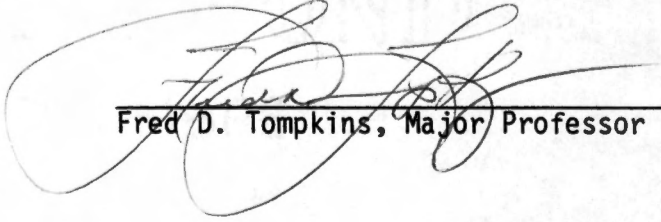
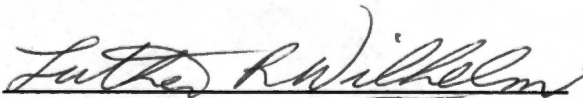
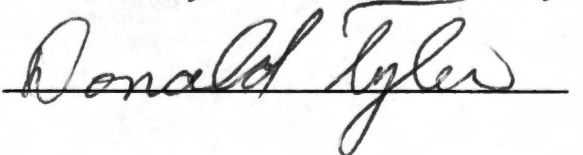


To the Graduate Council:

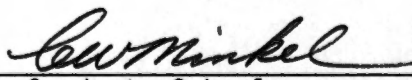
I am submitting herewith a thesis written by Gary Richard Walker entitled "Effect of Tillage and Trafficking on Soil Properties as Indicated by Cone Penetrometer Measurements." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Agricultural Mechanization.


Fred D. Tompkins, Major Professor

We have read this thesis
and recommend its acceptance:

Accepted for the Council:


The Graduate School

EFFECT OF TILLAGE AND TRAFFICKING ON SOIL PROPERTIES
AS INDICATED BY CONE PENETROMETER MEASUREMENTS

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Gary Richard Walker

August 1984

100% COTTON FIBRE
TWIN COTTON BOND

To: My family for their love and support.

ACKNOWLEDGMENTS

The author wishes to express his appreciation to Dr. Fred D. Tompkins who served as major professor. His guidance and patience throughout the program were greatly appreciated.

Appreciation is also extended to Dr. Houston Luttrell, Agricultural Engineering Department Head, for making equipment available for this project.

The guidance and advice of Dr. Luther R. Wilhelm and Dr. Donald D. Tyler, committee members, were greatly appreciated.

Thanks are also extended to Dr. William Sanders for his guidance and help with statistical inferences.

A very special thanks to Robert S. Freeland, graduate student in Agricultural Engineering, for assistance in software programming, data collection, and friendship.

A special thanks to Steve Shoulders, graduate student in Agricultural Engineering, for consulting and friendship.

The author wishes to thank John Wilkerson for his help and advice on this project.

The author wishes to express appreciation and gratitude to Mr. Paul Elliott, Mr. Walker Garner, and Mr. Jimmy Hightower of the Agricultural Engineering Research Shop for their advice and work on the penetrometer throughout this project.

Finally the author wishes to thank the graduate students of the Agricultural Engineering Department who provided advice and support on the project.

ABSTRACT

An evaluation of the capabilities of a microprocessor-based, tractor-mounted soil cone penetrometer for sustained acquisition of reliable, repeatable data was initiated. Based on in-field observations, the penetrometer electronic data handling package and hydraulic system were modified to allow improved machine performance.

The penetrometer was then used to collect soil data in soybean plots subjected to continuous annual applications of six different tillage practices. After data acquisition, analyses of variance were performed to determine depth of tillage influence and to indicate differences in soil strength which could be attributed to particular tillage practices. Effects of trafficking on soil strength properties were also determined using cone index. Results indicated that no-tillage plots continually cropped with soybeans followed by a wheat cover crop tended to have higher cone indices to a depth of 10 inches than any other tillage treatment. Highest cone index values were observed between 4 and 8 inches in depth for the various tillage treatments considered collectively. Wheel-track penetrations tended to have higher cone index values than either row-middle or under-row penetrations to a depth of 10 inches.

TABLE OF CONTENTS

CHAPTER	PAGE
I. INTRODUCTION	1
Background and Statement of Problem.	1
Objectives	2
II. REVIEW OF LITERATURE	4
History of Penetrometers	4
Types of Cone Penetrometers.	5
Uses and Applications of Cone Penetrometers.	8
Factors Affecting Cone Index	9
Soil Penetration Theories.	12
Moisture and Density Effects on Cone Index	18
Measurement of Soil Bulk Density and Moisture Content.	20
III. EXPERIMENTAL EQUIPMENT AND PROCEDURES.	24
Description of Equipment	24
Experimental Design and Nomenclature	35
Description of Plot Area	39
Field Tests and Machine Modifications.	41
Field Data Acquisition	45
Data Analysis.	48
IV. RESULTS AND DISCUSSION	51
Penetrometer Evaluation.	51
Penetrometer Measurements.	51
V. SUMMARY AND CONCLUSIONS.	73
Summary.	73
Conclusions.	75
Recommendations for Further Improvements	76
BIBLIOGRAPHY	77
APPENDICES	86
APPENDIX A	87
APPENDIX B	91
VITA	93

LIST OF TABLES

TABLE	PAGE
1. Summary of Kostritsyn's Theory for Penetration by Cones . . .	16
2. Analysis of Variance Table and Tests of Hypothesis Used in the Experimental Design.	37
3. Analyses of Variance to Determine if Differences in Tillage and Trafficking Affect Cone Index and Work Required to Penetrate the Top 12-Inch Layer of Soil	53
4. Analyses of Variance to Determine if Differences in Tillage and Trafficking Affect Cone Index and Work Required to Penetrate the Top 2-Inch Soil Layer	55
5. Analyses of Variance to Determine if Differences in Tillage and Trafficking Affect Cone Index and Work Required to Penetrate the Soil Layer from 2 to 4 Inches Deep.	57
6. Analyses of Variance to Determine if Differences in Tillage and Trafficking Affect Cone Index and Work Required to Penetrate the Soil Layer from 4 to 6 Inches Deep.	65
7. Analyses of Variance to Determine if Differences in Tillage and Trafficking Affect Cone Index and Work Required to Penetrate the Soil Layer from 6 to 8 Inches Deep.	66
8. Analyses of Variance to Determine if Differences in Tillage and Trafficking Affect Cone Index and Work Required to Penetrate the Soil Layer from 8 to 10 Inches Deep	68
9. Analyses of Variance to Determine if Differences in Tillage and Trafficking Affect Cone Index and Work Required to Penetrate the Soil Layer from 10 to 12 Inches Deep.	70
A1. Cone Index Means for Six Tillage Practices on a Lexington Silt Loam by Depth.	88
A2. Cone Index Means by Traffick Condition at Various Soil Depths for Six Tillage Treatments in a Lexington Silt Loam. .	89
A3. Bulk Density by Traffick Condition at Various Depth for Six Tillage Treatments in a Lexington Silt Loam	90
B1. Moisture Content Values by 2-Inch Depth Increments for Six Tillage Treatments.	92

LIST OF FIGURES

FIGURE	PAGE
1. Relationship of Specific Resistance and Specific Pressure in Kostritsyn's Theory	15
2. Summarization of Greacen and Rankine-Columb Soil Deformation Theory	19
3. Soil Cone Penetrometer Frame and Track Including Carriage Assembly (from Wilkerson, 1983)	25
4. Penetrometer Shaft Bearing Housing.	27
5. Three-Position, Four-Way Direction Control Valve Activated by Either of Two 12-Volt DC Solenoids Used to Control Fluid Flow to the Hydraulic Cylinder.	28
6. Penetrometer Carriage Assembly Consisting of the Hydraulic Cylinder and Trolley Wheel Assembly Which Allows Movement Parallel with the Soil Surface.	29
7. Steel Cable (0.25-Inch) Attached to a Modified 12-Volt Winch for Driving the Penetrometer Carriage Assembly.	30
8. Top and Side Views of Gear-Encoder Mechanism for Depth Position Measurements	32
9. Transducer Used to Measure the Fluid Pressure Acting on the Piston of the Hydraulic Cylinder.	33
10. Troxler 3411-B Moisture Density Gauge Used to Measure Wet Bulk Density.	34
11. Discrete Locations Where Penetrations Were Made Within a Setup in Each Tillage Treatment	38
12. Plot Diagram for the Tillage Treatments Used in Evaluating the Penetrometer.	40
13. Schematic of Simple Pulley System Used to Check Penetrometer Calibration.	44
14. Discrete Location Where Density Measurements Were Taken Between Two Adjacent Setups	47

FIGURE

PAGE

15. Average Cone Indices of Six Tillage Treatments as Functions of Depth of Penetration	56
16. Average Cone Indices of Row-Middle (R), Under-Row (U), and Wheel-Track (W) Penetrations as Functions of Depth Within the Disk Tillage Treatment.	58
17. Average Cone Indices of Row-Middle (R), Under-Row (U), and Wheel-Track (W) Penetrations as Functions of Depth Within the No-Tillage Treatment.	59
18. Average Cone Indices of Row-Middle (R), Under-Row (U), and Wheel-Track (W) Penetrations as Functions of Depth Within the Previous No-Tillage Treatment	60
19. Average Cone Indices of Row-Middle (R), Under-Row (U), and Wheel-Track (W) Penetrations as Functions of Depth Within the Moldboard Plow Tillage Treatment.	61
20. Average Cone Indices of Row-Middle (R), Under-Row (U), and Wheel-Track (W) Penetrations as Functions of Depth Within the Under-Row Subsoil Tillage Treatment	62
21. Average Cone Indices of Row-Middle (R), Under-Row (U), and Wheel-Track (W) Penetrations as Functions of Depth Within the Chisel Plow Tillage Treatment	63

CHAPTER I

INTRODUCTION

I. BACKGROUND AND STATEMENT OF PROBLEM

The quasi-static cone penetrometer has been employed for various types of measurements since its development by the Army Corps of Engineers at Waterways Experiment Station (Army, 1948). Originally the penetrometer was developed for measuring the ability of soil to support traffic, or trafficability, and to predict the tractive capability of off-road military vehicles (Knight and Fretiag, 1962; Wismer and Luth, 1974). The relationship between cone penetration force per unit area of the cone cross section, hereafter referred to as cone index, and draft force was investigated by Johnson et al. (1978), and Gill and Vanden Berg (1968). Research using the penetrometer to relate root penetration and seedling emergence to cone index was done by Bowen (1976).

Basic cone penetrometers are hand-operated instruments with the penetration force being indicated by the deflection of a proving ring. Some major disadvantages of hand-held penetrometers include

- 1) measurements are taken and recorded manually,
- 2) high manual labor requirement, and
- 3) maximum penetration force is limited by the operator's body weight.

Penetration tests were developed as a fast and simple method for obtaining information about in-situ soil strength. A penetration test involves some method of driving the penetrometer shaft into the soil at a constant velocity while recording the depth and corresponding cone index.

Variations of the soil cone penetrometer include a hand-held electronic recording penetrometer, a hand-held penetrometer utilizing a small pin plotter, and a 3-point hitch mounted penetrometer with force transducer and potentiometer interfaced to an X-Y plotter for recording cone index and depth, respectively. With the design and development of a microprocessor-based, tractor-mounted soil cone penetrometer (Wilkerson, 1983), the ability to make a large number of soil penetrometer measurements in relatively short periods of time was acquired. Using the penetrometer developed by Wilkerson et al. (1982) an investigation of the ability of the machine to gather data useful in evaluating in-situ soil conditions was initiated.

II. OBJECTIVES

The objectives of the study were as follows:

1. Evaluate the capability of the experimental machine for sustained acquisition of reliable, repeatable data; and make necessary machine modifications to facilitate operation under field conditions.
2. Based upon penetrometer data collected for plots subjected to various tillage practices, determine:

- a. if penetrometer measurements indicate differences in soil strength which can be attributed to continuous applications of a particular tillage practice,
- b. if penetrometer measurements can identify the depth of influence of various tillage practices, and
- c. if penetrometer measurements can indicate the effects of trafficking on soil strength properties.

CHAPTER II

REVIEW OF LITERATURE

I. HISTORY OF PENETROMETERS

The basic idea of pushing a rod into the ground to measure soil strength was developed by Collin in 1846 (Perumpral, 1983). Collin used a needle-type penetrometer to estimate cohesion properties of various clay soils.

Development of the cone test which utilized a 90-degree cone apex angle for determining penetration resistance as a function of depth was the next recorded advance in the use of penetrometers as soil measurement devices. In 1931, Danish railroads developed a pocket penetrometer for bearing pressure determination (Perumpral, 1983). Then in 1936, P. Barentsen received a patent for a sleeve-type penetrometer, which is better known as the static cone penetrometer. The different array of penetrometers, hand-held or machine type, and the varieties of penetrometer tests have made penetrometer data interpretation difficult. Standardization of both penetrometer design and penetration test procedures were prompted by this difficulty.

ASAE standard S313.1 for cone penetrometers is intended for the following purpose:

1. To provide a common method of expressing general soil mechanical conditions and facilitate the reporting and interpretation of soil data by different research workers.

2. To assist those who work with different soils and soil conditions and who need a measure of soil mechanical properties for comparative purposes.
3. To provide a common system of characterizing soil properties from which it may be possible to develop performance and prediction relationships (ASAE, 1983).

In 1948, the U.S. Army Corps of Engineers developed a cone penetrometer for predicting soil trafficability (Army, 1948). The penetrometer was hand held and had a maximum penetration depth of 30 inches. Modified versions of that penetrometer have been used for various applications where a resistance to a given penetrating force was desired.

II. TYPES OF CONE PENETROMETERS

Penetrometers have been used for various applications since their introduction by Collin in 1846. Reasons for their popularity include the following:

1. measurements are quick, easy, and economical;
2. data analysis is easy; and
3. they provide a good tool for investigating undisturbed sands where sampling is very difficult (Perumpral, 1983).

One disadvantage associated with penetrometer use is that there is no direct observation of sampling.

Sanglerat (1972), European Symposium (1974), and Schmertmann (1975) made reviews of different penetrometers and their uses for

in-situ soil measurement. Based on tip geometry and rate of penetration, penetrometers were classified as static, quasi-static, dynamic, quasi-static and dynamic, screw, and inertial.

The static-type advance method of the penetrometer tip is through incremental constant load. Consequently, tip speed is very slow. The quasi-static penetrometer tip advance method uses hydraulic or mechanical loading, with a rate of penetration not to exceed 72 inches per minute. The dynamic-type penetrometer makes use of the impact of a dropped weight to provide the penetration force. The rate of penetration is variable and proportional to resistance. Quasi-static penetrometers are considered superior to dynamic penetrometers due to data utility (European Symposium, 1974 and Perumpral, 1983). The screw-type penetrometer uses a weighted helical cone and has a variable rate of penetration. An inertial-type penetrometer is dropped or propelled into the soil with the rate of penetration being variable.

The cone penetrometer developed at the Waterways Experiment Station (1948) had a circular cone with an apex angle of 30 degrees and a base area of 0.5 square inches. The cone was mounted on a 36-inch long, 0.38 inch diameter graduated shaft. Indication of penetration resistance was provided by a calibrated proving ring attached to a dial indicator gauge. The soil resistance was indicated in force per unit base area, or cone index.

A penetration test using the penetrometer described involved first setting the dial indicator to zero. While the penetrometer was forced into the ground, dial indicator gauge readings were taken at

1-inch increments of cone penetration. Maintaining a constant penetration tip speed of 72 inches per minute was necessary for obtaining accurate and reliable measurements. Because of time and labor requirements of that system, more elaborate cone penetrometers have been developed to allow greater quantities of data to be gathered. The first of these modified versions were hand-operated recording soil penetrometers (Hendrick, 1969; Prather et al., 1970; Carter, 1967).

Carter (1969) developed an integrating penetrometer to provide average soil strength measurements. This penetrometer used a force transducer, an operational amplifier, and a signal generator for obtaining penetrometer measurements.

Williford et al. (1972) developed a tractor-mounted cone penetrometer which used an X-Y plotter to record cone index as a function of depth. A similar penetrometer was developed by Smith and Duman (1978).

In the late 1970's the use of microprocessors as system controlling apparatuses became widespread. Wilkerson et al. (1982) developed a microprocessor-based, tractor-mounted soil cone penetrometer for soil strength measurements. A double-acting hydraulic cylinder drove the penetrometer shaft, which was mounted on a carriage assembly that moved in a horizontal plane parallel to the ground surface and covered a maximum span of 144 inches. Depth of penetration was measured using an absolute optical shaft encoder attached to a small gear transmission, which had a 28:1 gear ratio (1 revolution of the optical encoder equals 28 inches of linear cone movement). In the

past most depth measurements done electronically used a linear potentiometer. However, due to false signal readings and electromotive forces, Wilkerson chose the optical shaft encoders. Measurement of force needed to penetrate a given soil was obtained with a transducer which measured the pressure of the hydraulic fluid in the cylinder. Knowledge of the cylinder area allowed calculation of the force acting on the cylinder shaft. Knowing the force applied and the base area of the cone, cone index values were analytically obtained.

III. USES AND APPLICATIONS OF CONE PENETROMETERS

Penetrometer tests have been used to measure shear strength of soils (Plantema, 1957; Meyerhof, 1956, 1963; Konder, 1960; Begemann, 1969), determine soil load supporting capacities (Van der Veen, 1957; Bogdanovic, 1961; Lukenbach, 1961; Debeer, 1963), and predict the tractive capabilities of off-road vehicles (Wisner and Luth, 1974). The cone penetrometer has been used to estimate tillage tool performance (Threadgill, 1982), locate soil hardpans (Gerald and Cowley, 1964), measure vehicle traffic compaction of soils (Raghavan and McKyes, 1977), and characterize soil for crop growing ability (Raghavan and McKyes, 1977). Bowen (1976) and Morton and Buchele (1960) used the cone penetrometer to determine soil resistance to root penetration and seedling emergence. The cone penetrometer has been used to measure in-situ soil density of cohesionless soils (Meyerhof, 1956; Rodin, 1961; Leigh and Nixon, 1961; Schultze and Meltzer, 1965) and to assess the settling of structural footings on sands (DeBeer and Martens, 1957; and

Schmertmann, 1970). Morrison (1980) used the cone penetrometer to determine compaction gradients in tobacco bales, while White et al. (1983) used the cone penetrometer to control the density of wood chips stored in bins.

IV. FACTORS AFFECTING CONE INDEX

Experiments at the U.S. Army Waterways Experiment Station have shown that soil properties, probe geometry, and penetration method have an effect on cone index measurements (Knight, 1948; Turnage, 1974; Collins, 1971). Reference to cone index hereafter in this thesis indicates a measure of soil strength and represents the resistance of a given soil to a penetration force. Cone index depends on soil type, cohesion, internal angle of friction, adhesion, soil-metal friction, viscosity, elastic modulus, bulk density, moisture content, probe geometry, and rate of penetration (Ayers and Perumpral, 1982). Collins (1971), Hayes and Ligon (1977), Wells and Tresuwan (1977), and Ayers and Perumpral (1982) developed empirical relations defining cone index as a function of bulk density and moisture content. Ayers and Perumpral (1982) used the following equation form:

$$CI = C_1 D^{C_4} / (C_2 + (MC - C_3)) \quad (1)$$

where,

CI = Cone Index

D = Bulk Density

MC = Moisture Content

C₁, C₂, C₃, C₄ = Soil Constants

The equation was reported valid with R-square values ranging from 0.94 to 0.98 for known laboratory soil mixtures of Zircon sand and Fireclay. However Upadhyaya et al. (1982) reported the equation to be invalid for the prediction of in-field cone index values on Delaware soils. Upadhyaya et al. (1982) acknowledged that controlled field studies should yield better relationships than random field data.

Freitag et al. (1970) and Schafer et al. (1969, 1973) classified the reactions of a probe pushed into the ground as

1. soil shear near the probe tip,
2. soil compression, and
3. soil-metal friction along the surface of the probe.

The resistance of the soil was then influenced by

1. probe geometry,
2. soil physical properties, and
3. rate of probe movement through the soil.

