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An Analog Technique for Soil-tool Systems

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AN ANALOG TECHNIQUE

FOR

SOIL-TOOL SYSTEMS

By

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This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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LIST OF SYMBOLS AND TERMS

δ - Prediction factor, $\delta = \pi_1/\pi_{1m}$

δ_F - Force prediction factor, $\delta_F = F/A$

F - Draft force on a prototype tool

A - Draft force on a model tool

n - Length scale, ratio of prototype length to model length

s - A dimensionless exponent associated with δ for the soil-tool system under consideration

S - A dimensionless exponent associated with δ_F for the soil-tool system under consideration

k - Subscript referring to cone penetrometers

c - Subscript referring to chisels

d - Subscript referring to disks

π_1 - Performance Pi term for system

Prototype: The physical system for which the predictions are to be made.

Model: A device which is so related to a physical system that observations on the model may be used to predict accurately the performance of the physical system in the desired respect.

Distorted Model: A model in which some design condition is violated sufficiently to require correction of the prediction factor.

Pi term: A Pi term (denoted by π) is a dimensionless and independent quantity formed by two or more groups of variables influencing the phenomenon.

Soil-Machine System: A system in which dynamic interaction between soil and a machine takes place.

Soil-Tool System: A system in which dynamic interaction between soil and a tillage tool takes place.

Soil-Cone Penetrometer System: The soil-tool system in which the cone penetrometer is the tillage tool

Soil-Chisel System: The soil-tool system in which the chisel is the tillage tool.

Soil-Disk System: The soil-tool system in which the disk is the tillage tool.

Analog-Prototype System: A system in which measurements on an analog tool would be used to predict the performance of a prototype tool.

INTRODUCTION

Throughout the history of agriculture man has sought improved methods of tilling soil. Technological developments in recent years have enabled man to apply large amounts of mechanical energy to soil tillage. But, as the energy limitations of the world begin to be realized, the development of more efficient means of soil tillage will become increasingly important.

In tillage machine design, as in other engineering design fields, the designer has three basic methods of predicting the performance of a system. Murphy (12) states these methods as (i) application of existing laws and formulas, (ii) observations on the actual systems, and (iii) use of model systems, or similitude. The first method has not been successfully applied to tillage, while the second method has been and still is widely used in evaluating the performance of tillage machines. However, it is expensive, time consuming, and restrictive. Within the last 20 years, the third method which uses modeling and similitude theory has been applied to tillage studies. Some of the advantages of studying modeled tillage systems are:

i. better control of the environment,

ii. better control over soil conditions,

iii. better application of instrumentation technology,

iv. less expense with model construction, and

v. easy alteration of models.

This research was conducted to further the application of modeling and similitude theory to soil-machine systems. The goal was to investigate and expand the application of an analog prediction technique which was proposed by Schafer (20).

LITERATURE REVIEW

Various fields of engineering utilize model studies as an effective design tool that allows an engineer to evaluate the performance of a structure or machine preceding its construction. Model studies have been successfully applied in many areas, e.g., structures, heat transfer, fluid mechanics, and mechanical vibrations etc.

Similitude theory which is used in evaluating model studies is explained by Murphy (12):

> A model is a device which is so related to a physical system that observations on the model may be used to predict accurately the performance of the physical system in the desired respect. Those principles which underlie the proper design and construction, operation, and interpretation of test results of these models comprise the theory of similitude.

A brief explanation of similitude theory and the basic principles that relate its application to soil-tool systems has been presented by Freitag, Schafer, and Wismer (6).

Application of similitude theory to tillage implement performance was initiated by Barnes, Bockhop, and McLeod (3). Bockhop studied the prediction of draft force on a 25.4 cm (10 in.) concave disk from force measurements on a 12.7 cm (5 in.) concave disk. Using a list of soil variables established by Nichols (13, 14), Bockhop was able to satisfy all the proposed design conditions. Therefore, true model theory was considered applicable. The disks were operated in soils with low and high clay contents. The results indicated that the model disk predicted the prototype disk better at low clay content, than at the higher clay content.

In a similar disk study, McLeod (3) modified Nichols' list of significant soil variables, and was unable to satisfy all the design conditions of the proposed model soil-disk system. Therefore, distorted model theory was applied. An improvement on the model to prototype predictions indicated that application of the theory of distorted models was more appropriate than the theory of true models used by Bockhop. In review Wismer, Freitag, and Schafer (23) point out that the results from McLeod's soil-disk system suggest that some significant variables were not identified and other design conditions not considered were distorted.

The majority of the research that followed McLeod's disk study was based on distorted model theory. This theory was applied because of an inability to define and model soil properties adequately. Young (24) suggests three basic methods for handling distortion:

i. To neglect certain variables that may be only slightly significant but lead to the distortion,

ii. To determine the effect of the distortion, either analytically or experimentally, to account for its influence, or

iii. To determine the effect of the distortion empirically.

A majority of the subsequent soil-machine research with models used the empirical approach.

Studies by Larson (9) and Reaves (15) employed distorted model theory to determine a prediction factor that would relate model to prototype forces. Larson resolved a prediction factor for each distortion factor in a soil-moldboard plow system.

Reaves investigated modeling of triangular chisels. His objective was to relate the prediction factor to soil parameters measured with a cone penetrometer and ring shear annulus. Reaves reported the cone penetrometer superior to the annulus in accounting for the distortion in the soil-chisel system.

As indicated by Verma (21), the basic problems that McLeod, Larson, and Reaves encountered were:

i. an inadequate system of soil characterization, and

ii. an unsatisfactory method of determining the prediction factor.

Also, each researcher's conclusions were related only to the specific soil-tool systems in the respective studies.

After recognizing these problems, Schafer (17) hypothesized that if the soil properties in the design conditions were the same in the model and prototype, the prediction factor could be expressed as a function of the length scale and pi-terms containing soil properties. The performance data from 7.62- (3 in.), 15.24- (6 in.), and 30.48-cm (12 in.) diameter concave disks were analyzed to determine the prediction factor. Then, this factor was used to predict the draft on 45.76 cm (18 in.) and 60.96 cm (24 in.) disks.

The results led Schafer (18) to propose a more simplified distorted model system in which the prediction factor was a function of the length scale alone. The form of the relationship was:

$$\delta = n^s$$

where, δ = prediction factor

n = length scale, and

s = a dimensionless exponent for the soil-tool system under consideration.

This relationship adequately described several soil-tool systems such as, triangular chisels, bulldozer blades, moldboard plows, sweeps, cone penetrometers, and concave disks. The theory is satisfied by the following simplifying assumptions:

i. all pertinent soil properties are included in one term,

ii. all soil properties are constant throughout the profile,

iii. all acceleration forces are insignificant when tools are operated at low velocity, and

iv. soil properties with dimensions of force and length are pertinent in a soil-tool system.

In Schafer's research the exponent s seemed to vary with tool type, soil type, and soil conditions. As indicated by Schafer (20), the limitation of this technique is that s must be determined empirically. Therefore, two or more models of the tool must be tested to establish s. This makes the technique time consuming and more expensive.

Verma (21) encountered problems with a nonuniform soil profile during development of a compensated model theory for a soil-chisel system. Later, Verma (22) proposed a distorted model theory for a non-uniform soil profile which was based on the same data as the compensated model study. It was theorized that different chisel sizes operating at scaled depth were in effect encountering different soil conditions when operating in a nonuniform vertical strength profile. Verma reasoned that if all tools were operated at the same depth they would encounter the same strength profile. Therefore, all chisels were tested at the same depth. As in Schafer's study, the prediction factor was considered a function of the length scale in the form:

$$\delta = n^{(s-t)},$$

where (s-t) is a dimensionless exponent for the soil-tool machine system under consideration. The exponent (s-t) remained relatively constant irrespective of soil type and condition. However the results are very restrictive because the chisels had no pertinent vertical length. Therefore, as indicated by Verma (22) this technique required the pertinent vertical geometry of the soil-tool system be designed with its vertical length scale equal to unity.

More recently, Schafer and Reaves (20) have proposed a distorted model prediction technique that was based on the use of an analog device. Schafer theorized the system as follows:

> The analog device would be a simple device, such as cone penetrometer, and that measurements on the analog device could be acquired much more easily than on a series of models of the prototype. Then, measurements on the analog device would be used in a prediction system to predict the performance of a prototype system.

A cone penetrometer was used as an analog device for a triangular chisel. Schafer developed the prediction equation:

$$F_c = A_c \, n^{S_{ck} S_k}$$

and

$$S_{ck} = S_c / S_k,$$

where "c" and "k" denote the chisel and cone, respectively.

F_c - the predicted prototype force

A_c - force on the model

n - length scale

S_k - dimensionless exponent from distorted soil-cone system,

$\delta_F = n^{S_k}$, and

S_c - dimensionless exponent from distorted soil chisel system,

$\delta_F = n^{S_c}$.

Schafer envisioned that systematic changes in S_c and S_k would cause S_{ck} to remain constant over various soil types and conditions. Therefore once S_{ck} was established for a given soil, measurements on one model chisel to obtain A_c and several cones to obtain S_k would be the only data necessary for prediction of forces on the prototype chisel. This analog technique gave adequate predictions for the chisels that were investigated when the depth of operation was distorted as in Verma's research. The theory was not extended to other tools of different geometrical shape.

Distortion which is introduced by an inadequate description of soil properties was recognized throughout the reported research. The three major factors contributing to distortion were stated by Freitag, Schafer, and Wismer (6) as:

i. Not all the pertinent soil properties have been identified,

ii. Practical measurement of soil properties is often difficult or impossible,

iii. Soil properties are difficult or impossible to scale.

Studies by Johnson (8), Bailey (2), and Flenniken (4) have investigated different soil property concepts. Although these studies have revealed important information, they did not provide a conclusive quantitative description of pertinent soil properties.

Two decades have passed since Bockhop applied the principles of similitude to a study of a modeled soil-disk system. Research following that of Bockhop encountered the same basic problem which resulted from an inadequate description and quantification of pertinent soil properties and their influence on specific tillage tools. The inability to model or define soil properties has prompted researchers to apply distorted model theory. This theory has in the past and will in the future play an important part in our understanding of modeling soil-machine systems, as Verma (22) comments, "the application of the theory of distorted models in soil-machine systems appears inevitable, at least until scientists can adequately define soil properties such that scaling of pertinent soil properties becomes practical."

THEORY AND OBJECTIVES

In many past studies of distorted model tillage systems the concept of relating the prediction factor to distorted pi terms has failed to evolve an adequate model-prototype prediction system which can be applied over a broad range of conditions. Recently, Schafer (18) proposed that the prediction factor for force could be determined through the relationship:

$$\delta_F = F/A = n^S, \qquad 1$$

where δ_F - Force prediction factor,

F - Prototype force,

A - Model force,

n - Length scale, and

S - Exponent for the soil-tool system.

Schafer developed the relationship from observed soil-tool system data pi-terms obtained by application of similitude theory. The proposal requires that all tools be operated in soil with equal properties throughout and at low velocities to minimize time effects.

Later, Schafer (20) expanded this concept by proposing an analog prediction technique for distorted model systems. He proposed that a simple tool, such as a cone penetrometer could be utilized as an analog device to develop a technique for predicting the performance of a more complex soil-tool system.

Schafer derived the analog prediction equation with a cone penetrometer as an analog to a soil-chisel system. The analog technique is based on the validity of equation 1 for both the analog and prototype performance, so

$$F_c = A_c\, n^{S_c} \qquad 2$$

and $$F_k = A_k\, n^{S_k}, \qquad 3$$

where "k" and "c" represents the cone and chisel, respectively. The analog prediction equation is derived directly from equations 2 and 3 where

$$F_c = A_c\, n^{S_{ck} S_k} \qquad 4$$

and $$S_{ck} = S_c/S_k. \qquad 5$$

F_c is the prototype force and A_c is the force on the model of the prototype. The complete derivation of equation 4 has been reported by Schafer (20). A generalized form of the analog prediction equation becomes

$$F_i = A_i\, n^{S_{ij} S_j} \qquad 6$$

and $$S_{ij} = S_i/S_j, \qquad 7$$

where "i" and "j" represent the prototype and analog, respectively. This analog technique is based on the concept of "same soil" conditions for both the model and prototype. An explanation of "same soil" can be found in Freitag (6).

As Schafer explained, this technique requires that measurements must be made on several model sizes of the prototype tool and the analog tool to determine S_{ij}. However, S_{ij} may be constant over various soil types or conditions because of systematic changes in S_i and S_j. So once S_{ij} was known, only measurements on one model and several sizes of the analog tool would be needed for force prediction of the prototype. In proposing this technique, Schafer hypothesizes that the forces on the analog and prototype could be governed by the same soil properties or by different properties that are correlated or vary systematically.

The potential of the analog technique developed by Schafer to reduce the amount of test data required for performance prediction of tillage tools and its simplicity led to this research. Combinations of the cone penetrometer, triangular chisel, and concave disk were evaluated as possible analog-prototype systems. These tools were studied because they represent a wide range of shapes and actions in tilling soil.

The objectives of this research were:

1. Determine if the distorted force prediction equation, $\delta_F = n^S$, can be applied to the soil-tool systems studied.

2. Determine the influence of soil conditions and operating procedures on the proposed analog technique.

3. Determine which of the three proposed analog-prototype systems: cone-chisel, cone-disk, or chisel-disk were least influenced by soil condition and operational procedure.

EXPERIMENTAL DESIGN AND PROCEDURE

Selection of Soil-Tool Systems

The soil-tool systems included in this study were the cone penetrometer, triangular chisel, and spherical disk. The cone penetrometer and chisel were selected because of their simple geometry and operation. Both tools have been studied extensively in past tillage research including the analog-prototype system proposed by Schafer. The spherical disk was selected because it is a common agricultural tool of rather complex shape and the design could benefit through the use of an analog-prototype system.

Three sizes of chisels and four sizes of cones and disks were used. Length scales were chosen as 1, 2, 3, 5 relative to the smallest size. The chisel with the length scale 2 was excluded because of limited test bin area. The sizes of the tools were selected arbitrarily within the restriction that the smallest tool should be large enough to produce the same fundamental soil behavior as the largest tool.

The cone penetrometers and chisels were designed and constructed by the author while the disk blades were selected from those available at the National Tillage Machinery Laboratory (NTML), Auburn, Alabama. All soil contact surfaces were highly polished steel.

Cone Penetrometer. All cones (Figure 1) had an apex angle of 45°. This deviates from a standard 3.2 sq cm (0.5 sq in.) cone penetrometer (1) which has an apex angle of 30°, but Freitag (5) found little difference in cone forces for apex angles between 30° and 90°. Thus, a cone with a 45° apex angle was used since it was easier to construct than a cone with a 30^{o} apex angle. The base diameters of the cones are listed in Table 1. These diameters give length scales of 1, 2, 3, and 5 relative to the smallest diameter.

