SOIL TILLAGE STUDIES WITH MODEL PLANE CHISELS

BY

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ABSTRACT

The physical characteristics of particle size distribution, compactability and plasticity of Ottawa sand and Haney clay were determined.

Direct shear tests were used to relate dry bulk density, soil water content and normal pressure to the shear strength of Ottawa sand and Haney clay.

The static and kinetic values of soil-metal friction were determined for each of three chisel shaped tillage machines with Ottawa sand and Haney clay. The friction values were then related to normal pressure, area of contact and soil water content for each soil.

Tillage studies were conducted and the forces resulting from soil-machine interaction were measured. For each soil, these forces were related to soil water content, dry bulk density, machine width and machine velocity.

The soil and chisel variables were combined in accordance with the Buckingham π theorem to form dimensionless ratios. These dimensionless ratios were combined to form equations for use in model-prototype predictions. The accuracy of these predictions was found to vary with soil water content, dry bulk density and machine velocity.

Since all measurements recorded during the course of this study were analyzed by statistical procedures, the resulting equations do not represent basic physical relationships. Caution should therefore be used if these equations are to be applied to values beyond the range of values analyzed in this report.

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LIST OF NOMENCLATURE ABBREVIATIONS AND DEFINITIONS

Ø	Angle of internal friction -- angle between Mohr failure envelope and horizontal axis.
B	soil dry bulk density -- weight of oven dried soil per unit volume (lb/in^3).
B_{max}	maximum dry bulk density obtained with standard Proctor test (lb/ft^3).
C	cohesive strength -- soil shear strength at zero normal stress (lb/in^2).
C_u	coefficient of uniformity -- indicates slope of particle size distribution curve, determined by D_{60}/D_{10}.
D_{10}	diameter at which 10% of the sample is composed of smaller diameter particles.
D_{60}	diameter at which 60% of the sample is composed of smaller diameter particles.
E	soil void ratio -- ratio of volume of void space to volume of soil solids in a given soil sample.
F_x	draft force -- horizontal reaction force along axis of chisel movement.
F_z	vertical force -- vertical reaction force caused by chisel action.
KF	kinetic friction -- resistance to motion over soil-metal interface while motion is occurring at a uniform rate.
LL	Lower Atterberg limit -- minimum water content in percent at which soil exhibits plasticity.
M_y	Moment about the horizontal axis which passes at right angle to direction of chisel movement.
n	machine scale factor -- ratio between prototype machine size and model machine size.
N, σ_2	normal pressure -- the normal stress acting at right angles to failure surface in soil shear test or soil-metal friction.
PI	plasticity index -- the water content difference between upper and lower plastic limits.

PS	peak shear stress -- the maximum shear stress value as determined from shear stress-deformation curve.
R	resultant force -- maximum force reaction to soil-chisel interaction.
SF	static friction -- resistance to motion over soil-metal interface when motion is imminent.
SS	steady shear stress -- that value of soil shear strength where shear strength remains relatively constant in spite of increasing deformation.
TL	Chisel area -- chisel width times length below soil surface.
UL	upper Atterberg limit -- the maximum soil water content in percent at which a soil sample exhibits plasticity.
V	machine velocity -- velocity in in/sec at which the chisel being studied passes through a soil mass.
W	soil water content -- the weight of water per unit weight of dry soil expressed on a percentage basis.
Wopt	the water content at which maximum dry bulk density occurs for standard Practor test.

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INTRODUCTION

Statement of the problem

While soil cultivation machines helped form a basis for agriculture, man has been unable to determine a complete mathematical relationship involved between these machines and the soil. Consequently he has been unable to do quantitative design either for minimizing the forces and energies involved or for creating a specific soil condition. In fact, trial and error methods have been merely expanded in order to develop increasingly complex tillage tools without knowing either their reaction forces or their effects in advance. In most instances where engineers or other scientists have attempted to develop a quantitative soil-machine relationship, they have been prompted by a need to develop an immediate, single complex tillage tool (such as an advanced mouldboard plow) or the study has been restricted to an extremely small part of the overall picture. One must note that while early workers did not have access to modern, high speed electronic computers, this type of equipment has been used only to a limited extent for data analysis in many recent projects.

Following an observation of the almost complete lack of progress in attempts to understand soil-machine interactions, this project was designed so that the individual effects of soil physical characteristics, soil strength properties, soil machine size and operating variables might be studied and analyzed in an independent, orderly fashion.

