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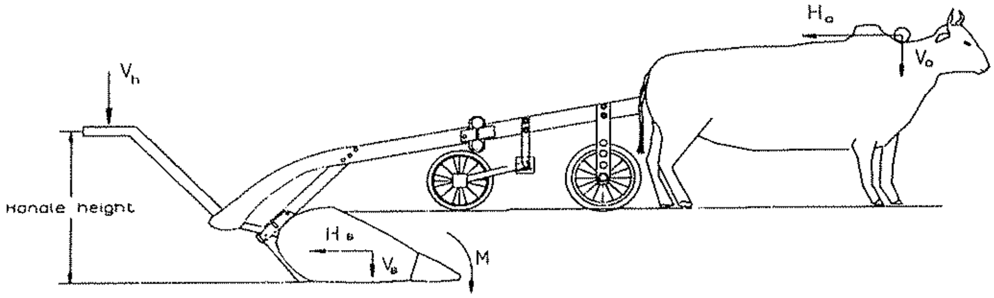
PERFORMANCE OF A CURVED ANIMAL DRAWN TILLAGE IMPLEMENT

Girma Gebresenbet



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Content **page**

Abstract

The performance of animal drawn implements should be within the range of the pulling capacity of draught animals. The effects of design and operational parameters such as tail angle, side rake angle and radius of curvature of a curved soil tillage implement on horizontal and vertical forces have been investigated under laboratory conditions.

Seven different wings of different radii of curvature (150, 200, 250, 300, 350, 400 and 450 mm) were designed. The range of tail angle used was between 32° and 54° and the range of side angle was between 40° and 65°.

The effect of curvature on the horizontal force showed anomalous behaviour for different tail angles. For smaller tail angles (about 30° to 40°) the horizontal force decreased significantly with an increase of radius. For a tail angle of about 45°, the horizontal force decreased first with the increase of radius of curvature and then increased with further increase of radius. For tail angles greater than 50° the horizontal force increased with an increase of radius. The variation of the behaviour of radius and force relation is presumably due to the edge rake angle, since it varies with the radius. For larger radii, the effect of edge rake angle on the horizontal force is much more pronounced than the effect of radius on the horizontal force.

For the vertical force (directed downward), it was observed that, for all tail angles used, the force increased significantly with a decrease of radius and this relation was described well by a third order polynomial equation.

Variation of tail angle showed a significant effect on both horizontal and vertical forces. This is mainly due to an increase of normal compression forces and gravitational force when the tail angle is increased. For the range of tail angle used the horizontal force could be described by a trigonometric model.

The effect of variation of side rake angle on the resulting forces for different speeds and radii was also investigated. Experimental investigation showed that variation of speed and

radius affects the of side rake angle and force relation. The study recommends a combination of larger radius and smaller side rake angles for high speed operations to achieve a good penetration performance and reduced horizontal force.

From the analysis made, a radius of about 275 mm was found to be an optimum for a curved implement. On the basis of the results obtained from the soil bin experiments and from the basic design of a conventional mouldboard plough and an ard type plough, a reversible animal drawn plough was designed.

Notation

θ	turning angle	μ	coefficient of soil-metal friction
α_t	tail angle	g	acceleration due to gravity
β_s	side rake angle	C_1, C_2, C_3, C_4	constants used in the exponential models
R	radius of implement curvature	$k_{\alpha h}, k_{\alpha v}, k_{\alpha t}$	constants
m	mass of the soil	H	horizontal force
v	operational speed	V	vertical force
b	operational width	$k_{h1}, k_{h2}, k_{h3}, k_{h4}$	constants used for the horizontal force polynomial models
l	length of soil-engaging part of the implement	$k_{v1}, k_{v2}, k_{v3}, k_{v4}$	constants used for the vertical force polynomial models
α	rake angle	P	force of inertia
A	adhesion	δ	friction angle
C	cohesion		
β	angle between the end points of sector of a circle	ϕ	shearing angle
W	gravitational force	ρ	soil bulk density
d	operational depth	k_{sg}	constant representing the contribution of soil and design parameters
N	normal force		

1. Introduction

1.1. General

The rural population in most developing countries consists of about 80-95 % of the total population and the overwhelming majority of them are small scale farmers. Though the small-scale farming system is of subsistence type it plays a very important role in the economy of these countries since the bulk of the agricultural production is from this sector, and the economy of the country mainly depends on agriculture. In these countries, the continuous fast growth rate of the population cause food insufficiency, and today millions of people becoming victims of famine. It became impossible to increase production, based only on human labour and hand tools, and cope with the demand for food and other agricultural products for home consumption.

The agricultural implements used in these countries are age-old, out-dated, inefficient, time consuming and demand a great deal of physical strength while putting them into use. Using these implements it cannot be possible to guarantee sustainability and raise the standard of living of small scale farmers and economic capacity of these countries as a whole.

As regards the conventional tractor drawn implements, these are manufactured for and utilized in most industrial nations whose climatic conditions are non tropical by nature. Those developing countries that use the conventional tractor drawn implements are utilizing the tools only on a very small scale and by a fraction of their farming population[1]. The typical agricultural tractors used for large scale farming in countries like Kenya, Tanzania and Ethiopia are large, powerful and not economically sustainable for the majority of small-scale farmers. The small-scale subsistence farmer may have tasks requiring mechanization but these are most probably operations of lighter work loads performed at relatively low speed. The use of the modern tractor has proved to be an economic problem for the small-scale farmer. Capital cost, spare parts availability, mismanagement and misuse among other factors have made the modern tractor inappropriate for most developing countries farmers.

The demands of lower energy input and promotion of soil and water conservation and increase of production motivates the need for the developments of new tillage system in developing countries[2,3]. Especially in developing countries, energy is the main input to increase agricultural production. Development of farm machineries in this respect plays important role to decrease the required energy. Tillage consumes more than one-third of the energy needed in the total farm operations[4]. This required intensive research work to develop tillage machines.

The present work searches for a knowledge of the main characteristics of the animal draught-implement-soil system with respect to lower energy requirement and appropriate soil operation which is in line with the required soil and water conservation methods.

1.2. Environmental oriented tillage

The main objective of farmers in developing countries is to produce more agricultural products with the lowest possible energy input. The soil should be loosened to create favourable conditions for plant growth. However, the soil operation process should not, somehow, accelerate soil erosion process. In relation with soil preparation, the loosened soil can be carried away down - hill by rain water. This is very severe especially for fields having higher slopes.

Soil tillage and management are of paramount importance both regarding growing success and energy demands. It is widely known that soil erosion is a very crucial problem that needs particular attention, and therefore, it is necessary to integrate mechanization and the techniques of soil and water conservation with the aim to maintain sustainability in terms of production and environmental conservation in the long term. The result of the present work intends to promote effective environmental oriented soil operation.

Soil tillage has in many cases been wrongly regarded as of the causes of soil erosion. Where as it may be the most effective method to reduce erosion if a suitable farming system and agricultural technology are developed. Appropriate tillage system must not only be profitable and productive, but also should be sustainable. This can only be done if soil erosion could be controlled sufficiently.

So far, available literature on tillage issues indicate that the main objective of tillage is not only to develop desirable soil structure, provide adequate air capacity and exchange, loosen the soil to allow root penetration, control weed, segregate soil, mixing of plant residues, but also to reduce soil erosion by increasing rapid infiltration, drainage, forming rough surfaces such as ridges, contours etc. to reduce run-off.

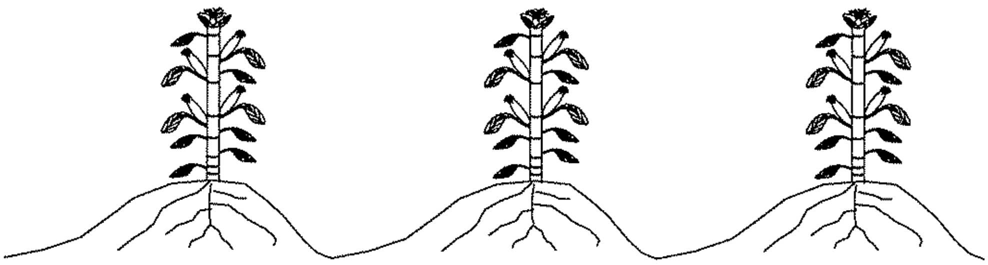

Fig. 1. Ridging cultivation

In connection to the compilation of a manual for ox-mechanization in Zambia[5], the Ministry of Agriculture & cooperatives of Republic of Zambia extensively discussed important aspects such as ox-mechanized crop production, ox-training, ox-drawn implements for crop production and soil conservation measures. A comprehensive account was given on the advantages of ridge cultivation and attempts were made to prove that ridge cultivation is the best alternative from both soil conservation and promotion of plant growth points of view. Kuipers[6] emphasized that tied ridging, contour farming and furrow system are the most conventional soil conservation methods. Ridges can be formed using ridgers. The ridges should lie horizontally so that the rain water remains in the deeper rows (Fig. 1). In the following season, the ridges split and new ridges could be formed at the deeper rows while the original ridges changed to deeper rows.

Concerning various farming systems tested in developing countries (where soil erosion is severe) to date, ridge cultivation (especially tied ridges) is considered to be one of the best alternatives for sustainable agricultural production and effective soil and water conservation.

Hence, the development of improved farm implements (i.e., pertinent to effective labour and technological efficiency and low level energy conservation) must be complementary to the farming methods applied in a given region. Here the objective is mainly geared to fulfil the requirements of both plant growth and proper soil and water management.

1.3. Draught animal power

Draught animals remain the main and best alternative power sources as an intermediate technology to attain a sustainable situation and enhance the economic development of most developing countries.

In most developing countries, horses, mules, oxen, buffalo, camels and donkeys are the common draft animals and are mainly in use for cultivation, processing, transportation and water pumping. Oxen, horses and donkeys are the most common among the fore-mentioned animals. Horses and donkeys are mainly used for transport while oxen are used for cultivation. Donkeys are used to a limited extent as pack animals and occasionally to pull carts. A rough estimation of working animal population was made by Ramaswamy[7] in some developing countries. According to Ramaswamy's report there are about 14 million working animals in Ethiopia and 1.5 million in Tanzania. The level of utilization of draught animal power (DAP) for harrowing, planting, transportation, ridging and weeding is small but is increasing steadily.

Effective utilization of DAP to fulfil its full potential could only be achieved if draught animals are considered as a feasible form of energy which can be used and attempt to upgrade it in conjunction with modern technologies. Currently, there is no nationally co-ordinated research on DAP in many of the developing countries with this philosophy in mind.

The system draught animal power-tillage implement-soil has been ignored hitherto by many of the previous researchers. More attention have been paid to soil management, which is one component of this system, and several studies have been made on this topic. However, since each component is an integrated part of the system and each component by one way or another affects each other, research results obtained without considering the effects from the other components may not be viable.

To fit to the range of pulling capacity of draught animals, in conjunction with the optimization of implement parameters and required soil operation methods, forces resulted during operational for the range of operation speed and depth, should be investigated.

Therefore, simultaneous studies on the physiological ability of the animal, the physical properties of soil, required qualities of operation and the effects of geometrical shape of tillage implements should be conducted. In the foreseeable future it is intended to conduct such integrated projects in collaboration with University of Nairobi and ILCA, International Livestock Centre for Africa. As an introduction to such projects, currently, it is intended to study the implement-soil part of the system.

1.4. Soil-implement system

Degree of soil deformation or type of soil failure depends on :

a) soil conditions,
b) operational speed, and
c) shape of an implement.

Plessis[8] investigated the performance of chisel plough tines having two different shape at their points. Both tines had the same width, the shape of the point of the first tine was triangle with a sharp point while the second had a flat with a straight sharp cutting edge. In the first case, the soil was mixed and the clods were broken well. He reported that below the soil surface, the soil is compressed sideways forming a distinct v-shaped furrow. Plessis explained further that the reason of mixing was that the soil moves upward forming a mound which was carried forward by the tine. He pointed out that soil at the top of the mound tumbles forwards and sideways and observed a good mixing. The reaction of the second point on the soil was less aggressive. At low speeds, the point passed through the soil and no considerable mixing process has been observed.

The blocky nature of the soil, when operating using the flat sharp point, and the curved planes of failure from the point to the surface indicating that tillage results from a cutting action while in the case of triangular shape of the point the soil failure seems to have resulted from the compressing forces imposed in a number of directions by the angular point.

Kitani[9] reported that the use of double-blade tillage machine reduced the draught up to 50%. To reduce the draught by means of introducing tensile failure in cutting process, i.e., reduce the compression, Kitani used double-blade mouldboard plough for the field experiment. As a sub-blade he used a rotating disk mounted above the share and reported that a good pulverizing performance with significant draft reduction was achieved.

Quality of soil operation is usually evaluated by measuring the size of clods formed and percentage of trash covered. The percentage of trash covered can be measured in relation to the total cultivated area. The conventional method under use to measure size of clods formed is by measuring the mean diameter of clods using the seiving method.

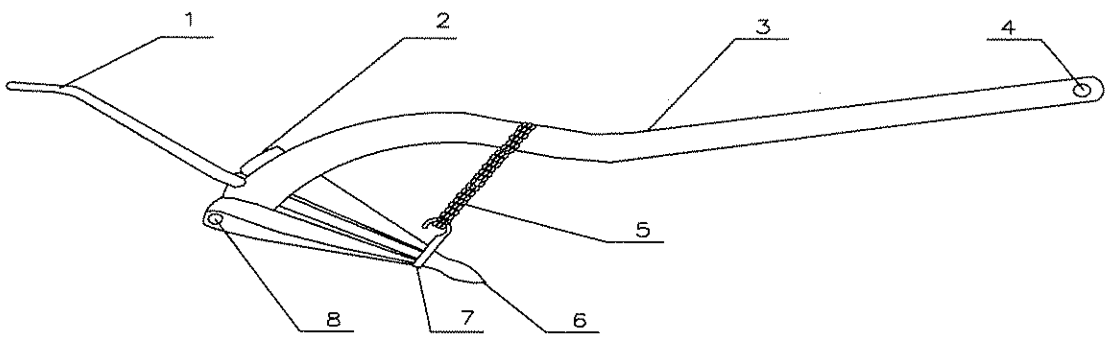

Fig. 2. Ethiopian ard type plough

As regards to tillage operation in developing countries where the problem associated with soil erosion is very severe, tillage should not aggravate the problem. It rather increases infiltration and should serve as both water and soil conservation. During primary tillage, turning of a soil slice may not be necessary especially in dry areas. In these regions a better pulverization performance can be achieved by an ard type plough (Fig. 2) than a conventional mouldboard plough. Another advantage of an ard type plough is that it leaves the surface rough after operation and this is appropriate for erosion control purposes. Therefore, development of tillage implements, especially for regions subjected to soil erosion, should be based on an ard type ploughs.