Upadhyaya et al. (1982), using the classifications stated by Freitag et al. (1970), employed dimensional analysis techniques to develop a prediction equation for cone index as a function of bulk density and moisture content. The equation had the following general form:

$$CI/E = BD/PD * MC \quad (2)$$

where

CI = Cone Index

E = Bulk Modulus

BD = Bulk Density

PD = Soil Particle Density

MC = Moisture Content

On the basis of Equation 2, Upadhyaya et al. (1982) conducted two sets of experiments at two distinct moisture contents while bulk density was varied. The second experiment varied the moisture content while density was held constant. Their results showed poor correlation between cone index and moisture content at the 95 percent confidence level. For the second experiment with bulk density held constant while moisture content was varied, poor correlation coefficients lead Upadhyaya et al. to state that no definite trends could be established for cone index while the moisture content was varied.

Hassan (1983) studied the relationship between the cone penetrometer and the soil cutting resistance of Caribbean soils. In his study, Hassan used work done by McKyes and Ali (1977), Hattiaratchi and Reece (1967), and Young and Chen (1980), which stated that soil cutting resistance could be estimated if properties of the soil and the dimensions of the cutting blade were known. According to Houlsby (1982), the soil cutting resistance depends upon soil shear strength. Since penetrometer cone index values are a measure of soil shear strength, a relationship between soil cutting resistance and cone index should exist. Hassan (1983) used empirical equations reported by Whitney et al. (1982) as a basis for estimating soil cohesion and internal angle of friction as functions of moisture content and cone index. Hassan concluded from his studies that soil cohesion and internal angle of friction were strongly related to cone index.

V. SOIL PENETRATION THEORIES

Several theories exist for describing the reaction of soil to penetration. As stated previously, the soil-cone interaction depends on density, moisture content, soil type, and stress history. Taylor (1971) showed that to accurately represent soil penetration action the physical characterization of the soil must be dealt with in separate components, namely

1. soil strength and
2. residual soil forces after displacement.

Taylor used plant root growth to study the soil reaction to penetration. Taylor (1971) concluded from his studies that plant roots displace substantial quantities of soil from their paths of growth. Greacen et al. (1968) and Taylor (1971) concluded that frictional effects near the root tip were negligible and that soil displacement in the vicinity of the enlarging root must be radial as opposed to axial. Therefore, Taylor summarized his findings by saying that it is desirable to separate soil strength effects from soil physical conditions in assessing fundamental soil parameters.

Sanglerat (1979) concluded that when the cone is first inserted in the soil, the penetration force is proportional to depth. As depth increases, the penetration force, at some point, becomes constant. Sanglerat (1979) found that only a few inches of penetration are needed in compressible soils before a constant penetration force is achieved. Two basic approaches for modelling soil penetration include Kostitsyn's

Soil Deformation Theory (Kostritsyn, 1956), and the Rankine-Coulomb Soil Deformation Theory (Greacen et al., 1968).

Kostritsyn (1956) demonstrated that soil penetration was an action of cutting and was defined by the degree of soil confinement in the neighborhood of the cutter. He made use of vertical rather than horizontal cutters in his studies and observed that as the cutter entered the soil a rupture effect occurred near the surface of the soil. This rupture effect caused the soil to move upward. As the depth of penetration increased, the soil movement was parallel to the direction of travel of the cutter. Kostritsyn's studies indicated that, at some depth, penetration force would begin to be linearly related to depth. At some greater depth confinement of the soil caused pure cutting as opposed to other types of soil failures observed at shallower depths. As discussed previously, as a probe or cutter is forced into the soil, failure during penetration occurs in the immediate area of the probe tip. Kostritsyn made no distinction between penetration and cutting. Cutting thus generally implies a localized soil failure near the cutter. Therefore, localized soil failure as opposed to the mode of soil failure is used to describe soil behavior. Kostritsyn developed empirical relationships for cone-type cutters based on his soil deformation theory. He used two components to describe the soil resistance to penetration:

1. specific resistance resistance to deformation and
2. specific pressure of the soil.

From all indications, Kostritsyn limited his experiments to wet, dense soils. This explains why only pure cutting was investigated, and why phenomena ahead of the cone were not considered. Kostritsyn proposed that specific resistance to deformation was made up of two components:

1. stress from elastic deformation, and
2. stress from plastic deformation.

According to Kostritsyn (1956), specific resistance to deformation, denoted as the variable (K_1) in Figure 1, has the greatest effect on the prediction of penetration resistance. Furthermore, specific pressure of the soil, denoted as (K_2), has a small influence on penetration resistance as compared to K_1 . He concluded that K_2 represented the stress on the outer surface of the cone and considered K_2 to represent only elastic deformation. Kostritsyn found K_1 tended to vary as soil displacements reached 0.196 inches from the probe surface, but concluded that for a similar soil the same coefficients, K_1 and K_2 , were usable for soil-machine systems involving both cones and knives.

Kostritsyn's theory is generally regarded as sound, but caution should be used in its application (Gill and Vanden Berg, 1968). Actual stress-strain behavior is probably inaccurately represented because of the indirect manner in which it was studied (Gill and Vanden Berg, 1968). No distribution of stress is admitted to exist on the cutter when a distribution would seem logical (Gill and Vanden Berg, 1968). Therefore, the implied soil behavior has not been determined. A mathematical summary of Kostritsyn's theory on cones is presented in Table 1 (Tollner and Verma, 1983).

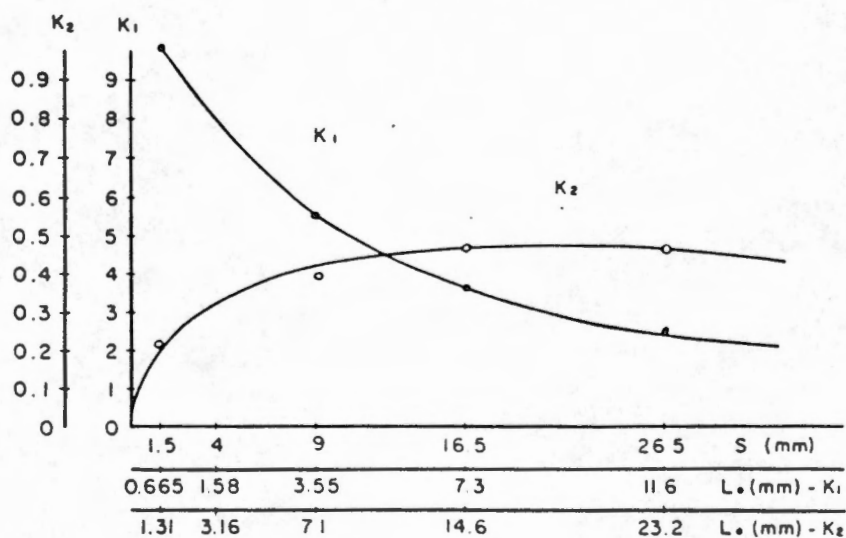
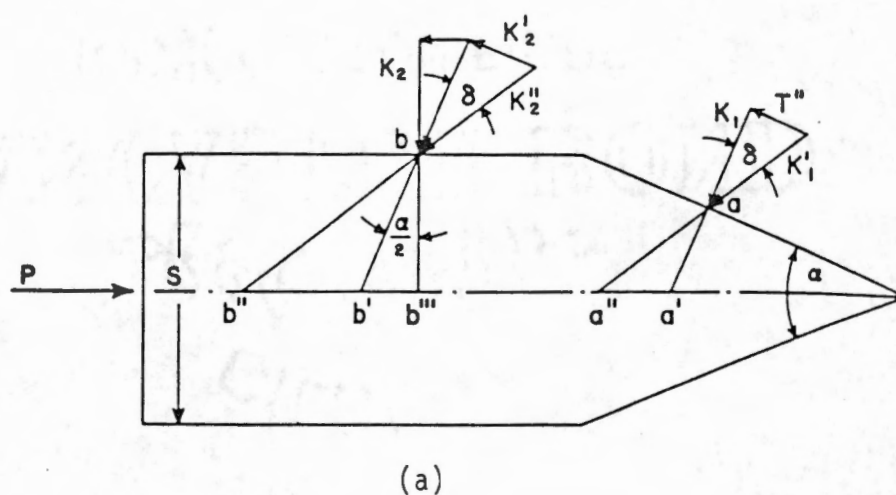


Figure 1. Relationship of specific resistance and specific pressure in Kostritsyn's Theory.
 (a) Definition sketch for Kostritsyn's Theory. (b) Relation for K_1 and K_2 in Kostritsyn's Theory relative to displacement length (copied from Gill and Vanden Berg, 1968).

Table 1. Summary of Kostritsyn's Theory for Penetration by Cones

$$P = \pi r^2 K_1 (1 + \mu \operatorname{ctg}(\alpha/2)) + 2 \mu r K_2 L$$

P = penetration pressure

r = cone base radius

K_1 = coefficient of specific soil deformation stress

μ = coefficient of soil-metal friction

α = cone apex angle

L = length over which elastic forces act

K_2 = specific soil pressure due to soil elasticity

$$L_0 = \frac{2}{3} r \frac{\cos(\frac{\alpha}{2}) + \sin(\frac{\alpha}{2}) \tan(\frac{\alpha}{2} + \delta)}{\cos(\frac{\alpha}{2} + \delta)}$$

L_0 = average length of soil deformation by a cone

$\delta = \tan^{-1}(\mu)$

Kostritsyn found that probe geometry influenced the distribution of stresses near the probe tip. The probe can act like a knife that slides through the soil without having soil-metal friction, or the probe can create a compaction zone where soil sticks to the probe. Therefore, probe geometry is of great importance when investigating soil-cone behavior. Zelenin (1950) showed that a mass of soil may gather on a blunt tip and move as a rigid body with the tool. Friction of this type is known as soil-soil friction, where soil slides against soil. As the probe tip becomes less blunt the force needed for penetration may not be affected, but as the probe tip approaches the geometry of the soil body, soil-soil friction tends to cease. The friction force resisting penetration is reduced to soil-metal friction where the soil starts to slide as the tool enters the ground. Zelenin (1950) reported that cone tip angles in excess of 50 degrees usually yield to soil-soil friction rather than soil-metal friction.

Greacen et al. (1968) adapted the Rankine-Coulomb theory for use in compressible soils based on a compression-load relation with the soil under failure. They modeled the soil reaction to penetration by assuming that the pressure required to cause soil movement was due to stress caused during soil deformation. Stress was directly related to soil-metal friction. They were able to mathematically model the penetration process by using soil-metal friction to estimate the force required to cause soil deformation. Zones of penetration influence were found to exist and were defined as four regions, which were

graphically plotted (Figure 2). Greacen et al. reported that certain parameters, including cohesion and internal angle of friction, must estimate soil conditions as closely as possible if accurate results are to be obtained. Results from their study showed good correlation between actual soil bulk densities and those predicted using the model he developed.

VI. MOISTURE AND DENSITY EFFECTS ON CONE INDEX

Several factors affecting cone index have been investigated since the development of the static cone penetrometer by the Army (1948). A general consensus from these studies is that moisture content and bulk density are two parameters reflecting some measure of soil shear strength. Chesness et al. (1972), Wells and Tresuwan (1977), Mulqueen et al. (1977), Smith (1964), and Knight (1948) all reported that moisture content and bulk density have considerable effects on cone index measurements. Many empirical relationships have been developed between cone index, moisture content, and bulk density.

Ayers and Perumpral (1982) developed an empirical relationship between cone index, moisture content, and bulk density in the form of Equation 1 previously presented. Most studies do not investigate cone indices at low moisture levels, the situation which tends to produce the highest cone index values but not necessarily the highest densities. This observation was made by Knight (1948), Hough (1957), and Smith (1964). Perumpral and Ayers (1981) found that the maximum cone index occurred at the moisture content producing the maximum shear strength

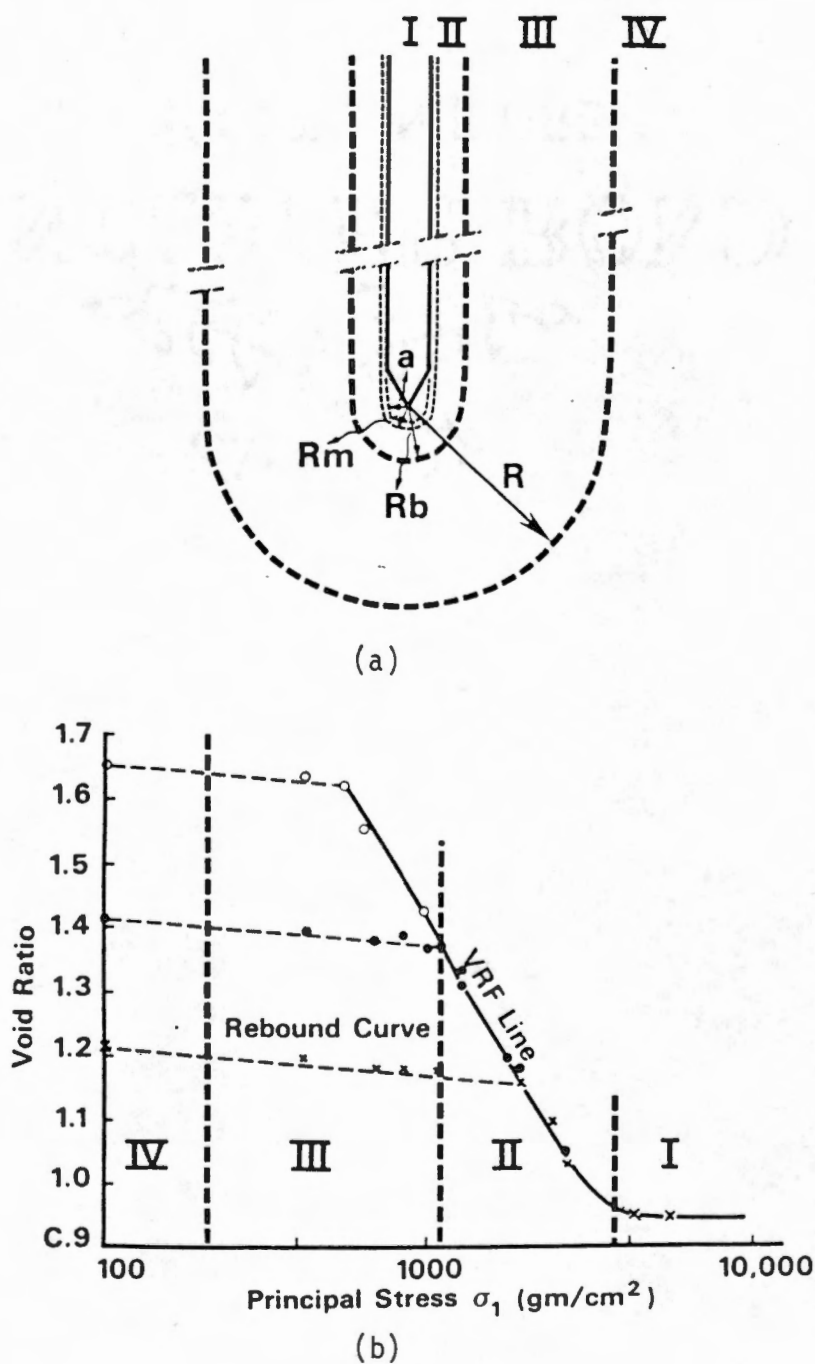


Figure 2. Summarization of Greacen and Rankine-Columb Soil Deformation Theory.

(a) Definition sketch for soil failure regions in the Greacen et al. (1968) Theory. (b) Typical voids ratio versus principal stress relation showing the four soil zones in (a).

using the triaxial compression test. Studies have shown that cone index increases with density and decreases with moisture content. Tests conducted by Turnage (1974) showed that small increases in bulk densities cause large increases in cone index measurements.

Knight (1948) conducted soil penetration tests and concluded that

1. cone index decreased as moisture content increased,
2. cone index is affected mainly by density, which has less effect at high moisture levels than at low moisture levels, and
3. cone index measurements are affected by soil type.

VII. MEASUREMENT OF SOIL BULK DENSITY AND MOISTURE CONTENT

Bulk density is the dry mass of soil per unit volume (Erbach, 1983) and is commonly measured by oven drying to obtain a moisture-free sample and then dividing the sample weight by its volume. Revut and Rode (1969) and Erbach (1983) defined bulk density to be the specific gravity of soil, which is the ratio of weight of a given volume of soil in its natural state to an equal volume of water at 4 degrees Celsius.

Factors which have no apparent effect on bulk density include soil particle arrangement and size distribution of soil pores. However, a decrease in total soil porosity causes an increase in bulk density due to more soil being compressed into a unit volume.

Bulk density as a lone, independent soil measurement is not very useful. However, bulk density in conjunction with moisture content measurements are useful for predicting soil strength, trafficability, plant growth, water infiltration rate, and power required for tillage (Erbach, 1983).

Soil moisture content is defined as the ratio of the weight of water to the weight of solids in a given mass of soil (Means and Parcher, 1963), expressed as a percentage. Soil moisture content affects tillage, planting, plant growth, chemical application, and bulk density changes.

Many different methods of determining soil bulk density are available. Among these methods are scattering and attenuation radiation, cone index, soil core, and excavation. Rozhkov (1970) made use of a single probe device to record bulk density using reflected gamma radiation as a measuring source. Freitag (1971) reported that the volume of soil influencing the gamma count rate was approximately equal to the volume of soil between the probe and source. This type of density measurement considers the average density between layers of soil (Vomocil, 1954).

Gamma radiation is also used in the attenuation method for measurement of density. Van Bavel et al. (1957) reviewed radiation theory and concluded that the inverse square law applied only to primary radiation and that secondary radiation results were not useful in density measurements. Attenuation is usable from depths of 2 inches to 6 feet, with the error in measurement considered to be less than

that with the conventional core method of density measurement (Revut and Rode, 1969; Freitag, 1971; Corey et al., 1971; Bridge and Collis-George, 1973; Gurr and Jakobsen, 1978; Soane and Henshall, 1979; Soane, 1976).

Measurement of soil bulk density using the core method involves employing metal cylinders to encase the soil, thereby reducing the chances of disturbing the in-situ soil condition. Many types of devices have been designed to sample the soil. Types include the soil sampling tube (Veihmeyer, 1929), the core sampler (Kelly and Haise, 1947), the core sampler with trimming ring (Wells, 1959), the modified exploration drill rig (Jensen et al., 1960), a powered sampler (Buchele, 1961), cylindrical rings (Revut and Rode, 1969), heat shrinkable tubes (Mielke, 1973), a hydraulic core sampler (Ginn et al., 1978), and a hydraulic sampler using a jack hammer as the driving mechanism (Foale et al., 1982).

A third method of determining bulk density is known as excavation. A known volume of soil is removed, and its mass is determined to allow calculation of the bulk density (Blake, 1965). Determination of the volume of soil may be difficult due to soil disturbance during excavation. This method is generally considered only applicable to gravelly soils.

Soil moisture content can be measured in a variety of ways. Methods include the tensiometer, neutron scattering, gamma-ray attenuation, electrical resistance, gravimetric, immersion, sulfuric acid, and pycnometer. Reynolds (1970) reported that the error in moisture

content measurement could be reduced if moisture content was based on volume rather than weight basis. De Vires (1969) reported that using gamma-ray attenuation for moisture measurements produced an error of plus or minus 0.6 percent which was due to random emission.

Studies have been conducted to test the capabilities of gamma-ray sources versus conventional methods (Van Bavel et al., 1957); Corey et al., 1971; Lal, 1974; Reginato, 1974; Vigier and Campbell, 1980; Rawitz et al., 1982; Gameda et al., 1983). These studies indicate that soil texture has an effect upon the accuracy of measurements obtained. Since gamma-ray gauges are supplied with factory calibration curves, difficulties often arise when density measurements are made. Gameda (1983) studied two types of gamma-ray devices, a Troxler 3401 Moisture Density Gauge and a Campbell Pacific Nuclear Stragauge. They concluded that both devices give good results. However, the single probe (Troxler) had limited use because of probe length. The dual probe (Campbell Pacific) gave better results than the single probe. However, when compared with conventional methods, the overall correlation coefficients of both probes were found to meet or exceed those of conventional methods for bulk density measurements.