Study Objectives

1) To select two basic soils, one being cohesionless and the other exhibiting cohesive properties and to determine their physical characteristics of particle size distribution, compactability and upper and lower Atterberg limits.
2) To determine the effects of dry bulk density, soil water content and applied normal pressure on the shear strength of each soil.
3) To determine the magnitude and characteristics of static and kinetic friction when movement occurs between the soil-chisel interface and to determine the effects of interface area, applied normal pressure, soil water content and dry bulk density on the friction forces for each chisel and soil to be studied.
4) To determine for each soil the effects of dry bulk density, water content, chisel width and velocity on the reaction forces for flat, chisel shaped machines inclined to enter the soil at 45 degrees to the direction of motion.
5) To use the Buckingham π theorem for developing a series of dimensionless ratios involving all measured and calculated soil, soil-chisel and chisel variables and then by regression analysis, to develop prediction equations capable of correlating these dimensionless ratios so that soil-chisel reaction forces are indicated.

Project outline

In accordance with the previously stated objectives, Ottawa sand and Haney clay were selected as soils with the qualities desired for the scope of this project. Both soils were subjected to mechanical analytical procedures in order to determine their particle size distribution and Atterberg limits. Both soils were then subjected to standard Proctor tests in order to develop a sound basis for understanding the effects of soil water content and dry bulk density on input energy relationships for these soils. Direct shear tests were then carried out on each soil and the soil shear strength was related to the following variables; normal load, soil water content and dry bulk density.

Three chisel widths; 0.75, 1.50 and 2.25 inches were studied in friction tests by moving each over prepared soil surfaces. The reaction forces were measured to determine the soil-metal friction involved. For each chisel and for each soil, the normal load, soil water content and dry bulk density were varied so that their effects on the soil-machine friction forces might be developed on a quantitative basis.

The final portion of the study was then carried out by moving each chisel at various velocities through a large sample of each soil. The consequent reaction forces were measured as soil water content and dry bulk density were varied under measured conditions. These forces were then related to directly measurable soil and chisel variables as well as to the composite variables of soil shear strength and soil-metal friction.

REVIEW OF LITERATURE

Soil testing procedures

Most of the accepted test procedures for determining soil strength parameters have evolved from testing and predicting for static conditions. These test procedures have been directly applied to the dynamic reactions of soil tillage. With regard to the soils considered for this project, Ottawa sand is cohesionless and is a relatively simple physical medium for study and prediction when compared with cohesive Haney clay which has been described as a viscoplastic material (13).

Lambe (15) provides an excellent basic description of many of the standard soil testing procedures as well as depicting the methods of presentation and the usefulness of the test results. Each test outline also includes a brief description of the soil mechanics theories involved and the interactions and effects involved when soil parameters and/or test procedures are varied. He also states that while the shear strength of a cohesive soil generally increases as the rate of shear is increased, the shear strength of a cohesionless soil varies less than 2% for shear rates between 0.1 and 0.0006 inches per minute.

Panwar and Siemens (19) were able to relate soil failure energy relationships and shear strength to water content and dry bulk density for a Drummer silty clay loam soil. These relationships were developed from the results of a series of direct shear tests and unconfined compression tests.

Gill (8) was able to develop a relationship between progressive losses of soil water by a soil sample with corresponding dry bulk density increases and was consequently able to verify the existence of a shrinkage limit on the basis of quantitative tests.

By applying X-ray techniques to soil studies, Kitani and Persson (14) developed procedures capable of direct measurement of axial displacement within a soil sample. The displacement which they measured and were able to describe quantitatively was caused by the compression of a soil sample by triaxial shear test apparatus. Using this technique they were also able to relate normal stresses to measured variable lateral stresses.

Kim (13) was also able to directly measure soil deformation induced by applied stresses by using Moire fringe techniques which he developed for cohesive soils.

Vomocil and Chancellor (28) related the compressive and tensile strength of remoulded samples of Yolo silt loam, Yolo silty clay and Columbia silt loam to both volumetric water content and moisture retention pressure.

Nichols (17) was a pioneer in the field of soil tillage studies and his series of articles entitled "The Dynamic Properties of Soils" outlined a series of test results and theories capable of relating some of the soil strength properties to physically measurable soil variables.

Fox, et al. (7) determined the energy required to pulverize a soil sample to a desired state and related this energy to the moisture content and particle sizes of the soil sample. They also related soil shear strength to soil moisture content.