2. Objectives

As mentioned previously, soil tillage operations have major effects on the power source needed and soil and water conservation. In this respect, it is the main objective of the current work to search for the means to minimize the energy input through determining the parameters (implement, soil and performance parameters) influencing the force produced during operation and also to suit the design parameters and the soil operation to environmentally oriented tillage methods. Energy requirement of animal drawn ploughs of various designs should be studied by measuring forces resulted during operation. Apart from that, pertinent soil parameters, operational speed and depth will be measured simultaneously with the force measurements. To meet the objectives, instrumentation for force and soil parameter measurements should be developed.

The first phase of the project was to study the influence of design parameters of an ard type plough. The radius of curvature of a wing, side rake angle and tail angle were assumed to be important parameters to be investigated. The basis for the choice of these parameters was emanated from the results of literature review and practical experiences.

The main objectives of the current work are to:

(1) study, identify and optimize the design factors which may have an influence on energy requirement, quality of the required soil operation and soil conservation methods (through measurements of the resulting forces, pertinent soil parameters, and turning and fragmentation degree of the soil),

(2) develop instrumentations which could be used to collect data of soil parameters and evaluate the performance of implements,

(3) develop the design of an animal drawn reversible plough using the optimum design parameters identified during the experiment.

3. Functional requirements of an appropriate plough

In the present work, in developing the design of tilling implement the following criteria were considered.

(1) During primary tillage the soil should be turned 180° in some cases, i.e., in plain fields where soil erosion is not severe, and 135° or 90° in other cases, especially in dry areas and where soil erosion is critical.

(2) The soil should be pulverized and loosened to create favourable conditions for plant growth;

(3) Ridges should be formed to reduce the problem associated with soil losses.

(4) Parameters, for example angles and width, could be varied to suit to the pulling capacity of animals and also to the degree of inversion (this can be done by varying the side and tail angle of a tilling implement).

(5) There should be a mechanism which enables the plough to be used reversibly (in cases where ridges do not have to be formed).

(6) There should be a safety mechanism which allows the plough bottom to be withdrawn from work, when the soil resistance exceeds the maximum value which the animals can pull.

4. Materials and method

4.1. Soil bin and test rig

A detailed description of the test rig and the soil bin used is given elsewhere in the literature[10,11]. To conduct the investigation in the laboratory, a frictional soil type, sand, was used in the soil bin. Attempts have been made to use a uniform particle size to reduce separation. Approximately 6 m (Fig. 3) of the soil bin was filled with a coarse wet-sieved filter sand. The particle size distribution of the sand used is given in Table 1.

Table 1.
Particle size distribution of the sand used in the soil bin

	Particle size, mm				
	< 0.5	*0.5 - 1*	*1 - 2*	*2 - 4*	*4 - 6*
Fraction, %	*3.1*	*31.3*	*55.2*	*10.1*	*0.3*

Soil condition variations were observed during the first phase of the experiment. These variations are mainly due to variations of moisture content and particle size distribution along the entire profile. To reduce the effect of moisture content the sand was dried sufficiently and its variation is presented in Table 2. Variations due to the particle size distributions arises from the seiving characteristics of sand. To reduce this effect the sand was harrowed several times and levelled after every test.

4.2. Instrumentation

For the measurements of forces and moments, an extended octagonal ring type transducer was used. Using the transducer, horizontal, vertical and lateral forces and three moments could be measured simultaneously and independently of each other[12,13]. The interactions

Table 2.
Dry bulk density and moisture content distribution in the soil bin during the speed screening experiment measured after each replicate, Ri.

Depth of layer mm	*Bulk density, g/cm³*				*Moisture content, %*			
	R1	*R2*	*R3*	*R4*	*R1*	*R2*	*R3*	*R4*
0-20	*1.49*	*1.51*	*1.55*	*1.51*	*0.23*	*0.27*	*0.27*	*0.27*
20-40	*1.53*	*1.54*	*1.51*	*1.53*	*0.24*	*0.25*	*0.25*	*0.26*
40-60	*1.54*	*1.56*	*1.58*	*1.56*	*0.29*	*0.30*	*0.30*	*0.29*
60-80	*1.63*	*1.64*	*1.62*	*1.61*	*0.31*	*0.29*	*0.32*	*0.33*
80-100	*1.56*	*1.95*	*1.77*	*1.69*	*0.36*	*0.29*	*0.28*	*0.33*

between channels for the transducer used were below 1.5%. To control hysteresis and channel interactions the transducer was re-calibrated within each experimental block interval.

The transducer was mounted on a frame of the carriage (2) (Fig. 3). The carriage rolls on the rails of the test rig. The rolling speed was adjusted and then monitored by the computer. The operational depth was adjusted by moving the frame in the vertical direction. The vertical position of the frame was measured by a linear potentiometer (7). The distance between the tip of the model implement and the soil surface was measured by another linear potentiometer (5) and the required depth was determined from the measurements taken by the two potentiometers (5) and (7). The accuracy of the potentiometer was approximately +- 0.25 mm.

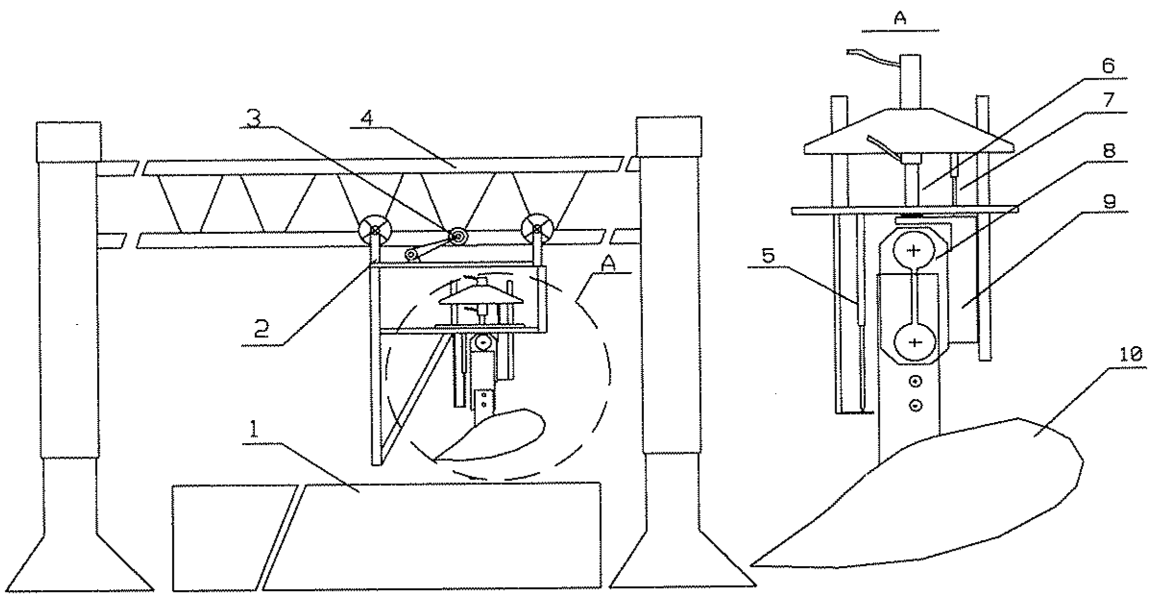

Fig. 3. Schematic view of the instrumented test rig[11]. (1) soil bin; (2) carriage; (3) pulse generator; (4) main frame; (5) linear potentiometer; (6) hydraulic cylinder; (7) linear potentiometer; (8) force transducer; (9) vertical adjustable sub-frame; (10) model implement

A pulse generator denoted by (3) in Fig.3 was used to measure speed. It was mounted on carriage (2) and its measuring accuracy was +- 0.4. It was driven using the rubber wheel on the rail together with carriage (2).

The sampling frequencies were 200 Hz for lower operational speeds and 100 Hz for higher speeds. Each sample consists of horizontal force, vertical force, moment in the plane of these forces, supply voltage, distance, speed and time.

4.3. Plough parameters

Based on the results of literature review and practical experience, the parameters of plough assumed to play important role in soil deformation process, and also influence the resulting forces are selected for experimental purposes. Several researchers reported the role of tail angle in the determination of forces acting on a conventional mouldboard plough. It was also reported that the relation between side rake angle and forces was significantly influenced by operational speed.

Söhne[14,15] has identified some design parameters of a plough, but how those parameters related to the soil loosening and pulverizing is not known.

Important parameters which may have a significant influence on the desired quality of operation point of view are (1) side rake angle, (2) radius of curvature and (3) tail angle (Fig.4)

It was assumed that tail angle and side angle together with their respective degree of curvature could influence (1) the turning degree of the soil slice to cover trashe, (2) pulverization or loosening of the soil to create favourable conditions for germination and (3) the resulting forces.

The present work was concerned with the following:
(1) How do the above parameters influence the resulting forces ?
(2) Do the above parameters influence the required quality of soil preparation ?
(3) What are the optimum values of the above parameters for the desired operation ?
(4) Is it possible for the farmer to vary the above parameters to fit to the desired operation ?

Fig. 4. a_t, tail angle; R, radius of curvature and B_s, side rake angle

For experimental purposes in the laboratory, seven different curved wings (similar to a cylindrical type mouldboard) having radius of curvature (R) of 150, 200, 250, 300, 350, 400 and 450 mm were manufactured. The side rake angles investigated were 40°, 45°, 50°, 55°and 60°, and the tail angles were 32°, 36°, 40°, 45°, 50°and 55°.

4.4. Experimental procedure

The experiment was divided into two parts. Part 1 deals with the investigation of force-tail angle and force-curvature relations while part 2 deals with force-side rake angle relation at various speeds. All the parameter combinations were randomized before conducting the experiments.

The sand was harrowed twice and levelled after every run. Levelling was made very carefully so as not to compact the soil. To observe whether soil moisture content varied or not, a test for moisture content was made before and after every block of the experiment.

In the first phase of the experiment, a constant depth and speed were used. Since the average speed of a pair of oxen varies between 0.5 and 1.2 m/s special attention should be given to this interval. However, the speeds 0.3, 0.5, 0.8, 1.2 and 2 m/s were used for experimental purposes.

The constant depth used was 60 mm. Difficulties appeared to maintain constant depth using the joint mechanism for all curvatures. The constant depth was adjusted by varying the side angle for different curvature. For the 150 mm radius it was 51°, for 200 mm 53°, for 250 mm 54°, for 300 mm 55.5°, for 350 mm 55.5°, for 400 mm 56° and for 450 mm it was 56°.

After harrowing and levelling, the carriage with the dynamometer and potentiometer were moved to approximately the middle of the soil bin and thereafter the gap between the tip of the implement and the soil surface was measured using the potentiometer. After taking the measurement, the carriage was moved to the starting position and the required depth was then adjusted automatically and monitored by the computer.

5. Forces acting on soil engaged part of a curved implement

5.1. Inversion of soil slice

The turning degree of soil slices and covering of trash are assumed to depend on operational speed, tail angle, side rake angle and curvature of the wing of a plough. By establishing the relationship between radius of curvature, speed, side rake angle, tail angle, forces and the turning degree of the soil slice, it should be possible to optimize the curvature of a wing of a plough, side rake angle, tail angle and speed needed to turn the soil to the required degree.

To reduce the magnitude of resulting forces during performance, the soil slice should turn around a fixed point in the vertical plane perpendicular to the line of travel. Then the slice turns without moving laterally or vertically if the linear speed of the slice and its rotational speed around a fixed point are constant.

It should be noted that there are both advantages and disadvantages of complete turning of soils. A complete turning promotes a good means of weed control, while a partial turn creates a rough surface field and this prevents soil loss due to erosion.

Turning angle, θ, of a soil slice may be expressed in a general form as:

$$\theta = f(\alpha_t, \beta_s, R) \tag{1}$$

where,

α_t is tail angle,
β_s is side rake angle and
R is radius of curvature.

The soil used in the soil bin was pure sand and therefore the influence of the above mentioned parameters on the turning degree of the soil was not investigated in the laboratory.

5.2. Force components resulting from a curved implement and soil interaction

When using implements of small radius, the soil is compressed and forced upward. The compression action causes the horizontal force to be increased and the lifting action results in an increase of vertical force.

A knowledge of the relationship between the radius of curvature of a plough and the resulting soil forces is very useful for designing purposes. The effect of radius of curvature on forces is mainly due to force of inertia and it may be expressed in the form:

$$P = \frac{mv^2}{R} \tag{2}$$

where,

P is force of inertia,

m is mass of the soil moved,

v is a linear speed of the soil mass moving along the curvature, and

R is radius of curvature.

The other component forces, rather than the inertia force, resulting during operation are:

- cohesive force,
- gravitational force,
- frictional (soil-metal) forces and
- normal reaction force.

The relationship between tail angle on the soil forces depends on width of the implement. As it can be observed from Figure 6, width, b depends on the length of the implement, l, and the sin of the tail angle (Eqn 3).