CHAPTER III

EXPERIMENTAL EQUIPMENT AND PROCEDURES

An evaluation of the capabilities of the microprocessor-based, tractor-mounted soil cone penetrometer (Wilkerson, 1983) for sustained acquisition of reliable, repeatable in-field data was begun. Plots within one soil type subjected to continuous annual applications of the same tillage practices with tillage levels ranging from no tillage to conventional plow-disk seedbed preparation were selected for the field tests. Based upon actual in-field needs, modifications allowing improved machine performance and data acquisition were made to the penetrometer.

I. DESCRIPTION OF EQUIPMENT

Penetrometer

Frame and track. The penetrometer is supported on a rigid frame and track which is designed to allow movement across a 144-inch span (Figure 3). A 12-foot tool bar is mounted to the frame facilitating attachment of the penetrometer to a tractor category II, 3-point hitch, and providing a means of transportation and in-field operation (Figure 3).

Penetrometer shaft. The penetrometer shaft is made of 416 stainless steel and machined to the specifications stipulated in ASAE standard S313.1 (ASAE, 1983) for cone penetrometers. The cone has a

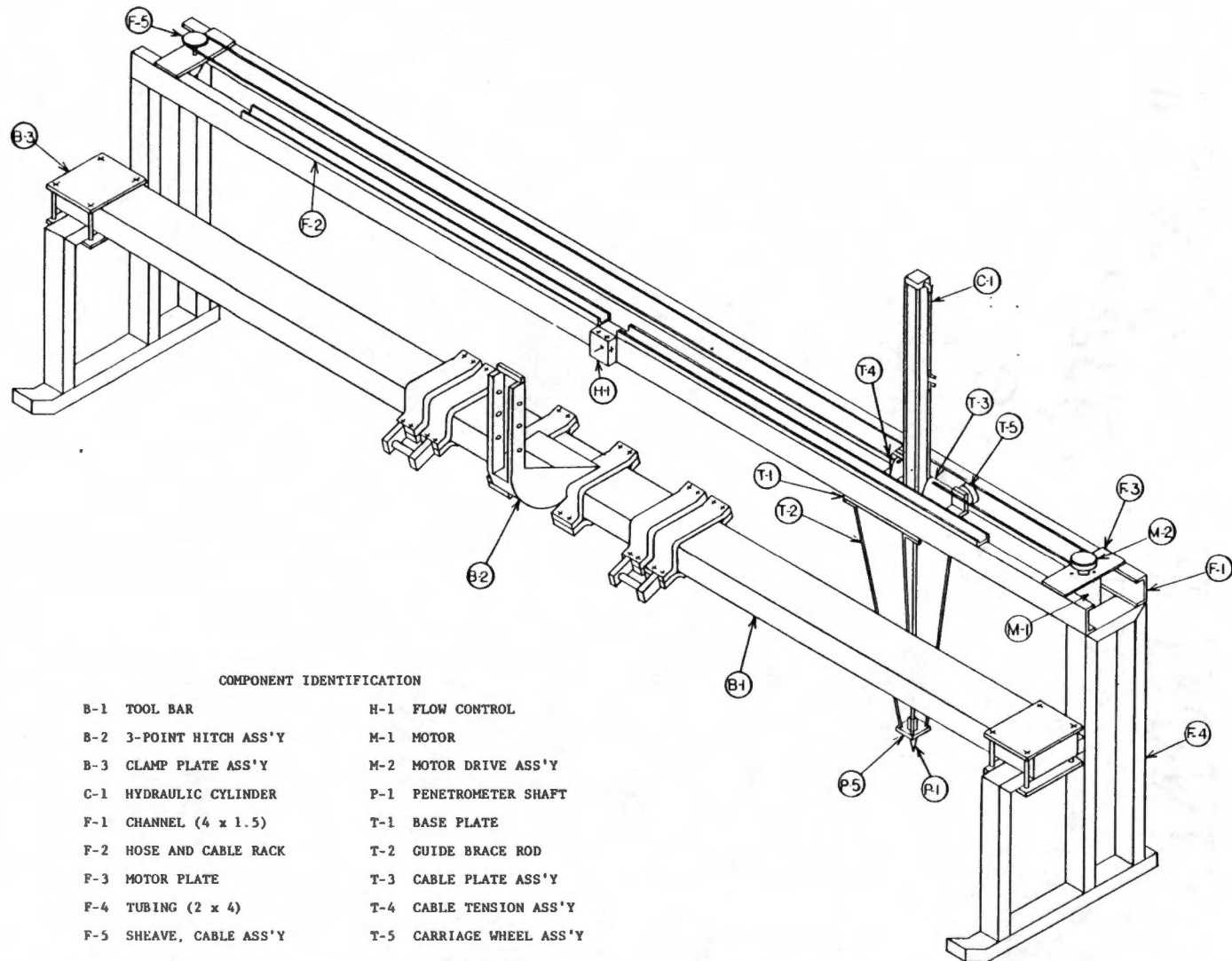


Figure 3. Soil cone penetrometer frame and track including carriage assembly (from Wilkerson, 1983).

30-degree apex angle and can be removed easily if excessive wear is detected. A deviation of 3 percent from cone specifications would result in a 5 percent error of cone index measurements (ASAE, 1983). The penetrometer shaft is coupled to a 2-inch by 28-inch double-acting hydraulic cylinder, which provides the force necessary for soil penetration. The penetrometer shaft is supported by a linear bearing and is kept aligned by four rods which are attached to the bearing housing and the base of the carriage assembly (Figure 4).

Hydraulic power. Hydraulic power to drive the penetrometer shaft is supplied by the tractor, through quick-disconnect couplers, allowing easy machine attachment. A three-position, four-way direction control valve, activated by either of two 12 volt dc solenoids, is used to control fluid flow to the hydraulic cylinder (Figure 5).

Carriage assembly. The penetrometer carriage assembly consists of the hydraulic cylinder mounted on a trolley wheel assembly to allow horizontal travel of the penetrometer back and forth across the track (Figure 6). The trolley assembly is driven by a 0.25-inch steel cable attached to a modified 12-volt winch (Figure 7). An optical shaft encoder is attached to the winch through a small pulley transmission achieving a 10.5:1 ratio. One revolution of the shaft encoder is equivalent to 10.5 feet of horizontal travel for the penetrometer carriage assembly.

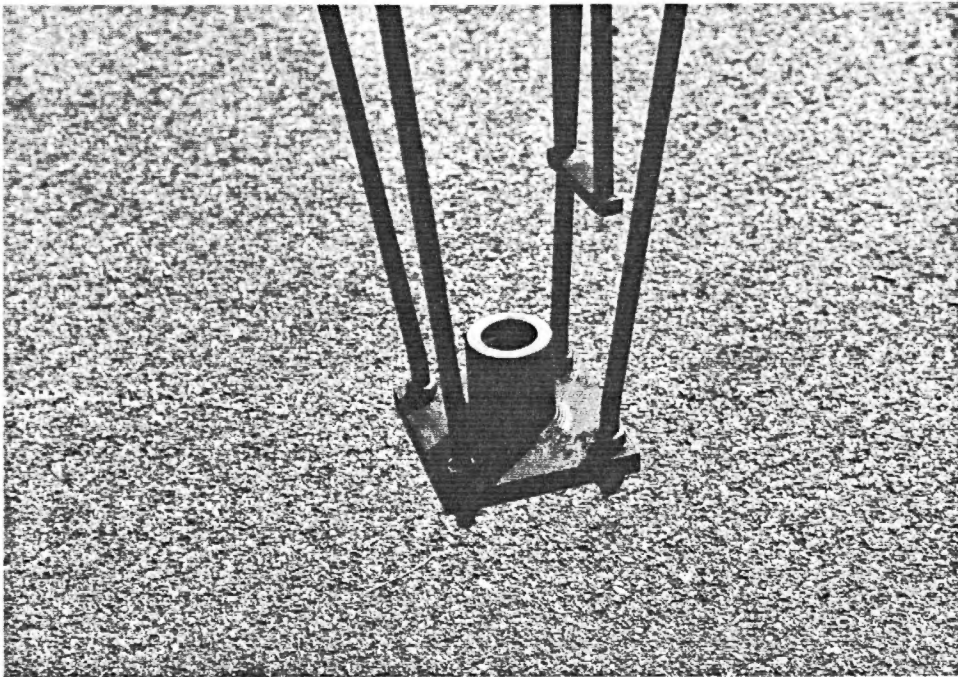


Figure 4. Penetrometer shaft bearing housing.

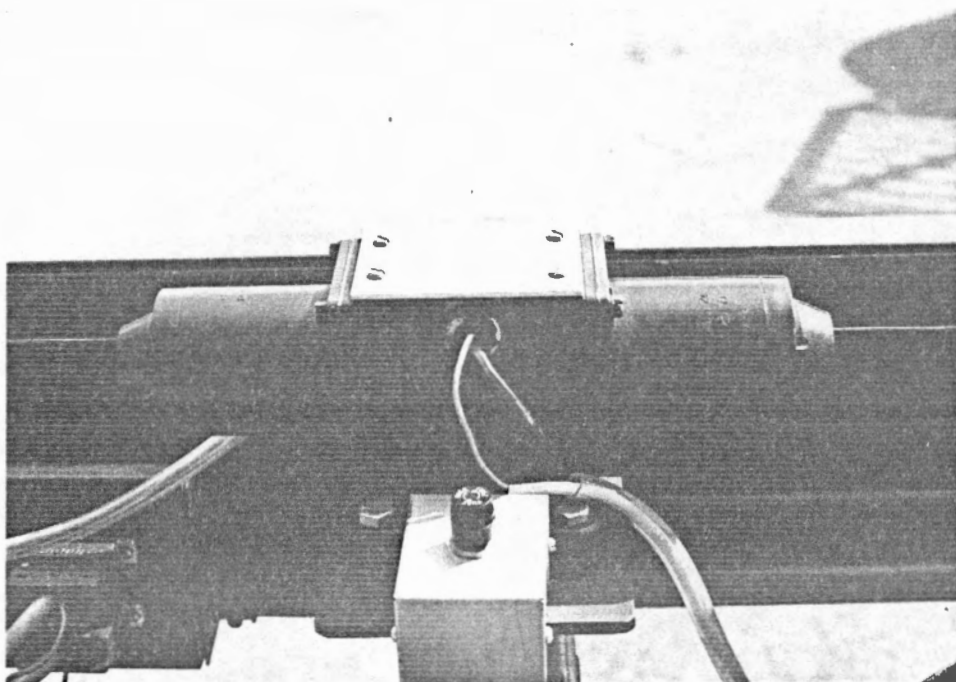


Figure 5. Three-position, four-way direction control valve activated by either of two 12-volt dc solenoids used to control fluid flow to the hydraulic cylinder.

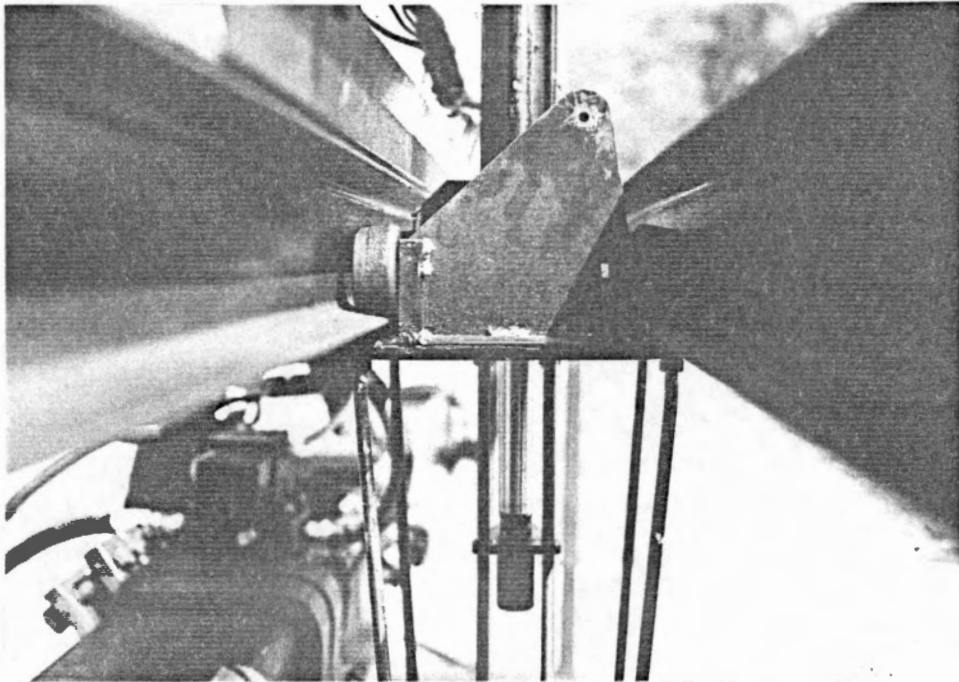


Figure 6. Penetrometer carriage assembly consisting of the hydraulic cylinder and trolley wheel assembly which allows movement parallel with the soil surface.

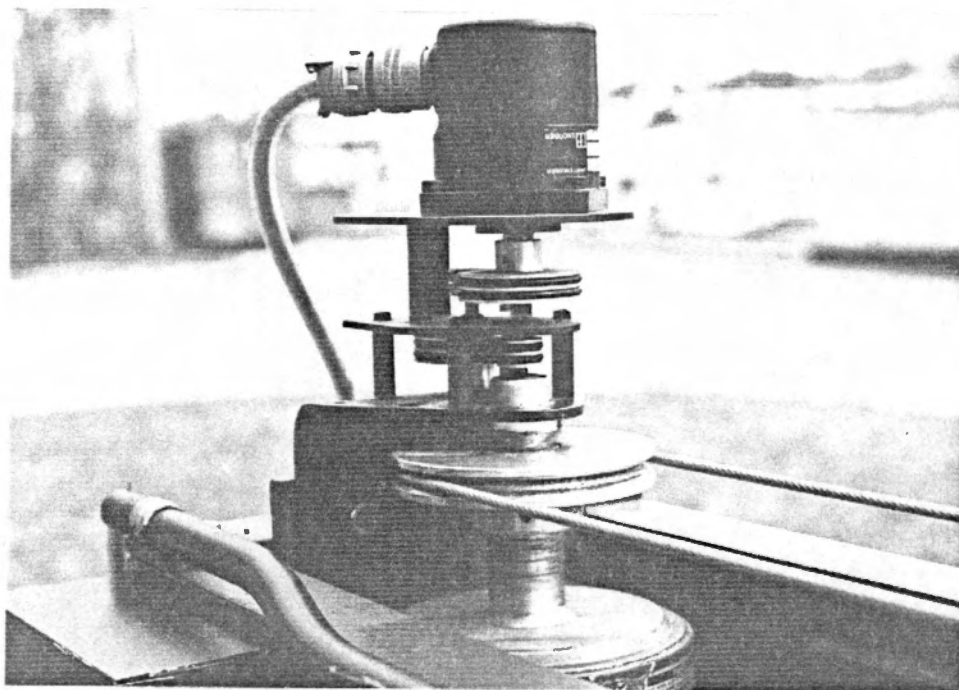


Figure 7. Steel cable (0.25-inch) attached to a modified 12-volt winch for driving the penetrometer carriage assembly.

Depth measurement. Depth of cone penetration into the soil is measured using an optical shaft encoder (Litton Inc. Model 76HP). A rack gear attached to the penetrometer shaft assembly transmits the linear travel of the shaft through a small gear transmission having a 28:1 ratio. When the cylinder extends full stroke, the optical encoder turns one revolution (Figure 8). Thus, one revolution of the shaft encoder is equal to 28 inches of linear cone travel.

Force measurement. Measurement of force on the base of the cone is accomplished indirectly using a pressure transducer (Celesco Model P2805 0-500 psi, Figure 9). Knowing both the pressure of fluid driving the hydraulic cylinder and the area of the hydraulic cylinder piston, the force being applied to the base of the cone can be analytically determined as the product of pressure and area.

Troxler Moisture and Density Gauge

Density measurements were taken with a Troxler 3411-B moisture density gauge (Figure 10). This gauge uses Cesium-137 for the source of radiation. Only wet density measurements were obtained because the gauge was incapable of accurate moisture readings below the soil surface. Calculation of dry basis density by the Troxler moisture density gauge depends upon hydrogen readings taken at the soil surface. These values are uncorrected for offset due to hydrogen held within the soil other than that contained in water. Since data were being taken below the soil surface, gauge moisture content measurements were not used to calculate dry density.

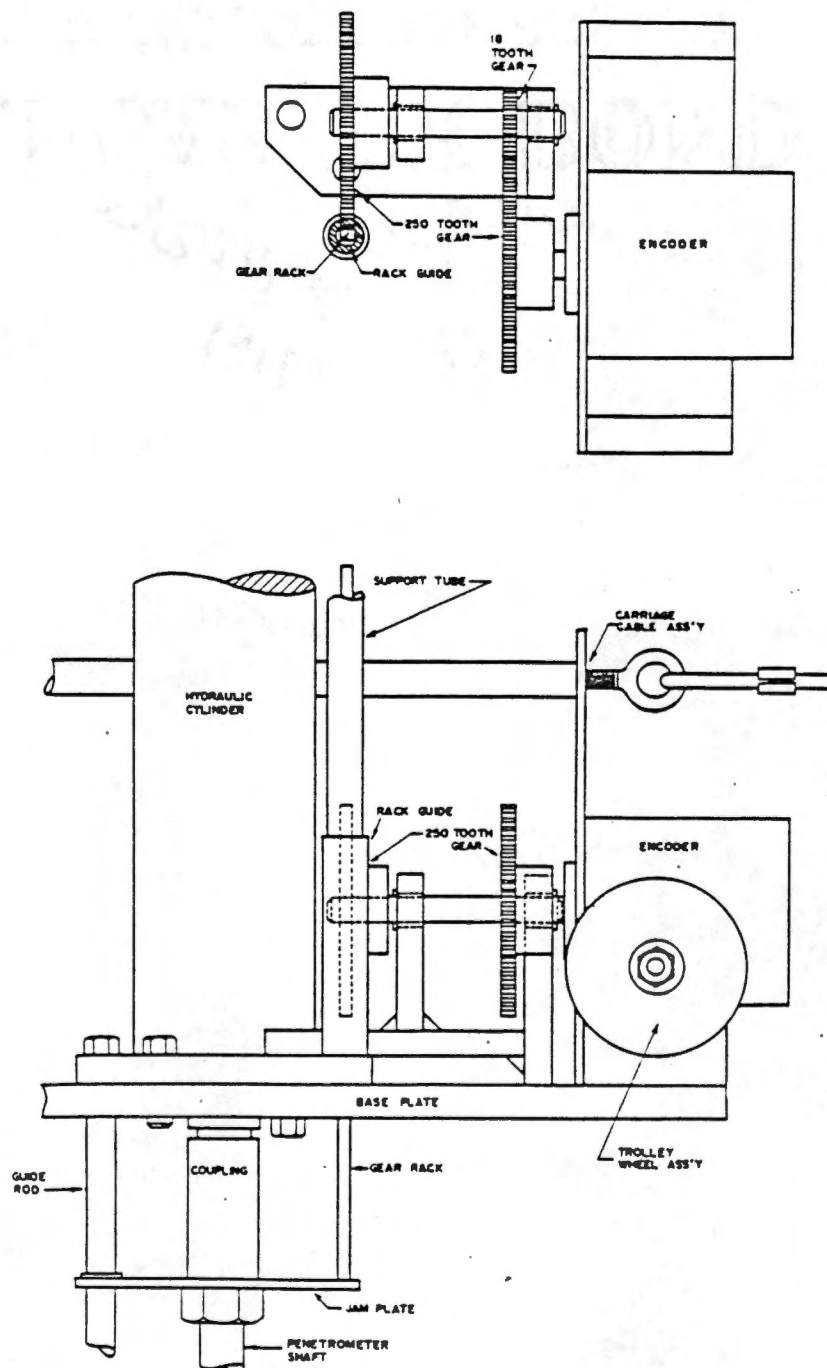


Figure 8. Top and side views of gear-encoder mechanism for depth position measurement. The gear rack, moving with the penetrometer, drives gears to turn the encoder (from Wilkerson, 1983).

