in the experiments were Massey Ferguson tractors of 60 hp and 75 hp respectively.

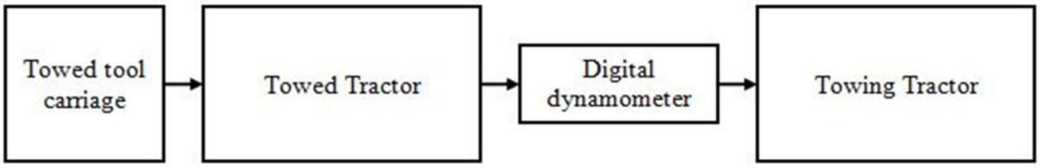
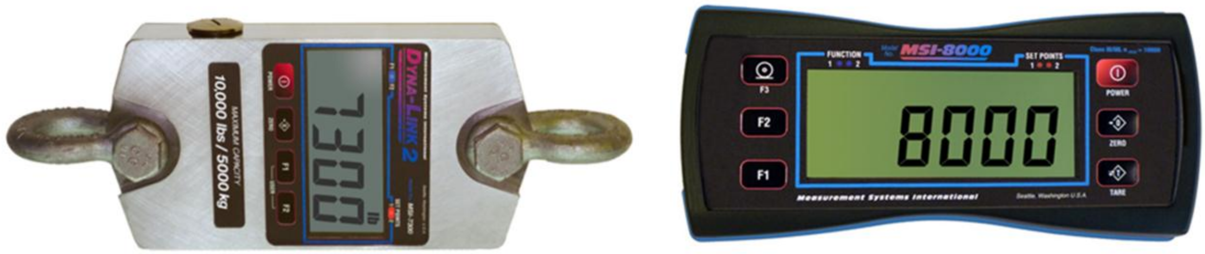


Figure 4 Experimental set-up (Ndisya et al. 2016)

The data acquisition system is shown in Figure 5.

Figure 5 Data acquisition system (Ndisya et al. 2016)

Figure 6 shows close-up pictures of the digital dynamometer and the remote display;



MSI 7300 dynalink 2 MSI 8000 Remote display

Figure 6 Digital dynamometer components

At the start of the experiments, a dry-run of the system was executed with the ripper tines disengaged to establish the rolling resistance values of the rear towed tractor and the towed tool carriage as shown in Figure 7. The value of the rolling resistance was subtracted from the draft force data during data analysis to establish the draft requirement as a result of the individual tillage tines. Subsequent experimental runs were conducted with the ripper tines engaged to collect data; the dynamometer then streamed draft force data wirelessly to the stationary data acquisition system.

Figure 7 A trial run with the dynamometer anchored between the tractors

Depth control was achieved by making settings to the tractor draft control hydraulic system and adjusting the anchor points of the ripper tines to the tool carriage iteratively until the target average ripping depth realized. Care was taken to maintain the inflation pressure of the tires of the rear tractor and the tool carriage at the same level. The ripping depth was confirmed by making measuring the furrow depth with a tape measure and a flat blade before a trial run at the staging area as demonstrated in Figure 8. The vertical distance between the top of the undisturbed soil surface to the point of deepest tool penetration was measured to be the ripping depth; this technique has been demonstrated by Rashidi et al. (2013). This study targeted two speed levels (i.e. low and high); the low speed level used was 3 km/h while the high speed level used was 5 km/h. The staging area was used to bring the ripping depth and the operational speed to the required values before a treatment run.

Figure 8 Furrow depth measurement (Canola Council of Canada 2016)

2.2.2 Experimental design

The study adopted the Factorial Completely Randomized Block design to investigate the effects of the rake angle on the draft requirement of 5 cm wide ripper tines of rake angles of 30°, 45°, 60° and 75° available at the University of Nairobi. The tines are shown in Figure 9. The study was conducted at average ripping depths utilized of 15, 25 and 40 cm; this was in-accordance to the results of a soil profile study that revealed that distinct soil layers at 0 – 15 cm (i.e. soil mixed with humus), 15–30 cm (i.e. top soil) and 30 – 50 cm (i.e. sub-soil). The operating speed for the study was set at 3 and 5 km/h; these speed levels represented the low speed and high speed for ripping within a Kenyan farm. The settings for ripping depth, rake angle and operating speed were combined and replicated four times to yield a total of 96 treatments for the study.