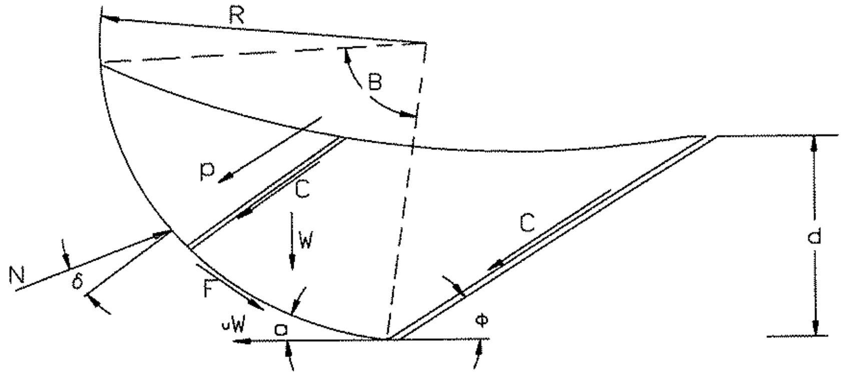

Fig. 5. Forces acting on a curved interface; P, force of inertia; F, frictional force along the surface of the implement; C, cohesive force; W, gravitational force; N, normal force; R, radius of curvature; d, operational depth; uW, frictional force at the bottom tip of the implement

$$b = l \sin(\alpha_t) \tag{3}$$

where,

b is operational width,

l is length of soil-engaging part of the implement, and

a_t is tail angle

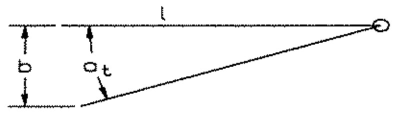

Fig. 6. Tail angle and operational width

Assuming that the resulting forces are proportional to operation width, and from Figure 5 and 6, simplified expressions for the horizontal and vertical force, for a constant speed may be written as:

$$H = \beta RA\cos(\alpha) - C\cos(\phi) + \frac{N\sin(\alpha)}{\cos(\delta)} - \frac{mv^2}{R}\sin(\alpha) - \mu W + k_{\alpha h} l \sin(\alpha_t) \tag{4}$$

$$V = \beta RA\sin(\alpha) + C\sin(\phi) - \frac{N\cos(\alpha)}{\cos(\delta)} + \frac{mv^2}{R}\cos(\alpha) + W + k_{\alpha v} l \sin(\alpha_t) \tag{5}$$

where A is adhesion, and $k_{\alpha h}$ $k_{\alpha v}$ are constants. The first terms in Eqn (4) and (5) represent soil-metal friction force. Most of the force components in Eqn (4) and (5) are speed and depth dependent. However, the effect of depth is mainly due to the gravitational force component. An approximate expression of the gravitational force may be:

$$W = \beta R b \rho g d + \frac{1}{2}\rho b g d^2 \cot(\phi) \quad (6)$$

where, d is depth,

ρ is soil bulk density, and

β is angle in radians.

All the above force components in Eqn (4) and (5) vary depending on the rake angle, soil-metal frictional angle, tail angle and also on the magnitude of radius of curvature. When investigating the forces acting on a curved implement, an important parameter to be considered is the edge rake angle of a curve. Curves with a bigger radius have a bigger edge rake angle (Fig. 7). From the earlier study made by Gebresenbet and Jönsson[11] the variation of force due to rake angle was significant. Both horizontal and vertical forces increased with rake angle and the model developed was a third degree polynomial.

In the present investigation, the edge rake angle increased automatically with the increase of radius of curvature and it might not be easy to control the influence of edge rake angle while investigating the effect of curvature on the forces.

In the soil bin, the adhesive force resulted from soil-metal frictional force and the cohesive force could roughly be constant since variation of the moisture content during the experiment was not significant (Table 2).

6. Results

6.1. Radius and force relation

Results of the investigations elucidated that the behaviour of radius and horizontal force relation depends on the tail angle. For smaller tail angles (about 30° to 40°) the horizontal force decreases significantly with an increase of radius (Fig. 8). It can be noted that the experimental data obtained for the horizontal force and radius relation for smaller tail angles confirmed the concept of Eqn (2), though the result had non-linear behaviour.

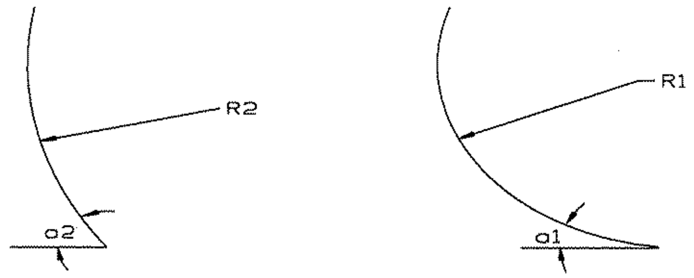

Fig. 7. Different curves have different edge rake angles which could influence the force - radius relations

Two types of equations, exponential equation of the form of Eqn (7) and a third order polynomial equation were tested to fit to the experimental data. Both models described the data sufficiently (Fig. 8). However, a better fit can be observed when using the exponential type of equation.

$$H = C_1 + C_2 e^{-C_3 R} \tag{7}$$

where,

H, horizontal force,

R, radius of curvature,

C_1, C_2, C_3 are constants

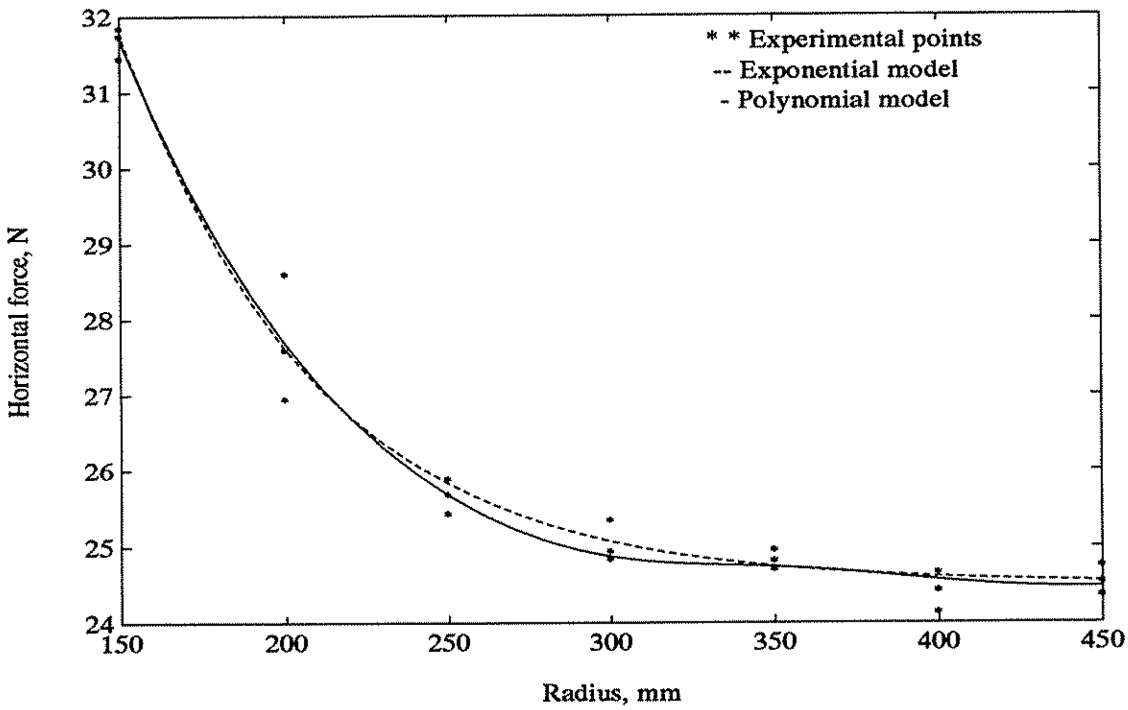

Fig. 8. Effect of radius on the horizontal force when 32° tail angle was used in the experiment

For the tail angle of about 45°, the horizontal force decreases first with an increase of radius of curvature and then increases with a further increase of radius (Fig. 9). For this range of tail angles, radii lying between 250 mm and 300 mm are found to be optimum.

Using the statistical analysis, a polynomial equation of the form given in Eqn (8) was developed to portray the experimental data of radius and horizontal force relation for the tail angle between 40° and 50°. The equation agrees well with the sampled data (Fig. 9).

$$H = k_{h1} - k_{h2}R + k_{h3}R^2 - k_{h4}R^3 \tag{8}$$

where,

H, horizontal force,

R, radius of curvature and

$k_{h1}, k_{h2}, k_{h3}, k_{h4}$ are constants

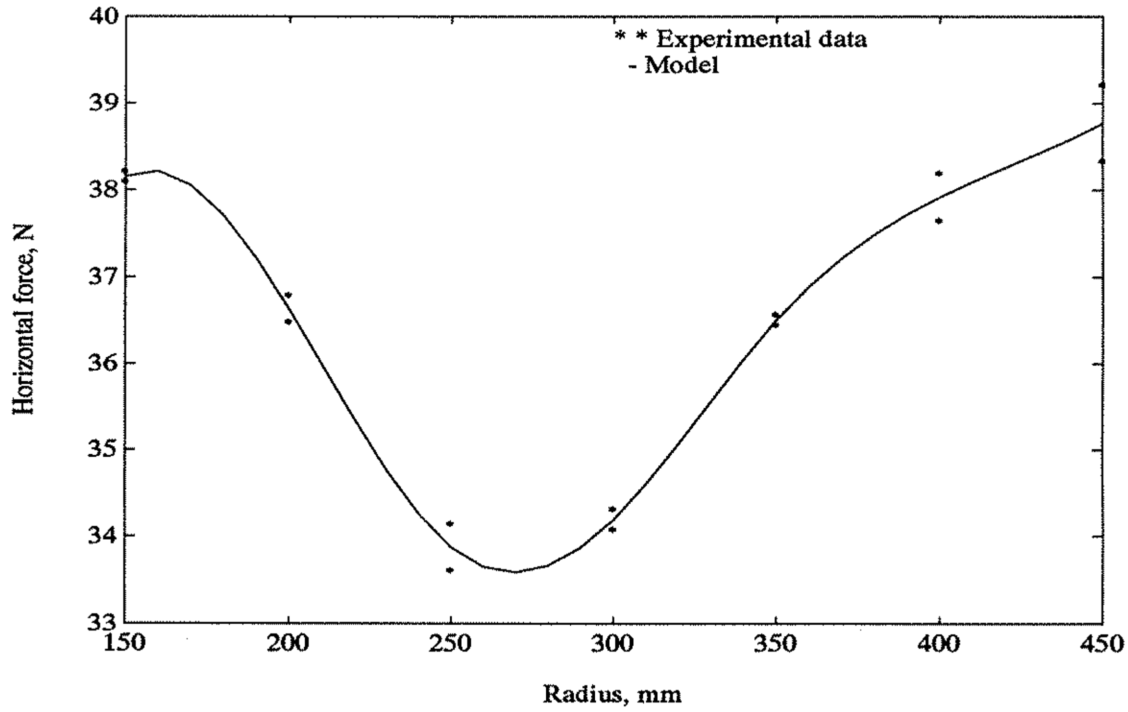

Fig. 9. Influence of curvature on horizontal forces when tail angles of 40 to 50° are used in the experiment

For large tail angles of greater than about 50° the horizontal force increases with an increase of radius (Fig. 10). As it was anticipated earlier in the text, for this range of tail angle, the horizontal force and radius relation was not only influenced by the tail angles used but also by edge rake angles. Curves with bigger radius have higher rake angles at the edges

(Fig. 7) than smaller curves and thus when the implement interacts with the soil, the resulting force automatically depends on both the rake angle and the radius. The increase of rake angle at the edge of the curve causes an increase of normal forces on the edge. Thus the complexity of the force and radius relationship due to tail angle might be because of the involvement of the edge rake angle and an increase of the amount of soil to be deformed when larger tail angles used. So, for this range of tail angles, the effect of edge rake angle on the horizontal force is more pronounced than the effect of curvature. A second degree polynomial equation was found best to describe the data.

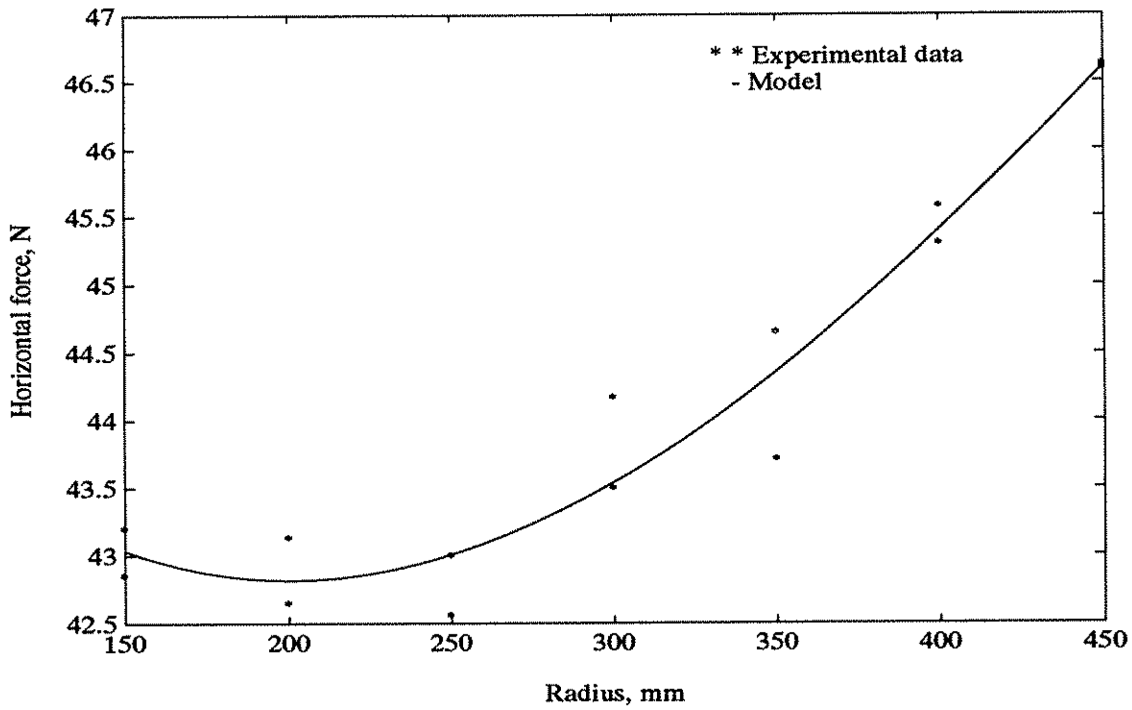

Fig. 10. Influence of curvature on horizontal forces when tail angles of 50 to 60° are used in the experiment

For the vertical force, it was observed that for all tail angles used, the vertical force decreases significantly with an increase of radius (Fig. 11). No important effects of the variations of tail angle or edge rake angle have been observed on the behaviour of vertical force and radius relation. In the earlier study[11] where only the effect of rake angle was investigated. A third order polynomial was best to illustrate the relation between rake angle and vertical force.