Soil-tool interactions

The interaction between a soil and a machine operated so as to rearrange this soil is an extremely complex area of study. Development of any relationship attempting to explain such interactions must involve understanding the individual and/or cumulative effects of all soil and machine variables included in the relationship and the manner in which they affect the interaction.

Nichols *et al*. (18) were able to determine the effects of plow share shape, amount of wear and angle of approach and the initial soil condition to the types and extent of reaction forces imposed by a soil sample. They measured the physical forces involved and the modes of soil reaction as a tillage tool passed through a soil mass. The latter were determined visually through a glass walled tillage bin.

Chisholm *et al*. (5) studied the relationships among the soil conditions and the forces acting on an individual tillage tool while its operation is being affected by other tools operating in conjunction with it. They determined that for a specific tool operating in an artificial soil, draft forces could be varied by over 25% depending on the degree and type of interference caused by the associated tools.

Wismer and Luth (30) were able to develop prediction equations for chisels operating in saturated clay soils. Their studies indicated a relationship between the apparent cohesive strength of a soil as determined by undrained triaxial shear tests and the resistance of the soil to the intrusion of a cone shaped penetrometer.

Nichols (17) was able to relate the force reactions involved in soil-metal friction to soil water content, tillage tool area, the surface condition of the tillage tool, the normal pressure applied to the soil-tool interface and, in cases of extremely loose soil conditions, to the dry bulk density of the soil. He was able to observe four distinct phases of soil-metal friction; compression, friction, adhesion and lubrication. The main distinguishing factor was soil water content.

Tillage tool similitude

A number of projects designed to evolve an understanding of the interactions between soils and tillage tools have been based on the theories of similitude and dimensionless ratios. The dimensionless ratios involve measurable parameters and are calculated by the Buckingham π theorem. This procedure has been successfully used in fluid mechanics and has been applied to the field of soil mechanics. Consequently, the soil and machine variables have been treated in manners which may or may not indicate their precise effect on specific soil-tool interactions. Some investigators have successfully used this procedure to develop satisfactory prediction equations for the specific conditions they were studying. Others, however, have not been so fortunate. All have been unable to provide explanations for either success or failure in terms of soil and/or tool parameters and their effect on soil mechanics.

Reaves, et al. (21) were able to develop similitude based prediction equations for a variety of chisels operating in an assortment of soil types. However, they have not included water content in any of their dimensionless ratios and did not mention the water contents at which the soils were tested.

Wang, et al. (29) state that they have developed equations capable of predicting draft forces with acceptable accuracy limits under any given range of soil conditions by conducting experiments in a different soil. They also claim the ability to estimate draft force within a model-prototype scale factor of 2 to 1 without having to resort to distorted models. These conclusions were stated following tests conducted on a single soil at an unstated water content. Unfortunately, they have deemed as unimportant and therefore have not indicated the extent of the experiments to be conducted in the different soils under consideration.

Tillage tool characteristics

The lack of available quantitative design parameters has resulted in most tillage tool designs being based on trial and error methods and qualitative observations. Very few tillage studies are designed to yield direct quantitative information regarding the interactions of various tool parameters or the effects of these interactions on tillage forces.

Kaufman and Totten (12) have outlined a qualitative process for developing a specific mouldboard plow while

Soehne (24) has outlined the development of tillage tools in relation to tillage requirements and indicates that improved quantitative knowledge might result in modifications and improvements to tillage tools.

Carlson (3) has outlined the development of mouldboard plows from the stages of qualitative analysis to the development of a mouldboard plow from theoretical quantitative knowledge. This quantitative knowledge is analyzed and converted to design criteria by use of a special computer program.

EXPERIMENTAL METHODS

Soil testing

Particle size analysis

Samples of Ottawa sand and Haney clay were subjected to a dry sieve analysis. Since no particles of Ottawa sand passed through 0.149 mm sieve openings, the particle size analysis was deemed completed. Haney clay was, however, subjected to a Bouyoucos hydrometer analysis as outlined by Lambe (15). The resulting data were then plotted on semi logarithmic graph paper and the values of D_{10}, D_{60} and the coefficient of uniformity were determined from these graphs.

Plasticity tests

Ottawa sand, being cohesionless, was not subjected to plasticity testing. However, the cohesive Haney clay soil was subjected to Atterberg limit tests as described by Lambe (15). The upper and lower Atterberg limits and plasticity index were thus determined.

