EFFECTS OF TREADER DESIGN AND OPERATING VARIABLES ON FORCE PREDICTION EQUATIONS IN OKLAHOMA

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PREFACE

This research has led to a quantitative understanding of the effect of depth of tillage, forward velocity and angle of orientation on treader draft, side-draft and vertical force. General multiplicative force prediction equations were developed to explain how treader operating variables affect soil forces. It was necessary to develop two vertical force prediction equations due to the difference in point leading as compared to point lagging.

I would like to thank Oklahoma State University for their financial assistance in the form of a one-half time assistantship throughout the duration of this research. Oklahoma State's financial support has made my studies in the United States possible. The completion of this research phase of my masters program was made possible by my Major Advisor, Dr. John Solie and I would like to offer my sincere thanks for his time, guidance and support. I would also like to thank my committee members, Dr. James Summers for his input, assistance and advice, and Dr. Willard Downs for his assistance in preparation of the final draft. I would like to express my appreciation to the staff of the agricultural engineering laboratories, who have been extremely friendly and helpful in assembling the tillage dynamometer. In particular, I would like to thank Bruce Lambert for his patience, efforts and electronics expertise.

I also would like to thank my American friends for their friendship and support and also my Australian friends for their many written communications. Many thanks to my parents, Mr. and Mrs. John Mulder, for their encouragement and support while I was in the United States of America.

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CHAPTER I

INTRODUCTION

One of the most important stages of crop production is the preparation of a seed bed. Wheat production involves several stages of tillage. The soil is initially broken by primary tillage implements, then conditioned by secondary tillage implements leaving a well prepared seed bed for planting. Primary tillage tools include moldboard plows, sweep plows, chisel plows and tandem and offset discs. Extensive studies of primary tillage tools have been conducted by Summers at al.(1986), Self et al.(1983), and Gerling (1983) for Oklahoma soil conditions. Primary tillage tools have been studied extensively due to the large amount of energy input required to operate them. In comparison, secondary tillage tools have received little attention.

A tillage tool used extensively for secondary tillage in Oklahoma wheat production is the treader. A treader was defined as a rolling gang of spiders which consisted of eight pointed tines. The spiders are evenly spaced along a central axle. This tillage tool is used extensively in the high plains wheat producing regions of the United States of America. The treader has several functions, primarily to prepare a seed bed by removing weeds and breaking clods, firming soil and incorporating chemicals. Quantitative understanding of the interaction of factors affecting treader operation is limited. Designers do not quantitatively understand how draft, side draft, and vertical force are related to depth of operation, angle of orientation, forward velocity, and treader rotational speed. For designers and machinery management personnel to better optimize treader operation, data needs to be collected to provide this information.

Objectives

The objectives of this research are:

1. To measure three orthogonal forces, forward velocity and rotational speed for three treader types.
2. To develop general force prediction equations by a similitude/dimensional analysis approach.

CHAPTER II

LITERATURE REVIEW

Introduction

No literature was found reporting any detailed investigations of treader operating variables. Manufacturers do not list engineering data. Frehlich and Kydd (1985) reported draft forces for Miller treaders (rotary flex weeders) as being 318 N/m at 9.7 km/h. They studied the Miller treader from the perspective of a potential buyer. Downs (1985) discussed the possibilities of treaders for combination equipment. He stated that treaders were used behind sweep plows to break up clods, uproot weeds and leave a suitable seed bed.

Rotary Tillers

Powered rotary tillers are similar to treaders in geometry. The methods and approaches used in rotary tiller studies may be useful for the study of unpowered rotary hoes and treaders. Kinzel et al.(1981) discussed the use of computer graphics to analyze rotary tillers. They set up matrix equations to study blade design in relation to the blade path. Hendrick (1980) tested a powered rotary tiller in a laboratory soil bin. He was interested in the efficiency of a powered tiller in comparison to a rigid chisel. He concluded the powered chisel was more efficient than a rigid chisel. Tillage performance was assessed on resulting clod size distribution, cross sectional area of soil disturbed, soil surface condition and specific power requirements (power/unit volume of soil).

Hendrick and Gill (1971a, b, c) extensively investigated power rotary tiller design parameters in a series of papers. Parameters analyzed involved direction of rotation, depth of tillage, ratio of peripheral to forward velocity, and blade clearance angle. Direction of rotation affected clod size. Reverse rotation resulted in larger clods due to blades breaking the soil rather than cutting through the soil when operating in a forward direction. They reported that reversed rotation reduced power input by 20% to 30%. Depth of operation combined with the cutting pitch affected the clod size distribution setting an upper limit on clod size. Cutting pitch was related to the ratio of forward and peripheral velocity.

Wright and Carter (1967) investigated the possibility of utilizing rotary hoes for chemical incorporation. They reported that the rotary tiller did an adequate job of chemical incorporation. Wright and Carter discussed rolling radius and blade curvature interaction on mixing. They reported reducing radius increased acceleration imparted to soil particles, causing increased incorporation or mixing.

Discs

Another rotating tillage tool was the unpowered disc. This tool has been studied from a different view point compared to rotary tillers. Hendrick and Gill (1976) investigated the effect of irregular cutting depths due to rotating circular tools. They concluded that the irregular depth was predictable and an effective depth could be calculated. Discs operated at excessive depths caused some soil areas to remain undisturbed.

Gill et al.(1980b) investigated the influence of velocity and disc angle on the ratio of rotational velocity to forward velocity. They reported that the absolute velocity of a point on the edge of a rotating disc had a cosinal nature with a maximum velocity when the point was at the lowest underground position.

Reaves et al.(1981) studied the effect of width and depth of cut on disc forces. They reported that vertical force was directly related to depth of penetration. The draft force of a disc was misleading when evaluating the influence of depth of cut on disc forces due to the fact that increased depth caused increases in the cross sectional area of soil disturbed. Gill et al., 1981, studied disc curvature effect on forces resulting in an optimum disc shape. The optimum shape was in the intermediate range of radii of curvature-to-disk diameter (1.33-2.92). They concluded that the relationship between draft and velocity was essentially linear. They also reported that an optimum disc angle of 25^{o} to 32^{o} reduced draft. Vertical force was a minimum at angles of 35^{o} to 40^{o}. Side-draft increased to a maximum at angles greater than 30^{o}.

Coulters

Tice and Hendrick (1986) studied coulter operating characteristics. They investigated kinematic data for several simple coulter geometries. They found coulter draft and vertical force were smallest for thin coulters with small wedge angles. In their study, a force ratio (draft divided by vertical force) was used to investigate coulter geometry. They concluded that the coulter geometry effect on force ratio was dependent on soil type. A velocity ratio (peripheral velocity divided by forward velocity) was found to be greatest for thick coulters with small wedge angles. They found a large velocity ratio to be the best for effective residue cutting. Coulter velocity was found to vary with depth of operation.

Similitude Tillage Studies

Larson et al. (1968) developed prediction equations for draft forces on moldboard plows. They compared model and prototype for different soil types and operating conditions in an effort to confirm the selection of pertinent variables. Quantities investigated included geometric plow dimensions and soil factors such as bulk density, soil cohesion, angle of internal shearing resistance and apparent soil cohesion. A similitude approach was utilized which involved nine dimensionless terms to develop prediction equations for distorted model prototype relationships.

Evans et al. (1985) used a similitude approach to investigate interaction effects between multiple chisel systems. A comparison of draft was made between two systems of different size. Comparison of draft was based on three different approaches; specific draft, draft ratio, and prediction factor. Specific draft was calculated by the draft on the tillage tools divided by the theoretical area of soil disturbed. Interaction between chisels was analyzed by using the draft of the center tool divided by the total draft for all three tools which gave a draft ratio. The prediction factor was the ratio of model to prototype draft forces. They concluded there was an optimum depth of operation to minimize specific draft.

Serohi and Reaves (1969) utilized similitude for studying cultivator sweep performance. They concluded that similitude techniques were adequate to predict cultivator sweep draft. They also stated soil parameters were lacking and needed to be determined for each soil.

Frietag et al. (1970) discussed requirements for similitude studies involving soils. They listed 32 soil parameters. Their appendices contained an extensive list of devices and methods for measuring soil parameters which included; direct shear test, ring shear test, shear graph, shear vane, plate penetration test, tilting plate penetrometer, cone penetrometer, vibratory test, tension test, beam loading, nuclear moisture density devices, density unit weight samplers, and particle size tests. The above list of soil measuring instruments indicated the numerous soil readings that could be included in tillage studies.

Mechanics and Soil Failure Involving Cutter Blades

Osman (1964) outlined theories of soil failure involving the mechanics of soil cutting blades. He investigated failure around both flat and curved blades passing through soil. Payne (1956) analyzed mechanical soil properties and performance of simple cultivator implements. He looked at effects of velocity, tine width and depth on draft in terms of soil failure to study wedge effects on the tine both qualitatively and quantitatively. He reported soil/metal friction was independent of velocity and concluded that sensitivity of draft to velocity should be small.

Oklahoma Tillage Studies

Self et al. (1983) studied draft and power requirements in Oklahoma soils of the following implements; a moldboard plow, a chisel plow equipped with points or sweeps spread 30 cm apart, a sweep plow, tandem and offset discs, and a chisel plow with 0.51 m centers. They were interested in primary tillage implements, considering these to be the high energy input component of tillage systems for Oklahoma.

Gerling et al. (1983) discussed minimum tillage systems for continuous wheat cropping in Oklahoma but did not include treaders. Summers et al. (1986) studied draft relationships for primary tillage in Oklahoma soils. Draft was found to be linearly proportional to velocity for chisel plows, disks, and sweep plows while the relation for moldboard plows was quadratic. Draft was found to be linear with depth for all four tillage implements investigated.

Downs (1985) discussed the use of treaders with sweeps and chisel plows. Treaders were considered to be very useful for Oklahoma conditions when combined with chisel and sweep plows for weed control and seed bed preparation.

Other Relevant Tillage Data

Frisby and Summers (1979) reported energy related data for the following implements; moldboard plows, chisel plows, field cultivators, tandem discs, row crop planters, grain drills, row crop planters, cultivators, and a hipper ripper. They compared their data with standards and other researchers.

Data Logger and Tillage Dynamometer

Summers et al. (1984) reported on the development of a second generation tractor performance monitor that could be used for general data acquisition on field implements. Reid et al. (1985) used a three point hitch dynamometer to measure draft using strain gages and a microcomputer based data acquisition system. This system enabled draft of any three point hitch system to be easily measured. Schoenleber (1955) and Zoerb (1963) discussed the use of strain gages for measuring forces. Clyde (1955) utilized strain gages to build a drawbar dynamometer.

Nyquist Criterion

Freeland et al. (1987) discussed the problems associated with sampling data with computers and explained the Nyquist Criterion. Signals should be sampled at a constant frequency of at least twice the frequency of the signals highest frequency component. In addition, sampling should occur for at least one full cycle of the signal's lowest frequency.

CHAPTER III

EQUIPMENT

Introduction

A machine was constructed in the Oklahoma State University Agricultural Engineering Laboratory to study the forces exerted by soils on treaders and develop general force prediction equations. This treader dynamometer (Figure 3.1) measured three orthogonal forces, forward velocity and treader rotational speed. A brief discussion of the design approach used for this machine will highlight some of its capabilities.

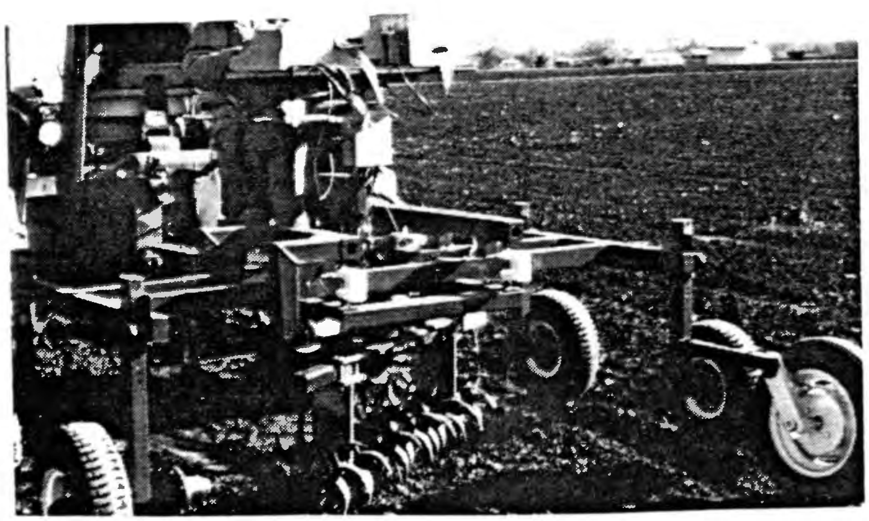


Figure 3.1. Treader Dynamometer

Force Measurement

Forces measured included draft, side-draft and vertical force. Moments were created by the draft and side-draft forces acting through the soil at the center of pressure. The load cell configuration measured the total vertical force while it cancelled the force created by the draft and side-draft moment components. It was necessary to ensure that the framework runs parallel with the soil surface for proper measurement. X, Y and Z force directions corresponded to draft, side-draft, and vertical force directions respectively.

The dynamometer used a rectangular frame suspended on four C-section load cells for vertical force measurement and restrained draft and side-draft in the horizontal plane by two C-section load cells located in x and y directions as shown by Figure 3.2. The purpose of suspending the framework by four load cells was to cancel moment effects due to draft and side-draft. The following proof shows how vertical force measurement was not affected by draft moments.

Sum moments about ($P_1 \cdot P_2$):

$$0 = (V_1 + V_2) \cdot A - X_o \cdot c - Z_o \cdot a \qquad (1)$$

where:
X_o = Draft Force
Z_o = Vertical Force
V_1 = Force in load cell #5
V_2 = Force in load cell #8
A, a, c = lever arm lengths (shown in Figure 3.2)

Sum Moments about $(P_3 \cdot P_4)$:

$$0 = Z_o \cdot (A - a) - X_o \cdot C - (V_3 + V_4) \cdot A \tag{2}$$

where:
X_o = Draft Force
Z_o = Vertical Force
V_1 = Force in load cell #5
V_2 = Force in load cell #8
(A-a), C, A = Lever Arm Lengths

Equate equations (1) and (2):

$$(V_1 + V_2) \cdot A - X_o \cdot c - Z_o \cdot a = Z_o \cdot (A - a) - X_o \cdot C - (V_3 + V_4) \cdot A \tag{3}$$

Reduces to:

$$V_1 + V_2 + V_3 + V_4 = Z_o \tag{4}$$

The above proof shows that vertical force measurement was not affected by moments created by draft forces. A similar proof would show that vertical force measurement was not affected by side-draft moments. The above proof was validated by placing known forces on the suspended frame. The dynamometer was found to measure three orthogonal forces accurately.

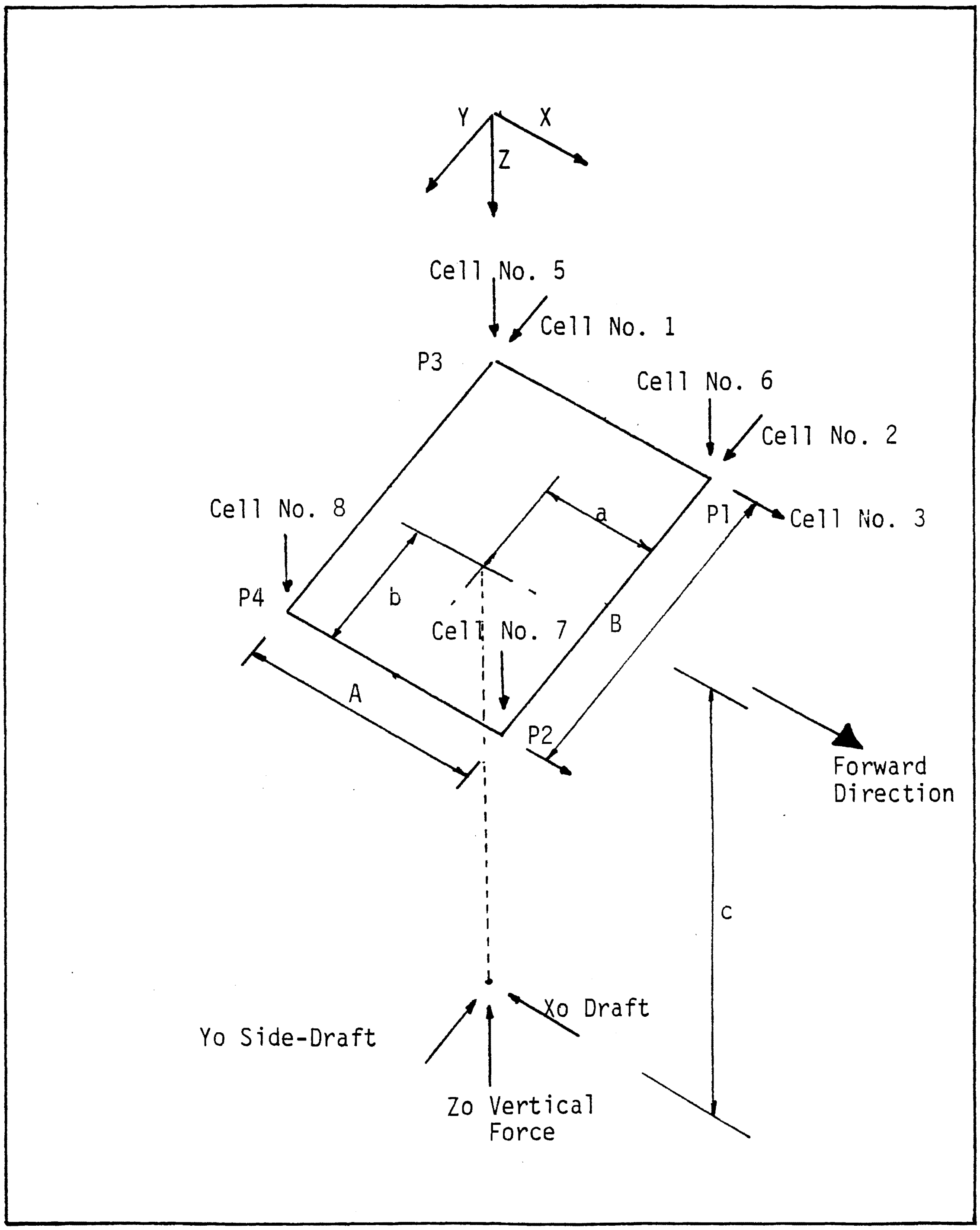


Figure 3.2. Suspended frame showing load cell location

Load Cells

C-section (Figure 3.3) load cell design was chosen to increase sensitivity and allow sufficient area for strain gage application. Each vertical load cell was designed for 2000 N. The horizontal cells were designed for loads of 900 N. Sensitivities of plus or minus 3.6 and 1.1 N/bit were achieved for the vertical and horizontal load cells respectively. A twelve bit, analogue to digital (A/D), converter with a gain of 1000 was used. A full bridge of strain gages (supply voltage equalled 10.09 volts) was used on each load cell. A full wheatstone bridge enabled temperature compensation. Aluminum 7075-T6 was chosen for construction due to increased sensitivity, high yield strength, machinability and availability.

Appendix A contains load cell calibration data. Each load cell was stamped with its respective number of one through eight. Numbers one and two measured side-draft, three and four measured draft and five, six seven and eight measured vertical forces. The cells were calibrated in both tension and compression. The dimensions of the load cells are contained in Appendix B.

Data Logger and Data Collection

Data Logger

An AIM 65 microcomputer, (Figure 3.4) described by Summers et al. (1984) was used to collect data. The data logger had an eight channel 12 bit A/D board which converts analogue voltage signals from load cell strain gauge bridges to digital signals. To measure velocities the data logger had two versatile interface adaptor (VIA) circuits with 16 bit counters. These counters were set in a decrementing mode.

Figure 3.3. C-section lateral and vertical load cells

Figure 3.4. Aim 65 microcomputer and floppy disc drive

Data Collection

A BASIC operating program (Appendix C) with two machine language subroutines collected, summed and averaged the force data. The data collection machine language subroutine (Appendix D) first started two counters which counted pulses generated by hall effect switches for speed readings (forward velocity and treader rotational speed). The data logger collected three blocks of 256 force readings for each load cell. The data collection subroutine read cells one through eight (switching channels zero through seven on the mutiplexer for the 12 bit A/D board) 256 times consecutively and repeated this three times.

Freeland et. al (1987) reported that the Nyquist Criterion of Sampling Theorem states a signal should be sampled at a constant interval of at least twice the frequency of its highest frequency component. In addition, the sampling should occur for at least one full cycle of the signal's lowest frequency. The highest frequency component at a maximum forward velocity of 12 km/h was 33 Hz and the time for one full cycle, at a low forward velocity of 8 km/h, was 0.053 seconds. The data collection subroutine sampled at a rate of 342 Hz which was 10 times the highest signal frequency. Time between readings was 0.0029 seconds. Data was collected over 2.245 seconds which allowed 42 signal cycles to occur at the low signal frequency. After the force data was collected, the two speed/pulse counters were interrupted and read.

The data collection machine language subroutine returned to the BASIC operating program. The BASIC operating program utilized a machine language summation subroutine (Appendix E) to sum the 768 (256 x 3) force readings for each load cell. The BASIC operating program calculated average force readings for each load cell and summed the respective cells to obtain average total forces for the x, y, and z directions of draft, side-draft, and vertical force respectively. Before running a test in the soil, a set of force readings which were the offsets, were taken with the machine stationary, level and with gauge wheels just off the ground. These average readings were subtracted from operating average readings to give absolute average forces taking treader weight and load cell offsets into account. This data was printed out on paper tape. The BASIC operating program had the option of storing all raw data (ie. the three blocks of 256 readings from the eight load cells) in ASCII form to floppy disc.

Velocity Measurements

Treader Rotational Speed

Treader rotational speed was measured using a hall effect switch and 60 tooth sprocket as shown in Figure 3.5. The 60 tooth sprocket was driven via a shielded flexible cable connected to the treader. The flexible shielded cable allowed angle changes through 60 degrees. The speed measurement unit could be quickly detached and attached to another treader. Each tooth generated a pulse as it passed the hall effect switch. The speed was measured by counting the pulses or number of sprocket teeth to pass the switch in a given time (program time of 2.245 seconds). The VIA on the datalogger used a 16 bit timer/counter circuit set for counting in a decrementing mode. Every 60 pulses was one treader revolution. By dividing the number of pulses by 60 and then dividing by the counting pulse time period, treader speed in revolutions per second was calculated.

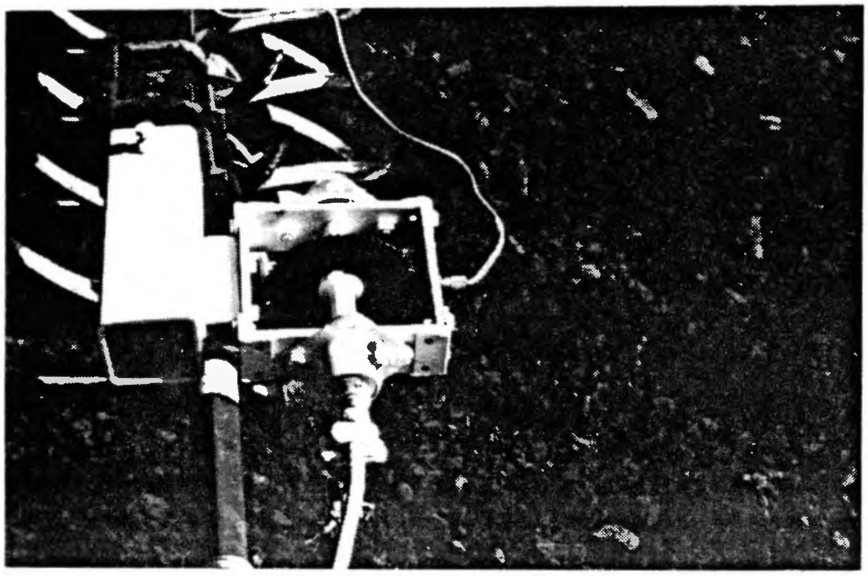


Figure 3.5. Treader speed measurement by a 60 tooth sprocket and hall effect switch

Forward Velocity

Forward velocity was measured by a fifth wheel equipped with a 60 tooth sprocket as shown in Figure 3.6. As teeth passed a hall effect switch, pulses were generated and counted by using another VIA on the datalogger. The timing circuit used another 16 bit timer counter set in a decrementing mode. Forward velocity was calculated by first determining the number of wheel revolutions per second. This was calculated in the same manner as the treader revolutions per second. The wheel perimeter (2.0701 m) multiplied by the wheel revolutions per second resulted in forward velocity measured in meters per second. The fifth wheel was located to the rear of the machine and ran in the gauge wheel track.

Velocity measurement accuracy was checked manually by measuring the time with a stop watch required to travel a known distance and calculating the velocity.

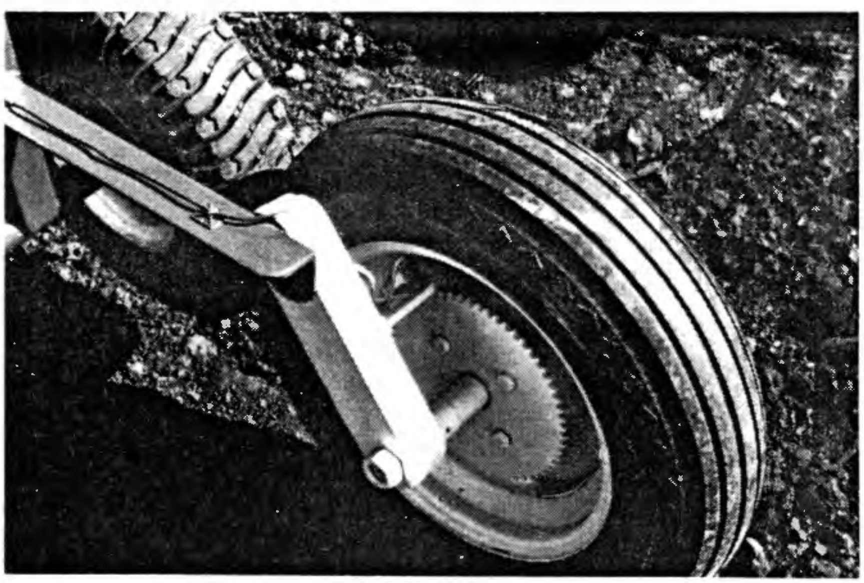


Figure 3.6. Forward velocity measurement with a hall effect switch and 60 tooth sprocket

Treaders

Treader Types

Treaders manufactured by Miller W Corp. of Stratton, Nebraska (Figure 3.7), Flex-King (now Sunflower) of Quinter, Kansas (Figure 3.8) and Richardson Manufacturing of Cawker City, Kansas (Figure 3.9), were tested to determine any significant difference in performance based on type and to develop general force-operating variable relationships. Treaders had the same radius of 0.225 m and spider spacing of 0.15 m. Overall treader length was 1.2 m. All three treaders were supported by two bearing mountings. The Miller treader had bearing supports at the outer axle ends and the Flex-King and Richardson bearing mountings were within the spiders.