The sampled data in the soil bin was subjected to statistical data analysis to determine the predicting equation to delineate the radius and vertical force relation. A third order polynomial equation (Eqn 9) portrayed adequately the relation (Fig. 11). The effect of radius on the vertical force is mainly due to the gravitational force since curved wings with smaller radius tend to lift the soil. However, an increase of vertical force is usually considered to be useful, because this condition improves the penetration ability of the implement.

$$V = k_{v1} - k_{v2}R + k_{v3}R^2 - k_{v4}R^3 \tag{9}$$

where R is radius,

$k_{v1}, k_{v2}, k_{v3}, k_{v4}$ are constants

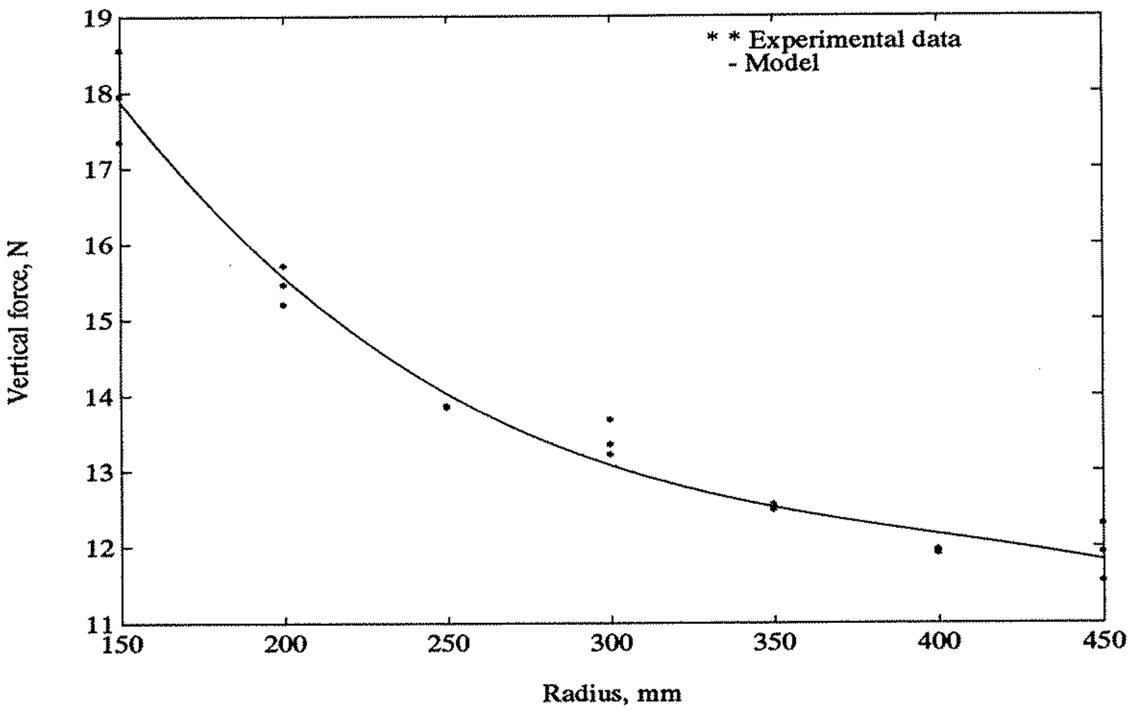

Fig. 11. Influence of variation of radius on vertical forces

6.2. Side rake angle - forces relation

The effect of rake angle on resulting forces has been examined by Payne and Tanner[16], Dransfied et al[17]., Siemens et al[18]., Gill and Vanden Berg[19], and Gebresenbet and Jönsson[11]. However, the effect of side rake angle of a curved tillage implement on the resulting forces has not been studied sufficiently. In the present work, investigations were made to demonstrate the force and side rake angle relation for various speeds and radii of a curved interface in the soil bin. As mentioned earlier, the range of side rake angle used was 40° to 65°.

The results of statistical analysis revealed that there is a significant influence of side rake angle on the horizontal force. The horizontal force decreases rapidily with an increase of side angle. A polynomial equation of the second order was fitted to the sampled data. The model accords well with the experimental results (Fig. 12) and the R^2 value was 0.99.

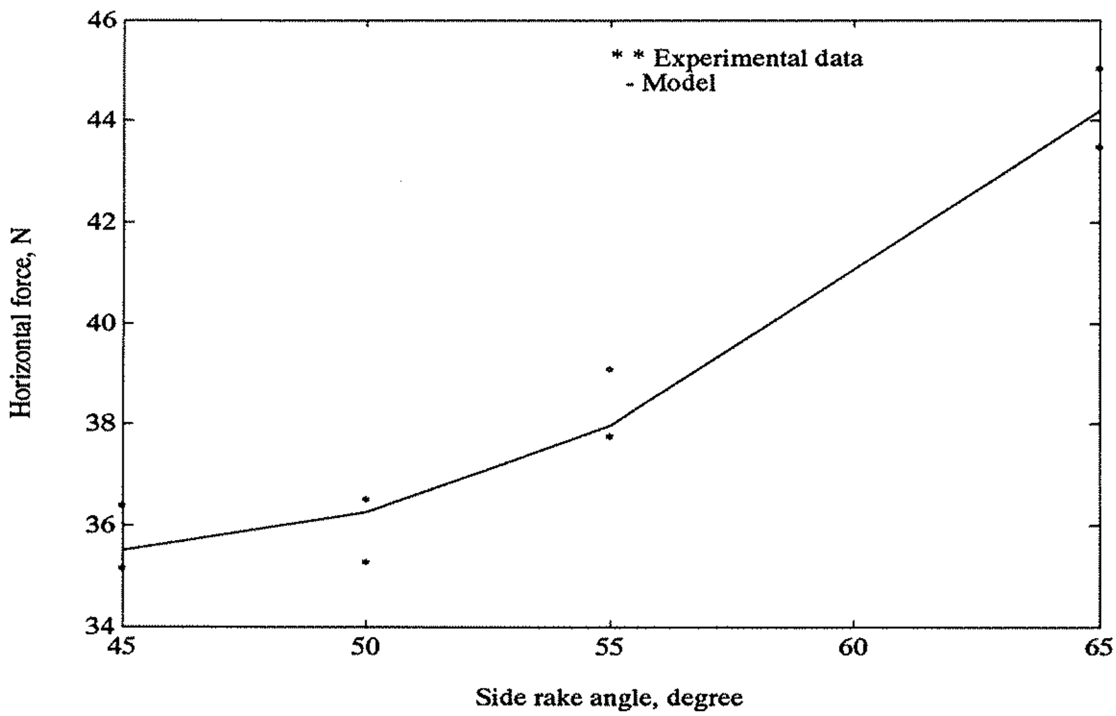

Fig. 12. Comparison of the model and the sampled data of side rake angle and horizontal force relation

For the vertical force, the relation with side rake angle was found to be the reverse. The force decreases with an increase of side rake angle (Fig. 13). The predicting model, second order polynomial, explained the experimental data adequately.

At higher side rake angles, the implement pushes the soil forward and aside rather than lifting. This could cause an increase of horizontal force and decrease the vertical force.

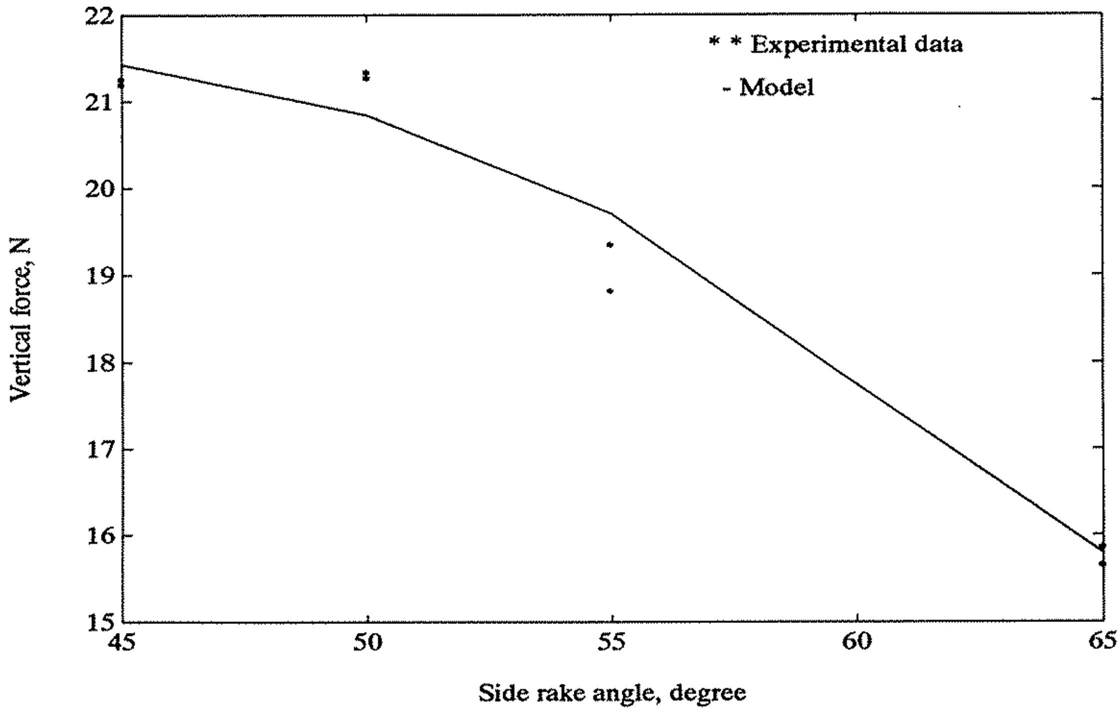

Fig. 13. Effect of side rake angle on the vertical force

6.3. Effect of speed and radius on force and side rake angle relation

Various plough types have usually been designed for different performances. For high speed operations, a specific design is necessary to reduce force due to speed. Otherwise if low speed ploughs are used the soil slices are thrown far away, and as a consequence the draught will be very high. This is disadvantageous from an energy requirement point of view and the quality of inversion and covering of trash can be worse.

For a curved soil engaged part of an implement, as mentioned earlier, the force of inertia is the main component which mainly depends on speed and radius. Tillage implements are meant to break, push aside and invert the soil. The operational behaviour of these types of implements makes the force and side rake angle relation very complex and speed plays an important role since the sideways movement of soil by implements like mouldboard ploughs depends on forward speed.

In the present work, the speeds used were 0.3, 0.5, 0.8, 1.2 and 2 m/s to study their effect on force - side rake angle relation. The speed of a draught animal varies between 0.5 and 1.2 m/s. Because of this, a special attention was given to the performance of the implement within the range of these speeds.

The behaviour of the graphs of horizontal force and side rake angle relation do not display an appreciable difference when using the speeds 0.5 and 1.2 m/s with the exception of the difference in the absolute value as depicted in Figure 14.

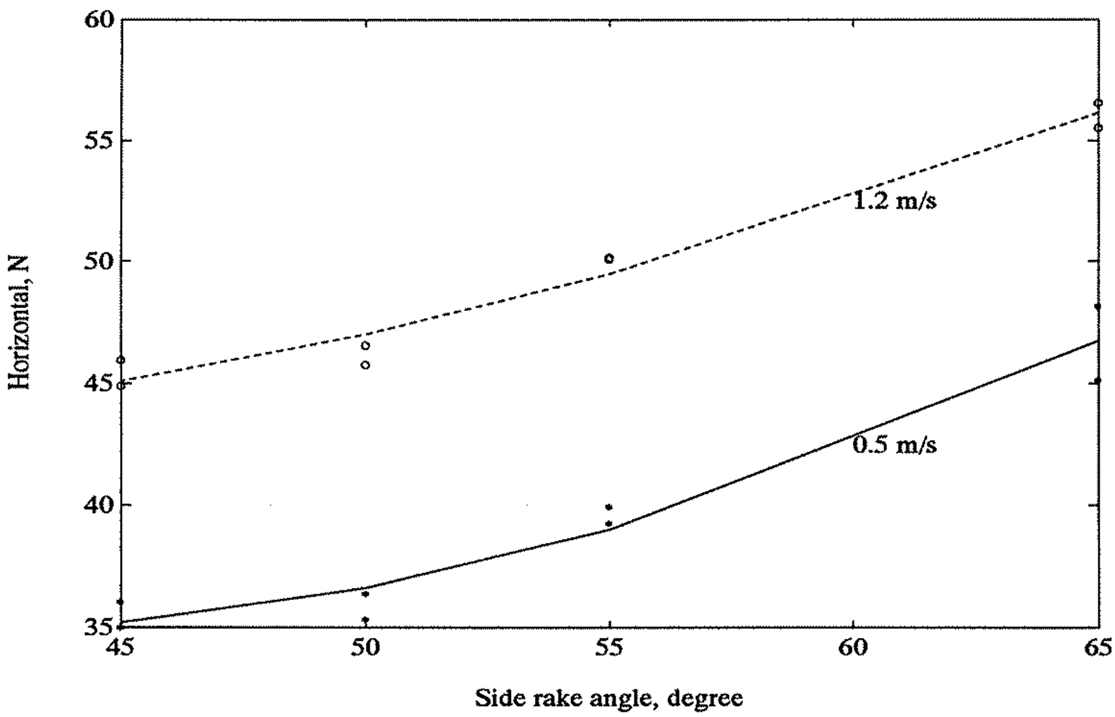

Fig. 14. Side rake angle and horizontal force relation for the speeds of 0.5 and 1.2 m/s

The result of experiments in the soil bin revealed that the behaviour of the side rake angle and vertical force relation is not in the same mode as the horizontal force and side rake angle relation for the fore-mentioned speeds. The effect of speed is less significant at larger side rake angles. When the speed of 1.2 m/s was used the vertical force decreased rapidly with an increase of side rake angle (Fig. 15). The relative value differences of the vertical force at lower side rake angles for the speeds used was much more greater than at higher side rake angles (Fig. 15). This result is similar with the earlier investigation on seed drill coulters[11]. Gebresenbet and Jönsson reported that for the lower speeds the vertical force and rake angle relation was linear and the behaviour changed for the higher speeds.