Chisel. All chisels (Figure 2) had a wedge angle of 30^{o}. Chisels with this wedge angle exhibited good tillage characteristics in prior research by Schafer (20). The base widths of the chisels are listed in Table 1. These widths gave length scales of 1, 3 and 5 relative to the smallest width.

Disk. The criteria for geometric description of a spherical disk blade were indicated by McCreery and Nichols (10) as diameter and radius of curvature. The diameters and radii of curvature of the disks are listed in Table 1. These dimensions give geometrically similar models with length scales of 1, 2, 3, and 5 relative to the smallest disk. The angle of approach was 35^{o} for all disks. This angle was selected to limit the influence of the radius of curvature on the draft force as suggested in a study by McCreery (11). A zero angle of inclination was used for all disks. The disks are shown in Figure 3.

Each tool will be referred to by an identification number such as Cone 1, Chisel 2, and Disk 3, etc., as defined in Table 1.

Statistical Design

The performance data for the cones, chisels, and disks operating at varied depths in six soil preparations were analyzed based on the following statistical design. A randomized complete block design was utilized to limit the effect of soil strength variation within the bin. Each bin was divided into three blocks or replications with duplicate tests

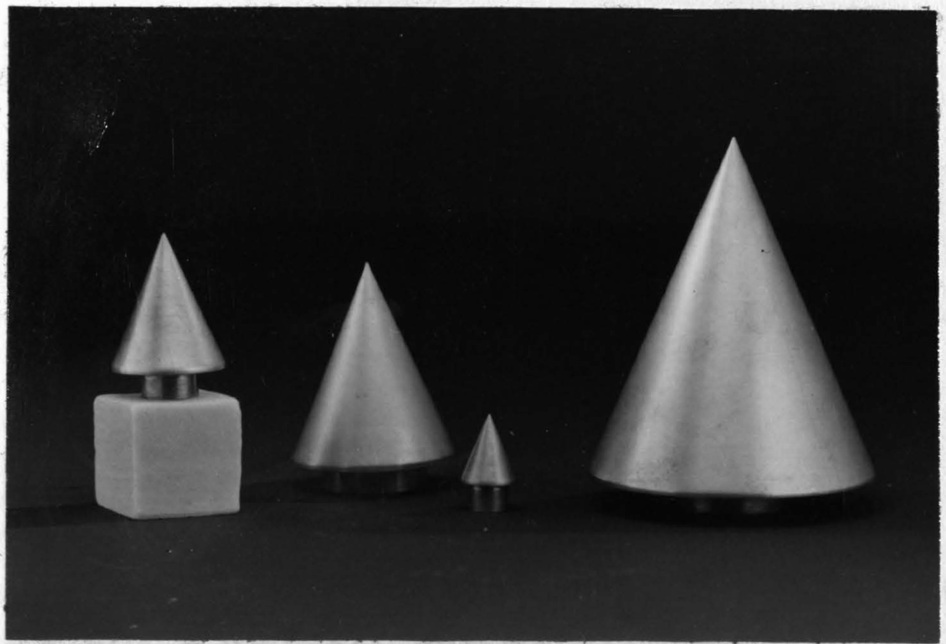

Figure 1. Model cones

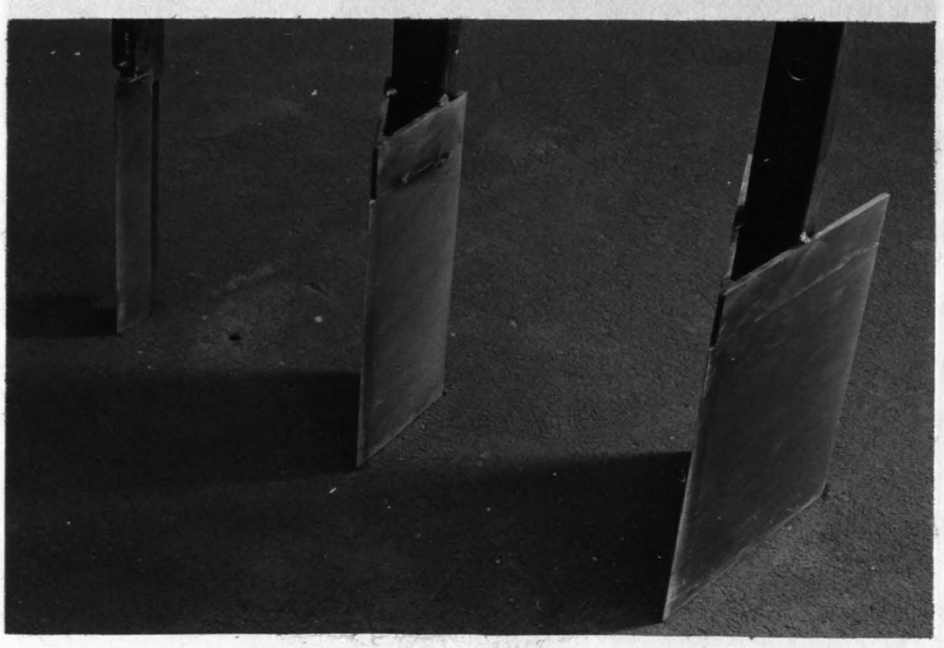

Figure 2. Model chisels

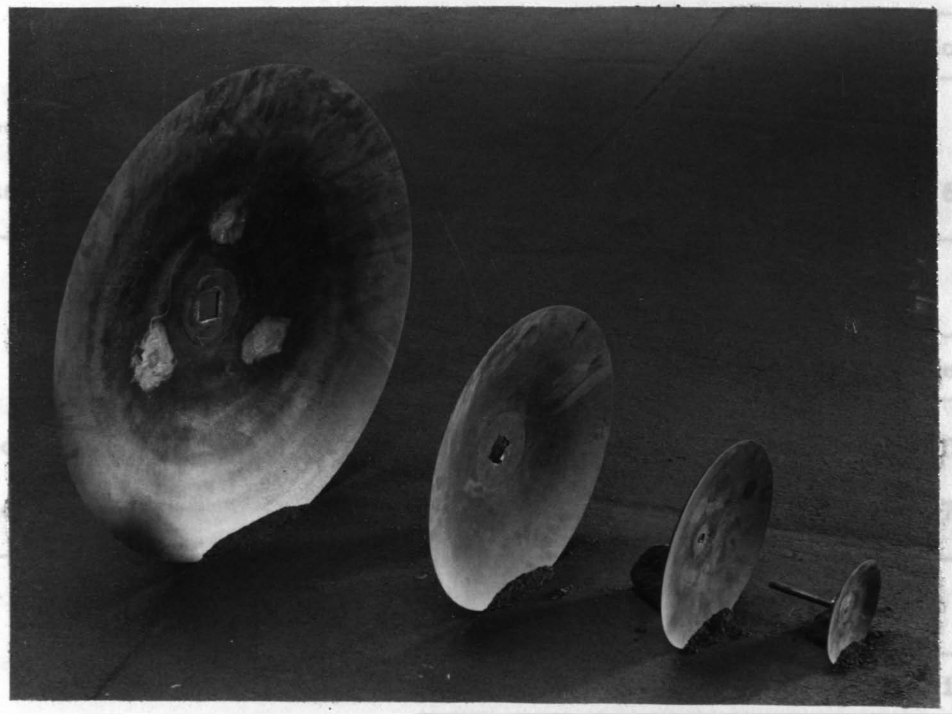

Figure 3. Model disks

Table 1

Summary of Tool Geometry

	CONES			
	Cone 1*	Cone 2	Cone 3	Cone 4
Apex Angle	45°	45°	45°	45°
Base Diameter (cm)	1.27	2.54	3.81	6.35

	CHISELS		
	Chisel 1	Chisel 2	Chisel 3
Wedge Angle	30°	30°	30°
Width (cm)	2.54	7.62	12.70

	DISKS			
	Disk 1	Disk 2	Disk 3	Disk 4
Diameter (cm)	12.95	25.91	38.86	64.77
Radius of Curvature (cm)	15.07	30.14	45.22	75.36

* Tool identification by type and size.

within each block. These duplicate tests which give an indication of sampling error were conducted as close to one another as possible. The block design of the soil bin is illustrated in Figure 22, Appendix C. Tests were conducted such that the order of testing of the different sized tools were randomized within tool type. The tool types were randomized within blocks, so that a specific tool would not always be tested in the exact same bin area for each soil preparation.

Test Facilities

All tests were conducted on the large indoor bin facility at the National Tillage Machinery Laboratory (NTML). The soil bins measure 57.91 meters long, 6.10 meters wide, and 1.52 meters deep and are shown in Figure 4.

The power car, dynamometer car, and instrument car provided the mobility and instrumentation necessary to conduct the tests. Figure 5 indicates the arrangement of these cars. Soil fitting equipment included a roto-tiller, leveling blade, watering device, flat-roller, plow-pack device, and penetrometer car.

Instrumentation for Data Acquisition

A MODCOMP III/15 digital computer system was used in the data acquisition and recording phase of testing. Schafer and Bailey (16) have reported the characteristics of this data acquisition, transmission, and recording system.

Because of the wide range of tool types and sizes, four different force dynamometers were required. The cone penetrometer system which is shown in Figure 6 used a 0-22241 N load cell (a one dimensional

Figure 4. Indoor soil bins

Figure 5. Arrangement of the power, dynamometer, and instrument cars

dynamometer) to measure penetration resistance.

Draft forces on the chisels were measured by a 0-11200 N three-dimensional force dynamometer which is the smallest of the two primary dynamometers on the dynamometer car. The chisels were mounted as shown in Figure 7.

Draft forces on the disks were measured by three different dynamometers. Disk 1 (refer to Table 1, page 17 for tool identification) was mounted on a 0-220 N two-dimensional force dynamometer. Disks 2, 3 and 4 used a 0-2250 N two-dimensional force dynamometer or the 0-11200 N three-dimensional force dynamometer depending on the maximum draft forces involved. Disk mountings are shown in Figures 8 and 9. Measurements of the vertical forces and moments of both the chisels and disks were recorded but were not included in the analysis. A variable resistance displacement transducer indicated the depth of operation from the soil surface for all tools.

The signals from the dynamometers and displacement transducer were conditioned and amplified into analog data by equipment in the instrument car. The analog data were recorded on an oscillograph for immediate output. Simultaneously, the data were converted from analog to digital for use and interpretation by the computer. The computer recorded the data, and immediately plotted the force vs. depth data on an X-Y plotter in the instrument car.

The oscillograph recording and the X-Y plotting were performed simultaneously as the test run progressed. At the end of each day of testing the data which were recorded on disk memory were transferred

