VERTICAL FORCES ON SOME FURROW OPENERS

AND DEPTH CONTROL DEVICES

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CHAPTER I

INTRODUCTION

An efficient soil tillage operation is one which minimizes the amount of energy required, consistent with achieving the desired tool position and soil conditions. Tillage system improvements have often resulted from a slow evolution or were developed through trial and error methods. With the aid of analysis and experimental design techniques, tillage systems can be expressed quantitatively and indicated improvements made in the method and equipment.

The research reported in this text was related to the general problem of better positioning and control of planter furrow openers relating to improved seed placement. A solution to the overall problem was not attempted, but the forces of some furrow openers and depth control devices were studied and certain relationships were established and expressed quantitatively. Vertical force requirements of furrow openers operating at various depths and speeds give some indications of what requirements must be made of depth gauging devices to maintain a predetermined depth of operation for seed placement.

This study was made in a soil bin to evaluate the effects of depth and speed of operation on the vertical forces of some commercial furrow openers and depth gauging devices. Relationships between vertical requirements of the tillage tools operating at given depths and speeds are presented.

When soil is used for crop production the roots of plants, farm equipment, and even air and water apply forces to the soil. If as a result of these forces the soil yields to the extent that its form is changed, it is behaving actively. If soil restrains such forces its behavior is passive.

Soil must be stressed and must yield to that stress if its condition is to be changed. Engineers designing tillage tools work with two basic factors; the shape of the tool moving through the soil and the manner in which the tool is moved. The final condition of the soil is dependent upon the initial soil condition, the shape of the tool, and the manner in which the tool is moved. Accurate classification of original soil conditions is the first step in achieving engineering planning goals involving soil management and tillage tool design (11).

In the soil region affected by a tillage tool, discontinuous fractures and collisions of aggregates occur which react upon the tool as impulse forces of various strengths. For each increment of tool travel there is a set of these random impulse forces. Although soil dynamic aspects of soil machine systems may be observed and in some respects measured, they are not well understood. The macroscopic soil-tool interaction is the resultant of many underlying phenomena. Soil is lifted, accelerated and thereby given potential and kinetic energies. In many cases it is manipulated such that a change in state occurs due to nonequilibrium conditions (14).

The ultimate goal of research on a soil machine system would be to refine the ability to predict machine performance to the point that it is adequate for virtually all applications. The evaluation of an evolved soil-tool system may be largely dependent on a combination of models. Model testing can lead to sufficient understanding of the basic behavior patterns that a general applicable analytical procedure can be devised. It is the intent of this study to contribute to a better understanding of soil-machine systems and how to control them.

CHAPTER II

REVIEW OF LITERATURE

The literature review included a study of background information in areas of soil bins and artificial soils, effects of physical properties of soils on the operation of tillage tools, and soil forces on individual tillage tools. No specific reference was found on the relation between vertical forces on seed furrow openers and precise depth control of the opener.

Soil Bins and Artificial Soils

The use of soil bins and various recipes of artificial soils have increased considerably in recent years. The soil bin provides a means for the researcher to control some of the variables encountered in field testing of tillage tools. The soil properties can be determined, held constant, and the soil is considered a homogeneous mass. According to Barnes (5) the fundamentals of the physical behavior of tillage tools are much more likely to be found from tests conducted under controlled laboratory conditions than from field tests. The first step in planning a model study is the identification of measurable physical variables which, when properly combined, will completely describe the physical phenomena under study.

Soil bins used for tillage research generally consist of a soil container, soil processing equipment and instrumentation for measuring the desired variables of the system. Until soil strength parameters are evaluated, test results from one experimental location cannot be quantitatively compared with those from another location.

Artificial soils containing spindle oil, fireclay and sand are good from the standpoint of stability and reproducibility, but do not produce strong cohesive characteristics (8). Reeves (27) used various concentrations of ethylene gylcol instead of spindle oil to change the soil cohesive properties. The glycol is hydroscopic and changes in relative humidity affect the soil properties due to the change in moisture content.

The soil properties used by most researchers to study soil-machine systems include angle of internal friction, cohesion, adhesion, bearing strength and soil-to-metal friction (38, 36, 34, 18, 3, 15). Abernathy (2) found the percentage of spindle oil, up to 20 percent by weight, had very little effect on the frictional properties. Cohesion, in the soil with spindle oil, was not affected by changes in density or by changes in oil content up to 20 percent. The soil-to-metal frictional characteristics of the artificial soil were unchanged by increasing the bulk density of the spindle oil and soil mixture.

Bailey and Weber (3) used artificial soil to evaluate various methods of determining the shear strength of soils. Two soils were used in the experiment. The first mixture consisted of Gooselake Fireclay plus 10 percent by weight of SAE-5W pure mineral oil. The second mixture consisted of equal parts of sand and volclay with 17 percent, dry weight basis, SAE 140 gear lubricant. The second mixture was more compactable than the first and was a more cohesive soil. Siemens and Weber (30) used the artificial soil mixture of Gooselake Fireclay mixed with SAE-5W pure mineral oil at a rate of 10 percent by weight in practical tillage experiments. The artificial soil was similar to a damp coarse silt and remained stable for a period of six months allowing considerable research to be carried on for a period of time with no significant changes in the soil properties

Mink (23) used an artificial soil mixture of fireclay sand and SAE 8 non-detergent hydraulic oil. The variations in draft, caused by differences in soil conditions, were found to vary only 1.49 percent over a period of three months. Cohron (10) and Chisholm (6) used a misture of fireclay, sand and low viscosity oil. Different portions of these materials have been used to produce a range of soil properties. Cohron found the internal friction angle and cohesive property could be varied by increasing the bulk density, but had little effect on the friction of metal-on-soil. He reported that although artificial soil properties remain stable for long periods of time they also cover only a narrow range and a greater variety of artificial soils are needed.

Korayem and Reeves (20) evaluated the use of artificial soil as a medium for model studies of tillage tools. The tools evaluated in these tests were plane chisels operating in a laboratory soil tank. They concluded that artificial soil can be used to perform tillage research. Although the binding agents had considerably lower cohesive properties than water, the familiar rupture planes did develop in the soil around the chisel, indicating the action of the tillage tool was similar to the expected action in a normal water-moistened soil.

Zoz (38) studied the effect of section thickness on the shear characteristics of an artificial soil. The soil used in this study was a 50-50 mixture by weight of crystal silica sand and bentonite clay. Ethylene glycol antifreeze was added to obtain a 20 percent liquid content by weight. All tests were made by controlling the rate of strain and measuring the resulting shear stress. A strain rate of approximately 1½ inches per second was used. As the rate of shear varied no change was noted in the stress-displacement curves. As the section thickness increased a greater amount of displacement was needed to reach the maximum shear stress and the maximum value of the shear stress decreased.

Luth and Wismer (22) studied the response of flat soil cutting blades in purely frictional sand. The artificial soil was considered as one of the simplest soils to be studied in a soil dynamics investigation. Sand sections representing three strength levels were used. Cone penetrometer measurements described the properties of each section. Triaxial shear measurements were made to determine values for the soil cohesion and internal friction angle. An annulus type measuring device was used to measure the coefficient of soil-to-metal friction. As could be expected, soil cohesion was essentially zero for the three strength levels used. The relative densities varied, but the internal friction angle was essentially the same for the high and medium strength sections. The coefficient of soil-to-metal friction was nearly constant for all three strengths. By using a non-linear least squares curve fitting technique, specific prediction equations for horizontal and vertical draft forces were obtained. In both cases the standard error of estimate expressed as a percentage of the mean was 13 percent. It is relatively easier to control the uniformity of the physical properties of dried sand and generally both the coefficient of internal friction and soil-to-metal friction can be eliminated from consideration. Therefore, Luth and Weismer's work gives some indication of the minimum level of scatter that can be expected in soil dynamics work.

Abernathy (2) used an "artificial fine" soil and an "artificial coarse" soil to study soil density modification with furrow openers of simple geometric shape. The solid phase of the fine soil mixture consisted of 20 percent Ottawa sand and 80 percent Wyoming Bentonite by weight. The liquid phase was 30 percent SAE-120 transmission oil on dry weight basis. The solid phase of the "artificial coarse" soil consisted of 80 percent Ottawa sand and 20 percent Wyoming Bentonite. The liquid phase consisted of 10 percent SAE-10 motor oil on dry weight basis. The soil properties for the fine soil was measured to have an internal friction angle of 35 degrees, cohesion 0.6, and soil-to-metal friction angle of 27 degrees. Properties of the coarse soil included an internal friction angle of 39 degrees, soil-to-metal friction angle of 22 degrees and no cohesion or adhesion. Chisholm (6) used an artificial soil mixture of 28.6 percent Ottawa flint shot white sand, 63.5 percent milled fireclay, and 7.9 percent Continental #11 spindle oil by weight to study the three dimensional interference between two tillage tools. For this mixture cohesion was 0.008 psi, adhesion was 0.000 psi, angle of soil-to-soil shear was 35.9 degrees and the angle of soil-to-metal shear was 21.5 degrees. It was found that the soil mixtures using oil as the liquid binder did not significantly change their physical properties during the several month test period.

Effects of Soil Properties on Tillage Tools

The literature dealing with tillage operations include references to soils in a wide range of physical conditions. These conditions materially affect the reactions of the soil and any discussion of tillage tool action should be prefaced with a description of the soil and its physical condition. Researchers who conduct soil-machine studies in soil bins usually adequately describe the soil, however, it becomes more difficult when the studies are made in the field.

An investigation by Soehne (31) into the process taking place on the moldboard plow showed fragmentation of the soil slice is brought about primarily through shearing, i.e., cohesion in the soil is overcome mainly by tangential stresses. Pure tensile stresses play only a secondary part. This applies not only to direct shear and torsional loading, but also to compression.

Soil bin studies with incline plane shaped tools found that the cutting edge tried to displace the soil upward, thus setting up a stress field. As soon as the tangential stress becomes equal in magnitude to the maximum shear stress, i.e., cohesion plus internal friction, a failure surface forms and expands until it reaches the soil surface. The clod of soil separated in this way pushes upward along the failure surface and the tool. This process repeats itself periodically. Each time a clod has separated itself the cutting resistance is reduced and gradually increases again due to the resistance to displacement in front of the cutting edge and at that time a new clod is formed. The working depth determines the distance between the failure surfaces. The greater the depth the closer to each other are the surfaces.

Components of the total necessary work include lifting, accelerating and breaking up the soil. Unproductive work include components due to soil-to-metal friction along the tool and soil-to-soil friction along the failure surface. Part of this unproductive work may again be attributed to lifting, part to accelerating and part to loosening the soil.

At a working depth of 10 cm and a forward speed of one m/sec, Springle determined the total cutting resistance in sand is made up as follows:

lifting--------16%	friction due to lifting---------38%
accelerating--- 4%	friction due to acceleration---- 3%
breaking up----20%	Friction due to breaking up-----19%

According to a mathematical model, the minimum angles for cutting resistance were found to be between 11 and 15 degrees. The accelerating forces increased with the square of the cutting speed, the result being a parabolic increase of the resistance in relation to the speed of cutting.

At speeds of less than one mph, where the largest peak-to-peak variations in force occurred, the failure phenomenon was independent of speed and was directly related to cohesion. From the shear plane failure, there was a transition to flow failure as speed was increased (33).

Previous work shows the shear value of the soil is directly proportional to the pressure applied. The lift and drag forces acting on furrow openers increases with an increase in the vertical and wedge angles. Soils with little cohesion cannot be compacted by sliding wedge-type furrow openers without some method of containing the soil. The passive pressure equation,

$$\sigma_1 = \gamma d K^4 + 2C\ (K^3 + K)$$

accurately predicted the amount of vertical pressure that could be applied to the furrow bottom of non-cohesive soils (2).

where:

σ_1 = Vertical pressure at which plastic flow will be imminent

γ = Bulk density of soil

d = Depth

C = Soil cohesion

K = Internal friction angle of soil, Tan $(45 + \phi/2)$

Nichols (25) stated that the main cause of variation of draft in controlled bin experiments is in cutting loose the furrow slice on the plow sole and the friction on the bottom of the furrow. The difference in draft and vertical forces on the plow bottom is largely caused by the effects of changes at the cutting edge of the share.

Soehne (31) reasoned that the pure cutting resistance of the soil is small and becomes important only when stones or roots are present or the cutting edge of the tool is dull. Concentrating on the soil segment rather than on the tool, he summed up the vertical forces and placed them in equilibrium by the equation:

$$0 = G - N_o\ (\cos\ \delta = \mu^1 \sin\ \delta) - N_1\ (\cos\ \beta - \mu \sin\ \beta) + (Cf_1 + \beta)\ \sin\ \beta$$

where:

G = Weight of soil segment

N = Normal load on the forward failure surface

δ = Lift angle of tool

μ^1 = Coefficient of soil-to-metal friction

μ = Coefficient of internal soil friction

β = Acceleration force of the soil

C = Soil cohesion

f_1 = Area of forward shear failure

Another theoretical equation by Wang (35) estimates the total draft force of tillage tools operating in any soil condition:

$$R/\rho L^3 = \{F\ (\Phi,\mu) + G\ (\Phi,\mu)\ C/\rho L + H\ (\Phi,\mu)(C/\rho L)^2\}\frac{V^2}{gL} = \text{constant}$$

where:

R = Draft force

μ = Apparent soil-material friction angle

C = Soil cohesion

V = Velocity of tool

L = Characteristic length

ρ = Bulk volume weight of soil

Φ = Coefficient of internal soil friction

The method established by Wang and Liang has two advantages over other model testing techniques in soil dynamics work: 1) the velocity of the prototype and model need not be limited to low velocity so forces due to velocity effects can be accounted for, and 2) soil properties except for internal friction angle, need not be closely maintained. This method is of special interest to researchers and designers of agricultural implements where tool sizes and operating velocities vary incrementally and within known ranges.

There are two common systematic methods of obtaining modeling laws of a system: 1) dimensional analysis method and 2) the method that makes an analysis of the characteristic equation governing the system. If the characteristic equation for the system is known the procedure is routine, however, this technique requires a much more detailed knowledge of the system than is required for dimensionsl analysis (37). A prediction equation may be developed to predict the actual values of forces encountered in field situations or to predict the optimum design condition based on a given criteria.

Barnes (5) suggests the properties of a soil to determine the reaction forces on tillage tools may be taken as:

W = Bulk volume weight (wet basis)

M = Moisture content

C = Clay content (apparent cohesion)

μ = Angle of soil-metal friction

Φ = Angle of shearing resistance

A = Apparent adhesion (soil-to-metal)

R = Resultant force (draft)

V = Velocity of tool with respect to the soil

g = Acceleration of gravity

λ = Other pertinent lengths

D = Diameter of disk

α = Angle of inclination

β = Disk approach angle

From these variables a function relationship among a group of dimensionless terms would have the general form:

$$R/_{WD}3 = f\ (\lambda/D, \frac{V^2}{gD}, \alpha, \Phi, \mu, \frac{C}{WD}, \frac{A}{WD}, \beta)$$

The best values for predicting both the geometry of the failure surface in front of the tools and the tool forces are the lowest values obtained for both cohesion and angle of shear resistance. Siemens (29) found the vertical draft component (F_z) was positive for tool angles greater than 70 degrees with respect to horizontal and negative for tool angles less than 70 degrees. Both F_x and F_z changed linearly with tool width for all tool angles.

Rowe and Barnes (28) developed an equation relating the influence of speed with respect to the force resisting the acceleration of the soil block.

$$B = \frac{W}{g} b \ t \ V_o \ V_s$$

where:

B = Force resisting the acceleration of the soil block

W = Bulk volume weight of soil

g = Acceleration due to gravity

b = Width of tool

t = Depth of tool

V_o = Horizontal velocity of tool

V_s = Rate of slip at the shear surface

In developing this relationship several assumptions were made:

1) The nature of soil failure ahead of an implement is a series of shear failures.
2) Angle of inclination of the surface of the soil failure to the major principal stress depends only on the soil frictional properties.
3) Both the shearing strength of the soil and the resistance to sliding of the soil over metal can be approximated by a linear function of the stress normal to the surface of shear or of sliding.

4) The soil can be considered a homogeneous and isotropic material.

The tests were conducted in a moving soil bin and a stationary dynamometer. Four natural soils were used in their studies. The tillage tool consisted of a flat plate, two inches long, four inches wide and inclined 25 degrees to the horizontal, such that the bottom edge was leading. As the velocity was increased from 0.75 feet per second to 2.75 feet per second, the draft increased in sandy soil approximately 15 percent, and in Colo silty clay loam the draft increased approximately 60 percent. When an analytical calculation of draft was made, acceleration of the soil contributed only a small part of the total draft force. The increase in draft with an increase in speed was mainly due to increased shear strength of the soil at a higher rate of shear. Results of this study indicated a reduction in the acceleration of the soil acted on by the tool would only result as a small reduction in the increase in the draft. Shearing strength of each of the four types of soils was found to increase as the rate of shear increased. The change was small for sandy soils, but became progressively larger for soils with higher clay content.

Soil strength defined by Gill (17) as the ability or capacity of a particular soil in a particular condition to resist or endure an applied force. Soil strength is also defined as the capacity of soil to withstand deformation or strain since strength is not evident without strain. Soil strength is a physical quantity. The problem is to measure and describe strength so a definite series of numerical values can be assigned to a soil. This problem has not been satisfactorily solved to date. Reasons for wide ranges of strengths observed in soils are, one difficulty in adequately measuring and describing, another is that strength actually changes when a force is applied and movement occurs. Strength then is a dynamic property of soil. The size of a dynamic property does not change during soil movement and conversely, the size of a static property does not necessarily remain fixed.

Shearing resistance due to internal friction is considered by Housel (19) and others as a mechanical property of soil masses which produce resistance to tangential displacement proportional to applied normal pressure. Internal friction is expressed in terms of the angle of internal friction, Φ, which is the tangent of the angle of internal friction. Coulomb's equation used extensively by soil mechanics and engineers, expresses the shearing strength of soil in terms of strength parameters with the relationship.

$$\tau = C + \sigma \tan \Phi$$

τ = Shearing stress at the point of soil failure

σ = Normal stress at the point of failure

C = Cohesion

Φ = Angle of internal friction

Nichols (25) found the relationship between the upward pressure applied by the point of a subsoiler and the horizontal pressure applied to the soil by the standard was very important to draft. Parameters have been developed and equated by Bernstein and Bekker (12) for describing soil bearing strength.

$$P = K Z^n$$

where:

P = Unit load

K = Modulus of deformation depending upon the size of the loading area, the cohesional effect and frictional properties of the soil

Z = Depth of sinkage

n = Sinkage exponent

Becker used the concept of K_c and K_Φ by expressing:

$$K = (K_c/b + K_\Phi)$$

where:

K_c = Cohesive modulus of deformation

K_Φ = Frictional modulus

b = Smaller dimension of the loading area

These parameters, C, Φ, n, K_c and K_Φ, are useful in describing strength properties of soils until more fundamental soil parameters can be determined and readily evaluated.

Two types of gauging devices under consideration include rolling or wheel type and sled. Resistance to a wheel rolling in the soil has several visible forms which include: sinkage or compaction, drag on the sides of the wheel, and a build-up of soil in front of the wheel above the original soil level. These complex forms of rolling resistance are difficult to represent by mathematical models. Knowledge of the shape and area of surface contact between wheels operating in soil and the total forces provides a means of calculating the stresses. Measuring the shape of the contact area is difficult. To obtain a dynamic contact area, devices have been rolled through the soil, stopped and lifted from the soil. The track left by the wheel is filled with plaster to reproduce the shape in the soil caused by the wheel.

Numerous tracer and grid measurements have been utilized. Enough measurements have been made to establish that a dynamically loaded contact area and a statically loaded contact area differ considerably in size and shape.

Generally energy losses in a rolling wheel can be divided into three parts: internal, rotational, and translational losses. Internal loss is due to axle-bearing friction and other mechanical imperfections together with the deflection of the carcass in the case of pneumatic tires. Shear deformation loss is partly due to slip losses and partly due to the tangential forces developed by the wheel used to support part of the weight of the axle. Translation loss is due to the horizontal integral of the radial force opposing the wheel linear or translational motion. The main effect of this force is to reduce the available drawbar pull of the wheel (26).

Soehne (31) used the following semi-empirical formula derived by Froehlick to calculate the stress distribution under tires in soils of various properties.

$$\sigma_Z + \frac{\nu P}{2\pi r^2} \cos \nu_{\Phi}$$

where:

σ_Z = Vertical normal stress at the point in question

P = Unit load at a point in the soil surface

ν = Concentration soil factor depending upon moisture content, cohesion and density of the soil

Φ = Polar coordinates of σ_Z.

CHAPTER III

EXPERIMENTAL DESIGN AND METHOD OF ANALYSIS

The purpose of this research was to measure the vertical forces imposed upon some furrow openers and gauging devices operating in an artificial soil. The study was limited to three furrow openers, three gauging devices, and one soil mixture of sand, clay and spindle oil. Soil density, cohesion, adhesion, coefficient of soil-to-soil internal friction, coefficient of soil-to-metal internal friction, and soil bearing strength were measured and held constant throughout the study.

Objectives of the Research

1) Measure the vertical forces on some seed furrow openers and depth control devices operating in an artificial soil.
2) Develop prediction equations relating the vertical forces of seed furrow openers and depth control devices operating at predetermined speeds and depths.
3) Develop prediction equations relating mechanical soil properties to the vertical forces on seed furrow openers and depth control devices.

Experimental Design

The research was planned to study the vertical forces on three furrow openers operating at speeds of one, three, and five feet per second. The openers were operating at depth increments of one-half inch from zero to three inches. Three gauging devices operated at speeds of one, three, and five feet per second and at 0.2 inch depth increments from zero to two inches.

The statistical design for determining the vertical force for the furrow openers and gauging devices was a replicated split plot design with the degrees of freedom partitioned as follows (10):

SOURCE	D.F.	FURROW OPENERS D.F.	GAGING DEVICES D.F.
Replications	(r-1)	2	2
Openers	(f-1)	2	2
Error (A)	(r-1)(f-1)	4	4
Velocities	(v-1)	2	2
Velocities x openers	(v-1)(f-1)	4	4
Error (B)	f(r-1)(v-1)	12	12
Depths	(d-1)	5	9
Depths x velocities	(d-1)(v-1)	10	18
Depths x openers	(d-1)(f-1)	10	18
Depths x openers x velocities	(d-1)(f-1)(v-1)	20	36
Error (C)	(f)(v)(r-1)(d-1)	9	162
TOTAL	(n-1)	161	269

where:

r = Number of replications

f = Number of tools

v = Velocity of tools with respect to the soil

d = Depth of tool in soil

Linear regression techniques were used to obtain a best fit plot of Coulomb's soil shear stress equation. The equation relates shear stress, τ, to soil cohesion and coefficient of internal friction. Twenty-six samples of artificial soil were tested to obtain observations for the soil-to-soil strength line and 24 soil samples were tested to obtain the soil-to-metal strength line. Shear stress, τ, was the dependent variable and normal stress, σ, was the independent variable for both series of tests. Correlation coefficients were used to relate the closeness of fit of the measured stresses to the regression line.

A logarithmic plot was made of the soil bearing data and an equation of the dependent variable in terms of the independent variable was obtained. The penetration pressure was the dependent variable and depth of sinkage was the independent variable. Four replications of ½ inch depth increments to a depth of three inches were recorded for each penetration plate diameter. A total of 24 observations were taken for each size of plate.

Dimensional Analysis and Development of Pi Terms

The study was designed on the basis of vertical force being the dependent variable. Other factors affecting the system as independent variables are designated as follows:

VARIABLE	SYMBOL	DIMENSION
Vertical Force	F	$M L T^{-2}$
Velocity	V	$L T^{-2}$
Depth of Tool Operation	D	L

Vertical Projected Area	A	L^2
Soil Cohesion	C	$M\ L^{-1}\ T^{-2}$
Soil Adhesion	α	$M\ L^{-1}\ T^{-2}$
Soil-Soil Coef. of Friction	θ	$M^0\ L^0\ T^0$
Soil-Metal Coef. of Friction	Φ	$M^0\ L^0\ T^0$
Frictional Modulus of Sinkage	K_Φ	$M\ L^{-(n+1)}\ T^{-2}$
Cohesive Modulus of Sinkage	K_c	$M\ L^{-n}\ T^{-2}$
Exponent of Sinkage	n	$M^0\ L^0\ T^0$
Soil Density	ρ	$M\ L^{-3}$
Acceleration of Gravity	g	$L\ T^{-2}$

There are two principal advantages for using dimensional analysis and similitude in a research study. First, grouping the pertinent variables often reduces the number of terms to be varied during the experiment. Second, using pi terms in the experimental organization may allow the experimental results to be more readily applied to systems other than the specific system studied.

In this study the use of pi terms would not reduce the number of terms to be varied, therefore, the tests were conducted using each variable instead of the pi terms developed from the variables. Values for each pi term were calculated from the variables and combined into relationships that could be applied to other systems. Equipment and techniques were available for varying the necessary variables under consideration while the remainder were held constant.

The vertical force component, F, was the dependent variable and the following pi terms were developed for the system:

$$\pi_1 = \frac{F}{\rho g A D} \qquad \pi_6 = \frac{D^2}{A}$$

$$\pi_2 = \frac{V^2}{Dg} \qquad \pi_7 = \frac{\alpha}{\rho g D}$$

$$\pi_3 = \frac{K_c}{A^{0.039}\rho g} \qquad \pi_8 = \Phi$$

$$\pi_4 = \frac{C}{\rho g D} \qquad \pi_9 = \theta$$

$$\pi_5 = \frac{K_\Phi}{A^{0.539}\rho g} \qquad \pi_{10} = n$$

With π_1 as the dependent pi term the relationship becomes:

$$\frac{F}{\rho g A D} = f\left(\frac{V^2}{Dg}, \frac{K_c}{A^{.039}\rho g}, \frac{C}{\rho g D}, \frac{K_\phi}{A^{.539}\rho g}, \frac{D^2}{A}, \frac{\alpha}{\rho g D}, \Phi, \theta, n\right)$$

The furrow openers and depth control devices tested were tools commercially available and are currently used by the agricultural industry. An effort was made to select tools that were significantly different with respect to their principle of operation and movement of the soil. Preliminary tests were conducted to assist in selecting the size and proportions of tools to be studied. The tools were required to be large enough such that variations of the independent factors would produce measurable changes in the vertical forces, but the tools had to be small enough to conduct the test in the available soil bin test area, 24 inches wide and approximately 12 inches deep, without interference from the soil bin walls.

Velocities of one, three, and five feet per second were selected to test the range of speeds within the capabilities of the soil bin. When the soil carrier belt was loaded, it would not operate at a constant speed below one fps due to belt slippage. Above five fps the volume of soil moved by the carrier belt at a depth of 10 inches was greater than the storage capacity of the system.

A maximum depth of operation of three inches for the furrow openers in the soil bin was selected based on the normal maximum depths the tools are expected to operate in the field. Preliminary tests showed ½ inch depth increments would provide sufficient data to detect differences in the vertical forces due to depth of operation. Since the penetration or sinkage of the depth control devices is by definition small for a given load, the maximum depth used for the depth control devices was two inches. A sinkage of two inches is considered an extreme field condition. Preliminary tests showed relatively higher loads were required to sink the depth control devices compared to the furrow openers. Therefore, the force measurements were made at depth increments of 0.2 inches for each gauging device.

The most informative method of analysis of the results of a factorial experiment depends on the nature of the variables. Since all variables defined for the system were quantitative, the response of the dependent variable is presented as a function of different levels of the independent variables in the form of a response surface. Response surfaces were developed with the dependent variable, vertical force, as a function of independent variables, speed, depth of operation, and tool area with the remaining variables of the soil tool system previously listed constant.