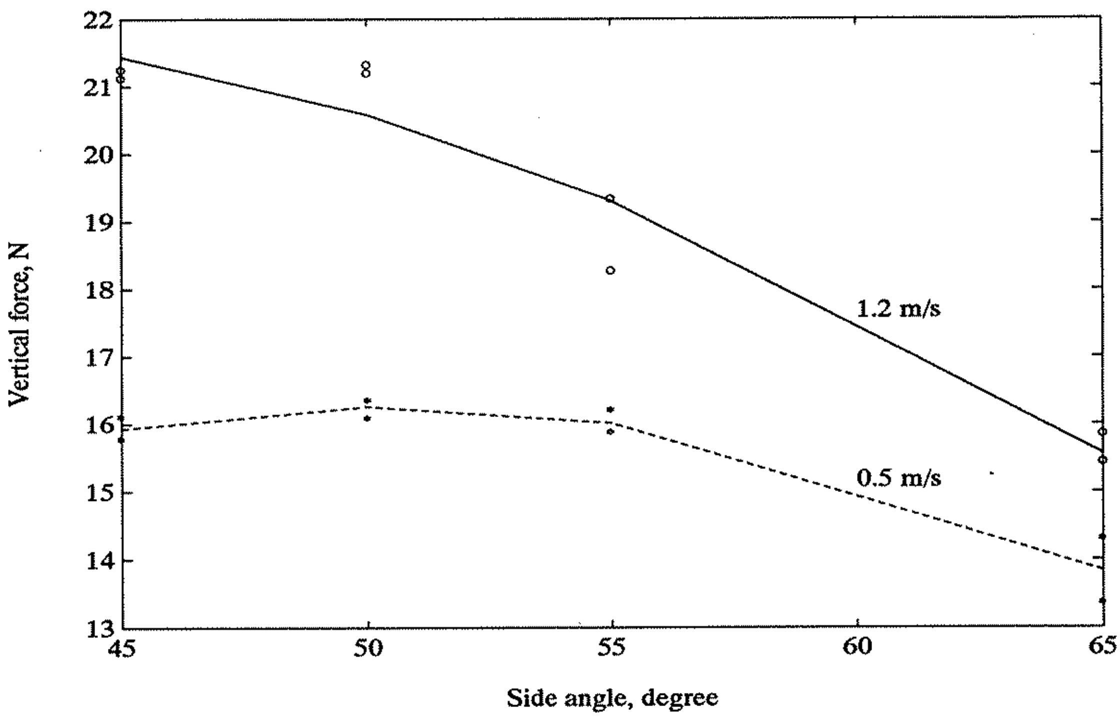

Fig. 15. Effect of speed on side rake angle and vertical force relations for the speeds 0.5 and 1.2 m/s

To study whether variation of radius has an impact on the force and side rake angle relation, radii of 200 and 400 mm were used. No appreciable differences in behaviour have been observed for horizontal force. However, it can be observed that the influence of radius increases with side rake angle (Fig 16). However, the models fitted to the data from the 200 and 400 mm radius have similar behaviour. Both models are second order polynomials.

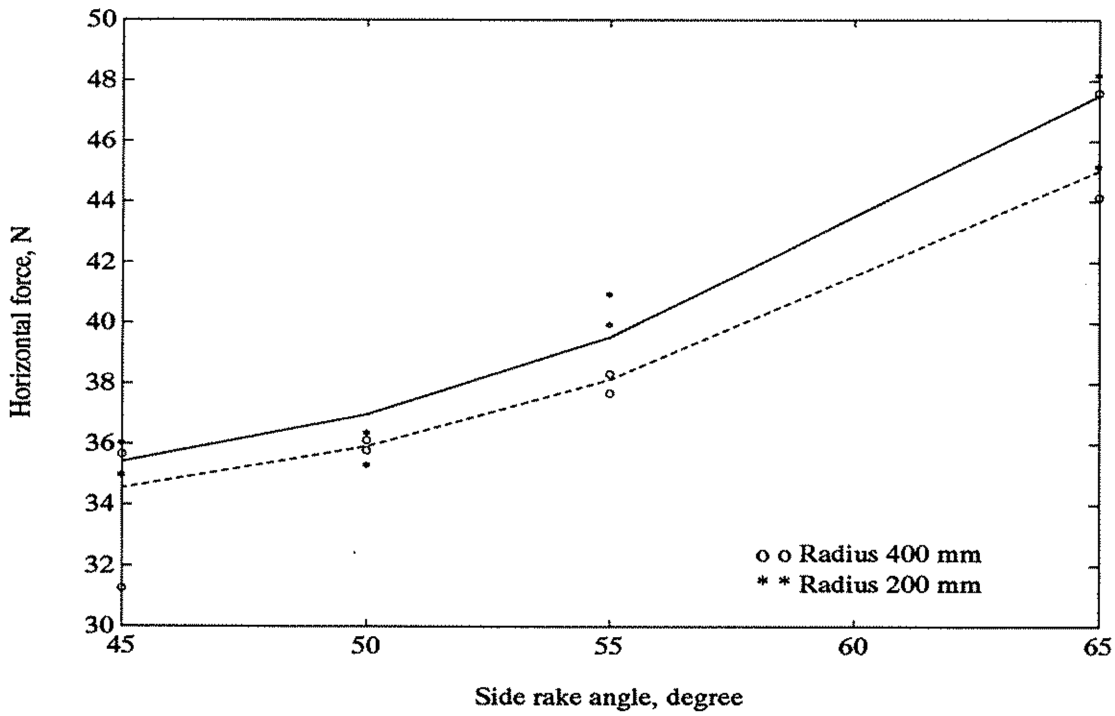

Fig. 16. Effect of radius on side rake angle and horizontal force relation

No significant influence of radius on the side rake angle and vertical force relation has been observed. The behaviour of the graphs of both curves of 200 mm and 400 mm radius are very similar (Fig 17). The models explained the experimental data for both cases have the same order. However as it is displayed in Figure 17, the impact of radius on the relative value difference of the vertical forces resulted from the two curves is appreciable.

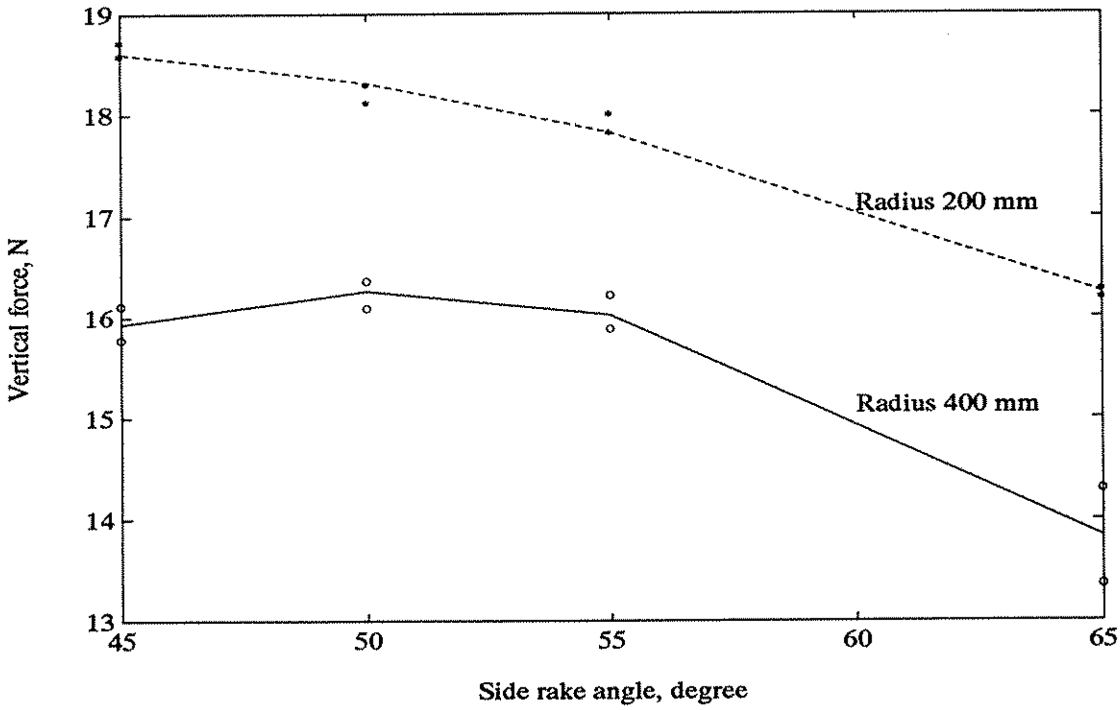

Fig. 17. Effect of radius on side rake angle and vertical force relation

6.4. Combined effects of speed and radius on forces and side rake angle relation

To examine the combined effect of radius and speed on the side rake angle and force relations, especial attention was given to the radii of 200 and 400 mm, and speeds of 0.5 and 1.2 m/s. The result showed that the horizontal force resulting from the combination of radius 400 mm and 1.2 m/s speed is greater than for the combination of 200 mm radius and 0.5 m/s speed for all side rake angles. This implies that speed has more influence on the horizontal force than radius for all the side rake angles used (Fig. 18). However the behaviour of models fitted to both combination were similar. Both models are second order polynomial equations.

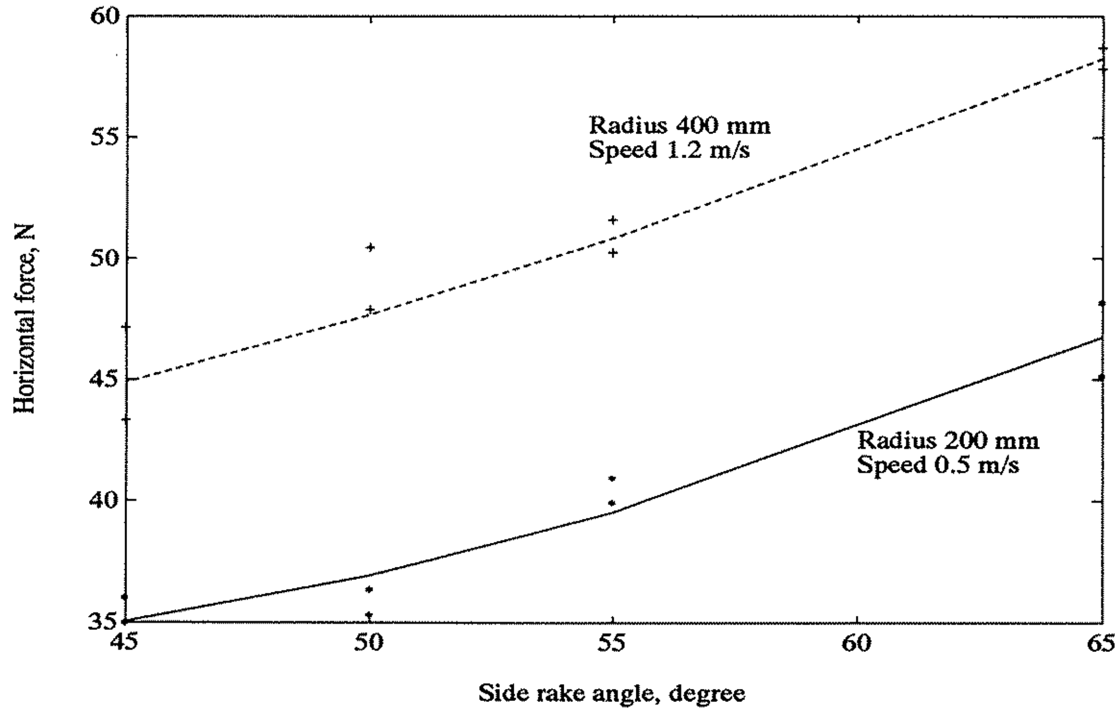

Fig. 18. Combined effects of speed and radius on horizontal force side rake angle relation

For smaller side rake angles, the vertical force on the 400 mm radius and speed 1.2 m/s was much more greater than on the 200 mm radius and 0.5 m/s speed. But for larger side rake angles the vertical force was smaller on the 400 mm radius and 1.2 m/s speed (Fig. 19). It can be observed that speed has more influence on the vertical force than radius when using smaller side rake angles. This behaviour changes the other way round for larger side rake angles. At about 63° side rake angle the vertical force of both the above combinations were equal (Fig. 19)

It can be noted that if tillage operations should be performed at higher speeds, curves with larger radius should be recommended to achieve a good penetration performances for the side rake angle of below about 60°. For larger side angles, the combination of smaller radius and speed could fit the requirement of less energy and effective penetration. In his investigation on the effect of speed on rate of penetration Gebresenbet[20] reported that using higher speeds leads to an increases of penetration performance of tilling implement. However unless the speed is kept constant small variations of speed can cause uneven depth operation[13,21].

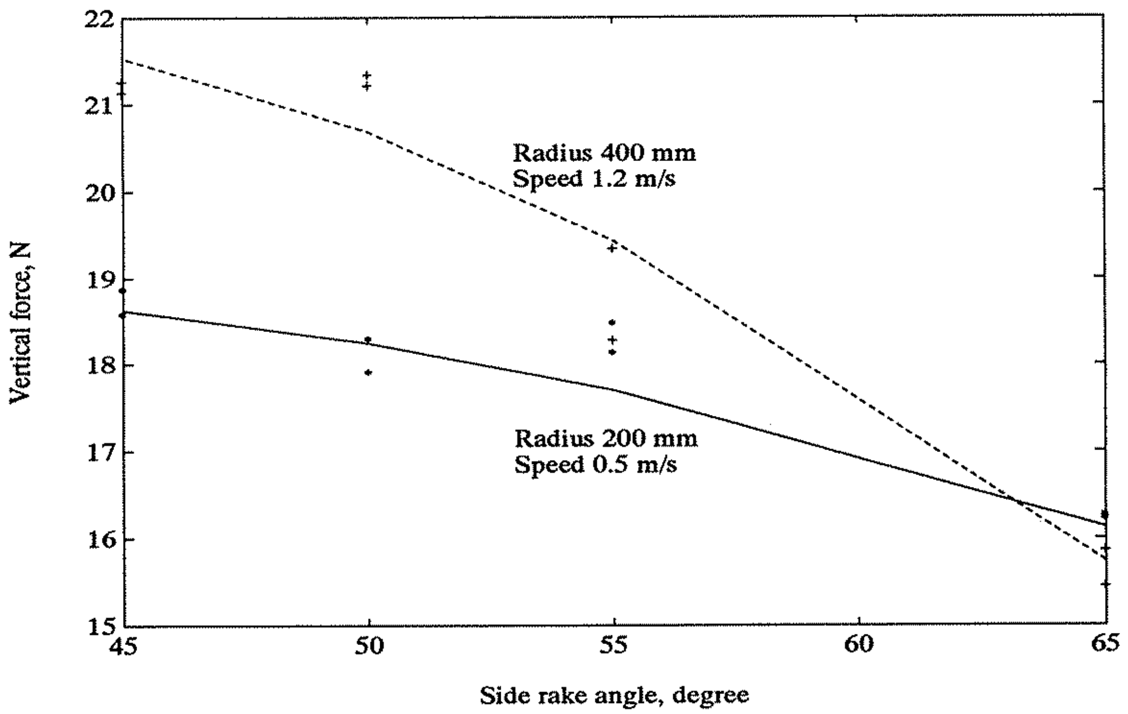

Fig. 19. Combined effects of speed and radius on vertical force side rake angle relation

6.5. Effect of radius and side rake angle on speed and force relation

The effect of variation of radius on the speed and force relation has been examined. The curves used had the radii of 150 mm and 450 mm. As depicted in Figure 20 the horizontal force increases slower with speed for the 450 mm radius than for the 150 mm.