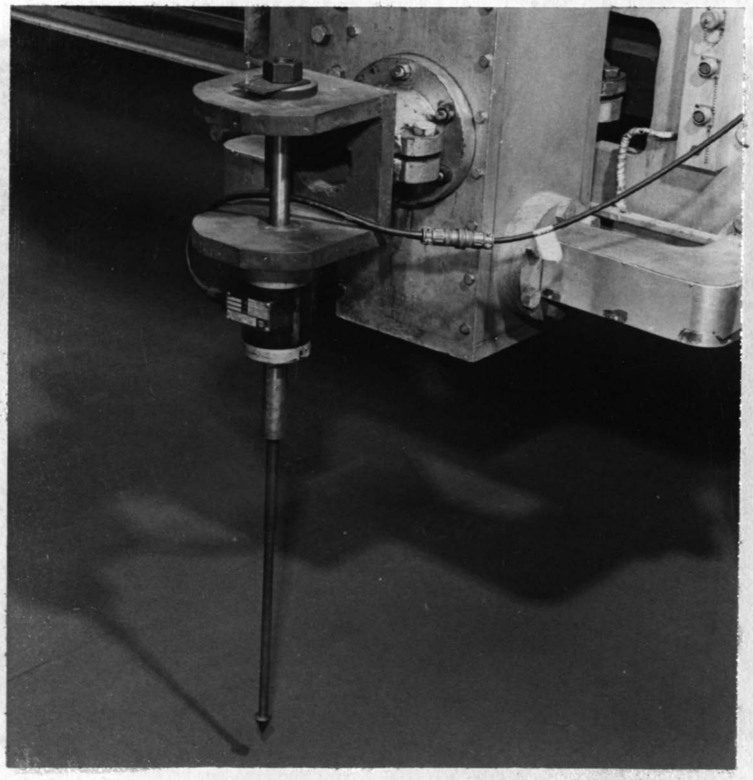

Figure 6. Cone penetrometer mount

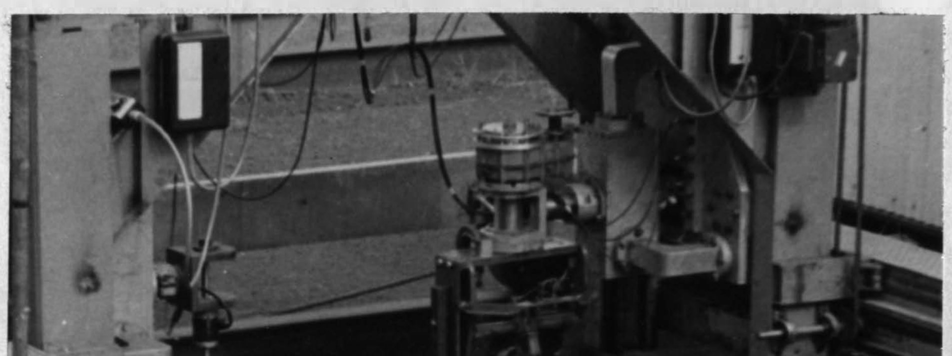

Figure 7. Chisel mount

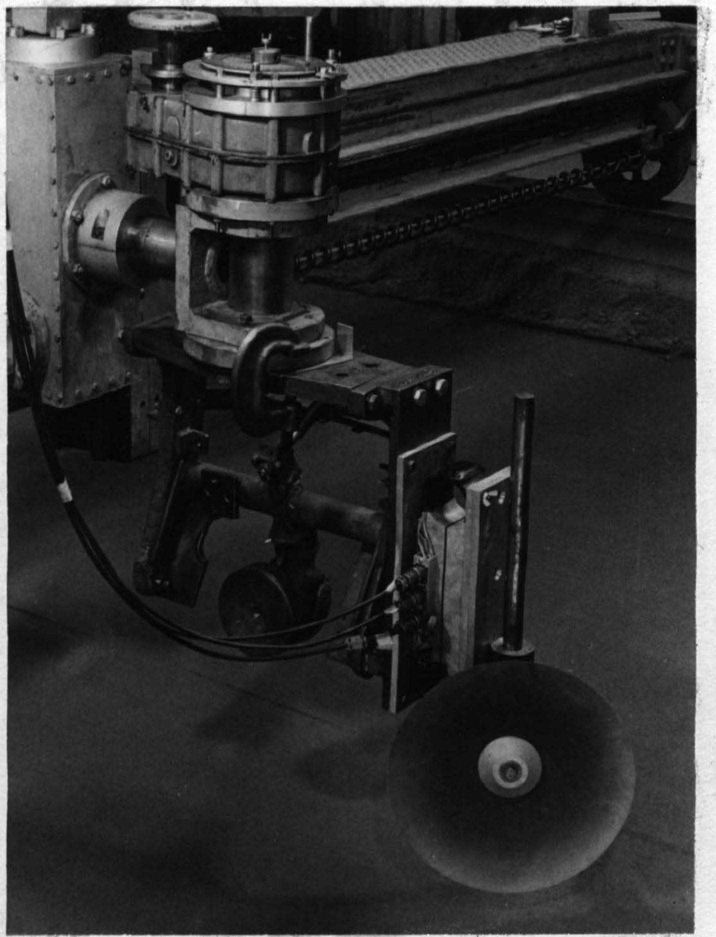

Figure 8. Disk 2 mounted on the 0-2250 N 2-D dynamometer

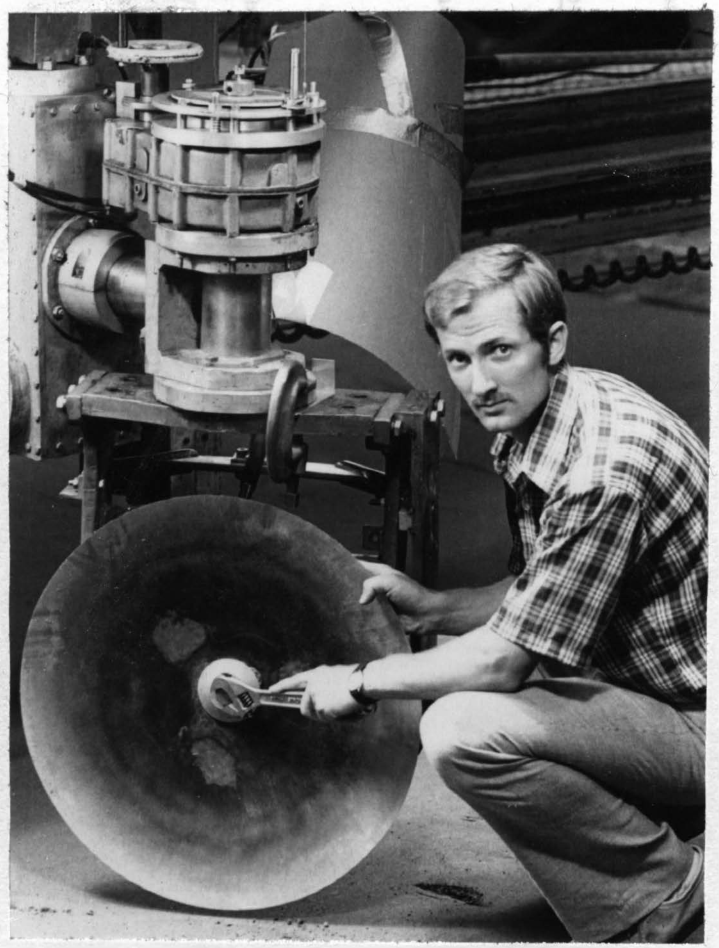

Figure 9. Disk 4 mounted on the 0-11200 N 3-D dynamometer

to magnetic tape for permanent storage. A schematic diagram of the instrumentation scheme is shown in Figure 10.

Soil Description

The two soils in the large indoor bins at the NTML were studied. These soils are identified as

i. Norfolk Sandy Loam, and

ii. Decatur Clay Loam.

The physical structures of these soils were very different as indicated by the mechanical analysis in Table 2. The Norfolk is a sandy soil, while the Decatur has a high clay content.

Table 2

Mechanical Analysis of Soils

Soil Type	Percent Sand > 0.05 mm	Percent Silt 0.05-0.002 mm	Percent Clay < 0.002 mm
Norfolk Sandy Loam (NS)	71.6	17.4	11.0
Decatur Clay Loam (DC)	26.9	43.4	29.7

Soil Preparation

The six soil preparations, reported in Table 6, Appendix A, were prepared from the Norfolk and Decatur soils at various moisture and penetration resistance levels. Each soil preparation required an individualized procedure. These procedures are summarized in Table 7, Appendix A.

The first step was to pulverize the soil with a roto-tiller to a

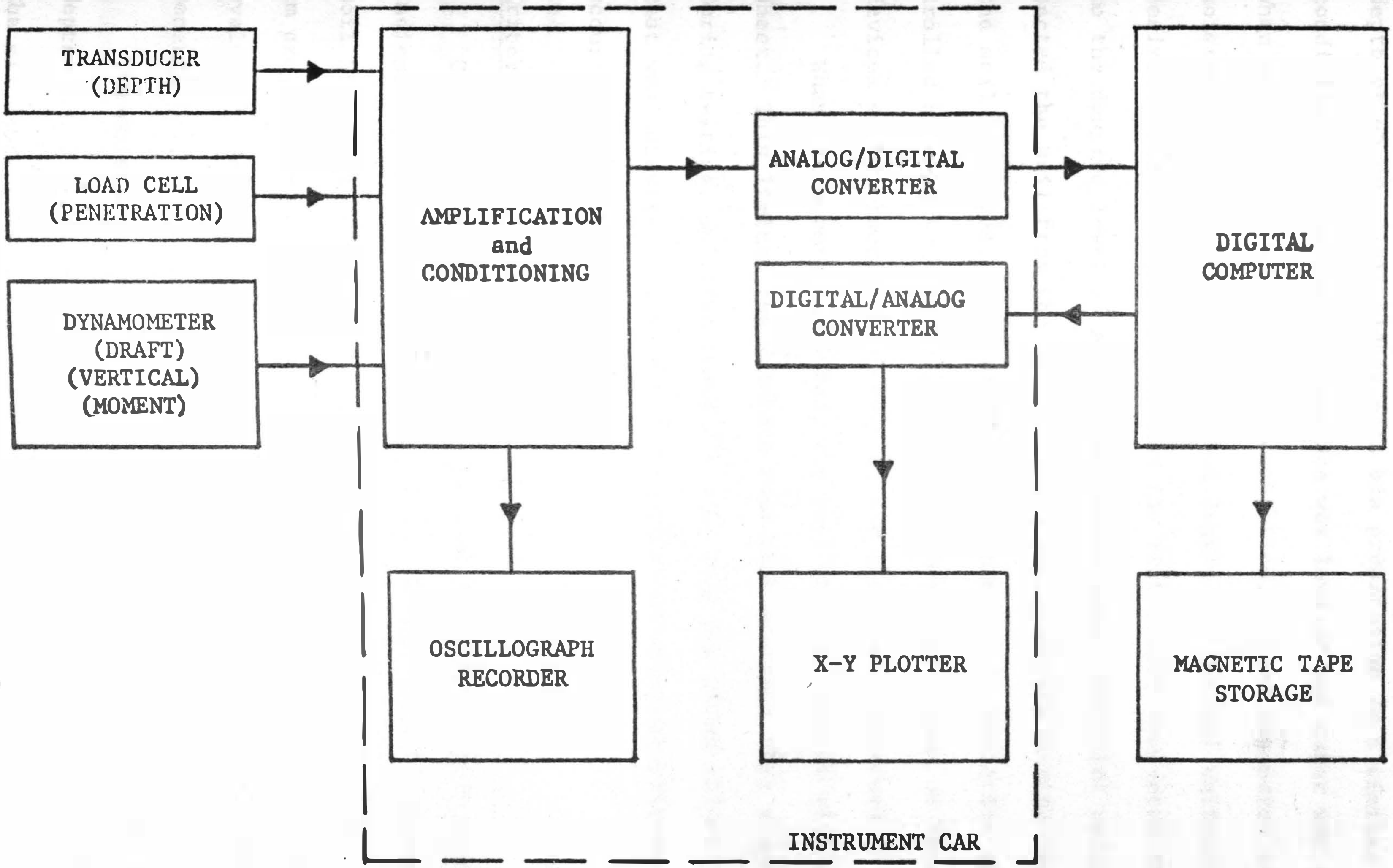

Figure 10. Schematic diagram of instrumention systems

depth of 45 cm. This places each bin preparation in a similar initial condition. Then, the soil surface was leveled and water was added when needed. The next process, compaction, varied depending on the moisture level, strength level, and degree of vertical uniformity desired. The plow-pack device and the flat-roller compacted the soil to the desired level of penetration resistance. The flat roller compacted the soil from the surface while the plow-pack device compacted the soil in stages. The degree and uniformity of compaction was controlled by changing the weight and the number of passes of these devices or by changing the depth of the plow-pack procedure.

When these were completed, the soil bin was covered with a plastic sheet. This limited the moisture loss that occurred from evaporation. During testing, only the immediate area that was being tilled in the test was uncovered. This procedure minimized moisture differences from occuring along the length of the soil bin.

Criteria for Evaluating Soil Preparations

Cone penetration resistance and moisture content were used to indicate the uniformity of the vertical strength profile during soil bin preparation. A standard cone penetrometer (1) with a 3.2 sq cm projected area, 30^{o} apex angle, and penetration rate of 3.05 cm/sec evaluated the uniformity of the vertical profile and the relative penetration resistance of the different soil preparations.

The moisture content and bulk density were determined at three depths: 0-6.4 cm, 7.6-14.0 cm, and 15.2-21.6 cm. These data for the six soil preparations are summarized in Table 6, Appendix A.

Testing Procedure

Data acquisition consisted of operating all tools in the six different soil preparations. The soil bin was divided into five sections along its length. The length of these sections represented the length of a chisel run which was approximately 8.5 meters. Cone 2 tests were taken at 0.91 meter intervals across the width of the bin within each section. The sectioning of the soil bin and location of penetrometer tests are shown in Figure 21, Appendix C. These tests gave an indication of the soil penetration resistance variation across the width and length of the bin.

Next, the bin was divided into three blocks or replications to satisfy the criteria of the statistical design chosen for the study. A schematic of a typical bin layout is shown in Figure 22, Appendix C. The various sizes of cones, chisels, and disks were tested twice within each replication. Testing began by taking cone 2 readings within a replication. Then, the various cone, chisel, and disk tests were conducted until that replication was completed. This procedure was repeated until all replications for a soil preparation were completed.

Cone penetrometer tests. The cone penetrometers were positioned perpendicular to the soil surface and forced vertically downward into the soil at a speed of 0.5 cm/sec. Penetration resistance was recorded as a function of depth from the soil surface to a depth of 30 cm. Zero depth was defined as the point at which the base of the cone breaks the plane of the soil surface.

Chisel tests. Chisel tests began by lowering each chisel into a small pit to a depth of 22 cm. The chisels, which were positioned perpendicular to the soil surface, acted similar to a vertical wedge. A test consisted of forcing the chisel through the soil at a speed of 0.10 m/sec. As the chisel moved through the soil, its depth was slowly decreased at a rate of 0.33 cm/sec until it was completely out of the soil. Thus, the draft force was expressed as a function of depth.

Disk tests. The procedure for the chisels and disks were the same except that the disks were started at scaled depths and widths of cut. The maximum operating depths were approximately 1/3 the disk diameter or 4.40 cm, 8.20 cm, 13.20 cm, and 20.0 cm from the smallest to largest disk, respectively. The widths of cut which remained constant throughout each disk run were 4.06 cm, 8.13 cm, 12.19 cm, and 20.32 cm from the smallest to largest disk, respectively. A furrow opener preceded the testing of each disk.

ANALYSIS AND DISCUSSION

Soil Uniformity Analysis

A major concern at the outset of the research was the variation of soil strength within the soil bins. As previously stated, cone 2 tests were taken across the length and width of the bin to monitor the profile variation within each bin. Any variation in the magnitude of the penetration resistance was considered an indication of soil strength variation within a bin. The penetration resistance of cone 2 vs. depth for all soil preparations are shown in Figure 11. Data points from cone 2 data curves at depths of 10, 40, 80, 120, 160, and 200 mm were used to access this variation. An analysis of variance which included soil preparation, depth, length, and width within length as factors indicated that variation along the length of the bin was greater than across the width of the bin. Therefore, the proposed statistical design which blocked along the length of the bin to reduce the effect of soil strength variation within the bin was satisfactory. The depth factor was highly significant. This significance probably resulted from the surface weaknesses of specific soil preparations.

With the soil fitting equipment available at the National Tillage Machinery Laboratory, it was difficult to obtain perfectly uniform profiles. These profiles were the best attainable.

Tool Data Analysis

The force values for all tools were recorded as a function of depth. Representative data samples of force vs. depth for the cone penetrometers, chisels, and disks are shown in Appendix D.