CHAPTER IV

EQUIPMENT AND PROCEDURE

Soil Bin

The soil bin designed and built by Batchelder et al., (4) was used for this study. A schematic diagram of the soil bin is shown in Figure 1. Photographs showing various portions and components of the soil bin are presented in Figures 2 through 4. The soil bin was designed to have a continuous flow of soil move past the stationary tool being tested. Continuous operation for extended periods of time gives an opportunity to vary the independent factors while their effects on the dependent factors can be observed. Restructuring the soil after being manipulated with an experimental tool is also eliminated. When operating, the soil is carried from the storage hopper through an exit orifice. The soil is moved on the carrier belt under the leveling blade, the compaction drum, past the nuclear density monitoring device and into the test area. After passing the test area, the soil falls from the carrier belt onto the return belt which carries the soil back to the lift pulley. The soil is contained between the surface of the lift pulley and the return belt as it is carried approximately 180 degrees around the pulley. The soil leaves the lift pulley due to centrifugal force and is deposited back into the storage hopper. The carrier belt is hydraulically driven and can be operated at speeds

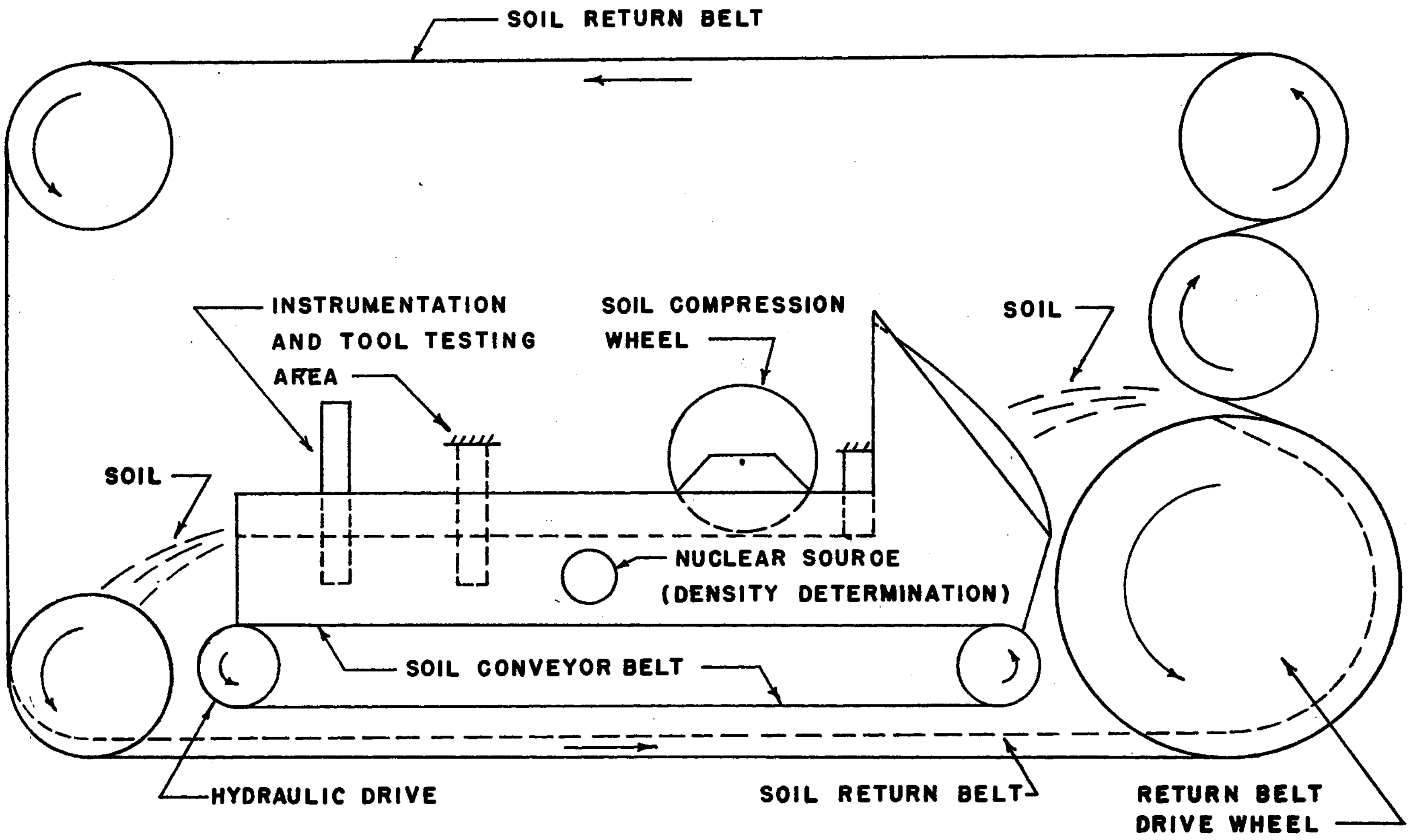


Figure 1. Schematic Diagram of the Continuous Linear Soil Bin

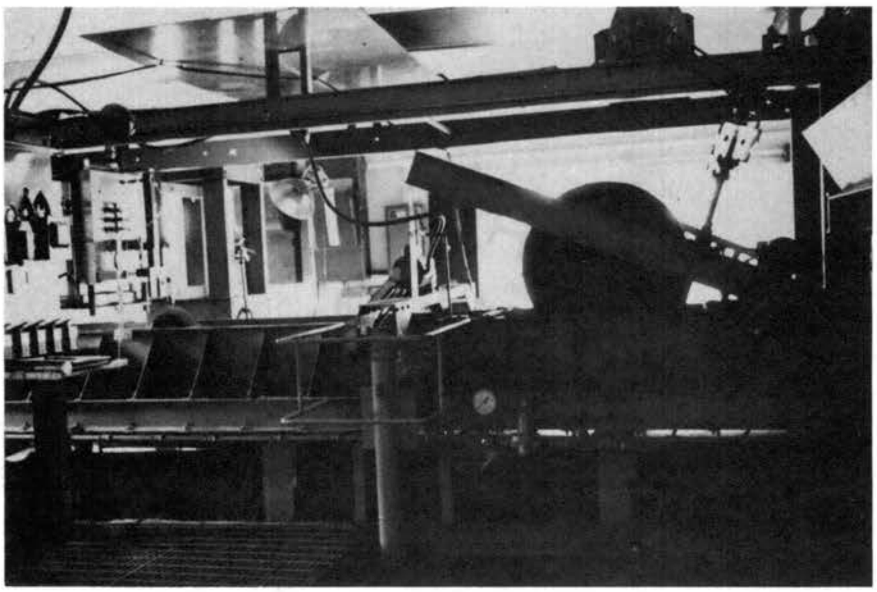


Figure 2. Side View of the Soil Bin Showing the Compaction Wheel, Density Meter and Test Area

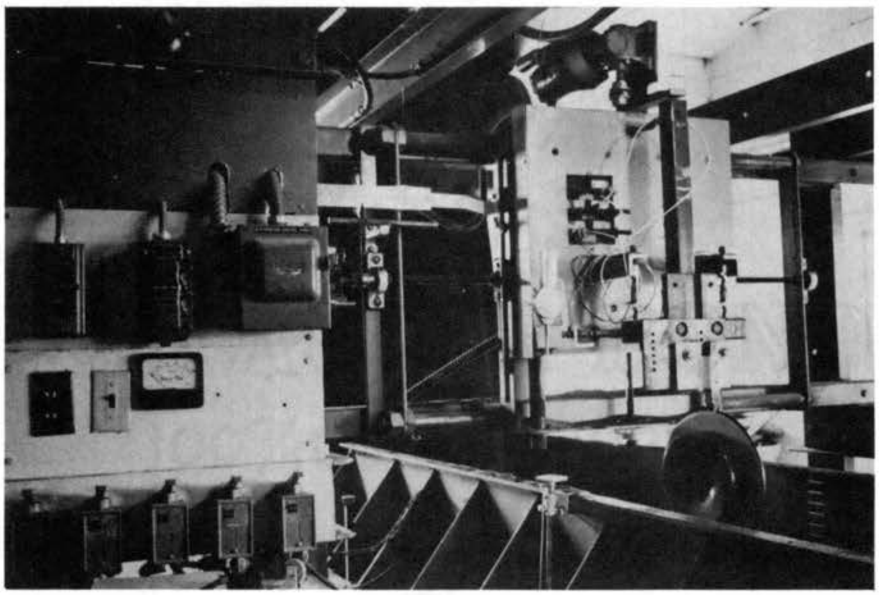


Figure 3. Control Panel and Test Area

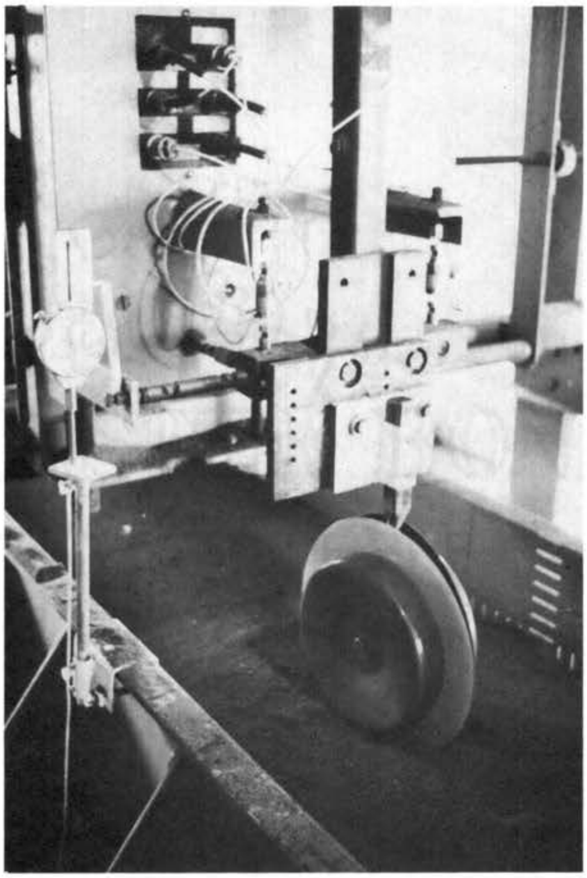
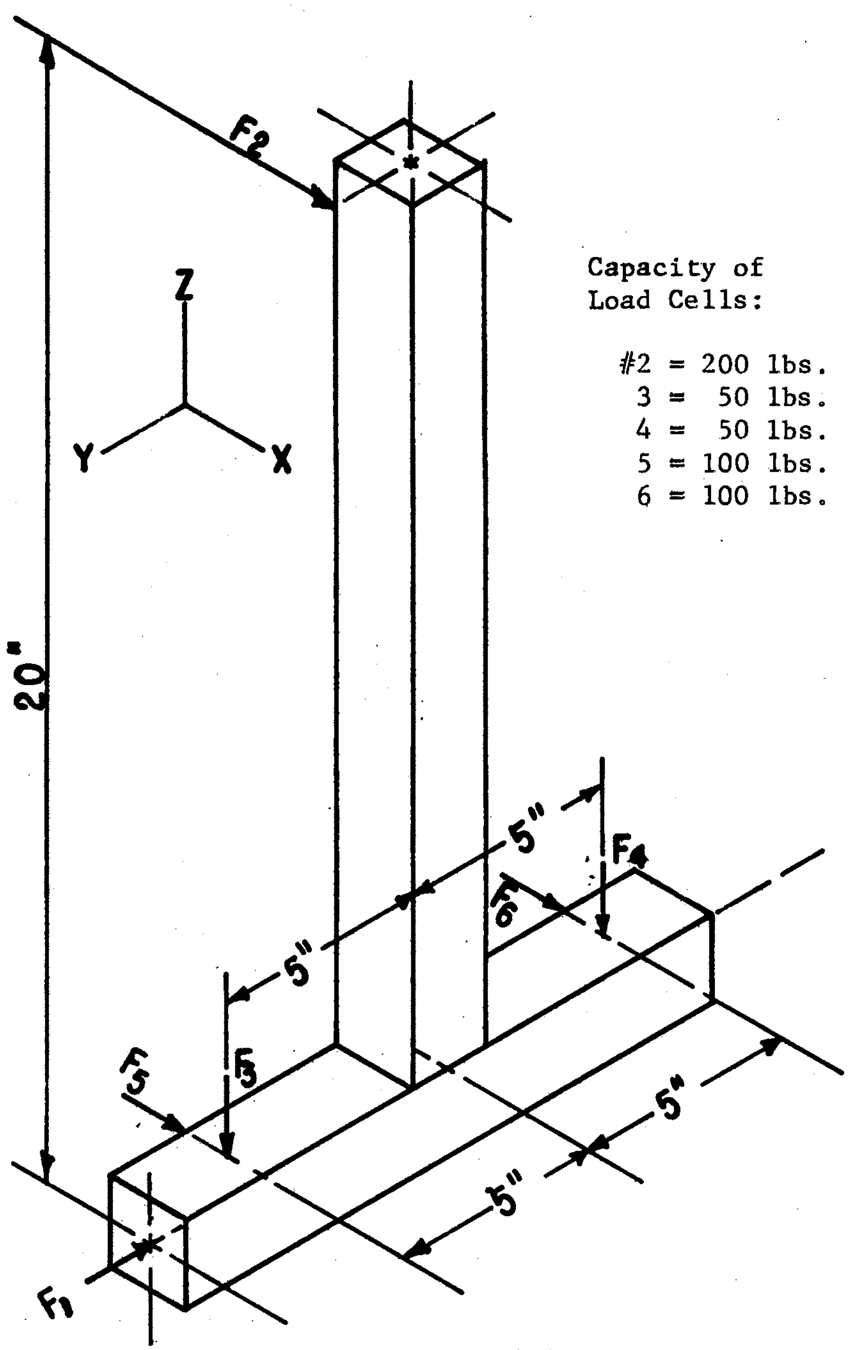


Figure 4. Test Area with the Double Disk and Depth Bands Mounted onto the Dynamometer

ranging between zero and eight feet per second. The tillage dynamometer is made up of six load cells positioned as shown in Figure 5. Due to symmetry of the tillage tools, load cell number one was disconnected. Signals from the load cells were received and recorded on five channels of the eight channel dynagraph recorder shown in Figure 6. Two channels of the recorder were used for recording soil velocity and soil density.

Soil density was measured in the test section with a Qualicon gamma radiation density gauge shown in Figure 7. Gamma radiation was transmitted across the soil layer and received by a detector located on the opposite side of the test bin. During operation the gamma rays travel from the source through the soil mass. The soil absorbs part of the radiation, but some radiation passes through the soil to the receiver. Radiation detected by the receiver provide a measure of the soil density. The amount of radiation through the soil is inversely related to density. An electrical signal is developed in the receiver proportional to the detected radiation. A signal travels from the receiver to a single stage amplifier where it is amplified and interpreted as soil density. Soil density was read directly from the meter shown in Figure 8 as well as being recorded on channel eight of the eight channel recorder. Before using the density measurement system in the test it was calibrated to produce a signal that was directly related to a known soil density. Calibration was accomplished by inserting an open-end metal container into the soil carrier belt. The container was two feet long, two feet wide and one foot high. Four cubic feet of soil was placed into the container at different levels of compaction. Meter readings were taken for each compacted sample.



Capacity of Load Cells:

#2 = 200 lbs.
3 = 50 lbs.
4 = 50 lbs.
5 = 100 lbs.
6 = 100 lbs.

$F_x = F_2 + F_5 + F_6$

$F_y = F_1$

$F_z = F_3 + F_4$

$M_x = 10F_4$

$M_y = 20F_2$

$M_z = 5F_2 + 10F_6$

Figure 5. Tillage Tool Dynamometer with Location of the 6 Load Cells

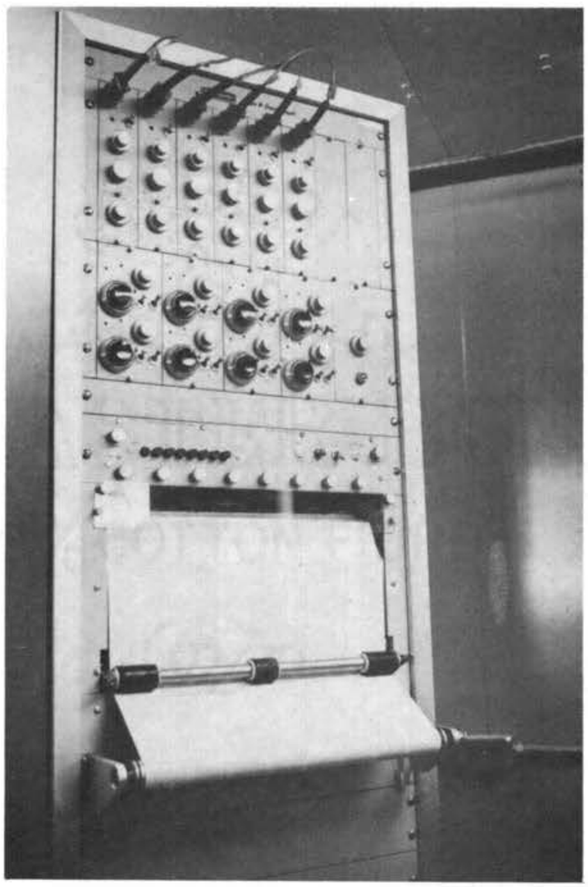


Figure 6. Beckman Eight Channel Recorder

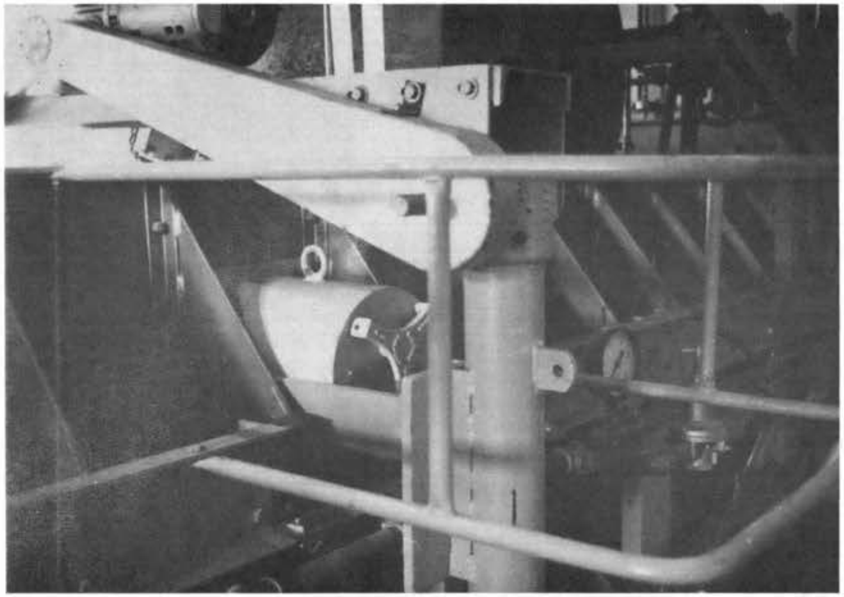


Figure 7. Qualicon Gamma Radiation Source for Measuring Soil Density

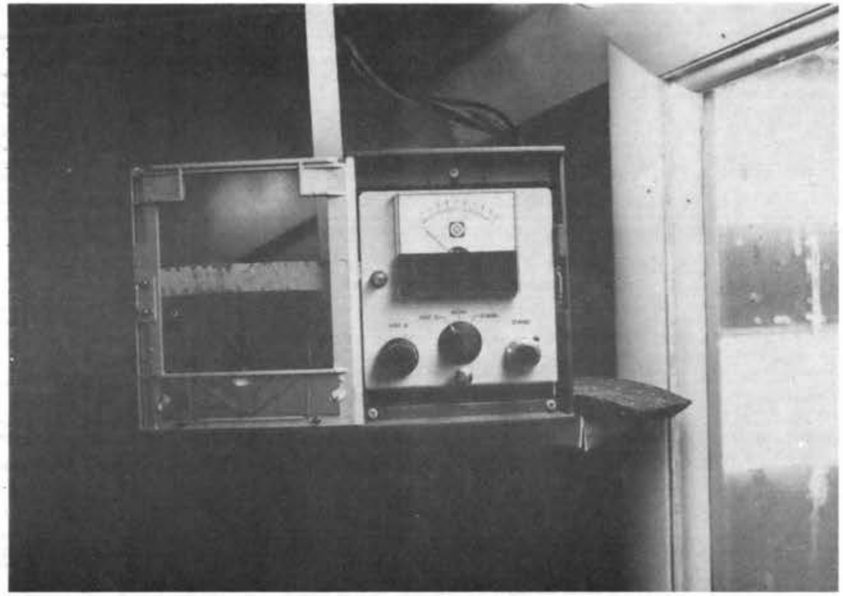


Figure 8. Amplifier and Soil Density Indicator

The samples were removed from the carrier belt, weighed and converted to pounds per cubic feet. Readings taken from the density meter were related to each soil sample and a straight line calibration curve plotted. Soil density was maintained at a constant meter reading of 90 throughout the test by adjusting the compaction wheel on the soil bin. A meter reading of 90 was equivalent to a density of 74 pounds per cubic foot. Technical specifications of the density monitoring system are presented in Appendix A.

Strain gauge type load cells with specifications as presented in Appendix A made up the force measuring dynamometer. Output from the recorder was linear with force applied to the load cells. Two 50 pound capacity load cells measured the vertical forces on the tools. Horizontal forces on the tools were measured, recorded and are presented in Appendix B, but were not considered in the analysis of the data. Preliminary test showed that since the tools were symmetrical and mounted in the center of the dynamometer, horizontal forces on the tools perpendicular to the direction of travel were effectively zero. Calibration and linearity of the load cells were checked by loading the cells in tension and compression with an Instron universal testing machine shown in Figure 9. The load applied by the testing machine was recorded simultaneously as the load from the load cell was recorded with a Sanborn recorder. Additional calibration checks were made on the load cells after they were mounted onto the dynamometer and connected to the eight channel recorder. Calibrated weights were applied to the dynamometer and load cells and the known loads were recorded. This calibration compared favorably to the electrical calibration furnished by the load cell manufacturer.

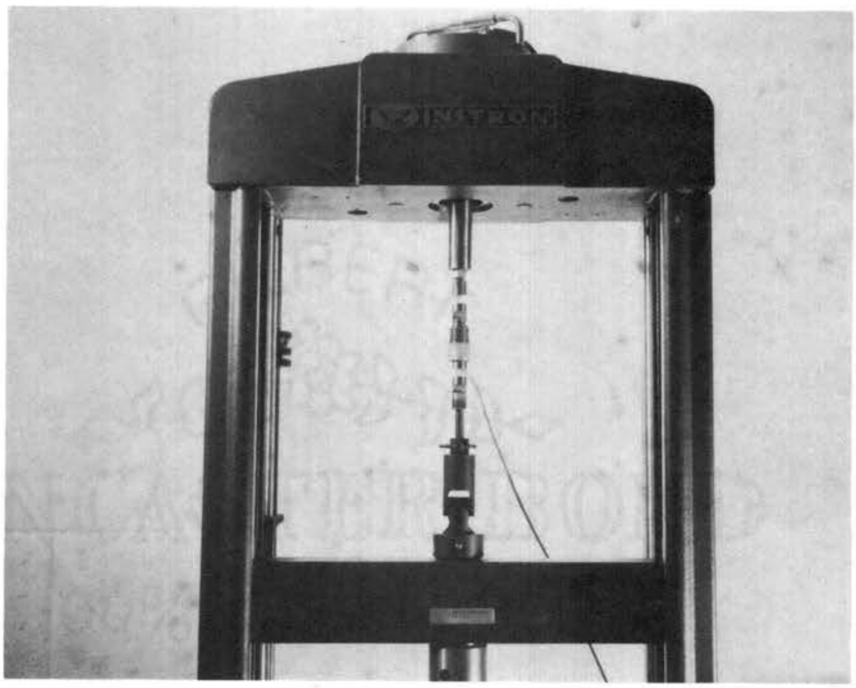


Figure 9. Load Cell Loaded by Universal Testing Machine for Checking Calibration and Linearity.

Provisions were made for the dynamometer to be positioned at any point in the vertical direction with respect to the soil. A dial micrometer with readability to the nearest .0001 inch was used to measure 0.2 inch changes in depth of the gauge wheels mounted to the dynamometer. A less sensitive scale marked on the dynamometer frame in 0.25 inch increments was used to measure 0.5 inch changes in the depth of the furrow openers. A tachometer generator and two remote dial indicators were used in conjunction with the dynagraph recorder to monitor the soil speed in the test section. Specifications for the tachometer are presented in Appendix A. The soil belt speed was set before each test and checked with a stopwatch and markings on the belt.

Soil Testing

An artificial soil was compounded based upon the ingredients used by others (4). The soil mixture was made up of 61.6 percent milled fireclay, 27.6 percent Ottawa silica white flint shot sand, and 10.8 percent number 11 Continental spindle oil by weight. Soil samples were taken at the beginning, the middle, the end of testing to determine the change in oil content during testing. The samples were analyzed by the Soil and Water Service Laboratory of Oklahoma State University. At the beginning of the test the oil content was detected to be 10.7 percent, 10.9 percent after one-half of the tests had been run and 10.8 percent at the end of the tests. Therefore, the oil content of the soil remained essentially constant throughout the tests.

Soil samples were also collected and analyzed to determine the strength properties at the beginning, at the midpoint and at the end of testing to detect any changes in cohesion, soil-to-soil angle of internal friction and soil-to-metal angle of internal friction. The soil strength tests were conducted with a Soiltest direct shear test apparatus in combination with an Instron universal testing machine as shown in Figures 10 and 11. Each soil strength specimen consisting of a measured quantity of artificial soil from the soil bin was placed into the round shear box. Each specimen was tamped 20 times with a 3/8 inch diameter round steel rod eight inches long to produce equivalent void ratios in all samples. The loading block was then placed on top of the material and the normal or axial load applied through a counter balanced hanger assembly. Grips made from thin strips of brass were placed in the shear rings on top of the upper ring and at the bottom of the lower ring perpendicular to the direction of the shearing force. The grips were used to restrain the upper and lower surface of the sample from moving relative to the confining ring. The upper grip which transmitted the normal load followed the motion of the shear box and was designed so the normal load acted on the specimen throughout the test. A shearing load was applied to the specimen by the universal testing machine at a rate of 0.02 inches per minute. A steel insert was made to replace the soil in the bottom shear ring during the soil-to-metal shear tests.

Two replications of four normal loadings were made for the soil-to-soil and soil-to-metal tests using three soil samples collected during the study. A total of 24 observations for each test was used in a linear regression analysis to determine the soil cohesion and angle of internal friction.

See p. 6

The plate penetration technique was used to determine the *penetration pressure* of the artificial soil. This technique was developed

Figure 10. Instron Universal Testing Machine with a Direct Soil Shear Testing Apparatus

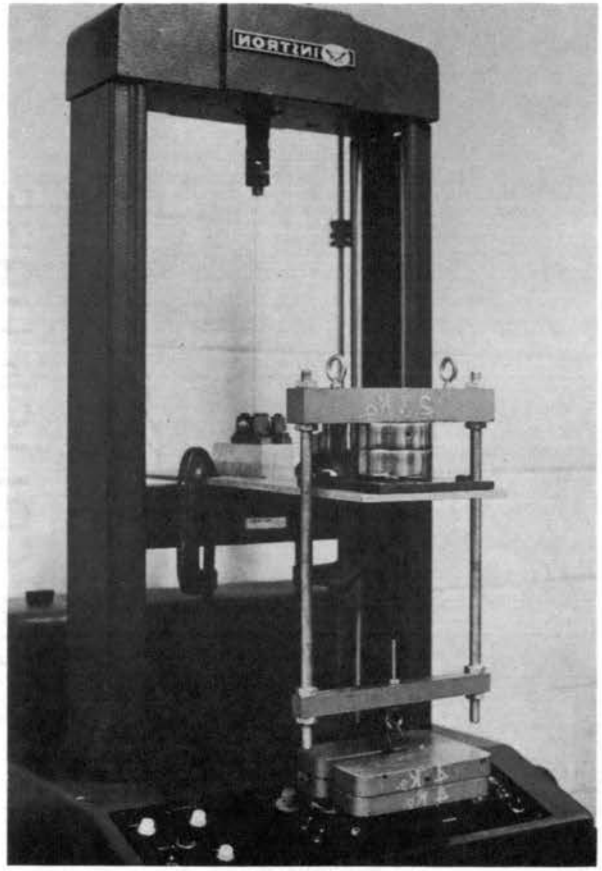


Figure 11. Soiltest Direct Shear Apparatus Used in Conjunction with Universal Testing Machine

primarily for predicting resistance to vehicle motion, however, Bekker and Associates at the Land Locomotion Laboratory developed the technique based on certain soil stress-strain relationships. Bernstein's original relation of soil stress and sinkage, $P = KZ^n$, was modified to a relation with one component for cohesion and one for friction. The modified equations give the relation $P = (K_c/b + K_\Phi)\, Z^n$ with the following soil parameters defined:

P = Penetration pressure, psi

K_c = Cohesive modulus of sinkage

K_Φ = Frictional modulus of sinkage

n = Exponent of sinkage

Z = Depth of sinkage

b = Radius of the penetrating plate

Two circular aluminum plates one inch and two inches in diameter, shown in Figure 12, were constructed in accordance with standard dimensions (32) and mounted on the soil bin dynamometer to measure the penetration pressure of the artificial soil. The soil on the carrier belt was prepared with a smooth surface at a density of 74 pounds per cubic foot. Each plate was placed on the static soil surface, Figures 13 and 14, and forced into the soil at a constant rate of 7.2 inches per minute to a depth of three inches. For each size of plate the sinkage and force required to penetrate the soil was recorded continuously on the Dynagraph recorder. Four replications of each plate size were made. Data taken from the recorder chart at ½ inch intervals are presented in Tables XI and XII of Appendix B.

The penetration pressure, P, in pounds per square inch was obtained at ½ inch intervals of sinkage, Z, to a depth of three inches. The

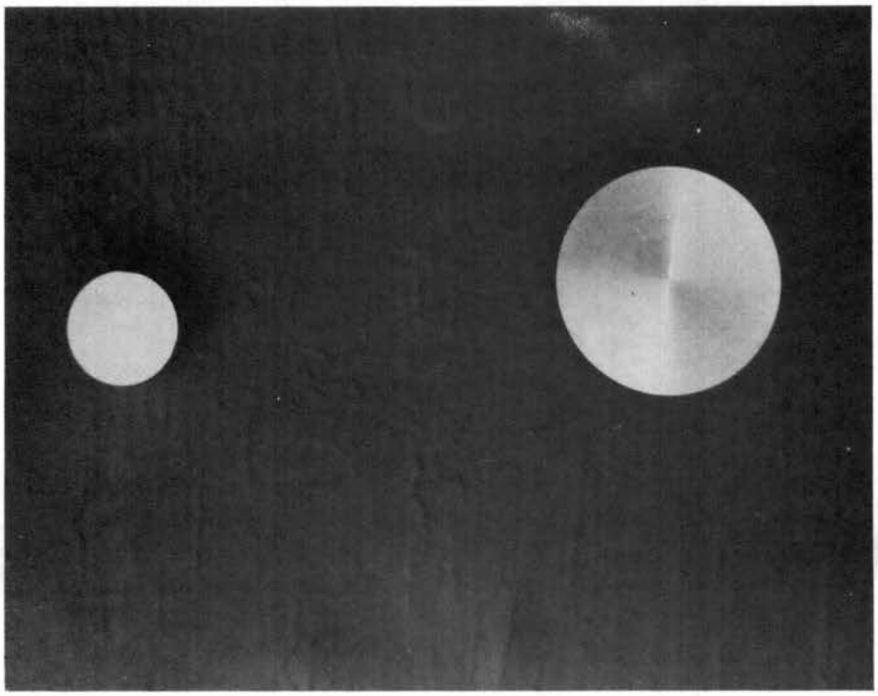


Figure 12. Circular Bearing Plates Used for Soil Penetration Tests

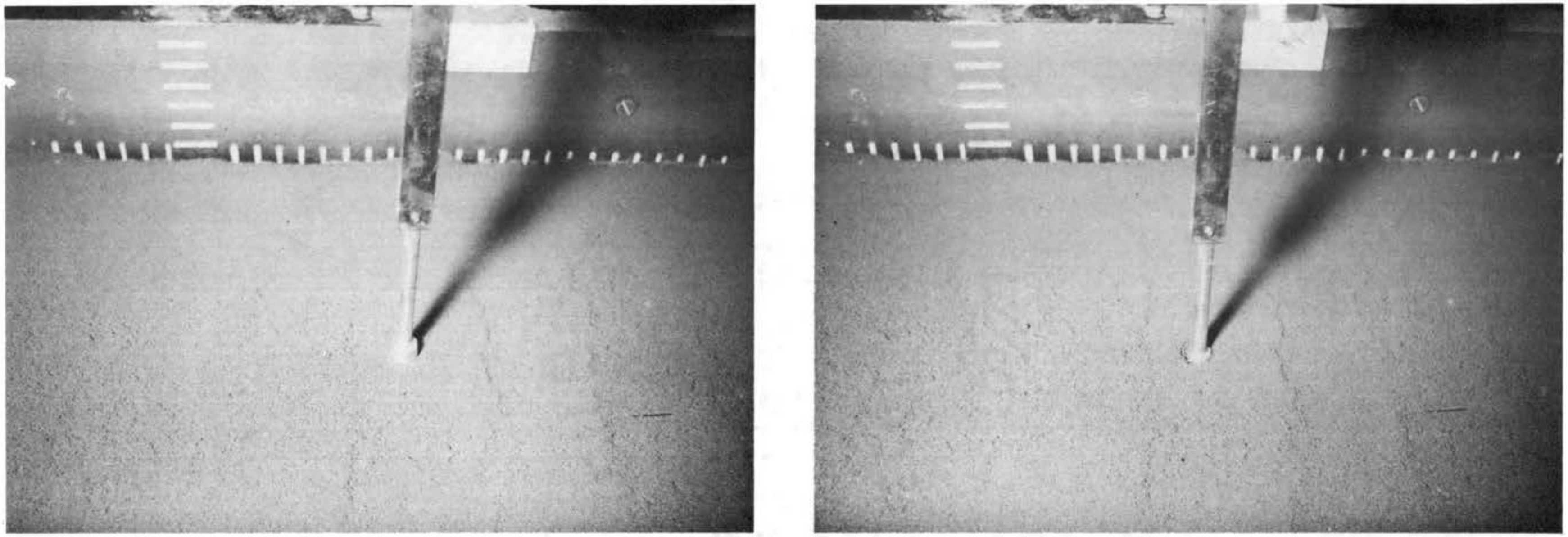


Figure 13. One Inch Diameter Bearing Plate on the Soil Surface and as it is Forced into the Soil

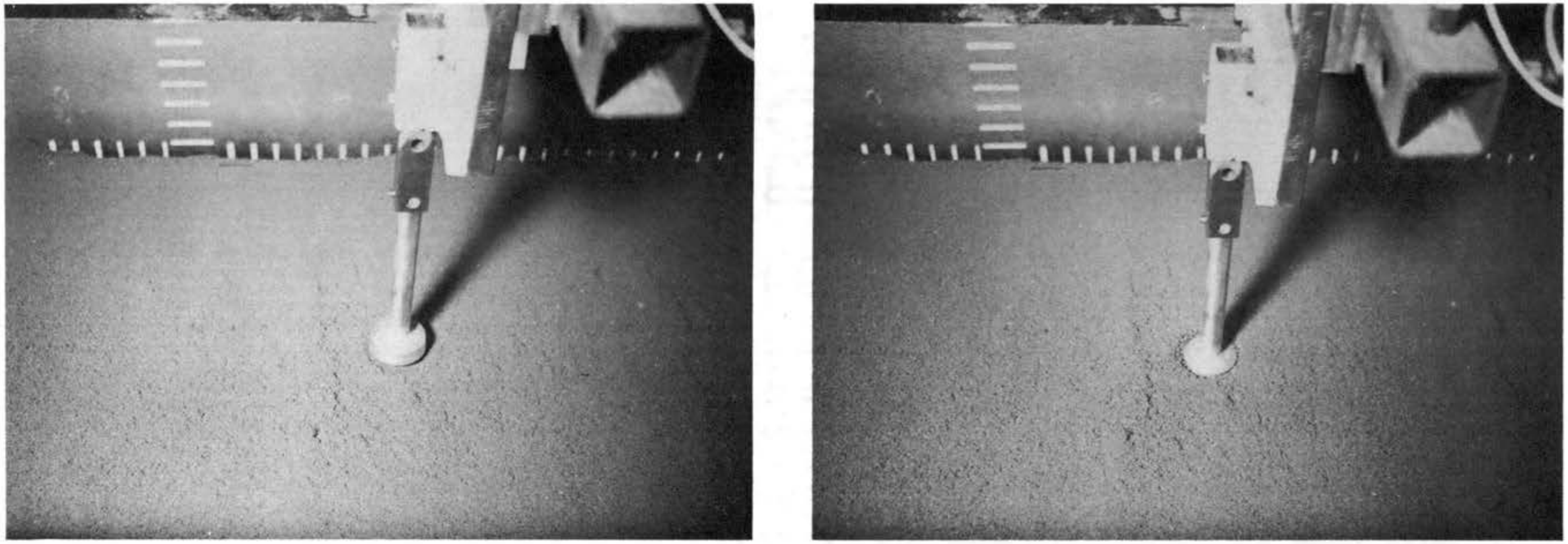


Figure 14. Two Inch Diameter Bearing Plate on the Soil Surface and as it is Forced into the Soil

log of the average pressure for four replications versus the log of the sinkage depth was plotted. Data for the two plates resulted in parallel straight lines, Figure 15, from which an evaluation of the parameters in Bekker's sinkage equation could be made (29).

$$P = (K_c/b + K_\Phi)\ Z^n \qquad (1)$$

at a depth of one inch, Z = 1

$$P_1 = (K_c/b_1 + K_\Phi) \qquad (2)$$

$$P_2 = (K_c/b_2 + K_\Phi) \qquad (3)$$

P_1 and P_2 represent the intersection of the ordinate of the curves for the one inch and two inch bearing plates respectively. Combining equations 2 and 3, equations for K_c and K_Φ are developed.

$$K_c = \frac{(P_2 - P_1)b_1b_2}{(b_1 - b_2)} \qquad (4)$$

$$K_\Phi = \frac{(P_1b_1 - P_2b_2)}{(b_1 - b_2)} \qquad (5)$$

$P_1 = 1.43$ psi

$P_2 = 1.25$ psi

$b_1 = 0.5$ inches

$b_2 = 1.0$ inches

$\log_e P_1 = 0.357 + 0.913\ \ell$

$z = 1$

$\log_e z = 0$

$P_1 = 1.429$

Substituting into equations 4 and 5 the cohesive modulus of sinkage, $K_c = 0.18$ lbs/in^{n+1} and the frictional modulus of sinkage, $K_\Phi = 1.06$ lb/in^{n+2}. The exponent of sinkage, n, was taken as the average slope of the bearing plate curves equal to 0.922. Penetration pressure for the artificial soil was dependent upon tool bearing area and depth of sinkage.