75° tine 60° tine 45° tine 30° tine

Figure 9 Ripper tines used (Ndisya et al. 2016)

Field experiments were conducted on an experimental plot measuring 60 m by 20 m; this plot was sub-divided into four blocks of equal size each measuring 25 m by 10 m; an allowance area of 5 m in length was left at the start and end of each sub-plot for staging, practice and turning. The treatments were randomly assigned to each block.

The digital dynamometer recorded between 15 to 20 datasets during a single experimental run. The number of data points depended on the stability of the tool carriage (i.e. freedom from vibrations) during the run; as such, some of the data points recorded were way below or above the mean of the recorded data stream. To eliminate the outliers in the measured draft datasets, the median of the data-streams was determined. Specific draft data was obtained by dividing the measured draft dataset by 5 cm (i.e. the width of the ripper tines).

2.2.3 Data-sets collected for soil characterization

Soil samples were taken from the field to determine the physical properties of the soil. Soil samples were collected systematically to ensure accurate representation of the conditions across the study plot. Sample pits were dug at 12 spots across the plot; sampling was then done at three levels across the pit profiles (i.e. 0–15 cm, 15–30 cm, 30–50 cm). This made total of 36 sampling spots.

The sampled soils were analyzed for: moisture content, bulk density, particle size distribution, particle shape distribution, shear strength parameters (i.e. cohesion and angle of internal friction), cone index and angle of repose; the results are provided in Table 1. These soil properties were essential to calibrating the numerical model. Field experiments were completed within three days to avoid considerable variations in the soil physical properties.

Table 1 Soil physical properties

Parameter	Average Value
Wet Bulk Density, kg/m^3	1818
Dry Density, kg/m^3	1527.7
Angle of Repose, Experimental, ^{o}	34
Angle of Repose, Simulation, ^{o}	33.6
Average Moisture Content, %	19
Cone Index, kPa	220.56
Insitu Cohesion, kPa	3
Insitu Angle of Internal friction, ^{o}	10
Soil Classification	Sandy Clay (54% Sand, 35% Clay, 11% Silt)

2.2.4 Computer modelling

The EDEM Academic™ software version 2.7.0 was applied to model and solve for the draft forces to ripping using various tool geometries. Modelling was conducted using a Toshiba Qosmio® Laptop with an i7 processor (2.64 Ghz Quad core), RAM of 8GB, storage space of 1TB and a 64-bit Windows 7 Operating System. The modelling process proceeded as follows;

a) Global settings

The units of measurement were set to SI to be used throughout the process; the global settings made in the main window of EDEM Academic™ are given in Table 2.

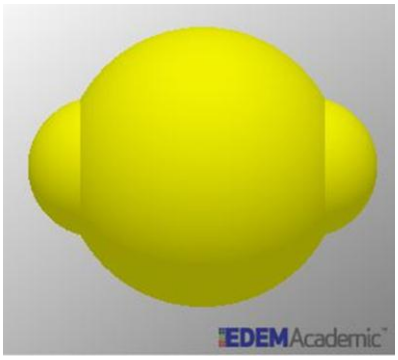
Table 2 Global settings in EDEM Academic™

Property	Units	Value
Work function	eV	0
Gravity	m/s^2	9.81
Poisson's ratio of steel	No units	0.3
Shear modulus of steel	Pascals	7 x 10^{10}
Density of steel	kg/m^3	7850
Poisson's ratio of soil	No units	0.25
Shear modulus of soil	Pascals	1 x10^7
Density of soil	kg/m^3	1818

b) Particle formulation

The soil samples retained in each sieve of the sieve analysis procedure in the laboratory were used to characterize the particle shapes. Shape characterization was conducted under a lit microscope with a high resolution digital camera; the soil particles were then re-modelled in EDEM Academic™ as a clump of spheres as described in Figure 10; the process involved combining three spheres of a similar diameter to form the target soil particle shape of a given diameter.