Flex-King. The Flex-King was shortened by reducing the number of spiders to nine. This left all three treaders with nine spiders. The Flex-King spider tines were made of 32x10 mm flat steel and had a constant curvature. Each spider consisted of two sections. Each section contained four tines spaced 90° radially apart. One section was rotated through 45° relative to the other section, and the sections were welded to either side of a circular plate.

Richardson. The Richardson tines had a semi-elliptical cross section with a major axis length of 35 mm and minor axis length of 10 mm. The flat side of the ellipse faced to the rear of the treader when operated in a forward direction. The tines were curved and twisted out of the spider plane in the treader axis direction. Alternating spiders were rotated 22.5° relative to the other spiders.

Miller. The Miller tines were manufactured from 38x10 mm flat steel. These tines were flat with a sharp bend approximately 90 mm out from the axle. The Miller spiders were aligned in the same manner as the Richardson.

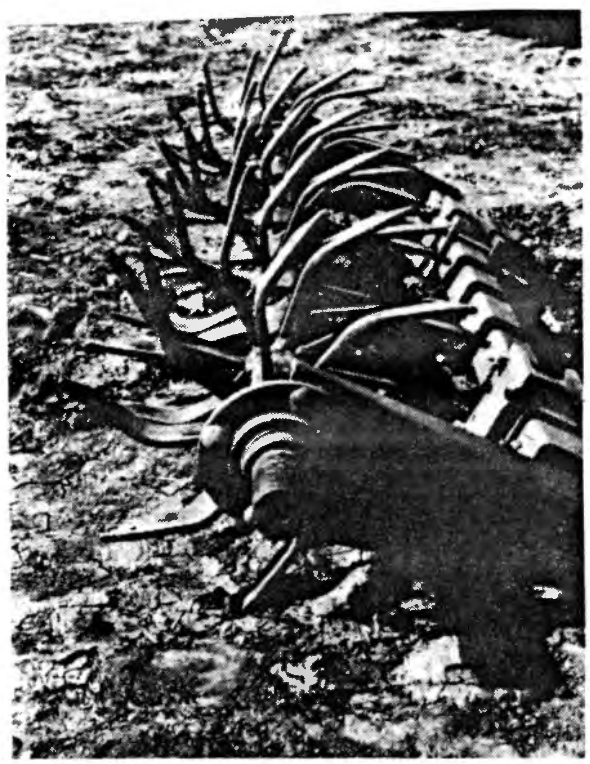


Figure 3.7. Miller Treader

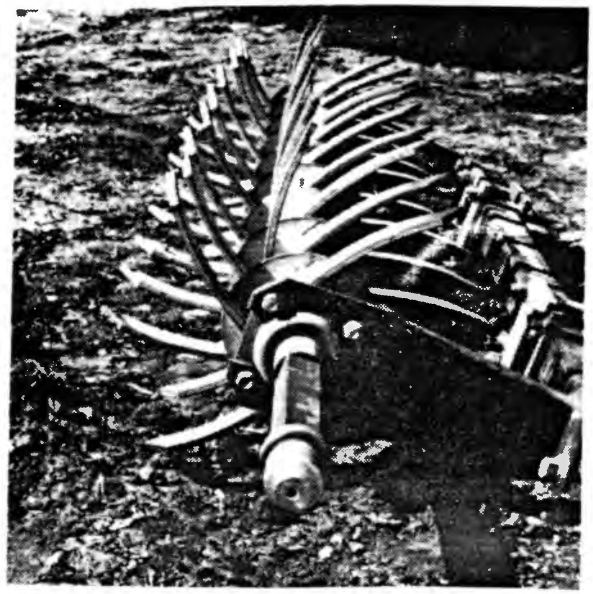


Figure 3.8. Flex-King Treader

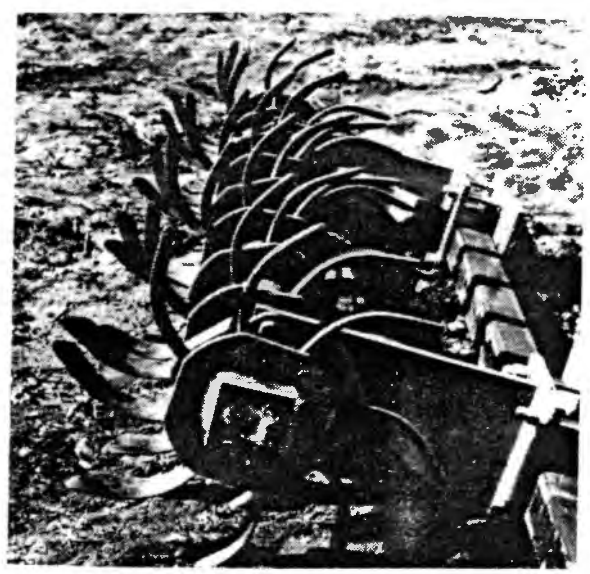


Figure 3.9. Richardson Treader

Treader Operation

Treaders can be operated in either a forward (normal) or reverse rotational direction. Treaders can be operated with the tine point leading or lagging as shown in Figure 3.10. Manufacturers claim that tine point leading offers greater penetration and tillage depth. When operated in the normal direction their purpose is to compact the soil and break up aggregates by a rolling motion as shown in Figure 3.11. When operated in reverse mode, they tend to work similarly to a rotary hoe, inducing more air into the soil by raking through the soil and throwing soil particles into the air.

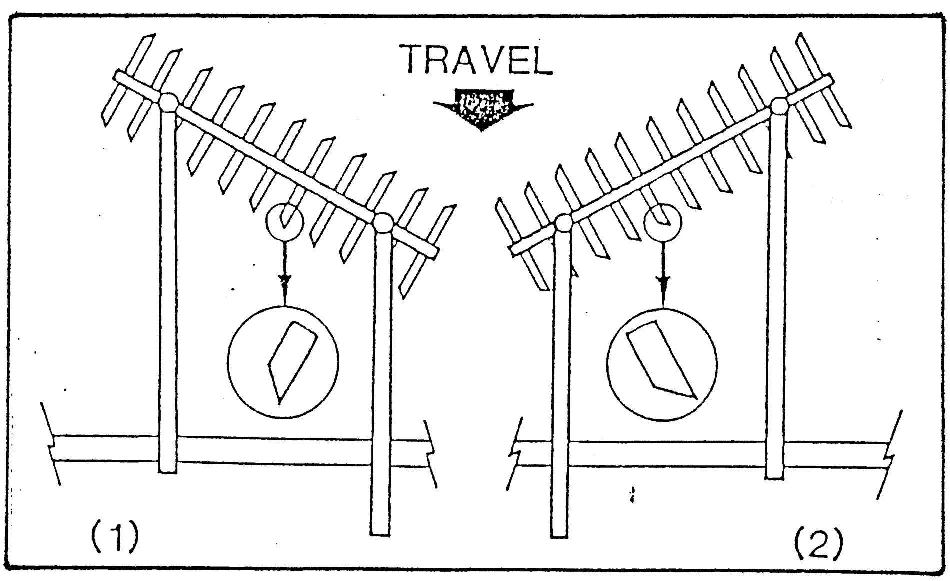


Figure 3.10. Treader tine tip leading(1) or tine tip lagging(2)

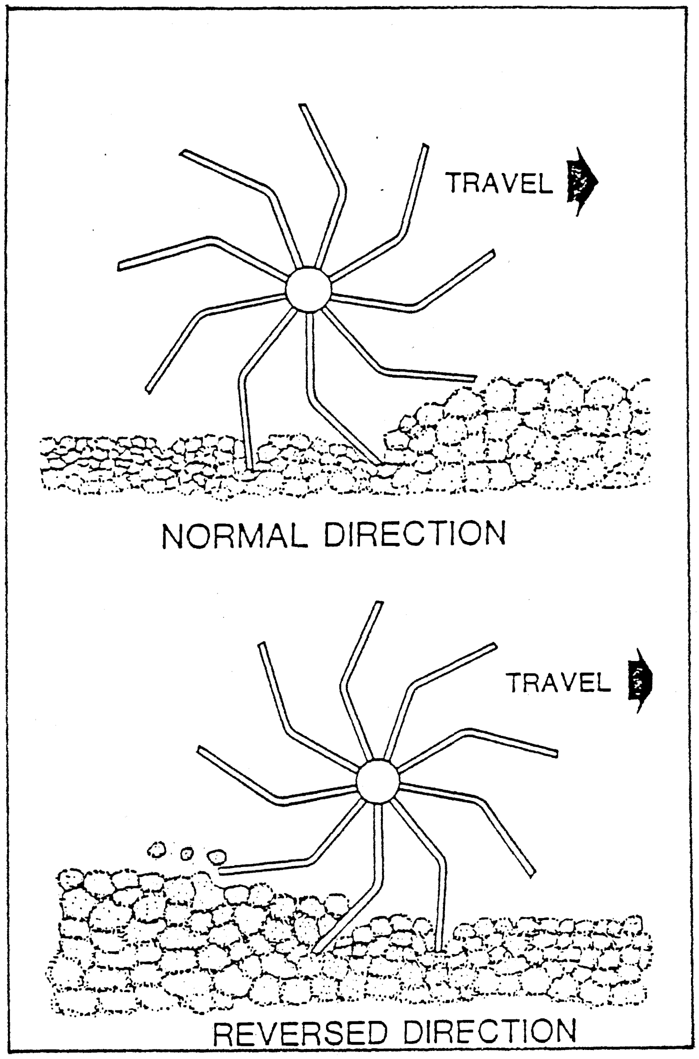


Figure 3.11. Treader Direction of Rotation

CHAPTER IV

METHODS AND PROCEDURES

Introduction

This experiment was designed to develop general orthogonal force prediction equations. A dimensional analysis or similitude approach enabled a reduction in the experimental size. The following discussion explains the approach used to design the experiment for data collection necessary to develop general force prediction equations.

Experimental Design for Force Prediction Equation Development

The variables which can be controlled are depth of operation, forward velocity, treader operation angle to direction of motion, and treader type. If a complete statistical approach were used, the experiment would become unmanageable requiring in excess of 500 plots. Time taken to conduct such an experiment would allow soil conditions to change significantly, making a determination of differences in treader design difficult to achieve. Murphy (1950) offered a solution to reducing the size of the experiment by using a similitude or dimensional analysis approach. The major advantage of a similitude approach is that it reduces the experiment to a manageable size while developing a dimensionally homogeneous prediction equation with some physical basis.

A similitude approach involved defining the pertinent quantities as listed in Table I. Once these quantities were defined, a check was made to determine their independence. Once independence has been established between pertinent quantities, as shown by Table II, dimensionless terms commonly called Pi terms, were developed.

The Buckingham Pi Theorem, (Murphy, 1950) stated: "the number of dimensionless and independent quantities required to express a relationship among variables in any phenomenon is equal to the number of quantities involved, minus the number of dimensions in which those quantities may be measured."

In equation form the Pi theorem is:

$$s = n - b \tag{5}$$

in which s is the number of pi terms, n is the total number of quantities involved and b is the number of basic dimensions involved. Murphy (1950) noted that: " the only restrictions placed on Pi terms is that they be dimensionless and independent". Table III lists a possible set of Pi terms. By reducing the matrix contained in Table IV, independence of Pi terms was indicated. The similitude approach assumed independence between pertinent quantities and independence between pi-terms. If these assumptions did not hold, then a new set of pertinent quantities would have needed to be developed.

TABLE I

PERTINENT QUANTITIES

		Symbol	Units
1.	Forces(x,y,z)	F	F
2.	Depth	D	L
3.	Cone Index	CI	FL^{-2}
4.	Forward velocity	V	LT^{-1}
5.	*Characteristic length	L	L
	-Radius		
	-Total treader width		
	-Tine width or length		
6.	Angle of orientation of treader	θ	-
7.	Treader peripheral velocity	S	LT^{-1}

* Characteristic length: treader radius, width or curvature length.

TABLE II

DIMENSION MATRIX

	F	D	CI	V	L	θ	S
F	1	0	1	0	0	0	0
L	0	1	-2	1	1	0	1
T	0	0	0	-1	0	0	-1

Rank = 3
No. of pertinent quantities = 7
Buckinghams Pi theorem s = n - b = 7 - 3
Therefore no. of Pi terms required = s = 4

TABLE III

POSSIBLE SET OF Pi TERMS

Pi Term	
Pi1 =	$\frac{F}{CI*L^2}$
Pi2 =	$\frac{D}{L}$
Pi3 =	$\frac{V}{S}$
Pi4 =	θ

TABLE IV

DIMENSION MATRIX INDICATED INDEPENDENT Pi TERMS

	Pi1	Pi2	Pi3	Pi4
F	1	0	0	0
D	0	1	0	0
CI	-1	0	0	0
V	0	0	1	0
L	-2	-1	0	0
0	0	0	0	1
S	0	0	-1	0

Rank = 4 therefore independent set of Pi terms.

A similitude approach resulted in the following prediction equation:

$$Pi1 = f(Pi2, Pi3, Pi4) \tag{6}$$

Pi1 is the dependent dimensionless quantity. Each Pi term contains one quantity which can be varied independently while other Pi terms are held constant. For Pi2, Pi3 and Pi4 working depth, forward velocity and treader orientation angle can be varied for the respective Pi term. An explanation of prediction equation development will be found in Chapter V.

Field Layout

To limit the size of the experiment and to collect enough data for an analysis, the experiment was designed as follows. Three depths, four forward velocities, and seven treader angles were run for each treader type. Note that only one variable is altered for each treatment.

An incomplete randomized block design (unbalanced experiment) was used, each block containing 36 treatments replicated four times. The experiment was blocked by soil type. Three treaders were run through twelve combinations of angle, depth, and forward velocity. The four average field velocities were 1.92, 2.29, 2.77, and 3.29 m/s. The three average working depths were 30, 60, and 90 mm. Treader angles used were -30°, -20°, -10°, 0°, $+10^{\circ}$, $+20^{\circ}$, and $+30^{\circ}$. Treader depth was preset by adjusting four gauge wheels. Depth was determined by measuring the distance from the center of the treader axle to the soil surface. Reported operating depth was the treader radius minus this distance. See Table V for an outline of the similitude experimental design and block randomization. A schematic to explain treader angle of orientation is shown in Figure 4.1. Four replications gave a total of 144 plots, each plot being 3 m by 15.25 m.

Penetrometer

A tractor mounted cone penetrometer described by Reithmuller (1982) was used to collect five cone index readings within each plot. Fifteen cone index readings were taken over a depth of 100 mm and averaged to produce a probe reading. The five probe readings were then averaged to produce an average plot cone index value. These values are contained in Appendix F.

Soil Description

Thirteen soil samples were taken across the field resulting with an average 12.22 percent moisture content (dry basis). The moisture content results are contained in Appendix G. These same samples were used to determine the soil texture by particle analysis. The field at the South Central Research Station, Chickasha, Oklahoma. The soil averaged 43 percent silt, 32 percent clay and 26 percent sand. The soil type was a Reinich silt loam in blocks 1 to 3, and a McLain silt loam in block four. The blocks were

TABLE V

TREADER EXPERIMENTAL DESIGN

Treatment #		Depth (mm)	Average Velocity (km/h)	Angle (°)	Block # I	II	III	IV
					Plot #			
1	Flex-King	60	1.92	-20	20	33	24	14
2	Flex-King	60	2.29	-20	11	16	9	29
3	Flex-King	60	2.77	-20	24	2	4	4
4	Flex-King	60	3.29	-20	2	8	30	11
5	Flex-King	60	2.77	-30	18	22	6	5
6	Flex-King	60	2.77	-10	15	27	5	8
7	Flex-King	60	2.77	0	26	5	16	3
8	Flex-King	60	2.77	10	3	20	2	26
9	Flex-King	60	2.77	20	9	1	20	21
10	Flex-King	60	2.77	30	19	26	25	22
11	Flex-King	30	2.77	-20	27	19	22	35
12	Flex-King	90	2.77	-20	22	15	8	19
13	Miller	60	1.92	-20	12	21	13	36
14	Miller	60	2.29	-20	33	17	36	24
15	Miller	60	2.77	-20	1	11	27	13
16	Miller	60	3.29	-20	8	3	15	10
17	Miller	60	2.77	30	23	29	17	12
18	Miller	60	2.77	10	21	6	11	20
19	Miller	60	2.77	0	30	24	21	33
20	Miller	60	2.77	-10	28	12	3	30
21	Miller	60	2.77	20	35	10	12	7
22	Miller	60	2.77	-30	32	28	10	1
23	Miller	30	2.77	-20	13	35	28	9
24	Miller	90	2.77	-20	4	9	33	25
25	Richardson	60	1.92	-20	36	32	26	15
26	Richardson	60	2.29	-20	6	23	32	17
27	Richardson	60	2.77	-20	17	7	34	34
28	Richardson	60	3.29	-20	16	18	19	31
29	Richardson	60	2.77	30	5	14	23	23
30	Richardson	60	2.77	10	14	25	18	27
31	Richardson	60	2.77	0	10	31	7	18
32	Richardson	60	2.77	-10	34	34	29	6
33	Richardson	60	2.77	20	31	36	1	16
34	Richardson	60	2.77	-30	7	30	14	2
35	Richardson	30	2.77	-20	25	13	35	28
36	Richardson	90	2.77	-20	29	4	31	32

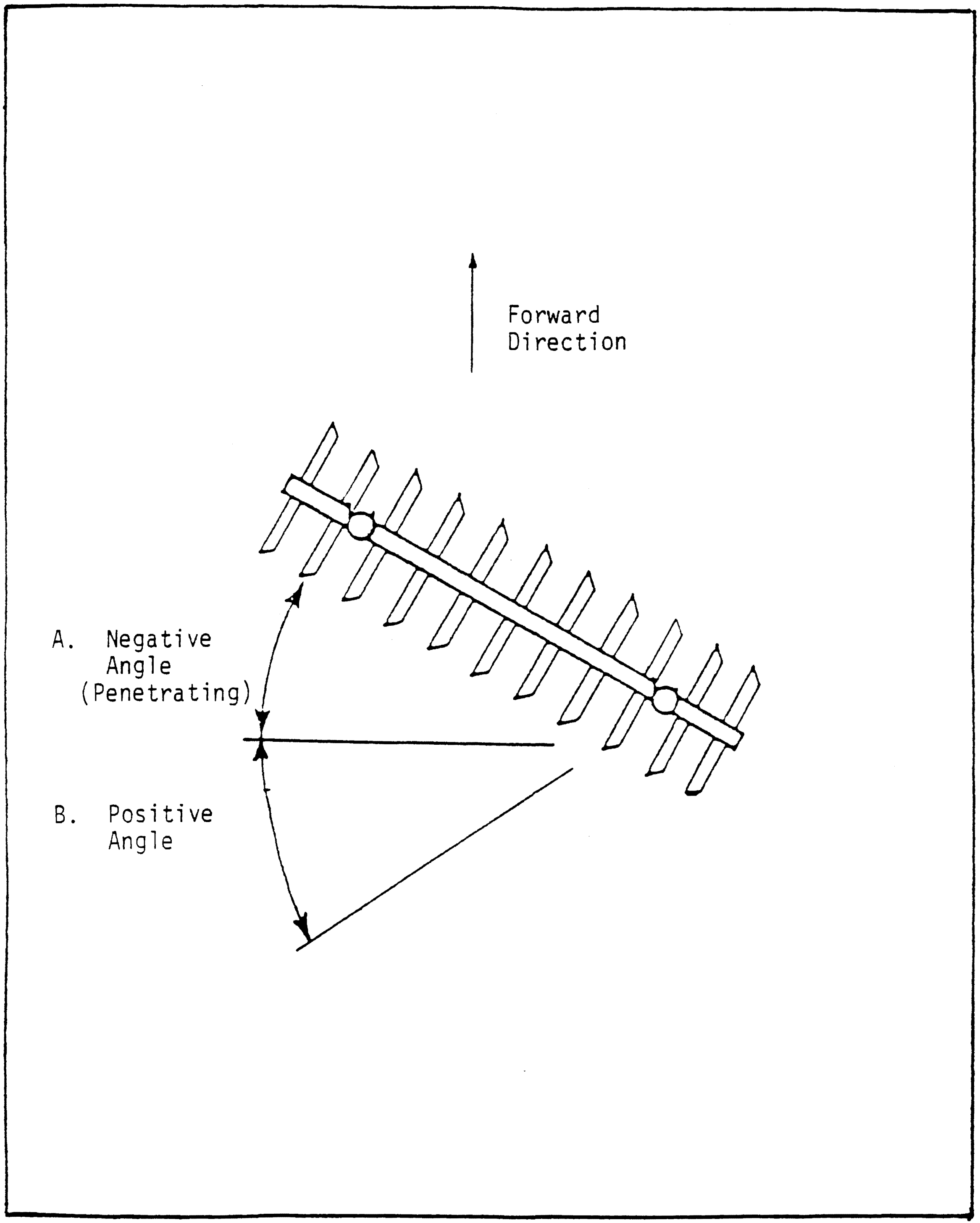


Figure 4.1. Schematic to Explain Treader Orientation Angle

placed in a direction to counteract the soil and field variability.

Previous Tillage

Prior to conducting the experiment, the soil was tilled at a depth of at least 100 mm with a sweep plow. Snow and rain fell on the plots which required the field to be cultivated by sweep plow again. The second sweep plowing was necessary due to the compaction caused by rain and snow. The field was cultivated twice with a spring tooth harrow to speed up the soil drying process leaving the soil in a condition typical for treader operation.

CHAPTER V

RESULTS AND DISCUSSION

Introduction

Data was analyzed in a number of methods to determine general multiplicative force prediction equations, significant differences among treaders and general relationships between forces and operating variables. Analysis methods included: Analysis of variance (ANOVA), correlation analyses, and linear regression using the Statistical Analysis System, (SAS, 1982) on an IBM 3081D mainframe computer. To conduct these analyses, three different data sets were used. In the first step, the entire data set of 144 observations was used in a similitude approach for force prediction equation development. Appendix F contains this entire field data set. This field data set was used for analysis of variance tests to determine significance of operating variables and interactions among treader-operating variables.

To determine general relationships between forces and operating variables (depth, forward velocity and treader orientation angle), the data set was reduced to average values for each treatment. Forces, cone index, forward and peripheral velocity were averaged for the four replications resulting in a data set of 36 average treatment values contained in Appendix H. This data set was used to develop general multiplicative force prediction equations.

To determine general relationships and gain an understanding of how treader forces change with depth, forward velocity and angle of orientation, the set of 36 treatment values were averaged by velocity, depth and angle over treader type. This data set consisted of 12 average values (one for each treatment) and was used to verify the general multiplicative force prediction equations developed. By reducing the field data to a set of 12, treader variability was removed which enabled development of general relationships between forces and operating variables.

Statistical Analysis

Analysis of variance was conducted on the field data set which contained 144 observations. This analysis (Table VI) showed significant variables and interactions for treader operation. ANOVA with a Means Duncan (SAS, 1982) was run to determine treader force rankings and investigate point leading as compared to point lagging.

Draft

An analysis of variance for draft data indicated that forward velocity (PR>F=0.0393) and treader angle (PR>F =0.0505) were significant. Increased velocity and larger angles produced increased draft forces. Treader

TABLE VI

ANALYSIS OF VARIANCE RESULTS SHOWING SIGNIFICANCE LEVELS FOR OPERATING VARIABLES

Source	DF	PR>F
Draft		
Depth	2	0.0001
Velocity	3	0.0393
Angle	6	0.0505
Treader Type	2	0.1472
Type * Depth	2	0.1523
Type * Velocity	6	0.2180
Type * Angle	12	0.2819
Block	3	0.1309
Side-draft		
Depth	2	0.0001
Velocity	3	0.0001
Angle	6	0.0001
Treader Type	2	0.0001
Type * Depth	4	0.0024
Type * Velocity	6	0.4358
Type * Angle	12	0.0002
Block	3	0.7744
Vertical Force		
Depth	2	0.0114
Velocity	3	0.0517
Angle	6	0.0001
Treader Type	2	0.0292
Type * Depth	4	0.1086
Type * Velocity	6	0.4423
Type * Angle	12	0.7349
Block	3	0.0018

interactions were not highly significant for type-depth, type-velocity and type-angle interactions. Although not a significant factor, the Richardson treader produced the highest average draft (Table VII).

Side-draft

Depth, velocity, angle and treader type were all highly significant (PR>F=0.0001). The Flex-King treader produced the highest side-draft, followed by the Miller with Richardson producing the lowest draft. Duncan's test declared all means significantly different (Table VII). Type-depth (PR>0.0024) and type-angle (PR>F=0.0002) interaction were both highly significant. Side-draft was shown to increase with increasing depth. Side-draft decreased as velocity increased. As the treader angle of orientation changed it reached a minimum or near zero value and then increased to a maximum at $\pm 30^{\circ}$.

Vertical Force

Decreased angle (PR>F=0.0001) and increased depth (PR>F=0.114) were highly significant factors which produced increased vertical forces. Decreased velocity (PR>F=0.0517) significantly increased vertical force. Treader type was a significant factor (PR>F=0.0292) affecting vertical force with Richardson (mean vertical force= 2139 N) higher than the Miller (mean vertical force= 2095 N) (Table VII). Vertical force for the Miller was higher than the Flex-King

TABLE VII

EFFECT OF TREADER TYPE ON DRAFT, SIDE-DRAFT AND VERTICAL FORCE FOR ALL VELOCITIES, DEPTHS AND ANGLES

	Treader Type	Average Force(N)	Grouping Alpha=0.05
Draft			
	Richardson	1381 N	A*
	Flex-King	1367 N	A
	Miller	1301 N	A
Side Draft			
	Flex-King	445 N	A
	Miller	309 N	B
	Richardson	232 N	C
Vertical Force			
	Miller	-1941 N	A
	Flex-King	-2095 N	A
	Richardson	-2195 N	A

*Mean in a column is followed by the same leter are not significantly different at the 0.05 level using Duncan's New Multiple Range Test.

(mean vertical force= 1941 N). Type-depth, type-velocity, and type-angle interactions were not highly significant for vertical force which indicated that the vertical force behaved similarly for all treader type interactions.

Direction of Treader Angle

Manufacturers claimed differences for operating treaders with tine points leading or lagging. Point leading was reported to offer better penetration. Point lagging firmed or compacted the soil. For this experiment, a negative angle indicated point leading. By performing an ANOVA and arranging means according to magnitude (MEANS DUNCAN), SAS determined significant differences and rankings.

A test was conducted to determine significant differences between point leading and point lagging. Only data for positive and negative angles were included in this test. This test indicated draft was not significantly different for point leading compared to point lagging (Table VIII). A highly significant difference (PR>F=0.0001) did occur for the side-draft for point leading which indicated significantly lower side-drafts. The vertical force was highly significantly different (PR>F=0.0004) for point leading and lagging. Vertical forces were significantly lower.