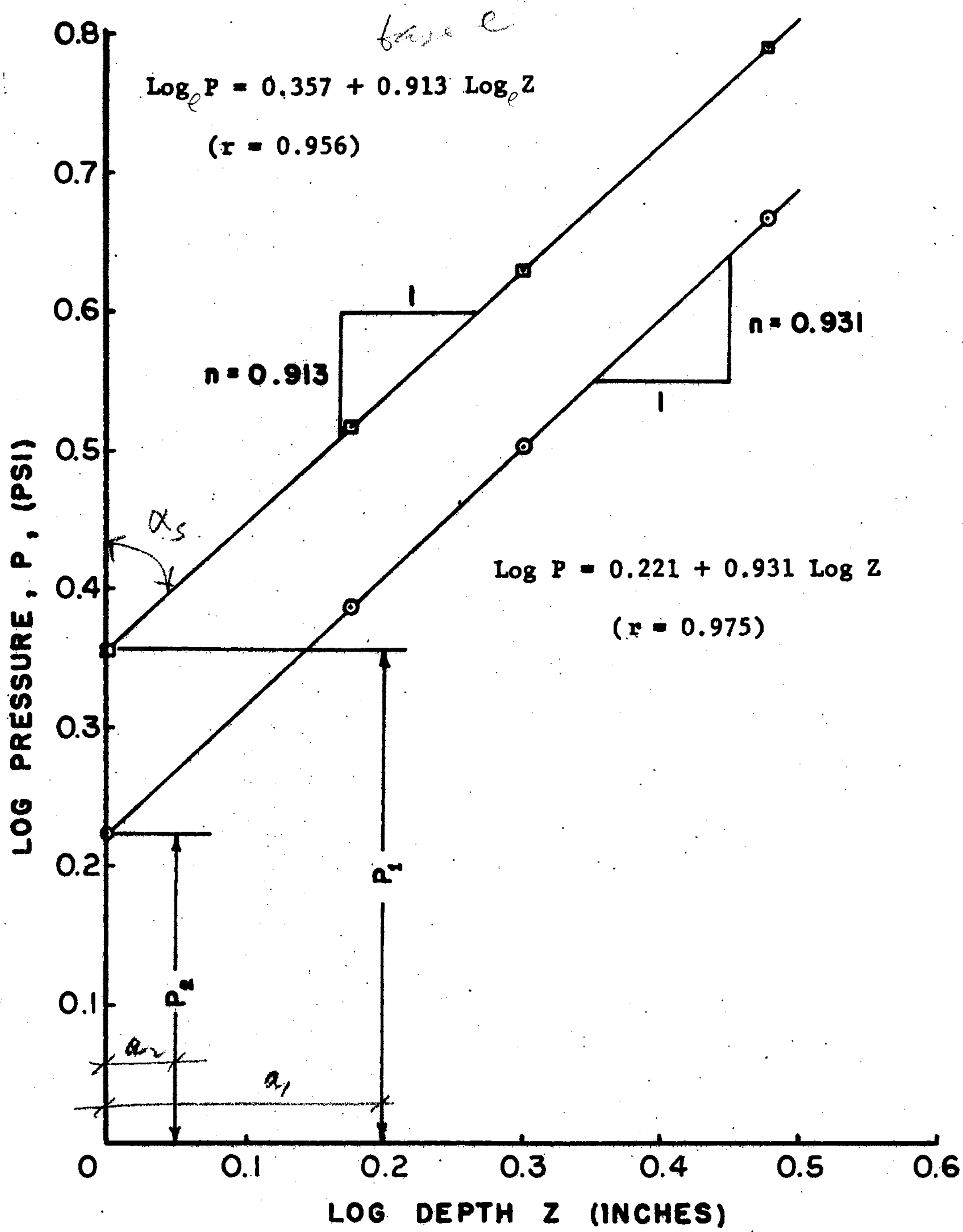


Figure 15. Pressure - Sinkage Relation for Plate Penetration Test

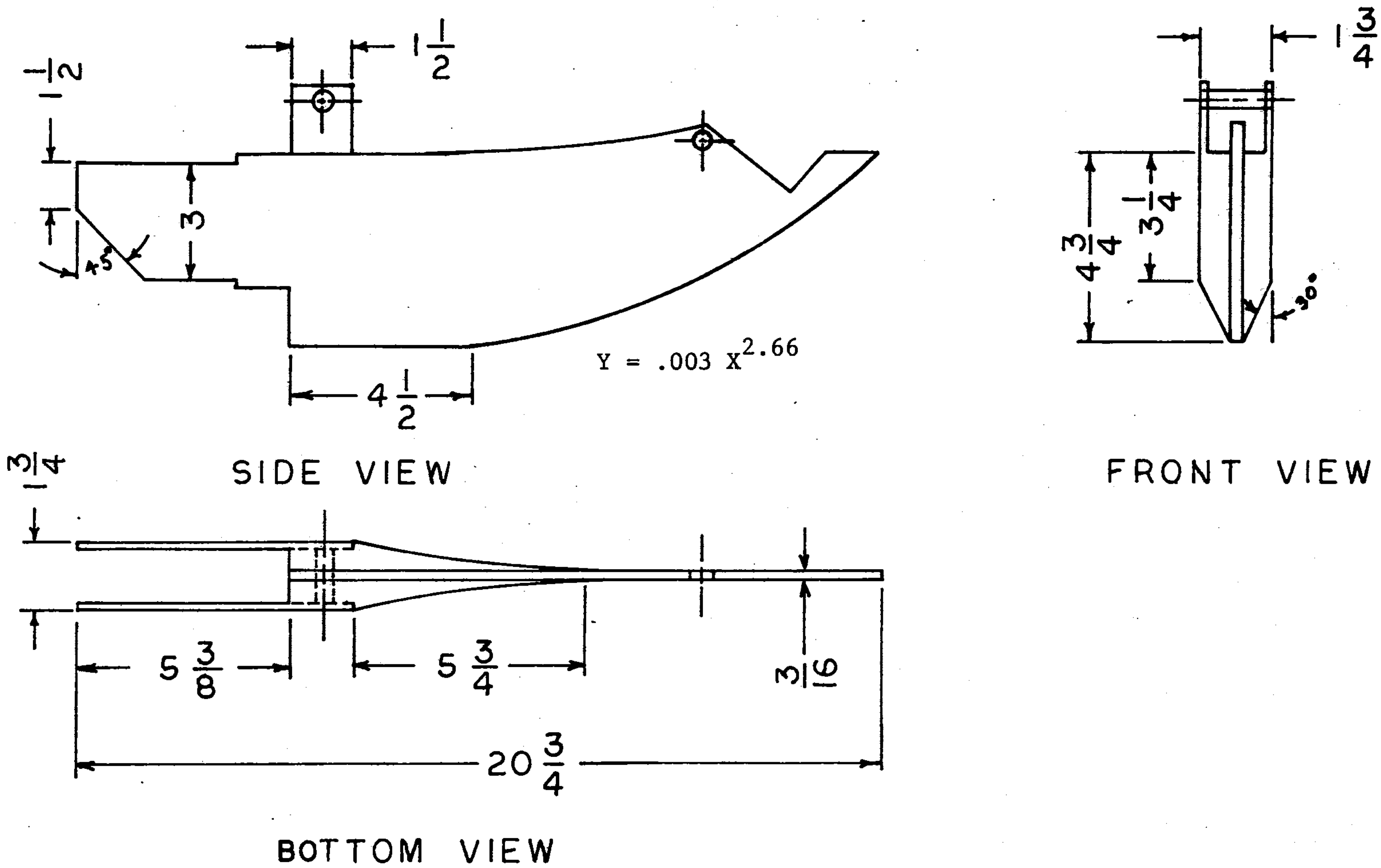


Figure 16. Runner Type Furrow Opener

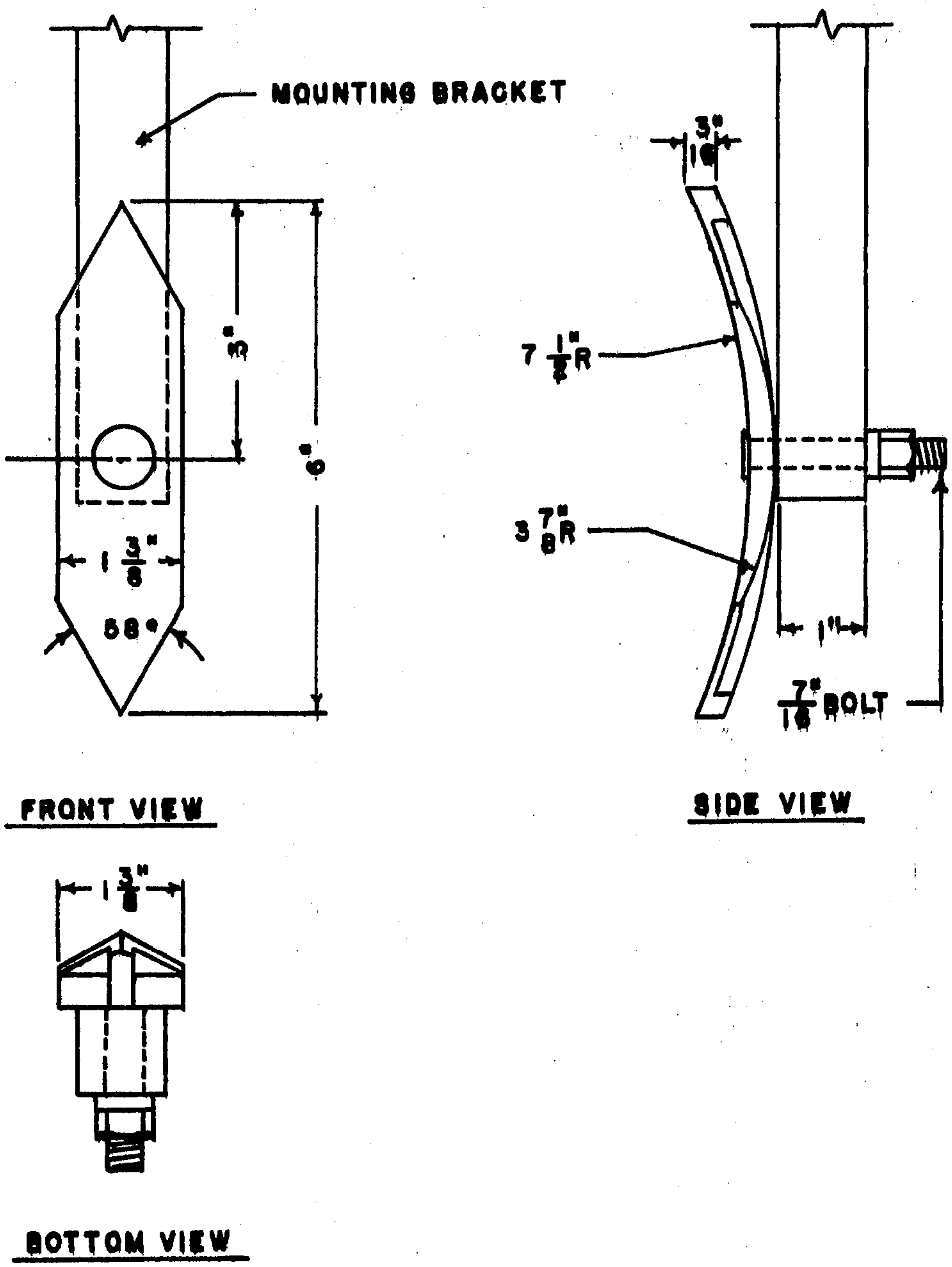


Figure 17. Chisel Type Furrow Opener

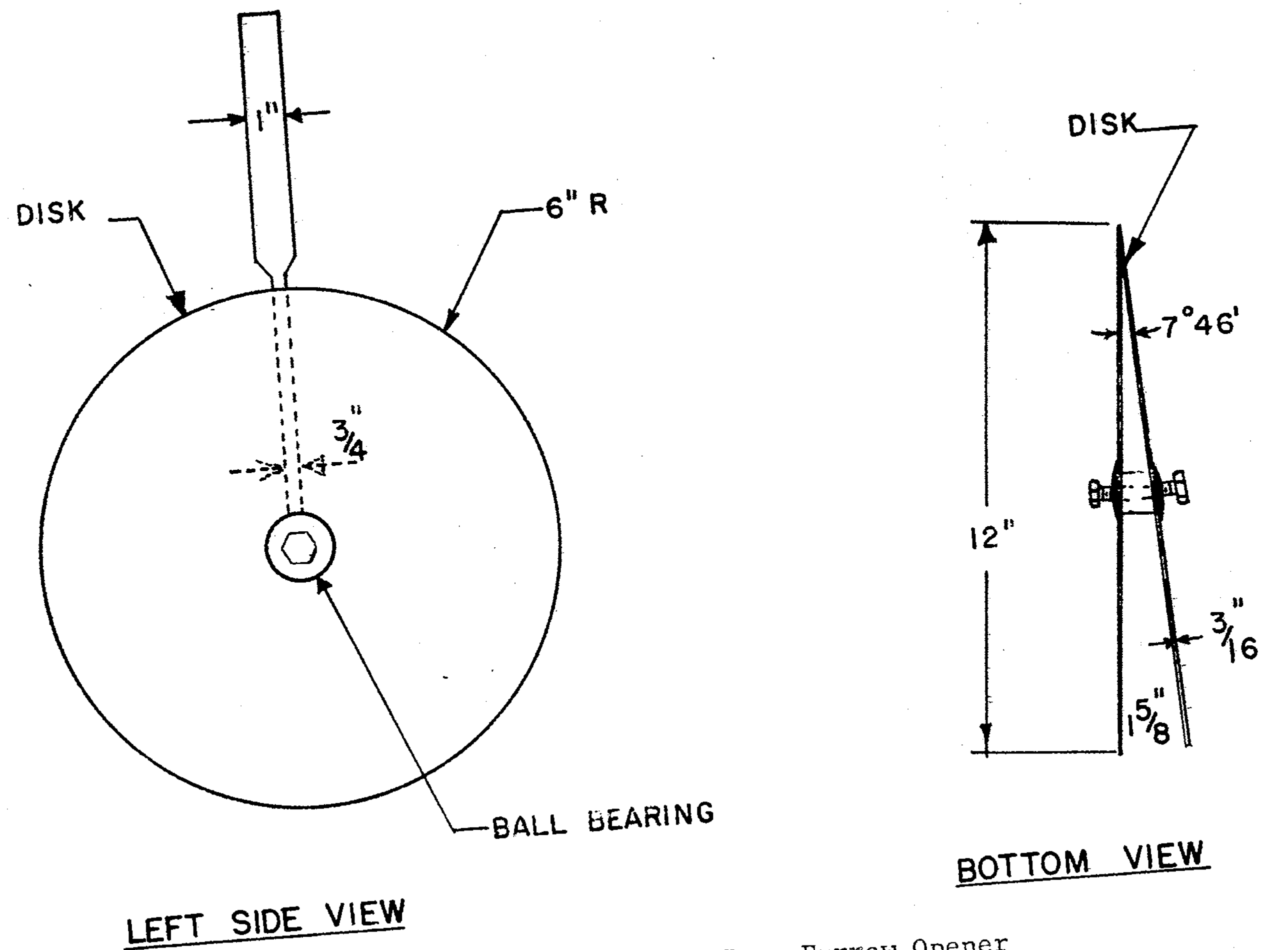


Figure 18. Double Disk Type Furrow Opener

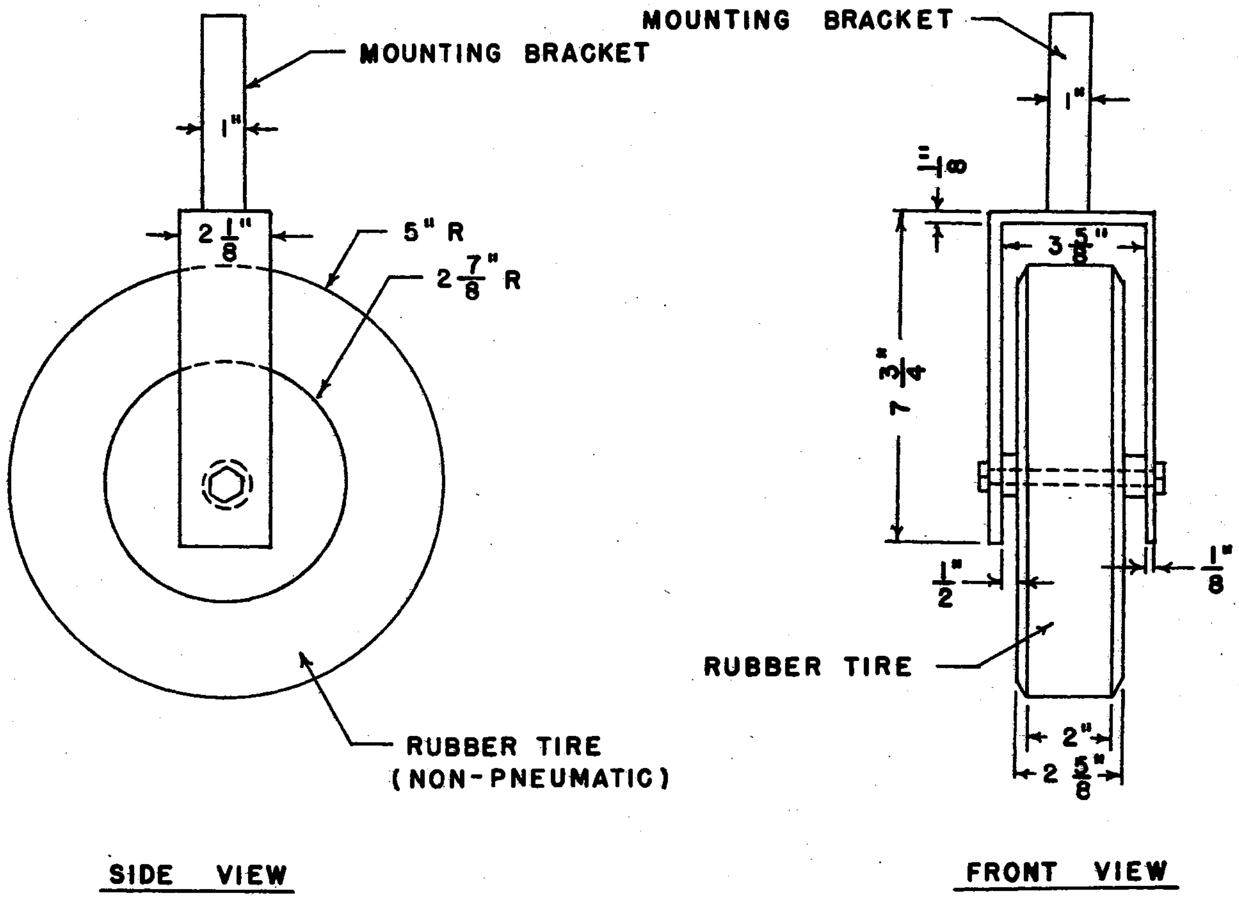


Figure 19. Gauge Wheel Gauging Device

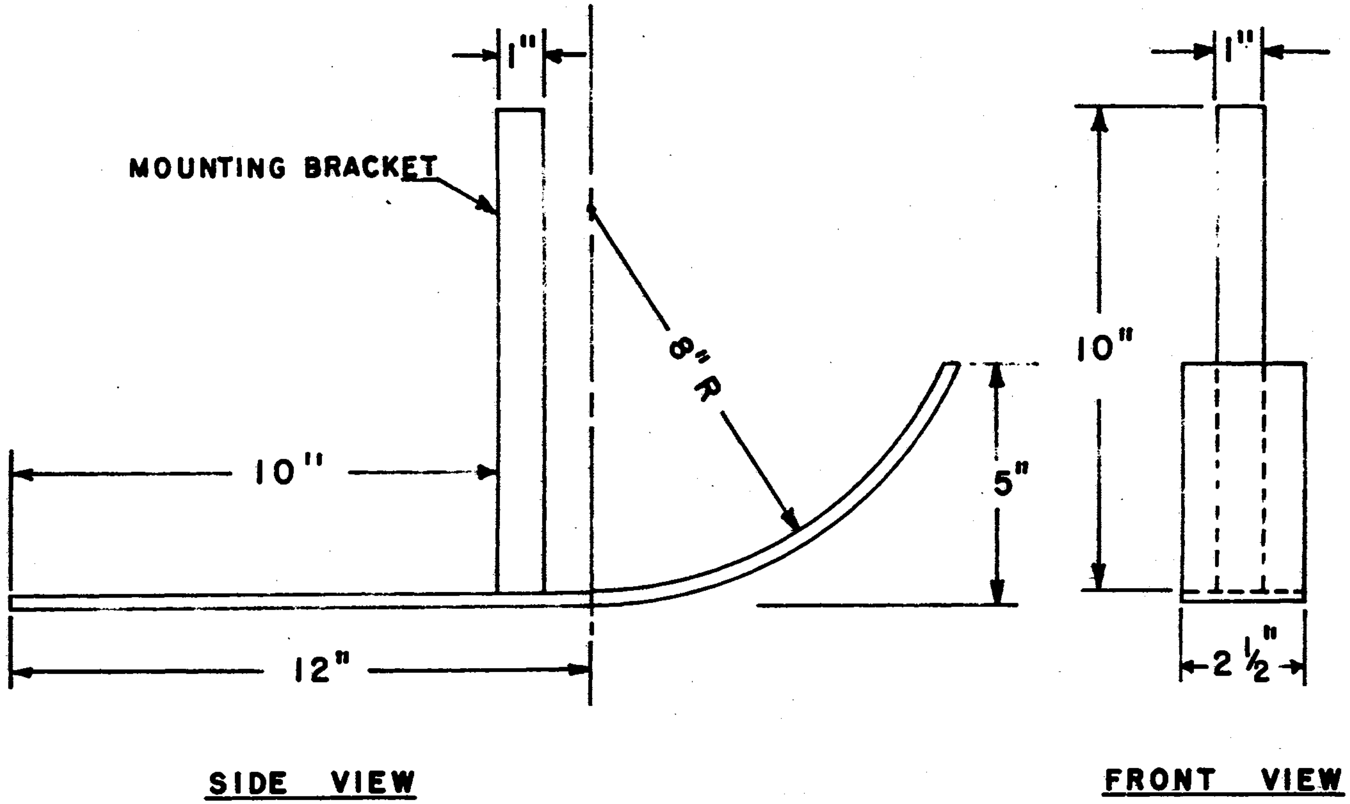


Figure 20. Slide Type Gauging Device

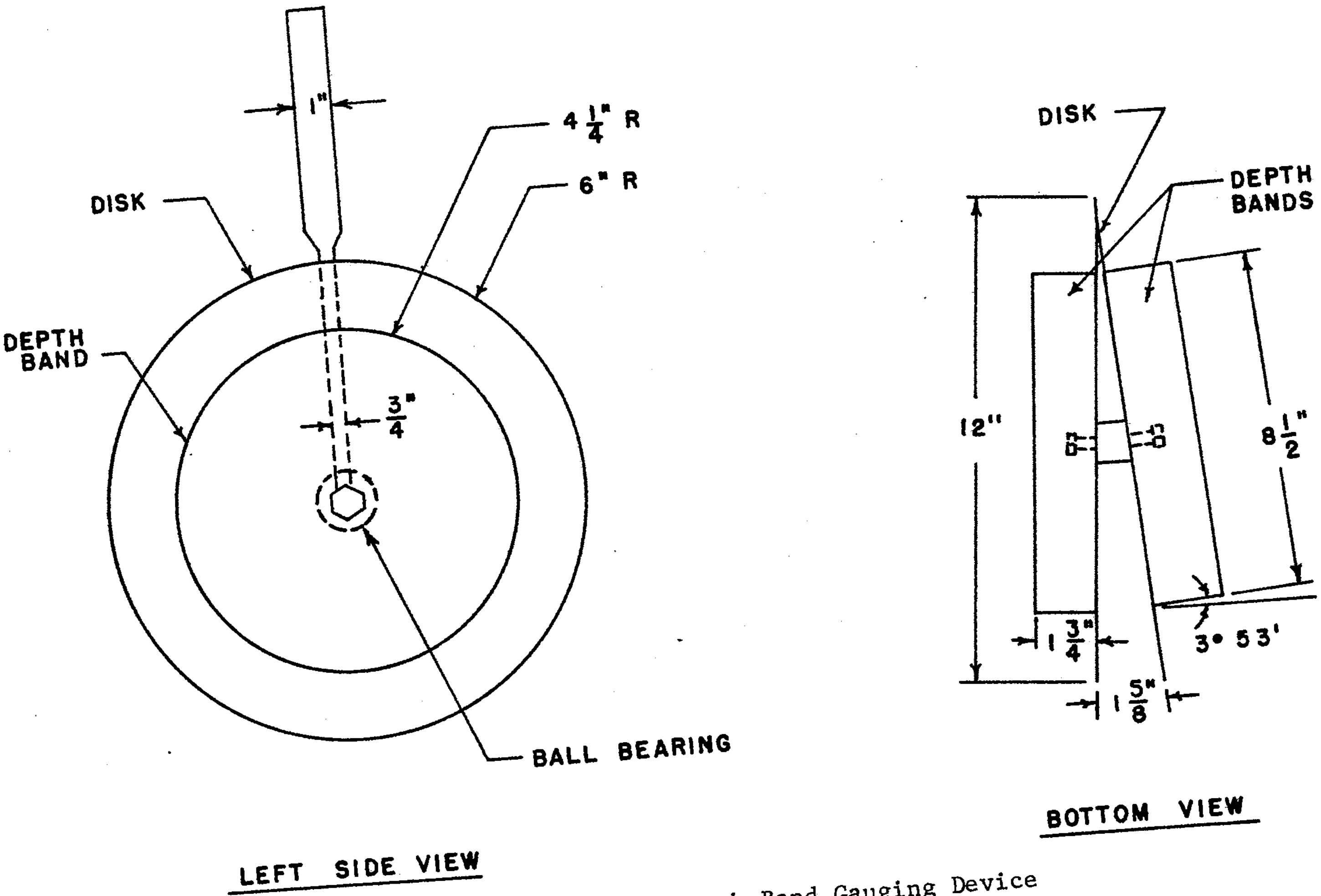


Figure 21. Depth Band Gauging Device

$$P = (0.18/b + 1.06)\ Z^{0.922} \qquad (6)$$

Tillage Tools to be Tested

The tillage tools used in the study included three furrow openers and three depth control devices. The tools were selected such that their dimensions would be within the soil bin size range and also provide different dynamic effects within the soil during operation. Schematic drawings of each tool are presented in Figures 16 through 21.

Procedure for Conducting Tests

The following procedures were used to collect data to be used in analyzing the overall study of vertical forces in the soil-tool system.