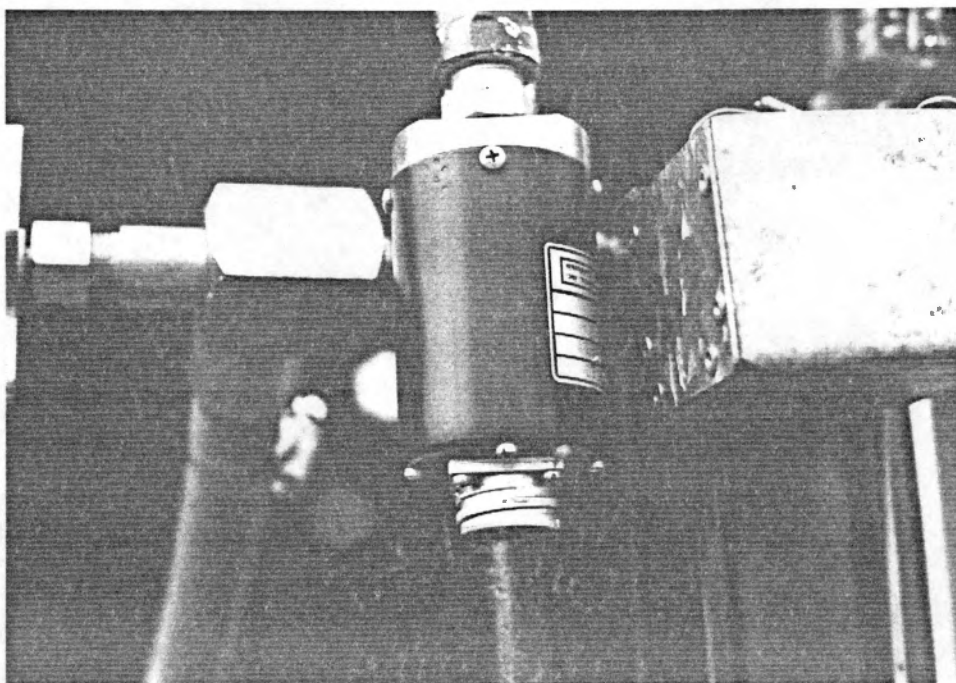


Figure 9. Transducer used to measure the fluid pressure acting on the piston of the hydraulic cylinder.

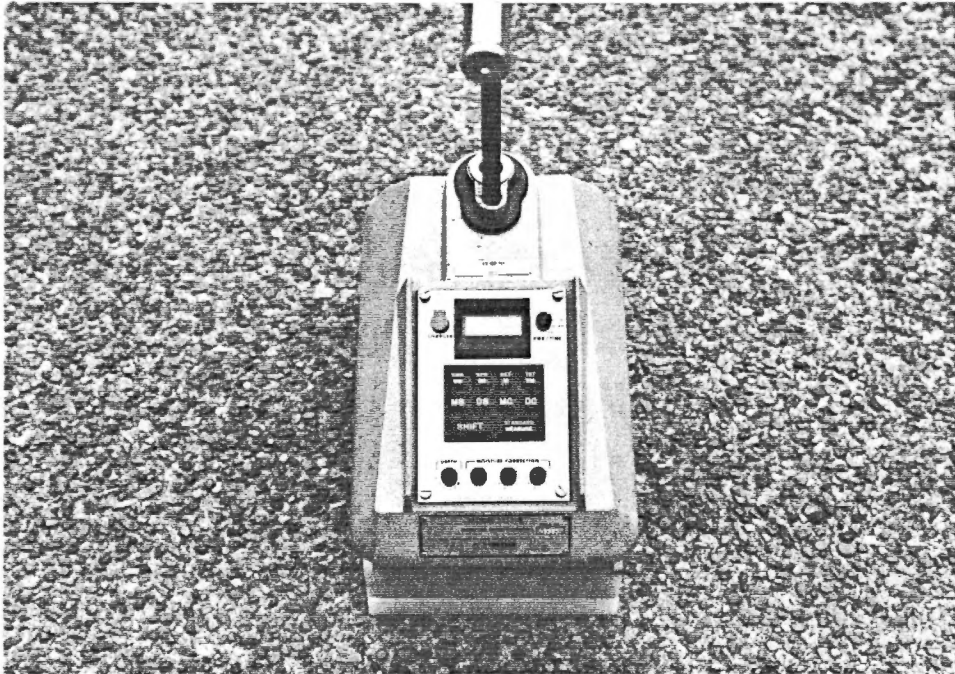


Figure 10. Troxler 3411-B moisture density gauge used to measure wet bulk density.

The factory calibration procedures consist of the accumulation of count rate data on five standard density blocks to insure that a standard deviation of plus or minus 0.15 pounds per cubic foot is attained. According to factory results, drift in the standard radiation count should be less than one standard deviation, which is interpreted as a 0.5 percent error for density measurements over a one work-day period (Troxler Laboratories, 1979).

A standard count was taken at the beginning of every day in which data were collected, and the counts each day were compared with collection counts from the previous day. Counts were found to be plus or minus 10 counts, well within the acceptable tolerance specified by the factory calibration procedure.

II. EXPERIMENTAL DESIGN AND NOMENCLATURE

The following terms are defined and presented for use as guidelines in the description of the experimental design.

- a. setup--a physical positioning of the penetrometer framework perpendicular to the row direction at a distinct site within a particular plot or tillage treatment.
- b. penetration--movement of the penetrometer shaft into the soil.
- c. under-row penetration--measurement taken directly in a planted row or drill within a particular tillage treatment.
- d. row-middle penetration--measurement taken equidistant between two planted rows where there has been no prior vehicular trafficking in a particular tillage treatment.

- f. no-tillage (previously)--land had been planted with soybeans using conventional tillage methods in years prior to the year this experiment was begun.

A nested experimental design employing equal sampling within treatments was used for field data acquisition and analysis (Table 2). Reference to replications hereafter is defined as a treatment repetition considered to be randomly assigned within the entire plot area. When treatment measurements were repeated, the repetition was considered as a replication. Thus, replications were nested within the treatments. This type of analysis reflected the manner in which the data were collected. Six tillage treatments with two replications were considered to determine if penetrometer measurements could detect variations between different tillage practices. Within each tillage treatment plot, four setups of the penetrometer were established at equal intervals across the plot. Each setup consisted of three penetrations to a depth of 12 inches: one row-middle penetration, one under-row penetration, and one wheel-track penetration (Figure 11). Within each tillage treatment, results from two adjacent setups were averaged arithmetically, effectively reducing the number of setups considered in the statistical analysis by two. Error terms used in tests of hypotheses were setups nested within replications and treatments, setups and penetration interactions nested within treatments and replications (see Table 2). Cone index and work done during penetration were the dependent variables with treatments, penetrations, and setups as

Table 2. Analysis of Variance Table and Tests of Hypothesis Used in the Experimental Design

Source of Variation	Degrees of Freedom
Treatments ←	5
Replications (Treatments) ←	6
Penetrations ←	2
Treatments*Penetrations ←	10
Penetrations*Replications (Treatments) ←	12
Setups (Replications Treatments)	12
Setups*Penetrations (Replications Treatments)	24

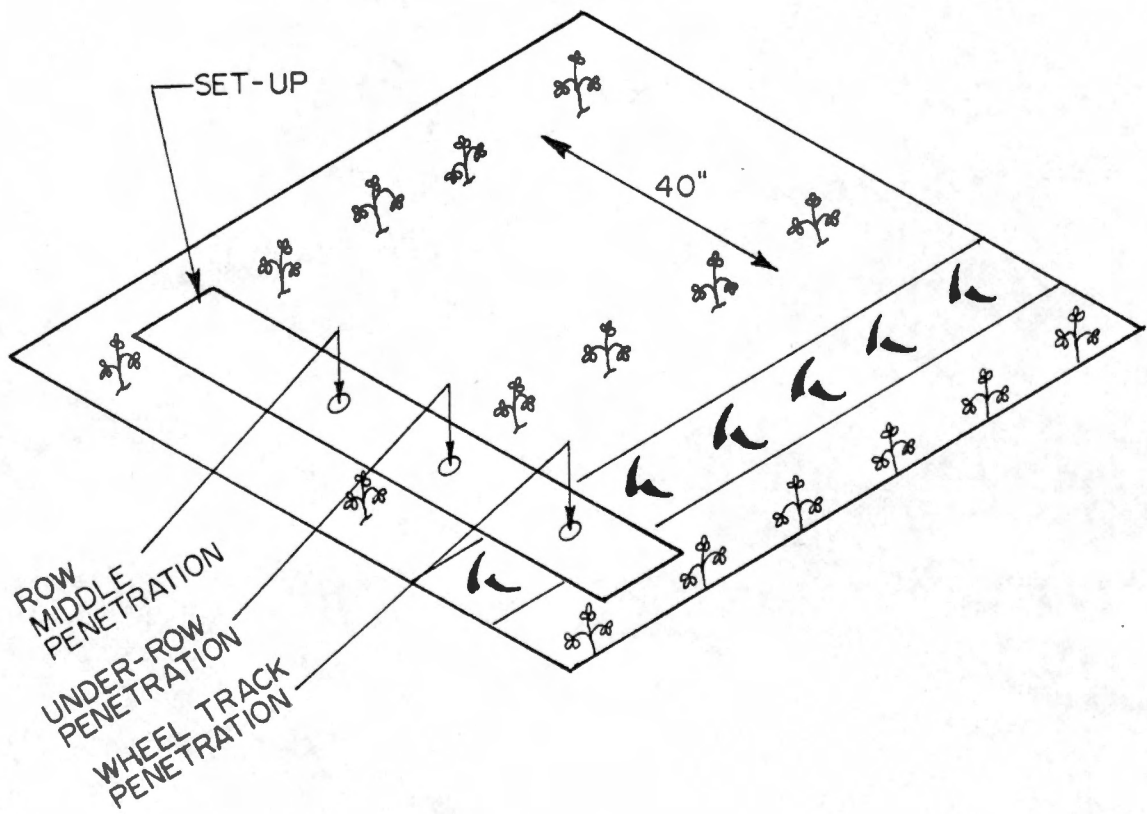


Figure 11. Discrete locations where penetrations were made within a setup in each tillage treatment.

independent variables. A total of 71 degrees of freedom were available for making statistical inferences.

III. DESCRIPTION OF PLOT AREA

Existing soybean plots in a Lexington silt loam soil subjected to continuous applications of a range of the same annual tillage practices were selected for use in evaluating the penetrometer. Tillage treatments were:

1. Disking (4 inches deep) followed by roller harrowing and planting.
2. No-tillage planting in wheat cover crop.
3. No-tillage planting in soybean stubble from the previous crop. Soybean crops in previous years had been produced using conventional seedbed preparation.
4. Moldboard plowing (6 inches deep) followed by disking, roller harrowing, and planting.
5. Under-row subsoiling (18 inches deep) followed by bedding, seed bed conditioning and planting between deep tillage furrows.
6. Chisel plowing (8 inches deep) followed by disking, roller harrowing, and planting.

Tillage treatment plots were each 20 feet in width by 60 feet in length. Twenty-foot alleys were maintained between plots to facilitate machine operation (Figure 12).

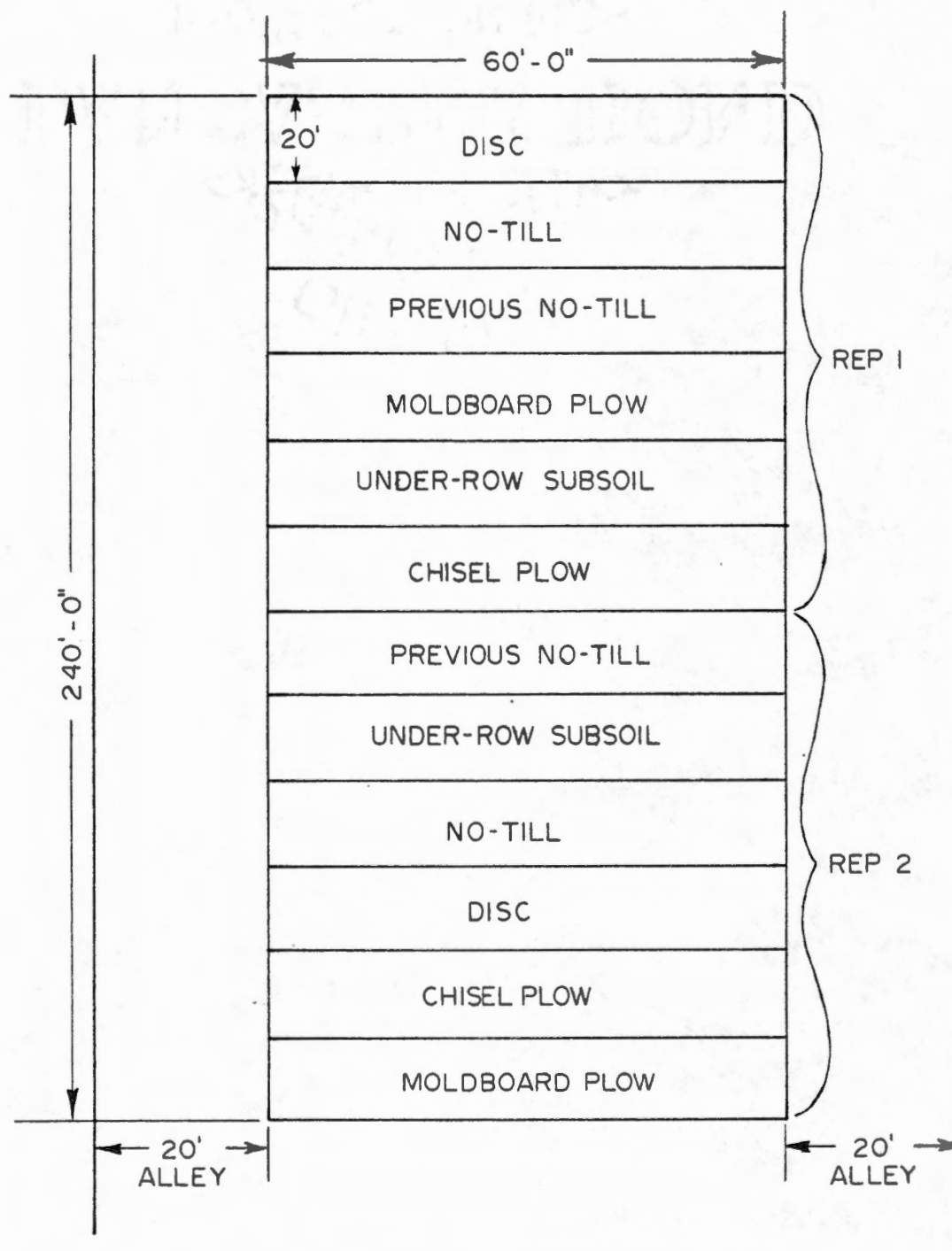


Figure 12. Plot diagram for the tillage treatments used in evaluating the penetrometer.

IV. FIELD TESTS AND MACHINE MODIFICATIONS

The six tillage treatments within one soil type were subjected to penetration tests to evaluate the capability of the penetrometer to acquire reliable, repeatable data. The penetrometer was transported to the West Tennessee Experiment Station at Jackson on June 21, 1983, for initial field tests. Penetrometer data were collected with no apparent machine malfunctions. However, bulk density and moisture content measurements were not obtained due to rain, making the data set incomplete.

Data collection was undertaken again on July 6, 1983. A malfunction of the DC to DC power converter in the control unit halted data acquisition, and the penetrometer was returned to the laboratory for repair and laboratory testing. An initial check of the penetrometer revealed several problems. During long periods of machine operation the control unit produced an excessive amount of heat. The source of the heat was the DC to DC converter mounted on the lower circuit board in the control unit. The heat caused other heat sensitive components in the control unit to malfunction. The DC to DC converter was relocated in the power supply box to alleviate that problem.

Relocation of the DC to DC converter (Analog Devices Model 951) required redesigning and fabrication of another electronic power supply unit. A series of electrical safety devices (fuses and diodes) were incorporated in the new design to protect the DC to DC converter and provide maximum protection for other control unit components.

A problem existed with the length of the communication cables connecting the control unit to the data mass storage device. The excessive length caused noise problems which resulted in malfunction of the tape recorder drive (Digital Equipment Corp. TU-58). Cable lengths were shortened to alleviate the problem.

The TU-58 tape drive unit was found to be very sensitive to dust and heat. A fan-pressurized, dust-free holding container was designed and fabricated to house the tape drive and allow data transfer to and from the unit without exposing the components to the outside environment.

Upon completion of laboratory tests, the penetrometer was returned to the field on July 18, 1983, for another attempt at data acquisition. After several penetrations produced seemingly random, unrepeatable data, the penetrometer was transported back to the laboratory for further diagnostic evaluation.

A flow and pressure test was performed using a hydraulic power supply with regulated flow, because fluctuations were observed in pressure measurement. Test results indicated that the pressure transducer was accurate within plus or minus one percent of actual pressures recorded. Further tests on the pressure transducer, using air as the fluid medium, indicated that the pressure transducer was functioning properly. Closer examination of pressure measurements recorded in the field indicated that high hydraulic fluid flow rates characteristic of the tractor used for driving the machine during the field tests was

the source of the problem. To alleviate that condition an additional flow control was put in series with the existing penetrometer hydraulic circuit to help dampen the pulses of hydraulic fluid discharged from the tractor.

A problem existed with the power Darlington transistors used to provide a constant 5-volt power source for the optical shaft encoders on the penetrometer. Tests indicated that accidental grounding of the transistors had caused them to fail. After transistor replacement, the power system performed properly.

Due to an error in the data transfer software program, the penetrometer would sporadically stop while the cone was still in the ground. To alleviate this problem, the program was changed to allow the control unit to reset and initiate another penetration. A manual override of the control unit was established using a simple two-pole switch, allowing retraction of the penetrometer shaft in case the control unit was unable to complete the routine.