Soil particle shape



Remodelled particle shape in EDEM Academic™

Figure 10 Soil particle shape remodelling (Ndisya et al. 2016)

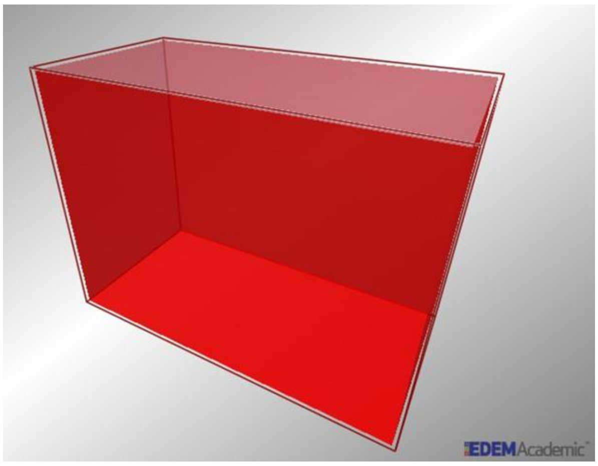
The particles were set to exhibit the log-normal size distribution with a mean of 0.7769 and a standard deviation of 1.82261. This was in-accordance with the results of laboratory sieve analysis test. EDEM Academic™ automatically calculated the properties of the base particles; these are provided in Table 3.

Table 3 Re-calculated base particle properties

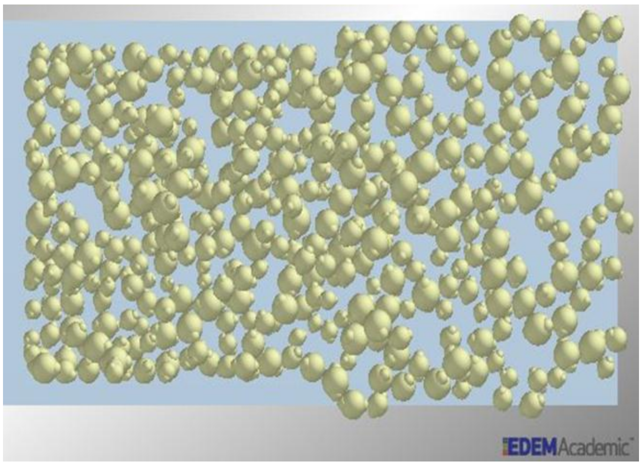
Property	Value
Base particle diameter	8 mm
Contact diameter	8 mm
Calculated particle mass	0.000515066 kg
Calculated particle volume	2.83314e-07 m^3
Particle material	Soil

c) Creation of geometry sections

Three types of geometries namely a virtual box, ripper tine models and a particle factory as shown in Figure 11 and Figure 12 were created. The virtual box of dimensions 400 mm length, 200 mm width by 500 mm height and a Particle Factory of 400 mm by 200 mm were created using EDEM Academic™ geometry modelling capabilities. Additionally, the ripper tines were modelled in AutoCAD Mechanical 2015 and then imported into EDEM Academic™ through the CAD import tool, repositioned and aligned along the longitudinal axis of the virtual box.