Soil Shear

Samples of the artificial soil were collected at the beginning, during and at the end of the furrow opener and depth control vertical force study. A total of eight subsamples were taken from each of the three samples. Each subsample consisted of enough soil to fill the shear rings approximately three-fourths full. A measuring cup was used to measure the same amount of soil for each test. After tamping the soil an upper grip was placed on top of the soil and normal weights were applied. Two shearing force tests were recorded for each of four normal loads. The normal loads included 3.88, 10.50, 14.9, and 23.7 pounds. The same tests were conducted to obtain soil-to-soil and soil-to-metal strength parameters. Loading was applied to the 2.5 inch diameter shear rings by the Instron testing machine at a constant rate of 0.02 inches per minute. The shearing load was determined by a distinct break in the force curve plotted by the testing machine recorder. Appropriate conversions of the data were made to produce a graph of shearing stress, psi, versus normal load, psi. A digital computer program was used to obtain a best fit for a linear model of the 24 data points. Soil cohesion and angle of internal friction respectively were obtained as the intercept and slope of the strength line.

$$\tau = c + \sigma \tan \phi$$

Vertical Forces on Tillage Tools

The replicated split plot experimental design to study the vertical forces applied to furrow openers and depth control devices was conducted as follows: A number was drawn from a box to randomly select whether the furrow openers or depth control devices would be tested first. A number was placed in the box for each of the three furrow openers and a random selection was made to determine the order of testing the openers. After a tool was selected, a number was placed in the box for each speed selected for the study. The speed at which the tool was operated was randomly selected until all speeds were tested. Once a speed was selected, a number was placed in the box for each depth of operation. The depths were randomly selected until all depths were tested for each speed. When all speeds and depths had been tested another tillage tool was randomly selected until all combinations of tools, speeds and depths were tested. The same procedure was used to select all variable combinations before a new replication of the study was made. A total of 162 and 270 tests were run for the furrow openers and depth control devices respectively.

Sufficient time was given for the recorder to warm up before calibrating it and recording data. The recorder for the load cells was calibrated each time it was turned on. After electrically calibrating each load cell the tillage tool was mounted on the dynamometer frame and positioned for impending contact with the soil. The depth gauges and recording styluses were positioned for zero depth and force. The recorded force, therefore, did not include the weight of each tillage tool. Soil velocity was set by timing the passage of two points on the carrier belt with a stopwatch and adjusting the speed of the hydraulic motor driving the belt. The soil velocity with respect to the tillage tool was recorded on channel seven of the recorder. The suppression adjustment dial on the density amplifier-indicator gave a reading of 90 when the soil density was 74 pounds per cubic foot. Soil density could be altered slightly with the compaction wheel. The compaction wheel was also used to smooth the soil surface for the tillage tool.

Projected Vertical Bearing Surface

The projected vertical surfaces consisted of the area of the tool bearing on the soil at each depth of operation. The areas were determined for static conditions. It was beyond the scope of this study to determine the dynamic bearing area of each tool. Previous studies reported by Gill and Vandenberg (17) indicates the dynamic bearing area of unpowered wheels operating in soft soils approximates the area the forward quarter of the wheel has in contact with the soil. Therefore, the bearing surface for each wheel type tool was considered one-half the static projected area. Tillage tools with nonuniform and nonsymmetrical dimensions were molded in plaster of paris at each depth the tools were operated. From the mold of each depth, the projected area was planimetered for each tillage tool. Tillage tools with uniform symmetrical dimensions were drawn to scale and the bearing areas were projected as a bottom view of the tool for each depth of operation.

Procedure for Recording Data

After the tool to be tested was mounted and soil speed and density were adjusted to a predetermined level, the recorder was adjusted to record a force of approximately zero on each load cell channel, two through six. Channels three and four of the recorder were used to record the vertical forces. The forces were recorded as positive when the load cells were in compression and negative when the cells were in tension. A zero reading obtained due to vibration of the system was recorded first then the randomly selected depth of operation was obtained by lowering the tool into the soil. If the tool was to run at a depth shallower than the preceding test the tool was raised above the desired depth and then lowered to the correct position. Therefore, all tests were recorded with each tool positioned by moving the dynamometer downward. When the tool was in position, the forces acting on the tool were traced on the recording chart for at least ten centimeters with the chart operating at a speed of five cm per second. The recording sensitivity was adjusted according to the load on each channel to give the maximum amplification of the force being measured. Two observations were taken at random from the recording of each test. All forces measured with the dynamometer are tabulated in Tables XV and XVI of Appendix B. Variations in length of the mounting bracket for each tool are presented in Tables XVII of Appendix B. Each force was corrected by subtracting the zero reading before analyzing the data.

Data from the soil bearing tests were recorded on channels three and four of the dynagraph. A reference point was put on the recording chart when the penetrating plate touched the soil and at a depth of three inches by tapping the dynamometer to cause a change in the force. The trace was subdiveded into one-half inch increments and the force required to penetrate the soil was tabulated as shown in Tables XI and XII of Appendix B. The average values of the penetration stress versus sinkage depth were plotted on logarithmic paper.

CHAPTER V

PRESENTATION AND DISCUSSION OF RESULTS

Resistance by the soil to penetration of three furrow openers and depth control devices was measured as the vertical force on the dynamometer. Horizontal forces parallel to the direction of movement to the soil were measured and the data are presented in Tables XV and XVI of Appendix B. The vertical forces were recorded in pounds according to Figure 5 as F_3 and F_4. The data are presented as forces recorded by the dynagraph without correction for zero depth readings. Zero depth corrections were made by the computer on the data before making a statistical analysis.

An analysis of variance using the replicated split plot design was made on the vertical force data recorded from the furrow openers and depth control devices separately with the Statistical Analysis System (SAS) computer program. Results of the Statistical Analysis for three furrow openers operating at three speeds and 0.5 depth increments to 3.0 inches are presented in Table I. The "F" values and levels of significance at which differences were detected for each entry are listed. The null hypothesis was not rejected if differences were detected at significance levels greater than one percent. On this basis, significant differences in vertical forces among the furrow openers and depths of operation were detected. However, the differences found due to furrow opener speeds with respect to the soil were

TABLE I

ANALYSIS OF VARIANCE FOR FURROW OPENER TEST

Source	D.F.	S.S.	M.S.	F	Significance Level (%)
Replications	2	4.715	2.357	0.824	50.30
Furrow Openers	2	122.066	61.033	21.342	00.90
Error "A"	4	11.439	2.859		
Soil Velocity	2	6.394	3.197	1.334	30.00
Velocity x Openers	4	0.703	0.176	0.073	98.60
Error "B"	12	28.750	2.396		
Tool Depth	5	143.944	28.789	211.069	00.01
Depth x Furrow	10	51.591	5.159	37.824	00.01
Depth x Velocity	10	4.129	0.413	3.027	00.27
Depth x Furrow x Velocity	20	3.538	0.177	1.297	20.21
Error "C"	90	12.276	0.136		
TOTAL	161	389.545			

not statistically significant at the one percent level. No significant differences among replications were indicated which gives confidence to the repeatability of the data with the equipment, instrumentation and techniques used. The interaction between furrow openers and tool speed was not significant and indicates the differences in the vertical forces due to speed were the same for all furrow openers. The mean vertical forces measured in pounds for each furrow opener and depth of operation are given in Table II. The differences in vertical forces among furrow openers for each depth of operation were not the same as indicated by the significant depth by furrow opener interaction. The depth by speed interaction was significant at the one percent level.

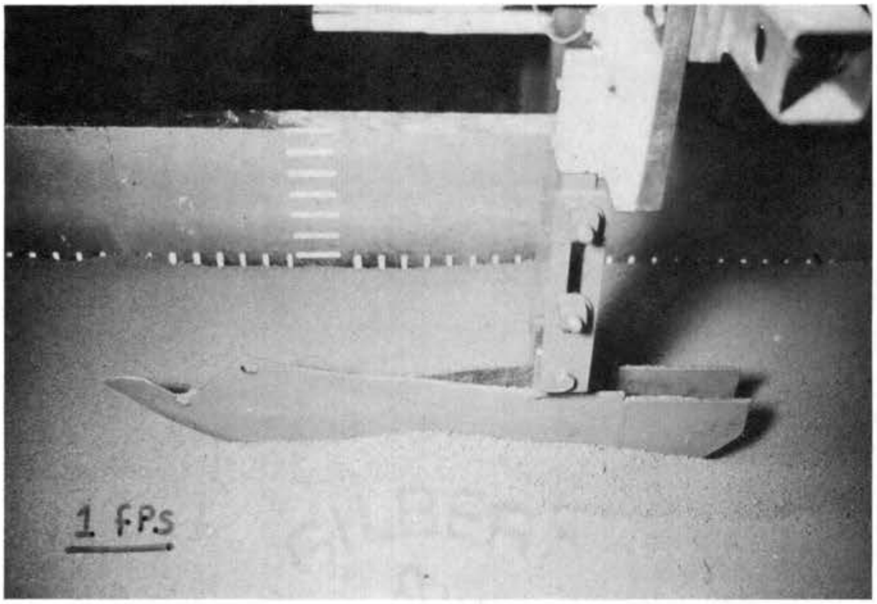
The effect of tool speed on soil displacement was visually significant. Figures 22, 23 and 24 show the soil movement by the runner, chisel and double disk furrow openers respectively operating at speeds of one and five fps and a depth of 2.0 inches.

Results of the statistical analysis of depth control devices operating at three speeds and 0.2 inch depth increments to 2.0 inches are presented in Table III. The "F" values and percent levels of significance detected for each entry in the analysis are listed. The null hypothesis was accepted if differences were detected at a significance level greater than one percent. Significant differences in vertical forces among depth control devices and depths of operation were detected. There were no significant differences detected among speeds at the one percent level, however, the differences were significant at the five percent level of probability. Replications were not significant, however, interactions of depth by gauge device and depth by speed were significant. The velocity by guage device interaction was

TABLE II

MEAN VERTICAL FORCES MEASURED IN POUNDS FOR EACH FURROW OPENER AND DEPTH OF OPERATION

Tillage Tool	Depth of Operation (inches)					
	0.5	1.0	1.5	2.0	2.5	2.0
Runner	0.63	0.91	1.30	1.90	2.50	3.40
Chisel	0.1	0.24	0.42	0.55	0.77	0.90
Double Disk	0.40	1.20	1.80	3.00	4.10	5.10



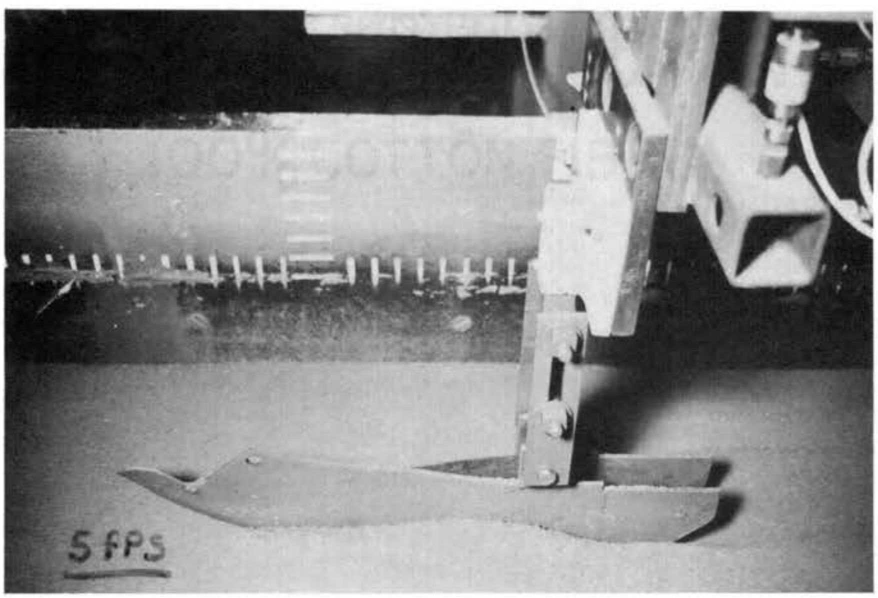


Figure 22. Comparison of Soil Displacement by the Runner Opener Operating at 1 and 5 fps and 2 Inches Deep

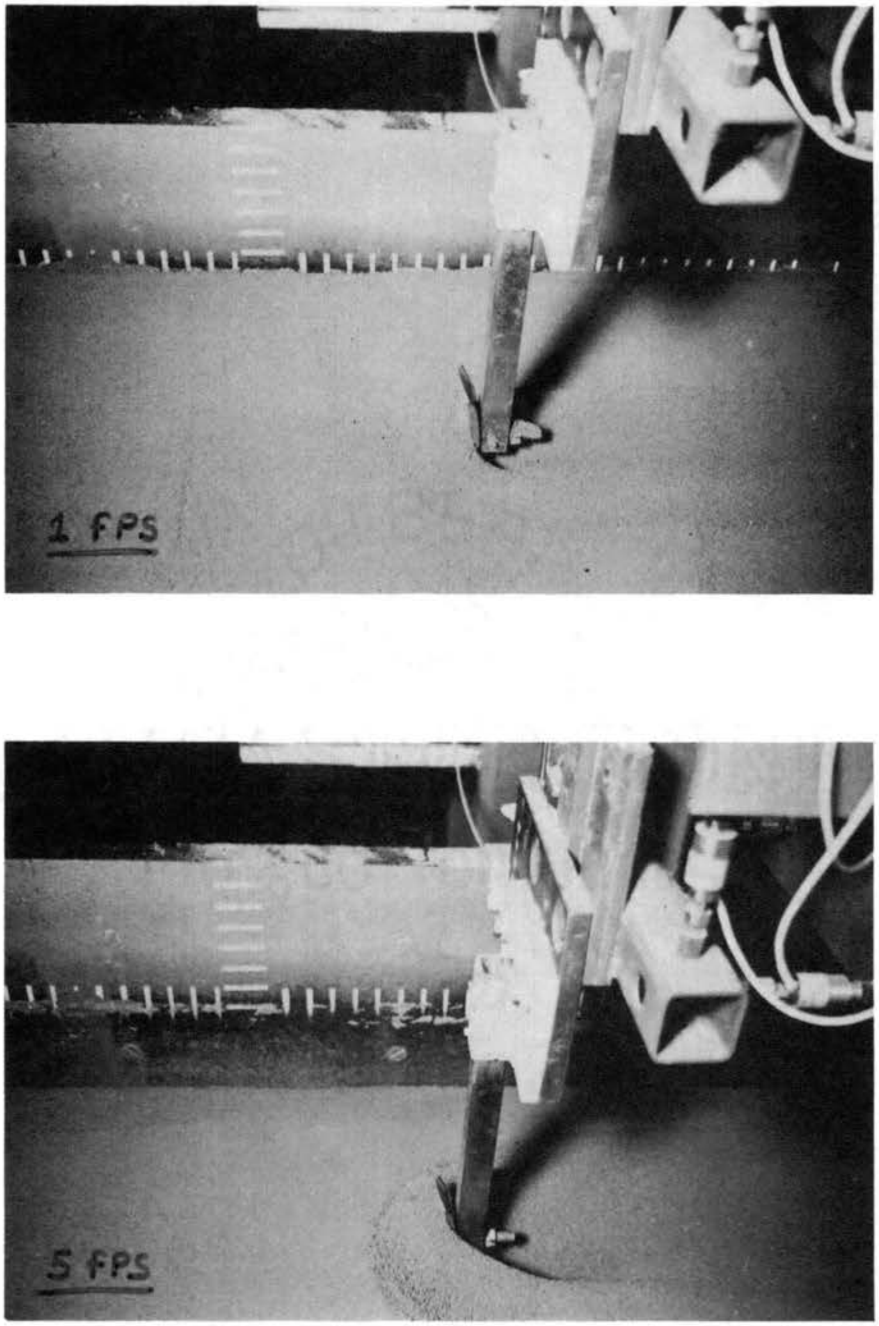


Figure 23. Comparison of Soil Displacement by Chisel Opener Operating at 1 and 5 fps and 2 Inches Deep

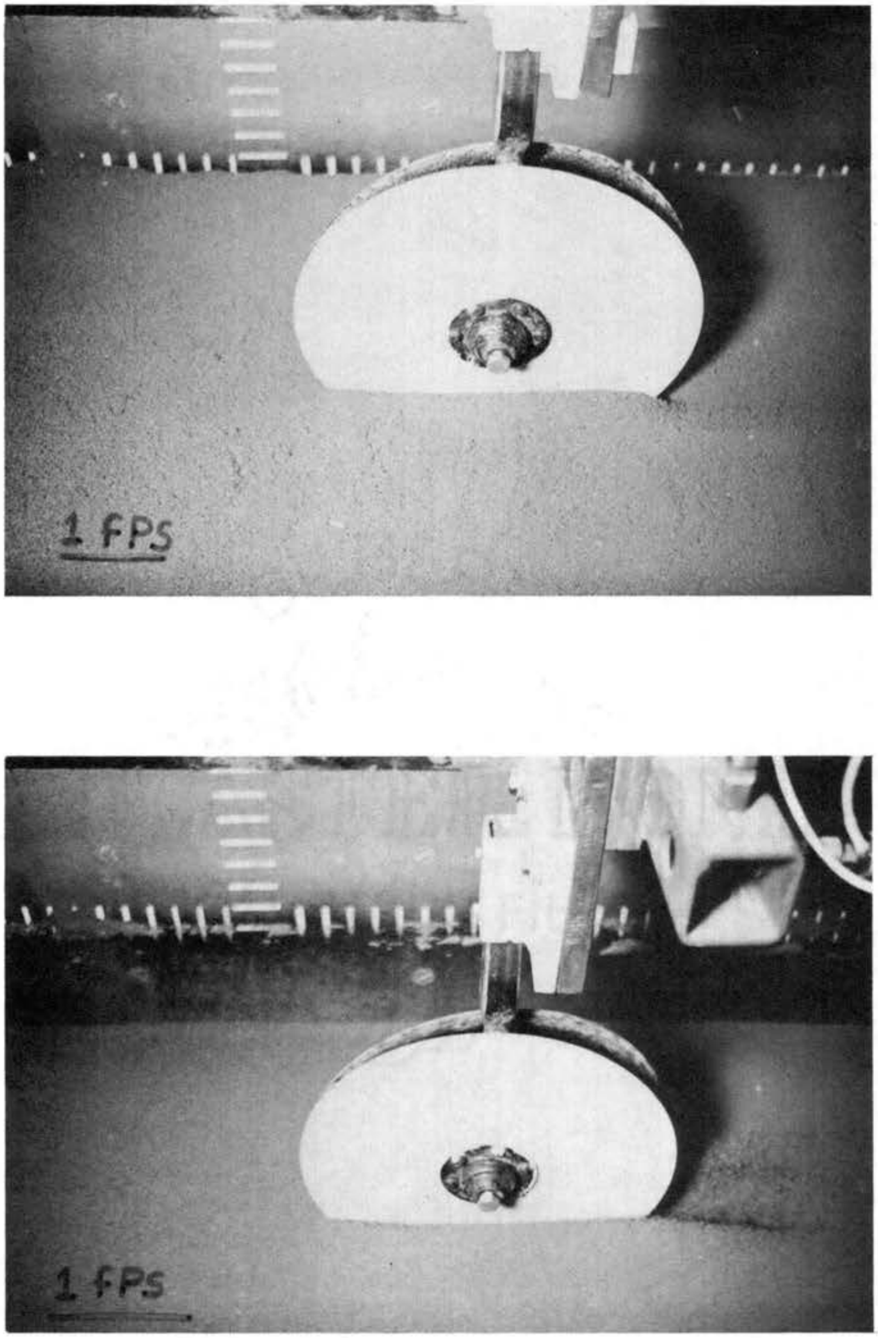


Figure 24. Comparison of Soil Displacement by the Double Disk Opener Operating at 1 and 5 fps and 2 Inches Deep

TABLE III

ANALYSIS OF VARIANCE FOR DEPTH CONTROL DEVICES

Source	D.F.	S.S.	M.S.	F	Significance Level (%)
Replications	2	11.626	5.813	0.912	50.66
Gauge Devices	2	5649.661	2824.831	443.402	0.04
Error "A"	4	25.483	6.370		
Velocity	2	285.786	142.893	6.068	1.50
Velocity x Gauge	4	169.196	42.299	1.796	19.41
Error "B"	12	282.589	23.549		
Depth	9	7757.344	861.927	941.797	0.01
Depth x Gauge	18	1826.000	101.444	110.845	0.01
Depth x Speed	18	34.1185	1.895	2.07	0.91
Depth x Gauge x Speed	36	14.340	0.398	0.435	99.75
Error "C"	162	148.262	0.915		
TOTAL	269	16204.404			

not significant indicating the differences in the vertical force due to the effects of speed were the same for all guaging devices. Mean vertical forces for each depth control device and depth of operation are given in Table IV.

Response equations, presented in Table V were developed by the Statistical Analysis System (SAS) stepwise regression technique and describe the relationships between vertical forces, tool speed and depth of operation. The regression of the variables were significant at the 10 percent level of probability. The coefficient of determination (R^2) shows the percent of variation in the dependent variable, vertical force, explained by the independent variables, speed and depth of operation. The maximum amount of variation in the vertical force explained by speed and depth was found by using all degrees of freedom for the independent variables. Values of R^2 ranged from a low of 70 percent for the chisel opener to 97 percent for the depth band gauging device when all possible combinations of the independent variables were included in the polynominal equation. The stepwise regression technique eliminated the terms that did not significantly contribute to the response equation at the 10 percent level. This reduced the R^2 values for each tool except the depth bands, however, the number of terms in the equation describing the vertical forces were reduced considerably.

The coefficients of determination were reduced a maximum of seven percentage points for the chisel opener, but did not decrease for the depth band gauging device. A comparison of the mean forces tabulated in Tables II and IV and the coefficients of determination obtained for the prediction equations in Table V shows a greater percentage of the

TABLE IV

MEAN VERTICAL FORCES MEASURED IN POUNDS FOR EACH GAUGING DEVICE AND DEPTH OF OPERATION

Tillage Tool	Depth of Operation (inches)									
	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Gauge Wheel	1.0	3.6	5.5	7.2	8.9	10.4	12.4	13.5	15.1	16.7
Slide	2.1	3.2	4.0	4.7	5.5	6.5	7.2	8.1	9.2	10.1
Depth Bands	2.5	5.7	9.6	13.1	16.1	18.9	21.6	25.0	27.7	29.6

TABLE V

RESPONSE EQUATIONS RELATING VERTICAL FORCE, SPEED AND DEPTH OF OPERATION FOR FURROW OPENERS AND DEPTH CONTROL DEVICES

Tillage Tool	Response Equation	R^2*	R^2**
Runner Opener	$F = 0.22D^2 + 0.10VD$	76	78
Chisel Opener	$F = 0.06VD^2 - 2.70 \times 10^{-3}V^2D^3$	63	70
Double Disk Opener	$F = 1.47D + 1.40 \times 10^{-2}VD^3$	78	79
Gauge Wheel	$F = 8.40D$	86	92
Slide Gauge Device	$F = 4.30D - 2.80 \times 10^{-2}V^2$	87	88
Depth Bands	$F = 7.5 + 19.15D - 1.78D^2 + 6.11V - 1.4V^2$	97	97

*Percent of the Variation in Force Accounted for by the Speed and Depth Polynominal Terms Significant at the 10 Percent Level.

**Percent of the Variation in Force Accounted for Using all Speed and Depth Degrees of Freedom in the Polynominal.

Legend:

F = Force, lbs.

V = Tool Speed, in/min.

D = Depth of Operation, in.

vertical forces were accounted for by speed and depth of operation as the vertical force on the tools increased. The reliability of the tests increased as the vertical forces on the tools increased. The measured vertical forces were all positive upward for all tools, depth of operation and speeds except the chisel opener. A negative downward force was measured for the chisel opener operating at a depth of 0.5 inches and a speed of 1.0 fps. The chisel opener prediction equation also gave a negative force with the tool operating under the same conditions.

To make the prediction equations more general and become applicable to other sizes and/or shapes of individual tillage tools, a relationship was developed between depth of operation and vertical projected bearing surface. The bearing surface is defined as the projected area a tool makes with the soil on a horizontal plane at a given depth. For example, the vertical bearing area for the runner opener operating at a depth of 0.5 inches was measured to be 3.68 square inches as shown in Figure 25. Projected bearing areas for each furrow opener and gauging device are shown graphically in Figures 25-30 and at all depths of operation in Tables XIII and XIV of Appendix B. The bearing surfaces were determined graphically for each dimensionally symetrical tool, whereas the tools with irregular shapes were molded in plaster of paris at each depth and the bearing area was planimetered.

Using the SAS stepwise regression technique, polynominal equations significant at the one percent level of probability were developed for each furrow opener and gauging device. The regression equations presented in Table VI relate area, A, as the dependent variable to the independent variable, depth. The percent of the variation explained by

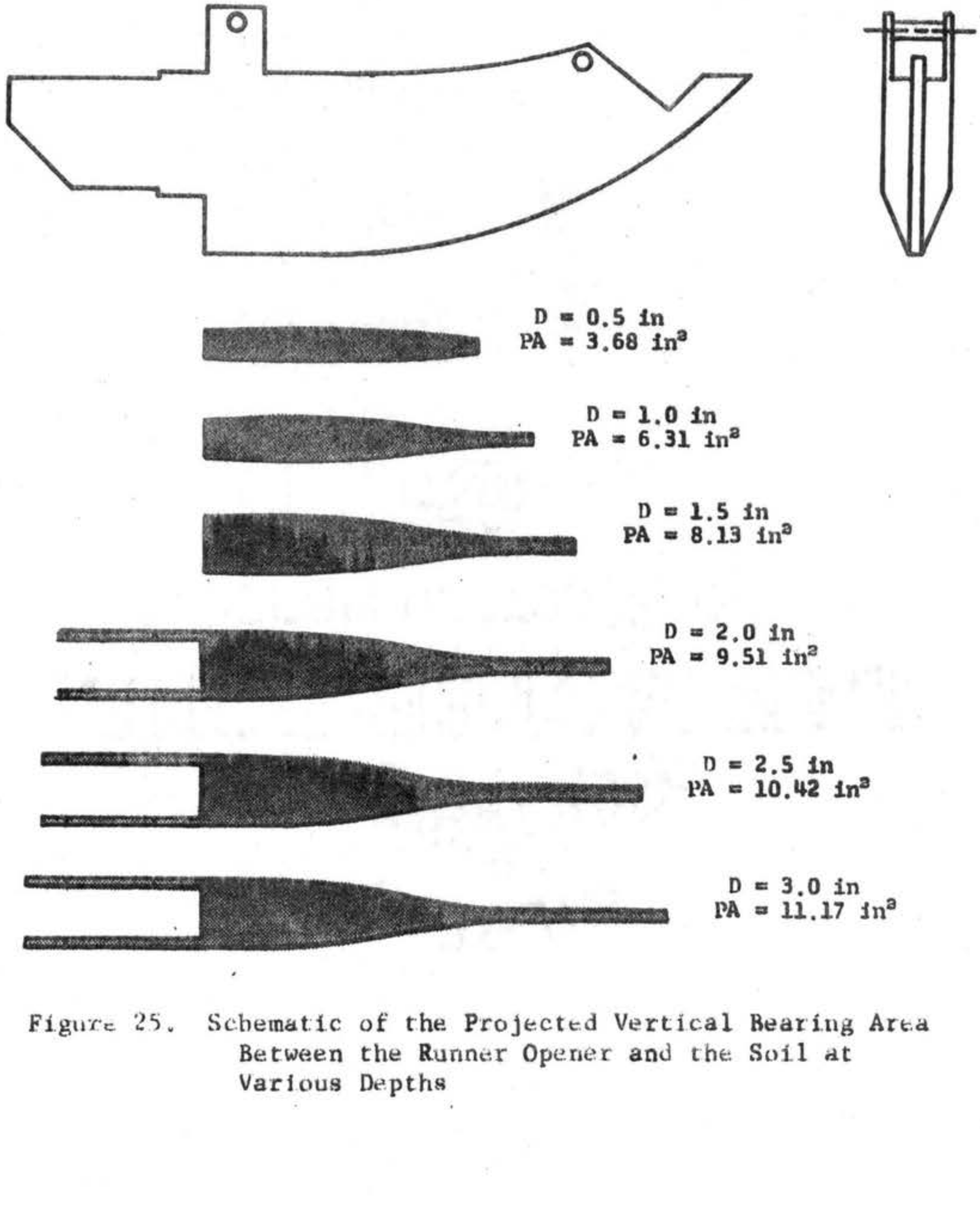


Figure 25. Schematic of the Projected Vertical Bearing Area Between the Runner Opener and the Soil at Various Depths

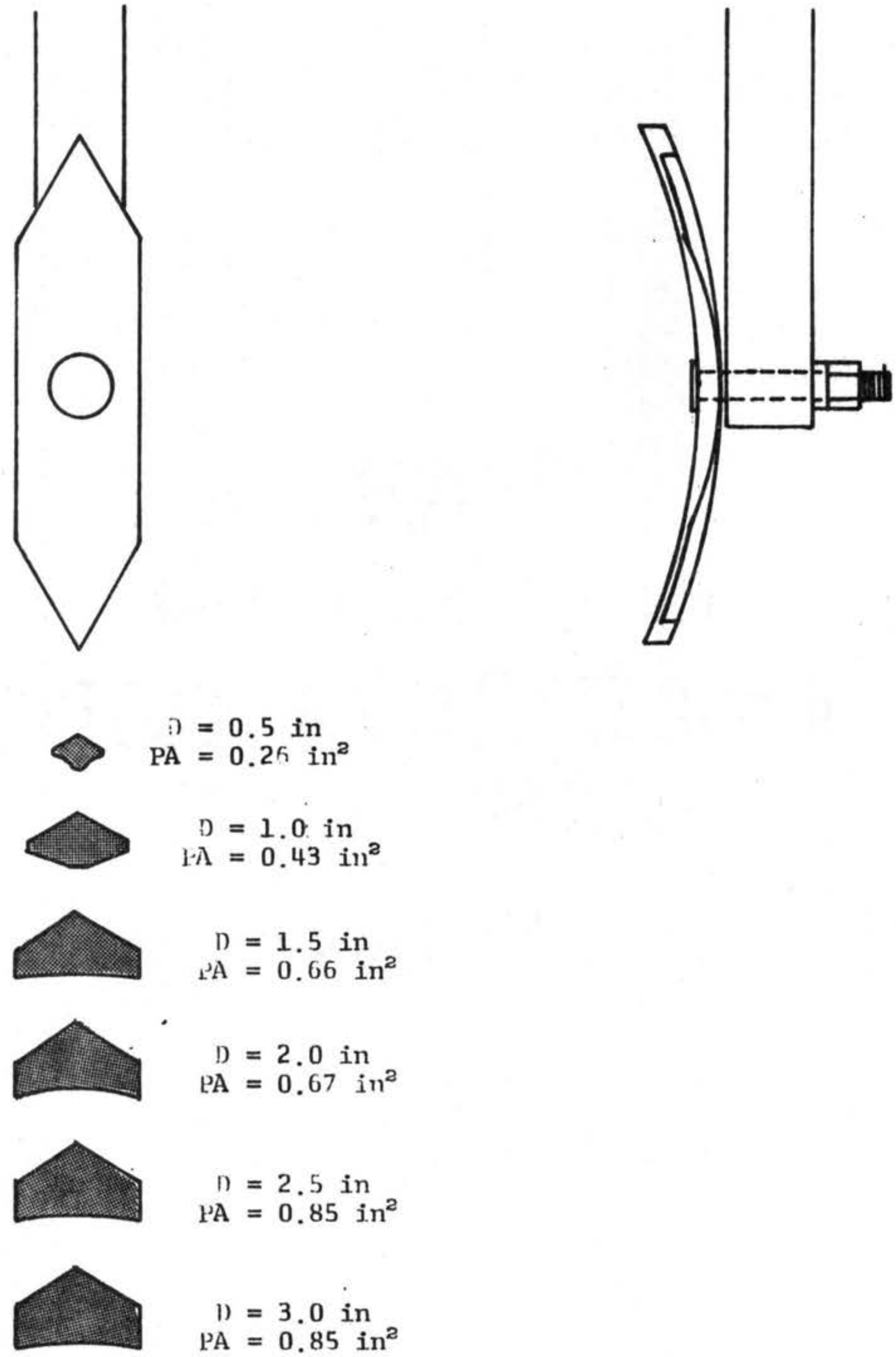


Figure 26. Schematic of the Projected Vertical Bearing Area Between the Chisel Opener and the Soil at Various Depths