Treader type was a significant factor (PR>F=0.0197) affecting absolute draft and absolute vertical force (PR>F=0.0299)but did not significantly affect absolute side-

TABLE VIII

ANALYSIS OF VARIANCE FOR THE ABSOLUTE VALUE OF DRAFT, SIDE-DRAFT AND VERTICAL FORCE AS A FUNCTION OF TREADER TYPE AND SIGN OF TREADER ANGLE OF ORIENTATION

Source	DF	PR>F
Draft		
Block	3	0.0955
Type	2	0.0197
Magnitude	2	0.0053
Sign	1	0.3844
Type * Magnitude	4	0.4185
Type * Sign	2	0.1140
Magnitude * Sign	2	0.8192
Type * Magnitude * Sign	4	0.7544
Side-draft		
Block	3	0.7477
Type	2	0.3909
Magnitude	2	0.9849
Sign	1	0.0001
Type * Magnitude	4	0.0099
Type * Sign	2	0.0025
Magnitude * Sign	2	0.0001
Type * Magnitude * Sign	4	0.9591
Vertical Force		
Block	3	0.0016
Type	2	0.0299
Magnitude	2	0.0016
Sign	1	0.0004
Type * Magnitude	4	0.8644
Type * Sign	2	0.4966
Magnitude * Sign	2	0.6579
Type * Magnitude * Sign	4	0.9281

Note: Analysis for an average velocity of 2.77 m/s, depth of 60 mm and angle of 0^{o} removed.

draft for the treaders operated at 2.77m/s, 60 mm depth and angles less than or greater than 0^{o} (Table VII). The Miller treader produced significantly lower draft forces than the other treader types (Table IX). The Richardson had significantly higher draft force than the Miller (Table IX).

The type by sign interaction was a highly significant factor (PR>F=0.0025) for side-draft (Table VIII). The Richardson leading produced significantly lower side-draft than the Flex-King leading and all treaders lagging. However, the Miller treader was not significantly different than the Richardson leading (Table X).

These differences in side draft and vertical forces for different point orientation can be explained by the manner the tool enters the soil and the amount of work done to the soil. With point leading, the tine has to shift more soil sideways, doing more work. With point leading, the reduction in vertical force can be explained by the tine entering the soil more like a knife. Vertical force and side-draft could both not be minimized by operating with point leading.

Initial and final soil conditions may be more important than the treader orientation angle to define preferred operation modes. The magnitude of forces may be related to the distribution of soil aggregates and size which result from a pass with a treader.

TABLE IX

EFFECT OF TREADER TYPE ON DRAFT, SIDE-DRAFT AND VERTICAL FORCE FOR -30^{o}, -20^{o}, -10^{o}, 10^{o}, 20^{o} AND 30^{o} ANGLES

	Treader Type	Average Force (N)	Grouping Alpha=0.05
Draft			
	Richardson	1364	A*
	Flex-King	1362	A
	Miller	1213	B
Side-Draft			
	Richardson	-118	A
	Miller	-112	A
	Richardson	- 41	A
Vertical Force			
	Richardson	-2224	A
	Flex-King	-2024	AB
	Miller	-1880	B

Note: Analysis for an average velocity of 2.77 m/s and depth of 60 mm.

*Mean in a column is followed by the same leter are not significantly different at the 0.05 level using Duncan's New Multiple Range Test.

TABLE X

EFFECT OF TREADER TYPE AND DIRECTION OF ORIENTATION COMBINATION ON ABSOLUTE VALUE OF DRAFT, SIDE-DRAFT AND VERTICAL FORCE

	Treader Type	Orient-tation	Average Force(N)	Grouping Alpha=0.05
Draft				
	Flex-King	Lagging	1406 N	A*
	Richardson	Leading	1389 N	A
	Richardson	Lagging	1338 N	A
	Flex-King	Leading	1318 N	A
	Miller	Leading	1295 N	A B
	Miller	Lagging	1130 N	B
Side Draft				
	Flex-King	Lagging	1056 N	A*
	Miller	Lagging	1007 N	A B
	Flex-King	Leading	974 N	A B
	Richardson	Lagging	905 N	A B
	Miller	Leading	783 N	A B C
	Richardson	Leading	669 N	C
Vertical Force				
	Miller	Leading	1708 N	A*
	Flex-King	Leading	1887 N	A B
	Richardson	Leading	1945 N	A B
	Miller	Lagging	2052 N	A B
	Flex-King	Lagging	2161 N	A B C
	Richardson	Lagging	2505 N	C

Note: Analysis for an average velocity of 2.77 m/s, depth of 60 mm and angle of 0^{o} removed.

*Mean in a column is followed by the same leter are not significantly different at the 0.05 level using Duncan's New Multiple Range Test.

Similitude Analysis

Similitude techniques were used initially in an attempt to formulate general force prediction equations. This technique involved forming dimensionless groups of pertinent quantities and establishing relationships between them. A similitude prediction equation would result in one of the following forms for this experiment:

$$Pi1 = A_o * Pi2 + A_1 * Pi3 + A_2 * Pi4 + A_3 \qquad (7)$$

or

$$Pi1 = A_o * Pi2^{A1} * Pi3^{A2} * Pi4^{A3} + A_4 \qquad (8)$$

where Pi1 = dependent dimensionless variable

Pi2, Pi3 and Pi4 are independent dimensionless variables and A_o, A_1, A_2, A_3 and A_4 are coefficients or exponents. Pi2 is a depth ratio, Pi3 is a speed ratio and Pi4 an angle.

Once this equation is developed, the dependent Pi term (Pi1) can be reduced, leaving a dimensionally homogenous equation with force as the dependent variable in terms of treader operating variables. To develop the force prediction equation, relationships are developed between Pi1 and Pi2, Pi3 and Pi4 as follows:

$$Pi1 = M_o * Pi2 + C_o \qquad (9)$$

$$Pi1 = M_1 * Pi3 + C_1 \qquad (10)$$

$$Pi1 = M_2 * Pi3 + C_2 \qquad (11)$$

where M_o, M_1, M_2, are slopes and C_o, C_1, C_2 are intercepts.

Table XI contains the form of Pi terms used in this analysis. By including either forward velocity and

TABLE XI

EQUATIONS USED TO CALCULATE VARIOUS Pi TERMS

Force Ratios (Length=0.15m or 0.225)

$$Pi1X = \frac{\text{X Force}}{\text{Cone Index x (Length)}^2} \qquad Pi1Z = \frac{\text{Z Force}}{\text{Cone Index x (length)}^2}$$

$$Pi1Y = \frac{\text{Y Force}}{\text{Cone Index x (Length)}^2}$$

Speed Ratios (Length=0.225m)

$$Pi3A = \frac{\text{Forward Velocity}}{\text{Treader Peripheral Velocity}}$$

$$Pi3B = \frac{\text{(Forward Velocity)}^2}{\text{Acc. due to Gravity x Length}}$$

$$Pi3C = \frac{\text{(Treader Peripheral Velocity)}^2}{\text{g x length}}$$

$$Pi3D = \frac{\text{(Forward - Peripheral)}^2}{\text{g x length}}$$

$$Pi3E = \frac{\text{(Forward - Peripheral)}}{\text{Forward Velocity}}$$

$$Pi3F = \frac{\text{(Forward - Peripheral)}}{\text{Peripheral Velocity}}$$

$$Pi3G = \frac{\text{1 - (Forward - Peripheral)}}{\text{Forward Velocity}}$$

$$Pi3H = \frac{\text{1 - (Forward - Peripheral)}}{\text{Forward Velocity}}$$

$$Pi3I = \frac{\text{Relative Velocity in X Direction}}{\text{Forward Velocity}}$$

$$Pi3J = \frac{\text{Relative Velocity in Y Direction}}{\text{Forward Velocity}}$$

$$Pi3K = \frac{\text{Relative Velocity in XY Plane}}{\text{Forward Velocity}}$$

Depth Ratio (Length=0.15m)

$$Pi2 = \frac{\text{Depth}}{\text{Length}}$$

Angle Ratios

Pi4 = Angle(Rads)

Pi4A = Sin (Angle)

Pi4B = Cos (Angle)

acceleration due to gravity or peripheral velocity and acceleration due to gravity, different Pi3 terms were formed. Relative velocities were calculated and used to develop additional combinations of Pi3 terms. Pi4 was defined as an angle Pi term and both sine and cosine of the angle were regressed against Pi1X, Pi1Y, and Pi1Z, draft, side-draft, and vertical force ratios respectively.

The linear regression analysis results are contained in Table XII. Regression analysis results were from the complete field data set which contained 144 observations. Plots of dependent Pi terms Pi1X, Pi1Y and Pi1Z against the independent Pi terms, Pi2, Pi3A and Pi4 are shown in Figures 5.1-5.9. Problems arose trying to develop relationships between the dependent Pi term and independent Pi terms because of low correlation between Pi terms. The scatter of the graphs and low regression correlation of dependent to independent Pi terms was primarily due to variability of the cone index.

Cone index was used to characterize soil strength and produce a dimensionless force Pi term. The coefficient of variation for cone index readings across the field plots ranged from 25 to 60 percent. The coefficient of variation for a treatment was as high as 40 percent. The coefficient of variation of cone index for the field was 50 percent. The average cone index for the field was 350 kPa and ranged from a low of 77 kPa to a high of 662 kPa. Such a large variation in cone index made prediction of the force ratio

TABLE XII

SIMILITUDE REGRESSION ANALYSIS RESULTS

Ind Var.	Dependent Variables PI1X		PI1Y		PI1Z	
	R^2	PR>F	R^2	PR>F	R^2	PR>F
PI2	0.3346	0.0002	0.3052	0.0005	0.4606	0.0001
PI3A	0.0461	0.1428	0.0530	0.1153	0.0741	0.0613
PI3B	0.0086	0.5317	0.0339	0.2099	0.0007	0.8599
PI3C	0.0181	0.3622	0.0474	0.1372	0.0016	0.7893
PI3D	0.0244	0.2888	0.0101	0.4962	0.0875	0.0412
PI3E	0.0466	0.1403	0.0531	0.1151	0.0756	0.0585
PI3F	0.0461	0.1428	0.0531	0.1151	0.0756	0.0585
PI3G	0.0005	0.8814	0.0033	0.6973	0.0348	0.2040
PI3H	0.0001	0.9394	0.0091	0.5195	0.0207	0.3288
PI3I	0.0466	0.1403	0.0531	0.1151	0.0756	0.0585
PI3J	0.0466	0.1403	0.0531	0.1151	0.0756	0.0585
PI3K	0.0408	0.1687	0.0486	0.1322	0.0644	0.0818
PI4	0.0361	0.0835	0.7434	0.0001	0.0010	0.7709
PI4A	0.0003	0.8827	0.0041	0.5605	0.0010	0.7740
PI4B	0.0016	0.7217	0.0011	0.7624	0.1207	0.0012