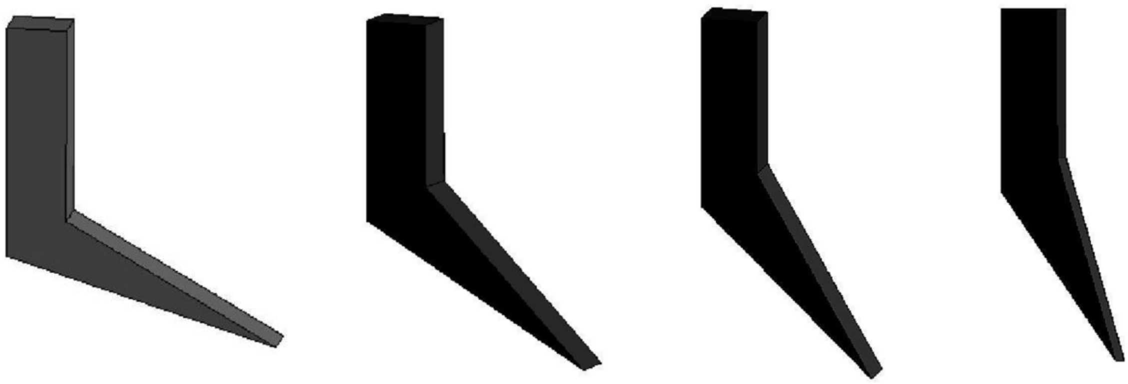


Empty virtual box



Particles dropping from the Particle Factory

Figure 11 Virtual box and particle factory (Ndisya et al. 2016)



30° Ripper Tine 45° Ripper Tine 60° Ripper Tine 75° Ripper Tine

Figure 12 Ripper tines models (Ndisya et al. 2016)

d) Particle factory and simulator settings

Particle factories are used to define where, when and how particles appear in a simulation. A dynamic factory type was specified in EDEM to enable the creation of particles as the simulation continued. The factory was also set to generate approximately 4,000 particles per second until the virtual box was filled. The particles were set to enter the virtual box at a velocity of 20 m/s and to be positioned and oriented randomly. The time-step for the model was set at 20% of the Raleigh time step and to run for 15 s with a target save interval of 0.1 s; this yielded a total of 150 data points for each treatment.

e) Model calibration and full scale simulation runs

Calibrating the model involved setting the macro-mechanical parameters to values similar to the physical properties of the soil and the ripper tines; these parameters were then adjusted iteratively until the model produced results that matched the results of the angle of repose test.

Other model parameters adjusted included; surface energy value for the Hertz-Mindlin with JKR contact model (5, 10, 15, and 20 J/m^2), coefficient of static friction (0.2, 0.4, and 0.6), and coefficient of rolling friction (0.06 and 0.12) and the coefficient of restitution (0.1, 0.2, 0.3, and 0.4). A total of 94 calibration simulations in batch mode representing 94 different and exclusive combinations of the above parameters were executed; the angles of repose were measured in EDEM Analyst® using the protractor tool as demonstrated in Figure 13; the parameter combination that gave an angle of repose similar to the physical test is given in Table 4.

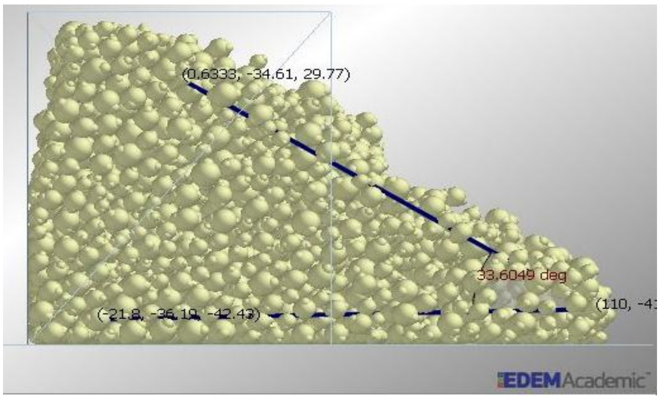


Figure 13 Slumped soil mass showing the angle of repose

Table 4 Soil en-masse calibration parameter settings

Parameter	Value
JKR Surface energy, J/m^2	5
Coefficient of restitution	0.2
Coefficient of static friction	0.4
Coefficient of rolling friction	0.06
Angle of repose, EDEM Academic™	33.6^o
Angle of repose, Physical Test	34^o

The calibration parameters obtained were then used to conduct the full scale simulation runs. The results of the simulation runs were extracted from the EDEM Analyst® by creating queries that displayed the draft forces on the ripper tine perpendicular to the direction of travel. The extracted datasets were exported from the EDEM Analyst® in a comma-separated (.csv) format for cleaning and analysis.