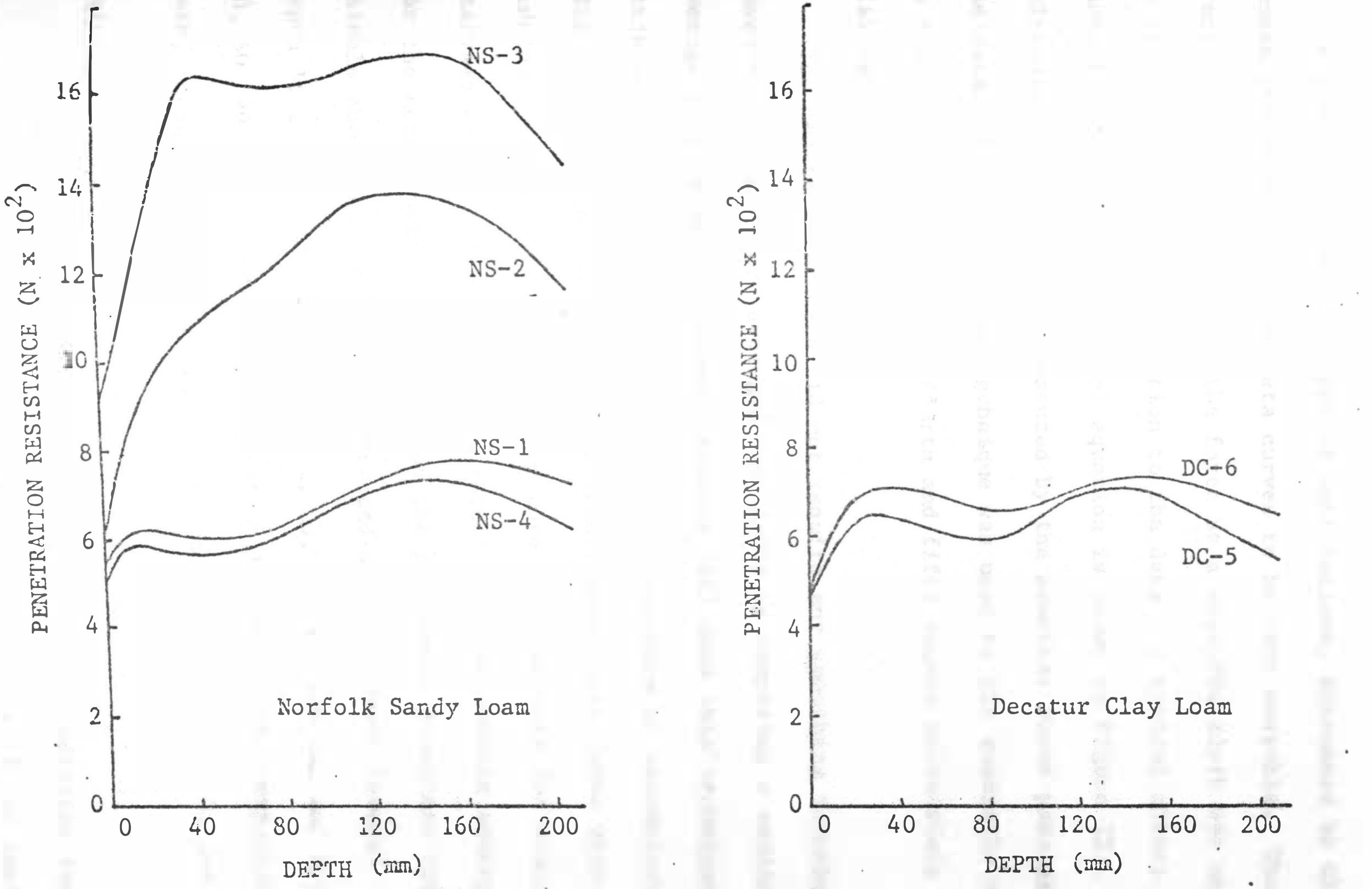

Figure 11. Vertical profiles for cone 2 for each soil preparation

A shearing-compacting type of soil failure, discussed by Gill (7), causes the chisel and disk data curves to be very unstable. Thus, practical representation of the force at a specific depth was obtained by fitting a polynomial equation to the data. A typical chisel data curve fitted with a polynomial equation is shown in Figure 12. The polynomial equation is represented by the smoother curve passing through the data. A least squares technique was used to fit quadratic equations to the chisel data and both fourth and fifth degree polynomials to the disk data.

The penetrometer data did not require any smoothing technique. However, the data were averaged over depth by computing a running average with respect to depth. Schafer (20) used this technique to minimize surface weakness effects and to introduce an accumulated force with depth effect. A typical cone penetrometer data curve with its running average curve is shown in Figure 13. The data for statistical analyses were extracted at scaled depths from the running average curve for the cone penetrometers and from the polynomial equations for the chisels and disks. Data were extracted at three depth levels: Depth 1; 10, 20, 30, 50 cm, Depth 2; 20, 40, 60, 100 cm, and Depth 3; 30, 60, 90, 150 cm from the smallest to largest tools, respectively. Note, these depths correspond to the length scales 1, 2, 3, and 5.

Force Ratio Analysis

In the following analysis the force ratio or prediction factor was formed by considering the larger tools as models of the smaller tools. Accordingly, the length scale becomes the smaller tool length

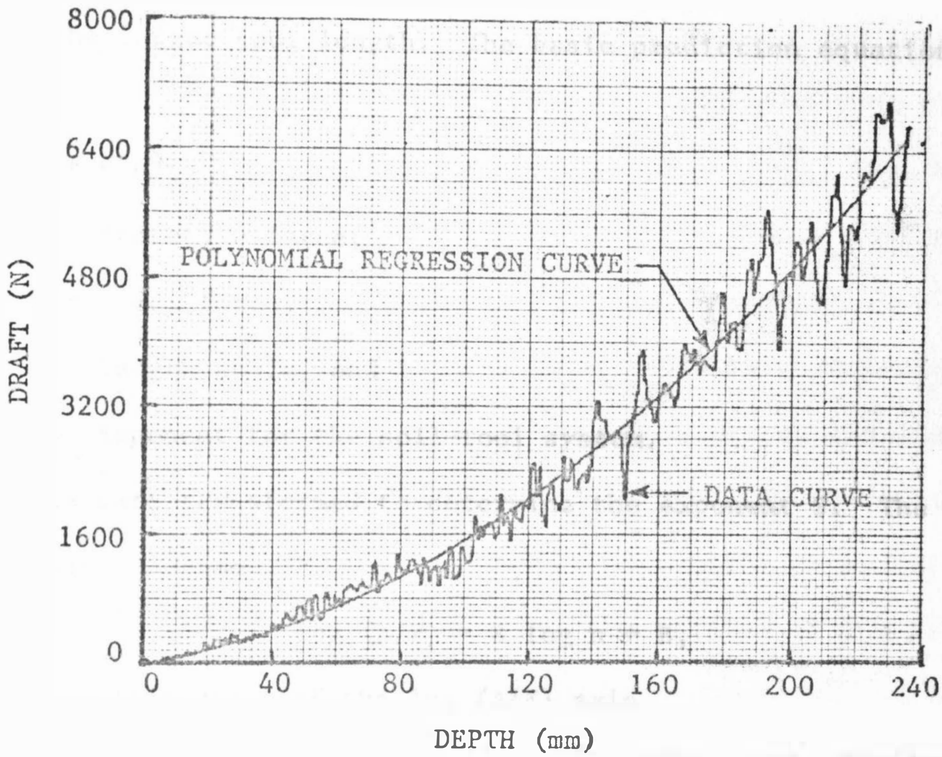

Figure 12. Data and polynomial regression curves for chisel 3, NS-2

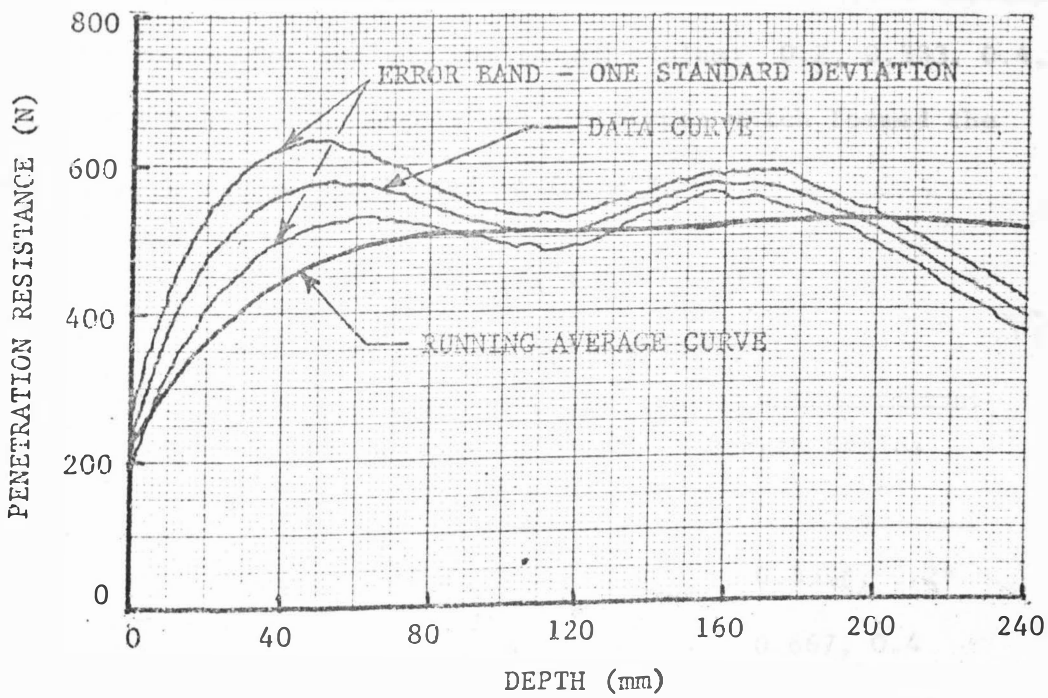

Figure 13. Data and running average curves for cone 1, NS-3

divided by the larger tool length. The basic prediction equation becomes

$$A/F = n^S,$$

where A - Prototype force,

F - Model force,

n - Length scale, and

S - Exponent for the soil-tool system.

The data were transformed to determine the exponent S. The regression model became

$$\log (A/F) = S \log n + B,$$

where B was the intercept of the log (A/F) axis.

A regression analysis of log force ratio (A/F) on the log length scale (n) was determined for each combination of tool type, soil preparation, and depth interval with the data pooled across replications. The regression include the length scales: 0.2, 0.333, 0.4, 0.5, 0.6, and 0.667. The models and prototypes which formed the specific length scales are listed in Table 3.

Table 3

Prototypes and Models

Prototypes (Tool No.)	Models (Tool No.)	Length Scales
1	2, 3, 4	0.5, 0.333*, 0.2*
2	3, 4	0.667, 0.4
3	4	0.6*

*Length scales formed by the three chisel sizes

Polynomial regression models of the first, second, and third degree were applied to the data. The analysis indicated that the linear model adequately represented the logarithmic data, and the intercept (B) was not significant which agrees with the theory that the function describing the data should pass through the point ($n = 1$, $A/F = 1$). With B nonsignificant, the linear function representing the data became $\log (A/F) = S \log n$ where S was the slope of the linear regression. Figures 14a and 14b indicate data with the least variation and the greatest variation about the fitted regression, respectively. The correlation coefficients for the linear regression of the logarithmic data are given in Table 8, Appendix B.

Because the logarithm of force ratio vs. the logarithm of the length scale was linear with a nonsignificant intercept, the relationship $A/F = n^S$ was used to describe the modeled soil-tool systems in this study.

Analysis of the Exponent S

The purpose of this analysis was to evaluate trends of S which existed between tool types. Similar trends between combinations of tools would indicate a possible analog relationship, with reference to equation 7. The values of the exponent S for the cones, chisels, and disks are listed in Table 9, Appendix B. The analysis of variance of S which included tool type, soil preparation, and depth interval as factors indicated that all factors and their interactions were significant at the 1 percent level. The analysis of variance is summarized in Table 4.

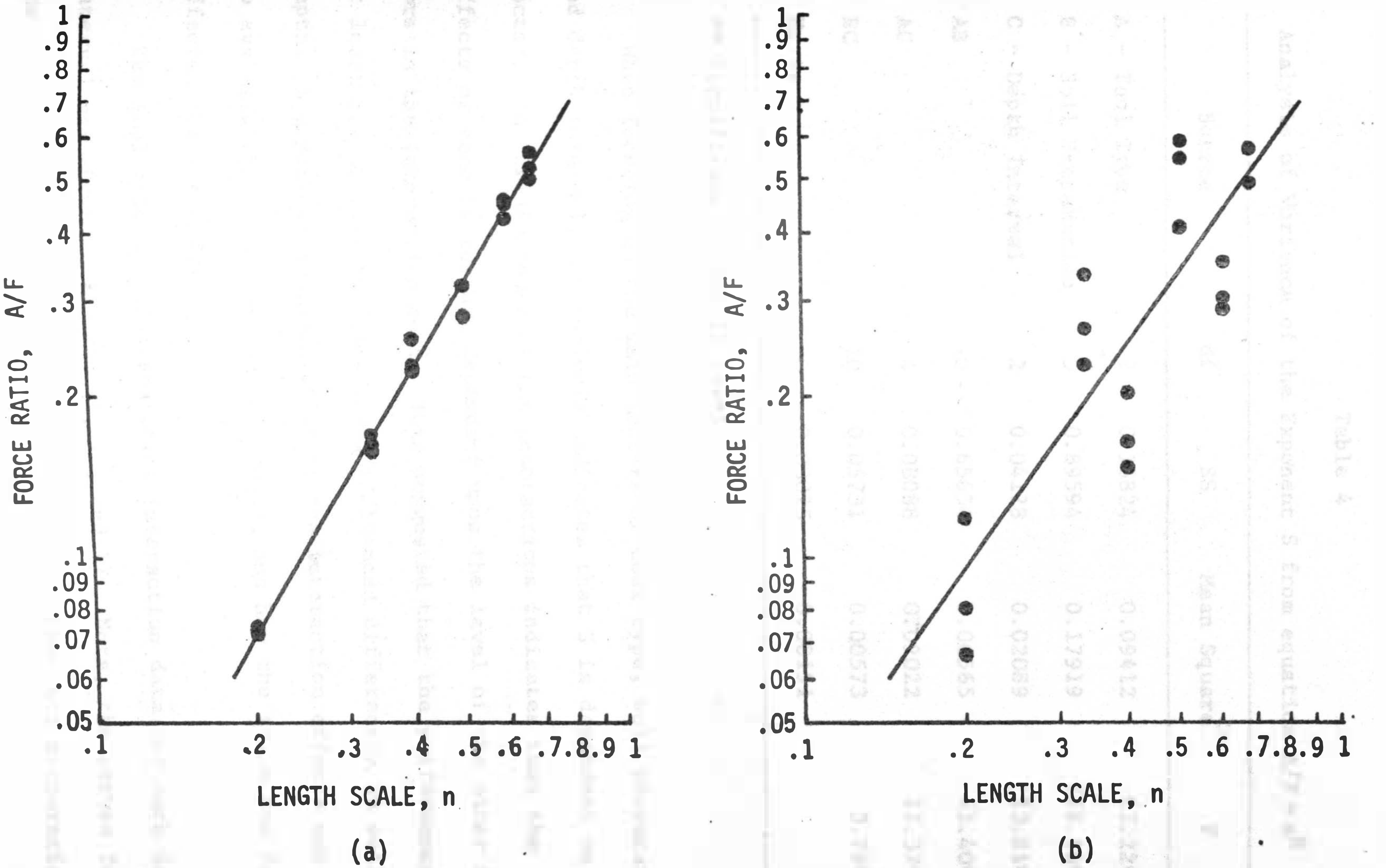

Figure 14. Regression of disk data.

Table 4

Analysis of Variance of the Exponent S from equation $A/F = n^S$

Source	df	SS	Mean Square	F
A - Tool Type	2	0.18824	0.09412	62.22**
B - Soil Preparation	5	0.89594	0.17919	118.46**
C - Depth Interval	2	0.04178	0.02089	13.81**
AB	10	0.65654	0.06565	43.40**
AC	4	0.08088	0.02022	13.37**
BC	10	0.05731	0.00573	3.79**
Error	20	0.03025	0.00151	

** Significant at the 1% level.

When focusing on the main factors of tool type, soil preparation, and depth interval, the analysis indicates that S is dependent on each factor. The significance of the interactions indicates that the effects of each factor are dependent upon the level of the other factors in the interaction term. This suggested that the performance of at least one or more tool types was influenced differently by soil and depth. A graphical representation of the interaction effects was used to evaluate the trends of specific tools, and how the soils and depths affected these trends.