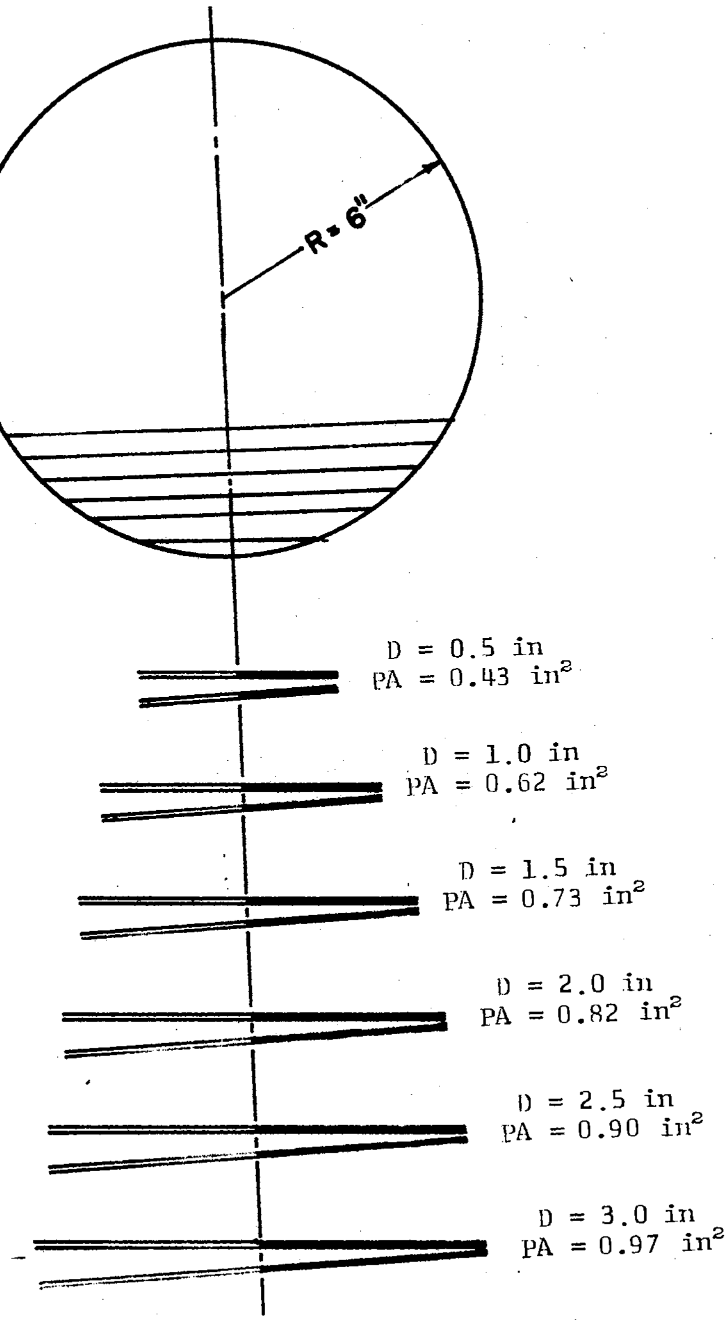


Figure 27. Schematic of the Projected Vertical Bearing Area Between the Double Disk Opener and the Soil at Various Depths

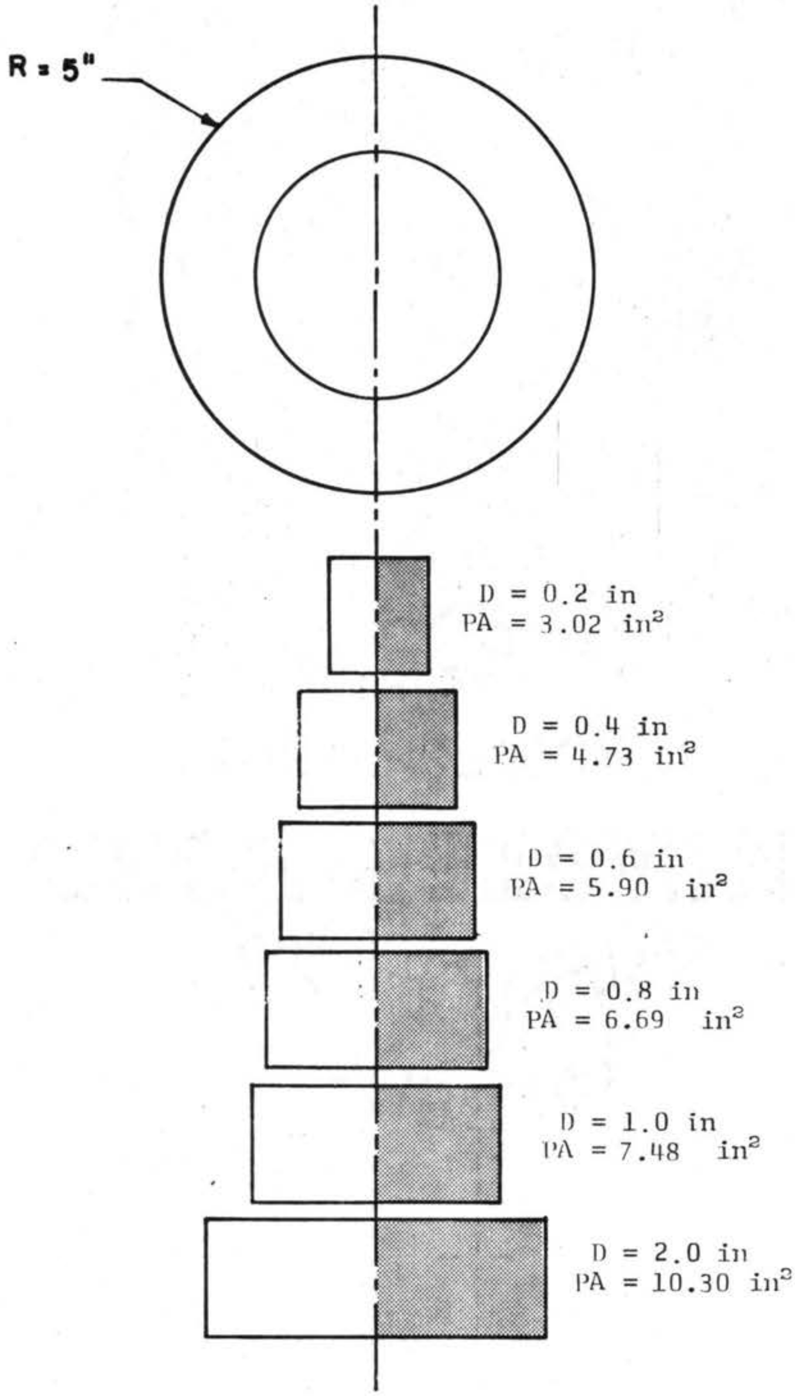


Figure 28. Schematic of the Projected Vertical Bearing Area Between the Gauge Wheel and the Soil at Various Depths

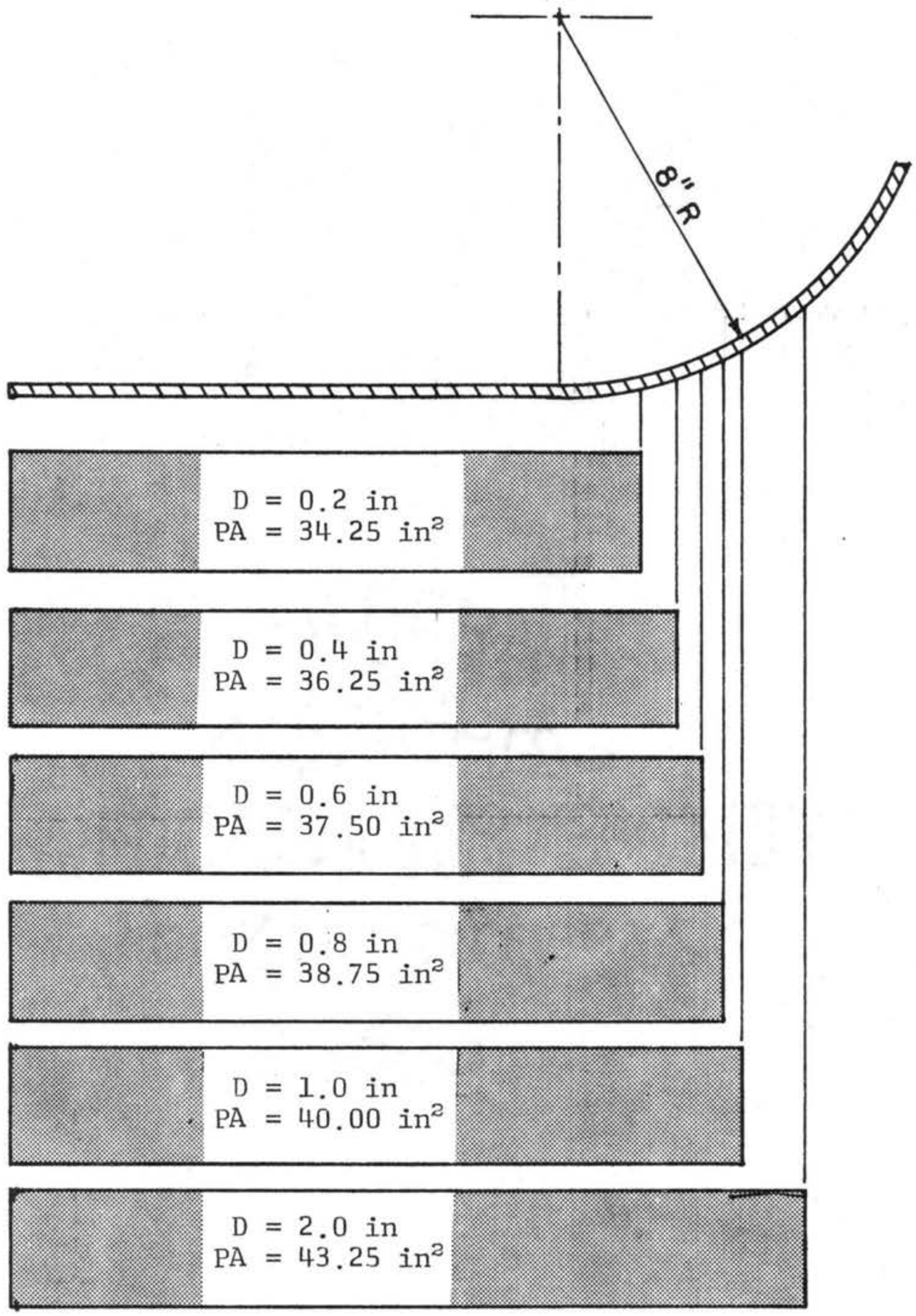


Figure 29. Schematic of the Projected Vertical Bearing Area Between the Slide Gauging Device and the Soil at Various Depths

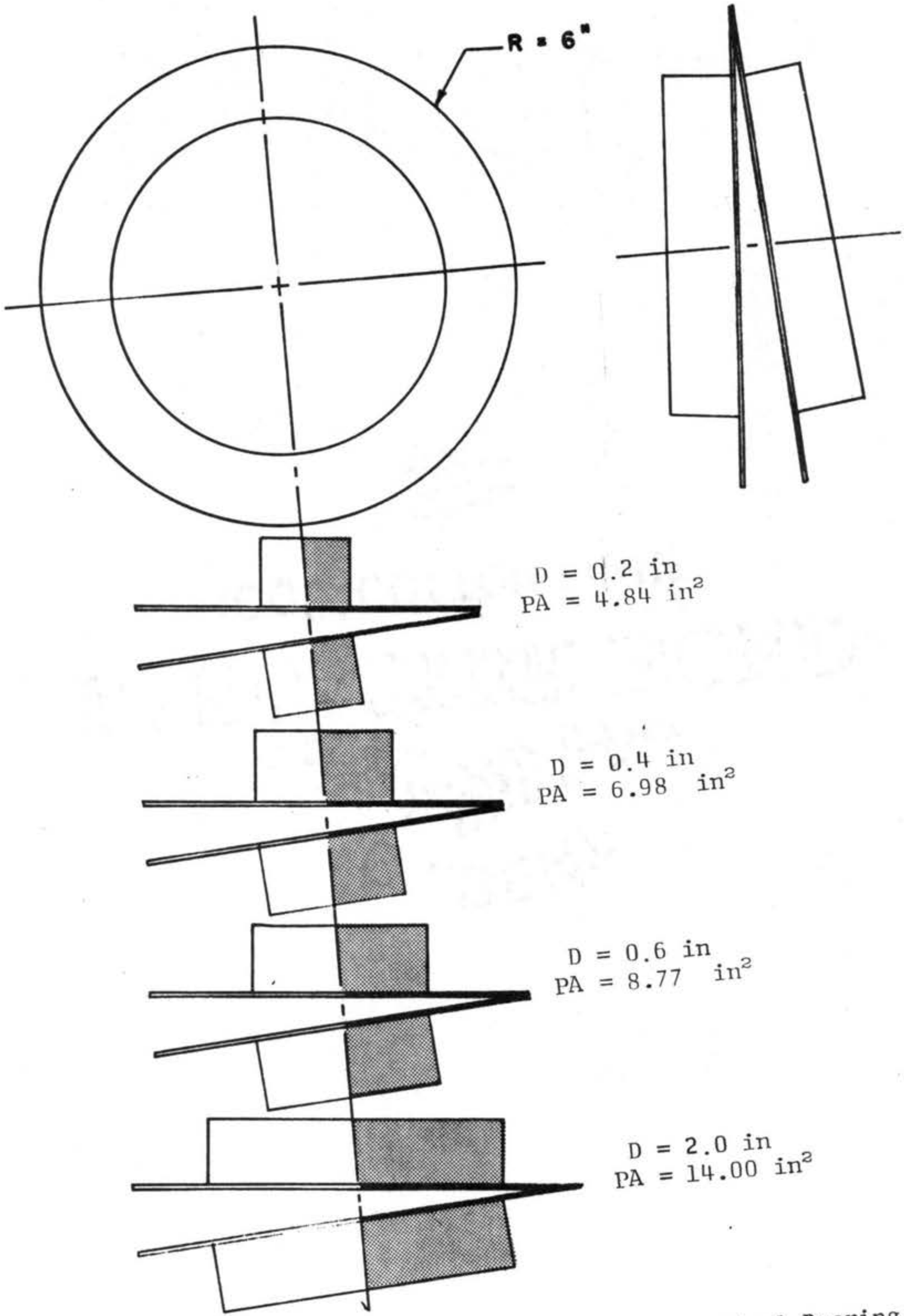


Figure 30. Schematic of the Projected Vertical Bearing Area Between the Depth Bands and the Soil at Various Depths

TABLE VI

PREDICTED EQUATIONS RELATING PROJECTED BEARING AREA AND DEPTH OF OPERATION FOR SOME TILLAGE TOOLS

Tillage Tool	Prediction Equation	R^2*
Runner Opener	$A = 0.92 + 6.18D - 0.93D^2$	99.8
Chisel Opener	$A = 0.09 + 0.29D$	94.9
Double Disk Opener	$A = 0.20 + 0.29D - 0.05D^2$	97.5
Gauge Wheel	$A = 1.88 + 7.27D - 1.58D^2$	99.5
Slide Gauge Device	$A = 32.14 + 11.18D - 5.08D^2 + 0.98D^3$	99.9
Depth Bands Gauge Device	$A = 3.39 + 9.4D - 2.07D^2$	99.4

*Percent of the Variation in the Dependent Variable Accounted for by the Independent Variables at the 1 percent Significance Level.

Legend:

A = Projected Bearing Area, in.^{2}

D = Depth of Operation, in.

the equations ranged from a low of 94.9 for the chisel opener to a high of 99.9 for the slide gauging device. Coordinate plots of the bearing surface equations for the furrow openers and gauging devices are presented in Figures 31 and 32 respectively. The bearing area curves show relative differences in the bearing areas among tillage tools. The curves for the runner opener and slide gauge device did not have an ordinate intercept since the bearing areas for these tools are step functions from a depth of zero to a depth slightly greater than zero. Values of area computed by the equation at a depth of zero are for continuous functions. The ordinate intercept of the depth band curve is not zero due to the effect of having the double disk in operation in the soil when the depth bands are at zero.

The correlation between projected vertical bearing surface and depth was high for all tools and therefore generalized response equations could be developed relating the mean vertical force as the dependent variable to the independent variables of tool speed and bearing surface. Using the average vertical force over all replications, the SAS stepwise regression technique selected the polynominal terms for the response equation significant at the one percent level. The equations presented in Table VII include the effects of replications which were not significant in the statistical analysis. At least 94.6 percent of the variation in force is accounted for among all tools. The response equation for the slide gauge device accounted for 98.9 percent of the variation of force due to speed and bearing area. Response surfaces for each furrow opener and depth control device were plotted and are shown in Figures 33-38.

To predict the vertical force response for different sizes of

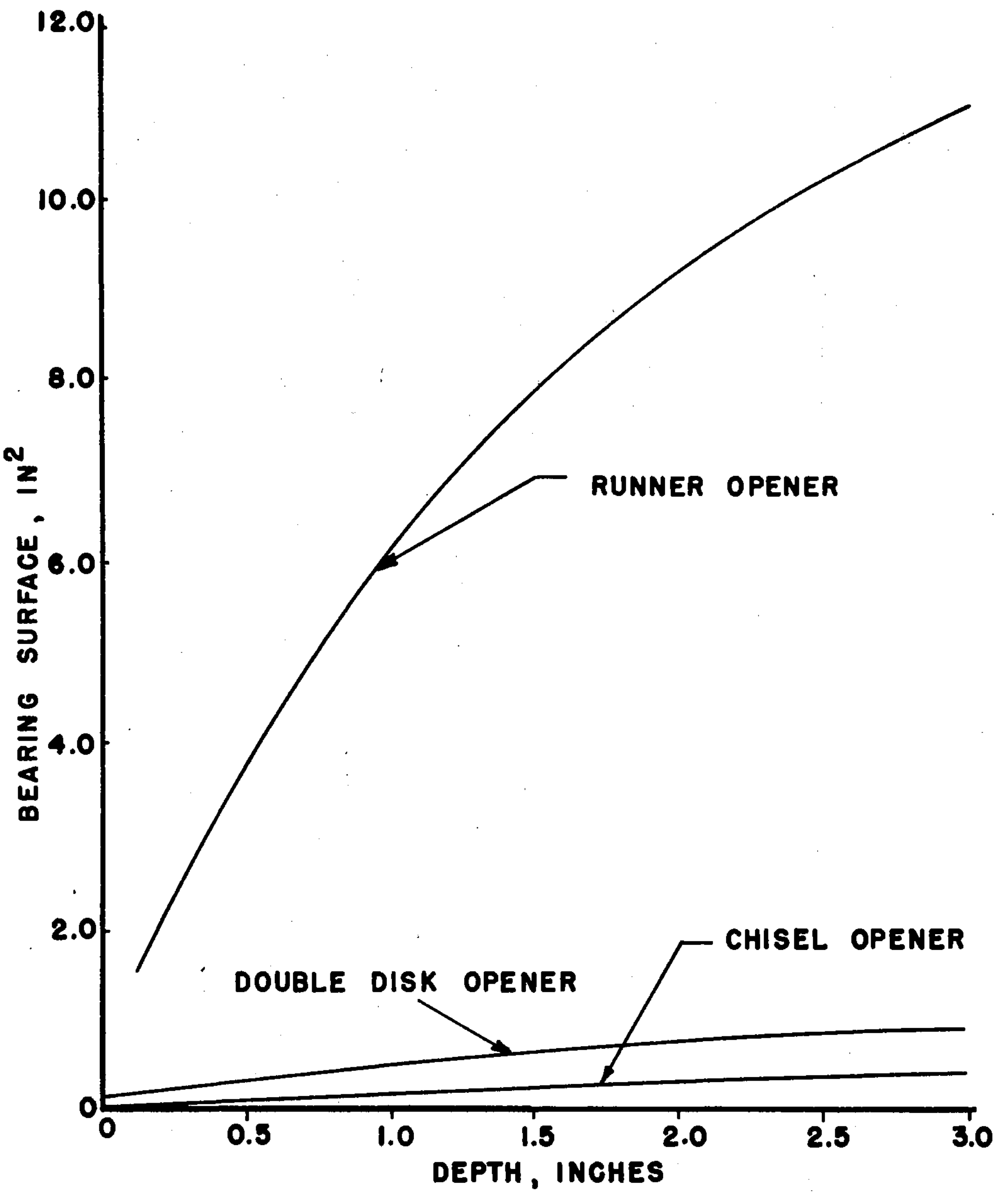


Figure 31. Response Curves Relating the Projected Bearing Area and Depth of Operation for Each Furrow Opener

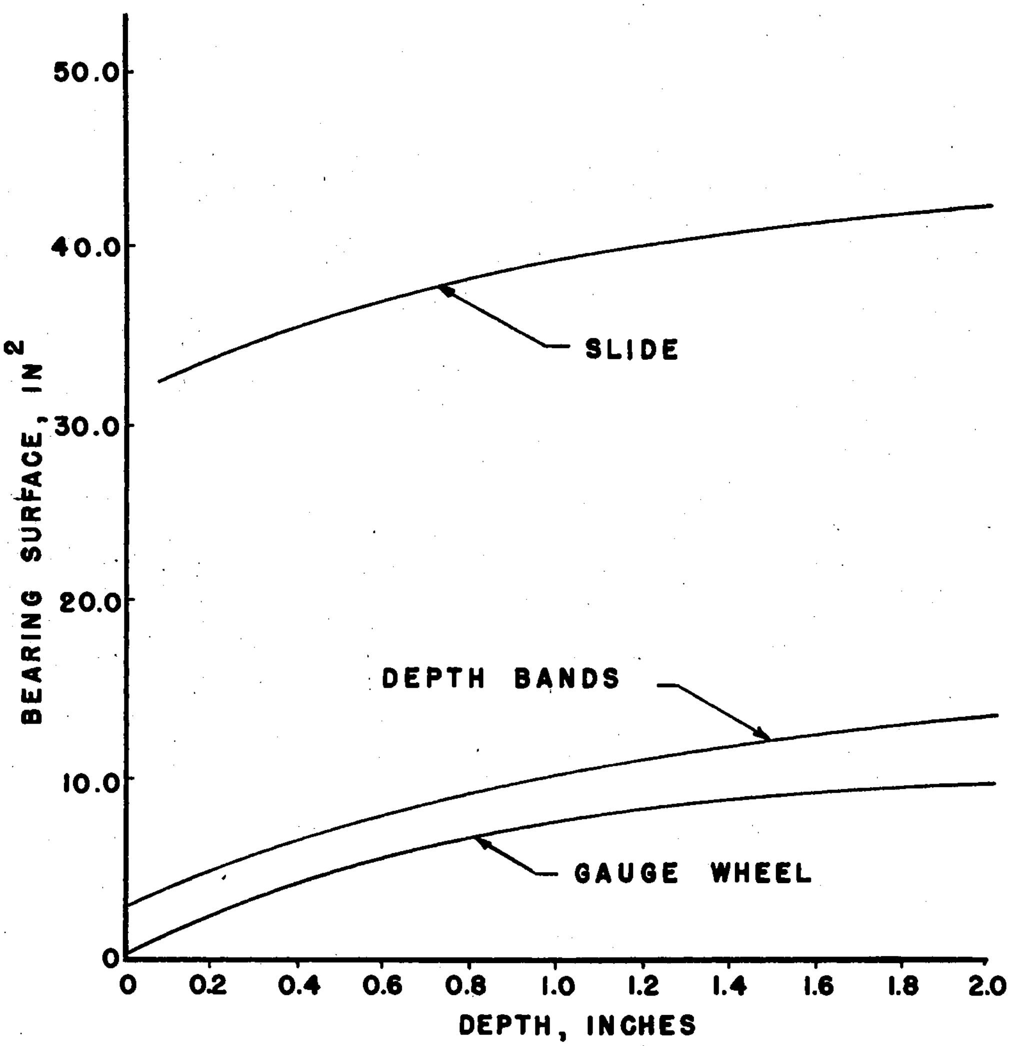


Figure 32. Response Curves Relating the Projected Bearing Area and Depth of Operation for Each Depth Gauging Device

TABLE VII

PREDICTION EQUATIONS RELATING FORCE, SPEED AND BEARING AREA FOR SOME TILLAGE TOOLS

Tillage Tool	Response Equation*	R^2
Runner Opener	$F^{**} = 0.66 + 9.12 \times 10^{-6} A^5 + 2.16 \times 10^{-5} VA^4$	97.5
Chisel Opener	$F = -0.13 + 9.7 \times 10^{-2} V + 1.02A^3$	96.1
Double Disk Opener	$F = 0.40 + 4.52A^4 + 0.39VA^5$	98.1
Gauge Wheel	$F = 0.10 + 0.16A^2$	94.5
Slide Gauge Device	$F = 2.96 + 2.7 \times 10^{-7} A^5 - 4.4 \times 10^{-7} V^2 A^3 - 9.71 \times 10^{-6} A^4$	98.9
Depth Bands	$F = -1.74 + 0.16A^2$	94.6

*Independent Variables That Account for the Dependent Variable at 1 Percent Significance Level

**Averaged Over Replications

Legend:

F = Force, lbs.

V = Tool Speed, in./min.