The cleaned predicted and measured draft force datasets were subjected to statistical analysis so as to draw inferences from the data. The following statistical operations were conducted in Statistical Package for Social Scientists (SPSS); the outliers in the draft data were eliminated using measures of central tendency (i.e. mean and median), the One Sample Kolmogorov-Smirnov Test was executed to confirm that the probability distribution of the draft datasets is normal (i.e. subsequent statistical tests such as ANOVA, t-test and regression require the input data to be normally distributed), Analysis of Variance (ANOVA) was applied to compare the means of the different treatments to the means of the predicted draft to check their effect on the draft force. This was also confirmed with the student t-test and Multi-linear regression was conducted to evaluate the correlation between the measured draft and the predicted draft.

3 Results and discussions

3.1 Statistical analysis of the draft data

3.1.1 Probability distribution test

The measured and predicted draft datasets were tested for normality by employing the One Sample Kolmogorov-Smirnov Test in SPSS; the null hypothesis that the datasets were normally distributed was tested. As shown in Table 5, the p-values (i.e. test statistics) for the datasets were found to be greater than 0.05 at the 95% level of confidence; the null hypothesis that the data sets were normally distributed was accepted.

Table 5 Probability distribution test

Source of data		Measured				Predicted
		Block 1	Block 2	Block 3	Block 4	
N		24	24	24	24	24
Normal parameters	Mean	1.1192	1.1392	1.1904	1.1667	1.1667
	Std. Deviation	0.81692	0.82774	0.83387	0.83622	0.83622
Most extreme diff.	Absolute	0.249	0.238	0.238	0.255	0.255
	Positive	0.249	0.238	0.238	0.255	0.255
	Negative	-0.125	-0.118	-0.130	-0.124	-0.124
Kolmogorov-Smirnov Z		1.218	1.167	1.167	1.291	1.249
Asymp. Sig. (2-tailed)		0.103	0.131	0.131	0.071	0.098

3.1.2 Comparison of means

a) Analysis of variance (ANOVA)

ANOVA for both datasets was conducted in SPSS with the draft force as the dependent variable and the rake angle as the factor to compare the means of the different datasets obtained using different ripper rake angles; the null hypothesis that the means of the were similar was tested. The p-values for the treatments for both the predicted and measured datasets were found to be less than 0.05 (i.e. 0.019 and 0.027 respectively) at the 95% level of confidence, the null hypothesis was thus rejected in favour of the alternative, the changes in the rake angle thus significantly influenced the draft force.

b) Student t-test

Table 6 Student t - test for the draft data

Paired Differences					t	df	Sig. (2-tailed)
Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
			Lower	Upper			
0.00625	0.09983	0.01019	-0.01398	0.02648	0.613	95	0.541

The paired samples t-test was executed in SPSS to compare the means of the predicted and measured draft datasets. The null hypothesis that the means of the two datasets were similar was tested. As shown in Table 6, the p-value is greater than 0.05 (i.e. 0.541 > 0.05), the null hypothesis that the means are similar is thus accepted. The student t-test thus presents strong evidence to the effect that the measured draft dataset was similar to the predicted draft dataset; this indicates that the computer model developed was an accurate representation of the ripping process.

c) Multi-linear regression

Regression was also performed in SPSS to investigate the degree of fit of the measured draft datasets to the predicted draft dataset. As shown in Figure 14, results indicated an extremely good fit with a coefficient of determination (R^2) of 0.986. The figure also shows the 95% confidence level line bounds; most of the data points lie within the bounds further confirming the excellent fit between the two datasets; this further confirms that the computer model developed was of high fidelity.