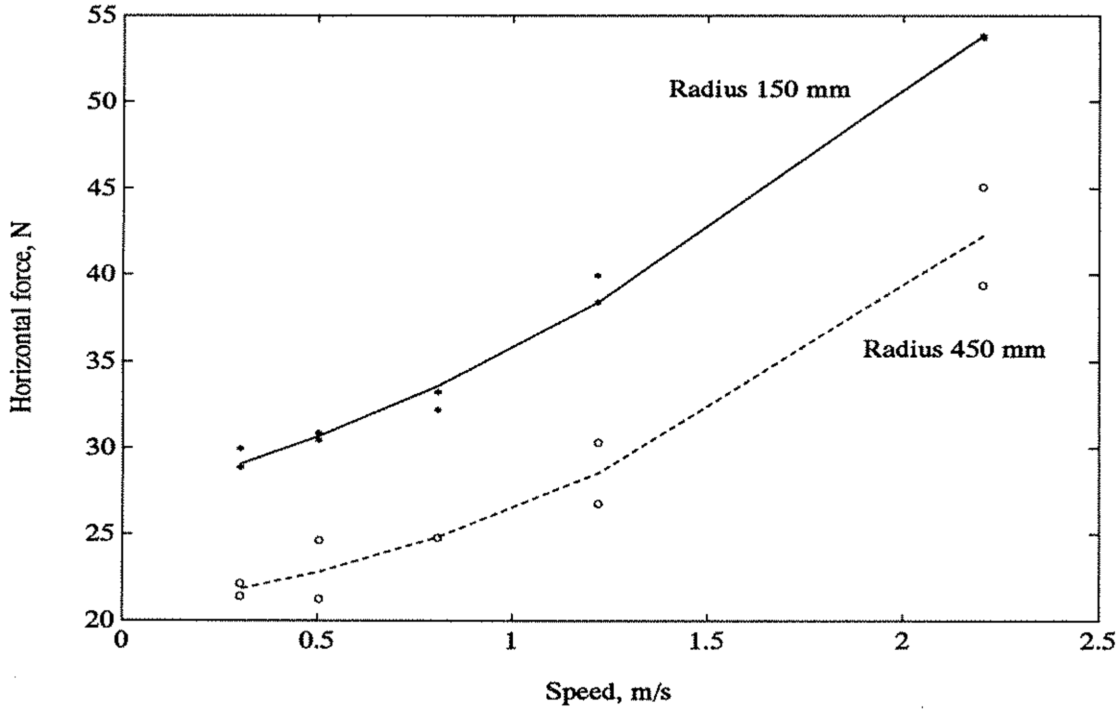

Fig. 20. Effect of radius on speed and horizontal force relation

The effect of radius is noteworthy on the speed and vertical force relation. The force increases very gradual on the radius 450 mm (Fig 21) and steeply on the 150 mm radius. This leads to the conclusion that curved implements with smaller radius are not recommendable for high speed operations.

To study the influence of side rake angle on the speed and force relation, curves mounted at 40°and 60°side rake angle were used. Without the exception of the differences in the absolute value, no remarkable difference in the behaviour of the graphs of horizontal forces was observed when using these side rake angles (Fig 22).

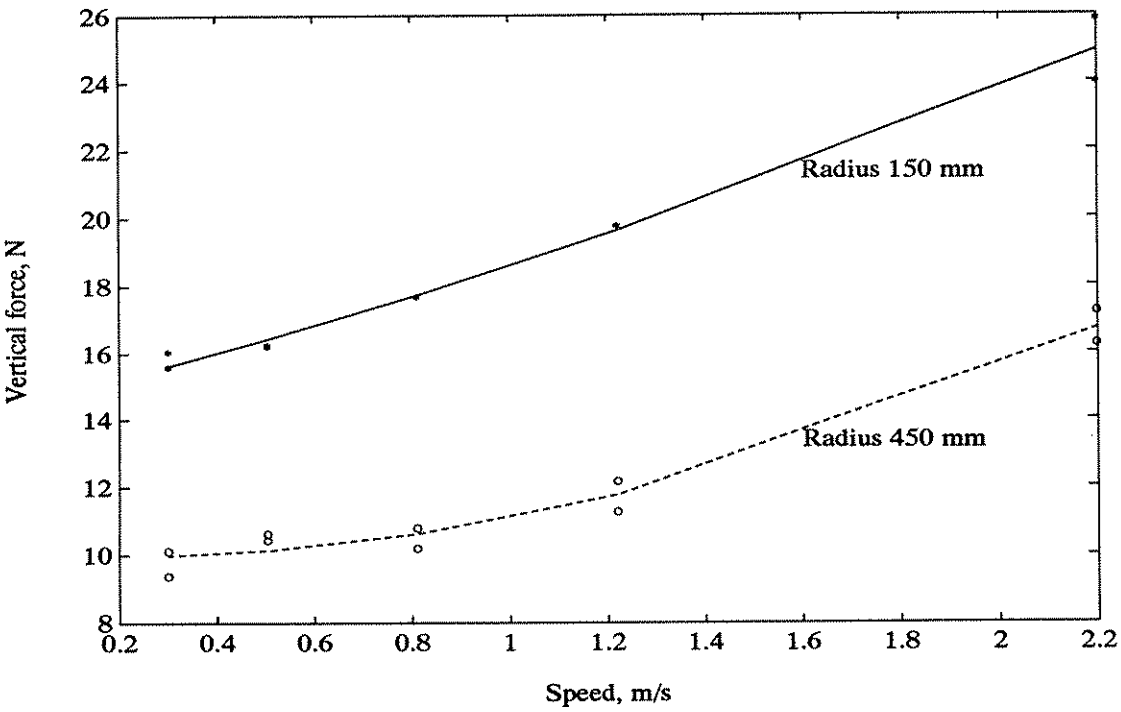

Fig. 21. Effect of radius on speed and vertical force relation

The relation between vertical force and speed was found side rake angle dependent. An increase of force with speed up to the speed of 1.2 m/s maintain analogous form when the wing was mounted at 40° side rake angle and at 60° (Fig 23). However, above the speed of 1.2 m/s the force increases more rapidly for the 40° side rake angle than 60°.

From Fig 22 and Fig 23, it can be noted that a curved implement mounted at 40° side rake angle has preferable performance for higher speed operations. A good penetration can be obtained with lower horizontal force.

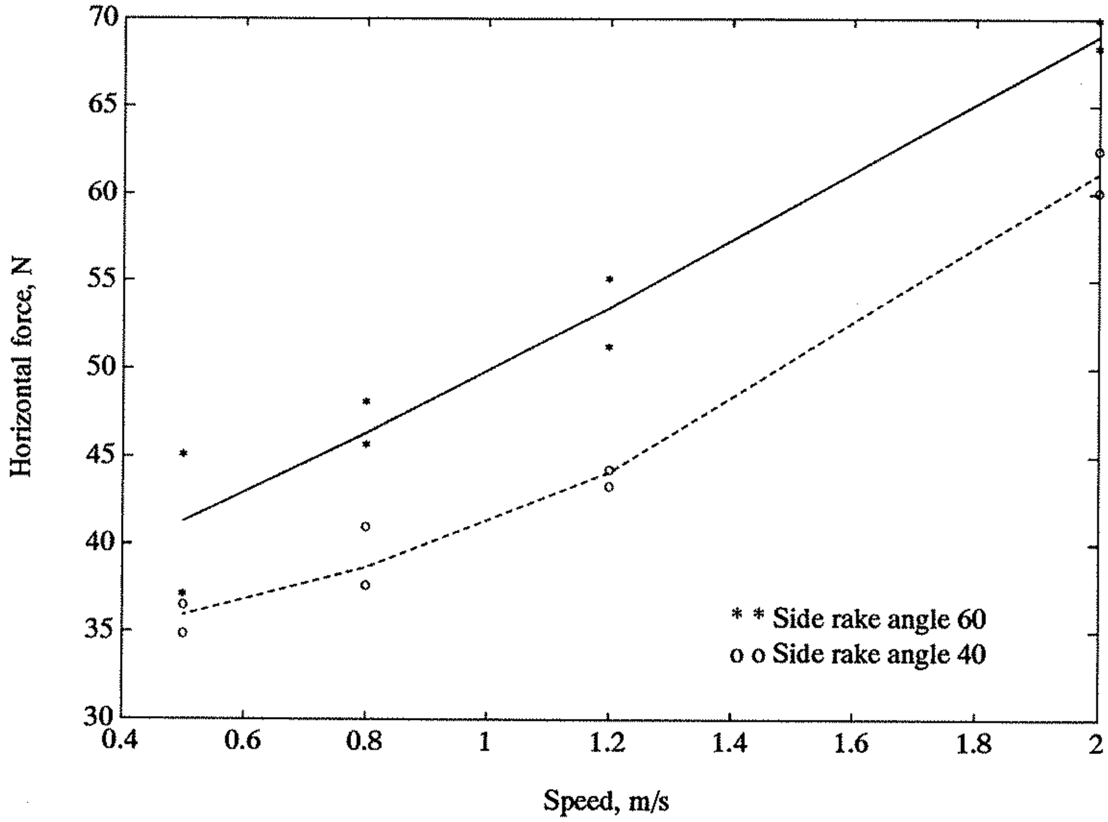

Fig. 22. Effect of side rake angle on speed and horizontal force relation

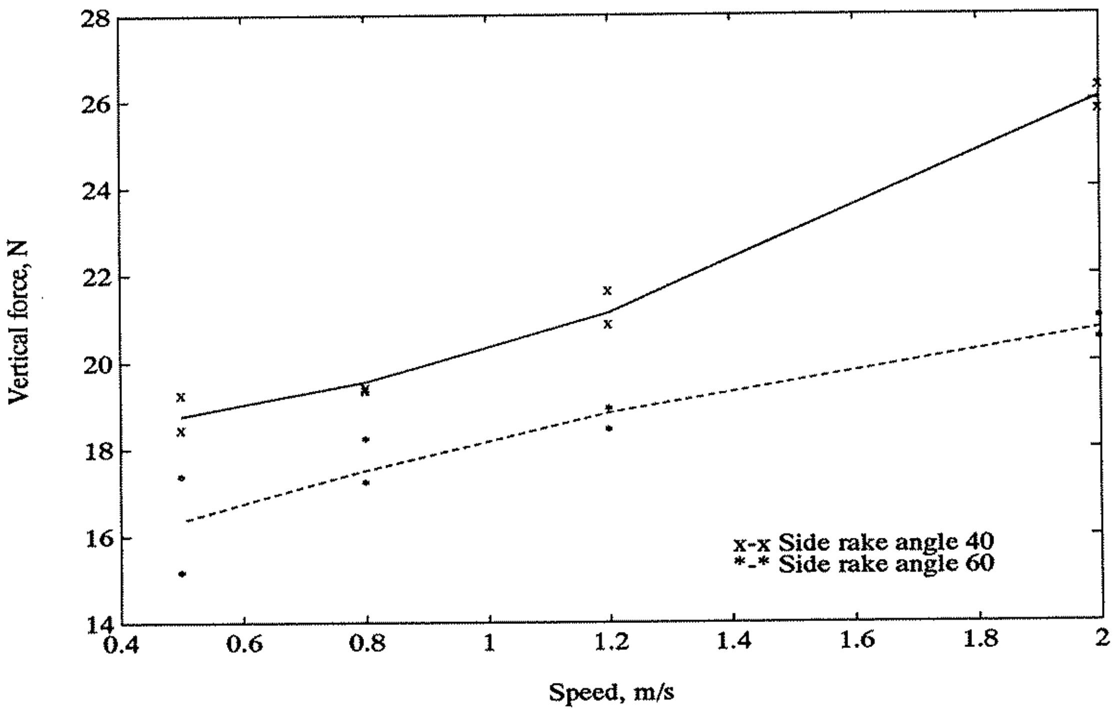

Fig. 23. Effect of side rake angle on speed and vertical force relation

6.6. Tail angle and force relation

Many researchers emphasized the tail angle as an important parameter to be considered when predicting the resulting forces from plough bodies during operation. However, the proposed predicting equations varied and might be related to specific conditions.

The tail angle could influence the resulting forces, inversion and pulverization. However, the functional relation between tail angle and forces, tail angle and degree of inversion has not been yet established well. For an implement moving at a constant speed, the resulting forces are mainly due to frictional, cohesive and compressing normal forces. For lower tail angles, the horizontal force is mostly due to friction, while for bigger tail angles it may be due to both the compressive normal force and frictional force.

In the current work, experimental investigation has been carried out to study the effect of tail angle on the horizontal and vertical forces. The range of tail angle used for investigation was from 32° to 54°. The results showed a significant influence of the variation of a tail angle on the horizontal force. The force increased with an increase of tail angle (Fig. 24). The relation was described best by a third degree polynomial but also could be explained sufficiently by a second order.

Width of ploughing varies together with tail angle. From earlier studies, horizontal force increased linearly with an increase of width[22]. Considering that the horizontal force is proportional with width and using Eqn (3) the horizontal force may be expressed as:

$$H = k_{sg} + k_{\alpha h} l \sin(\alpha_t) \tag{10}$$

where the constant k_{sg} represents all the terms in Eqn (4) except the last term characterizing the contribution of tail angle. The length, l, of the wing was 420 mm and the coefficient $k_{\alpha h}$ stands for soil conditions, design parameters and other operational parameters like speed and depth. An attempt has been made to fit Eqn (10) to the experimental data and it explained the data sufficiently (Fig.24).

The behaviour of the tail angle and vertical force relation was somewhat different from the horizontal force. The vertical force increased exponentially with an increase of tail angle. Three types of equations, third order polynomial, Eqn (10) and exponential equation (Eqn 11) were used to describe the experimental data. All could sufficiently portray the data, but a third order polynomial was found best to characterize the data (Fig.25 ?????).