A = Projected Bearing Area, $in.^2$

Equation for Response Surface in Table VII
(R^2 = 97.5)

Legend:

Force = Vertical Force
Speed = Tool Speed
Area = Tool Bearing Area

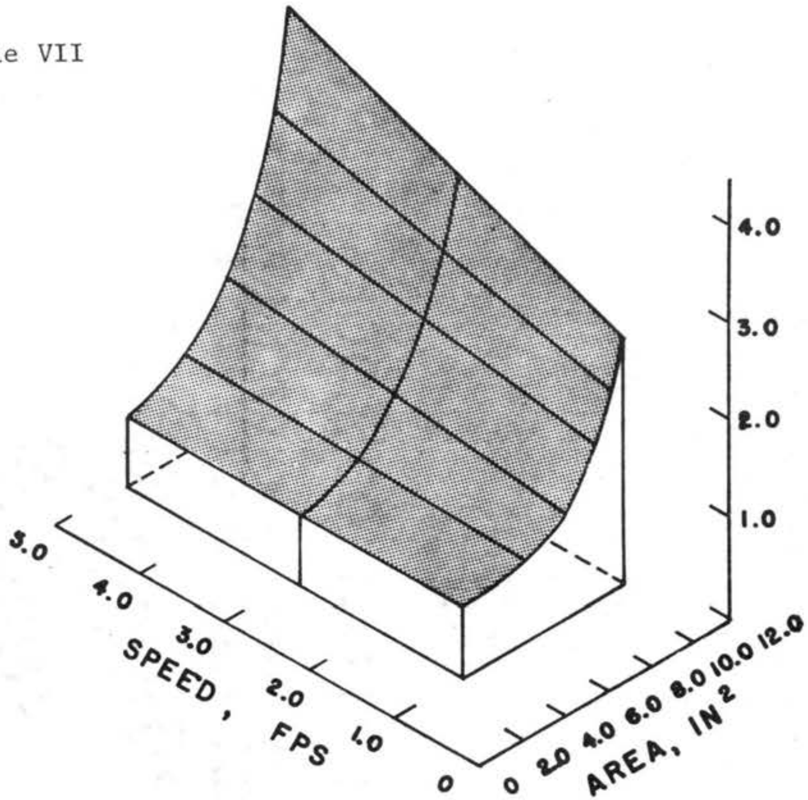


Figure 33. Runner Opener Response Surface

Equation for Response Surface in Table VII

(R^2 = 96.1)

Legend:

Force = Vertical Force
Speed = Tool Speed
Area = Tool Bearing Area

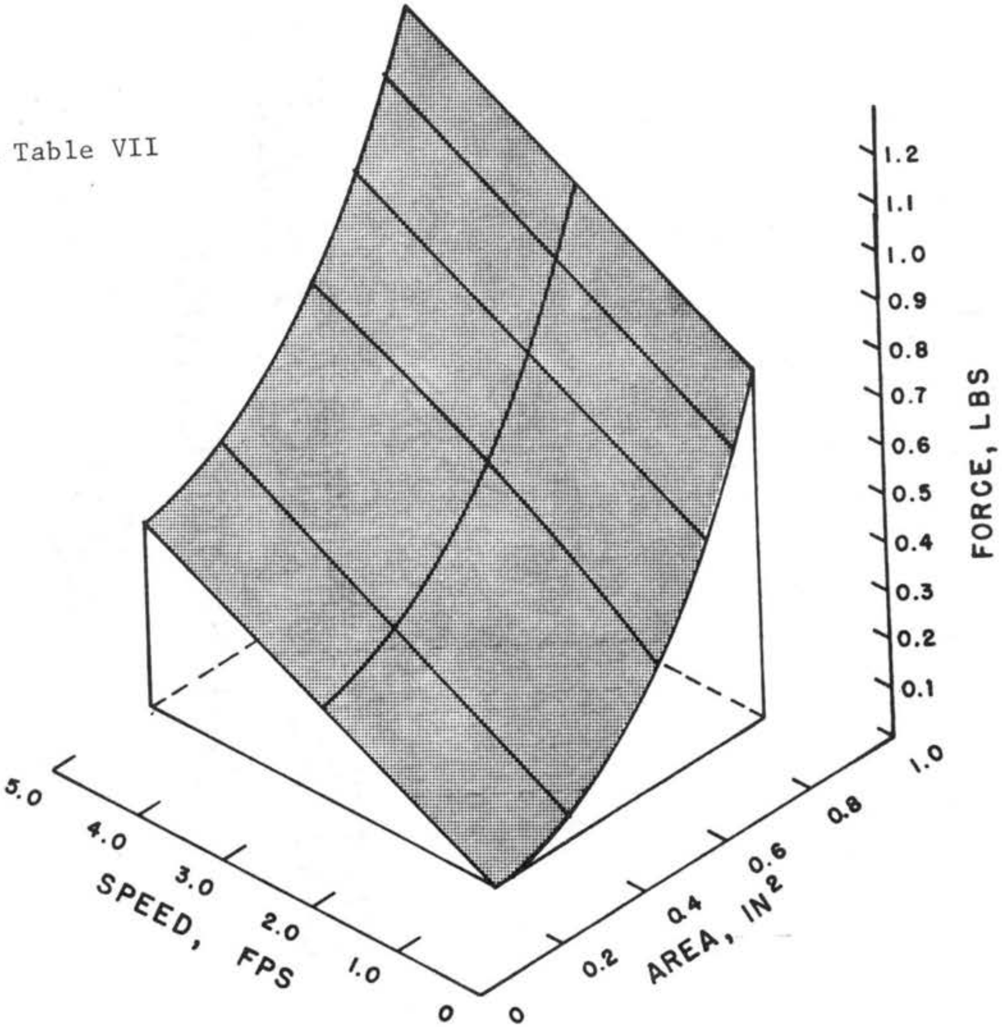


Figure 34. Chisel Opener Response Surface

Equation for Response Surface in Table VII
($R^2 = 98.2$)

Legend:

Force = Vertical Force
Speed = Tool Speed
Area = Tool Bearing Area

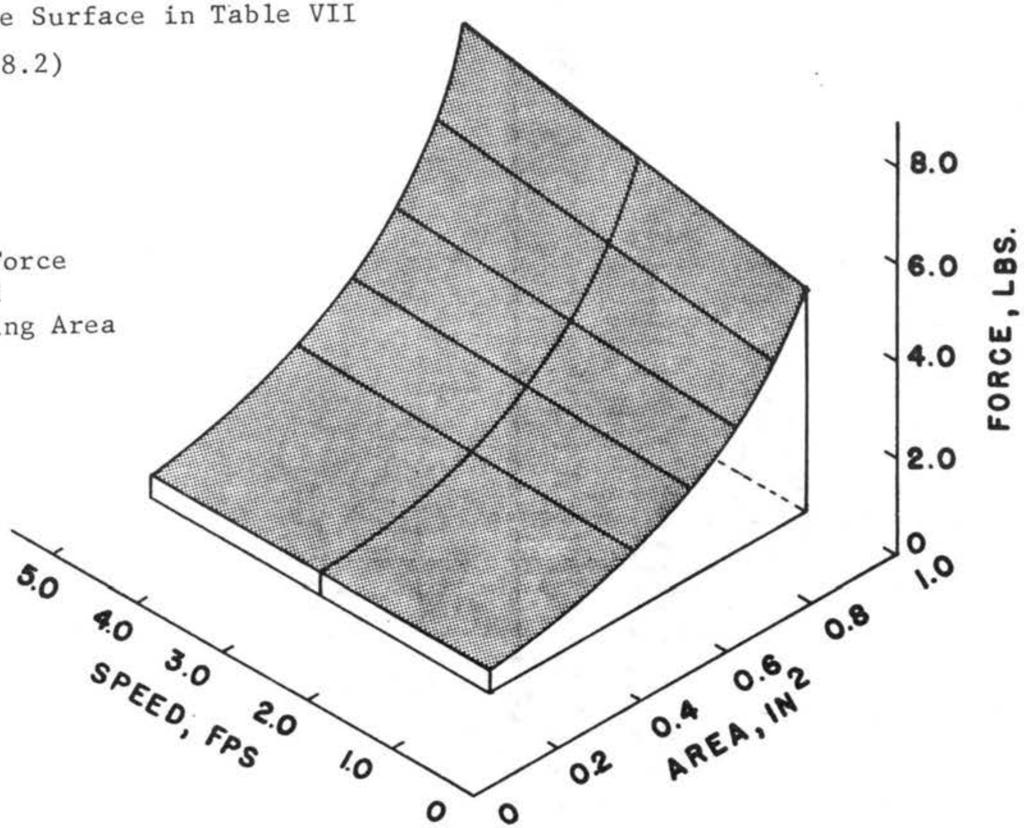


Figure 35. Double Disk Opener Response Surface

Equation for Response Surface in Table VII
(R^2 = 94.6)

Legend:

Force = Vertical Force
Speed = Tool Speed
Area = Tool Bearing Area

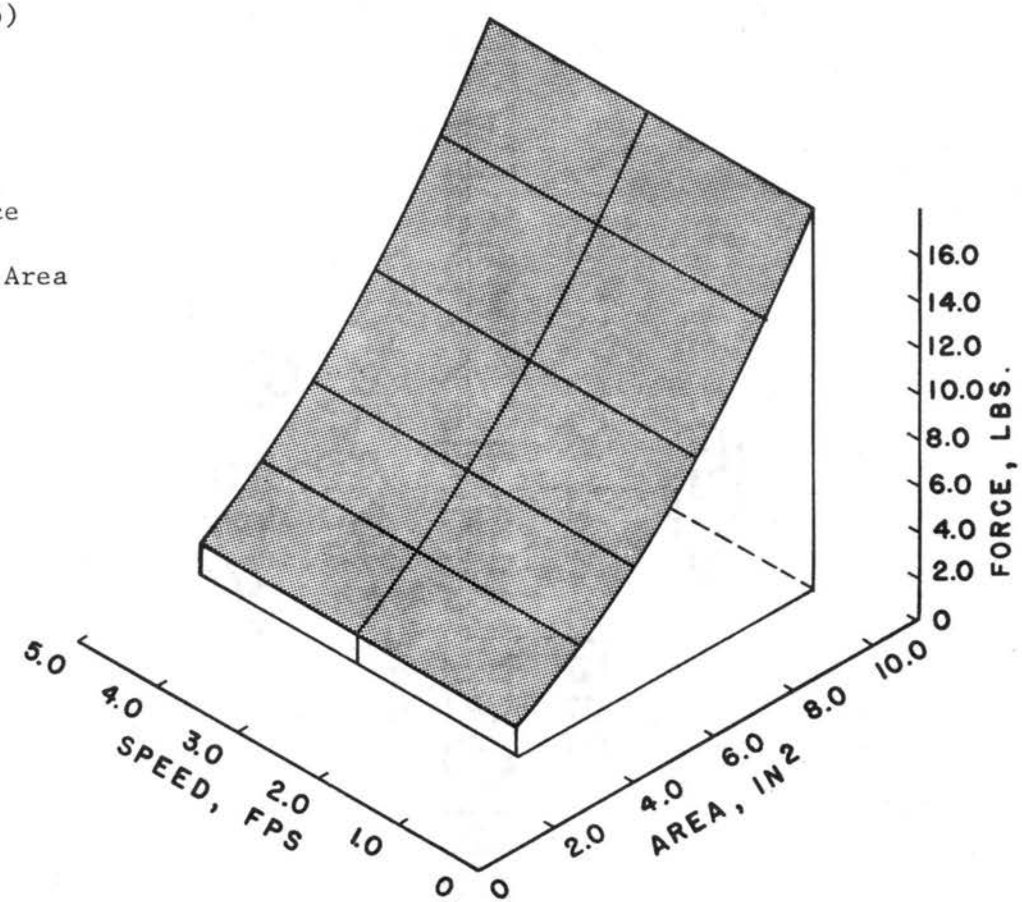


Figure 36. Gauge Wheel Response Surface

Equation for Response Surface in Table VII

(R^2 = 98.9)

Legend:

Force = Vertical Force
Speed = Tool Speed
Area = Tool Bearing Area

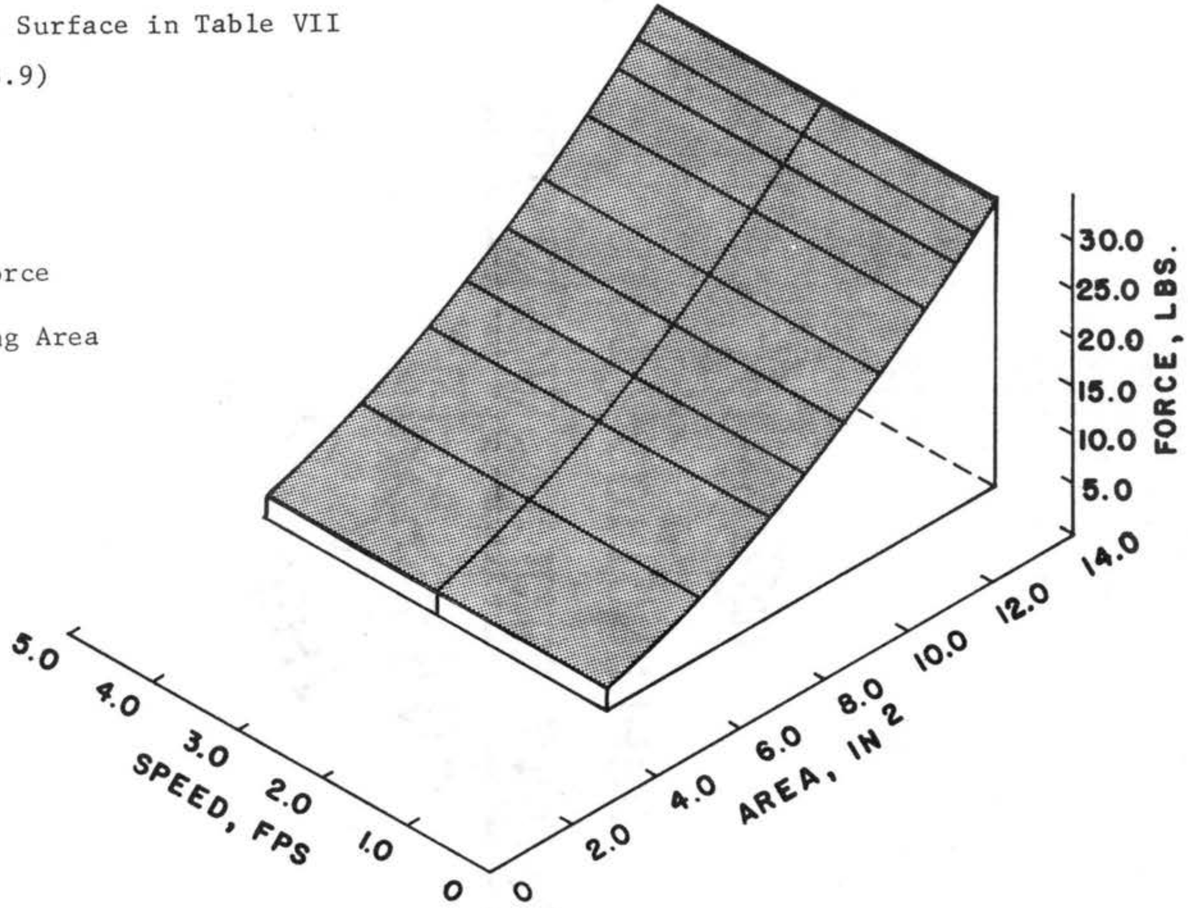


Figure 37. Slide Gauge Device Response Surface

Equation for Response Surface in Table VII

(R^2 = 94.6)

Legend:

Force = Vertical Force
Speed = Tool Speed
Area = Tool Bearing Area

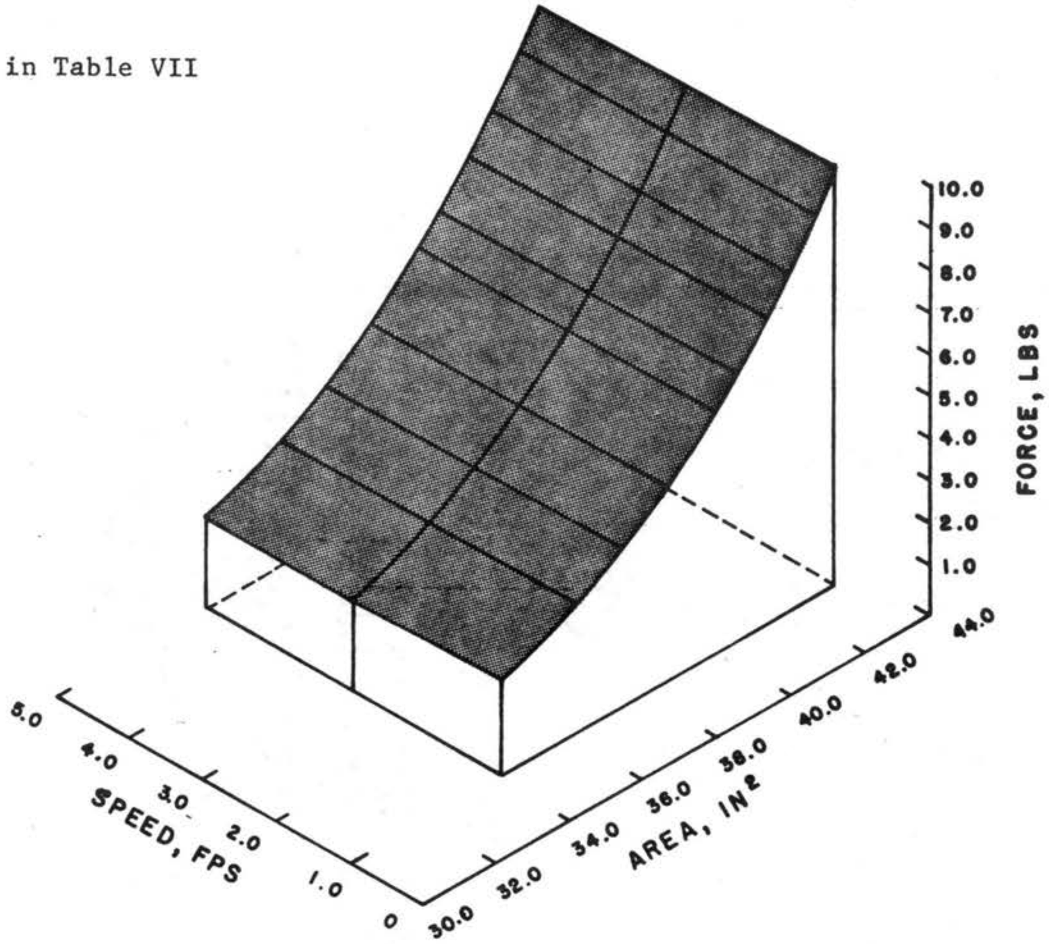


Figure 38. Depth Bands Gauging Device Response Surface

furrow openers and gauging devices operating under different conditions, 13 variables including soil properties were used to describe the soil-tool system. Using fundamental dimensions of mass, length and time, the variables were combined by dimensional analysis into 10 independent dimensionless pi terms. With π_1 as the dependent pi term, an expression relating the independent pi terms is as follows:

$$\frac{F}{\rho g A D} = f\left(\frac{V^2}{Dg}, \frac{K_c}{A^{.039}\rho g}, \frac{C}{\rho g D}, \frac{K_\Phi}{A^{.539}\rho g}, \frac{D^2}{A}, \frac{\alpha}{\rho g D}, \Phi, \theta, n\right)$$

Direct soil strength measurements on the artificial soil found the soil-to-soil coefficient of internal friction was 0.570 and the soil-to-metal coefficient of internal friction was 0.418, Figure 39. Soil properties of cohesion and adhesion were zero. Using spindle oil as the soil particle binding agent caused the true cohesion normally obtained from a high percentage of clay in an artificial soil mixture to be non-significant.

Bearing strength parameters of the artificial soil were determined by Bekker's technique. The cohesive modulus of sinkage, K_c, was found to be 0.18 pounds per inch^{n+1}; frictional modulus of sinkage, K_Φ, was found to be 1.06 pounds per inch^{n+2}; and the exponent of sinkage, n, was 0.922.

General soil-tool prediction equations were developed for each furrow opener and gauging device with certain limitations. The independent pi terms of soil-to-soil and soil-to-metal coefficients of friction and exponent of sinkage were constant for the study. The other pi terms varied only as depth of operation, speed and bearing area varied. With cohesion and adhesion equal to zero, π_4 and π_7 became zero. The response equations presented in Table VIII include

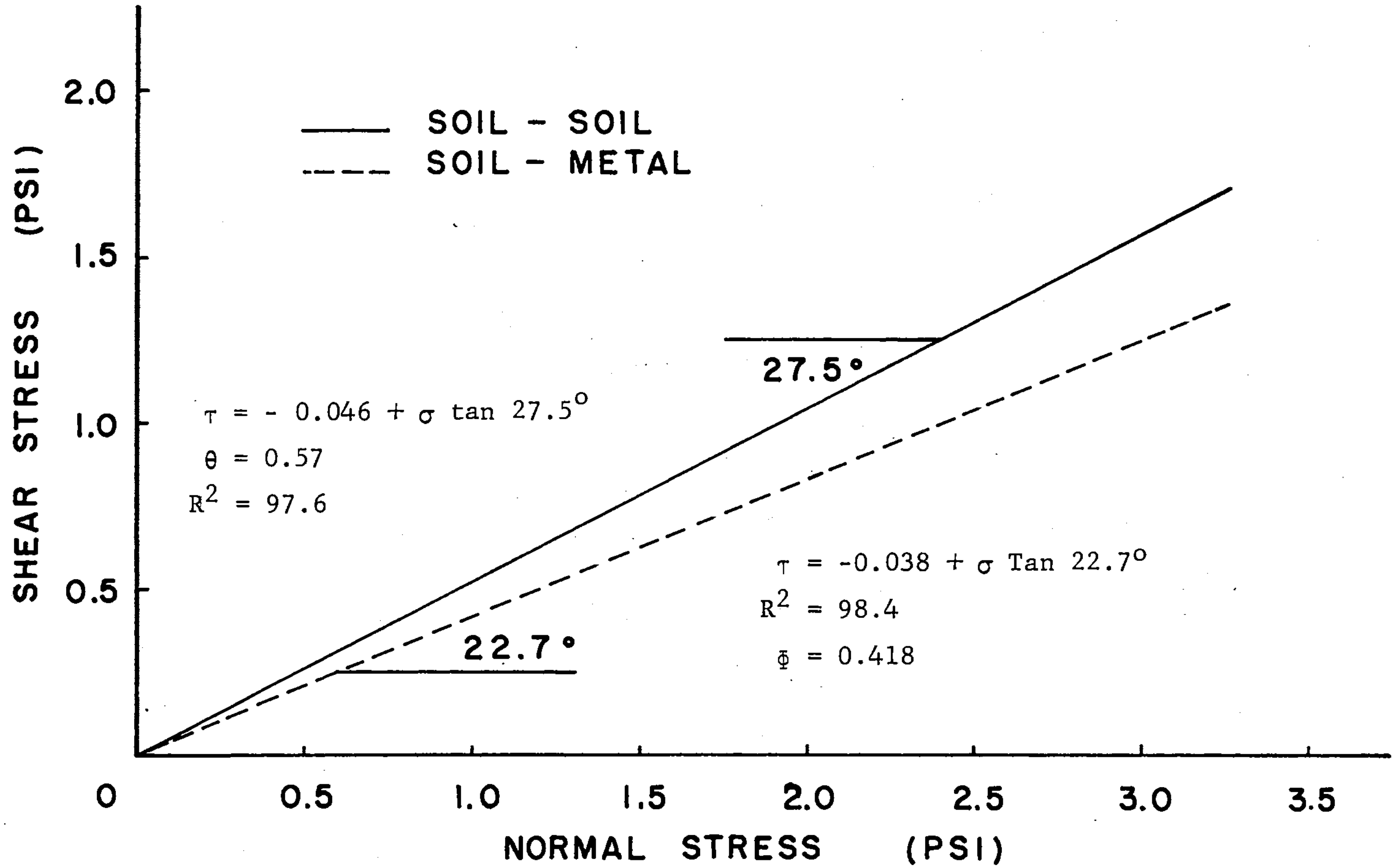


Figure 39. Soil Shear Strength

TABLE VIII

PREDICTION EQUATIONS RELATING DEPARTMENT PI TERM WITH INDEPENDENT PI TERMS FOR VERTICAL FORCES ON A SOIL-TOOL SYSTEM

Tillage Tool	Response Equation*	R^2
Runner Opener	$\pi_1 = 1.29x10^{-4}\pi_2 - 240.51\pi_3 + 6.03\pi_5 - 5.16x10^{-6}\pi_6$	88.2
Chisel Opener	$\pi_1 = 1.44x10^{-4}\pi_2 - 172.91\pi_3 + 0.94\pi_5 - 4.6x10^{-6}\pi_6$	90.7
Double Disk	$\pi_1 = - 1.37x10^{-4}\pi_2 + 1216.80\pi_3 - 9.90\pi_5 - 4.2x10^{-5}\pi_6$	84.8
Gauge Wheel	$\pi_1 = 1.2x10^{-5}\pi_2 + 1463.06\pi_3 - 35.71\pi_5 + 9.47x10^{-4}\pi_6$	77.5
Slide	$\pi_1 = - 1.2x10^{-5}\pi_2 - 7748.37\pi_3 + 428.31\pi_5 - 3.07x10^{-4}\pi_6$	95.8
Depth Bands	$\pi_1 = - 8.64x10^{-5}\pi_2 + 35.08\pi_3 + 7.44\pi_5 - 3.18x10^{-4}\pi_6$	62.1

*Values of Force Used in the Dependent Pi Term was Averaged Over Replications.

$\pi_1 = f(\pi_2, \pi_3, \pi_5, \pi_6)$. The coefficients of determination indicated a relative high percent of variation in π_1 was accounted for by the independent pi terms. A relationship between the dependent pi term, $\frac{F}{gAD}$, and nine independent pi terms can be theoretically predicted providing the values of some properties of the soil previously discussed are constant.

CHAPTER VI

SUMMARY, CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

Summary

Research undertaken and reported in this thesis was related to the general problem of improving the precision of the depth of operation of tillage tools. The specific problem involved a soil bin study to evaluate the vertical forces of three types of furrow openers and three depth control devices operating at predetermined depths and speeds. For the research problem selected, the following objectives were established:

1) Measure the vertical forces on some seed furrow openers and depth control devices operating in an artificial soil.
2) Develop prediction equations relating the vertical forces of seed furrow openers and depth control devices operating at predetermined speeds and depths.
3) Develop prediction equations relating mechanical soil properties to the vertical forces on seed furrow openers and depth control devices.

The objectives were accomplished using an artificial soil in a continuous linear soil bin instrumented to measure soil forces on the tillage tools. The experiment was organized in a replicated split plot statistical design. In collecting the data, the vertical forces were measured for each furrow opener operating at 1, 3 and 5 fps and 0.3 inch depth increments to 3.0 inches. The vertical forces were measured for each gauging device operating at 1, 3 and 5 fps and at 0.2 inch depth increments to 2.0 inches. Values for the mechanical soil properties were determined and held constant throughout the study.

A statistical analysis was made using the Statistical Analysis System (SAS) computer program technique. The analysis partitioned the sum of squares, conducted F tests on the mean squares, gave the level of significance for each partition and developed prediction equations. The SAS stepwise regression technique developed the prediction equations for each tillage tool with vertical force as the dependent variable and speed, depth, area and mechanical soil properties as independent variables. The percentage of variation in the dependent variable accounted for by the independent variables was given as the coefficient of determination (R^2).

A projected vertical bearing surface was defined and determined for each opener and gauge device. A prediction equation relating depth of operation and bearing surface for each tool was developed. The rate and magnitude of the effects of speed and tool bearing area on the vertical force experienced by each tool are presented graphically.

Dimensional analysis was used to combine 13 variables describing the soil-tool system into 10 dimensionless pi terms. With π_1 as the dependent variable and the remaining pi terms as independent variables, prediction equation were developed relating mechanical soil properties to the vertical forces on some furrow openers and depth control devices operating at varying speeds and depths.

Conclusions

The objectives of the study were fulfilled for the tillage system studied and the following conclusions are formed from an interpretation of the results.

1) Vertical forces were significantly different among the furrow openers and depth control tillage tools tested.
2) Differences in the vertical forces due to the tool depth of operation was detected at the one percent significance level.
3) Differences in the vertical forces due to speed of operation of the tools were not significant at the one percent level, however, differences were detected at the five percent level for the depth control devices. Therefore, at speeds less than five fps, vertical force was not significantly affected by speed of the furrow openers and depth control devices.
4) Adequate prediction equations were obtained relating vertical force, speed and depth of operation. Terms significantly affecting the vertical force were determined by a stepwise regression technique.
5) A projected vertical bearing area was related to depth of operation for each tool and adequate response equations relating vertical force, speed and bearing area were developed. The coefficient of determination (R^2) for each equation increased as the measured vertical force increased.
6) General prediction equations were developed to relate vertical

forces of the soil on the tools to mechanical properties of the soil. The equations are limited to constant soil property values.

Suggestions for Further Work

Recommendations for further study in most instances relate a need for additional soil bin equipment and methods. Results presented in this thesis describe effects from one artificial soil. How applicable the results are to field conditions depend upon how well soil properties can be modeled under simulated conditions. Additional studies on soils with varying amounts of cohesive and adhesive properties are needed to provide complete variations of all pi terms in the prediction equations.

Due to the limitations of the soil bin, tool speeds greater than five fps were not tested. In most instances, greater speeds are used in the field. The effects of soil temperature on soil forces were not considered since all tests in this study were conducted at a relatively constant temperature.

Specific use of the predicted forces on tillage tools operating under different soil conditions should be considered. A study to develop tools to provide and disperse the forces desired for a specific operation could be made. Additional or properly designed depth control devices with greater bearing capacity per unit of sinkage depth relative to the furrow opener could be developed.

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APPENDIX A

SPECIFICATIONS OF INSTRUMENTS

SPECIFICATIONS OF LOAD CELLS

The six load cells were purchased from Transducers, Incorporated, 11971 East Rivera Road, Santa Fe Springs, California 90670. These load cells were of the bonded strain gauge type. In each load cell, 4 strain gauges formed a full Wheatstone bridge, to produce an electrical output signal which was directly proportional to applied force.

Non-linearity (Terminal Method): 0.2% full scale tension and compression

Hysteresis (Unidirectional): 0.10% full scale

Sensitivity: 3 mv/v rated capacity

Accuracy of Full Scale Output: + 5% tension or compression

Zero Balance: + 5% full scale

Input and Output Resistance (350 ohms standard): + 10% tolerance

Temperature Effect on Zero Balance: less than 0.02% of load per ^{o}F

Temperature Effect on Output: les than 0.02% of load per ^{o}F

Temperature Range (compensated): 15 to 150^{o}F

Maximum Safe Temperature: 250^{o}F

Excitation Voltage Recommended: 10 volts, DC or AC

Maximum Safe Overload: 150% rated capacity

Maximum Excitation Voltage: 18 volts, DC or AC

<u>Ultimate Overload Rating</u>: 200% rated capacity

<u>Side Load Effect (1^o off axis)</u>: less than 0.25% full scale

<u>Side Load Effect (3^o off axis)</u>: less than 0.50% full scale

<u>Standard Temperature for Specifications</u>: 77^oF

SPECIFICATIONS OF THE TACHOMETER SYSTEM

The linear speed of the soil was monitored on the dynograph with a tachometer system. The system consisted of a DC tachometer generator, a tachometer voltmeter and channel seven of the dynograph recorder.

The generator and voltmeter were calibrated as a sub-system at the factory. The sub-system was purchased from Servo-tek Products Company Incorporated. The maximum error of the sub-system was calibrated to be one percent of the full scale reading. The generator and voltmeter were temperature compensated and calibrated at 25 degrees Centigrade. Accuracy was not affected by more than one-half percent of full scale for either an increase or decrease of 50 degrees Centigrade. Full scale meter reading was 1000 rpm, but the generator shaft was fitted with a driving disk of appropriate size so that 1000 rpm of the generator shaft was equivalent to 10 feet per second belt speed. The generator output was seven volts per 1000 rpm (6).

SPECIFICATIONS OF THE QUALICON DENSITY GAUGE

A system was used for measuring the density of the artificial soil in front of the soil-tool test area. The system consisted of a radioactive source, a radiation detector, a meter, and a recorder.

The radioactive source consisted of 2 curies of cesium 137. In operation, a shutter in the source housing was opened and radiation from the source passed through the soil and soil bin to the radiation detector. The amount of radiation received was inversely related to the density of the soil and directly proportional to a current developed in the detector. The electrical signal from the detector was conditioned and available at the meter and on channel eight of the dynagraph recorder. Detailed specifications (rise time, drift, etc.) of the source-detector meter sub-system were not supplied by the manufacturer. Values of soil density registered on the meter and recorder were calibrated with the artificial soil in place in the soil bin channel.

APPENDIX B

ORIGINAL DATA

TABLE IX

ORIGINAL DATA FOR SOIL-SOIL SHEAR STRESS

Sample No.	Normal Load (PSI)				
	4.830	3.034	2.136	1.687	0.790
I	2.119	1.385	1.043	0.695	0.642
I	2.629	1.426	0.943	0.733	0.587
II	2.914	1.508	1.080	0.917	
II	2.262	1.286	1.059	0.835	
III	2.955	1.773	1.100	0.794	
III	2.282	1.385	1.039	0.743	

TABLE X

ORIGINAL DATA FOR SOIL-METAL SHEAR STRESS

Sample No.	Normal Load (PSI)			
	4.830	3.034	2.136	1.687
I	1.956	1.131	1.049	0.642
I	2.058	1.273	0.823	0.774
II	2.038	1.202	0.866	0.784
II	2.078	1.182	0.835	0.733
III	2.058	1.019	0.892	0.591
III	1.875	1.121	0.866	0.570

Area of Shear Ring = 4.906
Rate of Loading = 0.02 in./min.
Chart Speed = 1.0 in./min.