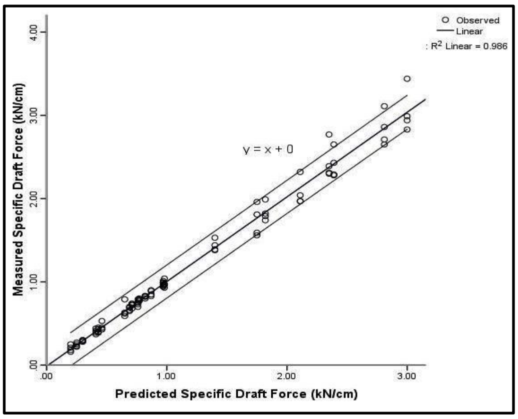


Figure 14 Line of fit between predicted and measured draft (Ndisya et al. 2016)

3.2 Effect of the rake angle on the draft requirement to ripping

The draft force reduced from a rake angle of 30° to attain a minimum at an angle of 45° then increased exponentially through the rake angle of 60° to attain a maximum at the rake angle of 75° as shown in Figure 15 and Figure 16.

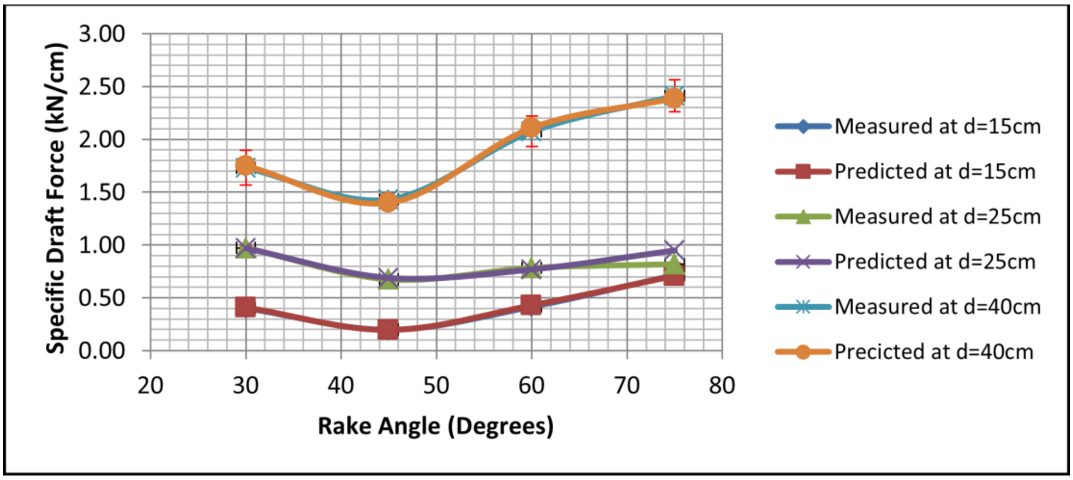


Figure 15 Specific draft against rake angle at operating speed of 3 kph

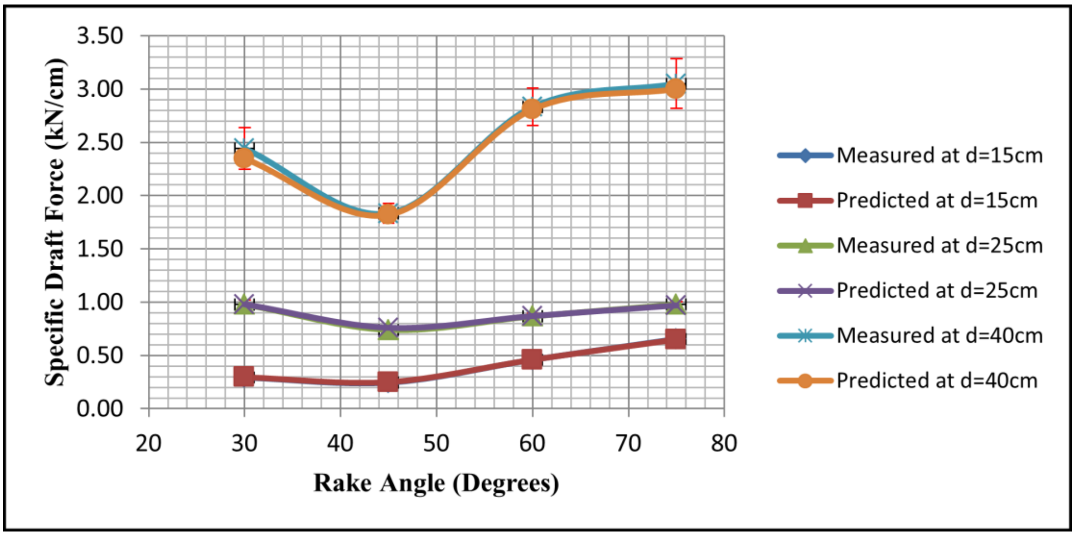


Figure 16 Specific draft against rake angle at operating speed of 5 kph

Table 7 gives the equations of the best fit to the predicted draft data.

Table 7 Equations of fit for the predicted draft data

Speed, km/h	Operating depth, cm	Equation of best fit	R^2
3	15	$y = -2E\text{-}05x^3 + 0.0037x^2 - 0.2038x + 3.77$	0.929
3	25	$y = -1E\text{-}05x^3 + 0.0025x^2 - 0.1538x + 3.65$	0.946
3	40	$y = -7E\text{-}05x^3 + 0.0123x^2 - 0.6304x + 11.59$	0.908
5	15	$y = -0.0001x^3 + 0.0188x^2 - 0.9578x + 17.23$	0.933
5	25	$y = -2E\text{-}05x^3 + 0.003x^2 - 0.1679x + 3.77$	0.951
5	40	$y = -0.0001x^3 + 0.0188x^2 - 0.9578x + 17.23$	0.910

The equations are cubic in nature exhibiting a local minimum at the rake angle of 45^o and a local maximum at the rake angle of 75^o; the results indicate that for minimization of the draft requirement during ripping, machinery operators should strive to operate at the optimum rake angle to of 45^o. This finding agrees with the observations of Tong and Moayad (2006) and Maswaure (1995) who recommended that for minimizing the draft forces, the tool rake angles must be set to between 30^o and 60^o.

4 Conclusions and recommendations