The tool type x soil preparation interaction data for each depth interval are shown in Figures 15, 16, and 17. Note, the curves for the cone and disk follow similar trends across the soil preparations

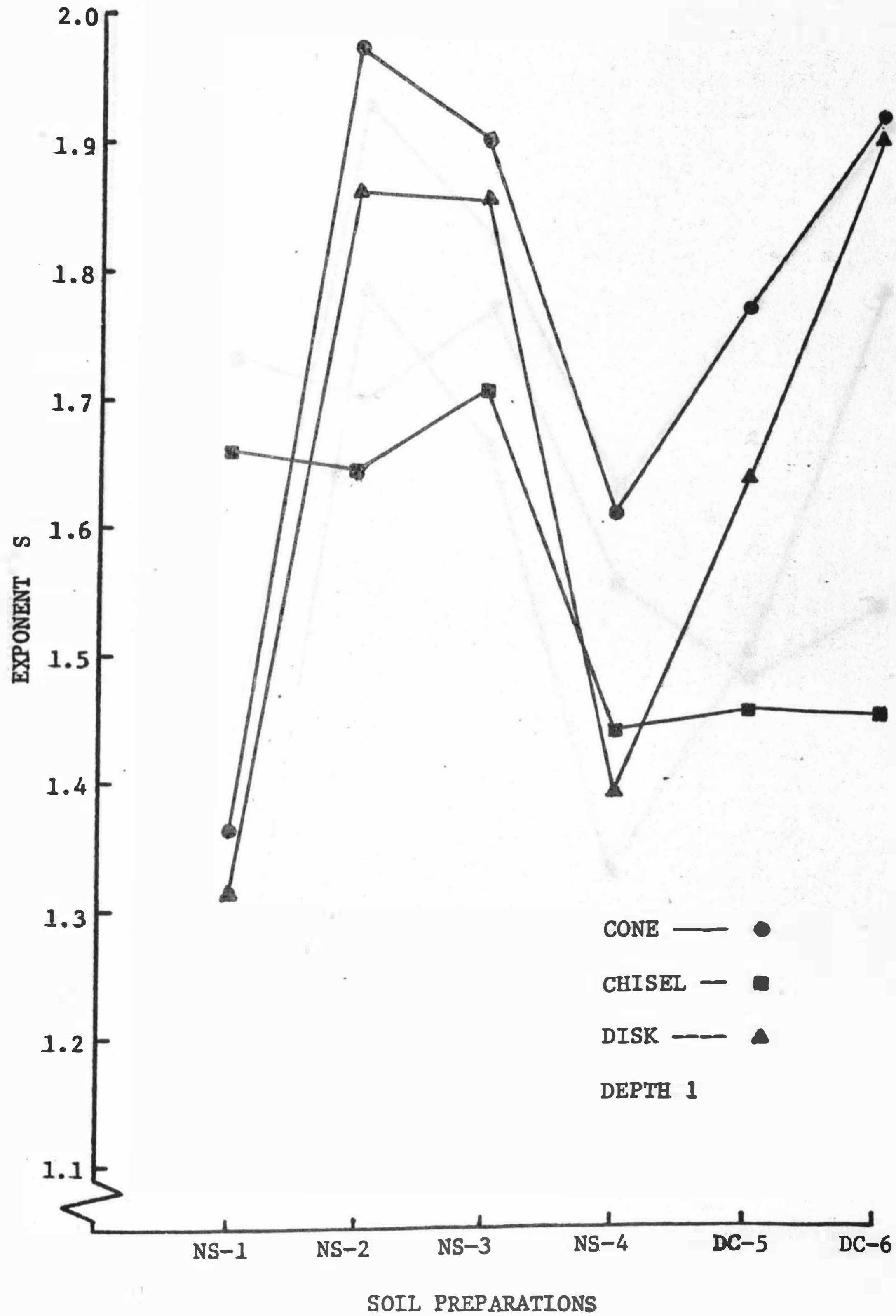

Figure 15. Tool type X soil preparation interaction of S, depth 1

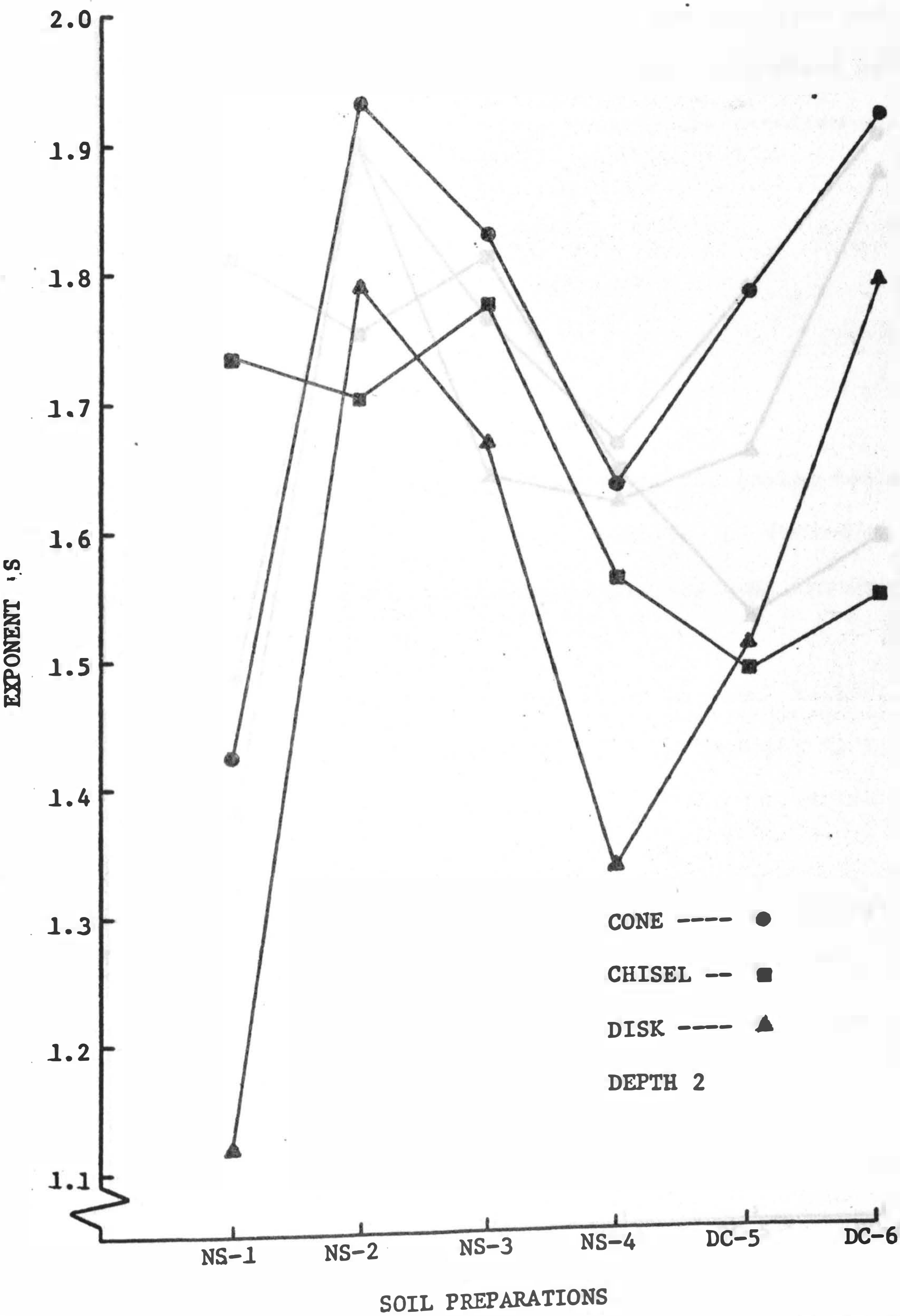

Figure 16. Tool type X soil preparation interaction of S, depth 2

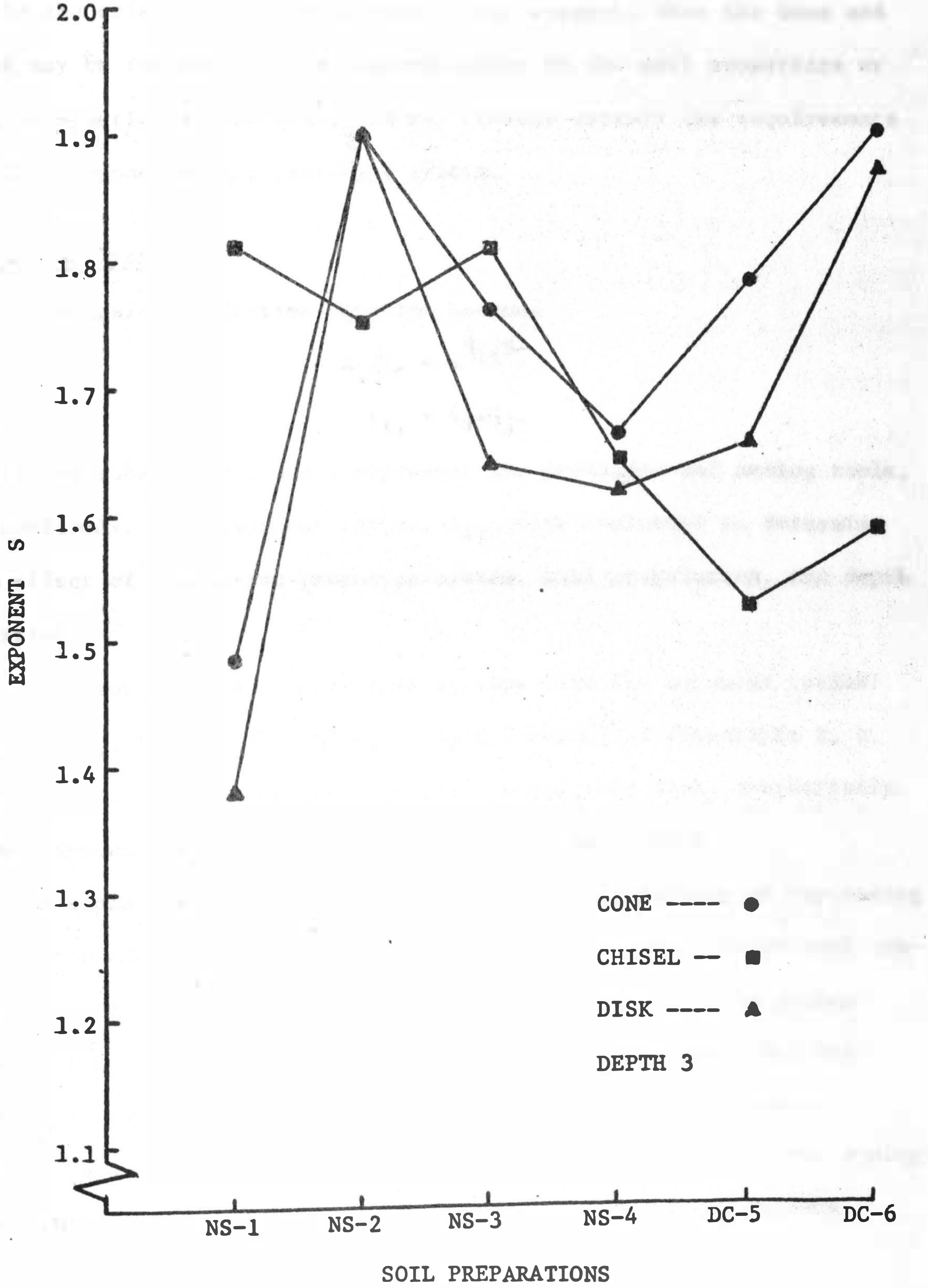

Figure 17. Tool type X soil preparation interaction of S, depth 3

while the chisel appears different. This suggests that the cone and disk may be influenced in a similar manner by the soil properties or characteristics of the soil, and may thereby satisfy the requirements of the proposed analog-prototype system.

Analog Analysis

The analog prediction equation becomes

$$A_i/F_i = n^{S_{ij}S_j}$$

and

$$S_{ij} = S_i/S_j,$$

where the subscripts i and j represent the prototype and analog tools, respectively. The exponent ratios, S_{ij}, were evaluated to determine the effect of the analog-prototype system, soil preparation, and depth interval.

The proposed analog-prototype systems form the exponent ratios: $S_{ck} = S_c/S_k$, $S_{dk} = S_d/k$, and $S_{dc} = S_d/S_c$, where the subscripts k, c, and d represent the cone penetrometer, chisel, and disk, respectively. These exponent ratios are listed in Table 9, Appendix B.

As explained by the theory on page 11 the usefulness of the analog prediction equation is dependent on S_{ij} being constant across soil conditions. Figures 15, 16, and 17 have already indicated the analog-prototype systems which tend to satisfy this stipulation. The following analysis will verify those trends if they are applicable.
The analysis of variance of S_{ij} as shown in Table 5 includes the analog-prototype system, soil preparation, and depth interval as factors.

Table 5

Analysis of Variance of the Exponent Ratio S_{ij} from Equation $A_i=F_i n^{S_{ij}S_j}$

Source	df	SS	Mean Square	F
A - Analog-Prototype System	2	0.06056	0.03028	30.41**
B - Soil Preparation	5	0.03028	0.00606	6.08**
C - Depth Interval	2	0.03154	0.0157	15.83**
AB	10	0.69100	0.07000	70.29**
AC	4	0.05281	0.01320	13.26**
BC	10	0.01270	0.00157	1.58 NS
Error	20	0.01992	0.00099	

** Significant at the 1% level.

The main factors A, B, and C were significant at the 1 percent level. This indicates that S_{ij} is dependent upon the system, soil, and depth; but this does not adequately explain specific systems and how the soils and depths affect these systems. Therefore, an examination of the interaction effects of the factors was used to compare the specific systems.