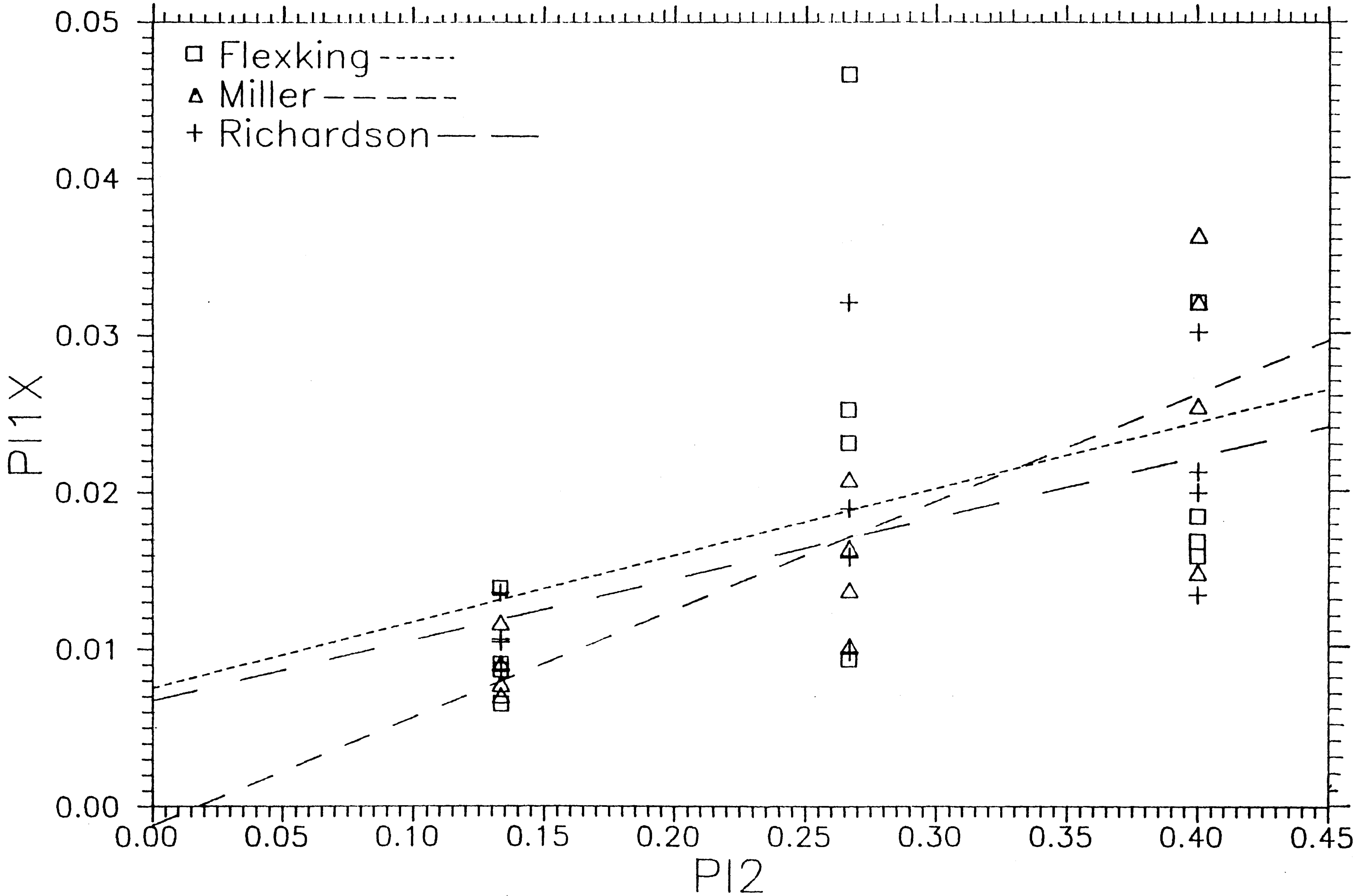


Figure 5.1. Draft Ratio Versus Depth Ratio

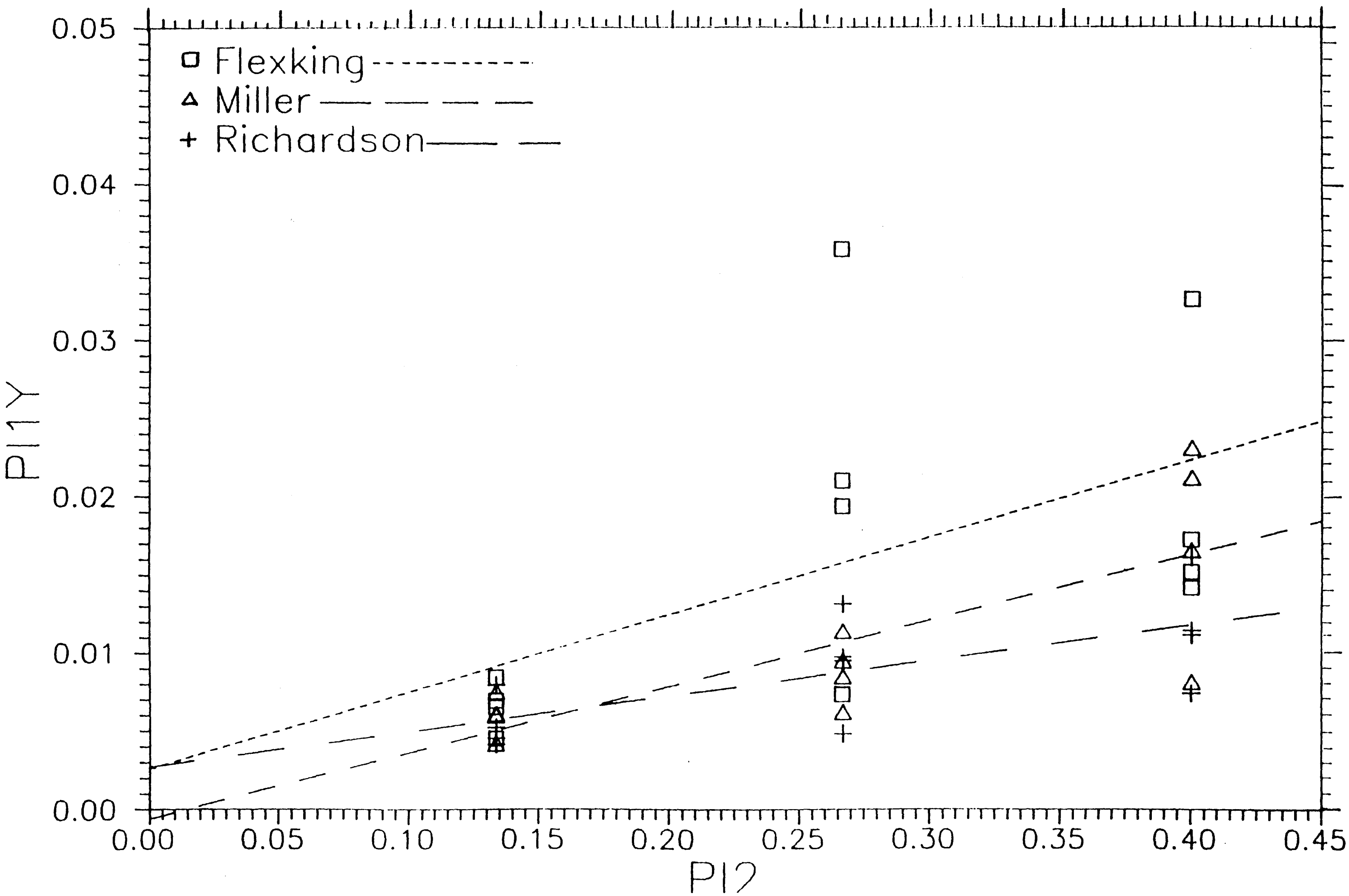


Figure 5.2. Side-Draft Ratio Versus Depth Ratio

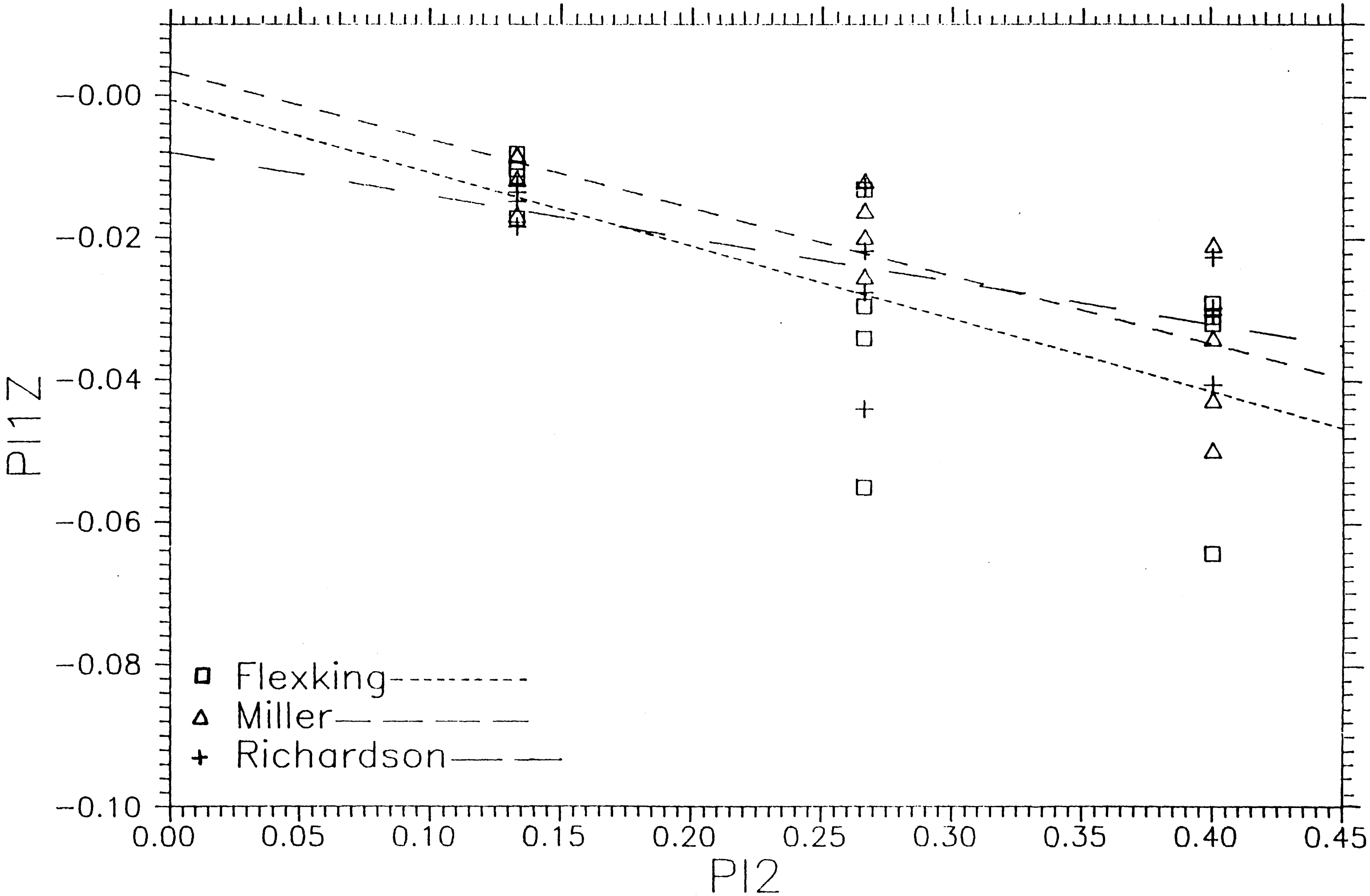


Figure 5.3. Vertical Force Ratio Versus Depth Ratio

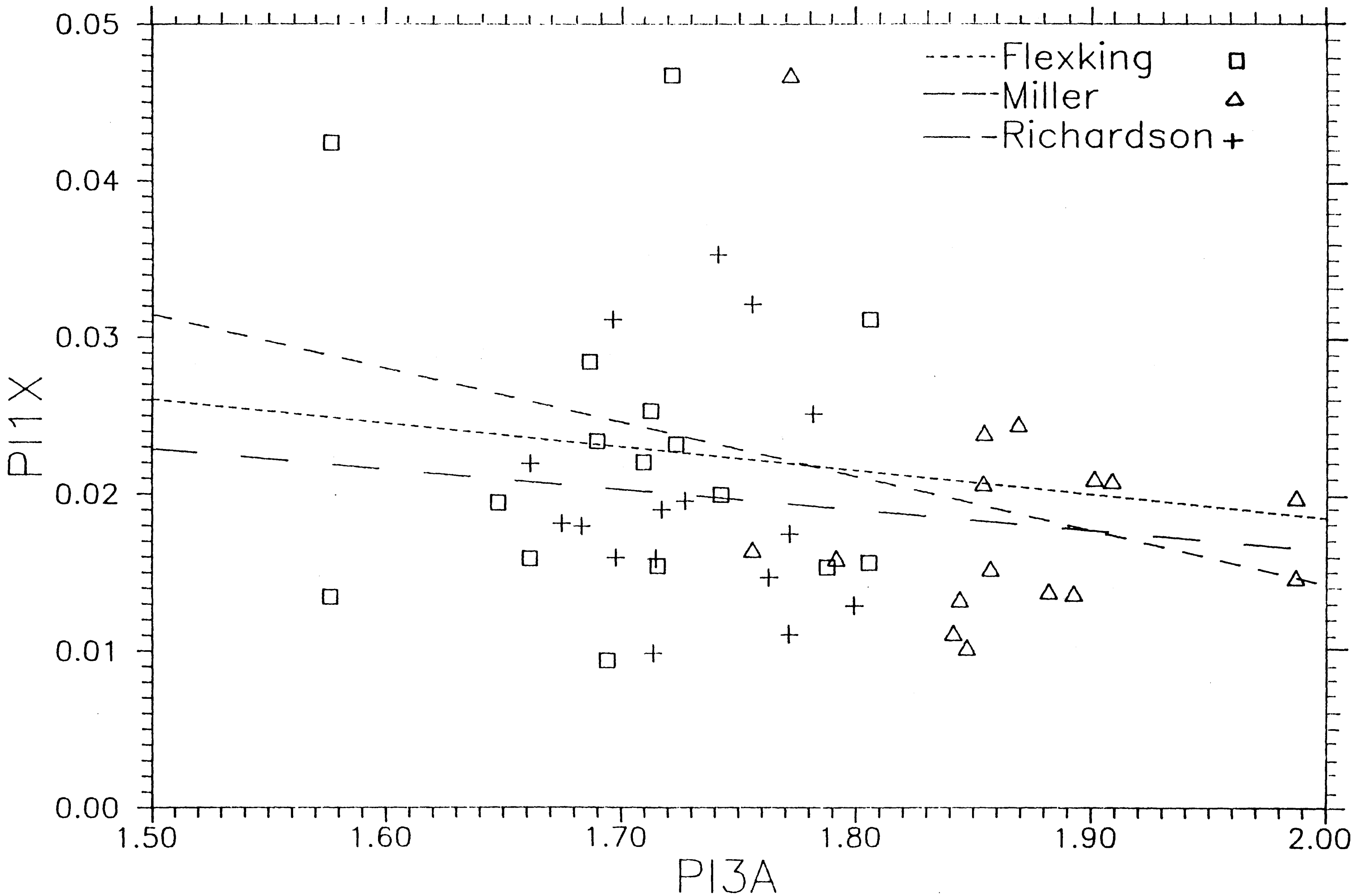


Figure 5.4. Draft Ratio Versus Velocity Ratio

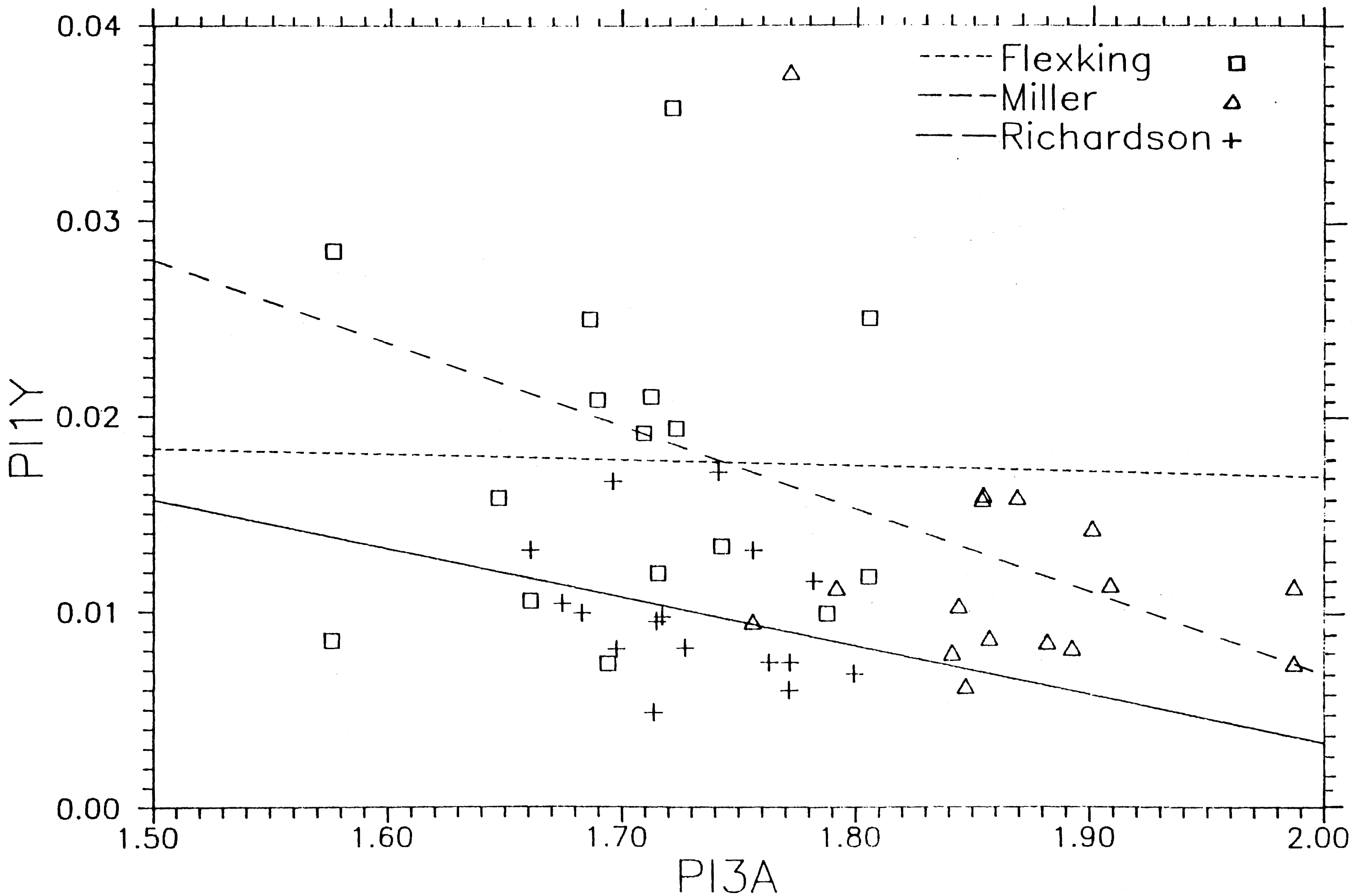


Figure 5.5. Side-Draft Ratio Versus Velocity Ratio

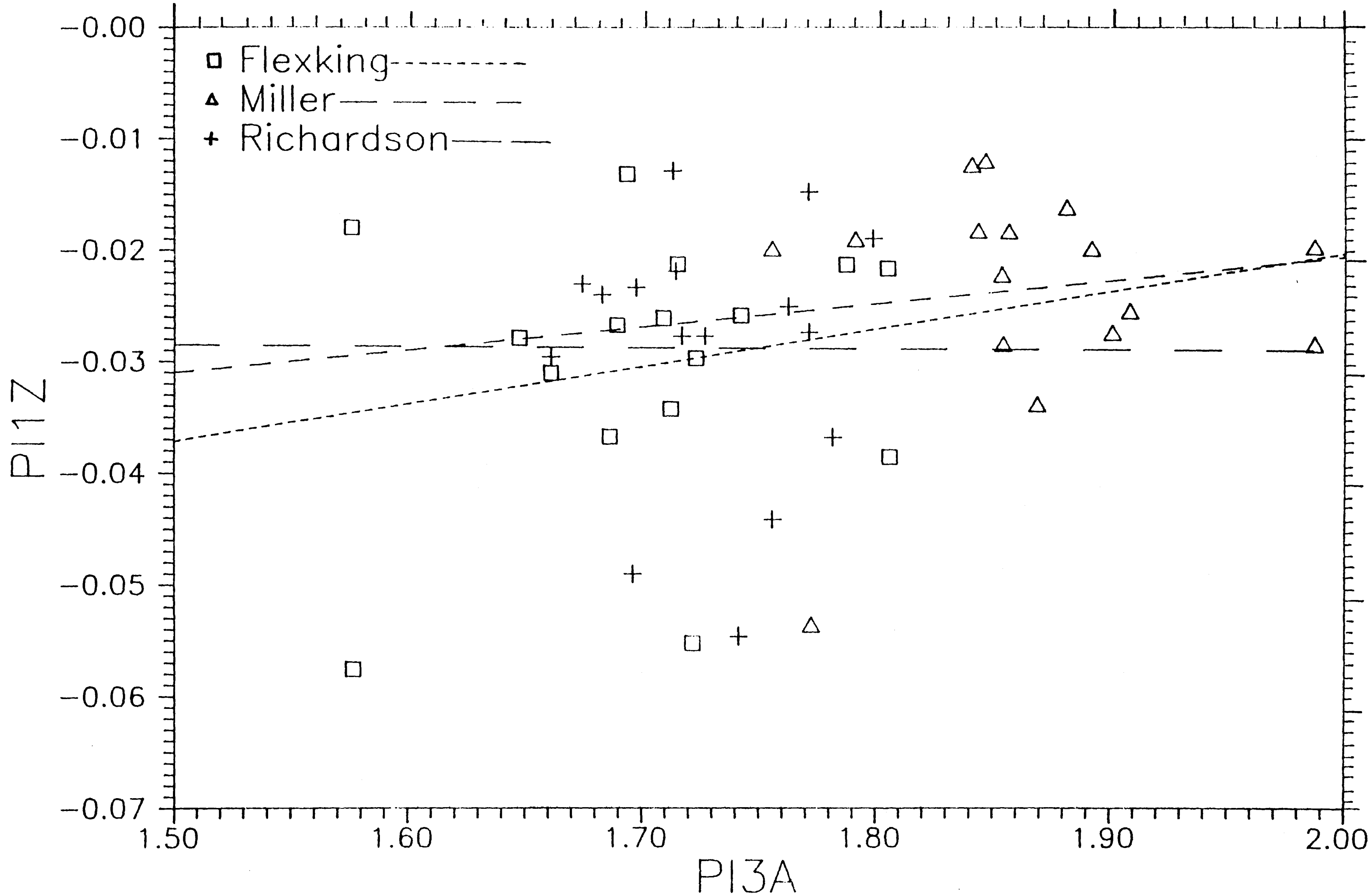


Figure 5.6. Vertical Force Ratio Versus Velocity Ratio

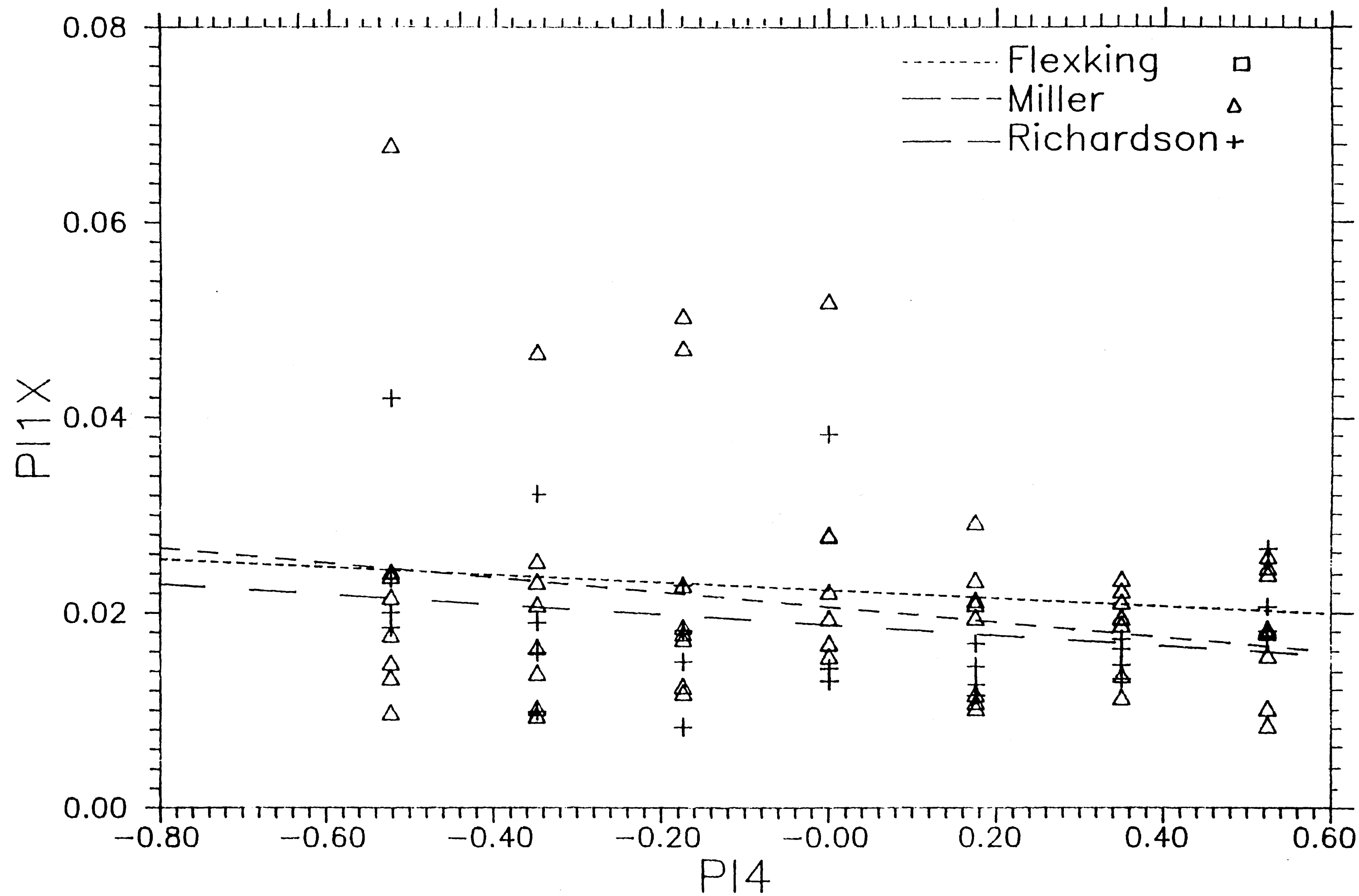


Figure 5.7. Draft Ratio versus Angle

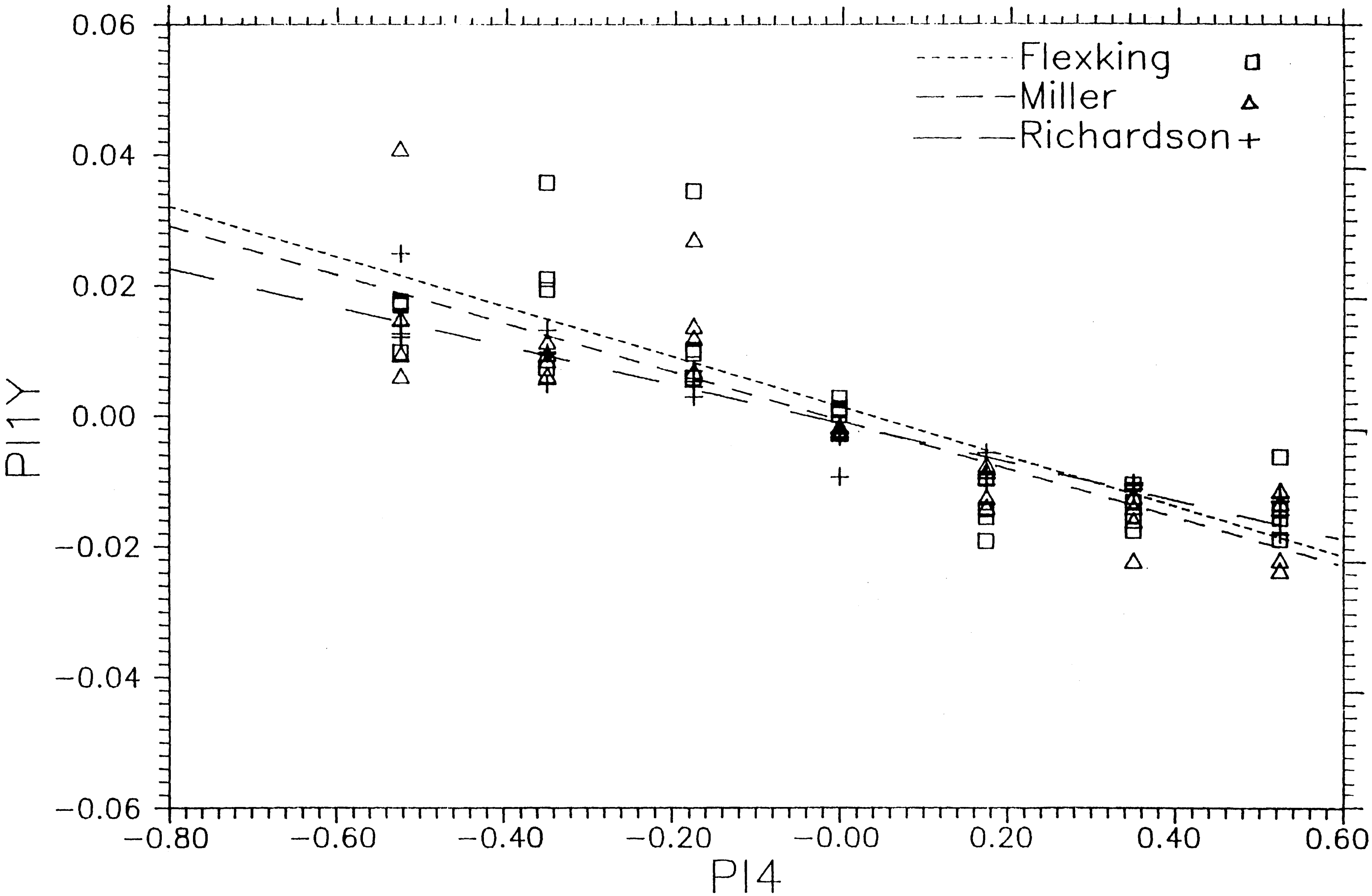
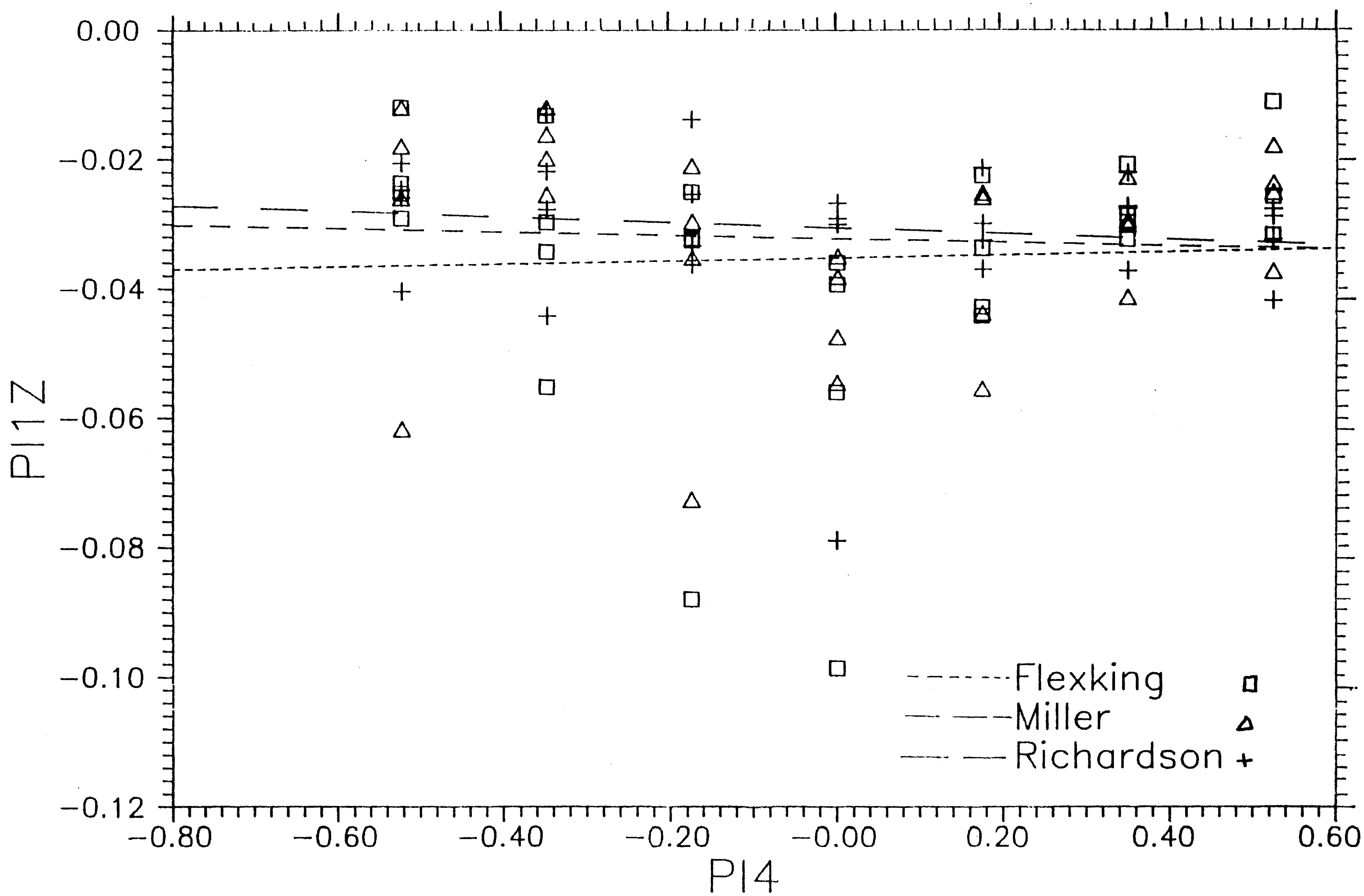


Figure 5.8. Side-Draft Ratio versus Angle



5.9. Vertical Force Ratio versus Angle

or Pil term difficult to achieve. To reduce the cone index variability, the average field cone index was included in Pil when calculated. This did not help appreciably, since force was dependent on soil strength and the ratio Pil became meaningless. The cone index reading would need to be taken simultaneously with force readings due to field variability for such a ratio to be meaningful. For the above reasons the direct use of similitude to develop force prediction equations was abandoned.

Depth, Velocity and Angle Relationships With Draft, Side-Draft and Vertical Forces

To establish relationships and an understanding of how depth, velocity and angle vary with force, data contained in Table XIII were plotted. From these plots the shape of relationships were established. Data for these graphs consisted of 12 averaged force values over block and treader type which removed field variability and treader type differences. Regression analysis slopes, intercepts and R^2 values for force-depth and force-angle for an average velocity of 2.77 m/s are contained in Table XIV. Force-velocity relationships at a depth of 60 mm and an angle of -20° are contained in Table XV.

Depth

The experimental design of three depths produced three graphs of draft versus depth, side-draft versus depth and

TABLE XIII

DRAFT, SIDE-DRAFT AND VERTICAL FORCE MEASUREMENT AVERAGED OVER FOUR REPLICATIONS AND THREE TREADER TYPES FOR A COMBINATION OF THREE DEPTHS, FOUR VELOCITIES AND SEVEN TREADER ANGLES

Operating Variables			Average Measured Forces		
Depth (m)	Velocity (m/sec)	Angle (degrees)	Draft (N)	Side-Draft(N)	Vertical Force(N)
0.060	1.92	-20	1468	895	-2148
0.060	2.29	-20	1420	914	-1953
0.060	2.77	-20	1300	824	-1717
0.060	3.29	-20	1357	894	-1769
0.060	2.77	-30	1427	989	-1637
0.060	2.77	-10	1259	639	-2268
0.060	2.77	0	1243	-116	-2610
0.060	2.77	10	1173	-962	-2446
0.060	2.77	20	1292	-1007	-2191
0.060	2.77	30	1409	-1157	-2082
0.030	2.77	-20	920	566	-1204
0.090	2.77	-20	1908	1331	-2977

TABLE XIV

REGRESSION ANALYSIS RESULTS FOR FORCE-DEPTH AND FORCE-ANGLE RELATIONSHIPS

Dependent Variable (N)	Independant Variable	Intercept	Slope	R^2	Pr > F
Draft	Depth (m)	388	16455	0.951	0.0001
Side-draft	Depth (m)	142	16744	0.702	0.0048
V Force	Depth (m)	-193	-29544	0.874	0.0002
Draft	2+Cos(180+ Angle)	-323	1532	0.8393	0.0040
Side-draft	Sin(180+2xAngle)	-90	1378	0.9453	0.0001
V Force	-2+Cos(180-4xAngle)	-1091	460	0.4719	0.0006
V Force-	-2+Cos(180-4xAngle)	-1517	345	0.5109	0.0090
V Force+	-2+Cos(180-4xAngle)	-546	641	0.7274	0.0004

V Force = Vertical Force
(+) is for positive Angles only
(-) is for negative Angles only
Note: The form of equations used for linear regression. For force-depth regression nine point were used. For force-angle regression, 21 data point were used.

TABLE XV

FORCE - VELOCITY RELATIONSHIPS

Dependent Variable	Intercept	Slope	R^2
V^{-2}			
Draft	1249	802.6	0.730
Side-draft	800	183.0	0.130
Vertical Force	-1488	-2389.0	0.907
$V^{-0.5}$			
Draft	869	817.0	0.677
Side-draft	768	179.0	0.112
Vertical Force	-343	-2451.0	0.854
V^{-1}			
Draft	1122	651.0	0.690
Side-draft	823	145.0	0.120
Vertical Force	-1107	-1946.0	0.870
V			
Draft	1631	-95.3	0.596
Side-draft	931	-19.2	0.083
Vertical Force	-2641	290.0	0.770
Power relationship $F = aV^b$			
Draft	1638	-0.18	0.639
Side-draft	933	-0.06	0.102
Vertical Force	2723	-0.40	0.825

Note 1: V = forward velocity.
Note 2: For power relationship; a = coefficient = intercept.
b = exponent = slope.

vertical force versus depth, all at a constant forward velocity of 2.77 m/s (average) and an angle of -20°. Figures 5.10, 5.11, and 5.12 illustrate linear relationships of force versus depth with force increasing as depth increased. These linear relationships are contained in Table XIV. These relationships were similar to those between force and depth for other tillage tools reported in the literature (linear with increased force with increased tillage depth).

Velocity

To determine velocity-force relationships, the average forward velocities (1.92, 2.29, 2.77 and 3.29 m/s) were used as the independent variable and average forces plotted against the four average forward velocities for a treader angle of -20° and a tillage depth of 60 mm. Figures 5.13, 5.14 and 5.15 illustrate the effect of velocity on force. Draft, side-draft and vertical force all decreased with increased velocity. Side-draft showed the smallest decrease with increased velocity. With the machine stationary, (zero forward velocity) the force would be that required to overcome static rolling resistance. As velocity increased, draft, side-draft and vertical force decreased. From the regression analysis results (Table XV) the best fit (highest R^2) was the inverse squared velocity relationship. Figure 5.13-5.15 contained only four points which were used for the regression analyses. The force-velocity data point for an