After tests in the laboratory were completed, a calibration routine was developed for the penetrometer using a simple pulley system (Figure 13). A known test weight was positioned to act against the shaft of the hydraulic cylinder used to drive the cone into the soil. A reading of the fluid pressure inside the cylinder was then taken based upon the pressure transducer indication. The force generated by the cylinder was computed as the product of the fluid pressure and the cross-sectional area of the cylinder. Low friction

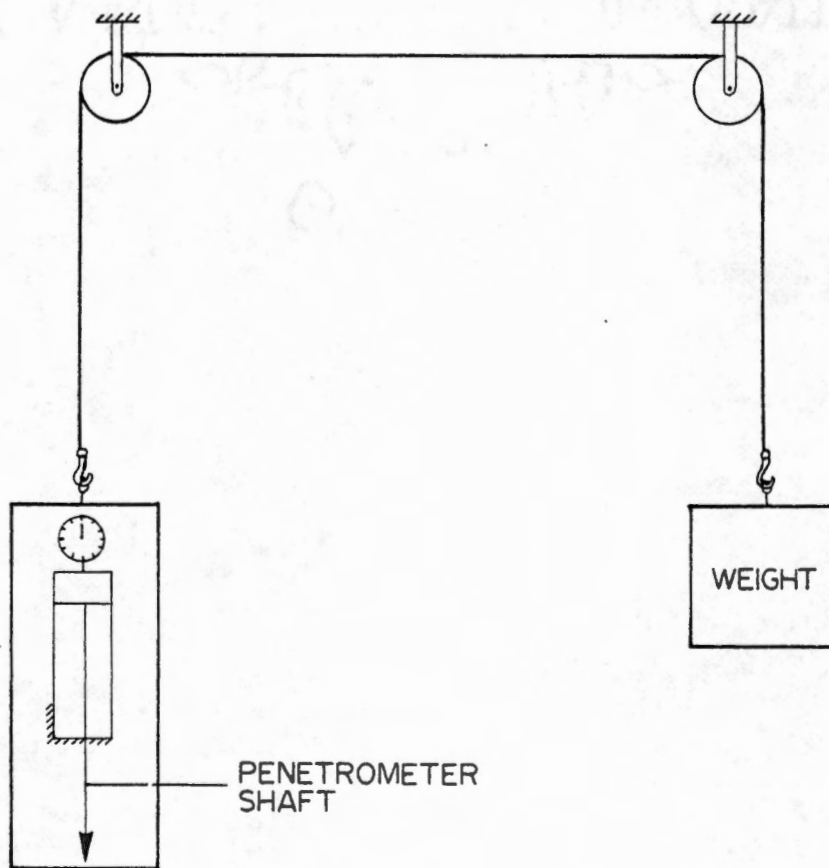


Figure 13. Schematic of simple pulley system used to check penetrometer calibration.

pulleys were used to minimize friction forces which likely introduced error in the calibration routine. Results indicated that force readings from the penetrometer were within 5 percent of any test weight used indicating that the pressure transducer provided an accurate measurement of fluid pressure. Test weights ranged from 25 to 500 pounds. The calibration routine was replicated three times to ensure validity of results.

The penetrometer was returned to the West Tennessee Experiment Station on October 17, 1983, for another attempt at field data acquisition. However, machine malfunctions again interrupted data collection and made it necessary to return the machine to the laboratory for additional work. Problems were frequently observed with power connectors. A change in the type of connector used was made to eliminate this problem. Five-pin DIN connectors with locking collars for secure electrical connections were selected. On October 31, 1983, the penetrometer was transported back to the field for data acquisition.

V. FIELD DATA ACQUISITION

Data collection using the microprocessor-based, tractor-mounted soil cone penetrometer was begun on November 1, 1983. A John Deere 4040 diesel tractor was used to transport the machine and to supply electrical and hydraulic power to the penetrometer drives.

The penetrometer was positioned perpendicular to the row direction with the cone being forced into the ground at discrete locations.

Penetration points were in a row-middle (20 inches from the previous row) which had no previous vehicular trafficking, in a plant row drill, and in a row-middle with a wheel-track (Figure 11, p. 38). The cone was forced into the ground to a depth of 12 inches with an integrated pressure reading taken at every 0.125-inch increment of depth. The penetrations at one machine location mentioned above are referred to in this thesis as a setup, with four such setups being taken in each tillage treatment plot. A total of 96 pressure readings per penetration were recorded on magnetic cassette tape for subsequent analysis.

Two bulk density samples were taken within each tillage treatment. A sample consisted of three bulk density measurements between two setups at points aligned with the discrete penetrations previously mentioned (Figure 14). Bulk density measurements with the Troxler density gauge at the discrete locations were taken at two-inch depth increments down to a depth of 8 inches. Bulk density dry basis, for all treatments were about 70 to 85 pounds per cubic foot for the entire 12 inches of soil (Table A3).

Soil moisture content was determined by using the core sampler method. Two moisture content samples were taken in each tillage treatment. A sample consisted of six sub-samples of 500 grams or more, each taken at two-inch increments down to a depth of 12 inches. Discrete sampling sites were located between two adjacent setups within a particular tillage treatment plot. The measurements described above were replicated twice for each of the six tillage treatments. Moisture

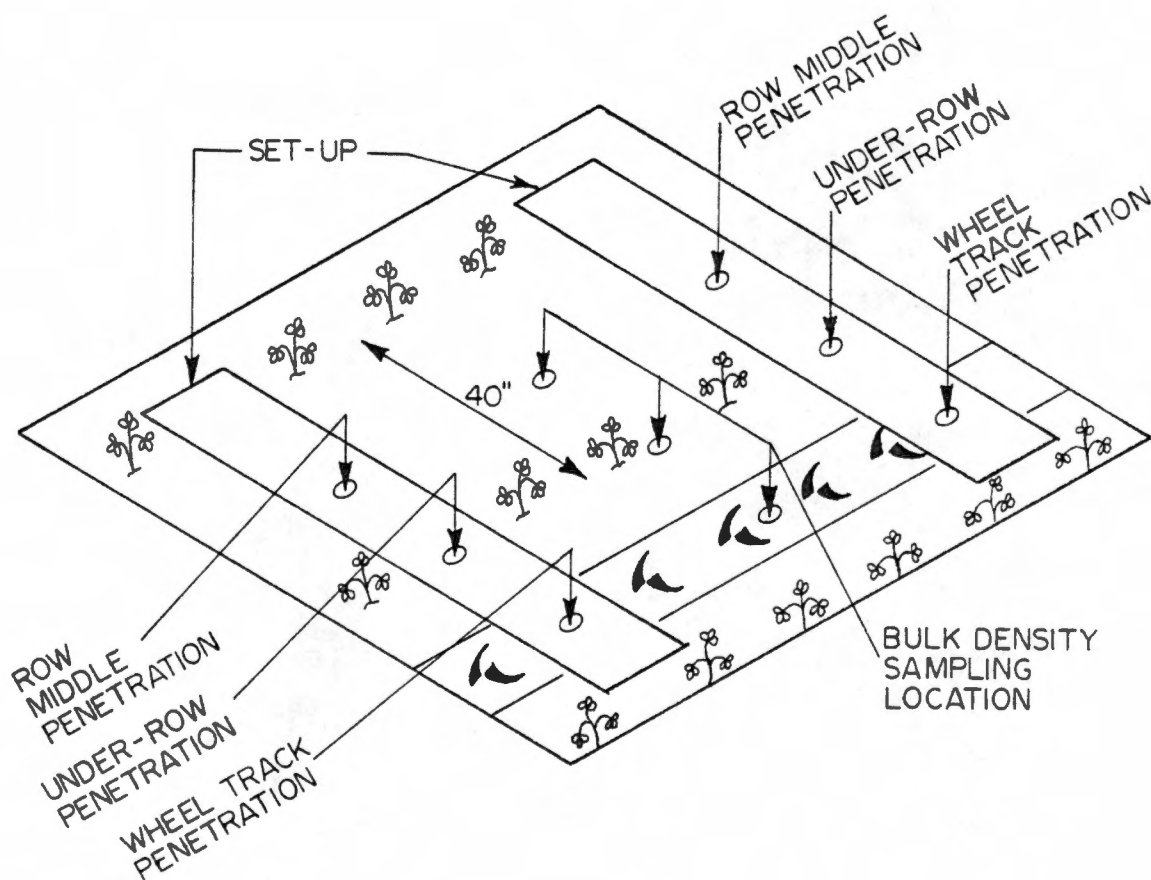


Figure 14. Discrete location where density measurements were taken between two adjacent setups.

content measurements ranged from 14 to 21 percent dry basis among the treatments and tended to increase with depth (Table B1).

VI. DATA ANALYSIS

Data were transferred from magnetic cassette tape to a DEC RL02 hard disk storage unit (Digital Equipment Corp.) for processing. Since the data were stored as octal values on the magnetic cassette tape, a software program was written to convert the data to decimal equivalents.

Since the excessive hydraulic fluid flow from the tractor created minor fluctuations in the pressure measurements indicated during a penetration, a smoothing function was used to remove these small spikes from the pressure readings. The smoothing function used was the following arithmetic expression:

$$X_n = \frac{X_{n-4} + X_{n-3} + \dots + X_{n+3} + X_{n+4}}{9} \quad (3)$$

where

X_n = a single discrete data value obtained during a penetration. Four data points lying on each side of a discrete data point were summed and divided by nine to obtain an average discrete data value.

Since cone index is the widely-accepted standard means of reporting penetrometer readings, converting pressure readings taken within the hydraulic cylinder into force acting on the base of the cone was necessary to obtain cone index values. Cone index was computed using the following equation:

$$\text{Cone Index} = P_c \quad (4)$$

where

P = discrete fluid pressure measurement value taken within the hydraulic cylinder, lb/in².

$c = 6.283$, constant appropriate for a 2-inch bore diameter hydraulic cylinder, in².

Two types of dependent variables were used to analyze the data. They were cone index and the amount of work done during a penetration. Cone index values were averaged over two-inch depth increments to obtain single discrete values representing soil resistance to penetration at the various depths. Work values were obtained by integrating pressure measurements over two-inch depth increments using Simpson's Rule of Integration (Kreyszig, 1972) to approximate the area under the pressure curve. This area represented the quantity of work done through two inches of soil penetration and is described mathematically by the following expression:

$$f(x)dx = \frac{h}{3}(y_0 + 4y_1 + 2y_2 + \dots + 2y_{2n-2} + 4y_{2n-1} + y_{2n}) \quad (5)$$

where

h = increment of depth between data values (inches)

y = discrete data value.

After obtaining cone index and work values by two-inch increments, adjacent setups within each tillage treatment were combined by arithmetic averaging to obtain a data set for the treatment. All

penetrations within each tillage treatment were graphically plotted, and the point at which the cone entered the soil for each penetration within a setup was found.

Pressure measurements recorded for each penetration prior to entry of the cone into the soil were averaged to obtain a correction factor which was subtracted from each data value recorded in the penetration. All penetrations were corrected in the same manner. This correction factor represents the force needed to overcome the frictional resistance to penetrometer shaft motion before soil contact was made.

A software program was written to arrange the information into data sets which were compatible with the Statistical Analysis System (SAS Institute, 1982). The data were subjected to analyses of variance using SAS to determine if penetrometer measurements indicate differences in soil strengths, to identify depth of tillage influence, and to indicate effects of vehicular trafficking. Two analyses of variances were performed on the data: 1) a general analysis including all the data considered collectively, and 2) analyses by 2-inch depth increments for each tillage treatment.

Means of cone index and work values were found at each two-inch depth of penetration for a particular tillage treatment to find differences among the six tillage treatments. A multiple regression analysis was performed to find if an empirical relationship existed between cone index, soil bulk density, and soil moisture content.

CHAPTER IV

RESULTS AND DISCUSSION

I. PENETROMETER EVALUATION

The microprocessor-based, tractor-mounted soil cone penetrometer was used to acquire data in plots subjected to continuous annual applications of the same tillage practices. After several attempts to acquire data in the field failed, major machine modifications were made as discussed in the previous chapter. After modifications were completed, the penetrometer performed satisfactorily and allowed acquisition of repeatable data which were considered reliable.

Problems with pressure surges are still present when excessive flow rates of hydraulic fluid are used in powering the penetrometer. Although actual data acquisition is not hampered, spikes in recorded pressure values do exist. Nonetheless, the data still follow the expected trend. Observations made during data acquisition indicate that the highest pressure readings consistently occurred at about the 6-inch depth across all plots. From these observations and actual data values recorded, the penetrometer appears to be a reliable mechanism for obtaining in-situ soil measurements.

II. PENETROMETER MEASUREMENTS

Analyses of variance were performed on two groupings of the data obtained: 1) the entire 12-inches of penetration considered as

one layer, and 2) 2-inch soil depth increments to a depth of 12 inches. Work performed during penetration and cone index were used as dependent variables in both analyses.

Analyses of Variance for Full Depth of Penetration

Tillage treatment did not significantly ($\alpha=0.10$) affect either cone index or work done in penetrating the soil to a depth of 12 inches (Table 3). Replications were significantly ($\alpha=0.10$) different when work was used as the dependent variable (Table 3). When cone index was used as the dependent variable, no significant difference between replications was indicated (Table 3). The cone index used was the average of several discrete values each representing two inches of penetration.

Penetrations were found significantly ($\alpha=0.10$) different indicating differences among row-middle, under-the-row, and wheel-track penetrations within a treatment (Table 3). This was true using both work and cone index as the dependent variables. Interactions between penetrations nested within treatments and replications were significant ($\alpha=0.10$) indicating penetration pattern of results varied among treatments. This initial overall analysis was used to give an indication of the magnitude of variation among treatments and to suggest if penetrations varied within treatments.

Analyses of Variance by 2-Inch Depth Increments

Analyses of variance for the top 2 inches of soil. Both treatments and penetrations were found to significantly ($\alpha=0.10$) affect the

Table 3. Analyses of Variance to Determine if Differences in Tillage and Trafficking Affect Cone Index and Work Required to Penetrate the Top 12-Inch Layer of Soil

Source of Variation	d.f.	SS	P>F
<u>Dependent Variable = Work</u>			
Treatments	5	292761.54	0.1543
Rep (Treatments)	6	144165.05	0.0882
Penetrations	2	84975.15	0.0178
Treatments*Penetrations	10	48248.20	0.7369
Penetrations*Rep (Treatments)	12	88865.47	0.0257
Setup (Treatments*Penetrations)	12	117802.40	--
Setup*Penetrations (Treatment*Rep)	24	70313.37	--
<u>Dependent Variable = Cone Index</u>			
Treatments	5	144060.47	0.2198
Rep (Treatments)	6	88637.77	0.4114
Penetrations	2	50308.52	0.0731
Treatments*Penetrations	10	31871.66	0.9132
Penetrations*Rep (Treatments)	12	92050.65	0.0134
Setup (Treatments*Penetrations)	12	159701.50	--
Setup*Penetrations (Treatment*Rep)	24	64136.58	--

work required to penetrate the top 2-inch soil layer. Using cone index as the dependent variable, penetrations and replications interacting with penetrations within treatments were found significant at the 90 percent probability level (Table 4). Separation of treatment cone index means by Duncan's Multiple Range Test indicated that the no-tillage treatment had a higher cone index for the top 2-inch layer of soil than any other treatment (Table A1, Figure 15). Separation of penetration cone index means showed the wheel-track penetration of the no-tillage treatment to be significantly ($\alpha=0.10$) different from the row-middle penetration for the top 2-inch layer of soil (Table A2).

Analyses of variance at the 2- to 4-inch depth. Both penetration and replications interacting with penetrations within treatments significantly ($\alpha=0.10$) affected the amount of work done during penetration (Table 5). Penetrations, treatments, and replications interacting with penetrations within treatments significantly ($\alpha=0.10$) affected cone index at the 2- to 4-inch depth (Table 5). Separation of treatment cone index means indicated the moldboard plow tillage treatment offered significantly ($\alpha=0.10$) less resistance to cone penetration than the no-tillage, disk, and under-row subsoil tillage treatments (Table A1, Figure 15). The smaller resistance to penetration was probably due to soil aeration and voids induced during the tillage operation. Separation of penetration cone index means indicated the wheel-track penetration in the no-tillage treatment had higher cone index values than the row-middle and under-row penetrations within the 2- to 4-inch depth increment (Table A2, Figures 16-21).

Table 4. Analyses of Variance to Determine if Differences in Tillage and Trafficking Affect Cone Index and Work Required to Penetrate the Top 2-Inch Soil Layer

Source of Variation	d.f.	SS	P>F
<u>Dependent Variable = Work</u>			
Treatments	5	1798.46	0.0331
Rep (Treatments)	6	407.75	0.8762
Penetrations	2	1881.21	0.0462
Treatments*Penetrations	10	2057.79	0.5750
Penetrations*Rep (Treatments)	12	2809.25	0.1118
Setup (Treatments*Penetrations)	12	2130.40	--
Setup*Penetrations (Treatment*Rep)	24	3164.50	--
<u>Dependent Variable = Cone Index</u>			
Treatments	5	44914.16	0.1741
Rep (Treatments)	6	23793.77	0.6189
Penetrations	2	45719.88	0.0791
Treatments*Penetrations	10	50854.38	0.7077
Penetrations*Rep (Treatments)	12	86848.99	0.0299
Setup (Treatments*Penetrations)	12	63152.23	--
Setup*Penetrations (Treatment*Rep)	24	70980.17	--

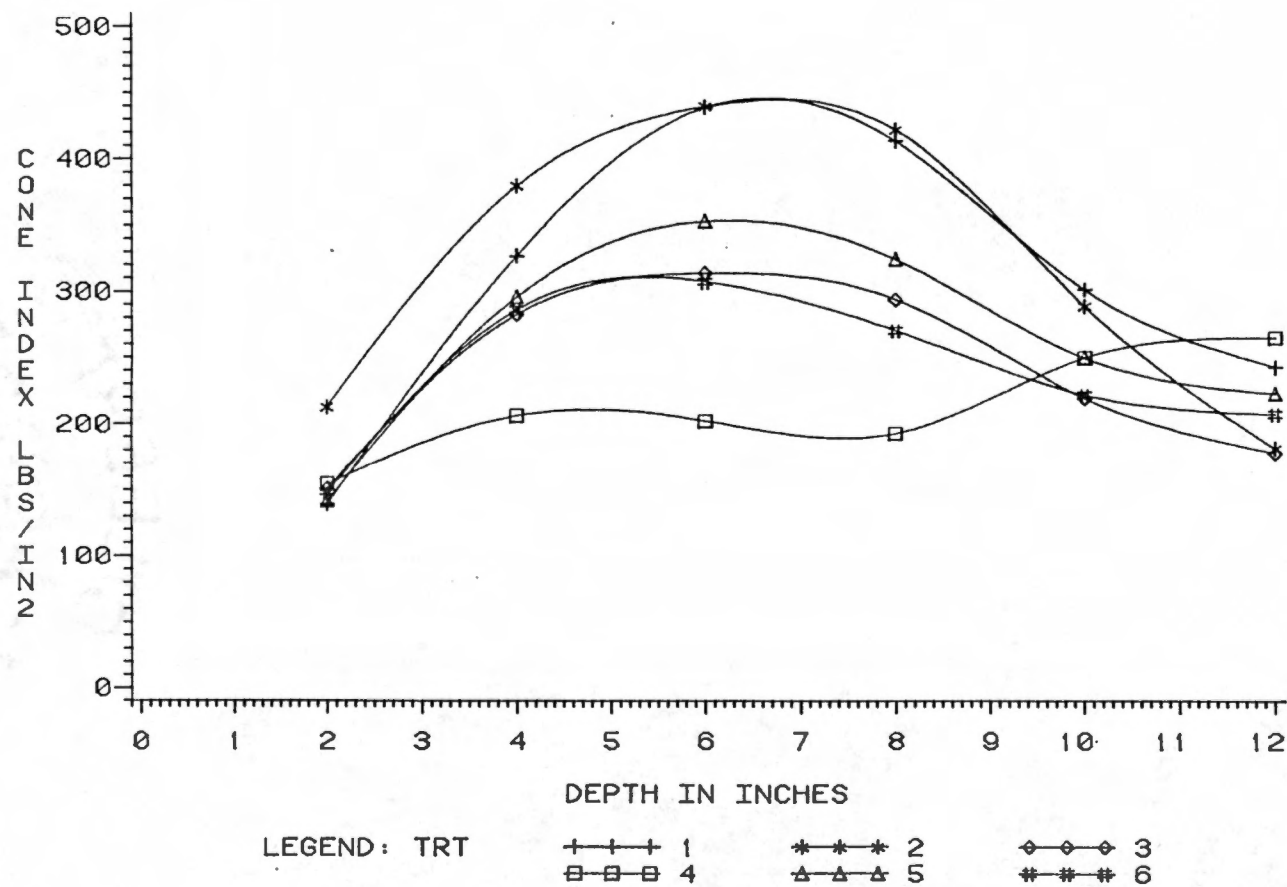


Figure 15. Average cone indices of six tillage treatments as functions of depth of penetration. Refer to page 39 for description of treatments.