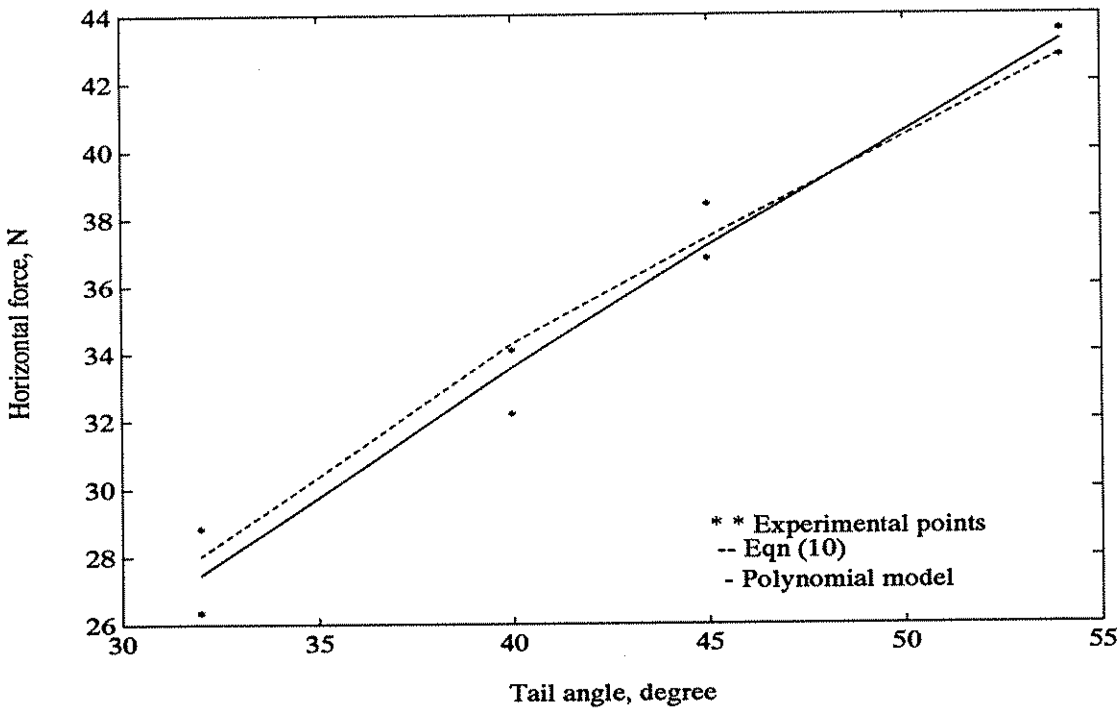

Fig. 24. Effect of tail angle on the horizontal force

$$V = k_1\left(1 - e^{-\alpha_t}\right) \tag{11}$$

where,

V is a vertical force,

α_t is a tail angle and

k_1 is a constant

It should be noted that, since the soil used in the soil bin was pure sand and of very low moisture content, the degree of inversion due to the variation of tail angle could not be studied. In the foreseeable future, i.e., in the second phase of the present work, the effect of tail angle on the degree of inversion of soils will be studied in the field.

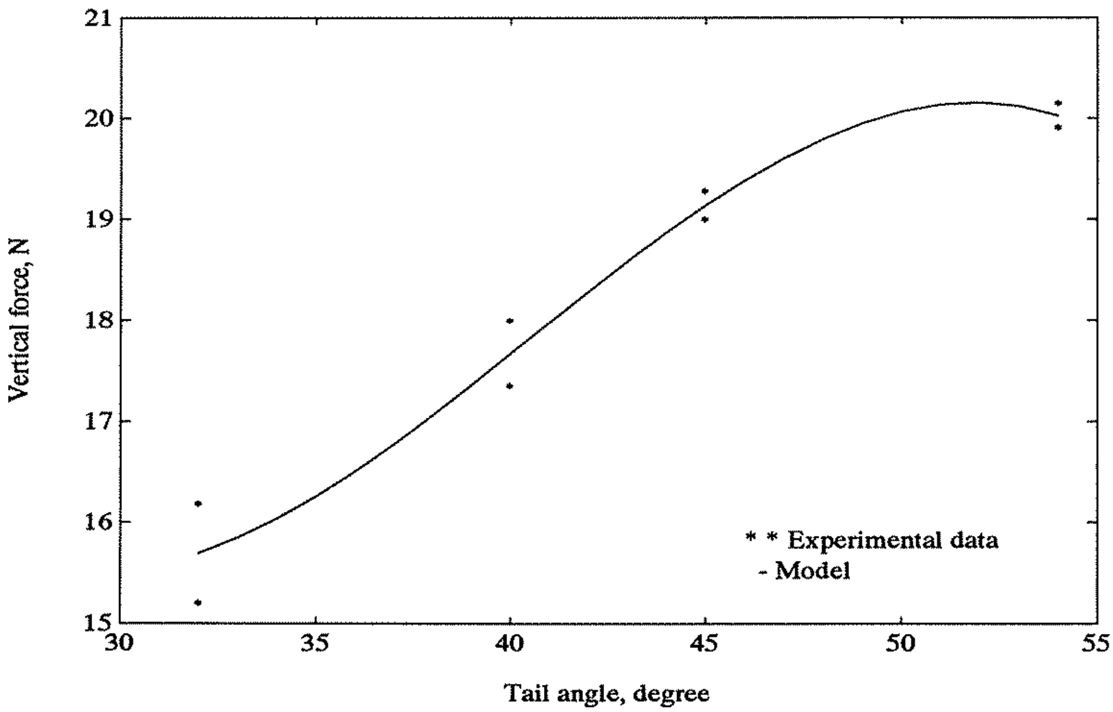

Fig. 25. Effect of tail angle on the vertical force

6.7. Effect of radius and speed on tail angle - force relation

The effects of radius and speed on the tail angle and force relation have been studied separately in the soil bin. From the result of the investigation, it was observed that for all the radii used, the behaviour of the horizontal force and tail angle relation was similar. The force increases rapidly with the tail angle up to about the angle of 45° and thereafter increases slowly with further increase of angle (Fig 26). Below 45° tail angle, the horizontal force resulted from the smaller radius are greater than on the bigger radius. The angle 45° is the intersection point for all curves and above 45° tail angle, the horizontal forces pronounced on the curves with bigger radius (Fig 26).

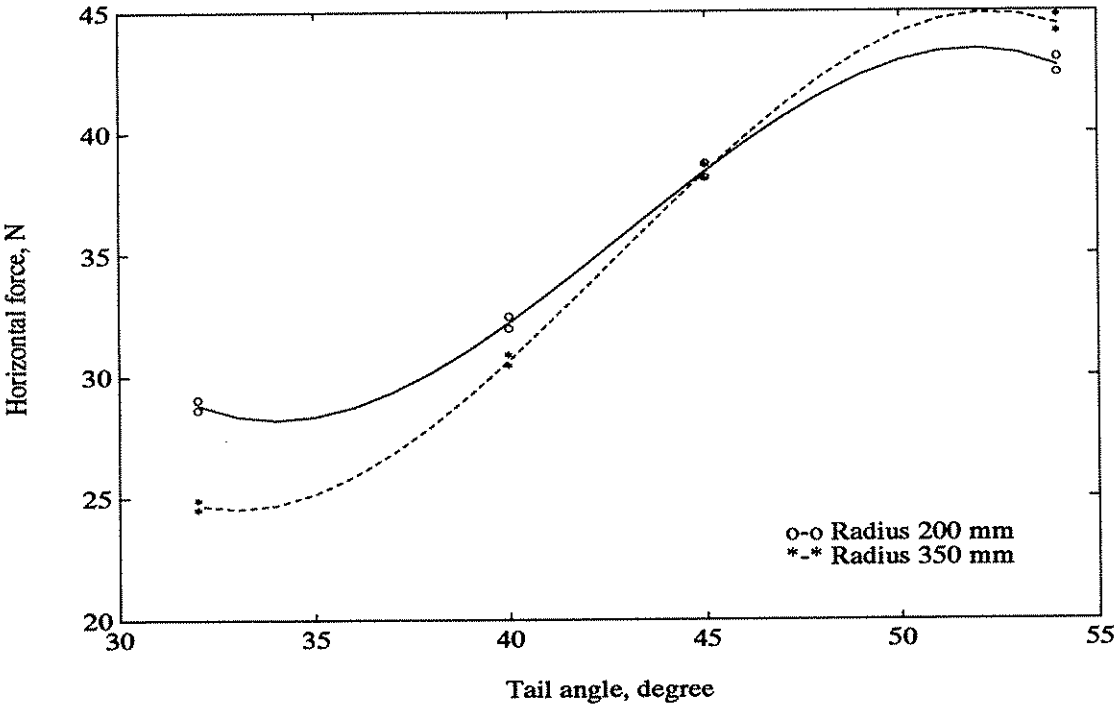

Fig. 26. Effect of radius on horizontal force - tail angle relation

From all curves used, the behaviour of the vertical force and tail angle relation was almost identical. For all curves, the force increases steeply up to 45° tail angle and thereafter increases very slowly with further increase of tail angle (Fig 27). However, for all tail angles used the vertical force resulted from the smaller radius are greater than forces resulted from the larger radius.

From the above results, wings of smaller radius can be recommended if larger tail angle or width should be used. Wings with larger radius can be recommended if smaller tail angle or width are to be used. This is advantageous from both energy requirement and quality of penetration performance points of view.

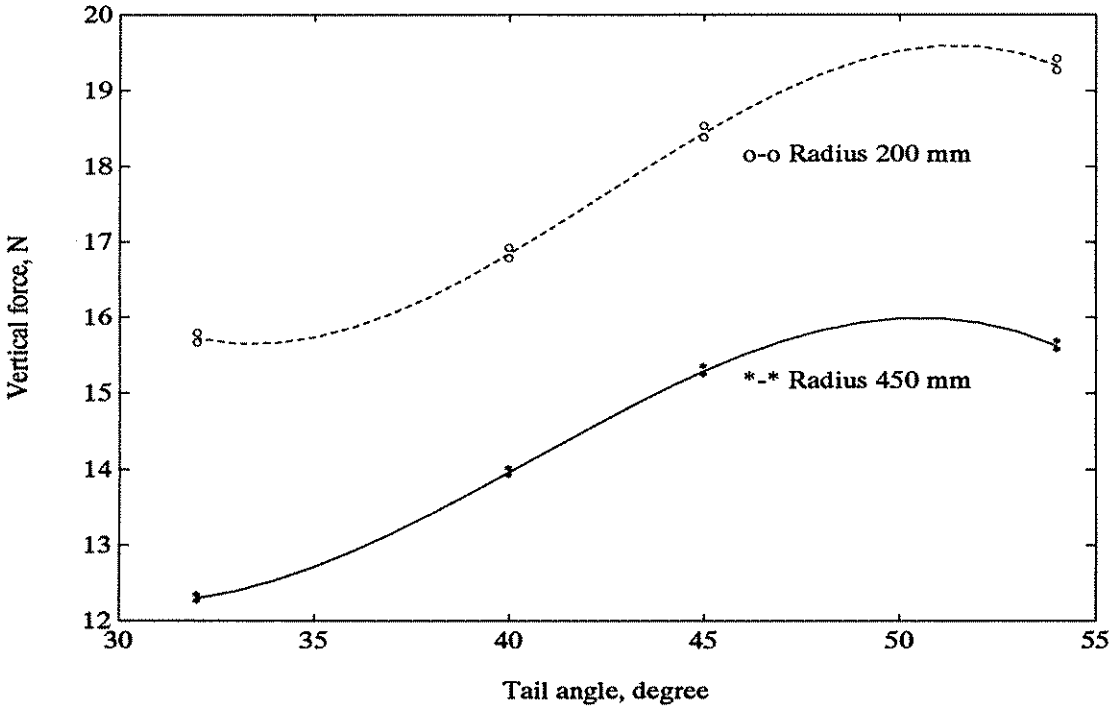

Fig. 27. Effect of radius on vertical force - tail angle relation

The influence of speed on the tail angle and force relation has also been examined. To study the relation, two speeds, 0.5 m/ and 0.8 m/s, were used. No appreciable difference in behaviour of the graphs obtained for the two cases can be observed. The differences in the absolute values of the experimental points, when using speeds 0.5 and 0.8 m/s, increased approximately linearly for every increase of tail angle (Fig. 28).

The effect of speed is very significant on the vertical force and tail angle relation. For lower tail angles, no significant difference was observed in comparison with the higher tail angles (Fig. 29). The impact of speed increased with an increase of tail angle. However , the behaviour of the graphs when using both speeds remained analogous.