This study aimed at investigating the effect of the rake angle of a ripper tine on the draft requirement of a ripping operation in a sandy-clay soil using the numerical modelling technique. The information gained in this study has potential applications in tillage research, tool design in the industry and tillage management by farm managers. This study established that ripping operations should be conducted at or near the rake angle of 45^o to reduce the draft requirement and consequently the energy consumption leading to significant cost savings. The applicability of computing techniques in modern agriculture and machinery design has also been demonstrated.

The soil-tool interaction during soil cutting with a ripper was investigated; this was done is a humic Nitisol (sandy clay soil). Further studies should be directed at modelling the forces that arise during soil loosening with other tools such as the mouldboard plough which is a commonly used tillage tool in Kenyan farms. Further studies are required to test the validity of the findings of this study in other soil types, particularly the black cotton soil; which presents a loosening challenge to a number of Kenyan farmers.

Two speed levels (3 km/h and 5 km/h) were used in this study; the draft was found to be marginally sensitive to the changes in speed level, further studies are recommended at finer speed level within the above range to make good observations on their effect on the draft force; however, most ripping operations are conducted within the range of 3 km/h (0.8 m/s) and 5 km/h (1.4 m/s) and as such, this study's observations at such a range are usable. Additional studies should be conducted with rake angles outside the range of 30^o to 75^o since the rake angle of 45^o established to be the angle for the minimum draft force and 75^o established to be the angle for the maximum draft force were only the respective minimum and maximum within that particular range; there could be other rake angles outside the range that give different values of the minimum and maximum draft force.

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