The analog-prototype system x soil preparation interaction (AB) was significant at the 1 percent level. The bar graph in Figure 18 indicates the variation of S_{ij} for each analog-prototype system across soil preparations with the data pooled across depths. The significance of this interaction was shown by the variation of the cone-chisel (S_{ck}) and the chisel-disk (S_{dc}) systems, while the cone-disk (S_{dk}) system was reasonably constant across soil preparations. This suggests that the

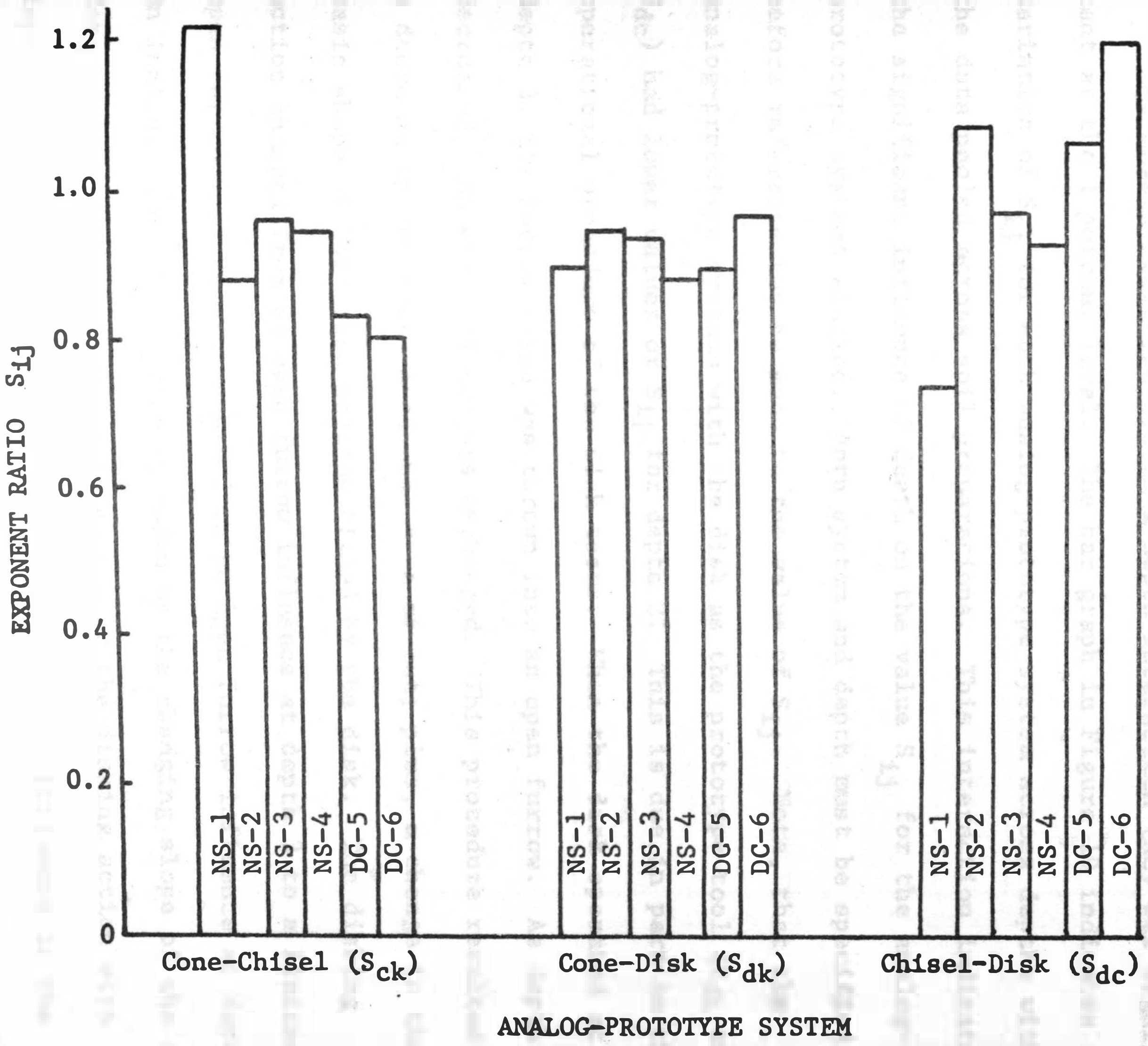

Figure 18. Variation of S_{ij} across soil preparations for each analog-protot pe system

cone and disk may be influenced in a similar manner by the various soil preparation, and indicates that the theory of the proposed analog technique was best satisfied by the cone-disk system.

The analog-prototype system x depth interaction (AC) was significant at the 1 percent level. The bar graph in Figure 19 indicates the variation of S_{ij} for each analog-prototype system across depths with the data pooled across soil preparations. This interaction indicates the significant influence of depth on the value S_{ij} for the analog-prototype systems studied. Both system and depth must be specified before reference can be made to the value of S_{ij}. Note, that the analog-prototype systems with the disk as the prototype tool (S_{dk} and S_{dc}) had lower values of S_{ij} for depth 2. This is due in part to the operational procedure of the disk tests. When the disk operated at depth 3, its furrow slice was thrown into an open furrow. As depth decreased, the width of cut was unchanged. This procedure resulted in a decrease in the cross-sectional area of cut; plus, a change in the basic shape of the cross-section tilled by the disk. The disking action changed from an open furrow influence at depth 3 to a limited open furrow influence at depth 2 to no open furrow influence at depth 1. An indication of this action is shown by the changing slope of the disk data curves in Appendix D. This change of the disking action with depth was one of the probable causes of the depth influence in the analog-prototype systems related to the disk. From the analysis of variance and the graphic representation it appears that depth was an influencing factor in all analog-prototype systems studied.

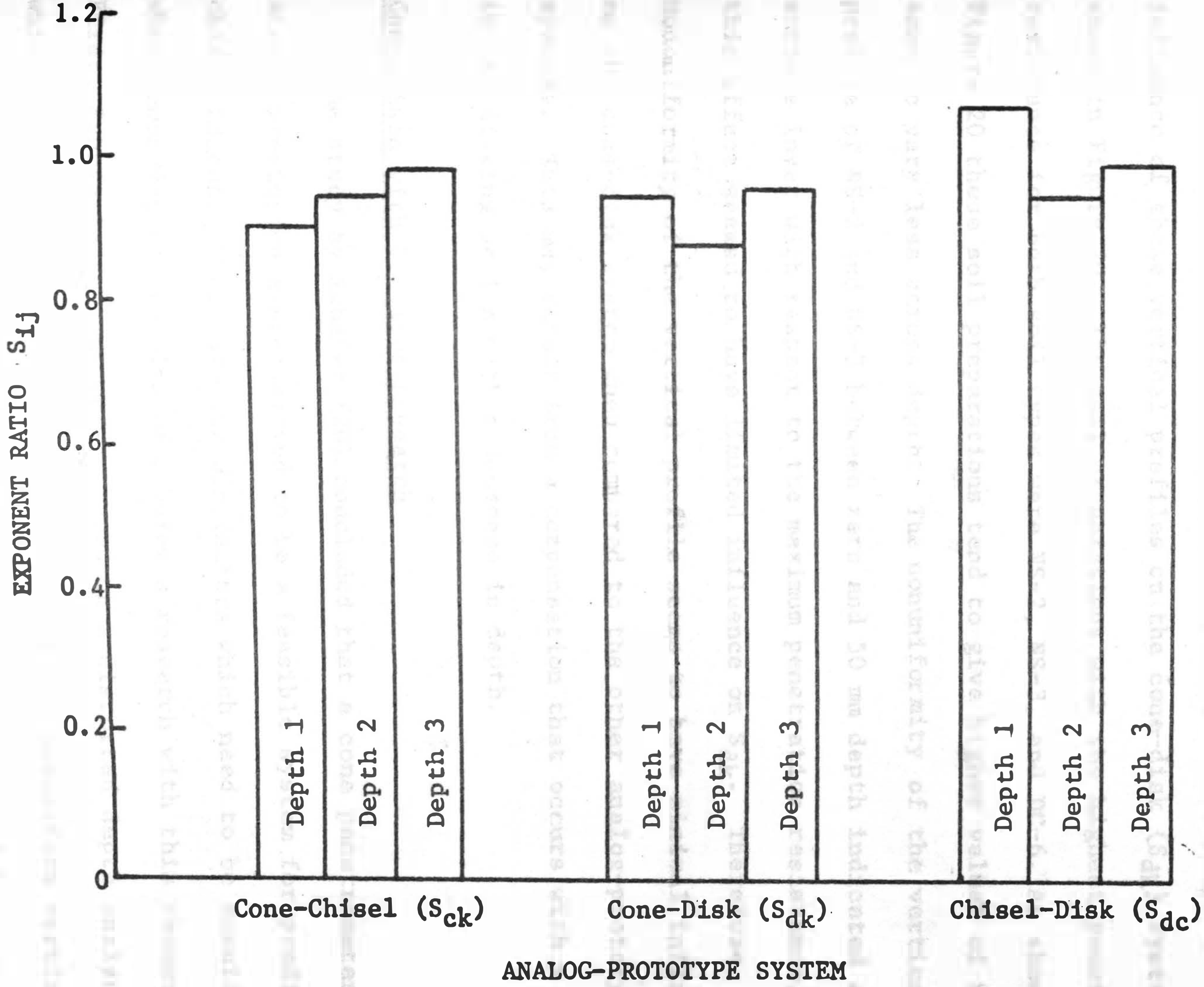

Figure 19. Variation of S_{ij} across depths for Analog-Prototype Systems

Influence of Soil Preparations

The vertical profiles of the soils as indicated by the penetration resistance of cone 2 vs. depth are shown in Figure 11, page 29. The influence of these vertical profiles on the cone-disk (S_{dk}) system is shown in Figure 20. The soil preparations with the highest penetration resistance for both soil types were NS-2, NS-3, and DC-6. As shown in Figure 20 these soil preparations tend to give higher values of S_{dk} and seem to vary less across depth. The nonuniformity of the vertical profile of NS-2 and NS-3 between zero and 50 mm depth indicated a weak surface layer with respect to the maximum penetration resistance, but this effect seemed to have limited influence on S_{dk}. Therefore, the nonuniformity of the vertical profile seems to have minimal influence on the cone-disk system when compared to the other analog-prototype systems. This may result from a compensation that occurs with a change in the disking action with a decrease in depth.

Comparison with Previous Research

The study by Schafer (20) concluded that a cone penetrometer analog prediction system proved to be a feasible system for predicting chisel forces. There are certain factors which need to be considered when comparing the results of Schafer's research with this research. First, Schafer's conclusion was based on a distorted depth analysis which was used to minimize the influence of the nonuniform vertical profile. In this study a scaled depth analysis was used because of the limited depth of operation of the soil-disk system. Initially, Schafer

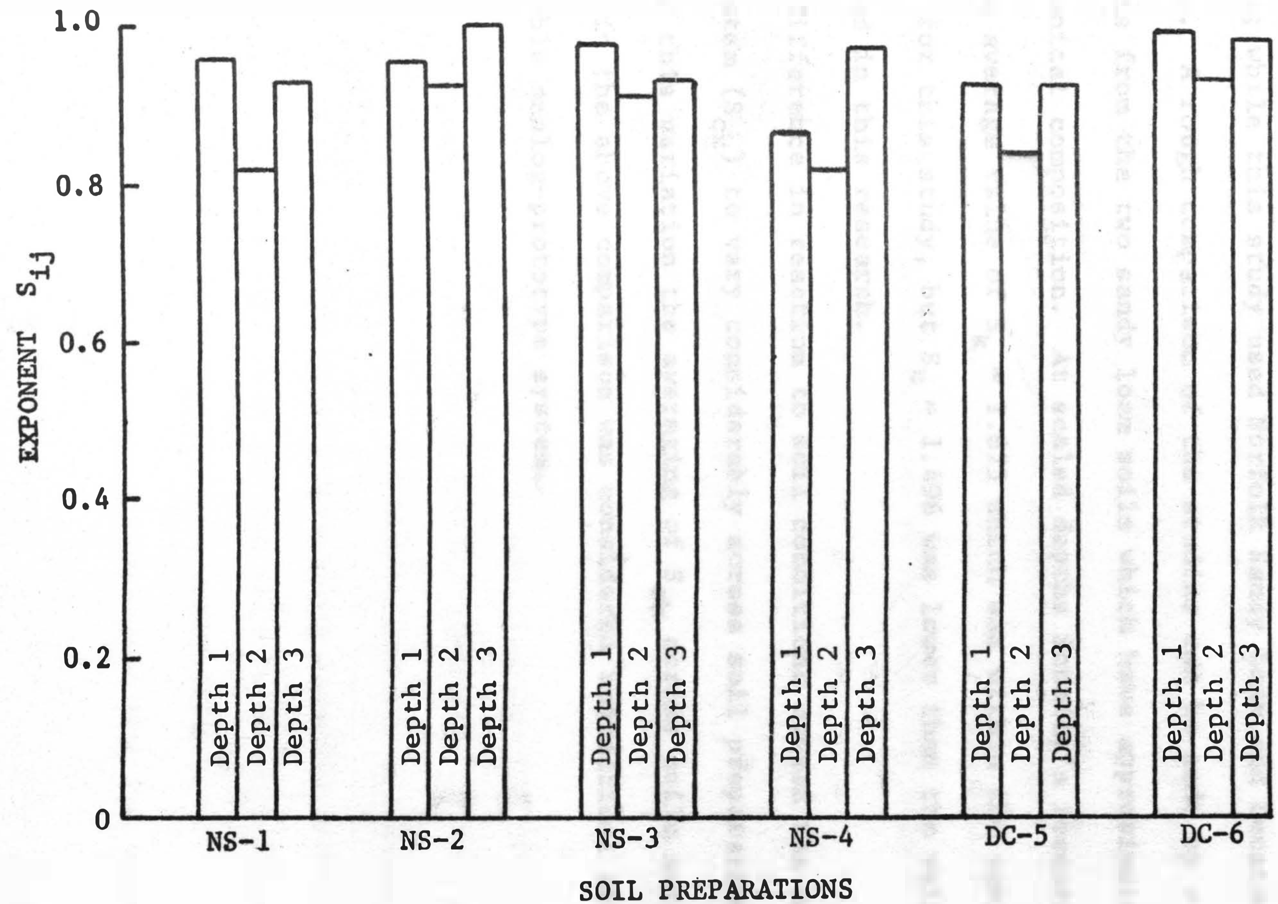

Figure 20. Variation of S_{ij} across depths for soil preparations for the cone-disk (S_{dk}) system

evaluated the cone-chisel system at scaled depths and concluded that the prediction system was unacceptable which agrees with the findings in this study. Secondly, Schafer used Hiawassee Sandy Loam and Lloyd Clay soils; while this study used Norfolk Sandy Loam and Decatur Clay Loam soils. A rough comparison of the studies can be made by evaluating the results from the two sandy loam soils which have approximately the same mechanical composition. At scaled depths Schafer's research data yielded an average value of $S_k = 1.675$ which was within the range of S_k values for this study, but $S_c = 1.496$ was lower than the values of S_c obtained in this research.

The difference in reaction to soil conditions caused the cone-chisel system (S_{ck}) to vary considerably across soil preparations. Because of this variation the averaging of S_{ck} across soils and scaled depths as in the above comparison was considered impractical in forming an acceptable analog-prototype system.

SUMMARY AND CONCLUSIONS

The feasibility of using an analog technique to predict the draft on a prototype tool from measurements on a model tool and an analog device was evaluated by this research. The analog-prototype systems studied were cone penetrometer-chisel, cone penetrometer-disk, and chisel-disk.