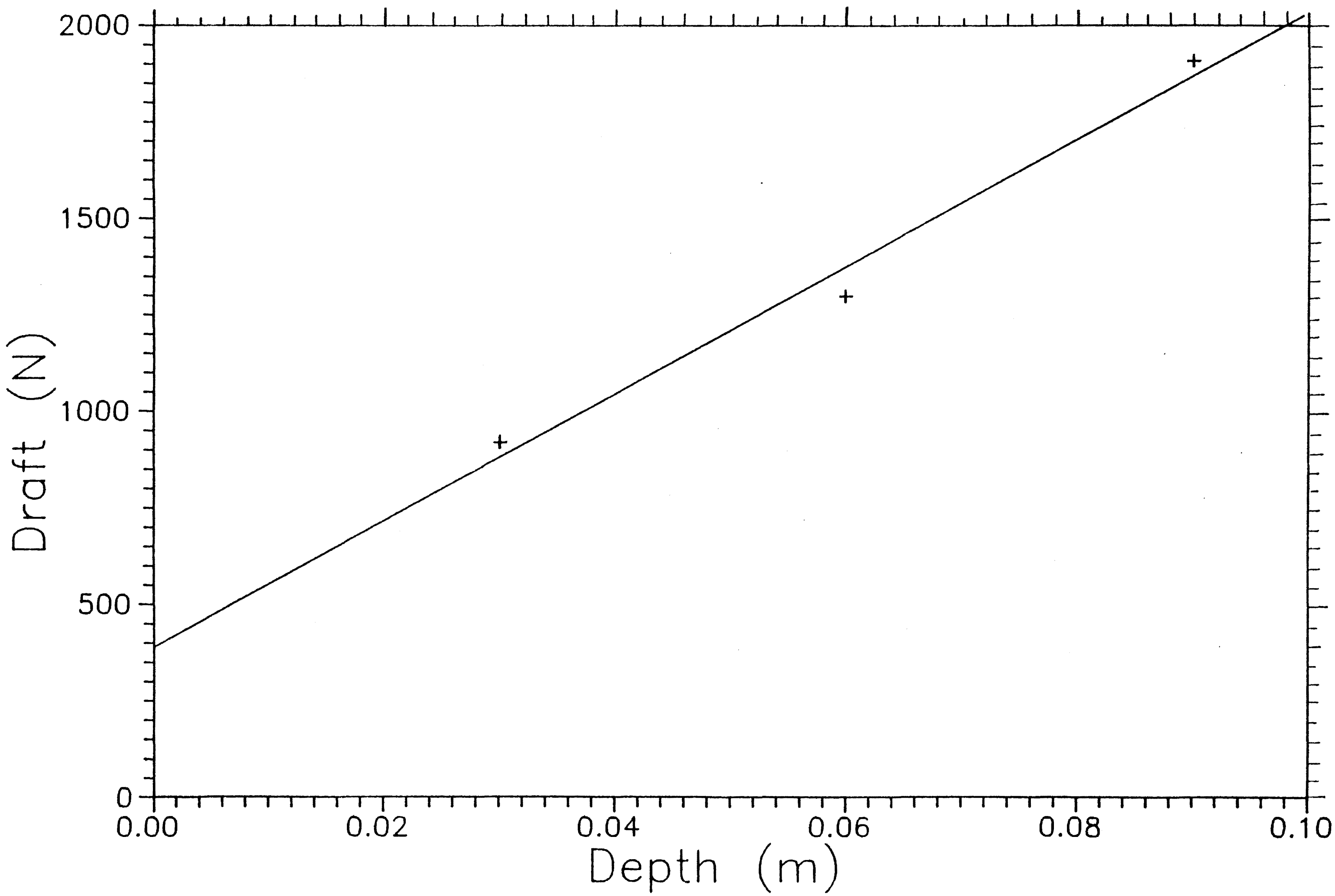


Figure 5.10. Draft Versus Depth Showing Linear Relationship

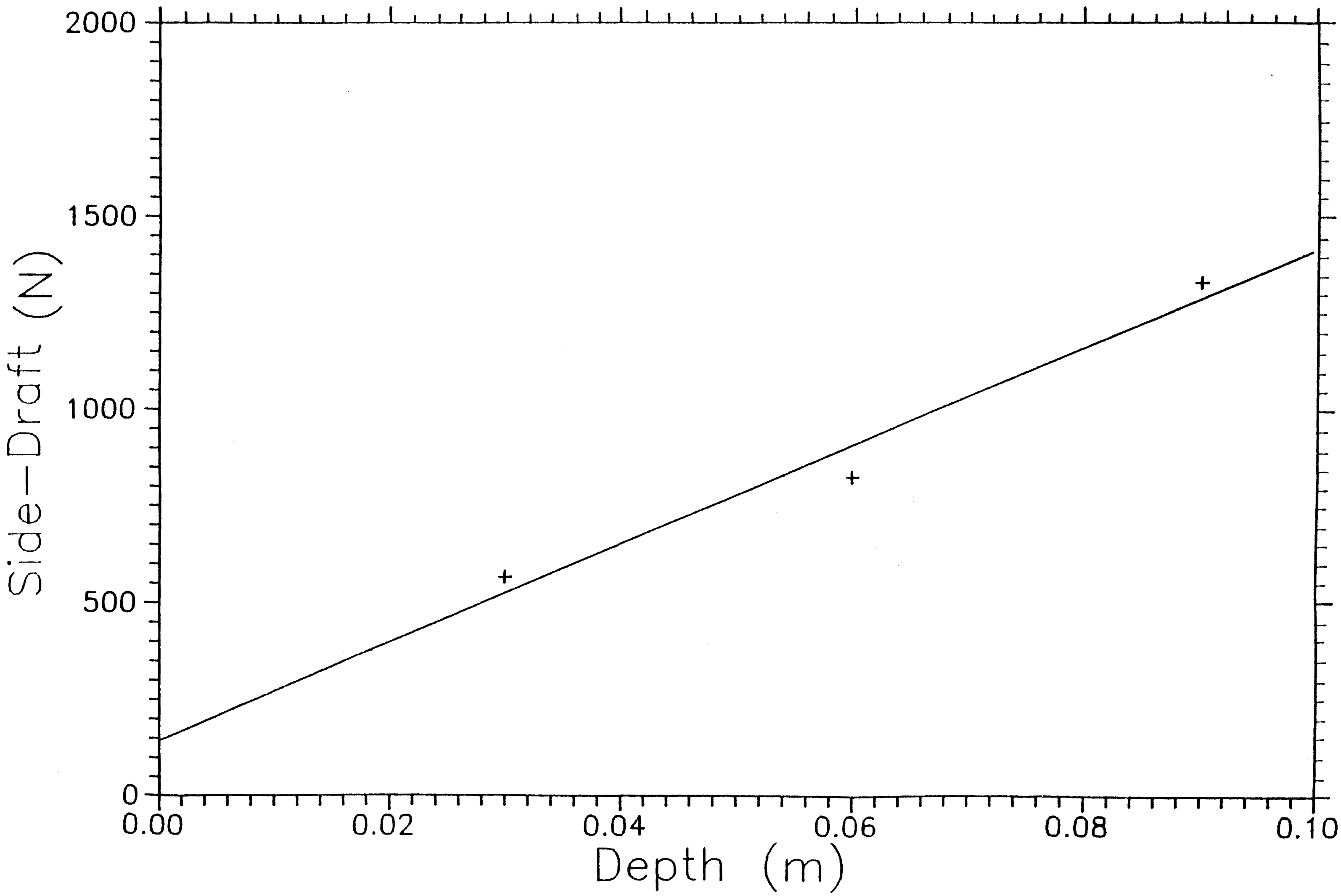


Figure 5.11. Side-Draft Force Versus Depth Showing Linear Relationship

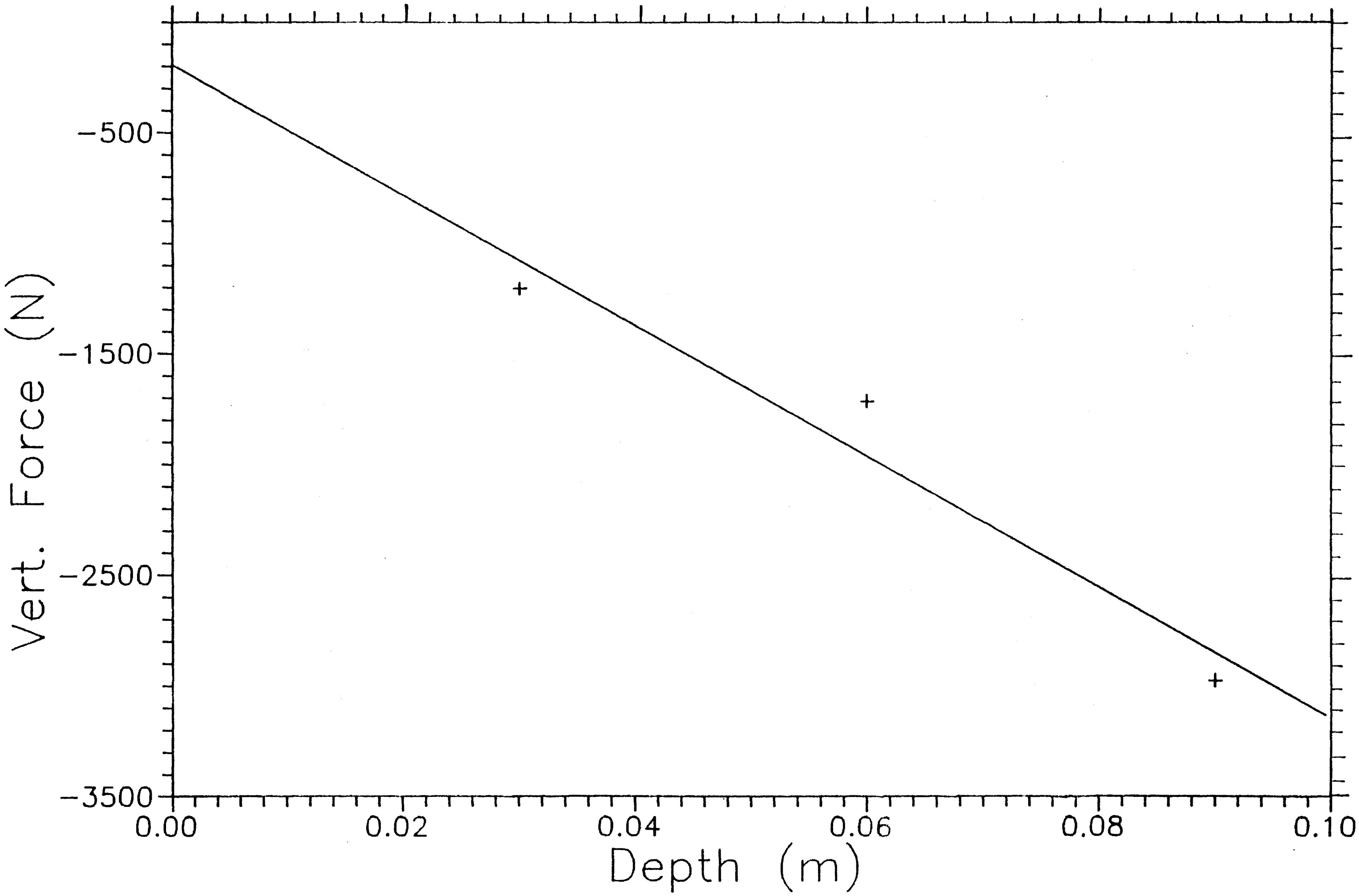


Figure 5.12. Vertical Force Versus Depth Showing Linear Relationship

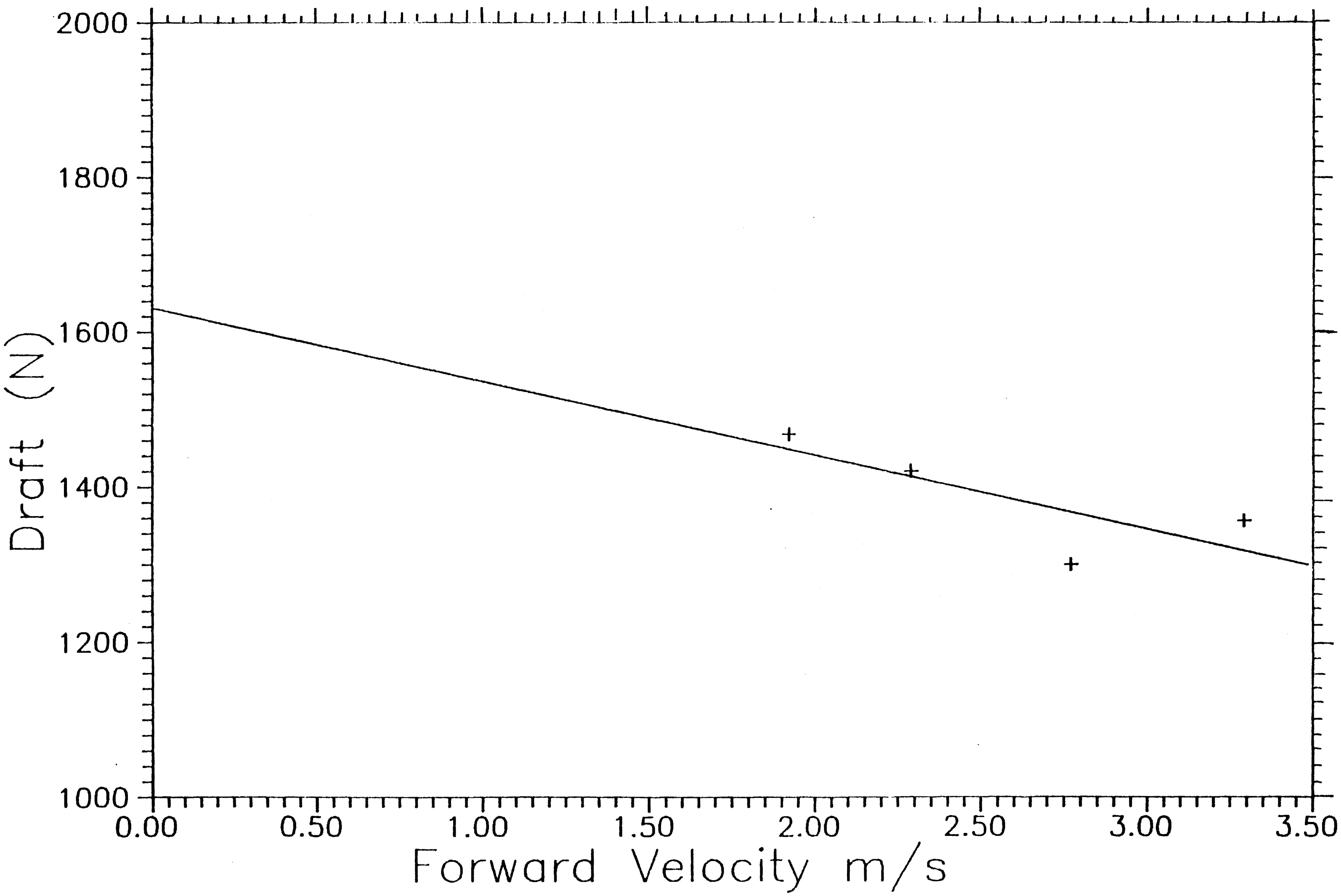


Figure 5.13. Draft Versus Forward Velocity

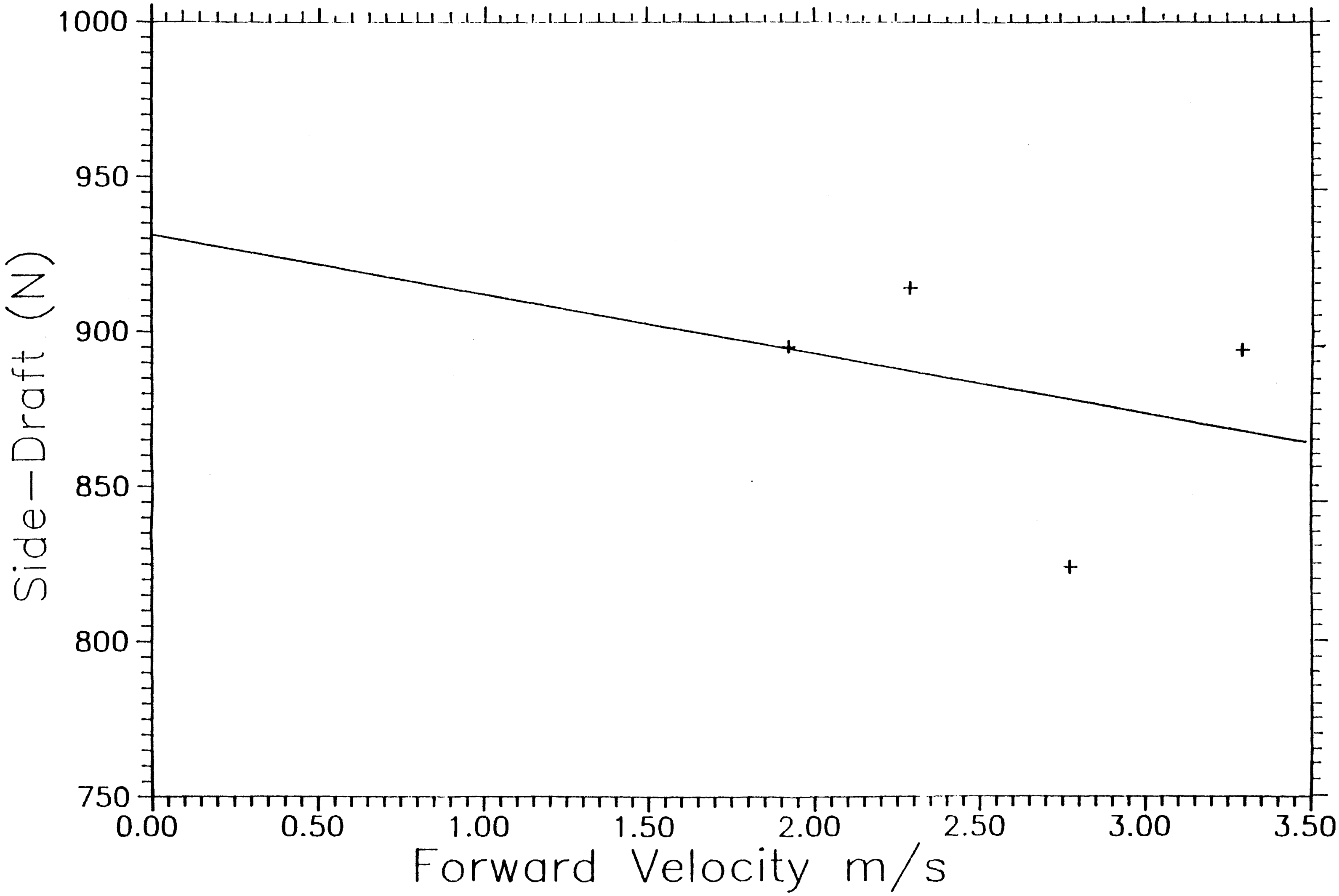


Figure 5.14. Side-Draft Force Versus Forward Velocity

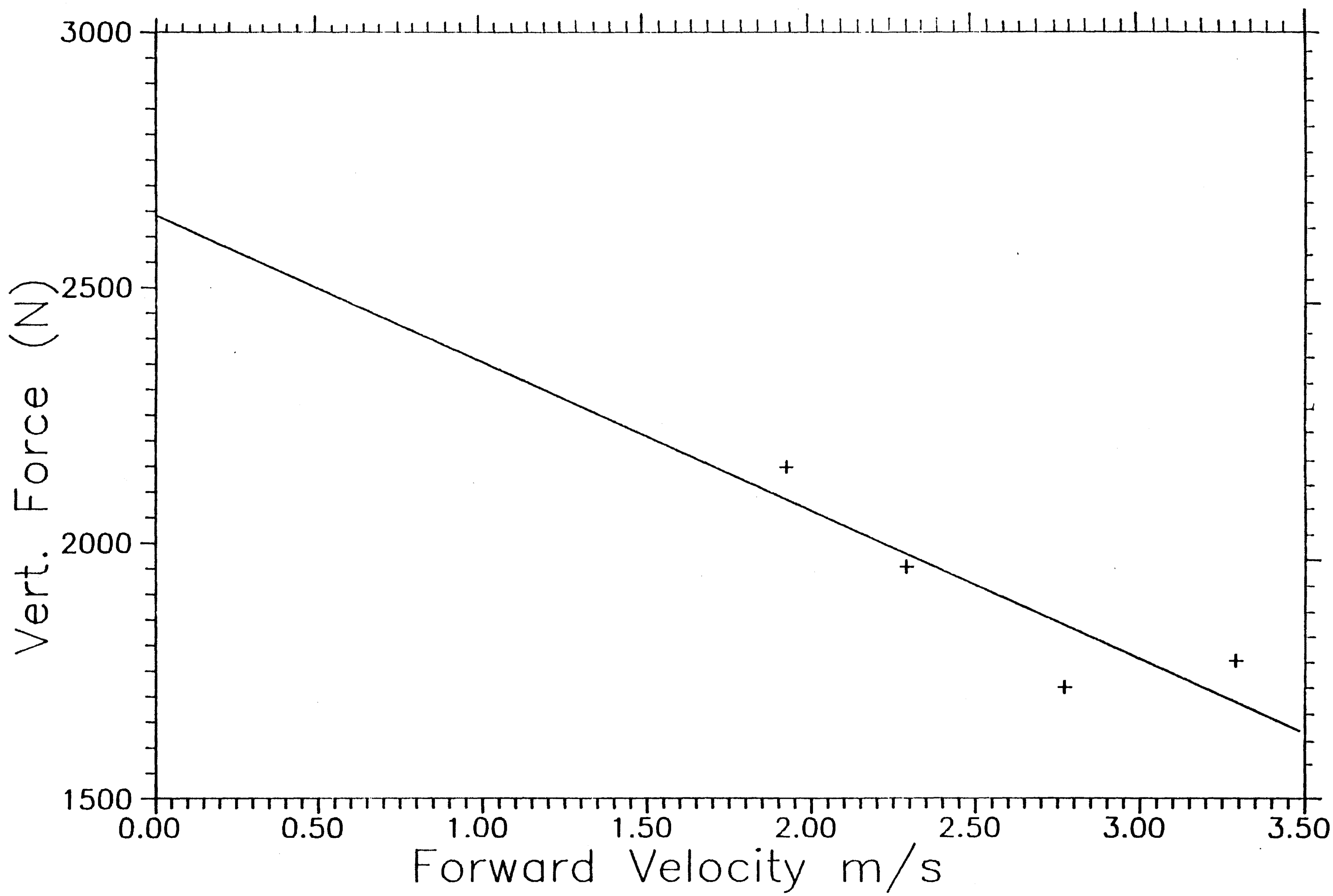


Figure 5.15. Vertical Force Versus Forward Velocity

average velocity of 2.77 m/s appeared to be an outlier and explained the higher R^2 for the inverse squared relationship. This data point had consistently lower force values. It was difficult to investigate a power relationship with the limited range of data collected. Further research whereby force is measured at increasing velocities from zero would provide the necessary data to justify a velocity-force relationship other than linear. For force prediction equation development a negatively sloped linear relationship was used since power relationships could not be justified physically. Most other tillage tools were reported to have positively sloped linear relationships between draft and velocity.

Angle

The effect of angle on draft, side-draft and vertical force are shown in Figures 5.16, 5.17 and 5.18 respectively. To plot these relationships, seven data points were used, since the experimental design consisted of seven angles (-30°, -20°, -10°, 0°, 10°, 20°, and 30°). These average force readings were taken at an average forward velocity of 2.77 m/s and depth of 60 mm. These curves appeared to be sections of sine and cosine functions. Sine and cosine functions were used for general force prediction equation development. Regression results and the form of the force-angle relationships are contained in Table XIV.

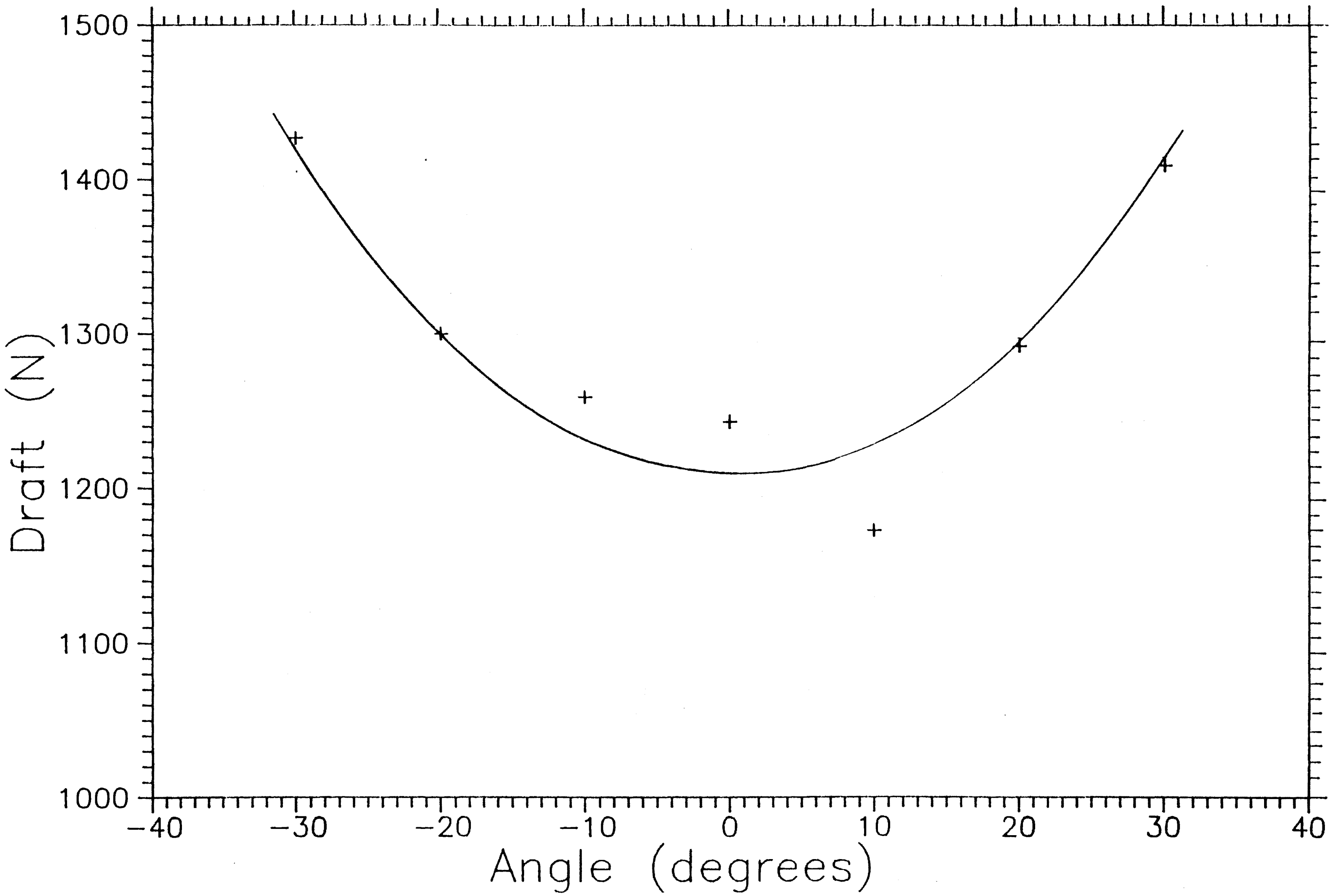


Figure 5.16. Draft Versus Angle

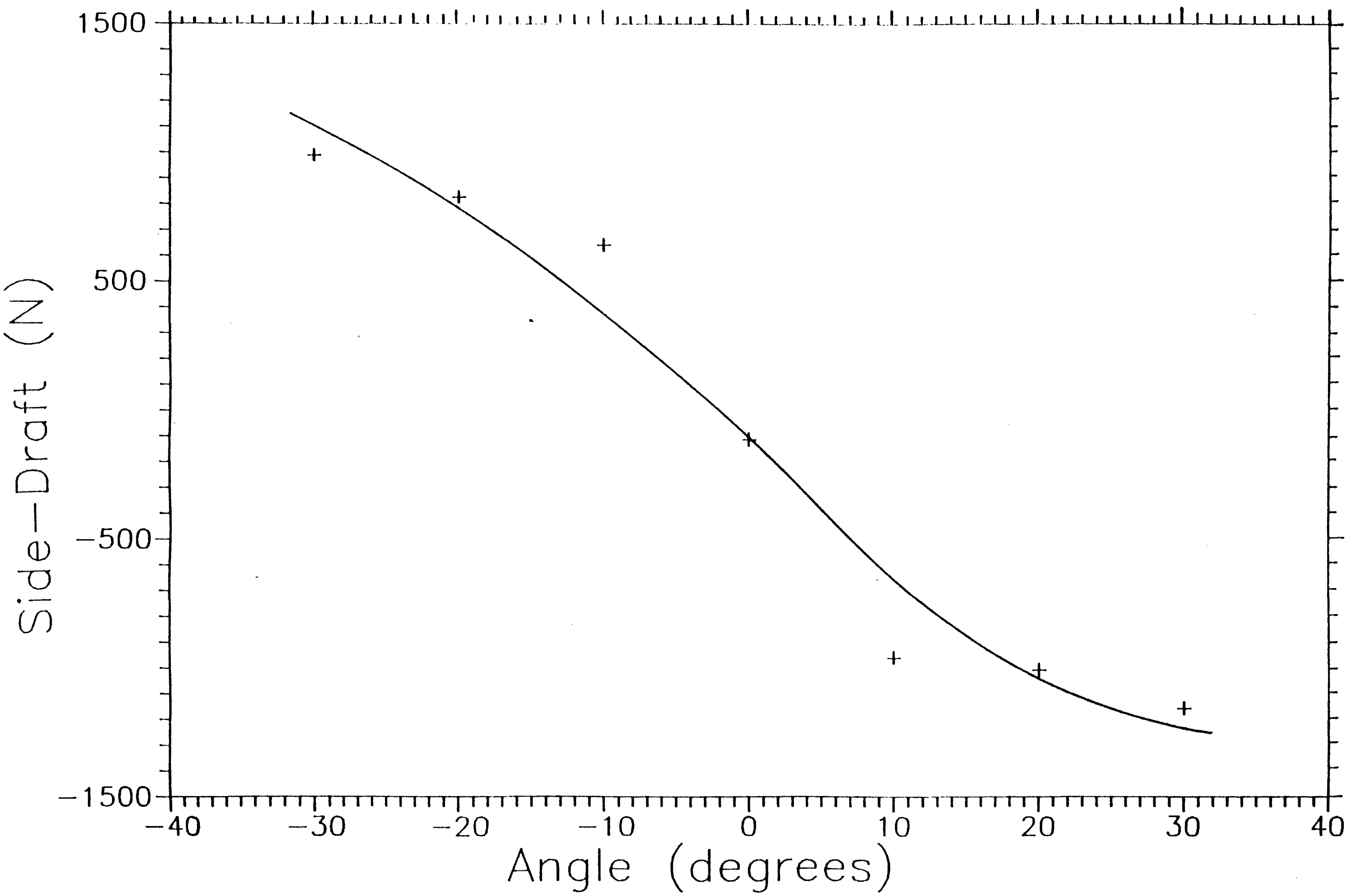


Figure 5.17. Side-Draft Versus Angle

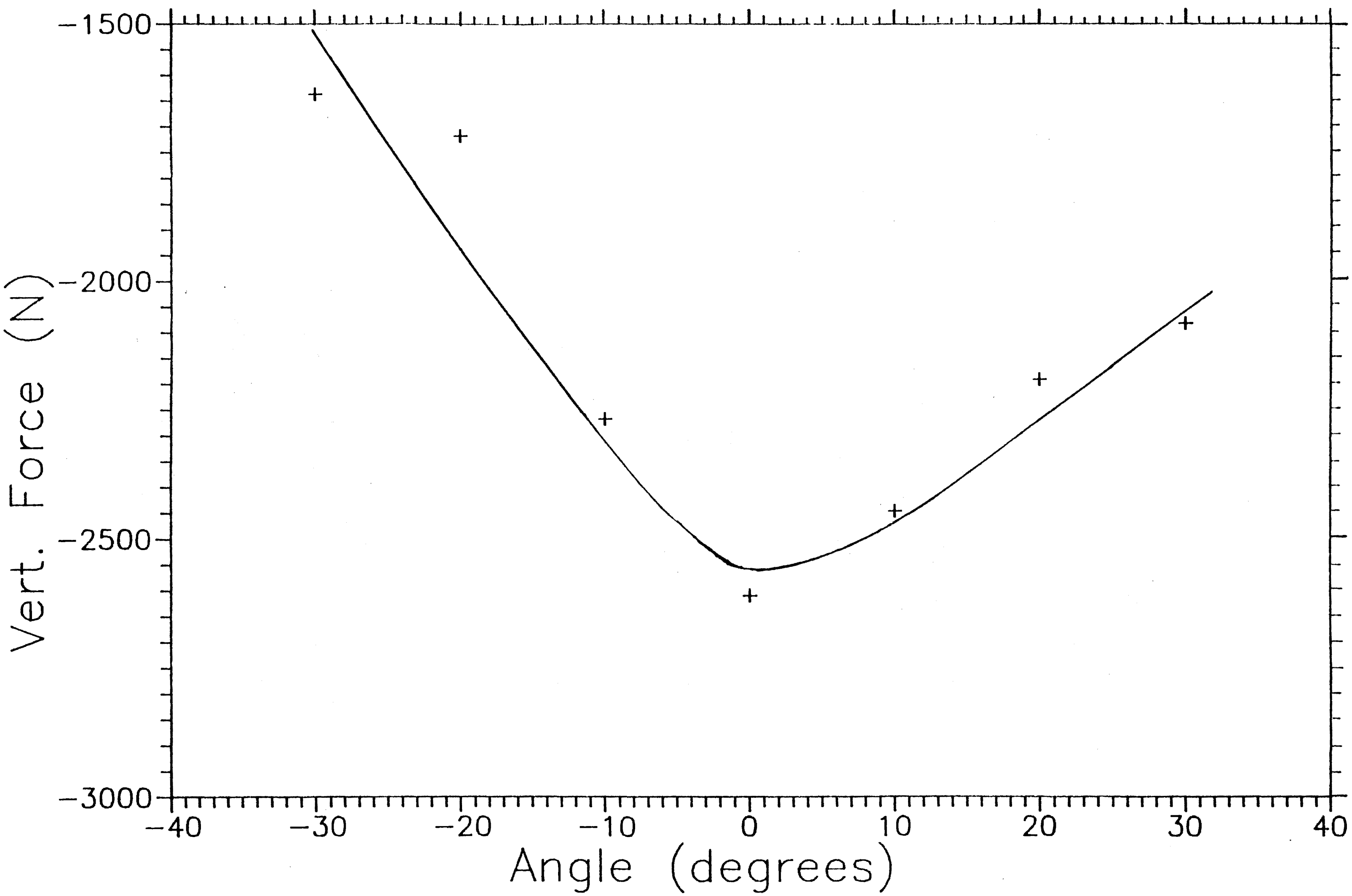


Figure 5.18. Vertical Force Versus Angle

When developing force-angle relationships boundary conditions were considered. Minimum draft occurred at zero degrees and increased for both positive and negative angles. The curve appeared symmetrical for both positive and negative angles of orientation. To fit a cosine curve a phase shift of 180 degrees was required. The phase shift accounted for draft being a minimum at 0° and for subsequent increases to a maximum at $\pm 30^{\circ}$. A magnitude of two was added to amplitude to create a minimum positive value at 180° instead of a maximum negative value. The increased draft with angle was due to the increased drag of the treader disturbing more soil.