Table 5. Analyses of Variance to Determine if Differences in Tillage and Trafficking Affect Cone Index and Work Required to Penetrate the Soil Layer from 2 to 4 Inches Deep

Source of Variation	d.f.	SS	P>F
<u>Dependent Variable = Work</u>			
Treatments	5	11479.64	0.1500
Rep (Treatments)	6	5558.43	0.2951
Penetrations	2	5649.73	0.0898
Treatments*Penetrations	10	6937.84	0.8710
Penetrations*Rep (Treatments)	12	14032.25	0.0143
Setup (Treatments*Penetrations)	12	8002.63	--
Setup*Penetrations (Treatment*Rep)	24	9892.43	--
<u>Dependent Variable = Cone Index</u>			
Treatments	5	194983.58	0.0833
Rep (Treatments)	6	68438.66	0.1487
Penetrations	2	46499.00	0.0883
Treatments*Penetrations	10	65658.74	0.0984
Penetrations*Rep (Treatments)	12	131703.64	0.0063
Setup (Treatments*Penetrations)	12	69303.36	--
Setup*Penetrations (Treatment*Rep)	24	80189.61	--

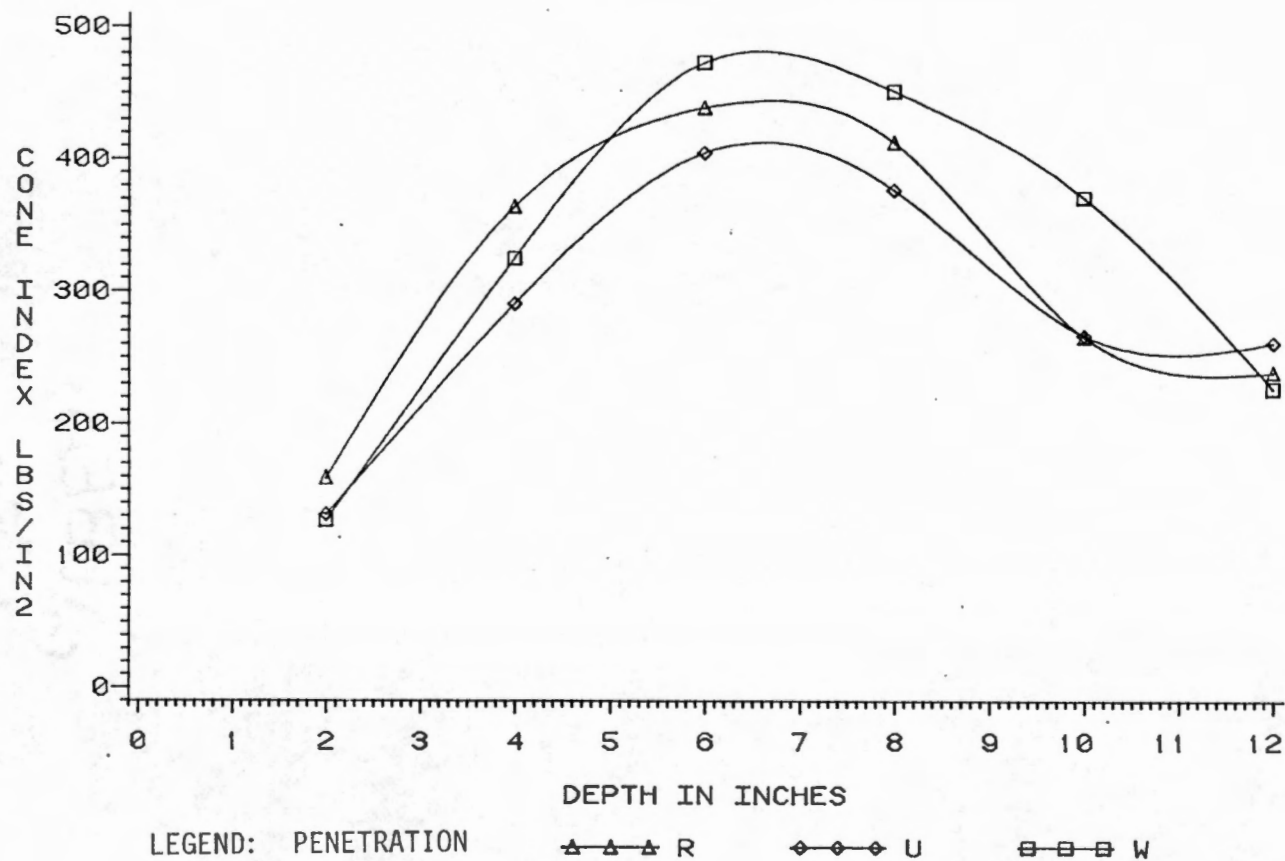


Figure 16. Average cone indices of row-middle (R), under-row (U), and wheel-track (W) penetrations as functions of depth within the disk tillage treatment.

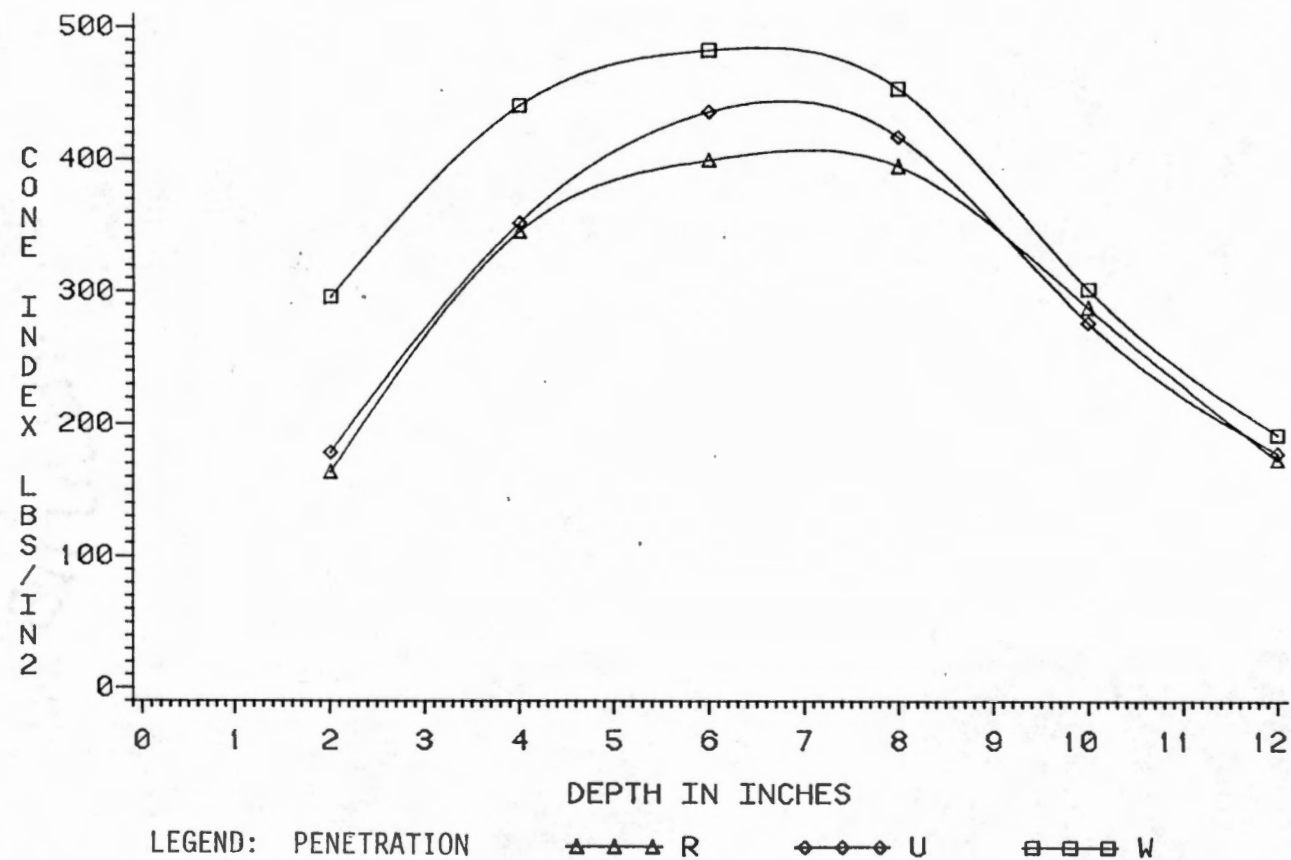


Figure 17. Average cone indices of row-middle (R), under-row (U), and wheel-track (W) penetrations as functions of depth within the no-tillage treatment.

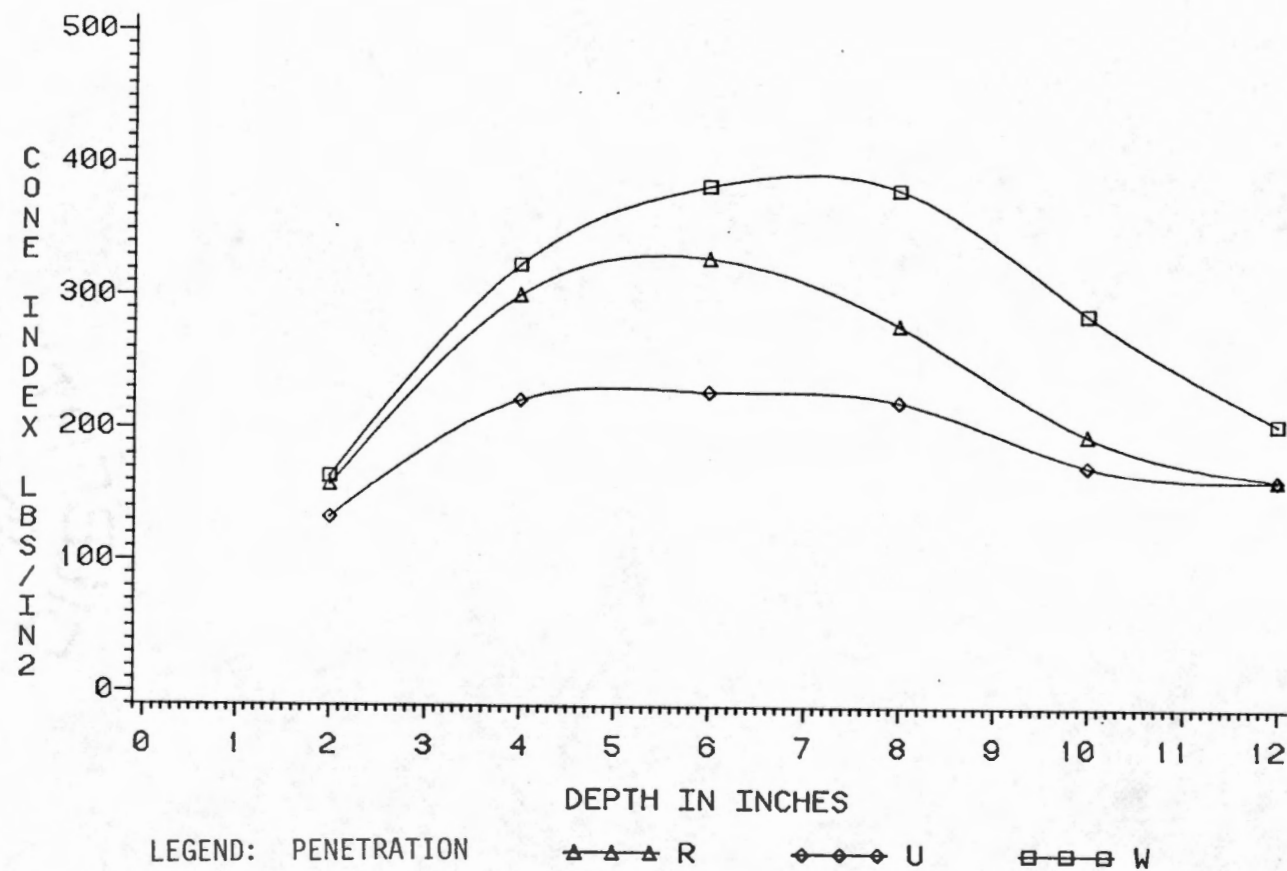


Figure 18. Average cone indices of row-middle (R), under-row (U), and wheel-track (W) penetrations as functions of depth within the previous no-tillage treatment. Refer to page 39 for detailed description of tillage treatment.

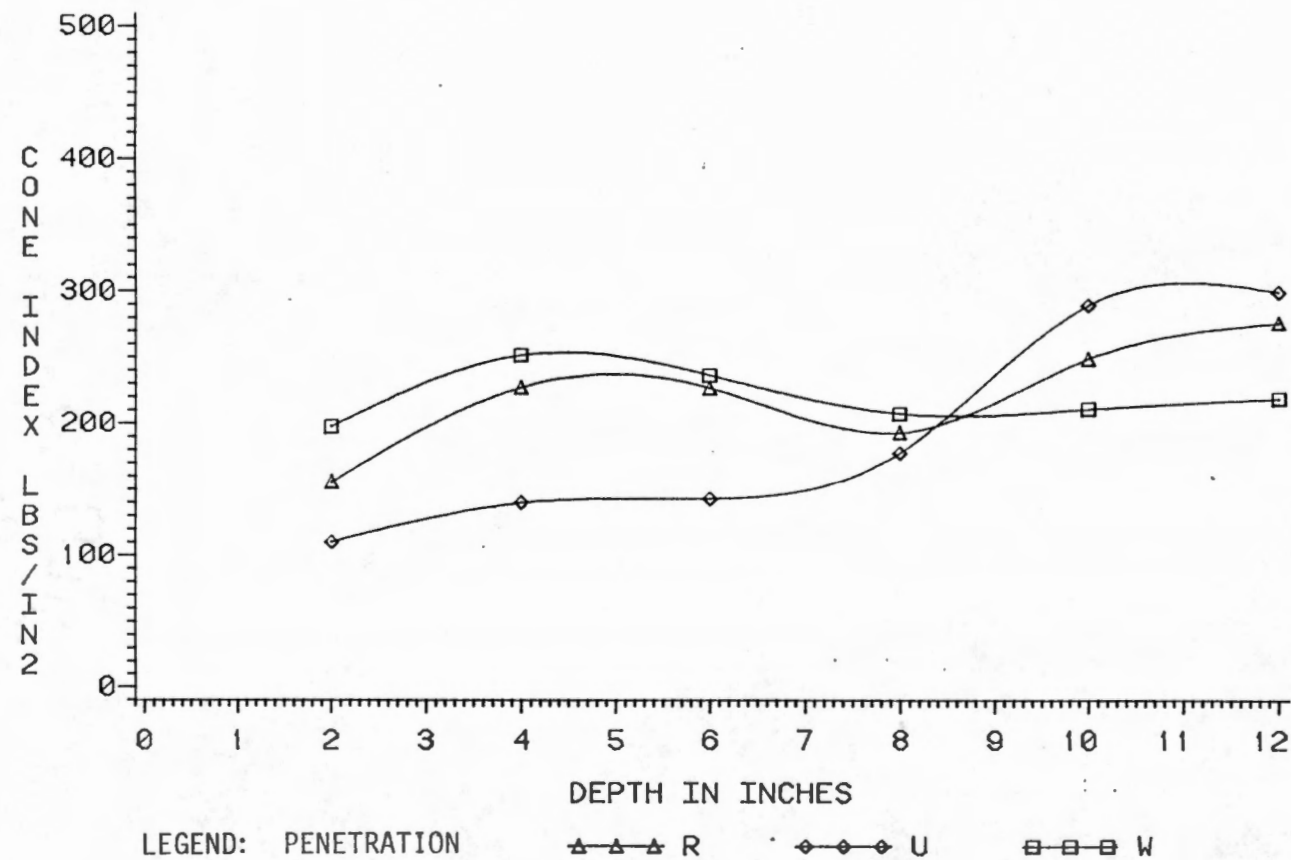


Figure 19. Average cone indices of row-middle (R), under-row (U), and wheel-track (W) penetrations as functions of depth within the moldboard plow tillage treatment.

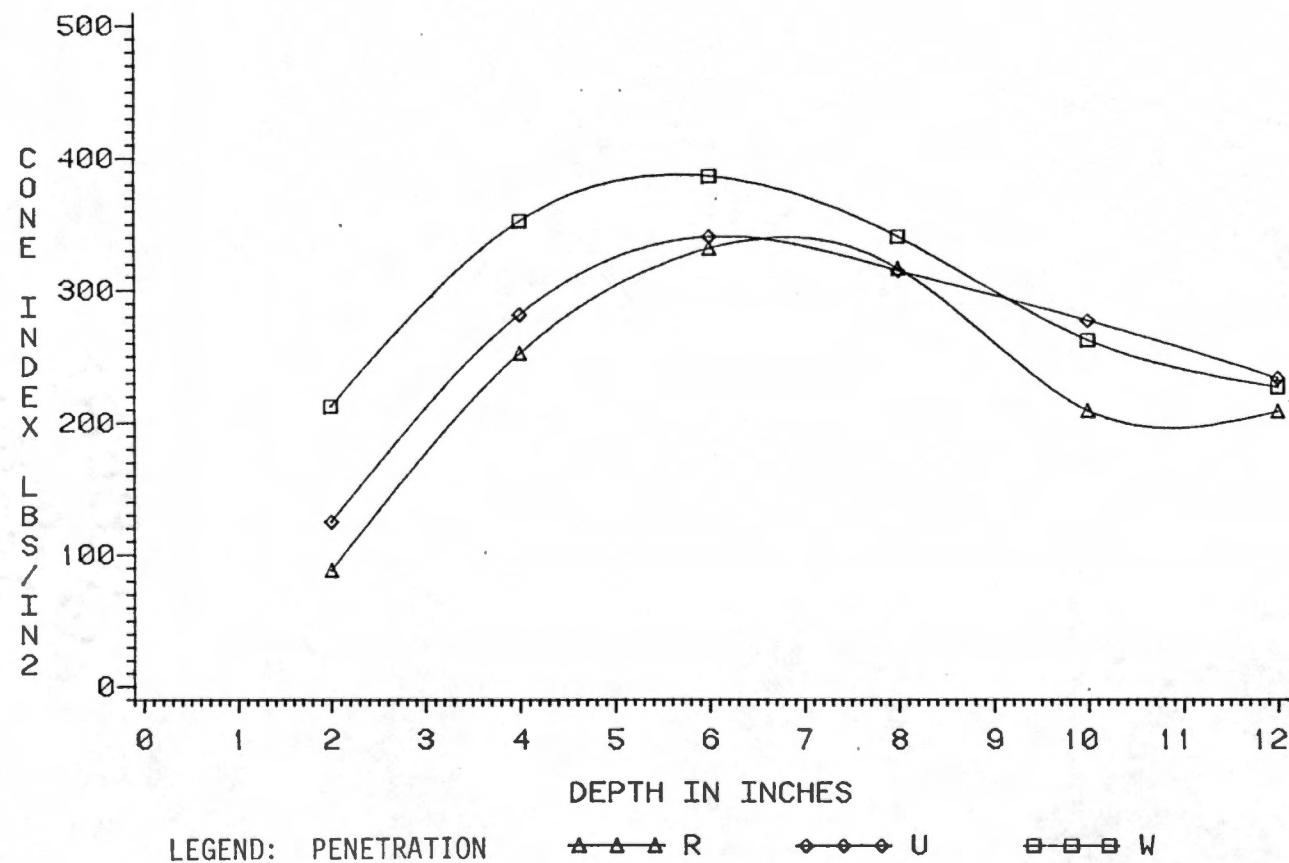


Figure 20. Average cone indices of row-middle (R), under-row (U), and wheel-track (W) penetrations as functions of depth within the under-row subsoil tillage treatment.