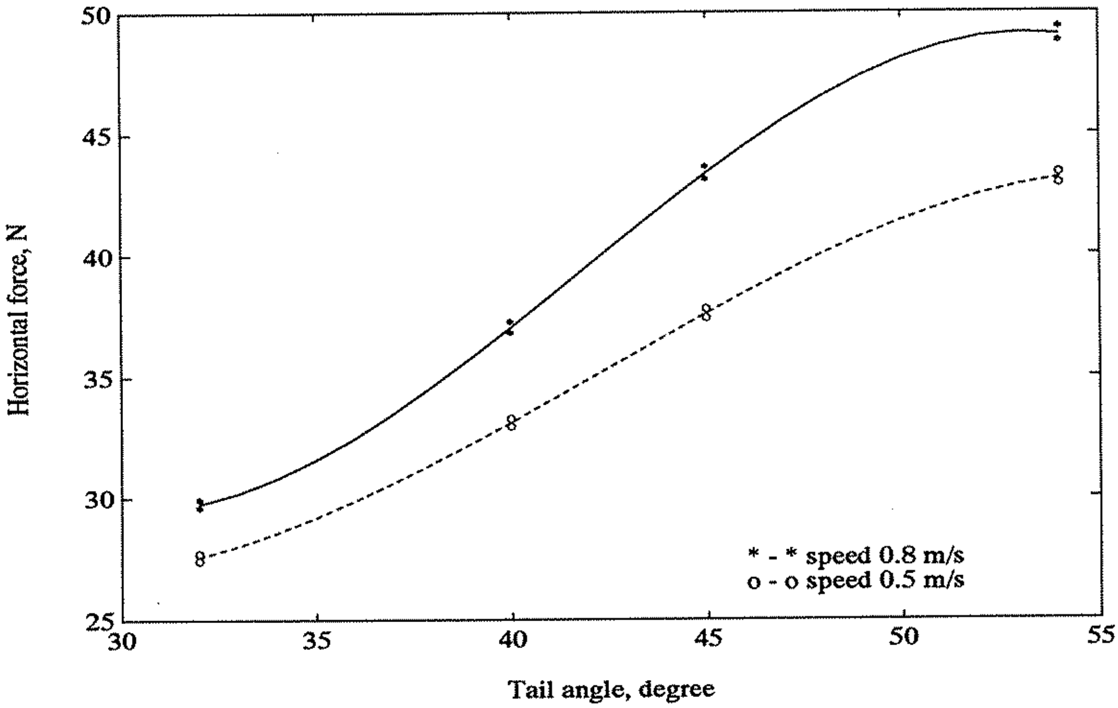

Fig. 28. Effect of speed on horizontal force and tail angle relation

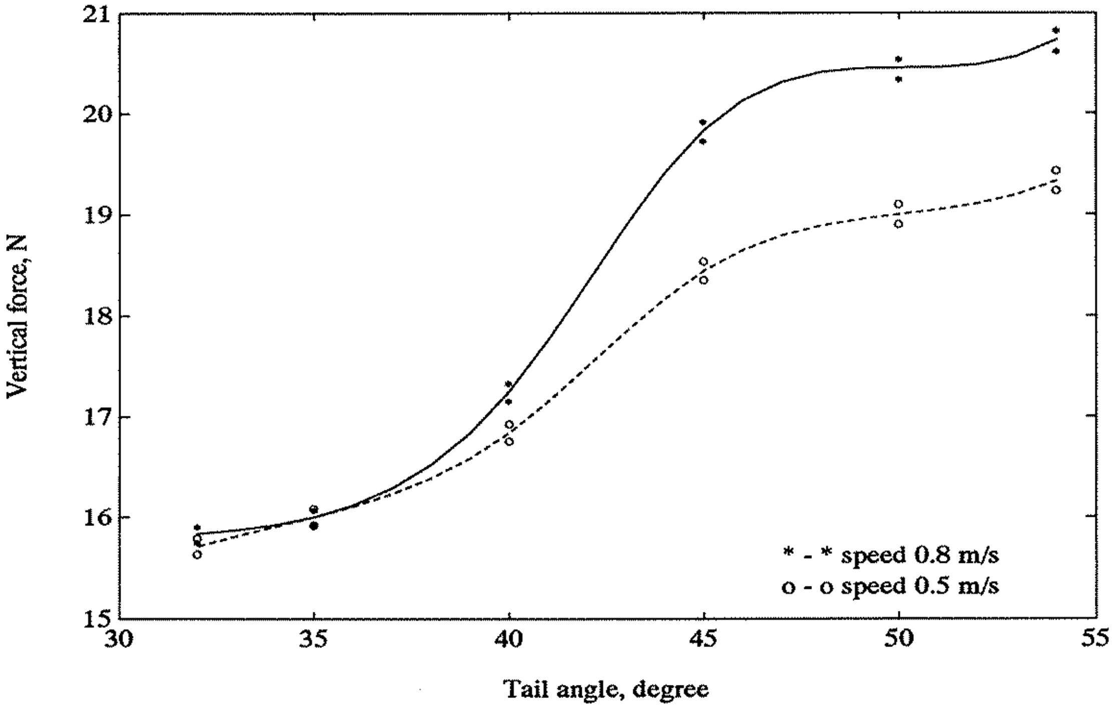

Fig. 29. Effect of speed on vertical force and tail angle relation

7. Design of an ard-type reversible plough

7.1. Design description

From the investigation made in the laboratory, a curvature of radius 275 mm was found to be the optimum value. The tail angles and side angles can be varied depending on the required turning degree and width. Based on the findings in the laboratory, basic designs of conventional mouldboard ploughs and Ethiopian ard type plough, a reversible plough has been designed. The developed plough (Fig. 30) has only one wing and can be reversed with an angle of reversibility of 110°. With the exception of the share point, all the plough components are made from wood and the total weight of the plough is about 10 kg. The design is so simple that it can be manufactured by local farmers themselves or blacksmiths and is light enough for transportation.

Both the share (1) (Fig. 30) and the wing (2) are mounted on the straight beam (5). The beam is mounted on a landside (3) in such a way that it can rotate 360°. The wing can be rotated around the common joint of wing and share point to vary the tail angle. Several alternative joints (4), as depicted in Figure 30, between the wing and the straight beam are designed to vary the tail angle with constant depth. The curved part of the pulling beam is mounted on the straight beam and the landside.

The plough is equipped with force measuring dynamometer (7) (Fig. 30), a wheel (9) for the measurement of ploughing speed and depth to conduct field experiments. The dynamometer is mounted between the curved and straight part of the pulling beam (6). The joints between the curved beam and the dynamometer was designed in such a manner that when the pulling force reaches about 2 kN looses. Using the dynamometer, three forces, i.e., horizontal, vertical and lateral forces and three moments can be measured simultaneously[12].

7.2. Angle of pull

To achieve stability, the line of action of the resultant soil forces and the line of pull should coincide. Angle of pull of an ard type plough can be adjusted by varying the height of the hitching point. Variation of angle of pull affects penetration of the plough and the vertical and horizontal force ratio. For conventional mouldboard ploughs this ratio varies[23], between 0.22 and 0.31. Assuming that this relation holds for the animal-drawn ploughs, the angle of pull could be estimated by calculating the arctangent of the ratios of vertical and horizontal forces.

Angle of pull for the Ethiopian traditional plough varies from 10° to 20°. For the present model, the angle of pull used was 15° and the calculated maximum bending moment for

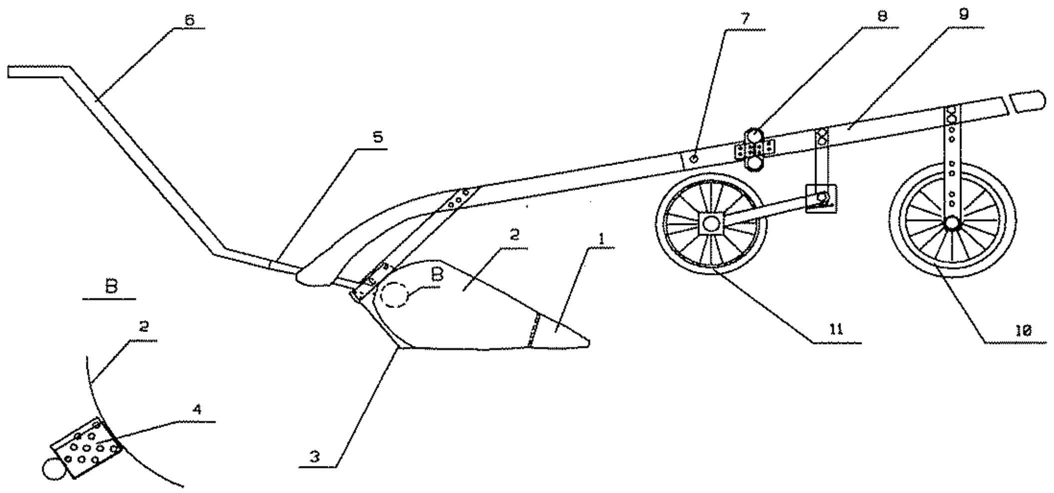

Fig. 30. Schematic view of the developed reversible plough. (1) share; (2) wing; (3) landside; (4) joint mechanism; (5) straight beam; (6) handle; (7) safety bolt; (8) extended octagonal ring dynamometer; (9) pulling beam; (10) depth control wheel; (10) depth and speed measuring wheel

the maximum resulting force of 2 kN was 100 Nm. If animals of different height and the same pulling beam are used, then the angle of pull should be changed automatically. In that case the rake angle of the bottom of the plough can be adjusted to maintain a good penetration and stability.

If the line of pull coincides with the line of action of the resultant force, then the line of action passes through 'the centre of action of the component forces, i.e., on the plough body (Fig. 31). To achieve this, the first part of the beam of the plough (the part nearer to the plough bottom) should be curved so that the remaining part (the straightened part)

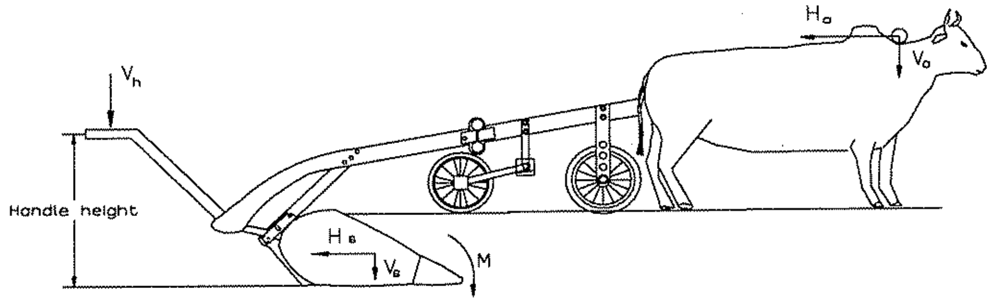

Fig. 31. Forces acting on a reversible model plough

should coincide with the line of action. Such an arrangement decreases bending moment on the beam and a beam is then subjected only to tension, and therefore a lighter beam could be used.

7.3. Handle height of the plough

Very few investigations have been made hitherto to optimize the height of a plough handle from an ergonomics point of view. Gite[24] studied Indian farmers to determine the optimum height of plough handle. He suggested that the height of a plough handle for an Indian farmer to be between 732 mm to 842 mm. Unpublished reports from research institutions in Ethiopia reported the above magnitude to be about 870 mm. For the newly developed reversible plough, the maximum height used is 900 mm and this can be adjusted to any height up to 700 mm if required.

8. Conclusions and discussions

Optimization of a curved tillage implement's design parameters, such as tail angle, side rake angle and radius are assumed to be important in terms of energy requirement. Results of the present investigations confirm the assumptions made. The resulting forces during operation are significantely affected by the variation of the design parameters.

The force and radius relation depends on the magnitude of tail angles. For smaller tail angles (about 30 to 40°) the horizontal force decreases significantly with an increase of radius. For the tail angle of about 45°, the force decreases with an increase of radius up to the radius of about 275 mm thereafter increases with further increase of radius. For the tail angles greater than 50°, the force increases with radius.

The above relation was not only influenced by the tail angles used but also by edge rake angles. Curves with bigger radius have larger edge rake angles than smaller curves and thus when the implement interacts with the soil, the resulting forces automatically depend on both the edge rake angle and the radius. The involvement of edge rake angle made the radius - horizontal force relation very complex. An increase of rake angle may cause an increase of the amount of soil to be disturbed even below the operational depth.

The influence of tail angle on the radius and vertical force relation was not significant. For all the tail angles used, the vertical force decreases exponentially with radius. This could be obvious since the amount of soil to be lifted decreases with an increase of radius.

From the assessment made a curve with the radius of about 275 mm was found to be optimum for soil operations with attenuated energy requirement.

The result of the present study on the tail angle and forces relation showed a considerable effect of variation of tail angles on both horizontal and vertical forces. For an implement moving at constant speed and smaller tail angles, the horizontal force is mainly due to friction. But for bigger tail angles it is due to both compressing normal force and frictional force. When bigger tail angles are used the implement pushes the soil not only aside but also forward and this results in a remarkable increase of especially the horizontal force.

The vertical force increased rapidly with tail angles up to 45° and increased slowly with further increase of tail angle. Both the horizontal and vertical forces could be described by the trigonometric equation, $H(V) = k_{\alpha t} l \sin(\alpha)$, where l is the length of the soil-engaging part of the wing and $k_{\alpha t}$ is constant.

The impact of speed on the tail angle and forces relation increases linearly with the tail angle. The tail angle and horizontal force relation was also found to be radius dependent. From the results of investigations made, wings of smaller radius could be recommended if larger tail angles should be used. Wings with larger radius could be recommended if smaller tail angles are to be used. This is advantageous from both energy requirement and quality of penetration performance points of view.

The effect of variation of side rake angle on the resulting forces was found to be considerable. The horizontal force increases with side rake angle while the vertical force decreases with an increase of side rake angle. The relations between side rake and the forces depend on operational speed and radius. The influence of speed was much more pronounced on the vertical force and side rake angle relation in comparison with the horizontal force. The effect of speed decreases with an increase of side rake angle. This could be due to the decrease of the amount of soil to be lifted and thrown.

Variation of radius has not shown a remarkable effect on the behaviour the side rake angle and forces relations with the exception of the differences in the absolute values. The differences in the relatives values of the vertical force were more considerable when comparing with the horizontal force.

The result of the investigation made on the combined effects of speed and radius revealed that speed plays important role than radius in the side rake angle and forces relations. The horizontal force resulted from the combination of larger radius and speed is greater than the combination of smaller radius and speed for all side angle used. However, this behaviour applies for the vertical force only for the side rake angles below 63°. The combination of smaller radius and higher speeds results in the unnecessary increase of the forces. Therefore, from the results observed, curves with larger radius could be recommended for the operation to be performed at higher speeds and lower side rake angles (below 63°) to achieve a good penetration performances and for the side rake angles above 63° the opposite combination could be an advantage.

Variations of radius and side rake angle showed appreciable effect on the speed and force relations. The effect of radius was noteworthy and the behaviour of the graphs for both the vertical and horizontal forces are almost similar. The forces increased gradually with speed for bigger radius and steeply for the smaller radius. This leads to the conclusion that curved implements with smaller radius should not be recommended for high speed operations.

Different behaviours of forces and speed relation have been observed when smaller and larger side rake angles were used. The horizontal force increased slowly when the implement mounted at smaller side rake angle while the vertical force increased rapidly for the same position of the implement. This enable us to conclude that implements mounted at smaller side rake angle require less horizontal force and a good penertation performance can be attained.

Polynomial equations were fitted to the sampled data using the statistical analysis to describe the force-radius, force-tail angle, force-side angle, force - speed relations and combined effects of radius and speed on side rake angle - force relations. Most of the equations fitted were second and third order polynomial models and elucidated the experimental data sufficiently.

On the basis of the results of the investigation made in the soil bin and on the basic design parameters of Ethiopian ard type plough and a conventional mouldboard plough, a reversible animal-drawn plough was developed. Except the share point, all the components of the plough were made from wood. The weight of the plough is 10 kg.

The dynamometer of the type used in the soil bin and the devices used to measure speed and depth are integrated into the plough to perform field experiments. Using the developed implement, a preliminary field test has been performed.

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