Side-draft reacted differently to angle than draft. For negative angles, side-draft started at a maximum value at -30° and decreased to approximately zero for zero angle. As angle increased positively, the side-draft magnitude increased and changed sign to negative values which indicated a change in the direction of the force. Boundary conditions showed that a sine curve within 90° and 270° would fit the side-draft-angle relationship. This required a phase shift of 180°. Double the angle was required to produce a maximum side-draft at 45° and -45°. Side-draft would be expected to be a maximum at 45° and -45° and decrease to zero as the treader was rotated through 90°. The direction of side-draft showed that the force pushed on the rear surface of the tine. An analogy of a semi-rolling treader is that of a tire towed at an angle.

The vertical force had a maximum magnitude at zero degrees. This indicated that the force to push tines through the soil was greatest when the treader rolled along with no slice action occurring. This relationship had the form of a cosine curve but was not symmetrical. Boundary conditions indicated that as the treader was rotated through 45° from zero, the magnitude goes from a maximum to a minimum which was similar to a cosine function in the region 90° to 180°. A cosine curve was fitted with a phase shift of 180° and the angle multiplied by four to suit the boundary conditions. As treader angle increased negatively (point leading), the vertical force decreased, but not linearly. As angle increased positively, vertical force decreased but not at the same rate as for negatively increasing angles. At $+30^{\circ}$ the vertical force magnitude equalled approximately 2000 N as compared to 1600 N at -30°. This indicated a 20 percent difference in vertical force magnitude for negative angles compared to positive angles. A symmetrical function could not be used to describe this relationship due to the fact that lower vertical forces were noticeable at negative angles. The disc was reported to react similarly to the treader with decreased vertical force with increased angles up to $35\text{-}40^{\circ}$.

The vertical force had a range of 1000 N with a maximum of approximately 2600 N for a treader operated at a 60mm depth and average forward velocity of 2.77 m/s. The side-draft ranged from +1000 N to -1000 N with approximately zero side-draft at zero degrees, 60mm depth and average forward velocity of 2.77 m/s. The draft force had a minimum of approximately 1250 N and increased to 1400 N as angle increased to $\pm$ 30^{o} when operated at a depth of 60 mm and average forward velocity of 2.77 m/s.

Force Prediction Equation Development

The following section discusses the development of force prediction equations for draft, side-draft and vertical forces by multiplicative models. Due to the relationships observed among other tillage tools for depth, forward velocity and angle, it was suggested that a multiplicative equation would better represent the physical basis of treader operating variables as compared to linear additive models. For the multiplicative model, operating variables (depth, forward velocity and angle) were combined into one value. A similitude approach would have resulted in equations that were dimensionally homogeneous and either linear additive or multiplicative depending on the relationships between force Pi terms and depth, velocity and angle Pi terms.

Forces were modeled in terms of depth, forward velocity and angle by studying the individual relationships (as in the previous section) between force and an operating variable. These were then combined into a general prediction equation. The individual relationships were built using analyses from previous sections, including graphs and a knowledge of how the equations should predict treader operation in terms of operating variables. For example, as velocity increased the force decreased, so the prediction equation had to model this physical aspect of treaders. Boundary conditions were also considered in this development in relation to angle.

To arrive at the "best" multiplicative model, different forms of the force-velocity relationship were tried in the model. The 36 averaged data points were substituted into these functions and operating variables multiplied together in their respective form to produce 36 pairs of force data. Linear regression was applied to this data and resulted in force prediction equations for draft, side-draft and vertical force for different forms of velocity. These results are contained in Table XVI. For vertical force, two equations were developed for point leading and point lagging. The multiplicative equations with the highest R^2 values, all of which used a negatively sloped linear expression for velocity, are as follows:

$$\text{Draft} = A_o * \text{Depth} * (m_1 * \text{Velocity} + C_1) * [2 + \text{Cos}(180 + \text{Angle})] + A_1 \quad (12)$$

where:

$A_o = 11.58$
$A_1 = 336.05$
$m_1 = -95.3$
$C_1 = 1631$
$R^2 = 0.7581$

TABLE XVI

REGRESSION ANALYSIS RESULTS FOR MULTIPLICATIVE FORCE PREDICTION MODELS USING DIFFERENT VELOCITY TERMS

Dependent Variable	Intercept	Slope	R^2
	Model Velocity Term: (m x V + C)		
Draft	336.73	11.58	0.7581
Side-draft	-52.05	27.05	0.9452
Vertical Force (±)	-637.25	-5.86	0.6664
Vertical Force (∓)	-341.37	-6.72	0.7953
Vertical Force (+)	-1503.22	-3.17	0.5158
	Model Velocity Term: (V^{-1})		
Draft	564.99	32710.93	0.6408
Side-draft	-59.94	62097.88	0.9266
Vertical Force (±)	-801.11	25516.39	0.5914
Vertical Force (∓)	-555.41	28780.63	0.7039
Vertical Force (+)	-1486.22	16412.67	0.5212
	Model Velocity Term: (Velocity)		
Draft	658.05	4017.17	0.4592
Side-draft	-8639.95	-37.95	0.9261
Vertical Force (±)	-962.93	3098.96	0.4754
Vertical Force (∓)	-788.08	3407.57	0.5371
Vertical Force (+)	-1550.39	2011.54	0.4982
	Model Velocity Term: $(\text{Velocity})^{-0.5}$		
Draft	379.69	24875.00	0.7509
Side-draft	-57.00	38738.00	0.9417
Vertical Force (±)	-	-	-
Vertical Force (∓)	-352.00	20214.00	0.7881
Vertical Force (+)	-1501.00	9725.00	0.5164
	Model Velocity Term: (V^{-2})		
Draft	945.05	43869.86	0.3682
Side-draft	-53.86	150112.00	0.8536
Vertical Force (±)	-1322.64	39527.91	0.3531
Vertical Force (∓)	-1179.93	42779.04	0.4127
Vertical Force (+)	-1459.19	46447.88	0.5284

Note: + or - indicates whether positive or negative angles were used in the regression analysis.

$$\text{Side-draft} = B_o * \text{Depth} * (m_2 * \text{Velocity} + C_2) * [\text{Sin}(180 + 2 * \text{Angle})] + B_1 \quad (13)$$

where:
B_o = 27.0
B_1 = -52.05
m_2 = -19.2
C_2 = 931
R^2 = 0.9452

$$\text{Vertical Force (point leading)} = C_o * \text{Depth} * (m_3 * \text{Velocity} + C_3) * [-2 + \text{Cos}(180 - 4 * \text{Angle})] + C_1 \quad (14)$$

where:
C_o = -6.72
C_1 = -341.22
m_3 = 290
C_3 = -2641
R^2 = 0.7953

$$\text{Vertical Force (point lagging)} = D_o * \text{Depth} * (m_3 * \text{Velocity} + C_3) * [-2 + \text{Cos}(180 - 4 * \text{Angle})] + D_1 \quad (15)$$

where:
D_o = -3.17
D_1 = -1503.22
m_3 = 290
C_3 = -2641
R^2 = 0.5188

Note: Units for prediction Equations:

Force (N)
Depth (m)
Velocity (m/s)
Angle (^{o})

To verify the equations, average operating values for the 12 treatments were substituted into the multiplicative force prediction equations (12), (13), (14), and (15) which produced a set of predicted data (Table XVII). These predicted values of draft, side-draft and vertical force

TABLE XVII

PREDICTED FORCE VALUES USING MULTIPLICATIVE PREDICTION EQUATIONS

Average Operating Parameters			Predicted Forces		
Depth (m)	Velocity (m/s)	Angle (degrees)	Draft (N)	Side-Draft(N)	Vertical Force(N)
0.060	1.92	-20	1403	881	-2168
0.060	2.29	-20	1377	373	-2074
0.060	2.77	-20	1343	864	-1952
0.060	3.29	-20	1307	853	-1820
0.060	2.77	-30	1413	1182	-1453
0.060	2.77	-10	1300	435	-2390
0.060	2.77	0	1285	-52	-2558
0.060	2.77	10	1300	-539	-2470
0.060	2.77	20	1343	-968	-2263
0.060	2.77	30	1413	-1286	-2028
0.030	2.77	-20	840	406	-1147
0.090	2.77	-20	1847	1322	-2757

TABLE XVIII

REGRESSION ANALYSIS RESULTS FOR MULTIPLICATIVE FORCE PREDICTION MODELS

Dependent Variable	Intercept	Slope	R^2
Draft	-10.70	1.008	0.926
Side-draft	-19.20	1.018	0.965
Vertical Force (±)	- 8.50	0.993	0.926
Vertical Force (−)	9.70	1.002	0.924
Vertical Force (+)	-31.40	0.988	0.931

Note: + or - indicates whether positive or negative angles were used in the regression analysis.

were used as the dependent variables and plotted against 12 average measured values. Linear regression results for average measured values versus theoretical values are contained in Table XVIII. The slope and intercept constants indicated how well the prediction equations predict averaged measured data. A slope of 1.00 and intercept of 0.00 would indicate an excellent fit. The R^2 value indicates how much variability is explained by the prediction equation. Figures 5.19, 5.20 and 5.21 illustrate how the predicted values fit the average measured values.

Limitations of Experiment

If a complete block experimental design had been conducted instead of a similitude approach, more could be learned about the interaction of velocity, depth and angle and justified relationships developed. Due to the fact that depth was varied at a constant velocity, extrapolation on how the depth-force curves may appear at different velocities and angles can only be assumed. It would be expected that increased velocity would shift the curve. A curve of similar slope but with a smaller intercept would be expected since forces decreased with increases in velocity.

If forces had been measured at greater depths and varying velocities, the velocity curves would be shifted by an increase in the intercept with slope remaining constant. The same extrapolations can be made for force-angle relationships. For increased depth, force-angle curves

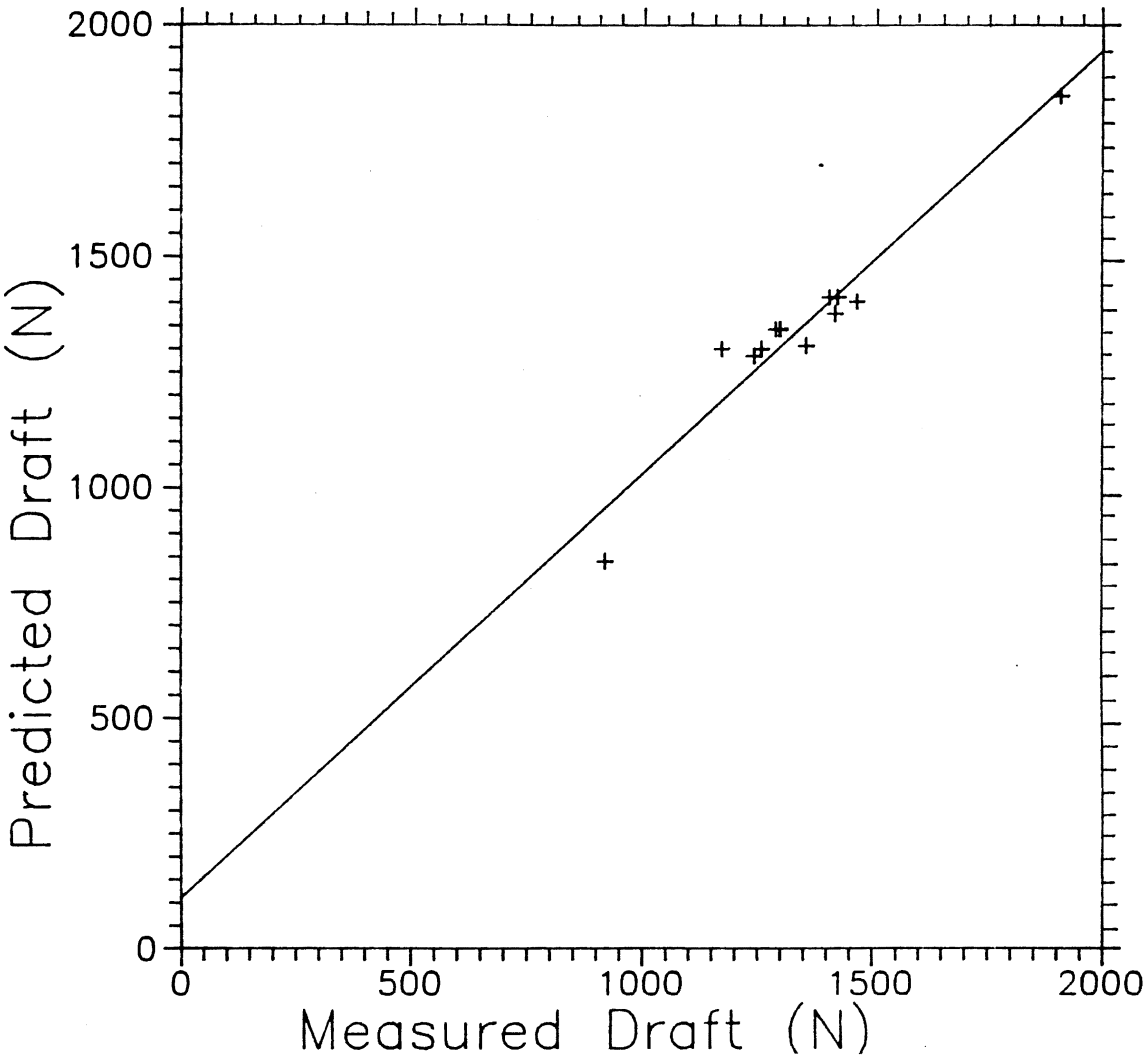


Figure 5.19 Predicted Draft using Multiplicative Prediction Equation versus Average Measured Draft

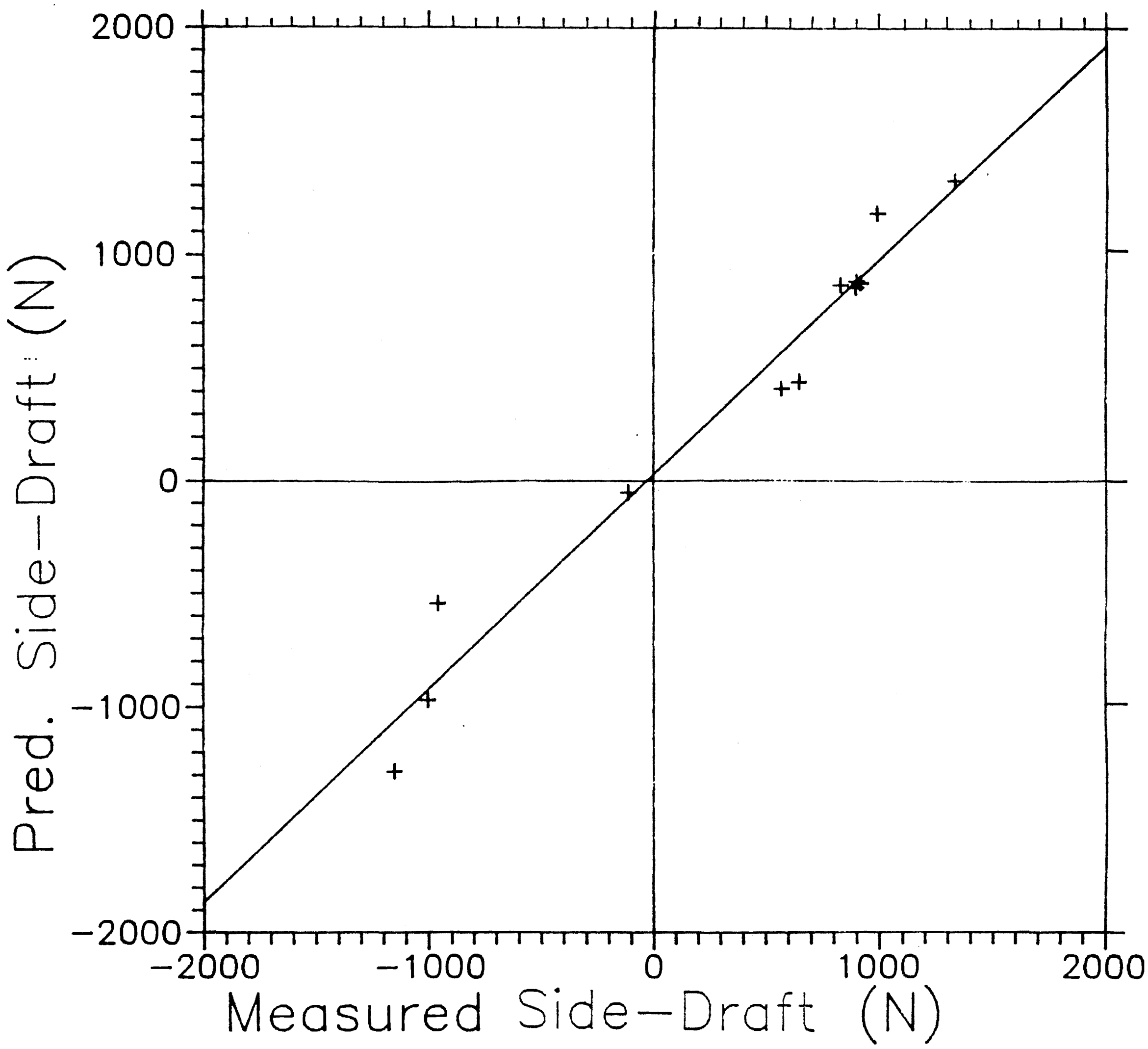


Figure 5.20. Predicted Side-Draft using a Multiplicative Prediction Equation versus Average Measured Side-Draft

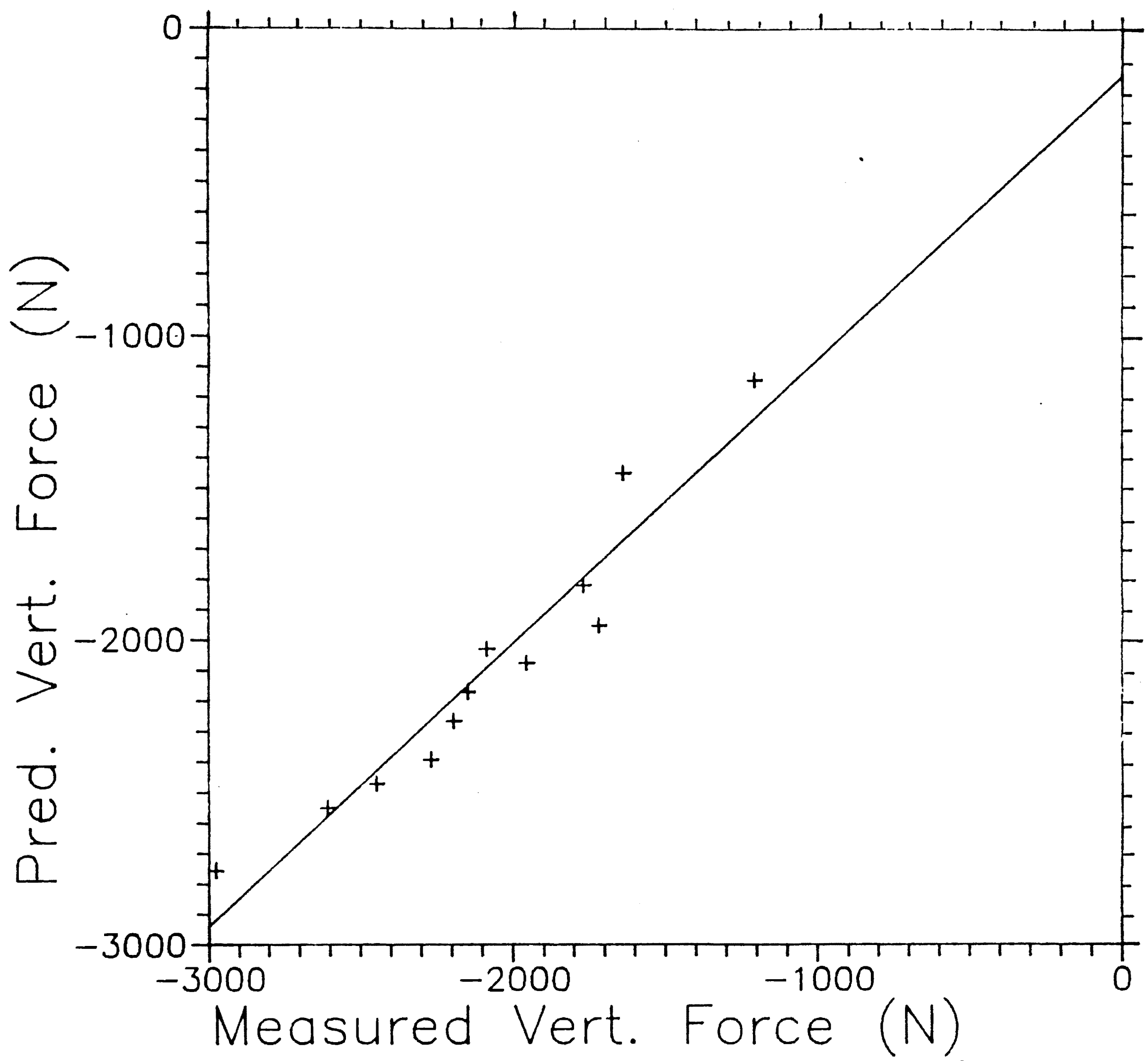


Figure 5.21 Predicted Vertical Force using Multiplicative Prediction Equation versus Average Measured Vertical Force

would shift by an increase in forces overall. If force-angle graphs were plotted at decreased velocities, an increase in reported values would be expected. The assumptions made above were found to hold for other tillage tools. Therefore, it was reasonable to assume that the assumptions will hold for treaders.