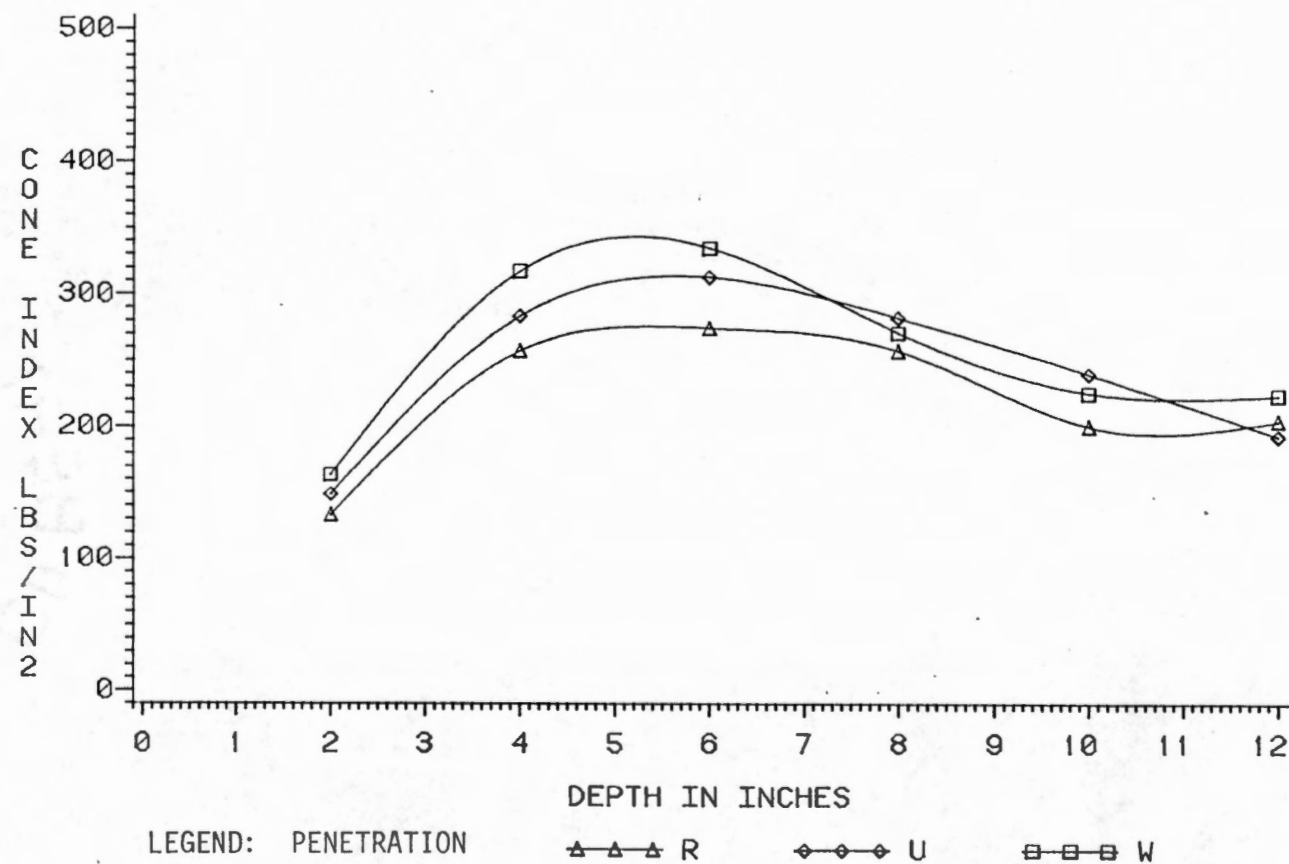


Figure 21. Average cone indices of row-middle (R), under-row (U), and wheel-track (W) penetrations as functions of depth within the chisel plow tillage treatment.

Analyses of variance at the 4- to 6-inch depth. Treatments, penetrations, and replications interacting with penetrations within treatments significantly ($\alpha=0.10$) affected the dependent variables work and cone index (Table 6). Separation of treatment cone index means indicated that the disk and no-tillage treatments were significantly ($\alpha=0.10$) higher than previous no-tillage, moldboard plow, and chisel plow treatments (Table A1; Figure 15, p. 56). However, the moldboard plow tillage treatment had significantly ($\alpha=0.10$) lower cone index values than any other tillage treatments possibly due to soil aeration and voids induced during the plowing operation, thus reducing the force needed to penetrate the soil.

Separation of cone index means by penetration indicated differences among penetrations in all tillage treatments with the exception of under-row subsoil and chisel plow tillage treatments (Table A2; Figures 16, 17, 18, and 19). Wheel-track penetrations tended to have higher cone index values within the 4- to 6-inch depth increment for all tillage treatments. This result suggests that the effect of trafficking extends to at least this depth.

Analyses of variance at the 6- to 8-inch depth. Treatments, penetrations, and replications interacting with penetrations within treatments significantly ($\alpha=0.10$) affected both cone index and work done during a penetration (Table 7). Separation of tillage treatment cone index means indicated that the disk, no-tillage, and under-row subsoil tillage treatments in the 6- to 8-inch depth increment were

Table 6. Analyses of Variance to Determine if Differences in Tillage and Trafficking Affect Cone Index and Work Required to Penetrate the Soil Layer from 4 to 6 Inches Deep

Source of Variation	d.f.	SS	P>F
<u>Dependent Variable = Work</u>			
Treatments	5	45721.32	0.0225
Rep (Treatments)	6	8758.76	0.1336
Penetrations	2	4944.81	0.0647
Treatments*Penetrations	10	5729.71	0.7878
Penetrations*Rep (Treatments)	12	9909.14	0.0331
Setup (Treatments*Penetrations)	12	8463.61	--
Setup*Penetrations (Treatment*Rep)	24	8275.30	
<u>Dependent Variable = Cone Index</u>			
Treatments	5	486590.79	0.0165
Rep (Treatments)	6	81821.00	0.2960
Penetrations	2	43496.07	0.0472
Treatments*Penetrations	10	64913.60	0.8362
Penetrations*Rep (Treatments)	12	97859.23	0.0246
Setup (Treatments*Penetrations)	12	118008.72	--
Setup*Penetrations (Treatment*Rep)	24	76773.79	--

Table 7. Analyses of Variance to Determine if Differences in Tillage and Trafficking Affect Cone Index and Work Required to Penetrate the Soil Layer from 6 to 8 Inches Deep

Source of Variation	d.f.	SS	P>F
<u>Dependent Variable = Work</u>			
Treatments	5	43881.02	0.0347
Rep (Treatments)	6	10150.43	0.4304
Penetrations	2	4066.79	0.0421
Treatments*Penetrations	10	4510.78	0.6690
Penetrations*Rep (Treatments)	12	6483.14	0.0707
Setup (Treatments*Penetrations)	12	18942.11	--
Setup*Penetrations (Treatment*Rep)	24	6459.78	--
<u>Dependent Variable = Cone Index</u>			
Treatments	5	461844.19	0.0477
Rep (Treatments)	6	123545.43	0.2511
Penetrations	2	38573.22	0.0769
Treatments*Penetrations	10	36970.95	0.7347
Penetrations*Rep (Treatments)	12	69302.08	0.0887
Setup (Treatments*Penetrations)	12	162042.69	--
Setup*Penetrations (Treatment*Rep)	24	73245.36	--

significantly ($\alpha=0.10$) different from the moldboard plow and chisel plow tillage treatments (Table A1; Figure 15, p. 56). Separation of penetration cone index means indicated the wheel-track penetration to be significantly ($\alpha=0.10$) different from both the row-middle and under-row penetrations in the disk tillage treatment. Significant differences at the 90 percent probability level were indicated between the wheel-track and under-row penetrations in the no-tillage previously treatment (Table A2; Figure 16, p. 58; Figure 18, p. 60).

Analyses of variance at 8- to 10-inch depth. The work required to penetrate the soil layer varied significantly ($\alpha=0.10$) among penetrations (Table 8). When cone index was used as the dependent variable, no significant differences were found (Table 8). Cone index means by treatment are shown in Table A1 and are illustrated in Figure 15. The moldboard plow tillage treatment cone index in the 8- to 10-inch depth increment increased over that observed in the 6- to 8-inch soil layer probably due to a tillage pan formed by soil compressed beneath the plow wedge as the tool was pulled through the soil. Separation of penetration cone index means indicated differences among penetrations in the disk and under-row subsoil tillage treatments (Table A2; Figures 16 and 20), although the analyses of variance did not show significant differences. Occurrence of penetration cone index means significantly ($\alpha=0.10$) different with a Duncan's Multiple Range Test when no significant differences were indicated in the analyses of variance can be attributed to the differences in mathematical methodology employed in

Table 8. Analyses of Variance to Determine if Differences in Tillage and Trafficking Affect Cone Index and Work Required to Penetrate the Soil Layer from 8 to 10 Inches Deep

Source of Variation	d.f.	SS	P>F
<u>Dependent Variable = Work</u>			
Treatments	5	4366.89	0.6620
Rep (Treatments)	6	7832.48	0.3335
Penetrations	2	3786.40	0.0749
Treatments*Penetrations	10	2063.22	0.3823
Penetrations*Rep (Treatments)	12	3819.17	0.2636
Setup (Treatments*Penetrations)	12	12176.83	--
Setup*Penetrations (Treatment*Rep)	24	5726.25	--
<u>Dependent Variable = Cone Index</u>			
Treatments	5	68663.57	0.5474
Rep (Treatments)	6	93901.61	0.4358
Penetrations	2	64739.91	0.1659
Treatments*Penetrations	10	21105.61	0.3358
Penetrations*Rep (Treatments)	12	60472.50	0.1296
Setup (Treatments*Penetrations)	12	176984.02	--
Setup*Penetrations (Treatment*Rep)	24	71111.53	--

the two procedures (Sanders, 1984). This phenomenon occurs frequently. The analysis of variance F-test uses an averaging method to detect statistical differences; whereas, a Duncan's Multiple Range Test detects variations between adjacent means as seen in the disk and under-row subsoil tillage treatments (Sanders, 1984; Table A2).

Analyses of variance at the 10- to 12-inch depth. Replications nested within treatments significantly ($\alpha=0.10$) affected both cone index and work done during penetration (Table 9). Separation of treatment cone index means indicated the moldboard plow tillage treatment to be significantly ($\alpha=0.10$) different from the no-tillage and previous no-tillage treatments (Table A1; Figure 15, p. 56) in cone penetration resistance. Separation of penetration cone index means indicated the wheel-track offered a greater resistance to penetration than the under-row and row-middle regions in the previous no-tillage treatment (Table A2; Figure 18, p. 60, Figure 20, p. 62, Figure 21, p. 63, respectively). Treatment and penetrations being significantly ($\alpha=0.10$) different when the Duncan's Multiple Range test was performed is the same type of occurrence discussed earlier in this chapter.

Analyses of variance by depth were performed to detect differences among tillage treatments and penetrations. Separation of treatment and penetration cone index means by the Duncan's Multiple Range Test was used to indicate the differences in tillage treatment effects upon the dependent variables cone index and work done during penetration, and to detect trafficking patterns within a particular tillage

Table 9. Analyses of Variance to Determine if Differences in Tillage and Trafficking Affect Cone Index and Work Required to Penetrate the Soil Layer from 10 to 12 Inches Deep

Source of Variation	d.f.	SS	P>F
<u>Dependent Variable = Work</u>			
Treatments	5	7391.46	0.2685
Rep (Treatments)	6	5229.81	0.0326
Penetrations	2	1659.63	0.5406
Treatments*Penetrations	10	79.63	0.8063
Penetrations*Rep (Treatments)	12	2146.12	0.7509
Setup (Treatments*Penetrations)	12	3042.47	--
Setup*Penetrations (Treatment*Rep)	24	6281.36	--
<u>Dependent Variable = Cone Index</u>			
Treatments	5	70630.70	0.3321
Rep (Treatments)	6	58877.97	0.0402
Penetrations	2	23703.03	0.4820
Treatments*Penetrations	10	1353.57	0.7532
Penetrations*Rep (Treatments)	12	27979.04	0.4554
Setup (Treatments*Penetrations)	12	36592.68	--
Setup*Penetrations (Treatment*Rep)	24	54390.13	--

treatment. Figures 16-21, pp. 58-63, and Table A2 indicate that, in general, the wheel-track offered greater resistance to penetration than under-row and row-middle penetrations among all the tillage treatments. Figure 15, p. 56, is a graphical representation of tillage treatment cone index means which shows the no-tillage treatment tending to have the highest cone index values among the tillage treatments to a depth of about 10 inches (Figure 15). As discussed previously, the moldboard plow tillage treatment had the lowest cone index values among the treatments to a depth of about 8 inches. A gradual increase in cone index value to the 12-inch depth indicates the possible formation of a tillage pan between 8 and 12 inches in depth in the moldboard plow tillage treatment.

In 1982, Tyler et al. concluded an experiment using the same six tillage treatments described previously to study the effects of soybean tillage practices on soil properties, diseases, cyst nematodes, and yield. Their results indicate that over a four-year period (1979 to 1982) the no-tillage treatment produced greater soybean yields than the other tillage treatments.

Multiple Regression Analysis

A multiple regression analysis was performed in an attempt to obtain a prediction equation relating cone index to soil moisture content and soil bulk density. All tillage treatment soil moisture content values, which increased by depth, ranged from 14 to 21 percent dry basis. Typical dry bulk density values ranged from 70 to 85 pounds

per cubic foot for all tillage treatments. Due to the variability between penetrations, a single equation representative of the data obtained could not be found. To represent cone index as a function of bulk density and moisture content, equations representing the wheel-track, under-row, and row-middle penetrations within each tillage treatment were needed. A total of 18 equations were thus necessary to obtain R-square values of 0.80 or higher, which were considered necessary for a reliable analytical model for the penetrations.

CHAPTER V

SUMMARY AND CONCLUSIONS

I. SUMMARY

An evaluation of the capabilities of a microprocessor-based, tractor-mounted soil cone penetrometer used for collecting data in plots subjected to continuous annual applications of various tillage practices was initiated. Based upon in-field observations, modifications allowing improved machine performance were made to the penetrometer to facilitate acquisition of reliable, repeatable data. Although data acquisition is not hampered, problems with pressure surges due to excessive hydraulic fluid flow rates still exist when the penetrometer is powered by a tractor with a high-capacity hydraulic pump.

Two analyses of variance were performed on the penetrometer data acquired: 1) the entire 12 inches of penetration considered as one mass, and 2) 2-inch soil depth increments to a depth of 12 inches. The analyses of variance for the entire 12-inches considered collectively indicated no significant ($\alpha=0.10$) effects among treatments on either of the dependent variables, cone index or work done during penetration. However, penetrations significantly ($\alpha=0.10$) affected cone index and work done in penetrating the soil, indicating differences among the row-middle, under-row, and wheel-track penetrations within treatments. The general analyses of variance over the entire 12 inches of soil was used to determine if differences existed among

treatments and penetrations. Based upon these analyses, a more detailed investigation was warranted.

Analyses of variance by 2-inch depth increments were performed on the data to detect differences among treatments and penetrations. A Duncan's Multiple Range Test was used to separate treatment cone index means, which were averages of several discrete values. Treatment cone index means were also used to detect depth of influence of various tillage practices. Penetration cone index means were separated using Duncan's Multiple Range Tests to indicate trafficking effects on soil strength properties. In general, soil moisture content increased with depth from 14 to 21 percent dry basis among all treatments. Soil bulk density values ranged from 70 to 85 pounds per cubic foot dry basis for all treatments.

The top 2 inches of soil indicated the no-tillage treatment to have the highest cone index among tillage treatments with the wheel-track penetration tending to be the most resistant to cone penetration. The 2- to 4-inch depth increment indicated the moldboard plow tillage treatment to be significantly ($\alpha=0.10$) lower in cone index than the disk, under-row subsoil, and no-tillage treatments with the wheel-track penetration again tending to be hardest to penetrate. The 4- to 6-inch depth increment indicated the disk and no-tillage treatments to have significantly ($\alpha=0.10$) higher cone index values than the moldboard plow treatment. The wheel-track again tended to offer the most resistance to penetration. The 6- to 8-inch depth increment indicated the disk, no-tillage, and under-row subsoil tillage treatments to be

statistically ($\alpha=0.10$) higher in cone index than the moldboard plow tillage treatment with the wheel-track penetration again tending to have higher cone index values than under-row or row-middle penetrations. The 8- to 10-inch depth increment showed no statistical differences among tillage treatments. Wheel-track penetrations tended to have highest cone index values over all the treatments. The 10- to 12-inch depth increment tended to indicate higher cone index values in the moldboard plow tillage treatment. No trafficking pattern was indicated at the 10- to 12-inch depth increment with penetrations not significantly affecting either cone index or work done during soil penetration.

II. CONCLUSIONS

1. The microprocessor-based, tractor-mounted soil cone penetrometer with modifications was a reliable mechanism for obtaining in-situ soil penetration measurements.
2. No-tillage plots continually cropped with soybeans followed by a wheat cover crop tended to have higher cone indices to a depth of 10 inches than any other tillage treatment.
3. Highest cone index values were observed between 4 and 8 inches in depth for the various tillage treatments considered collectively.
4. Wheel-track penetrations tended to have higher cone index values than either row-middle and under-row penetrations to a depth of 10 inches.

III. RECOMMENDATIONS FOR FURTHER IMPROVEMENTS

An auxiliary hydraulic power supply consisting of a pump, 2.0 to 3.0 gallons per minute maximum at 500 pounds per square inch of pressure, and a 1.5 gallon sump attached to the left leg of the penetrometer frame should be considered for driving the penetrometer shaft due to pressure surges in hydraulic fluid caused by excessive hydraulic fluid flow rates from the tractor. This auxiliary hydraulic power supply could be driven by a hydraulic motor powered by the tractor hydraulic system.

The possibility of combining the control unit and the mass storage system into a single package should be evaluated. The present mass storage system is not suited for the harsh environment encountered in the field. Refinement of the present software allowing more parameters to be controlled directly by the operator should be considered.

BIBLIOGRAPHY

BIBLIOGRAPHY

- Army. 1948. Development of testing instruments. Technical Memo, 3-240.
- Army. 1959. Soils trafficability. Technical Bulletin Eng. 37.
- ASAE. 1983. Soil cone penetrometer, Standard No. 313.1. Agricultural Engineering Yearbook. American Society of Agricultural Engineers, St. Joseph, MI 49085.
- Ayers, P. D. and J. V. Perumpral. 1982. Moisture and density effect on cone index. TRANSACTIONS of the ASAE 25(2):1169-1172.
- Begemann, H. K. S. 1969. The dutch static penetration test with the adhesion jacket cone. L. G. M. Mededelingen Publications Delft Lab for Soil Mechanics, 12(4) April, 1969.
- Blake, G. R. 1965. Bulk density. In methods of soil analysis. Part 1. American Society of Agronomy.
- Bogdanovic, L. J. 1961. The use of penetration tests for determining the bearing capacity of piles. Proceedings 5th International Conference on Soil Mechanics and Foundation Engineering, II: 17-22.
- Bowen, H. D. 1976. Correlation of penetrometer cone index with root impedance. ASAE Paper No. 76-1516. American Society of Agricultural Engineers, St. Joseph, MI 49085.
- Bridge, B. J. and N. Collis-George. 1973. A dual source gamma-ray traversing mechanism suitable for the non-destructive simultaneous measurement of bulk density and water content in columns of swelling soil. Australian Journal of Soil Research 11:83-92.
- Buchele, W. F. 1961. A power sampler of undisturbed soils. TRANSACTIONS of the ASAE 4(2):185-187, 191.
- Carter, L. M. 1967. Portable recording penetrometer measures soil strength profiles. Agricultural Engineering 46(6):348-349.
- Carter, L. M. 1969. Integrating penetrometer provides average soil strength. Agricultural Engineering 50(10):618-619.