TABLE XI

ORIGINAL DATA FOR PENETRATION PRESSURE, PSI, RECORDED FOR 1.0 INCH DIAMETER BEARING PLATE

	Soil Depth (inches)					
Replication	0.5	1.0	1.5	2.0	2.5	3.0
I	0.89	1.91	2.68	3.44	4.33	5.22
II	1.78	2.80	3.82	4.97	5.99	7.13
III	1.53	2.55	3.57	4.46	5.61	6.50
IV	0.89	1.91	3.31	4.20	5.22	6.24

TABLE XII

ORIGINAL DATA FOR PENETRATION PRESSURE, PSI, RECORDED FOR 2.0 INCH DIAMETER BEARING PLATE

	Soil Depth (inches)					
Replication	0.5	1.0	1.5	2.0	2.5	3.0
I	1.08	1.78	2.54	3.31	4.07	4.27
II	0.76	1.40	2.04	2.80	3.38	4.08
III	0.86	1.59	2.29	3.24	4.04	4.84
IV	0.86	1.59	2.29	3.24	4.04	4.84

TABLE XIII

FURROW OPENER BEARING SURFACE (IN^2)

Furrow Opener	Depth of Operation					
	0.5	1.0	1.5	2.0	2.5	3.0
Runner	3.68	6.32	8.13	9.15	10.40	11.17
Chisel	0.13	0.22	0.33	0.39	0.43	0.45
Double Disk	0.23	0.61	0.73	0.82	0.90	0.97

TABLE XIV

GAUGING DEVICES BEARING SURFACE (IN^2)

Gauge Device	Depth of Operation									
	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Gauge Wheel	3.02	4.78	5.90	6.69	7.48	8.36	8.94	9.32	9.71	10.30
Slide	34.25	36.25	37.5	38.75	40.00	40.62	41.38	42.00	42.75	43.25
Depth Bands	4.84	6.98	8.77	9.67	10.57	11.47	12.37	13.11	13.64	14.00

TABLE XV

ORIGINAL DATA OF FURROW OPENER FORCES
RECORDED FROM THE LOAD CELLS

REPLICATION I

RUNNER OPENER

OBS	VEL	DEPTH	F2 A	F2 B	F3 A	F3 B	F4 A	F4 B	F5 A	F5 B	F6 A	F6 B
	0	0.0	-0.60	-0.60	-0.10	-0.10	-0.20	-0.20	0.20	0.20	-0.10	-0.10
	1	0.5	-0.70	-0.70	0.50	0.50	-0.80	-0.70	0.80	0.80	0.0	0.0
	1	1.0	-0.80	-0.90	0.50	0.60	-0.20	-0.20	1.20	1.20	0.50	0.60
	1	1.5	-1.00	-1.00	0.70	0.60	0.0	0.0	1.80	1.80	1.00	1.00
	1	2.0	-2.10	-2.10	1.20	1.10	-0.10	-0.10	3.00	3.00	2.30	2.30
	1	2.5	-3.20	-3.20	1.50	1.50	0.10	0.20	4.30	4.30	3.50	3.50
	1	3.0	-4.40	-4.50	1.90	1.90	0.30	0.30	6.00	6.00	5.00	5.10
	0	0.0	-0.60	-0.50	0.0	0.0	-0.30	-0.30	0.20	0.20	-0.10	-0.10
	3	0.5	-0.80	-0.80	-0.20	-0.20	0.10	0.10	0.20	0.30	0.0	0.0
	3	1.0	-1.00	-1.00	0.0	0.0	0.10	0.20	1.00	1.00	0.30	0.30
	3	1.5	-1.70	-1.80	0.70	0.70	0.20	0.30	1.80	1.80	1.00	1.00
	3	2.0	-2.80	-2.90	2.00	2.00	-0.40	-0.40	3.20	3.20	1.20	1.30
	3	2.5	-4.00	-4.00	2.00	2.00	0.0	0.0	4.80	4.80	3.80	3.90
	3	3.0	-5.50	-5.50	2.50	2.60	0.40	0.40	6.80	6.80	5.70	5.80
	0	0.0	-0.30	-0.30	0.0	0.0	1.20	1.20	0.0	0.0	0.0	0.0
	5	0.5	-0.30	-0.40	-0.30	-0.40	3.40	3.40	0.30	0.30	0.10	0.10
	5	1.0	-0.80	-0.80	0.30	0.30	3.20	3.20	1.10	1.10	0.70	0.70
	5	1.5	-1.40	-1.40	-0.70	0.80	3.00	3.10	0.90	0.90	0.60	0.60
	5	2.0	-2.20	-2.20	1.80	1.80	2.70	2.80	3.00	3.00	2.40	2.40
	5	2.5	-3.30	-3.30	2.50	2.50	2.50	2.60	4.70	4.70	3.90	3.90
	5	3.0	-4.90	-4.90	2.80	2.80	2.60	2.70	6.70	6.80	5.70	5.70

TABLE XV (Continued)

REPLICATION I

CHISEL OPENER

	VEL	DEPTH	F2		F3		F4		F5		F6	
OBS			A	B	A	B	A	B	A	B	A	B
	0	0.0	-0.10	-0.10	-0.40	-0.50	1.00	0.90	0.30	0.40	0.20	0.30
	1	0.5	-1.00	-1.00	0.10	0.10	0.50	0.50	0.70	0.80	1.10	1.10
	1	1.0	-0.30	-0.20	0.10	0.20	0.50	0.50	0.0	0.0	0.40	0.40
	1	1.5	-0.30	-0.30	-0.70	-0.70	1.20	1.30	0.10	0.20	0.80	0.80
	1	2.0	0.0	0.0	-0.70	-0.80	1.30	1.30	-0.30	-0.30	0.40	0.40
	1	2.5	-1.30	-1.30	0.20	0.20	0.50	0.50	1.20	1.30	1.70	1.80
	1	3.0	-2.00	-2.00	-0.60	-0.70	1.50	1.50	2.00	2.00	2.70	2.70
	0	0.0	0.0	0.0	-0.60	-0.60	1.20	1.30	-0.30	-0.40	0.20	0.30
	3	0.5	-0.10	-0.10	-0.60	-0.60	1.20	1.10	-0.20	-0.30	0.40	0.50
	3	1.0	-0.30	-0.30	-1.00	-1.00	1.60	1.70	0.0	0.0	0.70	0.80
	3	1.5	-0.80	-0.80	0.10	0.20	0.70	0.80	0.60	0.60	1.00	1.00
	3	2.0	-1.10	-1.10	-0.50	-0.50	1.50	1.50	1.20	1.30	1.80	1.90
	3	2.5	-1.80	-1.80	-0.30	-0.40	1.50	1.50	2.10	2.20	2.70	2.80
	3	3.0	-2.80	-2.80	0.50	0.60	0.90	1.00	3.40	3.50	3.70	3.80
	0	0.0	-0.40	-0.50	-0.80	-0.80	0.30	0.30	-0.40	-0.40	0.0	0.0
	5	0.5	-0.20	-0.20	-0.80	-0.80	1.00	1.00	-0.10	-0.20	0.30	0.30
	5	1.0	-0.70	-0.80	0.0	0.0	0.10	0.20	0.40	0.50	0.80	0.80
	5	1.5	-1.20	-1.20	0.0	0.10	0.50	0.50	1.20	1.20	1.50	1.50
	5	2.0	-2.00	-2.00	-0.40	-0.50	0.70	0.80	2.00	2.00	2.50	2.50
	5	2.5	-3.00	-3.00	0.10	0.10	0.50	0.50	3.30	3.30	4.60	4.70
	5	3.0	-4.00	-4.00	-0.20	-0.20	0.70	0.80	4.50	4.50	4.70	4.80

TABLE XV (Continued)

REPLICATION I

DOUBLE DISK OPENER

OBS VEL	DEPTH	F2 A	F2 B	F3 A	F3 B	F4 A	F4 B	F5 A	F5 B	F6 A	F6 B
0	0.0	-0.50	-0.50	0.80	0.90	-0.10	-0.10	0.0	0.0	0.20	0.20
1	0.5	-0.40	-0.40	-0.40	-0.40	0.40	0.40	0.0	0.0	0.0	0.0
1	1.0	-0.30	-0.30	-0.10	-0.10	0.70	0.70	0.20	0.20	0.10	0.10
1	1.5	-0.70	-0.70	-0.50	-0.40	1.50	1.50	0.50	0.50	0.50	0.50
1	2.0	-1.00	-1.00	-0.20	-0.30	2.40	2.50	0.90	0.90	1.00	1.00
1	2.5	-1.60	-1.60	-0.90	-0.90	3.60	3.60	1.30	1.30	1.80	1.80
1	3.0	-2.00	-2.00	-1.50	-1.40	5.40	5.40	2.00	2.00	2.80	2.90
0	0.0	0.0	0.0	0.0	0.0	0.40	0.30	0.0	0.0	-0.10	-0.10
3	0.5	-0.20	-0.20	0.0	0.0	0.60	0.60	0.20	0.20	0.10	0.10
3	1.0	-0.30	-0.30	0.10	0.10	1.00	1.00	0.60	0.60	0.50	0.50
3	1.5	-0.60	-0.70	0.30	0.30	1.60	1.60	0.70	0.80	0.70	0.70
3	2.0	-1.20	-1.20	0.40	0.40	2.80	2.80	1.20	1.10	1.50	1.50
3	2.5	-2.50	-2.50	-0.10	-0.10	4.10	4.10	1.60	1.60	2.50	2.40
3	3.0	-2.50	-2.50	-0.70	-0.70	6.10	6.10	2.50	2.50	3.70	3.70
0	0.0	0.0	0.0	0.0	0.0	1.00	1.00	0.0	0.0	0.0	0.0
5	0.5	-0.10	-0.10	0.20	0.30	1.00	1.00	0.20	0.30	0.20	0.20
5	1.0	-0.30	-0.30	0.0	0.0	1.50	1.40	0.30	0.40	0.40	0.40
5	1.5	-0.70	-0.70	0.30	0.20	1.50	1.70	0.60	0.60	0.90	0.90
5	2.0	-1.20	-1.20	0.30	0.30	3.90	4.00	1.30	1.20	1.70	1.70
5	2.5	-1.80	-1.80	0.40	0.40	4.60	4.70	2.10	2.20	2.90	2.70
5	3.0	-2.90	-2.90	-1.00	-1.00	8.00	8.00	2.70	2.60	4.20	4.30

TABLE XV (Continued)

REPLICATION II

RUNNER OPENER

OBS	VEL	DEPTH	F2 A	F2 B	F3 A	F3 B	F4 A	F4 B	F5 A	F5 B	F6 A	F6 B
	0	0.0	0.0	0.0	0.0	0.10	1.00	1.00	0.10	0.10	0.30	0.30
	1	0.5	-0.20	-0.20	0.80	0.80	1.00	1.00	0.40	0.40	0.40	0.30
	1	1.0	-0.60	-0.60	1.00	1.00	1.10	1.10	0.80	0.80	0.60	0.60
	1	1.5	-1.00	-1.00	1.50	1.60	0.60	0.60	1.50	1.50	1.20	1.20
	1	2.0	-1.80	-1.80	2.00	2.00	0.30	0.30	2.50	2.50	2.00	2.00
	1	2.5	-2.80	-2.80	2.50	2.50	0.30	0.30	3.80	3.80	3.10	3.20
	1	3.0	-4.00	-4.00	3.00	3.00	0.30	0.30	5.50	5.50	4.50	4.50
	0	0.0	0.0	0.0	0.10	0.0	0.0	0.0	0.20	0.20	0.20	0.20
	3	0.5	-0.20	-0.20	0.10	0.10	0.30	0.40	0.40	0.50	0.40	0.40
	3	1.0	-0.80	-0.80	0.50	0.50	0.30	0.30	1.00	1.00	0.70	0.70
	3	1.5	-1.40	-1.40	1.00	1.00	0.20	0.20	2.00	2.00	1.50	1.50
	3	2.0	-2.00	-2.00	1.00	1.00	0.90	0.90	3.00	3.00	2.50	2.50
	3	2.5	-2.40	-2.40	2.40	2.40	0.40	0.50	4.90	4.90	3.80	3.80
	3	3.0	-5.00	-5.00	3.10	3.10	0.50	0.50	7.00	7.00	5.60	5.50
	0	0.0	-0.20	-0.30	0.50	0.50	-0.40	-0.40	0.0	0.0	0.0	0.0
	5	0.5	-0.60	-0.60	0.70	0.70	0.20	0.20	0.20	0.20	0.10	0.10
	5	1.0	-0.80	-0.80	0.50	0.50	0.50	0.50	0.60	0.60	0.60	0.60
	5	1.5	-1.40	-1.40	1.50	1.50	0.70	0.70	1.20	1.20	1.50	1.50
	5	2.0	-2.40	-2.40	2.20	2.30	0.70	0.70	3.00	3.00	2.40	2.40
	5	2.5	-3.50	-3.50	2.00	2.00	1.30	1.30	4.50	4.50	3.80	3.80
	5	3.0	-5.00	-5.00	3.90	3.90	0.60	0.60	7.00	7.00	5.40	5.40

TABLE XV (Continued)

REPLICATION II

CHISEL OPENER

OBS	VEL	DEPTH	F2		F3		F4		F5		F6	
			A	B	A	B	A	B	A	B	A	B
	0	0.0	0.0	0.0	0.60	0.60	0.30	0.20	0.0	0.10	0.0	0.0
	1	0.5	-0.20	-0.20	0.20	0.20	0.40	0.40	0.10	0.10	0.20	0.30
	1	1.0	-0.20	-0.30	0.0	0.0	0.60	0.60	0.20	0.20	0.20	0.30
	1	1.5	-0.20	-0.20	0.80	0.80	0.30	0.40	0.60	0.60	0.50	0.60
	1	2.0	-0.50	-0.50	1.00	1.00	0.60	0.60	1.20	1.20	1.00	1.10
	1	2.5	-1.30	-1.30	0.80	0.80	1.00	0.90	1.70	1.80	1.60	1.60
	1	3.0	-2.00	-2.00	1.00	1.00	1.00	1.00	2.40	2.40	2.50	2.50
	0	0.0	0.0	0.0	0.10	0.0	0.10	0.0	0.10	0.10	0.0	0.0
	3	0.5	0.0	0.0	-0.10	-0.10	0.40	0.30	0.20	0.20	0.20	0.20
	3	1.0	-0.30	-0.30	-0.10	-0.20	0.70	0.80	0.30	0.30	0.40	0.50
	3	1.5	-0.70	-0.70	-0.10	-0.10	0.50	0.40	0.90	0.90	0.80	0.80
	3	2.0	-1.30	-1.30	0.0	0.0	0.50	0.50	2.50	2.50	2.50	2.50
	3	2.5	-1.80	-1.80	0.0	0.0	1.20	1.10	2.40	2.40	2.60	2.50
	3	3.0	-2.80	-2.80	-0.10	-0.10	1.20	1.30	3.40	3.50	3.50	3.50
	0	0.0	0.0	0.0	-0.20	-0.20	-0.20	-0.30	0.0	0.10	0.0	0.10
	5	0.5	0.0	0.0	-0.20	-0.20	-0.20	-0.20	0.20	0.30	0.20	0.20
	5	1.0	-0.30	-0.30	0.0	0.0	-0.30	-0.30	0.70	0.70	0.90	0.90
	5	1.5	-1.00	-1.00	0.10	0.10	-0.10	-0.10	1.30	1.30	1.40	1.50
	5	2.0	-1.80	-1.80	0.30	0.30	0.0	0.0	2.30	2.30	2.40	2.40
	5	2.5	-2.50	-2.50	0.40	0.50	0.0	0.0	3.50	3.50	3.50	3.50
	5	3.0	-3.30	-3.30	0.50	0.50	0.10	0.10	4.90	4.90	4.70	4.70

TABLE XV (Continued)

REPLICATION II

DOUBLE DISK OPENER

VEL OBS	DEPTH	F2 A	F2 B	F3 A	F3 B	F4 A	F4 B	F5 A	F5 B	F6 A	F6 B
0	0.0	0.0	0.0	0.0	0.0	1.40	1.40	0.10	0.10	0.40	0.30
1	0.5	-0.20	-0.20	-0.10	-0.10	4.10	4.10	0.20	0.20	-0.30	-0.20
1	1.0	-0.30	-0.30	-0.20	-0.20	5.10	5.10	0.20	0.30	0.0	0.0
1	1.5	-0.40	-0.40	-0.30	-0.30	5.90	6.00	0.40	0.50	0.30	0.20
1	2.0	-1.00	-1.00	-0.40	-0.40	6.50	6.50	0.70	0.80	0.70	0.70
1	2.5	-1.30	-1.30	-0.60	-0.60	6.80	6.80	1.30	1.20	2.30	2.30
1	3.0	-1.80	-1.80	0.20	0.20	6.20	6.20	2.70	2.70	2.50	2.50
0	0.0	-0.60	-0.60	-0.10	-0.10	0.50	0.50	-0.20	-0.30	-0.30	-0.30
3	0.5	-0.80	-0.80	-0.20	-0.20	0.80	0.90	-0.10	-0.10	-0.10	-0.10
3	1.0	-0.80	-0.80	0.50	0.60	0.40	0.30	0.10	0.10	0.0	0.0
3	1.5	-1.00	-1.00	-0.20	-0.30	2.30	2.30	0.30	0.30	0.50	0.50
3	2.0	-1.60	-1.60	-0.30	-0.30	3.20	3.20	0.60	0.60	1.20	1.30
3	2.5	-2.00	-2.00	-0.80	-0.80	6.10	6.00	1.20	1.20	2.10	2.10
3	3.0	-2.80	-2.80	-1.00	-1.00	6.30	6.30	2.00	2.00	3.40	3.40
0	0.0	-0.70	-0.70	-0.50	-0.50	3.50	3.50	-0.10	-0.10	-0.10	-0.10
5	0.5	-0.80	-0.80	-0.40	-0.40	3.50	3.50	0.0	0.0	0.0	0.0
5	1.0	-1.00	-1.00	0.10	0.10	4.50	4.50	0.10	0.20	0.10	0.20
5	1.5	-1.00	-1.00	-0.40	-0.40	6.20	6.20	0.40	0.40	0.70	0.70
5	2.0	-1.70	-1.70	-0.50	-0.50	6.00	6.00	0.80	0.90	1.30	1.30
5	2.5	-2.00	-2.00	-0.50	-0.70	8.80	8.70	1.30	1.30	2.20	2.10
5	3.0	-2.80	-2.80	-0.10	-0.10	9.00	9.00	2.20	2.20	3.10	3.10

TABLE XV (Continued)

REPLICATION III

RUNNER OPENER

OBS	VEL	DEPTH	F2 A	F2 B	F3 A	F3 B	F4 A	F4 B	F5 A	F5 B	F6 A	F6 B
	0	0.0	0.10	0.10	0.10	0.10	-0.20	-0.20	0.0	0.0	-0.40	-0.40
	1	0.5	0.10	0.10	0.80	0.80	-0.10	-0.10	0.50	0.40	-0.10	0.0
	1	1.0	0.10	0.10	0.70	0.80	0.0	0.0	0.50	0.50	0.10	0.10
	1	1.5	-0.10	0.0	1.00	1.00	0.10	0.0	1.00	1.00	0.50	0.50
	1	2.0	-0.50	-0.50	1.70	1.70	0.40	0.50	2.20	2.30	1.50	1.50
	1	2.5	-1.00	-1.10	1.80	1.70	0.50	0.50	3.00	3.00	2.50	2.60
	1	3.0	-2.00	-2.00	1.80	1.90	0.60	0.70	4.30	4.30	4.00	4.00
	0	0.0	0.10	0.10	0.0	0.0	0.0	0.0	0.20	0.20	1.00	0.0
	3	0.5	0.10	0.10	1.00	1.00	-0.50	-0.50	0.50	0.50	0.30	0.30
	3	1.0	-0.20	-0.20	1.20	1.30	-0.40	-0.40	1.00	1.00	0.60	0.70
	3	1.5	-1.00	-1.00	1.80	1.70	-0.20	-0.20	1.90	1.90	1.50	1.50
	3	2.0	-1.80	-1.80	1.70	1.70	0.0	0.0	3.00	3.00	2.50	2.50
	3	2.5	-3.00	-3.00	2.90	2.90	0.0	0.0	4.50	4.50	4.00	4.00
	3	3.0	-4.80	-4.80	3.40	3.30	0.10	0.10	6.60	6.50	6.30	6.30
	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.10	-0.10
	5	0.5	0.0	0.0	1.00	1.00	-0.70	-0.70	0.0	0.0	0.10	0.10
	5	1.0	-1.00	-1.00	1.20	1.10	-0.80	-0.80	5.50	5.50	-0.20	-0.20
	5	1.5	-1.40	-1.40	0.50	0.60	-0.10	-0.10	4.20	4.30	0.50	0.50
	5	2.0	-2.80	-2.80	1.10	1.00	-0.40	-0.50	7.70	7.60	1.30	1.30
	5	2.5	-4.00	-4.00	1.80	1.80	-0.40	-0.40	7.80	7.80	1.30	1.30
	5	3.0	-4.80	-4.80	3.30	3.20	0.0	0.0	5.70	5.70	5.60	5.60

TABLE XV (Continued)

REPLICATION III

CHISEL OPENER

OBS	VEL	DEPTH	F2 A	F2 B	F3 A	F3 B	F4 A	F4 B	F5 A	F5 B	F6 A	F6 B
	0	0.0	-0.10	-0.10	0.20	0.20	-0.70	-0.80	-0.10	-0.10	-0.10	-0.10
	1	0.5	-0.40	-0.20	0.30	0.20	-0.70	-0.80	-0.10	-0.10	-0.10	-0.20
	1	1.0	-0.60	-0.30	0.30	0.20	-0.70	-0.70	0.0	0.0	0.0	0.0
	1	1.5	-0.60	-0.30	0.40	0.40	-0.70	-0.70	0.70	0.70	0.30	0.30
	1	2.0	-1.00	-0.50	0.50	0.50	-0.70	-0.60	0.70	0.70	0.70	0.80
	1	2.5	-1.00	-0.50	0.50	0.60	-0.60	-0.50	1.30	1.30	1.20	1.20
	1	3.0	-1.60	-0.80	0.60	0.70	-0.50	-0.50	2.20	2.20	2.20	2.20
	0	0.0	0.0	0.0	0.10	0.10	0.10	0.0	0.10	0.10	0.0	0.0
	3	0.5	0.0	0.0	0.50	0.50	0.0	0.0	0.50	0.50	0.10	0.20
	3	1.0	0.0	0.0	0.50	0.50	0.10	0.20	1.00	1.00	0.50	0.50
	3	1.5	-0.10	-0.10	0.50	0.50	0.30	0.30	1.40	1.40	0.90	1.00
	3	2.0	-0.80	-0.80	0.60	0.50	0.30	0.30	2.00	2.00	1.60	1.60
	3	2.5	-1.60	-1.60	0.60	0.50	0.50	0.60	3.00	3.00	2.60	2.60
	3	3.0	-2.60	-2.60	0.50	0.50	0.60	0.70	3.70	3.80	3.70	3.70
	0	0.0	0.10	0.0	-0.20	-0.20	-0.10	-0.10	0.10	0.10	0.0	0.0
	5	0.5	0.0	0.0	0.60	0.70	-0.50	-0.60	0.10	0.20	-0.10	-0.10
	5	1.0	-0.10	-0.10	0.50	0.50	-0.40	-0.40	0.60	0.60	0.30	0.30
	5	1.5	-0.80	-0.70	0.60	0.60	-0.40	-0.30	1.00	1.00	0.70	0.80
	5	2.0	-1.50	-1.50	0.80	0.70	-0.30	-0.30	1.90	1.90	1.50	1.50
	5	2.5	-2.00	-2.00	0.90	0.80	-0.30	-0.30	2.50	2.50	2.20	2.30
	5	3.0	-2.80	-2.80	0.80	0.90	-0.30	-0.20	3.50	3.50	4.20	4.30

TABLE XV (Continued)

REPLICATION III

DOUBLE DISK OPENER

VEL OBS	DEPTH	F2 A	F2 B	F3 A	F3 B	F4 A	F4 B	F5 A	F5 B	F6 A	F6 B
0	0.0	-0.20	-0.20	0.0	0.0	0.0	0.0	0.0	0.0	0.10	0.10
1	0.5	0.0	0.0	0.20	0.30	-0.10	-0.10	0.0	0.0	0.0	0.0
1	1.0	-0.80	-0.80	0.50	0.50	0.20	0.20	0.10	0.10	0.10	0.20
1	1.5	-0.40	-0.40	0.60	0.60	1.00	0.90	0.30	0.40	0.70	0.70
1	2.0	-1.20	-1.20	0.50	0.60	2.20	2.20	0.70	0.80	1.30	1.30
1	2.5	-1.40	-1.40	0.0	0.0	3.60	3.60	1.30	1.30	2.40	2.40
1	3.0	-2.20	-2.20	-0.50	-0.50	5.50	5.50	2.00	2.00	3.60	3.60
0	0.0	-0.10	-0.10	0.0	0.0	0.0	0.0	0.0	0.0	0.10	0.10
3	0.5	-0.10	-0.10	0.50	0.60	-0.50	-0.50	0.10	0.20	0.20	0.20
3	1.0	-0.20	-0.20	1.00	1.00	0.90	0.90	0.60	0.60	0.40	0.50
3	1.5	-0.70	-0.60	0.60	0.70	1.30	1.30	0.60	0.70	0.80	0.80
3	2.0	-0.80	-0.80	1.20	1.20	2.50	2.50	1.20	1.30	1.40	1.40
3	2.5	-0.80	-0.80	0.40	0.40	4.00	4.00	2.00	2.00	2.50	2.50
3	3.0	-2.30	-2.30	0.0	0.0	5.20	5.20	2.50	2.50	4.00	4.00
0	0.0	0.20	0.20	-0.40	-0.40	0.10	0.0	0.10	0.10	0.0	0.0
5	0.5	0.10	0.10	1.10	1.10	-0.60	-0.60	0.10	0.10	0.0	0.0
5	1.0	0.0	0.0	0.50	0.50	0.80	0.80	0.20	0.20	0.50	0.50
5	1.5	-1.10	-1.10	0.60	0.60	1.00	0.90	0.30	0.30	0.60	0.60
5	2.0	-1.80	-1.80	1.30	1.30	1.50	1.50	0.80	0.80	1.20	1.30
5	2.5	-2.00	-2.00	1.80	1.80	2.50	2.50	1.20	1.20	3.20	3.30
5	3.0	-2.00	-2.00	2.30	2.40	3.40	3.40	2.00	2.00	3.00	3.00

TABLE XVI

ORIGINAL DATA OF GAUGE DEVICE FORCES RECORDED FROM THE LOAD CELLS

REPLICATION I

GAGE WHEEL

OBS	VEL	DEPTH	F2 A	F2 B	F3 A	F3 B	F4 A	F4 B	F5 A	F5 B	F6 A	F6 B
	0	0.0	1.00	1.00	0.0	0.0	0.0	0.0	0.20	0.20	0.0	0.0
	1	0.2	1.00	1.00	0.50	0.50	0.50	0.40	1.00	1.00	0.90	0.90
	1	0.4	1.00	1.00	1.60	1.70	1.50	1.50	1.00	1.10	1.00	1.00
	1	0.6	1.00	1.00	2.50	2.50	2.40	2.50	1.20	1.30	1.00	1.00
	1	0.8	1.00	1.00	3.50	3.50	3.20	3.10	2.20	2.20	2.00	2.00
	1	1.0	1.00	1.00	4.20	4.20	3.90	3.90	2.90	2.80	2.80	2.80
	1	1.2	1.00	1.00	4.80	4.80	4.80	4.70	3.80	3.90	3.80	3.80
	1	1.4	1.00	1.00	5.40	5.30	5.60	5.70	4.70	4.70	4.70	4.70
	1	1.6	1.00	1.00	6.10	6.10	6.20	6.30	5.60	5.70	5.70	5.70
	1	1.8	0.90	0.90	6.20	6.30	7.20	7.30	6.60	6.60	6.80	6.80
	1	2.0	0.40	0.40	7.20	7.30	7.80	7.80	8.00	7.90	8.00	7.90
	0	0.0	0.10	0.10	0.20	0.20	0.0	0.0	0.0	0.0	0.0	0.0
	3	0.2	0.0	-0.10	0.30	0.30	0.10	0.10	0.30	0.30	0.10	0.20
	3	0.4	-0.20	-0.20	2.00	2.00	1.60	1.60	0.90	0.90	0.60	0.60
	3	0.6	-0.20	-0.20	3.30	3.40	3.10	3.10	1.20	1.20	1.00	1.00
	3	0.8	-0.30	-0.30	4.50	4.40	4.20	4.20	1.80	1.90	1.70	1.70
	3	1.0	-0.90	-0.90	5.30	5.30	5.00	5.00	2.50	2.50	2.30	2.40
	3	1.2	-1.30	-1.30	6.00	6.10	6.00	6.00	3.20	3.20	3.00	3.00
	3	1.4	-1.70	-1.60	7.20	7.10	7.00	7.00	4.00	4.00	4.00	4.00
	3	1.6	-2.00	-2.00	8.00	8.00	7.80	7.90	4.80	4.80	4.90	4.90
	3	1.8	-2.70	-2.70	8.80	8.90	8.50	8.60	4.00	4.00	6.00	6.00
	3	2.0	-3.20	-3.20	9.50	9.50	9.40	9.50	3.30	3.30	6.90	6.90
	0	0.0	0.0	0.0	0.0	0.0	-0.10	-0.10	0.10	0.10	0.0	0.0
	5	0.2	0.0	-0.10	1.00	1.00	0.80	0.80	0.70	0.80	0.20	0.30
	5	0.4	0.0	-0.10	2.00	2.10	1.70	1.80	1.00	1.00	0.70	0.70
	5	0.6	-0.10	-0.10	3.00	3.00	2.90	2.90	1.40	1.40	1.00	1.00
	5	0.8	-0.40	-0.40	4.00	4.00	3.90	3.90	1.90	1.90	1.70	1.70
	5	1.0	-0.80	-0.80	4.90	4.90	5.00	4.90	2.50	2.40	2.20	2.30
	5	1.2	-1.00	-1.00	5.80	5.70	6.00	6.00	3.30	3.30	3.00	3.10
	5	1.4	-1.40	-1.40	6.40	6.50	6.80	6.80	4.00	4.00	4.00	4.00
	5	1.6	-2.00	-2.00	7.40	7.50	7.50	7.50	5.00	5.00	4.80	4.80
	5	1.8	-2.40	-2.40	8.80	8.80	8.70	8.70	6.00	6.00	6.00	6.00
	5	2.0	-3.00	-3.00	9.80	9.80	9.70	9.70	5.20	5.20	7.00	7.00

TABLE XVI (Continued)

REPLICATION I

SLED

OBS	VEL	DEPTH	F2 A	F2 B	F3 A	F3 B	F4 A	F4 B	F5 A	F5 B	F6 A	F6 B
	0	0.0	-0.10	-0.10	0.30	0.30	0.20	0.20	0.20	0.20	0.0	0.0
	1	0.2	-0.10	0.0	0.50	0.50	0.50	0.60	0.80	0.90	0.20	0.30
	1	0.4	-0.40	-0.40	0.60	0.70	2.20	2.20	1.70	1.70	1.20	1.20
	1	0.6	-1.00	-1.00	1.40	1.40	2.70	2.70	2.40	2.50	2.00	2.00
	1	0.8	-1.30	-1.20	2.00	1.90	2.80	2.80	3.00	3.00	2.40	2.50
	1	1.0	-2.00	-2.00	2.50	2.60	3.60	3.60	4.00	4.10	3.50	3.60
	1	1.2	-2.30	-2.20	2.80	2.80	4.00	3.90	5.00	5.00	4.50	4.60
	1	1.4	-2.80	-2.90	3.30	3.30	4.90	4.90	6.00	6.10	5.50	5.50
	1	1.6	-3.20	-3.20	3.00	3.00	6.00	6.00	7.00	7.00	6.80	6.90
	1	1.8	-4.00	-4.00	3.70	3.80	6.50	6.50	8.20	8.20	8.00	7.90
	1	2.0	-4.50	-4.50	5.10	5.10	6.90	7.00	9.50	9.40	9.00	9.10
	0	0.0	-0.10	-0.10	0.50	0.50	0.50	0.50	0.0	0.0	0.0	0.0
	3	0.2	-0.30	-0.30	1.00	1.00	1.00	1.00	1.00	1.00	0.60	0.50
	3	0.4	-0.70	-0.80	1.50	1.50	1.80	1.80	1.70	1.80	1.30	1.30
	3	0.6	-1.00	-1.00	1.80	1.80	1.80	1.80	2.10	2.10	2.00	1.90
	3	0.8	-1.30	-1.30	2.00	2.00	3.00	3.00	3.00	3.00	2.80	2.80
	3	1.0	-1.80	-1.80	2.40	2.40	3.40	3.40	3.90	3.90	3.50	3.50
	3	1.2	-2.00	-2.00	3.00	3.00	3.60	3.70	4.80	4.80	4.40	4.40
	3	1.4	-2.50	-2.50	3.10	3.20	4.80	4.70	5.80	5.80	5.50	5.60
	3	1.6	-3.00	-3.00	3.90	4.00	5.80	5.80	7.00	7.00	6.80	6.90
	3	1.8	-3.50	-3.40	4.80	4.90	6.00	6.00	7.90	7.90	7.80	7.80
	3	2.0	-4.00	-4.00	5.30	5.30	6.50	6.50	9.30	9.30	9.00	9.00
	0	0.0	-0.10	-0.10	0.0	0.0	1.70	1.70	1.00	1.00	1.00	1.00
	5	0.2	0.0	0.0	1.20	1.30	2.00	2.00	1.80	1.80	1.60	1.60
	5	0.4	-0.30	-0.30	1.00	1.00	2.50	2.60	2.00	2.00	2.00	2.00
	5	0.6	-1.00	-1.00	1.40	1.50	3.00	3.00	2.70	2.70	2.60	2.60
	5	0.8	-1.40	-1.40	2.00	2.00	3.00	3.10	3.30	3.30	3.20	3.20
	5	1.0	-1.60	-1.60	2.60	2.70	4.00	4.00	4.70	4.70	4.50	4.50
	5	1.2	-2.00	-2.00	3.00	3.00	4.40	4.30	5.60	5.60	5.40	5.50
	5	1.4	-2.70	-2.80	3.00	3.00	4.80	4.90	6.20	6.30	6.00	6.00
	5	1.6	-3.20	-3.20	4.00	4.00	5.10	5.10	7.20	7.30	7.10	7.10
	5	1.8	-3.40	-3.40	4.30	4.30	6.30	6.40	8.50	8.50	8.50	8.60
	5	2.0	-4.10	-4.20	5.00	5.00	6.50	6.60	9.50	9.50	9.50	9.50