Treader Peripheral Velocity as a Function of Forward Velocity

Treader speed was measured in revolutions per second and forward velocity as meters per second. Knowing the treader radius of 0.225 m, the treader peripheral velocity can be calculated as follows:

$$V_p = N * 3.1416 * 2 * r \tag{16}$$

where V_p = peripheral velocity (m/s)
N = treader revs. per second
r = treader radius (m)

Figure 5.22 indicates a linear relationship between peripheral velocity and forward velocity. A linear regression analysis of peripheral velocity versus forward velocity results in the following equation.

$$V_p = 0.87 * V_f - 0.01 \tag{17}$$

where V_p = peripheral velocity (m/s)
V_f = forward velocity (m/s)
R^2 = 0.8265
PR¶F = 0.0001

This equation indicates that peripheral velocity is approximately 87 percent of the forward velocity. The

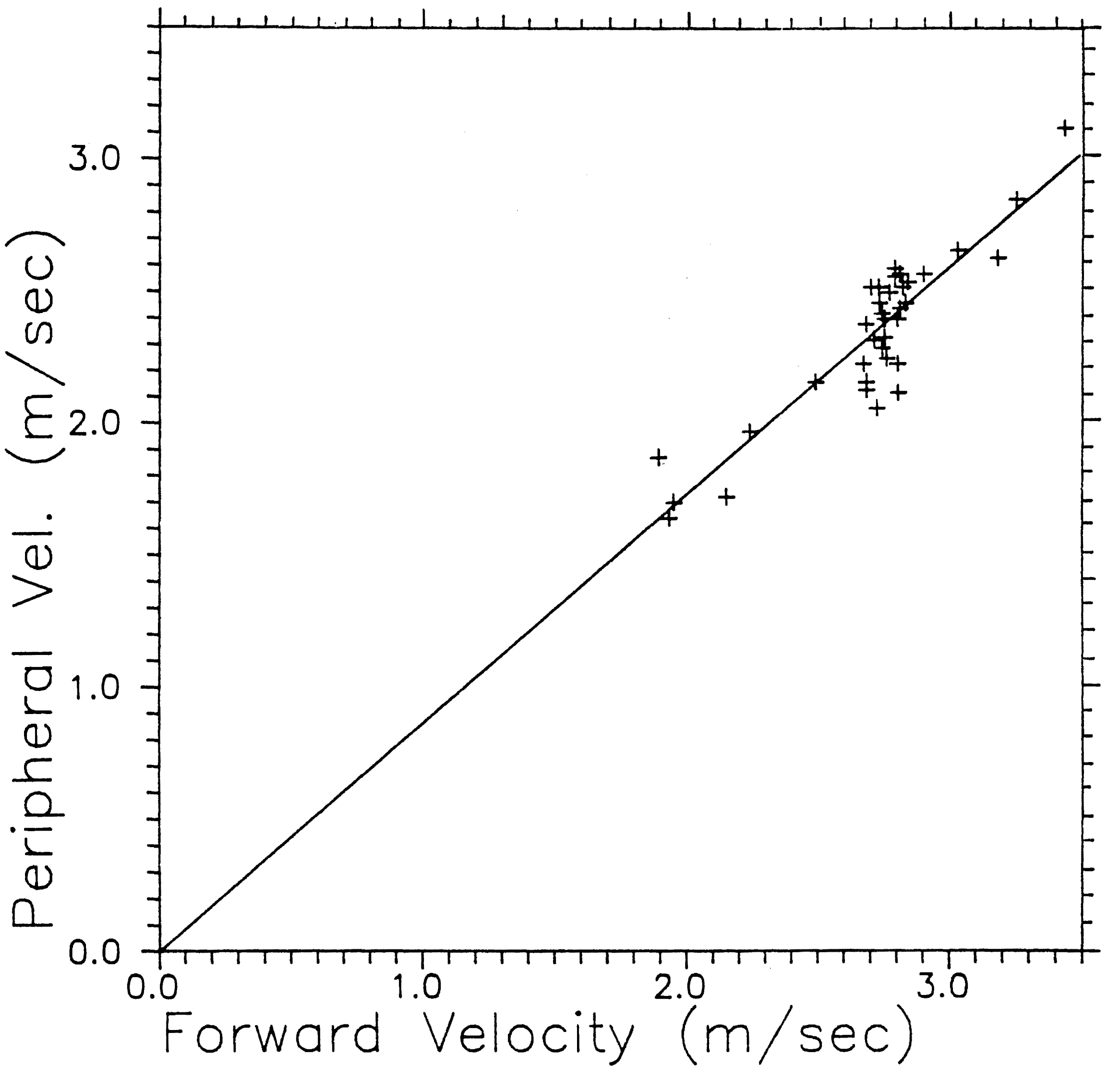


Figure 5.22. Peripheral Velocity as a Function of Forward Velocity

intercept is approximately zero indicating that at zero velocity, peripheral velocity equals zero. The intercept also indicates that peripheral velocity can be predicted as a function of forward velocity to within one hundredth of a meter per second.

Bite Length

Bite length for rotary hoes and treaders is defined as the distance along the soil surface between tine-soil interaction or entrance position. For treaders the bite length may be calculated as follows:

$$B_L = \frac{V_f}{N * 8} \qquad (18)$$

where B_L = Bite length (m)
V_f = forward velocity (m/s)
N = treader revs. per second

Each treader has eight evenly spaced tines per spider. Since treader peripheral velocity is a direct function of forward velocity, bite length should remain constant. This is based on the assumption that peripheral velocity is directly proportional to forward velocity. Constant bite length can be shown by substituting for forward velocity in terms of peripheral velocity, then substitute for peripheral velocity in terms of treader revolutions per second.

Substitute for forward velocity in terms of peripheral velocity:

$$B_L = \frac{V_p}{0.87 * N * 8} \qquad (19)$$

where B_L = Bite length (m)
V_p = peripheral velocity (m/s)
N = treader revs. per second

Now substitute for peripheral velocity in terms of treader revolutions per second:

$$B_L = \frac{N * 3.1416 * 2 * 0.225}{0.87 * N * 8} \qquad (20)$$

where B_L = Bite length (m)
N = treader revs. per second

$$= 0.203 \text{ m}$$

$$B_L = 0.203 \text{ m} = \text{constant}$$

The above equation shows that as velocity varies, bite length remains constant. If bite length remains constant, the forces (draft, side-draft and vertical) should not be affected. This leads to the argument that decreases in force with forward velocity were not bite related.

CHAPTER VI

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary

A tillage dynamometer was successfully developed to measure draft, side-draft, vertical force, forward velocity and treader rotational speed. A similitude experiment was conducted at Chickasha, Oklahoma using the treader dynamometer to collect data for three types of treaders. This field data was used to develop general force prediction equations by first gaining an understanding of how forces are affected by the operating variables depth, forward velocity and angle of orientation.

Draft, side-draft and vertical force were directly proportional to depth of operation. As the depth of operation increased, forces increased linearly. This research has shown that as velocity increased, draft, lateral and vertical forces all decreased. For prediction equation development, force was considered to change negatively linearly with velocity. The highest R^2 for a force-velocity relationships were found for an inverse velocity squared relationship. No reason explaining why velocity should change as an inverse squared relationship was found. For this reason, force as a negatively sloped linear function of velocity was used in the prediction equation even though a lower R^2 was found for the individual relationship. Using the negatively sloped linear force-velocity relation in the multiplicative equations, higher R^2s were found for the general prediction equations.

Force-angle relationships were based on sine or cosine functions. Functional relationships were developed and used in the force prediction equations. Draft was found to be a minimum at zero degrees while vertical force was a maximum. Side-draft changed direction (sign) as the treader orientation angle passed through zero degrees with maximum side-drafts occurring at $\pm$ 30°. The effect of tine point leading or lagging on vertical force was investigated. With tine point leading, vertical forces were reduced. This supported manufacturer±s claims that point leading offers greater penetration.

Three treaders were investigated for treader type effects. Treader type was a significant factor for vertical force over all observations. Type was significant for draft and vertical force for all angles greater or less than 0° at 60 mm depth and 2.77 m/s velocity. The treader-direction of orientation (sign) interaction was significant for side-draft. Further investigation of the geometric parameters and post and pre-tillage soil conditions are needed to be able to make conclusions about the benefits of a particular treader design. Criteria defining preferred soil conditions resulting from secondary tillage for enhancing crop growth would need to be developed to compare treader types and make recommendations concerning which treader design leaves the soil in an optimum agronomic condition.

Four multiplicative force prediction equations were developed. Draft and side-draft can be predicted in terms of depth of operation (m), forward velocity (m/s) and angle of orientation (degrees) by one equation for each force. The sign of the angle depended on the orientation of tine tip. Negative angles were designated by tine tip leading. Vertical force prediction required two equations, one for positive angles (tine tip lagging) and the other for negative angles (tine tip leading).

Force prediction equations are as follows:

$$\text{Draft} = A_o * \text{Depth} * (m_1 * \text{Velocity} + C_1) * [2 + \text{Cos}(180 + \text{Angle})] + A_1 \quad (21)$$

where: A_o = 11.58
A_1 = 336.05
m_1 = -95.3
C_1 = 1631
R^2 = 0.7581

$$\text{Side-draft} = B_o * \text{Depth} * (m_2 * \text{Velocity} + C_2) * [\text{Sin}(180 + 2 * \text{Angle})] + B_1 \quad (22)$$

where: B_o = 27.0
B_1 = -52.05
m_2 = -19.2
C_2 = 931
R^2 = 0.9452

Vertical Force (tine tip leading) = C_o * Depth *

$$(m_3 * \text{Velocity} + C_3) * [-2 + \text{Cos}(180 - 4 * \text{Angle})] + C_1 \quad (23)$$

where:
C_o = -6.72
C_1 = -341.22
m_3 = 290
C_3 = -2641
R^2 = 0.7953

Vertical Force (tine tip lagging) = D_o * Depth *

$$(m_3 * \text{Velocity} + C_3) * [-2 + \text{Cos}(180 - 4 * \text{Angle})] + D_1 \quad (24)$$

where:
D_o = -3.17
D_1 = -1503.22
m_3 = 290
C_3 = -2641
R^2 = 0.5188

Note: These equations were developed for a treader with a length of 1.20 m. In order to use these force prediction equations in per meter terms, it is necessary to divide by the treader length of 1.20 m.

Conclusions

1. Forces increased linearly as depth of tillage increased.
2. Forces decreased as forward velocity increased and was considered linear for velocities between one and four m/s.
3. Draft force was a minimum for zero degrees and increased for both positive and negative angles of orientation.
4. Side-draft changed direction as angle of orientation passed through zero degrees and the maximum side-draft occurred at $\pm$ 30°.
5. Vertical force was a maximum at zero degrees and could be minimized by operating treaders with tine tip leading.

6. Peripheral treader velocity was directly proportional to forward velocity and had a constant bite length of 0.203 m for the treader types tested.

7. A similitude approach to develop force prediction equations was abandoned due to high variability in cone index values within the field.

Recommendations

A number of recommendations for further investigation can be made to better understand treader operation.

1. To develop complete force-velocity relationships, forces should be measured over a greater range of velocities. This lwould verify the decreases in force with increases in velocity over a greater range of velocities.

2. To validate the force prediction equations, future analyses should use a complete block experimental design. This would confirm interpolation of force-operating variable relationships.

4. Further work is needed to measure the effect of treaders on soil structure and aggregate distribution.

5. A criteria to define soil-tillage interactions in terms of suitability for crop production should be developed.

6. Geometric parameters including radius, tine shape and spider geometry could be investigated to optimize design of treaders. Recommendations concerning benefits of different treader types and geometric effects would result from further studies in this area.

REFERENCES

Clyde, A.W. 1955. Drawbar Dynamometer Using Strain Gages. Agricultural Engineering. August 1955, pp. 521-522.

Downs, H.W. 1985. Combination Tillage Tools. Oklahoma State University Extension Facts. No.1222.

Evans, D.E., C.E. Johnson and R.L. Schafer. 1985. Some Similitude Aspects of Multiple Chisel Systems. ASAE Paper No.85-1036 American Society of Agricultural Engineers, St.Joseph, MI 49085.

Freeland, R.S., F.D. Tompkins and L.R. Wilheim. 1987. "Keeping Test Errors Within Acceptable Limits." Agricultural Engineering, March/April. pp. 13-15.

Frehlich, G.E. and H.D. Kydd. 1985. Evaluation Report 401 - Miller Rotary Flex Weeders. Prairie Agricultural Machinery Institute.

Frietag, D.R., R.L. Schafer and R.D. Wismer. 1970. Similitude Studies of Soil Machine Systems. TRANSACTIONS of the ASAE. 13(2): 201-212.

Frisby, J.C. and J.D. Summers. 1979. Energy Related Data for Selected Implements. TRANSACTIONS of the ASAE. 22(5): 1010-1011.

Gerling, J.F., H.W. Downs, J. Solie, and J. Stiegler. 1983. Minimum Tillage Systems For Continuous Wheat Cropping in Oklahoma. American Society of Agricultural Engineers. Paper no. 83-1525 St. Joseph, MI 49085.

Gill, W.R., C.A. Reaves, and A.C. Bailey. 1981. The Influence of Harrow Disk Curvature on Forces. TRANSACTIONS Of the ASAE. 24(3): 579-582.

Gill, W.R., C.A. Reaves and A.C. Bailey. 1980(a). The Effect of Geometric Parameters on Disk Forces. TRANSACTIONS of the ASAE. 23(2): 266-269.

Gill, W.R., C.A. Reaves and A.C. Bailey. 1980(b). The Influence of Velocity and Disk Angle on the Kinematic Parameter Lambda of Disks. TRANSACTIONS of the ASAE. 23(6): 1344-1348.

Hendrick, J.G. 1980. A Powered Rotary Chisel. TRANSACTIONS of the ASAE. 23(6): 1349-1352.

Hendrick, J.G. and W.R. Gill. 1978. Rotary Tiller Design Parameters, V:Kinematics TRANSACTIONS of the ASAE. 21(4): 658-660.

Hendrick, J.G. and W.R. Gill. 1976. The Irregularity of Soil Disturbance Depth by Circular and Rotating Tillage Tools. TRANSACTIONS of the ASAE. 19(1): 230-233.

Hendrick, J. G. and W.R. Gill. 1971a. Rotary Tiller Design parameters Part I-Direction of Rotation. TRANSACTIONS of the ASAE. 14(4): 669-674.

Hendrick, J.G. and W.R. Gill. 1971b. Rotary Tiller Design Parameters PartII-Depth of Tillage. TRANSACTIONS of the ASAE. 14(4): 675-678.

Hendrick, J.G. and W.R. Gill. 1971c. Rotary Tiller Design Parameters Part III-Ratio of Peripheral and Forward Velocities. TRANSACTIONS of the ASAE. 14(4): 679-683.

Hillel, D. 1980. Fundamentals of Soil Physics. Academic Press, Inc. Harcourt Brace Jovanovich, Cary, Florida 32887.

Kinzel, G.L, R. Holmes and S. Huber. 1981. Computer Graphics Analysis of Rotary Tillers. TRANSACTIONS of ASAE. 24(6): 1392-1399.

Larson, L.W., W.G. Lovely and C.W. Bockhop. 1968. Predicting Draft Forces Using Model Moldboard Plows in Agricultural Soils. TRANSACTIONS of the ASAE. 11(5): 665-668.

Murphy, G. 1950. Similitude in Engineering. The Ronald Press Company, New York, New York.

Osman, M.S. 1964. The Mechanics of Soil Cutting Blades. Journal Agricultural Engineering Research. pp. 313-328.

Payne, P.C.J. 1956. The Relationship between the Mechanical Properties of Soil and the Performance of Simple Cultivation Implements. Journal of Agricultural Engineering Research. pp. 23-50.

Reaves, C.A., W.R. Gill and A.C. Bailey. 1981. Influence of Width and Depth of Cut on Disk Forces. TRANSACTIONS of the ASAE. 24(3): 572-578

Reaves, C.A., A.W. Cooper and F.A. Kummer. 1968. Similitude in Performance Studies of Soil-Chisel Systems. TRANSACTIONS of the ASAE. 11(5): 658-660,664.

Reid, J.T., L.M. Carter and R.L. Clark. 1985. Draft Measurements with a Three-Point Hitch Dynamometer. TRANSACTIONS of the ASAE. 28(1): 89-93.

Reid, J.T. 1978. A Comparison of Energy Input of Some Tillage Tools. American Society of Agricultural Engineers. Paper No. 78-1039 St Joseph, MI 49085.

Reithmuller, G.P. 1982. Micro-Computer Based Data Acquisition for a Tractor Mounted Penetrometer. Unpublished M.S. Thesis, Oklahoma State University.

SAS Institute Inc, 1982. <u>SAS Introductory Guide: Third Edition</u>. Cary, NC: SAS Institute Inc.; 1985. pp. 956.

SAS Institute Inc, 1982. <u>SAS Users Guide: Basics Version 5 Edition</u>. Cary, NC: SAS Institute Inc.; 1985. pp. 923.

SAS Institute Inc, 1982. <u>SAS Users Guide: Statistics Version 5 Edition</u>. Cary, NC: SAS Institute Inc.; 1985. pp. 956.

Schoenleber, L.H. 1955. Strain Gages and Stress Coat in Machinery Design. Agricultural Engineering. May 1955, pp. 309-317, 323.

Self, K.P., A. Khalilian, D.G. Batchelder, P.D. Bloome and G. Reithmuller. 1983. Draft and Power Requirements of Tillage Implements in Oklahoma Soils. American Society Of Agricultural Engineers. Paper no. 83-1038 St. Joseph, MI 49085.

Serohi, B.S and C.A. Reaves. 1969. Similitude Techniques Applied to Performance of Cultivator Sweeps. TRANSACTIONS of the ASAE. 12(6): 786-789.

Summers, J.D., A. Khallian and D.G. Batchelder. 1986. Draft Relationships For Primary Tillage in Oklahoma Soils. TRANSACTIONS of the ASAE. 29(1): 37-39.

Summers, J.D., D.G. Batchelder and B.W. Lambert 1984. Second Generation Tractor Performance Monitor. American Society of Agricultural Engineers, Paper No.84-1080 St. Joseph, MI 49085.

Tice, E.M., and J.G. Hendrick. 1986. "Coulter Operating Characteristics. American Society of Agricultural Engineers. Paper No. 86-1534, St. Joseph, MI 49085.

Wright, M.E. and W.H. Carter W.H. 1967. Design and Operating Characteristics of Rotary Hoe Type Devices for Soil Incorporation. TRANSACTIONS of the ASAE. 10(2): 256-259.

Young, D.F. 1968. "Similitude of Soil Machine Systems'. Transactions of the ASAE. 11(5): 653-657.

Zoerb, G. C. 1963. A Strain Gage Dynamometer for Direct Horsepower Indication. Agricultural Engineering. August 1985. pp. 434-435, 437.

APPENDIX A

LOAD CELL CALIBRATION

Cell Number	Intercept	Slope	R^2
1	-3179.4	1.098	0.9998
2	1494.4	-1.050	0.9999
3	1890.1	-1.042	0.9999
4	963.5	-1.039	0.9999
5	5580.7	-3.546	0.9999
6	7832.3	-3.570	0.9999
7	4703.5	-3.202	0.9999
8	4057.2	-3.542	0.9999

Calibration equations have the following form:

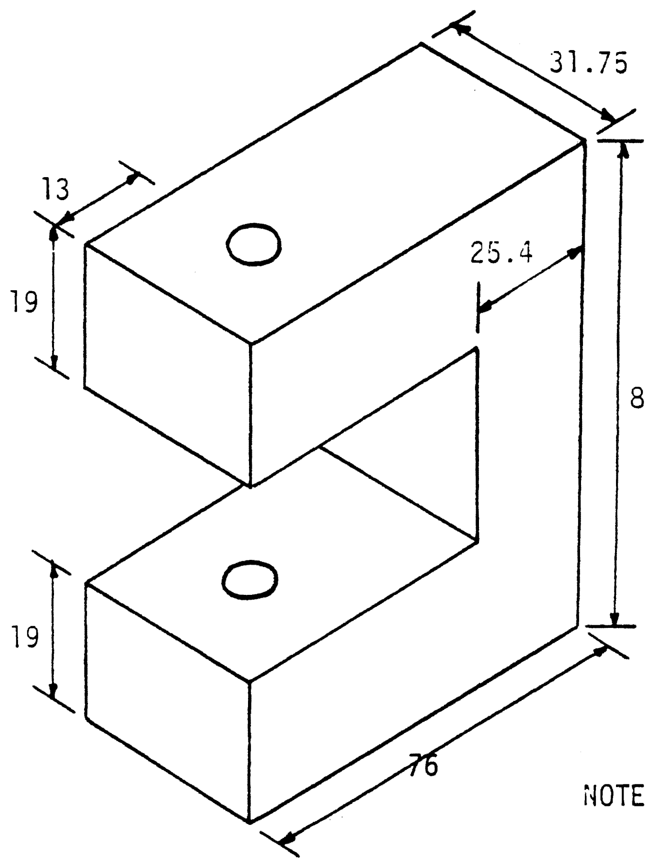
$$\text{Load (N)} = \text{Slope} \cdot \text{A/D Reading} + \text{Intercept}$$

Positive load indicates tension and negative load indicates compression.

APPENDIX B

LOAD CELL DRAWINGS

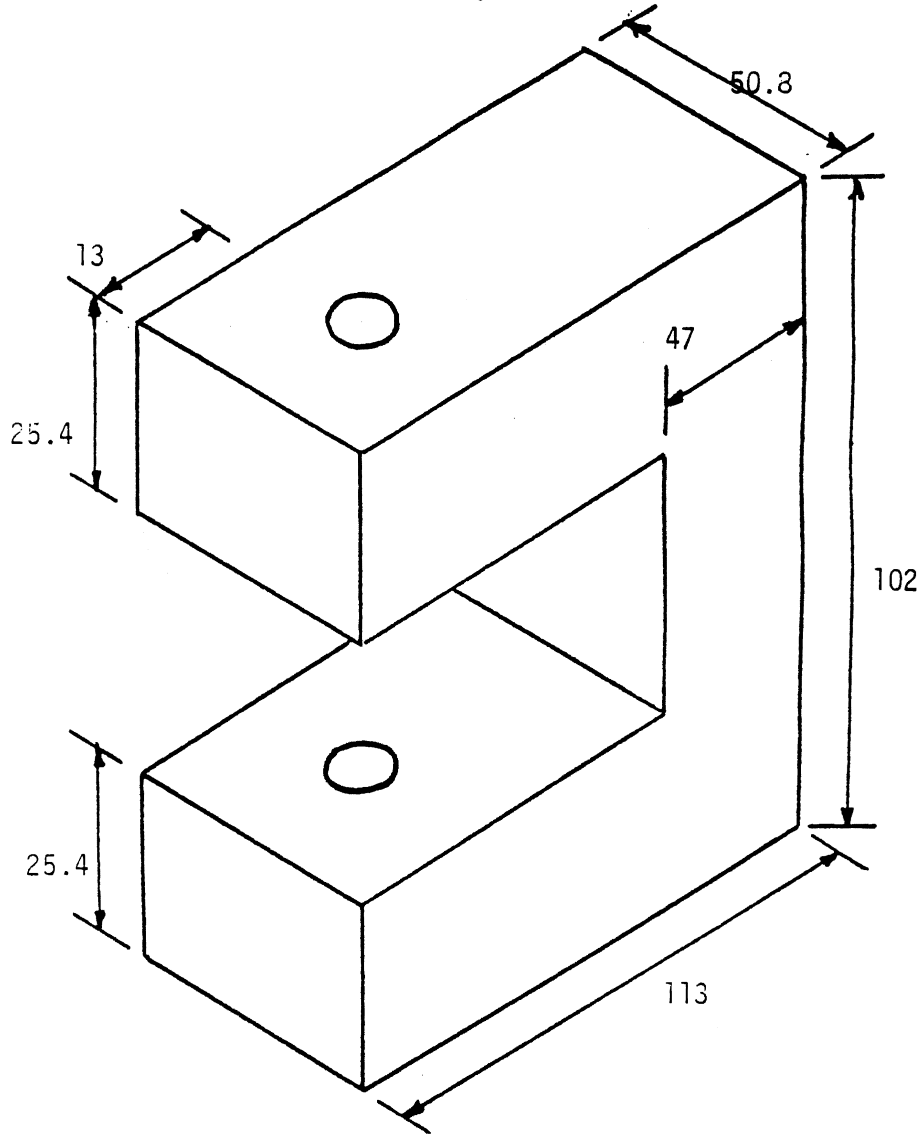
NOTE: Tap and drill 5/16" (24 threads per inch) centered holes for ball joints.



NOTE: All dimensions in mm

Small Load Cell used for measuring draft force and lateral force.

NOTE: Tap and drill 5/16"(24 threads per inch)
centered holes for ball joints.



NOTE: All dimensions in mm.

Large Load Cell used for Measuring
Vertical Force.

APPENDIX C

BASIC OPERATING PROGRAM

Variables

TI=Data Collection Time
Per=Tire perimeter
Y(1)-Y(8)=Insitu load-cell offsets
A(1)-A(8)= Calibration y intercepts
B(1)-B(8)= Load-cell slopes
LF= lateral or side draft
DF= Draft force
VF= Vertical force
SP= Forward velocity
TS= Treader rotational speed

Basic Program

```
5 CT= 65535
10 TI=2.245
15 Per=2.0701
100 A(1)=-713.0738:B(1)=0.2463215
110 A(2)=335.149:B(2)=-0.2355364
120 A(3)=423.8926:B(3)=-0.2336765
130 A(4)=216.0881:B(4)=-0.2330964
140 A(5)=1251.556:B(5)=-0.7953686
150 A(6)=1756.525:B(6)=-0.8005437
160 A(7)=1054.824:B(7)=-0.7181832
170 A(8)=909.8882:B(8)=-0.7943955
300 INPUT "TREADER TYPE";TT$
400 INPUT "DEPTH";D$
500 INPUT "SPEED";S$
600 INPUT "ANGLE";A$
650 FOR L=1 TO 8
651 FL(L)=0
652 NEXT L
700 FOR K=1 TO 5
800 FOR I=1 TO 8
850 R(I)=0
900 NEXT I
1000 PRINT"ENTER PLOT NUMBER";
1010 INPUT PN$
```

```
1020 PRINT;
1035 POKE 42001,128
1040 PRINT"PLOT NUMBER=";PN$
1045 POKE 42001,0
1070 PRINT"ENTER "S" TO START DATA COLLECTION"
1080 GETA$:IF A$§¶"S"THEN 1080
1085 PRINT"                                        "
1200 POKE 4,182
1210 POKE 5,08
1220 ZV=USR(WD)
1260 PRINT"FINISHED DATA COLLECTION"
1300 POKE 4,114
1310 POKE 5,08
1320 ZV=USR(WD)
1330 PRINT"SUMMING FINISHED"
1350 GOSUB 1509
1370 POKE 42001,0
1400 PRINT"STORE AVERAGE DATA? Y/N";
1410 INPUT X$
1415 IF X$="N" THEN 1508
1420 C$=PN$+"          "
1450 POKE 1281,1
1460 POKE 1283,0:POKE 1285,0
1480 FOR I =1 TO 10
1490 POKE 1303+I,ASC(MID$(C$,I,1))
1500 NEXT I
1502 POKE 4,0:POKE 5,8
1503 ZV=USR(X)
1504 GOSUB 1509
1505 POKE 4,40:ZV=USR(X)
1508 GOTO 1800
1509 J=0
1510 FOR X=1 TO 8
1515 PRINT
1520 R(X)=PEEK(28688+J)+PEEK(28689+J)*256
1525 R(X)=R(X)+PEEK(28690+J)*65536
1530 J=J+4
1540 F(X)=R(X)*B(X)/768+A(X)
1545 F(X)=F(X)*4.459091
1546 F(X)=F(X)-FL(X)
1550 PRINT"F";X;"="F(X)
1560 NEXT X
1565 PRINT
1570 LF=F(1)+F(2)
1580 DF=F(3)+F(4)
1590 VF=F(5)+F(6)+F(7)+F(8)
1610 PRINT"LATERAL FORCE=";LF
1620 PRINT"DRAFT FORCE=";DF
1630 PRINT"VERTICAL FORCE="VF
1700 SP=(CT-PEEK(28672)*256-PEEK(28673)/(60*TI)*PER
1710 PRINT"FORWARD SPEED=";SP;"M/SEC
1750 TS=(CT-PEEK(28674)*256-PEEK(28675)/(60*TI)
1760 PRINT"TREADER SPEED="TS"REVS/SEC
1780 PRINT"TREADER TYPE";TT$
```

```
1781 PRINT"DEPTH=";D$
1782 PRINT"SPEED=";S$
1783 PRINT"ANGLE";A$
1798 RETURN
1800 PRINT "STORE ALL DATA?(Y/N)";
1810 INPUT W$
1820 IF W$="N" THEN 1910
1845 C$="ALL"+C$
1850 FOR I=1 TO 10
1860 POKE 1303+I,ASC(MID$(C$,I,1))
1870 NEXT I
1880 POKE 4,81
1890 POKE 5,08
1895 ZV=USR(X)
1896 PRINT "DUMP COMPLETE"
1900 IF K¶1 THEN GOTO 1910
1903 FOR L=1 TO 8
1904 FL(L)=F(L)
1905 NEXT L
1910 NEXT K
1920 GOTO 300
2000 END
```

APPENDIX D

MACHINE LANGUAGE DATA COLLECTION SUBROUTINE

Raw Data Memory Locations

$4000	Load cell #1-	Low Byte
$4001	Load cell #1-	High Byte
$4002	Load cell #2-	Low Byte
$4003	Load cell #2-	High Byte
$4004	Load cell #3-	Low Byte
$4005	Load cell #3-	High Byte
$4006	Load cell #4-	Low Byte
$4007	Load cell #4-	High Byte
$4008	Load cell #5-	LOw Byte
$4009	Load cell #5-	High Byte
$400A	Load cell #6-	Low byte
$400B	Load cell #6-	High Byte
$400C	Load cell #7-	Low Byte
$400D	Load cell #7-	High Byte
$400E	Load cell #8-	Low Byte
$400F	Load cell #8-	High Byte

Etc. Repeating this block 767 times.