- Chesness, J. L., E. E. Ruiz and C. Cobb Jr. 1972. Quantitative description of soil compaction in peach orchards utilizing a portable penetrometer. TRANSACTIONS of the ASAE 15(2):217-219.
- Collins, J. G. 1971. Forecasting trafficability of soils. Tech. Memo. No. 3-331. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.
- Corey, J. C., S. F. Peterson and M. A. Wakat. 1971. Measurement of attenuation of 137 Cs and 241 Am gamma-rays for soil density and water content determinations. Soil Science American Proceedings. 35(2):215-219.
- DeBeer, E. E. and A. Martens. 1957. Method of computation of an upper limit of the heterogeneity of sand layers on the settlement of bridges. Proceedings Fourth International Conference on Soil Mechanics and Foundations Engineering. 1:275-282.
- DeBeer, E. E. 1963. The scale effect in the transposition of the results of deep sound tests on the ultimate bearing capacity of piles and caisson foundations. Geotechnique.
- DeVries, J. 1969. In-situ determination of physical properties of the surface layer of field soils. Soil Science American Proceedings. 33:349-353.
- Erbach, Donald C. 1983. Measurement of soil moisture and bulk density. ASAE Paper No. 83-1553. American Society of Agricultural Engineers, St. Joseph, MI 49085.
- European Symposium on Penetration Testing. 1974. Stockholm, June, Vol. 1. State of the Art Reports.
- Foale, M. A., C. E. G. Holt, C. Edser, T. Dickson and M. E. McKay. 1982. A combination hydraulic ram and impulse soil coring mechanism. Journal of Agricultural Engineering Research. 27: 465-467.
- Freitag, D. R., A. J. Green and K. J. Melzer. 1970. Performance evaluation of wheels for lunar vehicles. U.S. Army Technical Report M-70-2.
- Freitag, D. R. 1971. Methods of measuring soil compaction. In compaction of agricultural soils. ASAE Paper No. 47-103. American Society of Agricultural Engineers, St. Joseph, MI 49085.

- Gameda, S., G. S. V. Raghavan, E. McKyes and R. Theriault. 1983. Single and dual probes for soil density measurement. ASAE Paper No. 82-1542. American Society of Agricultural Engineers, St. Joseph, MI 49085.
- Gerald, C. J. and W. R. Cowley. 1964. Hidden hardpans steal profits. *Crops and Soils* 17:11-12.
- Gill, W. R. and G. E. Vanden Berg. 1968. Soil dynamics in tillage and traction. Handbook 316, U.S. Dept. of Agriculture, Wash., D.C.
- Ginn, L. H., L. G. Heatherly and W. J. Russell. 1978. Assembly of mounting hydraulic soil core sampler on tractor front. *Journal of Agronomy* 70:512-514.
- Greacen, E. L., D. A. Farrell and B. Cockroft. 1968. Soil resistance to metal probes and plant roots. *Transactions 9th International Congress on Soil Sci.* 1:769-779.
- Gurr, C. G. and B. Jakobsen. 1978. Gamma probe for measurement of field bulk density and water content. In modification of soil structure. Emerson, W. W., R. D. Bond and A. R. Dexter (Eds.). John Wiley and Sons, New York. Pages 127-133.
- Hassan, O. S. Ali. 1983. Study on the relationships between the cone penetrometer and the soil cutting resistances of the Caribbean Soils. ASAE Paper No. 83-1039. American Society of Agricultural Engineers, St. Joseph, MI 49085.
- Hattiaratchi, D. R. P. and A. R. Reece. 1967. Symmetrical three dimensional soil failure. *Journal of Terramechanics* 3(4):45-67.
- Hayes, J. C. and J. T. Ligon. 1977. Prediction of traction using soil physical properties. ASAE Paper No. 77-1054. American Society of Agricultural Engineers, St. Joseph, MI 49085.
- Hendrick, J. G. 1969. Recording soil penetrometer. *Journal of Agricultural Engineering Research*. 14(2):183-186.
- Hough, B. K. 1957. Basic soils engineering. The Ronald Press Company, New York.
- Houlsby, G. T. 1982. Theoretical analysis of the fall cone test. *Geotechnique* 32, 2, 111-118.
- Jensen, M. E., W. H. Sletten and R. L. Ochs. 1960. Mechanized soil sampler with offset drive. *TRANSACTIONS of the ASAE* 3(1):22-24.

- Johnson, C. E., L. L. Jensen, R. L. Schafer and A. C. Baily. 1978. Some soil toll analogs. ASAE Paper No. 78-1037, American Society of Agricultural Engineers, St. Joseph, MI 49085.
- Kelly, O. J. and H. R. Haise. 1947. A soil sampling machine for obtaining undisturbed cores. Journal of American Society Agronomy 39:828-830.
- Knight, S. J. 1948. Trafficability of soils--laboratory test to determine effects of moisture content and density variation. Technical Memo. No. 3-240.
- Knight, S. J. and D. R. Freitag. 1962. Measurement of soil trafficability characteristics. TRANSACTIONS of ASAE 5:121-124, 132.
- Konder, R. L. 1960. A non-dimensional approach to vibratory cutting, compaction and penetration of soils. U.S. Army Technical Report No. 8.
- Kostritsyn, A. K. 1956. [Cutting of a cohesive medium with knives and cones]. Vsesolvzz/Akad. Sel'skhozlalstvennykh nauk. Zeml. Mekn. Shorn. Trudov (Leningrad) 3:247-290, illus [National Institute of Agricultural Engineering English Translation 58].
- Kreyszig, E. 1972. Advanced engineering mathematics. 3rd Ed. John Wiley and Sons, Inc., New York.
- Lal, R. 1974. The effect of soil texture and density on the neutron and density probe calibration for some tropical soils. Soil Science 117:183-190.
- Leigh, A. C. and I. K. Nixon. 1961. Comparison of in-situ tests for granular soils. Proceedings 5th International Conference on Soil Mechanics and Foundation Engineering Vol. I, pp. 499-507.
- Lukenbach, E. 1961. The determination of the permissible point load of piles by means of static penetration tests. Proceedings 5th International Conference on Soil Mechanics and Foundation Engineering, Vol. II, page 99.
- McKyes, E. and O. S. Ali. 1977. The cutting of soil by narrow blades. Journal of Terramechanics 14(2):43-58.
- Means, R. E. and J. V. Parcher. 1963. Physical properties of soil. Charles E. Merrill Books Inc., Columbus, OH, page 31.
- Meyerhof, G. G. 1956. Penetration tests and bearing capacity of cohesionless soils. Journal of the Soil Mechanics and Foundation Division American Society of Civil Engineers. Vol. 82, No. SM1.

- Meyerhof, G. G. 1963. Some recent research on the bearing capacity of foundations. *Canadian Geotechnical Journal* 1(1):16-26.
- Mielke, L. N. 1973. Encasing undisturbed soil cores in plastic. *Soil Society of America Proceedings* 37:325-326.
- Morrison, Jr., J. E. 1980. Use of recording penetrometer for evaluation of density profiles in bales of tobacco. *TRANSACTIONS of the ASAE* 23(1):261-264.
- Morton, C. T. and W. F. Buchele. 1960. Emergence energy of plant seedlings. *Agricultural Engineering* 41(7):428-431.
- Mulqueen, J., J. V. Stafford and D. W. Tanner. 1977. Evaluation of penetrometers for measuring soil strength. *Journal of Terra-mechanics* 14(3):137-156.
- Plantema, G. 1957. Influence of density on sounding results in dry, moist and saturated sands. *Proceedings 4th International Conference on Soil Mechanics and Foundation Engineering, Vol. I*, pp. 237-240.
- Perumpral, J. V. and P. D. Ayers. 1981. Moisture and density effect on cone index. *ASAE Paper No. 81-1047*. American Society of Agricultural Engineers, St. Joseph, MI 49085.
- Perumpral, J. V. 1983. Cone penetrometer application. *ASAE Paper No. 83-1541*, American Society of Agricultural Engineers, St. Joseph, MI 49085.
- Prather, O. C., J. G. Hendrick and R. L. Schafer. 1970. An electronic hand-operated recording penetrometer. *TRANSACTIONS of the ASAE* 13(1):385-386, 390.
- Raghavan, G. S. V. and E. McKyes. 1977. Study of traction and compaction problems of eastern Canadian agricultural soils. *Department of Agricultural Engineering, McGill University, Quebec*.
- Rawitz, E., H. Etkin and A. Hazan. 1982. Calibration and field testing of a two-probe gamma gauge. *American Journal of Soil Science* 46:461-465.
- Reginato, R. J. 1974. Gamma radiation measurements of bulk density changes in soil pedon following irrigation. *Soil Science Society of America Proceedings* 38:24-29.
- Revut, I. B. and A. A. Rode (Eds.). 1969. *Experimental methods of studying soil structure*. U.S. Dept. Agriculture.

- Reynolds, S. G. 1970. The gravimetric method of soil moisture determination. Parts I, II, and III. *Journal of Hydrology*. 11:258-273, pp. 371-378, 11:274-287, 11:288-300, respectively.
- Rodin, S. 1961. Experiences with penetrometers, with particular reference to the standard penetration test. *Proceedings 5th International Conference on Soil Mechanics and Foundation, Engineering*, Vol. I, pp. 517-521.
- Rozhkov, V. A. 1970. Radiation measurement of soil density and moisture content in agrophysical studies. *Soviet Soil Science* 2(5):613-620.
- Sanders, W. 1984. Personal communication.
- Sanglerat, G. 1972. *The penetrometer and soil exploration*. Elsevier Publication Company, Amsterdam.
- Sanglerat, G. 1979. *The penetrometer and soil exploration*. 2nd E. Elsevier, Amsterdam.
- Schafer, R. L., C. A. Reaves and D. F. Young. 1969. An interpretation of distortion in the similitude of certain soil machine systems. *TRANSACTIONS of the ASAE* 12(1):145-149.
- Schafer, R. L., D. R. Freitag and R. D. Wismer. 1973. Distortion in the similitude of soil machine systems. *Journal of Terra-mechanics* 9(2):33-63.
- Schmertmann, J. H. 1970. Static cone to compute static settlement over sand. *Journal of the Soil Mechanics and Foundations Division, American Society of Civil Engineers*, Vol. 96, No. SM3, pp. 1011-1043.
- Schmertmann, J. H. 1975. Measurement of in-situ shear strength. *Proceedings of the Conference on In-Situ Measurement of Soil Properties*. Vol. II, pp. 57-138.
- Schultze, A. and K. J. Meltzer. 1965. The determination of the density and modulus of compressibility of noncohesive soils by soundings. *Proceedings 6th International Conference on Soil Mechanics and Foundations Engineering*, Vol. I, pp. 354-358.
- Smith, J. L. 1964. Strength-moisture-density relations of fine-grained soils in vehicle mobility research. U.S. Army Engineer. Waterways Experiment Station, Vicksburg, Mississippi.
- Smith, L. A. and W. T. Dumas. 1978. A recording soil penetrometer. *TRANSACTIONS of the ASAE* 21(1):12-14, 19.

- Soane, B. D. 1976. Gamma-ray transmission system for in-situ measurement of soil packing state. Report 1974-76, Scottish Institute of Agriculture Engineering.
- Soane, B. D. and J. K. Henshall. 1979. Spatial resolution and calibration characteristics of two narrow probe gamma-ray transmission systems for the measurement of soil bulk density in-situ. *Journal Soil Science* 30:517-528.
- Statistical Analysis System. 1982. SAS users guide.
- Taylor, H. M. 1971. Root behavior as affected by soil structure and strength. In the plant root and its environment (ed., E. W. Carson). Proceedings at Virginia Polytechnical Institute and State University, July 5-16, 1971.
- Threadgill, E. D. 1982. Residual tillage effects as determined by cone index. *TRANSACTIONS of the ASAE* 25(4):853-863, 867.
- Tollner, E. W. and B. P. Verma. 1983. Modeling the cone penetrometer using similitude principles. ASAE Paper No. 83-1540, American Society of Agricultural Engineers, St. Joseph, MI 49085.
- Troxler Electronic Laboratories. 1979. 3400-b series surface moisture-density gauges. Troxler International, LTD.
- Turnage, G. W. 1974. Resistance of coarse-grained soils to high-speed penetration. U.S. Army Technical Report No. 3-652.
- Tyler, D. D., J. R. Overton and A. Y. Chambers. 1982. Soybean tillage effects on soil properties, diseases, cyst nematodes and yield. University of Tennessee, Knoxville.
- Upadhyaya, S. K., L. J. Kemble, N. E. Collins and T. H. Williams. 1982. Cone index prediction equations for Delaware soils. ASAE Paper No. 82-1542. American Society of Agricultural Engineers, St. Joseph, MI 49085.
- Van Bavel, C. H. M., N. Underwood and S. R. Rager. 1957. Transmission of gamma radiation by soils and soil densitometry. *Soil Science Society of America Proceedings* 21:588-591.
- Van der Veen, C. 1957. The bearing capacity of a pile predetermined by a cone. Proceedings 4th International Conference on Soil Mechanics and Foundation Engineering, Vol. 12, pp. 72-75.
- Veihmeyer, F. J. 1929. An improved soil sampling tube. *Soil Science* 27:147-152.

- Vigier, B. and J. A. Campbell. 1980. Calibration of a single gamma probe for measuring wet bulb density in organic soil. *Canadian Journal Soil Science* 60:133-135.
- Vomocil, J. A. 1954. In-situ measurement of soil bulk density. *Agricultural Engineering* 35:651-654.
- Waterways Experiment Station. 1948. Trafficability of soils-development of testing instruments. Technical Memo. No. 3-240.
- Wells, C. B. 1959. Core samplers for soil profiles. *Journal of Agriculture Engineering Research* 4:260-266.
- Wells, L. G. and O. Tresuwan. 1977. The response of various soil strength indices to changing water content. ASAE Paper No. 77-1055. American Society of Agricultural Engineers, St. Joseph, MI 49085.
- White, M. S., M. C. Vodak and D. C. Cupp. 1983. The effect of surface compaction on the moisture content of piled green hardwood chips. Forestry and Forest Products Dept., School of Forestry, VPI and SU, Blacksburg, VA.
- Whitney, B. D., K. E. Oskovi and R. B. Spiers. 1982. A simulation model for predicting soil moisture status and tillage research. No. 2, pp. 67-80.
- Williford, J. R., O. B. Wooten and F. E. Fulgham. 1972. Tractor mounted field penetrometer. *TRANSACTIONS of the ASAE* 15(2): 226-227.
- Wilkerson, J. B., F. D. Tompkins and L. R. Wilhelm. 1982. Microprocessor-based, tractor-mounted soil cone penetrometer. ASAE Paper No. 82-5511. American Society of Agricultural Engineers, St. Joseph, Mi 49085.
- Wilkerson, J. B. 1983. Microprocessor-based, tractor-mounted soil cone penetrometer. Master of Science thesis, The University of Tennessee, Knoxville.
- Wisner, R. D. and H. J. Luth. 1974. Off-road traction prediction for wheeled vehicles. *TRANSACTIONS of the ASAE* 17(1):8-10, 14.
- Young, R. N. and C. K. Chen. 1970. Analytical and experimental studies of soil cutting. ASAE Paper No. 70-676. American Society of Agricultural Engineers, St. Joseph, MI 49085.
- Zelenin, A. N. 1950. Basic physics of the theory of soil cutting. Moscow.

APPENDICES

APPENDIX A

Table A1. Cone Index Means for Six Tillage Practices on a Lexington Silt Loam by Depth

Tillage Treatment**	Depth Increment (inches)					
	0-2	2-4	4-6	6-8	8-10	10-12
	----- (Mean Cone Index, lb/in ²) -----					
1-Disk	139b*	326ab	438a	413a	301a	243ab
2-No Tillage	212a	379a	439a	421a	288a	181b
3-Previous No-Tillage	151b	282bc	313b	293bc	219a	177b
4-Moldboard Plow	154b	205c	201c	192c	249a	264a
5-Under-row Subsoil	141b	295ab	352ab	324ab	249a	222ab
6-Chisel Plow	148b	285bc	307b	270bc	221a	207ab
Average	158	296	342	319	255	216

* Means within a column followed by the same letter are not significantly different at the 90 percent level of probability.

** Refer to page 39 for a detailed description of the tillage treatments.

Table A2. Cone Index Means by Traffick Condition at Various Soil Depths for Six Tillage Treatments in a Lexington Silt Loam

Tillage Treatment *	Soil Depth Increment																	
	0 - 2 inches			2 - 4 inches			4 - 6 inches			6 - 8 inches			8 - 10 inches			10 - 12 inches		
	Under Row	Row Middle	Wheel Track	Under Row	Row Middle	Wheel Track	Under Row	Row Middle	Wheel Track	Under Row	Row Middle	Wheel Track	Under Row	Row Middle	Wheel Track	Under Row	Row Middle	Wheel Track
	----- (Mean Cone Index, lb/in ²) -----																	
1. Disk	131 **	159a	127a	290a	364a	325a	404b	438ab	473a	377b	412b	451a	267b	266b	371a	261a	239a	277a
2. No-Tillage	179ab	163b	296a	352b	346b	440a	436b	400c	483a	417a	395a	453a	276a	288a	302a	178a	173a	192a
3. No-Tillage Prev	133a	157a	164a	222b	301a	324a	228c	329b	384a	221b	279ab	382a	173a	196a	288a	163b	164b	206a
4. Moldboard Plow	110a	155a	197a	140a	227a	251a	143b	227a	236a	178a	193a	207a	290a	249a	211a	299a	276a	219a
5. Under-row Subsoil	125a	88a	212a	282a	252a	352a	341a	332a	386a	315a	317a	341a	277a	209b	262a	233a	209b	227ab
6. Chisel Plow	148a	133a	163a	283a	257a	317a	313a	274a	335a	282a	257a	271a	240a	200a	225a	193b	205ab	224a
Average	138	143	193	262	291	335	311	333	383	298	309	351	254	235	277	221	211	216

* For detailed description of tillage treatments, refer to page 39.

** Numbers in the same row for a given depth followed by the same letter are not significantly different at the 90 percent probability level.

Table A3. Bulk Density by Traffick Condition at Various Depth for Six Tillage Treatments in a Lexington Silt Loam

Tillage * Treatment	Soil Depth Increment														
	0 - 2 inches			2 - 4 inches			4 - 6 inches			6 - 8 inches			8 - 10 inches		
	Under Row	Row Middle	Wheel Track	Under Row	Row Middle	Wheel Track	Under Row	Row Middle	Wheel Track	Under Row	Row Middle	Wheel Track	Under Row	Row Middle	Wheel Track
	Density, lb/ft ³														
1. Disk	71	82	79	73	86	85	80	91	90	84	93	92	86	91	85
2. No-Tillage	65	73	76	74	82	85	83	86	89	64	89	90	85	85	85
3. No-Tillage Prev	72	74	77	80	81	84	84	85	88	87	87	89	86	88	87
4. Moldboard Plow	74	76	80	76	78	87	79	83	89	82	86	90	83	81	83
5. Under-row Subsoil	70	74	75	73	78	81	80	83	86	84	85	89	80	83	87
6. Chisel Plow	67	75	80	74	78	85	80	83	89	84	85	89	80	83	87

* For detailed description of tillage treatments, refer to page 39.

100% COTTON FIBRE
AND CASTLE BOND
100% COTTON FIBRE
100% COTTON FIBRE

APPENDIX B

Table B1. Moisture Content Values by 2-Inch Depth Increments for Six Tillage Treatments

Tillage Treatment**	Depth Increment (inches)					
	0-2	2-4	4-6	6-8	8-10	10-12
1-Disk	14	16	16	17	20	20
2-No-Tillage	22	19	20	21	21	21
3-Previous No-Tillage	21	20	19	20	21	20
4-Moldboard Plow	13	16	16	16	18	18
5-Under-row Subsoil	15	16	17	17	19	20
6-Chisel Plow	15	17	17	18	19	19
Average	17	17	18	18	20	20

** Refer to page 39 for a detailed description of the tillage treatments.

VITA

Gary Richard Walker was born in Knoxville, Tennessee, on April 28, 1959. He attended Soldiers Memorial Elementary School in Tazewell, Tennessee, and graduated from Claiborne County High School in 1977.

He attended The University of Tennessee, Knoxville, and received a Bachelor of Science degree in Agricultural Mechanization in June 1981. He accepted a research assistantship with The University of Tennessee Agricultural Engineering Department and completed the requirements for a Master of Science degree in Agricultural Mechanization in June 1984.

He is a member of the American Society of Agricultural Engineers.