TABLE XVI (Continued)

REPLICATION I

DEPTH BANDS

VEL	DEPTH	F2		F3		F4		F5		F6	
OBS		A	B	A	B	A	B	A	B	A	B
0	0.0	-0.10	-0.10	1.50	1.50	1.40	1.40	1.00	1.00	1.10	1.10
1	0.2	-0.30	-0.30	1.60	1.70	2.00	2.10	1.40	1.50	1.70	1.80
1	0.4	-0.80	-0.80	3.20	3.10	4.30	4.40	2.10	2.20	2.50	2.50
1	0.6	-1.50	-1.50	4.50	4.50	6.70	6.60	3.00	3.10	3.80	3.90
1	0.8	-2.10	-2.10	5.50	5.50	8.80	9.00	4.20	4.30	5.00	5.00
1	1.0	-3.10	-3.10	7.00	7.00	10.30	10.50	5.70	5.70	6.50	6.50
1	1.2	-4.30	-4.30	8.00	8.00	12.10	12.10	7.20	7.20	8.00	8.00
1	1.4	-5.60	-5.60	9.00	9.00	14.00	15.00	8.90	8.90	10.00	10.00
1	1.6	-6.70	-6.70	9.00	9.10	15.50	16.00	10.20	10.20	11.80	11.80
1	1.8	-9.00	-9.00	11.00	11.50	18.00	18.50	13.00	13.30	15.00	15.10
1	2.0	-9.60	-9.60	11.00	11.00	19.80	20.00	14.00	14.00	16.00	16.10
0	0.0	-0.30	-0.30	-0.30	-0.30	3.80	3.80	1.00	1.00	1.50	1.50
3	0.2	-1.00	-1.00	1.60	1.60	7.00	7.00	1.70	1.80	2.70	2.80
3	0.4	-1.50	-1.50	5.00	5.00	10.70	10.80	3.50	3.60	4.50	4.50
3	0.6	-2.20	-2.20	6.00	6.00	11.50	11.50	4.20	4.20	5.00	5.00
3	0.8	-2.50	-2.50	6.10	6.00	13.10	13.20	5.00	5.00	6.00	6.00
3	1.0	-4.40	-4.40	9.00	9.00	16.00	16.10	7.40	7.40	8.50	8.50
3	1.2	-5.00	-5.00	10.10	10.00	16.80	16.60	8.50	8.60	9.50	9.50
3	1.4	-6.00	-6.00	11.00	11.20	19.60	19.80	10.00	10.00	11.50	11.50
3	1.6	-8.40	-8.40	12.70	12.60	22.00	21.80	13.00	13.00	14.50	14.50
3	1.8	-8.80	-8.90	13.80	13.80	22.50	22.50	14.00	14.00	15.60	15.50
3	2.0	-10.70	-10.70	14.20	14.20	22.60	22.70	16.60	16.50	18.00	18.00
0	0.0	-0.80	-0.80	2.00	2.00	1.40	2.40	0.80	0.80	1.40	1.40
5	0.2	-1.00	-1.00	2.30	2.30	2.30	2.30	1.40	1.40	2.30	2.30
5	0.4	-1.30	-1.30	2.80	2.80	3.80	3.80	2.40	2.40	3.50	3.50
5	0.6	-2.10	-2.10	4.10	4.20	5.70	5.80	4.70	4.60	5.20	5.20
5	0.8	-3.50	-3.50	7.20	7.20	7.20	7.20	5.70	5.70	7.00	7.00
5	1.0	-4.50	-4.50	8.50	8.50	9.30	9.30	7.50	7.50	9.50	9.60
5	1.2	-6.20	-6.20	11.00	11.00	10.80	10.90	9.80	9.80	12.00	12.00
5	1.4	-7.30	-7.40	11.80	12.00	12.40	12.40	12.00	12.00	14.50	14.50
5	1.6	-9.30	-9.30	14.00	14.00	14.30	14.30	14.70	14.80	16.20	16.30
5	1.8	-11.60	-11.50	14.80	14.90	16.00	16.00	17.50	17.50	19.70	19.80
5	2.0	-13.50	-13.50	15.00	15.00	18.00	18.00	20.00	20.00	23.00	23.00

TABLE XVI (Continued)

REPLICATION II

GAGE WHEEL

VEL OBS	DEPTH	F2 A	F2 B	F3 A	F3 B	F4 A	F4 B	F5 A	F5 B	F6 A	F6 B
0	0.0	0.20	0.20	0.10	0.10	1.00	1.00	0.0	0.0	0.0	0.0
1	0.2	0.20	0.10	0.70	0.70	1.30	1.30	0.60	0.60	0.20	0.20
1	0.4	0.10	0.10	1.80	1.90	1.80	1.90	1.00	1.00	0.50	0.50
1	0.6	0.10	0.10	2.00	2.00	2.80	2.80	1.20	1.20	0.90	0.90
1	0.8	0.10	0.10	3.30	3.30	3.20	3.30	1.50	1.60	1.10	1.10
1	1.0	0.0	0.0	3.40	3.30	4.30	4.20	2.00	2.00	1.70	1.80
1	1.2	-0.10	-0.10	4.30	4.20	4.70	4.80	2.50	2.40	2.00	2.00
1	1.4	-0.40	-0.40	4.50	4.50	6.00	6.00	2.90	2.80	2.80	2.80
1	1.6	-1.00	-1.00	5.50	5.50	5.80	5.80	3.50	3.50	3.00	3.00
1	1.8	-1.20	-1.20	6.30	6.40	6.80	6.80	4.30	4.30	4.00	4.00
1	2.0	-1.40	-1.40	6.40	6.50	7.80	7.80	4.80	4.90	4.70	4.70
0	0.0	0.50	0.50	0.20	0.30	0.0	0.0	0.40	0.30	0.0	0.0
3	0.2	0.50	0.50	1.00	1.00	1.20	1.30	0.90	1.00	0.30	0.40
3	0.4	0.30	0.40	2.70	2.80	2.30	2.40	1.30	1.30	0.80	0.80
3	0.6	0.30	0.30	3.00	3.00	3.60	3.60	1.40	1.40	1.00	1.00
3	0.8	0.20	0.30	4.00	4.10	4.50	4.50	2.00	2.00	1.70	1.70
3	1.0	0.20	0.10	5.00	5.00	5.50	5.60	4.80	4.90	2.40	2.50
3	1.2	-0.60	-0.60	6.20	6.20	6.80	6.80	3.80	3.90	3.50	3.50
3	1.4	-1.00	-1.00	6.80	7.00	7.30	7.30	4.40	4.50	4.00	4.00
3	1.6	-1.00	-1.00	7.00	7.00	7.30	7.40	4.50	4.50	4.20	4.20
3	1.8	-1.40	-1.40	7.80	7.80	8.20	8.30	5.30	5.20	5.00	5.00
3	2.0	-1.90	-1.90	8.70	8.70	9.20	9.30	6.30	6.30	6.00	6.00
0	0.0	0.20	0.20	0.60	0.60	0.0	0.0	0.40	0.30	0.0	0.0
5	0.2	0.10	0.10	0.70	0.70	0.50	0.50	0.80	0.90	0.30	0.40
5	0.4	0.10	0.10	2.60	2.70	1.00	1.00	1.20	1.20	0.50	0.50
5	0.6	0.10	0.10	3.50	3.60	2.00	2.00	1.70	1.70	1.00	1.00
5	0.8	0.0	0.0	4.70	4.60	2.30	2.20	2.00	2.00	1.40	1.40
5	1.0	0.0	0.0	4.80	4.70	4.80	4.90	2.70	2.80	2.20	2.30
5	1.2	-0.40	-0.40	5.40	5.30	5.00	5.00	3.40	3.50	2.90	3.00
5	1.4	-0.80	-0.80	6.50	6.50	6.20	6.00	4.00	4.00	3.60	3.50
5	1.6	-1.10	-1.10	7.20	7.30	7.00	6.90	4.90	5.00	4.30	4.30
5	1.8	-1.80	-1.80	7.80	7.90	6.50	6.50	5.70	5.80	5.00	5.00
5	2.0	-2.00	-2.00	9.00	9.00	7.00	7.00	6.50	6.60	6.00	6.00

TABLE XVI (Continued)

REPLICATION II

SLED

OBS	VEL	DEPTH	F2 A	F2 B	F3 A	F3 B	F4 A	F4 B	F5 A	F5 B	F6 A	F6 B
	0	0.0	-0.20	-0.20	-0.70	-0.70	0.20	0.20	-0.30	-0.30	-0.20	-0.20
	1	0.2	0.0	-0.20	0.80	0.90	3.70	3.60	0.70	0.70	0.70	0.70
	1	0.4	-0.10	-0.10	1.00	1.00	4.70	4.70	1.10	1.10	1.00	1.00
	1	0.6	-0.70	-0.80	1.20	1.10	5.20	5.20	1.40	1.40	1.40	1.40
	1	0.8	-0.70	-0.90	1.20	1.20	5.20	5.30	2.00	2.00	2.00	2.00
	1	1.0	-1.00	-1.00	1.30	1.30	5.10	5.10	2.30	2.30	2.50	2.50
	1	1.2	-1.30	-1.30	1.70	1.60	5.80	5.90	3.00	3.00	3.00	3.00
	1	1.4	-1.90	-1.90	1.60	1.70	5.80	5.90	3.30	3.30	3.60	3.60
	1	1.6	-1.90	-1.90	2.00	2.00	6.20	6.20	4.30	4.30	4.50	4.50
	1	1.8	-2.70	-2.70	2.20	2.20	6.80	6.90	4.70	4.70	4.90	4.90
	1	2.0	-2.70	-2.70	1.90	1.90	7.10	7.10	5.70	5.70	6.00	6.00
	0	0.0	0.0	0.0	0.0	0.0	-0.20	-0.20	-0.20	-0.20	0.0	0.0
	3	0.2	-0.30	-0.30	1.20	1.20	0.10	0.0	0.30	0.30	0.80	0.80
	3	0.4	-0.70	-0.80	1.80	1.80	0.80	0.80	1.00	1.10	1.40	1.50
	3	0.6	-1.00	-1.00	2.00	2.00	1.00	1.00	2.00	2.00	2.20	2.30
	3	0.8	-1.70	-1.70	2.50	2.50	1.60	1.50	3.00	3.00	3.20	3.20
	3	1.0	-2.00	-2.00	3.00	3.00	2.00	2.00	3.30	3.30	4.30	4.40
	3	1.2	-2.50	-2.50	3.30	3.40	2.80	2.80	4.50	4.50	5.30	5.30
	3	1.4	-3.00	-3.10	4.00	4.00	3.00	3.00	5.20	5.20	6.40	6.50
	3	1.6	-4.00	-4.00	4.40	4.40	3.60	3.50	6.30	6.20	7.80	7.80
	3	1.8	-4.30	-4.30	5.00	5.00	4.00	4.00	6.20	6.20	9.00	9.00
	3	2.0	-5.00	-5.00	5.40	5.40	4.80	4.80	7.00	7.10	10.00	10.00
	0	0.0	0.0	0.0	-0.70	-0.70	-0.30	-0.30	-0.30	-0.80	-0.80	0.0
	5	0.2	-0.20	-0.20	1.30	1.30	-0.20	-0.20	0.0	0.0	0.30	0.30
	5	0.4	-0.30	-0.30	2.00	2.00	0.0	0.0	0.50	0.50	1.00	1.00
	5	0.6	-1.00	-1.00	2.00	2.00	0.40	0.40	0.60	0.60	1.00	1.00
	5	0.8	-1.30	-1.30	2.40	2.40	0.20	0.20	1.20	1.20	1.80	1.70
	5	1.0	-1.70	-1.70	2.60	2.80	0.40	0.40	1.90	2.00	2.20	2.20
	5	1.2	-1.80	-1.80	3.00	3.00	1.00	1.00	2.30	2.30	3.00	3.00
	5	1.4	-2.00	-2.00	3.60	3.80	1.40	1.40	3.10	3.10	3.80	3.80
	5	1.6	-2.30	-2.30	4.60	4.60	2.00	2.00	4.10	4.00	4.50	4.50
	5	1.8	-3.10	-3.10	3.60	3.60	3.20	3.20	4.50	4.50	5.00	5.00
	5	2.0	-3.10	-3.10	3.60	3.60	4.40	4.40	5.20	5.20	6.00	6.00

TABLE XVI (Continued)

REPLICATION II

DEPTH BANDS

OBS	VEL	DEPTH	F2 A	F2 B	F3 A	F3 B	F4 A	F4 B	F5 A	F5 B	F6 A	F6 B
	0	0.0	0.0	0.0	1.00	1.00	-4.00	-4.00	1.00	1.00	1.30	1.30
	1	0.2	0.30	0.30	1.50	1.50	-2.80	-2.80	1.80	1.80	2.20	2.30
	1	0.4	-0.10	-0.10	2.20	2.20	-2.00	-2.00	2.00	2.00	2.80	2.80
	1	0.6	-0.80	-0.80	3.40	3.40	1.40	1.40	2.80	2.90	3.50	3.50
	1	0.8	-1.20	-1.30	4.90	4.80	4.00	4.00	4.00	4.00	5.00	5.00
	1	1.0	-2.00	-2.00	5.00	5.00	6.00	6.00	6.10	5.90	5.00	6.00
	1	1.2	-3.00	-3.00	6.50	6.40	6.20	6.40	6.00	6.00	7.30	7.30
	1	1.4	-4.00	-4.00	6.40	6.50	8.40	8.40	7.30	7.40	8.90	8.90
	1	1.6	-4.90	-5.00	8.50	8.50	11.60	11.40	9.50	9.50	11.00	11.00
	1	1.8	-6.00	-6.00	8.80	8.90	12.40	12.20	10.80	10.80	12.70	12.80
	1	2.0	-7.10	-7.10	9.50	9.50	15.00	15.20	12.60	12.70	14.80	14.80
	0	0.0	0.0	0.0	0.80	0.80	6.00	6.00	1.00	1.00	1.50	1.50
	3	0.2	-0.20	-0.20	1.20	1.40	7.60	7.60	1.50	1.50	2.20	2.20
	3	0.4	-0.40	-0.40	3.50	3.60	9.00	9.00	2.50	2.50	3.50	3.50
	3	0.6	-1.00	-1.00	5.00	5.00	11.60	11.60	4.60	4.60	4.90	4.90
	3	0.8	-1.80	-1.90	6.80	6.80	14.20	14.20	5.00	5.00	6.00	6.00
	3	1.0	-3.00	-3.00	8.20	8.10	15.20	15.20	6.00	6.00	7.70	7.80
	3	1.2	-4.30	-4.30	10.00	10.00	16.60	16.60	8.00	8.00	9.80	9.80
	3	1.4	-5.00	-5.00	10.80	10.80	19.60	19.80	9.80	9.80	11.50	11.50
	3	1.6	-6.70	-6.70	12.50	12.50	22.40	22.20	11.90	12.00	13.80	13.90
	3	1.8	-8.00	-8.00	12.80	12.90	25.20	25.20	13.30	13.30	15.50	15.50
	3	2.0	-9.70	-9.70	13.80	13.70	26.00	26.00	15.50	15.50	17.80	17.80
	0	0.0	-0.50	-0.50	0.70	0.70	5.50	5.50	0.70	0.80	1.00	1.00
	5	0.2	-0.50	-0.60	1.40	1.40	7.60	7.60	1.60	1.60	2.30	2.40
	5	0.4	-0.60	-0.60	2.40	2.40	8.00	8.00	1.80	1.90	2.70	2.70
	5	0.6	-1.30	-1.30	4.40	4.40	12.00	12.00	3.30	3.40	4.10	4.10
	5	0.8	-2.00	-2.00	5.90	5.90	12.80	13.00	4.50	4.50	5.30	5.20
	5	1.0	-3.00	-3.00	7.30	7.30	14.60	14.60	6.00	6.00	7.10	7.10
	5	1.2	-4.00	-4.00	9.00	9.00	17.00	16.80	7.70	7.60	8.80	8.80
	5	1.4	-4.50	-4.50	9.00	9.00	16.00	16.20	8.00	8.00	9.20	9.20
	5	1.6	-6.00	-6.00	10.20	10.20	21.00	20.80	10.50	10.50	12.00	12.00
	5	1.8	-7.90	-7.90	11.60	11.60	22.00	22.00	12.50	12.50	13.80	13.90
	5	2.0	-9.00	-9.00	12.50	12.50	22.80	22.80	14.60	14.50	16.80	16.00

TABLE XVI (Continued)

REPLICATION III

GAGE WHEEL

OBS	VEL	DEPTH	F2		F3		F4		F5		F6	
			A	B	A	B	A	B	A	B	A	B
	0	0.0	0.0	0.0	0.0	0.0	0.10	0.10	0.0	0.0	0.0	0.0
	1	0.2	0.10	0.10	0.40	0.40	0.40	0.50	0.30	0.30	0.30	0.30
	1	0.4	0.10	0.10	2.40	2.40	1.90	1.90	0.50	0.50	0.50	0.50
	1	0.6	0.10	0.10	3.50	3.60	2.90	2.90	1.00	1.00	1.00	1.00
	1	0.8	0.10	0.10	4.10	4.20	3.90	3.90	1.60	1.50	1.50	1.50
	1	1.0	0.0	0.0	5.00	5.00	5.00	5.00	1.90	1.90	2.00	2.00
	1	1.2	-0.10	0.0	5.20	5.30	5.00	5.00	2.00	2.00	2.20	2.30
	1	1.4	-0.70	-0.70	7.40	7.30	6.30	6.30	3.20	3.10	3.40	3.30
	1	1.6	-1.20	-1.20	7.80	7.80	7.70	7.80	4.00	4.00	4.40	4.50
	1	1.8	-1.40	-1.40	8.20	8.20	8.80	8.70	4.80	4.70	5.00	5.00
	1	2.0	-2.00	-2.00	9.10	9.30	9.40	9.50	5.90	5.80	6.20	6.20
	0	0.0	0.10	0.10	0.10	0.10	0.20	0.20	-0.10	-0.10	0.0	0.0
	3	0.2	-0.10	-0.10	0.50	0.50	0.70	0.70	0.20	0.20	0.10	0.20
	3	0.4	0.10	0.10	2.90	2.80	3.00	3.00	0.80	0.80	0.90	0.90
	3	0.6	0.0	0.0	3.90	3.90	4.20	4.20	1.30	1.30	1.50	1.50
	3	0.8	-0.20	-0.20	5.00	5.00	5.30	5.30	2.00	2.00	2.10	2.20
	3	1.0	-0.50	-0.50	5.30	5.40	5.50	5.50	2.10	2.10	2.40	2.40
	3	1.2	-0.80	-0.80	6.20	6.20	6.60	6.60	2.90	2.90	3.00	3.00
	3	1.4	-1.40	-1.40	7.50	7.40	7.80	7.80	4.00	4.00	4.30	4.30
	3	1.6	-1.80	-1.80	7.70	7.80	8.00	8.00	4.70	4.60	4.80	4.80
	3	1.8	-2.20	-2.20	8.70	8.80	9.80	9.90	5.70	5.70	6.20	6.10
	3	2.0	-2.70	-2.80	9.00	9.00	10.20	10.20	6.00	6.00	6.60	6.60
	0	0.0	0.0	0.0	0.40	0.40	-1.00	-1.00	0.0	0.0	0.0	0.0
	5	0.2	-0.20	-0.20	0.80	0.90	-0.40	-0.50	0.30	0.40	0.10	0.20
	5	0.4	-0.20	-0.20	1.40	1.40	0.10	0.10	0.50	0.50	0.50	0.50
	5	0.6	-0.30	-0.30	2.00	2.00	0.50	0.60	0.80	0.70	0.60	0.70
	5	0.8	-0.60	-0.60	2.50	2.50	1.10	1.10	1.00	1.00	1.00	1.00
	5	1.0	-0.80	-0.80	3.20	3.30	1.90	1.90	1.50	1.50	1.50	1.50
	5	1.2	-1.00	-1.00	3.70	3.80	2.50	2.50	2.00	2.00	2.00	2.00
	5	1.4	-1.10	-1.10	4.70	4.80	3.70	3.60	2.50	2.60	2.50	2.60
	5	1.6	-1.30	-1.30	5.00	5.00	3.70	3.80	3.10	3.10	3.10	3.20
	5	1.8	-1.80	-1.80	5.60	5.70	4.40	4.40	3.80	3.80	3.80	3.70
	5	2.0	-2.00	-2.00	6.60	6.70	5.70	5.60	4.70	4.60	4.70	4.60

TABLE XVI (Continued)

REPLICATION III

SLED

OBS	VEL	DEPTH	F2 A	F2 B	F3 A	F3 B	F4 A	F4 B	F5 A	F5 B	F6 A	F6 B
	0	0.0	0.0	0.0	-0.20	-0.20	-0.10	-0.10	0.0	0.0	0.30	0.30
	1	0.2	-0.30	-0.30	1.50	1.50	-0.10	-0.10	0.40	0.40	0.60	0.60
	1	0.4	-0.60	-0.60	1.90	1.90	-0.10	-0.10	1.20	1.20	1.30	1.30
	1	0.6	-0.90	-0.90	2.20	2.20	1.00	1.00	1.60	1.60	1.90	1.90
	1	0.8	-1.10	-1.20	2.50	2.60	2.00	1.90	2.20	2.10	2.50	2.50
	1	1.0	-1.30	-1.30	2.20	2.20	2.00	2.00	3.30	3.30	3.70	3.70
	1	1.2	-1.70	-1.70	3.00	3.00	2.50	2.50	4.20	4.20	4.80	4.80
	1	1.4	-2.20	-2.30	3.00	3.00	3.70	3.70	4.80	4.80	5.10	5.10
	1	1.6	-2.70	-2.70	4.40	4.30	2.70	2.80	5.60	5.70	6.20	6.20
	1	1.8	-3.00	-3.00	4.20	4.20	4.50	4.50	6.70	6.70	7.10	7.10
	1	2.0	-3.00	-3.00	5.00	5.00	4.20	4.20	7.80	7.80	8.20	8.20
	0	0.0	-0.20	-0.20	0.0	0.0	-1.10	-1.10	-0.10	-0.10	0.0	0.0
	3	0.2	-0.60	-0.60	1.70	1.70	0.30	0.30	1.00	1.00	0.40	0.40
	3	0.4	-0.80	-0.80	2.10	2.10	1.00	1.00	1.50	1.50	1.00	1.00
	3	0.6	-1.00	-1.00	2.50	2.50	1.30	1.30	2.10	2.10	1.80	1.90
	3	0.8	-1.30	-1.30	2.80	2.80	1.50	1.50	3.00	3.00	2.80	2.80
	3	1.0	-1.80	-1.80	3.50	3.50	2.50	2.50	3.80	3.80	3.40	3.40
	3	1.2	-2.00	-2.00	3.60	3.60	2.80	2.80	4.50	4.50	4.20	4.30
	3	1.4	-2.50	-2.50	3.90	4.00	2.80	2.80	5.10	5.10	5.00	5.00
	3	1.6	-2.80	-2.80	4.50	4.50	2.90	2.90	6.00	6.00	5.90	5.90
	3	1.8	-3.10	-3.00	5.00	5.00	3.50	3.50	6.90	7.00	6.80	6.80
	3	2.0	-3.30	-3.30	5.60	5.60	4.10	4.10	8.00	8.00	7.80	7.80
	0	0.0	-0.20	-0.20	0.0	0.0	0.10	0.10	0.0	0.0	0.0	0.0
	5	0.2	-0.60	-0.60	2.00	2.00	0.60	0.60	0.50	0.50	0.50	0.50
	5	0.4	-1.00	-1.00	3.00	3.00	1.40	1.40	1.00	1.00	1.00	1.00
	5	0.6	-1.00	-1.00	3.60	3.60	1.60	1.60	1.50	1.50	1.50	1.50
	5	0.8	-1.20	-1.20	4.00	4.00	2.00	2.00	2.10	2.10	2.00	2.00
	5	1.0	-1.40	-1.40	4.40	4.40	2.20	2.20	2.50	2.50	2.50	2.50
	5	1.2	-2.20	-2.20	5.00	5.00	3.00	3.00	4.50	4.50	4.50	4.50
	5	1.4	-2.00	-2.00	4.80	4.80	3.20	3.30	3.90	3.90	3.80	3.80
	5	1.6	-2.50	-2.50	4.60	4.60	3.60	3.60	4.30	4.30	4.20	4.30
	5	1.8	-3.00	-3.00	5.20	5.20	3.60	3.60	5.40	5.50	5.30	5.40
	5	2.0	-3.20	-3.20	5.00	5.00	4.80	4.80	6.00	6.00	6.00	6.00

TABLE XVI (Continued)

REPLICATION III

DEPTH BANDS

VEL	DEPTH	F2		F3		F4		F5		F6	
OBS		A	B	A	B	A	B	A	B	A	B
0	0.0	0.20	0.20	0.0	0.0	0.0	0.0	0.20	0.20	0.10	0.10
1	0.2	0.0	0.0	1.00	1.00	2.70	2.70	0.20	0.20	2.00	2.00
1	0.4	-0.20	-0.20	2.00	2.00	4.80	4.80	0.90	0.90	1.50	1.50
1	0.6	-1.00	-1.00	3.50	3.60	7.00	7.00	1.80	1.80	2.80	2.70
1	0.8	-2.20	-2.20	5.20	5.20	8.30	8.30	3.00	3.00	5.00	5.00
1	1.0	-2.10	-2.10	6.20	6.20	11.00	11.00	4.30	4.30	6.40	6.40
1	1.2	-3.00	-3.00	6.80	6.90	12.30	12.30	5.10	5.00	6.50	6.50
1	1.4	-4.00	-4.00	8.00	8.30	14.50	14.50	7.00	7.00	9.40	9.40
1	1.6	-5.00	-5.00	8.40	8.30	16.30	16.30	8.30	8.30	11.20	11.20
1	1.8	-6.20	-6.20	10.00	10.00	17.80	17.80	10.00	10.00	13.00	13.00
1	2.0	-7.80	-7.70	11.30	11.00	18.50	18.50	12.00	12.00	15.20	15.20
0	0.0	-0.20	-0.20	0.0	0.0	0.0	0.0	0.10	0.10	0.20	0.20
3	0.2	-0.20	-0.20	1.70	1.70	2.30	2.30	1.00	1.00	1.20	1.20
3	0.4	-0.30	-0.30	3.20	3.20	4.60	4.60	1.70	1.70	2.00	2.00
3	0.6	-0.80	-0.80	4.90	4.90	7.40	7.40	2.80	2.80	3.40	3.40
3	0.8	-1.30	-1.30	6.30	6.30	9.60	9.50	4.00	4.00	5.00	5.10
3	1.0	-2.20	-2.20	7.00	7.00	11.40	11.50	5.30	5.30	6.40	6.40
3	1.2	-3.10	-3.10	8.30	8.20	13.50	13.50	6.70	6.70	8.10	8.10
3	1.4	-4.10	-4.10	9.30	9.40	15.50	15.50	8.20	8.20	10.00	10.00
3	1.6	-5.20	-5.20	9.20	9.40	17.00	17.20	9.80	9.80	11.90	12.00
3	1.8	-6.70	-6.70	11.30	11.20	18.50	18.50	11.40	11.40	14.00	14.00
3	2.0	-8.00	-8.00	11.30	11.50	20.20	20.30	13.00	13.00	15.60	15.70
0	0.0	0.0	0.0	-0.80	-0.80	-1.00	-1.00	0.0	0.0	0.0	0.0
5	0.2	0.0	0.0	1.00	1.00	-0.80	-0.80	0.0	0.0	0.20	0.20
5	0.4	-0.80	-0.90	2.10	2.10	0.50	0.50	1.00	1.00	1.00	1.00
5	0.6	-1.10	-1.00	3.50	3.50	2.50	2.50	1.80	1.80	2.00	2.00
5	0.8	-1.90	-1.90	4.50	4.50	6.30	6.20	2.80	2.80	2.90	3.00
5	1.0	-2.50	-2.50	5.80	5.80	5.60	5.80	4.00	4.00	4.30	4.30
5	1.2	-3.10	-3.10	6.80	6.90	7.00	7.10	5.30	5.30	6.50	6.50
5	1.4	-4.40	-4.40	8.00	8.00	8.00	8.00	6.60	6.60	7.00	7.00
5	1.6	-5.00	-5.00	9.00	9.00	9.60	9.70	8.20	8.20	8.70	8.70
5	1.8	-6.60	-6.50	10.00	10.00	11.00	11.00	9.80	9.80	10.20	10.20
5	2.0	-7.50	-7.50	11.20	11.20	12.40	12.40	11.50	11.50	12.30	12.00

TABLE XVII

LENGTH OF MOUNTING BRACKET FOR EACH TOOL*

1. Runner Opener = 18.50 in. to bottom of opener
2. Chisel Opener = 13.60 in. to center of the chisel
3. Double Disk Opener = 16.00 in. to center of the disk
4. Gauge Wheel = 12.25 in. to center of the wheel
5. Slide Gauge Device = 14.00 in. to bottom of the slide
6. Depth Bands Gauge Device = 16.00 in. to center of the bands

*From center line of the horizontal member of the Dynamometer.

VITA

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Doctor of Philosophy

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