$7000	Forward velocity counter High Byte
$7001	Forward velocity counter Low Byte
$7002	Treader speed counter High Byte
$7003	Treader Speed counter Low Byte

Data Collection Subroutine

Address	Op Code	Mnemonic	Operand	Remarks
08B6	A9	LDA	#$7F	
08B8	8D	STA	$903E	Disable via timer interrupt
08BB	A9	LDA	#$00	Input configuration

```
08BD   8D   STA   $9032          Port B
08C0   A9   LDA   #$20           Set bit 5 for pulse counting
08C2   8D   STA   $903B          ACR for via timer 2
08C5   A9   LDA   #$FF           Low byte for via counter 2
08C7   8D   STA   $9038          Address for low byte
08CA   A9   LDA   #$FF           High byte for via counter 2
08CC   8D   STA   $9039          High byte address, starts dec.

08CF   A9   LDA   #$7F           Disable via timer interrupts
08D1   8D   STA   $902E
08D4   A9   LDA   #$00           Input configuration
08D6   8D   STA   $9022          Port B
08D9   A9   LDA   #$20           Set BIT 5 for pulse counting
08DB   8D   STA   $902B          ACR for via. timer 2
08DE   A9   LDA   #$FF           Low byte for timer 2
08E0   8D   STA   $9028          Address for low byte
08E3   A9   LDA   #$FF           High byte for timer/counter 2
08E5   8D   STA   $9029          High byte address, starts dec.

08E8   A9   LDA   #$00           BAL for data addressing
08EA   85   STA   $E0            Address for BAL
08EC   A9   LDA   #$40           BAH for data addressing
08EE   85   STA   $E1            Address  for BAH
08F0   A9   LDA   #$01           Set index for 3 data sets
08F2   85   STA   $E6            Store index at $00E6
08F4   A9   LDA   #$03           "Data" count(blocks of 256
                                  decimal)
08F6   85   STA   $E2            Address for "data" index
08F8   A0   LDY   #$00           Zero Y register for data
                                 address indexing
08FA   A2   LDX   #$00           Set data index to $100
08FC   A9   LDA   #$00           Set MUX channel to force one
08FE   20   JSR   $0965          Goto force reading subroutine
0901   A9   LDA   #$01           Set MUX channel to force two
0903   20   JSR   $0965          Goto force reading subroutine
0906   A9   LDA   #$02           Set MUX channel to force three

0908   20   JSR   $0965          Goto force reading subroutine
090B   A9   LDA   #$03           Set MUX channel to force four
090D   20   JSR   $0965          Goto force reading subroutine
0910   A9   LDA   #$04           Set MUX channel to force five
0912   20   JSR   $0965          Goto force reading subroutine
0915   A9   LDA   #$05           Set MUX channel to force six
0917   20   JSR   $0965          Goto force reading subroutine
091A   A9   LDA   #$06           SEt MUX channel to force seven

091C   20   JSR   $0965          Goto force reading subroutine
091F   A9   LDA   #$07           Set MUX channel to force
                                 eight
0921   20   JSR   $0965          Goto  force reading subroutine

0924   CA   DEX
0925   D0   BNE   $08FC          Branch until 256 force
                                 readings taken
```

```
0927  C6  DEC  $E2
0929  D0  BNE  $08FA        Branch until three blocks of
                            256 taken
092B  A9  LDA  #$02         Delay parameters
092D  85  STA  $E9
092F  A9  LDA  #$00
0931  85  STA  $E7
0933  A9  LDA  #$00
0935  85  STA  $E8
0937  C6  DEC  $E8
0939  D0  BNE  $0937
093B  C6  DEC  $E7
093D  D0  BNE  $0933
093F  C6  DEC  $E9
0941  D0  BNE  $092F        End of delay
0943  C6  DEC  $E6
0945  D0  BNE  $08F4
0947  AD  LDA  $9039        Read speed counter high order
                            byte
094A  91  STA  ($E0),Y      Store data
094C  20  JSR  $09A0        Data address increasing
                            subroutine
094F  AD  LDA  $9038        Read speed counter low order
                            byte
0952  91  STA  ($E0),Y      Store data
0954  20  JSR  $09A0        Data address increasing
                            subroutine
0957  AD  LDA  $9029        Read treader speed high order
                            byte
095A  91  STA  ($E0),Y      Store data
095C  20  JSR  $09A0        Data address increasing
                            subroutine
095F  AD  LDA  $9028        Read treader speed low order
                            byte
0962  91  STA  ($E0),Y      Store data
0964  60  RTS
0965  8D  STA  $9FFA        Set MUX channel
0968  A9  LDA  #$00
096A  8D  STA  $A00B        ACR set time pulse on timer 2
096D  A9  LDA  #$26         Low order byte of time
096F  8D  STA  $A008        Low order byte address
0972  A9  LDA  #$00         High order byte of time
0974  8D  STA  $A009        High order byte address,
                            start timer 2
0977  A9  LDA  #$20         Set BIT 5 of accumulator
0979  2C  BIT  $A00D        Test time out signal
097C  F0  BEQ  $0979        Test again if not set yet
097E  AD  LDA  $A008        Clear timer 2 time out signal
0981  8D  STA  $9FFB        Start A/D conversion
0984  A9  LDA  #$02         Start of 26E-6 second delay
0986  85  STA  $E4
0988  C6  DEC  $E4
098A  D0  BNE  $0988        End of delay loop
098C  EA  NOP
```

```
098D  EA  NOP
098E  EA  NOP                  End of delay
098F  AD  LDA  $9FFE           Read data
0992  91  STA  ($E0),Y         Store data
0994  20  JSR  $09A0           Data address increasing
0997  AD  LDA  $9FFD
099A  91  STA  ($E0),Y
099C  20  JSR  $09A0
099F  60  RTS
09A0  18  CLC                  Clear carry
09A1  A5  LDA  $E0             ADL of data address
09A3  69  ADC  #$01            Increment address
09A5  85  STA  $E0             Store data ADL
09A7  A5  LDA  $E1             ADH of data address
09A9  69  ADC  #$00            Increment ADL if necessary
09AB  85  STA  $E1             Store data ADH
09AD  60  RTS
```

APPENDIX E

MACHINE LANGUAGE SUMMATION SUBROUTINE

Storage Locations

Summed data starts at 7010(hex)

$7010	Load cell #1-	Low Byte
$7011	Load cell #1-	Med. Byte
$7012	Load cell #1-	High Byte
$7014	Load cell #2-	Low Byte
$7015	Load cell #2-	Med Byte
$7016	Load cell #2-	High Byte
$7018	Load cell #3-	Low Byte
$7019	Load cell #3-	Med Byte
$701A	Load cell #3-	High Byte
$701C	Load cell #4-	Low Byte
$701D	Load cell #4-	Med. Byte
$701E	Load cell #4-	High Byte
$7020	Load cell #5-	Low Byte
$7021	Load cell #5-	Med. Byte
$7022	Load cell #5-	High Byte
$7024	Load cell #6-	Low Byte
$7025	Load cell #6-	Med. Byte
$7026	Load cell #6-	High Byte
$7028	Load cell #7-	Low Byte
$7029	Load cell #7-	med Byte
$702A	Load cell #7-	High Byte
$702C	Load cell #8-	Low Byte
$702D	Load cell #8-	Med. Byte
$702E	LOad cell #8-	High Byte

Summation Subroutine

Address	Op Code	Mnemonic Operand	Remarks
0872	A0	LDY#20	Zero summing storage locations
0874	A9	LDA#00	
0876	99	STA 7010,Y	
0879	88	DEY	
087A	10	BPL 0874	
087C	85	STA E0	
087E	A9	LDA#40	Load starting address for raw data storage locations
0880	85	STA E1	
0882	A0	LDY #00	
0884	98	TYA	
0885	0A	ASL A	X = 2 times Y (since 4 bytes per load cell for summing memory location)
0886	AA	TAX	
0887	B1	LDA (E0),Y	Low byte summing
0889	7D	ADC 7010,X	
088C	9D	STA 7010,X	
088F	C8	INY	
0890	E8	INX	
0891	B1	LDA (E0),Y	High byte summing
0893	7D	ADC 7010,X	
0896	9D	STA 7010,X	
0899	90	BCC 089E	
089B	FE	INC 7011,X	
089E	C8	INY	
089F	C0	CPY #10	
08A1	D0	BNE 0884	When Y equals 16, program continues. (16 bytes of raw data per loop)
08A3	A9	LDA #0F	
08A5	65	ADC E0	
08A7	85	STA E0	
08A9	90	BCC 08AF	
08AB	E6	INC E1	
08AD	A0	LDY #00	End of raw data set memory address
08AF	A5	LDA E1	
08B1	C9	CMP #70	
08B3	D0	BNE 0882	Stops summing if at the end of raw data set
08B5	60	RTS	

APPENDIX F

FIELD DATA

Treader Type	Replication	Depth mm	Velocity Code	Angle	Draft N	Side-Draft N	Vertical Force N	Forward Velocity m/s	Treader Revs/Sec.	Cone Index kPa
F	1	60	1	-20	1489	1126	-2066	1.94	1.14	424
F	2	60	1	-20	1681	1117	-3280	1.91	1.22	470
F	3	60	1	-20	1492	1213	-2139	1.91	1.23	341
F	4	60	1	-20	1015	816	-1258	2.06	1.21	145
F	1	60	2	-20	1386	1077	-1916	2.49	1.54	400
F	2	60	2	-20	1443	935	-2009	2.46	1.46	419
F	3	60	2	-20	1173	1020	-1392	2.61	1.62	237
F	4	60	2	-20	1465	1286	-1894	2.40	1.51	229
F	1	60	3	-20	1400	1094	-1973	2.97	1.86	662
F	2	60	3	-20	1342	1115	-1818	2.97	1.84	236
F	3	60	3	-20	1071	821	-1267	2.97	1.83	102
F	4	60	3	-20	1312	1098	-1683	3.20	1.97	252
F	1	60	4	-20	1382	1233	-1580	3.79	2.38	263
F	2	60	4	-20	1371	919	-1781	3.63	2.21	306
F	3	60	4	-20	1523	965	-2036	3.09	2.08	504
F	4	60	4	-20	1593	1069	-2163	3.21	2.16	167
F	1	60	3	-30	1834	1758	-2623	2.72	1.54	461
F	2	60	3	-30	1688	1347	-2281	2.55	1.43	348
F	3	60	3	-30	1424	1057	-1425	2.67	1.56	267
F	4	60	3	-30	1179	864	-1062	2.78	1.58	394
F	1	60	3	-10	1395	659	-2818	2.72	1.69	500
F	2	60	3	-10	1144	636	-2157	2.70	1.72	295
F	3	60	3	-10	1156	637	-2009	2.81	1.80	278
F	4	60	3	-10	873	598	-1525	2.84	1.86	77
F	1	60	3	0	1320	72	-3051	2.80	1.83	378
F	2	60	3	0	1256	10	-2545	2.74	1.78	288
F	3	60	3	0	1201	52	-2410	2.73	1.78	191
F	4	60	3	0	1261	67	-2396	2.87	1.94	108
F	1	60	3	10	1222	-1006	-2313	2.75	1.78	233
F	2	60	3	10	1186	-816	-2432	2.75	1.71	253
F	3	60	3	10	1244	-990	-2155	2.79	1.87	284
F	4	60	3	10	1221	-1012	-2363	2.86	1.86	466

F	1	60	3	20	1673	-1291	-2567	2.76	1.71	548
F	2	60	3	20	1426	-1028	-1914	2.72	1.71	300
F	3	60	3	20	1317	-785	-1909	2.80	1.62	263
F	4	60	3	20	1405	-1266	-2136	2.73	1.76	320
F	1	60	3	30	1228	-911	-1625	2.70	1.58	647
F	2	60	3	30	1514	-1191	-2121	2.67	1.58	367
F	3	60	3	30	1873	-1222	-2468	2.80	1.66	347
F	4	60	3	30	1567	-1149	-1924	2.80	1.65	270
F	1	30	3	-20	817	564	-1037	2.72	1.61	555
F	2	30	3	-20	943	677	-1190	2.78	1.67	462
F	3	30	3	-20	848	676	-1018	2.70	1.63	433
F	4	30	3	-20	955	580	-1190	2.80	1.67	305
F	1	90	3	-20	1816	1852	-3144	2.67	1.74	477
F	2	90	3	-20	1834	1627	-3692	2.58	1.60	510
F	3	90	3	-20	1762	1445	-2967	2.80	1.70	423
F	4	90	3	-20	1904	1928	-3814	2.67	1.67	263
M	1	60	1	-20	1672	954	-2412	1.91	1.02	376
M	2	60	1	-20	1640	824	-2211	1.91	1.02	497
M	3	60	1	-20	1786	1160	-2476	1.92	1.09	325
M	4	60	1	-20	1106	740	-1319	1.94	1.11	206
M	1	60	2	-20	1603	957	-2336	2.14	1.20	522
M	2	60	2	-20	1255	975	-1727	2.12	1.22	420
M	3	60	2	-20	1410	958	-1847	2.15	1.20	299
M	4	60	2	-20	1080	613	-1299	2.17	1.24	315
M	1	60	3	-20	976	592	-1152	2.75	1.58	425
M	2	60	3	-20	1167	717	-1372	2.66	1.50	376
M	3	60	3	-20	1565	855	-1916	2.86	1.59	334
M	4	60	3	-20	1342	775	-1625	2.78	1.68	363
M	1	60	4	-20	1179	834	-1415	3.09	1.83	330
M	2	60	4	-20	1366	1099	-1567	3.09	1.85	130
M	3	60	4	-20	880	625	-980	3.21	1.85	351
M	4	60	4	-20	1055	804	-1135	3.32	1.90	227
M	1	60	3	30	1282	-1441	-2266	2.56	1.59	561
M	2	60	3	30	1064	-788	-1492	2.81	1.61	264
M	3	60	3	30	1246	-1892	-1893	2.52	1.52	355
M	4	60	3	30	1198	-1072	-1811	2.80	1.60	216
M	1	60	3	10	1047	-767	-2657	2.60	1.72	455
M	2	60	3	10	1010	-796	-2355	2.67	1.80	414
M	3	60	3	10	1111	-533	-2113	2.81	1.84	169
M	4	60	3	10	976	-573	-2007	2.73	1.76	204
M	1	60	3	0	1419	-132	-3207	2.61	1.78	374
M	2	60	3	0	1120	-167	-2329	2.75	1.74	296
M	3	60	3	0	1273	-161	-2736	2.81	1.79	256
M	4	60	3	0	1533	-127	-3011	2.74	1.79	245
M	1	60	3	-10	427	839	-2562	2.75	1.65	540
M	2	60	3	-10	1295	872	-2154	2.79	1.71	323
M	3	60	3	-10	1271	731	-1964	2.83	1.72	120
M	4	60	3	-10	1255	760	-1940	2.84	1.71	245
M	1	60	3	20	1271	-1389	-2562	2.67	1.72	500
M	2	60	3	20	1193	-1127	-2100	2.72	1.71	226
M	3	60	3	20	1056	-755	-1632	2.81	1.71	241
M	4	60	3	20	1110	-947	-1741	2.75	1.71	263
M	1	60	3	-30	1187	746	-1473	2.81	1.45	543
M	2	60	3	-30	1432	908	-1743	2.64	1.40	429

M	4	60	3	-30	1374	829	-1251	2.89	1.60	90
M	1	30	3	-20	957	633	-1247	2.80	1.59	469
M	2	30	3	-20	1234	791	-1774	2.70	1.54	468
M	3	30	3	-20	876	521	-1050	2.84	1.56	552
M	4	30	3	-20	583	457	-638	2.85	1.64	333
M	1	90	3	-20	1828	1158	-2508	2.61	1.44	223
M	2	90	3	-20	2103	1364	-2816	2.67	1.56	366
M	3	90	3	-20	2215	1209	-3121	2.81	1.50	660
M	4	90	3	-20	2150	1416	-2867	2.64	1.54	297
R	1	60	1	-20	1938	824	-3042	1.92	1.15	494
R	2	60	1	-20	1309	694	-1928	1.95	1.15	452
R	3	60	1	-20	1461	710	-2260	1.92	1.17	184
R	4	60	1	-20	1029	557	-1378	1.92	1.15	414
R	1	60	2	-20	1644	986	-2215	2.27	1.45	333
R	2	60	2	-20	1270	586	-1863	2.20	1.31	225
R	3	60	2	-20	1661	692	-2355	2.23	1.37	378
R	4	60	2	-20	1654	885	-2603	2.27	1.42	236
R	1	60	3	-20	1353	810	-1866	2.78	1.72	379
R	2	60	3	-20	1572	807	-2294	2.80	1.73	368
R	3	60	3	-20	1532	627	-2106	2.83	1.71	212
R	4	60	3	-20	1164	572	-1529	2.81	1.74	525
R	1	60	4	-20	1619	818	-2764	3.24	1.95	490
R	2	60	4	-20	1397	709	-2043	3.20	2.00	389
R	3	60	4	-20	1370	759	-1830	3.22	2.03	339
R	4	60	4	-20	1551	893	-1967	3.33	2.11	380
R	1	60	3	30	1522	-1077	-2420	2.79	1.46	389
R	2	60	3	30	1331	-957	-2116	2.70	1.48	327
R	3	60	3	30	1621	-1188	-2541	2.75	1.41	350
R	4	60	3	30	1465	-998	-2300	2.65	1.48	245
R	1	60	3	10	1245	-886	-2947	2.72	1.72	438
R	2	60	3	10	1422	-933	-3187	2.72	1.73	436
R	3	60	3	10	1140	-711	-2503	2.74	1.72	301
R	4	60	3	10	1252	-612	-2314	2.74	1.77	482
R	1	60	3	0	825	-157	-1699	2.74	1.74	282
R	2	60	3	0	1270	-273	-2850	2.76	1.82	435
R	3	60	3	0	1290	-315	-2666	2.86	1.88	150
R	4	60	3	0	1154	-263	-2429	2.88	1.83	360
R	1	60	3	-10	1105	388	-1855	2.84	1.77	594
R	2	60	3	-10	1778	517	-3266	2.80	1.75	436
R	3	60	3	-10	1256	375	-2134	2.84	1.79	374
R	4	60	3	-10	1153	349	-1834	2.87	1.89	225
R	1	60	3	20	1225	-864	-2273	2.67	1.62	372
R	2	60	3	20	1864	-1282	-4254	2.76	1.60	509
R	3	60	3	20	892	-691	-1491	2.78	1.71	300
R	4	60	3	20	1078	-663	-1717	2.64	1.62	277
R	1	60	3	-30	1706	1114	-1906	2.92	1.86	411
R	2	60	3	-30	1777	1122	-2200	2.84	1.75	395
R	3	60	3	-30	1011	600	-1115	2.87	1.75	191
R	4	60	3	-30	1265	750	-1218	2.98	1.90	134
R	1	30	3	-20	941	448	-1372	2.78	1.69	479
R	2	30	3	-20	1000	584	-1357	2.81	1.73	326
R	3	30	3	-20	1109	481	-1578	2.84	1.77	470
R	4	30	3	-20	780	383	-1000	2.90	1.75	325
R	1	90	3	-20	1346	741	-2275	2.87	1.77	443

R	2	90	3	-20	1641	875	-2208	2.87	1.79	241
R	3	90	3	-20	2180	1141	-3154	2.75	1.74	454
R	4	90	3	-20	2112	1209	-3160	2.77	1.80	469

APPENDIX G

MOISTURE CONTENT ANALYSIS

Sample Content* #	Mass (gms) Wet	Mass (gms) Dry	% Moisture (Dry Wt. Basis)
1	87.89	79.89	10.01
2	105.93	94.52	12.07
3	95.64	87.02	9.91
4	132.48	115.46	14.74
5	111.60	98.42	13.39
6	106.96	94.35	13.37
7	121.62	105.81	14.94
8	122.36	106.11	15.31
9	102.45	92.97	10.20
10	99.68	91.53	8.90
11	101.76	90.28	12.72
12	128.30	112.37	14.18
13	107.86	98.90	9.06

	Average Moisture Content		12.22

* After oven drying for 24 hours at 105^{o} C, Hillel (1980).

APPENDIX H

AVERAGE DATA FOR EACH TREATMENT

AND TREADER

Treader Type	Relication	Depth mm	Velocity Code	Angle	Draft N	Side-Draft N	Vertical Force N	Forward Velocity m/s	Treader Revs/Sec.	Cone Index kPa
F	1	60	1	-20	1419	1068	-2186	1.95	1.20	345
F	2	60	2	-20	1367	1079	-1803	2.49	1.53	321
F	3	60	3	-20	1281	1032	-1685	3.03	1.88	313
F	4	60	4	-20	1467	1046	-1890	3.43	2.21	310
F	1	60	3	-30	1531	1256	-1848	2.68	1.53	368
F	2	60	3	-10	1142	633	-2127	2.77	1.77	288
F	3	60	3	0	1259	50	-2600	2.79	1.83	241
F	4	60	3	10	1218	-956	-2316	2.79	1.81	309
F	1	60	3	20	1455	-1093	-2131	2.75	1.70	358
F	2	60	3	30	1545	-1118	-2035	2.74	1.62	408
F	3	30	3	-20	890	624	-1109	2.75	1.65	439
F	4	90	3	-20	1829	1713	-3904	2.68	1.68	418
M	1	60	1	-20	1551	920	-2105	1.89	1.32	351
M	2	60	2	-20	1337	876	-1802	2.15	1.22	389
M	3	60	3	-20	1263	735	-1516	2.76	1.59	375
M	4	60	4	-20	1120	840	-1274	3.18	1.86	260
M	1	60	3	30	1198	-1298	-1866	2.67	1.58	349
M	2	60	3	10	1036	-667	-2283	2.70	1.78	328
M	3	60	3	0	1336	-147	-2821	2.73	1.78	293
M	4	60	3	-10	1312	801	-2155	2.80	1.70	307
M	1	60	3	20	1157	-1054	-2009	2.74	1.71	308
M	2	60	3	-30	1311	813	-1454	2.80	1.50	323
M	3	30	3	-20	913	600	-1177	2.80	1.58	456
M	4	90	3	-20	2074	1287	-2828	2.68	1.51	387
R	1	60	1	-20	1434	696	-2152	1.93	1.16	386
R	2	60	2	-20	1557	787	-2256	2.24	1.39	293
R	3	60	3	-20	1355	704	-1949	2.81	1.73	371
R	4	60	4	-20	1484	795	-2144	3.25	2.02	400

R	1	60	3	30	1485	-1055	-2344	2.72	1.46	328
R	2	60	3	10	1265	-786	-2738	2.73	1.74	414
R	3	60	3	0	1135	-252	-2411	2.81	1.82	308
R	4	60	3	-10	1323	482	-2522	2.84	1.80	407
R	1	60	3	20	1265	-875	-2434	2.71	1.64	365
R	2	60	3	-30	1440	897	-1610	2.90	1.82	283
R	3	30	3	-20	958	474	-1327	2.83	1.74	400
R	4	90	3	-20	1820	992	-2699	2.82	1.78	402

APPENDIX I

DATA INPUT PROGRAM FOR IBM PC

```
10  CLS
12 WIDTH "LPT1:",140
13 LPRINT CHR$(15)
14 LPRINT CHR$(27)"1"CHR$(15)
20 PRINT
25 REM         TREATMENT CODE:  FLEXKING---------F
26 REM                          MILLER-----------M
27 REM                          RICHARDSON-------R
28 REM         REPLICATION 1 2 3 OR 4
30 PRINT
40 PRINT
50 PRINT
60 PRINT"                                  A________ADD TO FILE"
70 PRINT"                                  P________PRINT FILE"
80 PRINT"                                  E________END PROGRAM"
90 PRINT"                             ??"
95 INPUT "CHOICE?" A$: IF A$="" THEN 95
100 IF A$ = "A" THEN 200
110 IF A$ = "P" THEN 500
120 IF A$ = "E" THEN END
200 OPEN "B:TREAD.DAT" FOR APPEND AS #1
205 INPUT "TREADER TYPE"; TYPE$
210 INPUT "REP"; R.
214 INPUT "DESIGN FORWARD VELOCITY"; DVEL
215 INPUT "DEPTH";D
218 INPUT "ANGLE";A
220 INPUT "X FORCE";X
230 INPUT "Y FORCE";Y
240 INPUT "Z FORCE";Z
250 INPUT "FORWARD VELOCITY";FVEL
260 INPUT "TREADER ROTATIONAL SPEED";TRS
270 INPUT "CONE INDEX";CI
370 BEEP:INPUT"THESE VALUES CORRECT";A$
380 IF A$="N" THEN 210
390 PRINT #1, USING "#.## ## # ### #### #### #### #.## #.##
   ####";T,D,DVEL,A,X,Y,Z,FVEL,TRS,CI
400 INPUT "MORE DATA?" A$
410 IF A$ = "Y" THEN 210
420 CLOSE
430 GOTO 10
500 LPRINT "TYPE REP   DEPTH VEL. ANGLE DRAFT SICE VERT.
FOR.VEL TRP. CONE INDEX"
```

```
510 LPRINT "_______________________________________________"
520 OPEN"B:TREAD.DAT" FOR INPUT AS #1
525 I=0:B=1
530 IF EOF(1) THEN GOTO 600
532 I=I=1
533 IF I¶4 THEN 536
534 B=B+.01
535 GOTO 540
536 B = INT(B)+1.01:I=1
540 INPUT #1,T,D,DVEL,A,X,Y,Z,FVEL,TRS,CI
550 LPRINT USING"##.##  ##    #       ###       ####   ####
   ####  #.##   ####    ";B,D,DVEL,A,X,Y,Z,FVEL,TRS,CI
560 LPRINT
570 GOTO 530
600 LPRINT CHR$(12)
610 CLOSE #1
620 GOTO 10
```

2

VITA

Steven J. Mulder

Candidate for the Degree of

Master of Science

Thesis: EFFECTS OF TREADER DESIGN AND OPERATING VARIABLES ON FORCE PREDICTION EQUATIONS IN OKLAHOMA

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