The various tool sizes formed the length scales 0.2, 0.333, 0.4, 0.5, 0.6, 0.667 relative to the larger tools. The generalized form of the proposed analog prediction equation as developed by Schafer (20) became

$$A_i = F_i\, n^{S_{ij} S_j}$$

and

$$S_{ij} = S_i / S_j,$$

where F-prototype force, A-model force, and the subscripts i and j represent the prototype and analog, respectively.

The usefulness of this analog technique is dependent upon how the soil properties affect the soil-tool systems involved. Therefore, if S_{ij} was constant across soil types and conditions for an analog-prototype system the proposed analog prediction equation could be easily applied. S_{ij} was evaluated for two soil types at different strengths with a total of 6 different soil conditions.

The variation of S_{ij} across soil preparations was the least for the cone-disk system.

The conclusions of this research were:

1. Schafer's distorted force prediction equation, $\delta_F = n^S$, was valid for the soil-tool systems studied. The exponent S for each

soil-tool system was influenced by soil conditions and depth of operation.

2. The exponent ratios S_{ij} from the analog prediction equation were influenced by soil conditions for the cone-chisel and chisel-disk systems, but tend to be independent of soil conditions for the cone-disk system.
3. The trends of a nonuniform strength profile as measured by a cone penetrometer were reflected in the soil-disk system.
4. The cone penetrometer-disk system proved to be the most feasible of the analog-prototype systems investigated.

RECOMMENDATIONS FOR FURTHER RESEARCH

The data and findings of this research suggest that further analysis and research may aid the design engineer in predicting performance of soil-machine systems. Specific suggestions include:

1. A distorted depth analysis of the cone penetrometer and chisel data acquired by this research could aid in understanding how a nonuniform soil profile influences the cone-chisel (analog-prototype) system.
2. A detailed study of the cone-disk system which makes direct force predictions of disk performance from cone performance in other soils would determine the validity and usefulness of this analog-prototype system.
3. Further research is needed to determine the soil properties which are pertinent to soil-tool systems.

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APPENDIX A

Soil Preparations

Table 6

Summary of Moisture, Density, and Strength of Soil Preperations

Soil Type	Test No.	Soil Depth (cm)	Moisture Content By Depth (%)	Moisture Content Test Avg. (%)	Bulk Density By Depth (gm/cc)	Bulk Density Test Avg. (gm/cc)	Maximum Cone Index* (N/cm^2)
Norfolk Sandy Loam	NS-1	0- 6.4	6.18		1.65		
		7.6-14.0	7.04	6.64	1.52	1.58	153
		15.2-21.6	6.72		1.58		
	NS-2	0- 6.4	6.59		1.74		
		7.6-14.0	7.40	7.18	1.77	1.75	289
		15.2-21.6	7.56		1.75		
	NS-3	0- 6.4	7.70		1.90		
		7.6-14.0	7.97	7.94	1.80	1.84	332
		15.2-21.6	8.15		1.81		
	NS-4	0- 6.4	7.81		1.74		
		7.6-14.0	8.31	8.15	1.61	1.67	180
		15.2-21.6	8.32		1.66		
Decatur Clay Loam	DC-5	0- 6.4	12.96		1.45		
		7.6-14.0	13.37	13.35	1.39	1.42	168
		15.2-21.6	13.72		1.42		
	DC-6	0- 6.4	14.15		1.60		
		7.6-14.0	14.51	14.60	1.55	1.62	195
		15.2-21.6	15.13		1.71		

* ASAE Recommendation: ASAE R1313.1 (1): 3.2 sq cm, 30^{o} cone penetrometer

Table 7

Summary of Soil Fitting Procedure

Soil Type	Test No.	Leveled[a]	Subsurface Compaction (Plow-Pack)[b]	Leveled	Surface Compaction (Flat Roller)	Surface Compaction (Large Steel Wheel)[c]
Norfolk Sandy Loam	NS-1	yes	depth: 10.2 cm 4 passes	yes	6 passes	no
	NS-2	yes	depth: 10.2 cm 4 passes	yes	8 passes	2 passes
	NS-3	yes	depth: 12.7 cm 4 passes	yes	4 passes	6 passes
	NS-4	yes	depth: 12.7 cm 2 passes	yes	4 passes	no
Decatur Clay Loam	DC-5	yes	depth: 12.7 cm 4 passes	yes	Flat roller: 4 passes Steel wheel: 4 passes Retilled to: 12.7 cm Flat roller: 2 passes	2 passes
	DC-6	yes	depth: 11.4 cm 4 passes	yes	Flat roller: 4 passes Steel wheel: 4 passes Retilled to: 12.7 cm Flat roller: 2 passes	2 passes

[a]Water added to regulate moisture content.

[b]Added weight: 746.5 kg.

[c]Added weight: 746.5 kg, except for DC-5 with no added weight.

APPENDIX B

Tool Performance Data

Table 8

Correlation Coefficients for the Regression of Log Force Ratio on Log Length Scale

Depth Interval	Soil Preparation	Tool Type: Cone	Chisel	Disk
Depth 1 (0-50 mm)	NS-1	0.952	0.972	0.881
	NS-2	0.984	0.968	0.910
	NS-3	0.985	0.975	0.967
	NS-4	0.960	0.971	0.976
	DC-5	0.981	0.994	0.933
	DC-6	0.990	0.898	0.988
Depth 2 (0-100 mm)	NS-1	0.961	0.983	0.887
	NS-2	0.990	0.984	0.954
	NS-3	0.988	0.989	0.979
	NS-4	0.957	0.987	0.964
	DC-5	0.989	0.991	0.963
	DC-6	0.991	0.919	0.981
Depth 3 (0-150 mm)	NS-1	0.969	0.986	0.855
	NS-2	0.991	0.989	0.977
	NS-3	0.990	0.994	0.997
	NS-4	0.961	0.992	0.949
	DC-5	0.992	0.987	0.980
	DC-6	0.989	0.935	0.992

Table 9

Exponent S from Equation $A/F=n^S$ for Tools, Soil Preparations, and Depths

Depth Interval	Soil Preparation	Tool Type Cone	Chisel	Disk
Depth 1 (0-50 mm)	NS-1	1.364	1.660	1.312
	NS-2	1.975	1.646	1.864
	NS-3	1.906	1.710	1.857
	NS-4	1.614	1.440	1.394
	DC-5	1.774	1.460	1.639
	DC-6	1.927	1.455	1.907
Depth 2 (0-100 mm)	NS-1	1.423	1.736	1.173
	NS-2	1.933	1.703	1.791
	NS-3	1.832	1.777	1.669
	NS-4	1.636	1.561	1.336
	DC-5	1.788	1.488	1.508
	DC-6	1.927	1.547	1.796
Depth 3 (0-150 mm)	NS-1	1.486	1.814	1.380
	NS-2	1.901	1.754	1.904
	NS-3	1.764	1.814	1.640
	NS-4	1.666	1.661	1.618
	DC-5	1.789	1.529	1.657
	DC-6	1.906	1.641	1.874

Table 10

Exponent S_{ij} from Equation $A_i = F_i n^{S_{ij} S_j}$ for Analog-Prototype Systems, Soil Preparations, and Depths

Depth Interval	Soil Preparation	Analog-Prototype Systems		
		Cone-Chisel (S_{ck})	Cone-Disk (S_{dk})	Chisel-Disk (S_{dc})
Depth 1 (0-50 mm)	NS-1	1.217	0.962	0.790
	NS-2	0.833	0.944	1.132
	NS-3	0.897	0.974	1.086
	NS-4	0.892	0.864	0.968
	DC-5	0.823	0.924	1.123
	DC-6	0.755	0.990	1.311
Depth 2 (0-100 mm)	NS-1	1.220	0.824	0.676
	NS-2	0.881	0.926	1.052
	NS-3	0.970	0.911	0.939
	NS-4	0.954	0.817	0.856
	DC-5	0.832	0.843	1.013
	DC-6	0.803	0.932	1.161
Depth 3 (0-150 mm)	NS-1	1.221	0.929	0.761
	NS-2	0.923	1.002	1.085
	NS-3	1.028	0.930	0.904
	NS-4	0.997	0.971	0.974
	DC-5	0.855	0.926	1.084
	DC-6	0.862	0.983	1.142

APPENDIX C

Soil Bin Layout for Testing

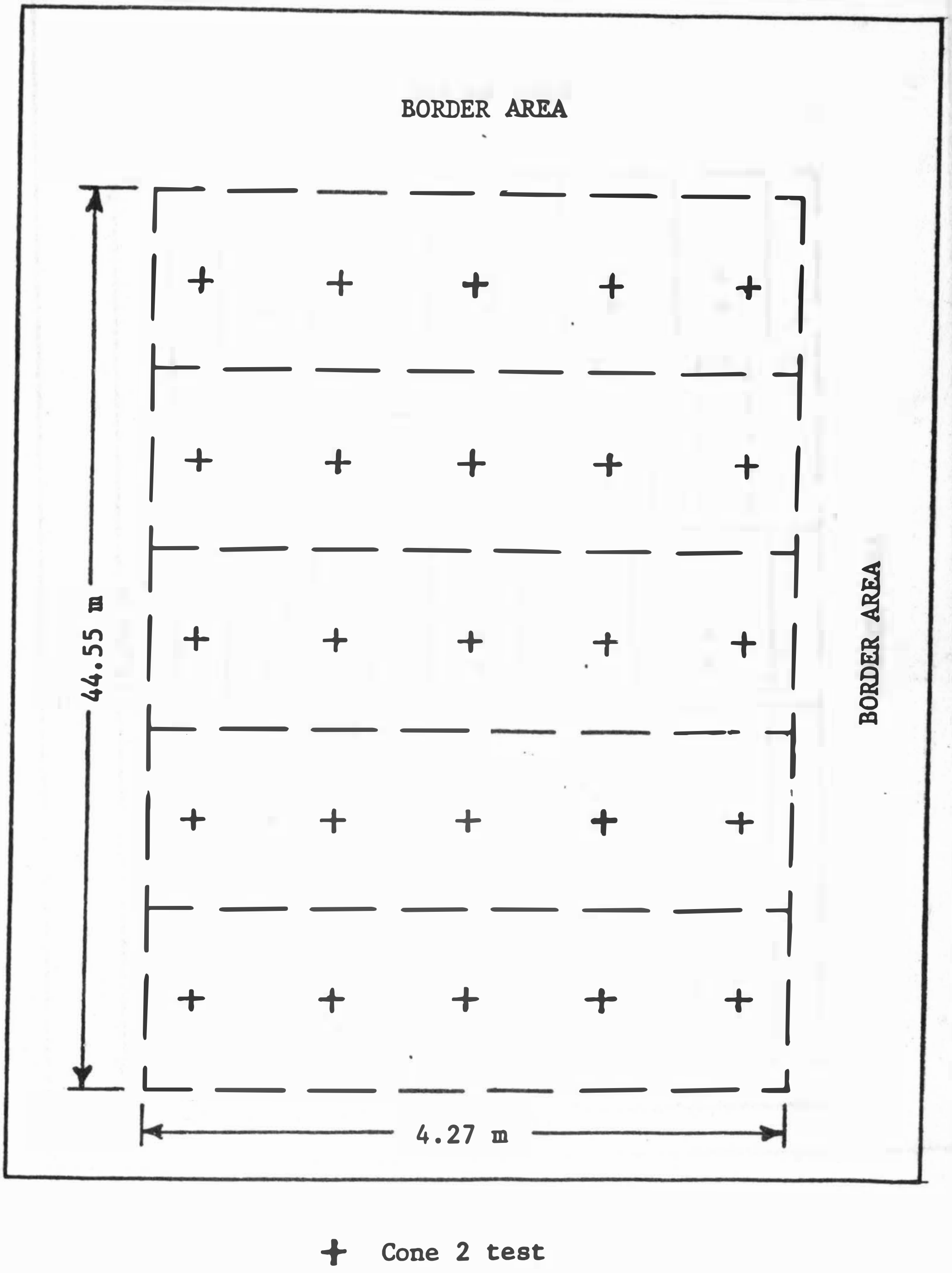

Figure 21. Soil bin layout illustrating sectioning of the bin, and location of cone 2 tests for finding strength variation within the bin

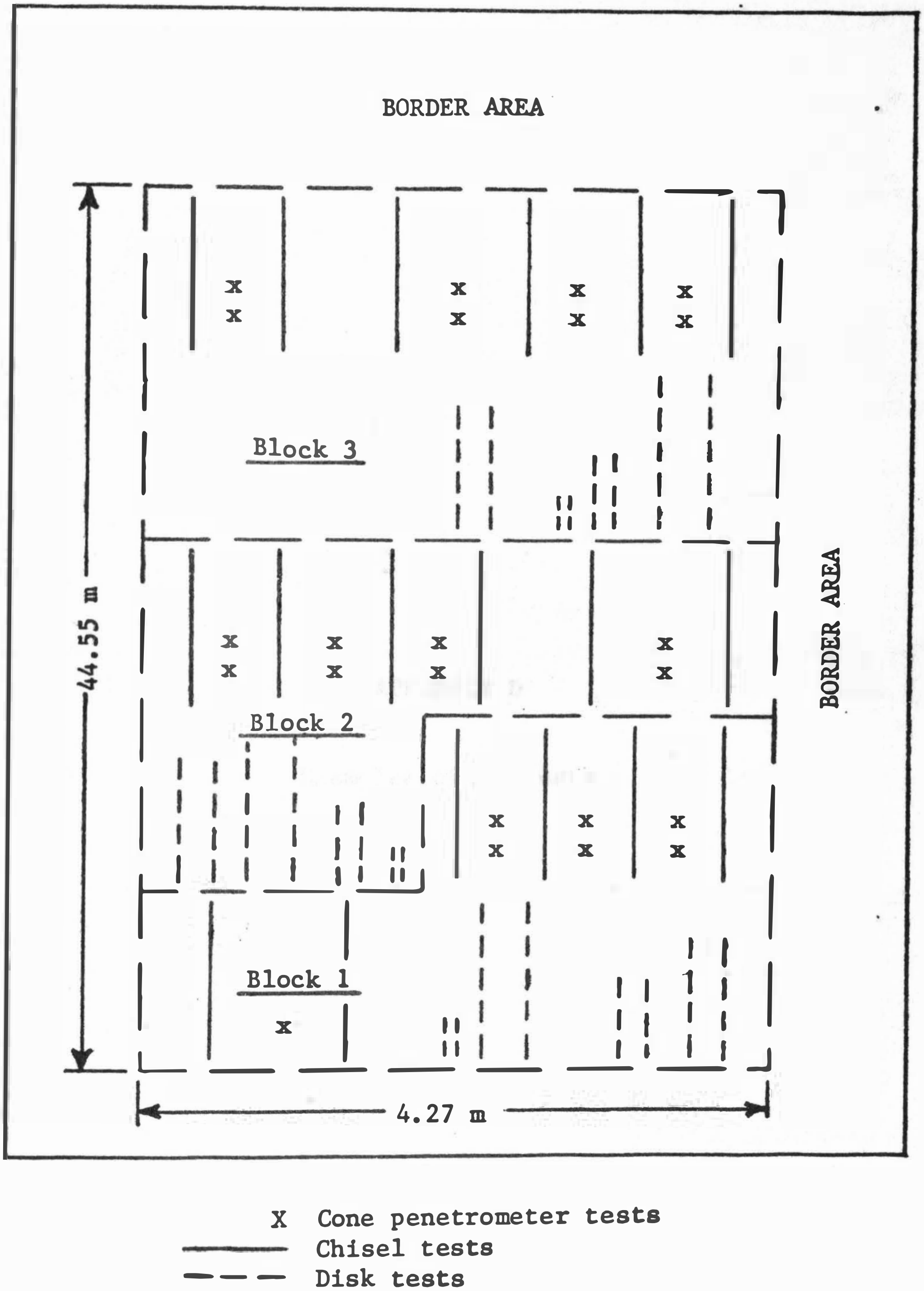

Figure 22. Soil bin layout for tool testing illustrating blocking technique of the statistical design

APPENDIX D

Examples of Raw Data

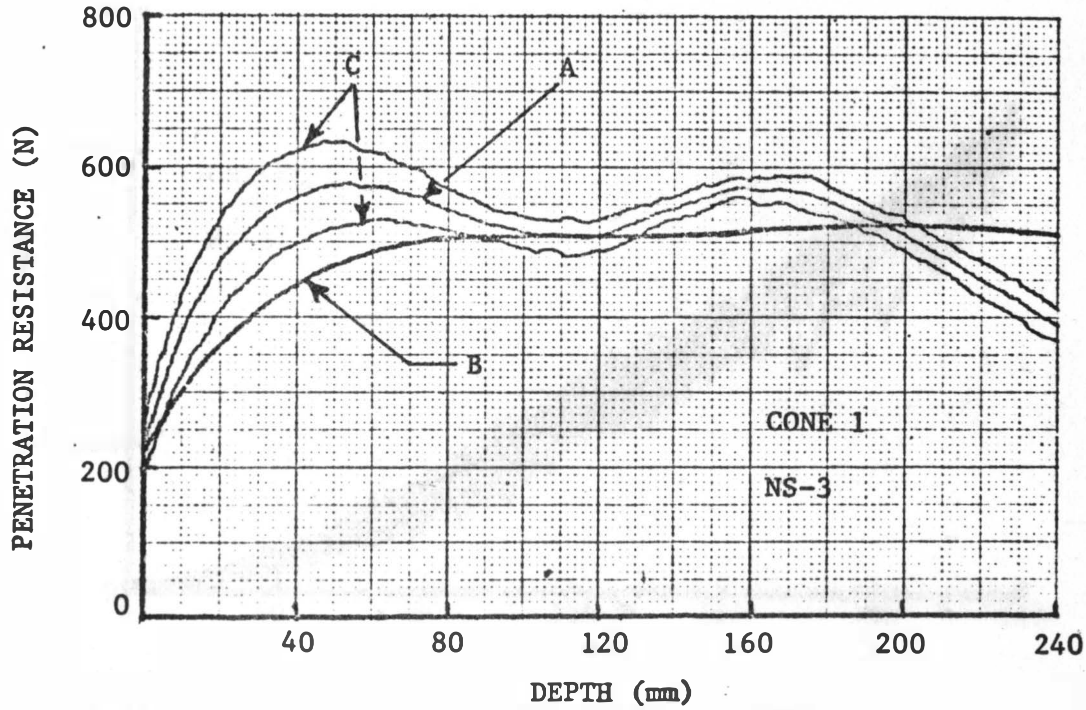

Figure 23. Cone penetrometer data curves for cone 1, NS-3, (A) cone penetrometer data, (B) running average, (C) error band of one standard deviation

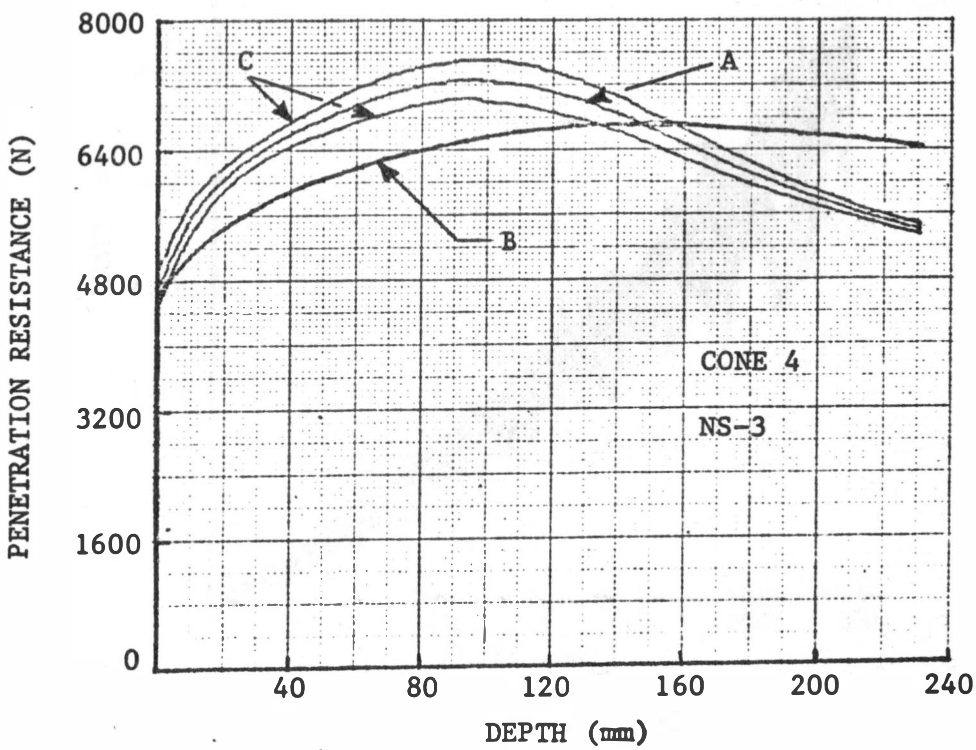

Figure 24. Cone penetrometer data curves for cone 4, NS-3, (A) cone penetrometer data, (B) running average, (C) error band of one standard deviation

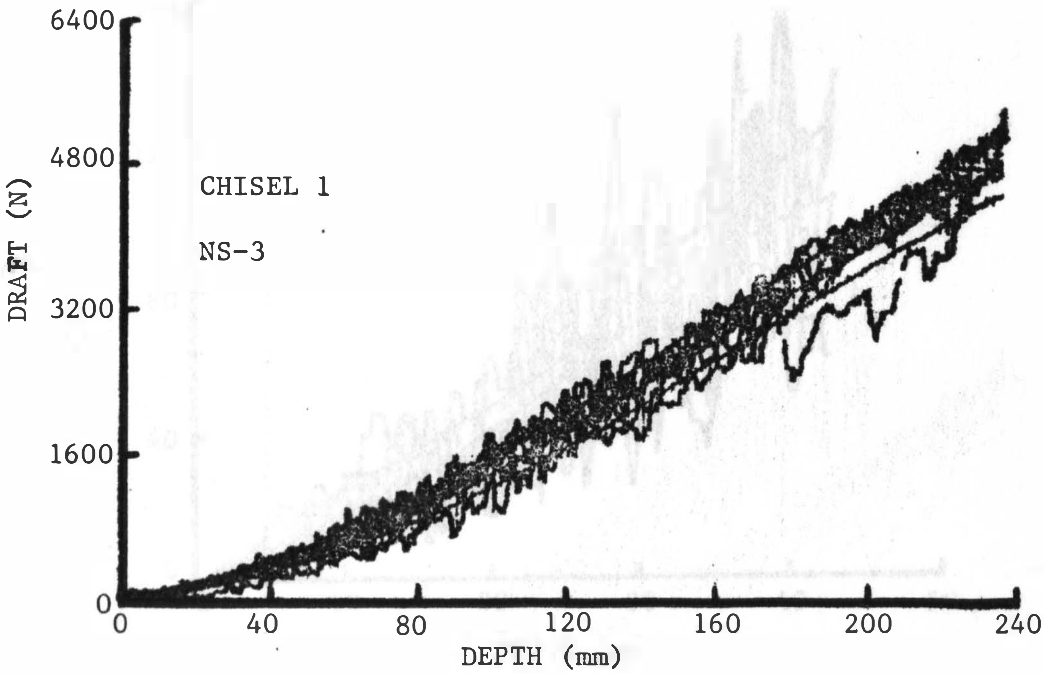

Figure 25. Chisel data curves for chisel 1, NS-3

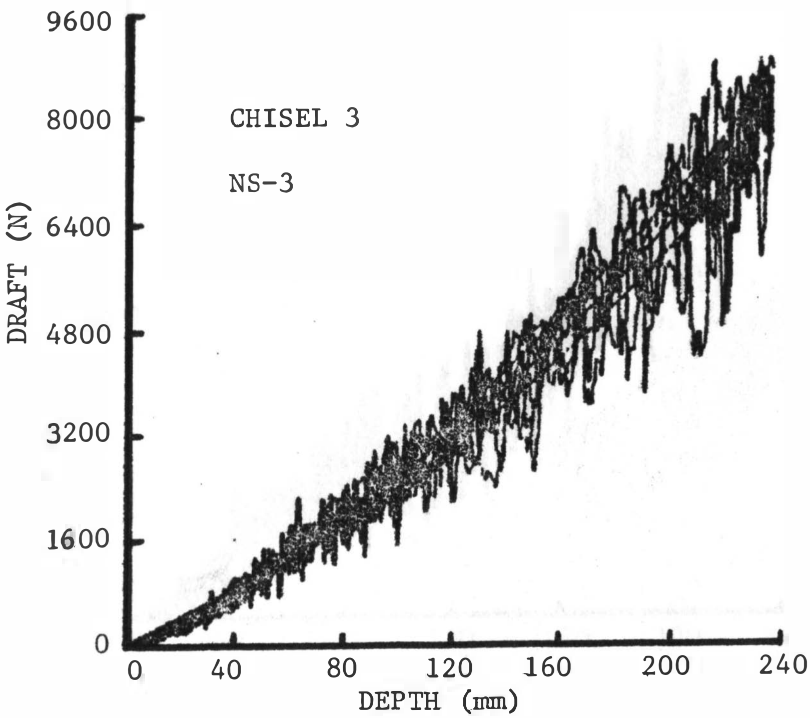

Figure 26. Chisel data curves for chisel 3, NS-3

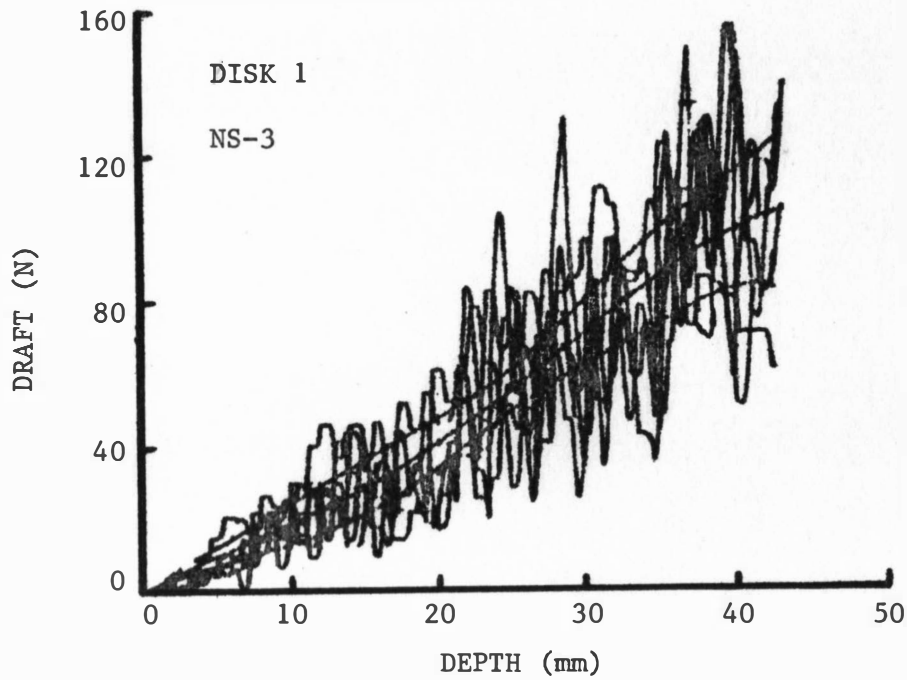

Figure 27. Disk data curves for disk 1, NS-3

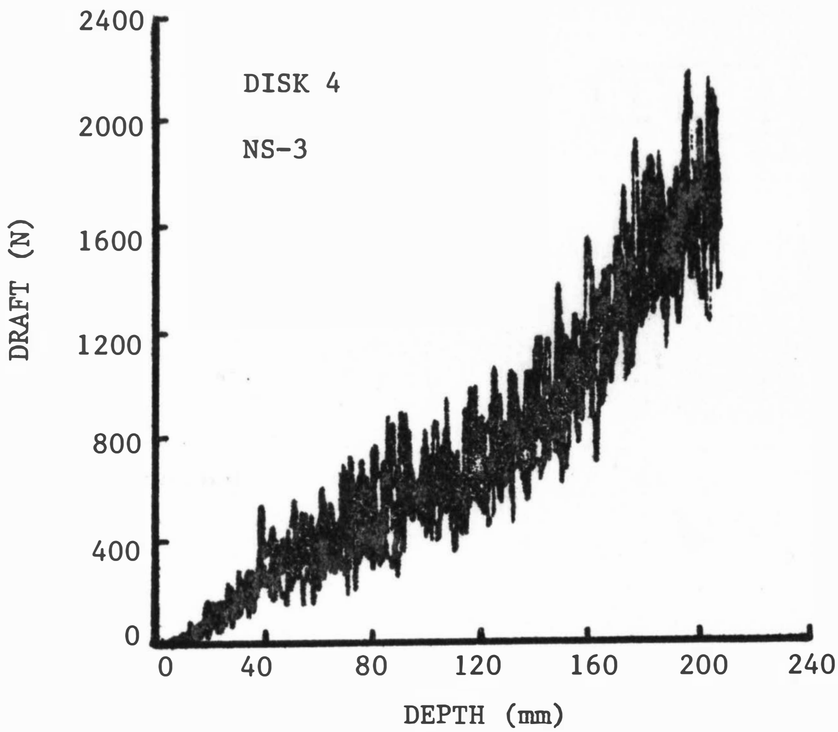

Figure 28. Disk data curves for disk 4, NS-3