Shear testing

A major problem in studying the relationships between the shear strength and dynamic strength properties of a soil is the selection of a suitable soil shear test procedure. Other investigators have noted differences resulting from varying the test procedures. Very little information is available to relate the actions and results of these test procedures to the actions and results imposed during tillage. Thus, various test procedures were studied for their shear actions and their corresponding usefulness. The factors most considered in selecting the test procedure were the freedom of soil pore water movement and the relative degree to which the shear failure planes would be predetermined during tillage. Consequently, the strain-controlled direct shear test described by Lambe (15) was selected as this procedure most closely indicated the shear failure behaviour during tillage testing with plane chisels. Each soil was shear tested in both compact and loose conditions at each of three water contents. Each of these combinations was also subjected to normal pressure of 3.75, 9.28 and 17.53 pounds per square inch. For Ottawa sand, the water contents were 0, 10.8 and 19.9 % while for Haney clay, they were 0, 16.8 and 27.7 %. These water contents were obtained by carefully hand mixing water with the soil samples to obtain uniformity. The soil samples were then subjected to shear testing. This mixing procedure was selected to maximize the similarity between shear testing and tillage testing where the volume of soil involved dictates this procedure be used.

Soil-chisel interface

Soil-metal friction

Soil-metal friction was the force required to move each chisel across the surface of a soil sample. An Instron tester was used to provide a constant rate of movement and a continuous record of friction force on an associated chart recorder. Each chisel was tested with normal loads of 0, 0.22 2.2 and 4.4 pounds plus the weight of the chisel and associated brackets. The soils were tested in both loose and compact conditions for water contents of 0, 10.0 and 19.2 % for Ottawa sand and 0, 10.0 and 26.3 % for Haney clay.

Tillage testing and equipment used

Equipment

A tillage test bed was designed and constructed to propel a tillage tool through an eight foot long soil sample at controlled velocities between zero and five miles per hour. The unit was powered by a one half horsepower speed controlled Servo-Tek electric motor. A tillage tool was carried on an aluminum carriage riding on Thomson ball bushings and case hardened, polished steel shafts to minimize friction drag and vibration.

Instrumentation

A transducer for measuring the forces along each of three orthogonal axes and the moments about each of these axes with each measurement being independent was developed for this study. (See Appendix A).

The basic measuring units were electrical resistance strain gauges. These gauges, each having a resistance of 500 ohms and a gauge factor of 2.12, were connected in wheatstone bridge configurations. Attempts were made to construct amplifiers suitable for amplifying the resulting signals using Motorola MC 1439 G operational amplifiers as a base. (See Appendix B). Serious and time consuming problems, including crosstalk between amplifier units and difficulty in isolating them from electrical noise in the surrounding area were encountered. These problems were solved before discovering that at the high rates of amplification required, these units lacked long term stability.

Consequently, the output from the transducers for F_z (vertical force) and M_y (moment about Y-axis) were fed into Brush model RD561200 amplifiers and the signal recorded on the associated Brush model BL-202 two channel chart recorder. The transducer output for draft force (F_x) was fed into an Ellis model BAM - 1 amplifier and then recorded on a model 7100-A Mosely chart recorder.

The chart speed for the Mosely recorder is precisely controlled. Therefore, the distance between 2 marks which are produced on the chart by the carriage passing over microswitches provides an accurate indication of machine velocity.

The variation in angle of approach of a tillage tool attached to the transducer is 0.16 degrees at the maximum design draft force of 150 pounds. This factor is important as the angle of approach for different sized tillage tools must be constant to maintain geometric similarity.

Tillage tools

Three widths of plane chisels were used to produce scale factors suitable for use in similitude with the smallest acting as a model for the other two, and the intermediate size acting as a model for the largest. Thus, scale factors of 1.5, 2.0 and 3.0 were studied. Observations of other experiments (10) indicate that depth of operation and chisel width have diverse effects on tillage draft forces. All chisels were therefore operated at the same depth of three inches and chisel area was related to the scale factor.

This factor creates dimensionally distorted models and adds to the distortion caused by the soils which are used for all machines. Also width, as a design variable, is controlled by machine designers while depth, as an operating variable, is controlled by any individual machine operator.

In order to maintain uniformity, all chisels were constructed from one piece of 1/8 inch thick hot rolled steel. Each was milled to within 0.002 inches of the desired width and then hand polished, with crocus cloth, to a mirror finish. The final lapping was parallel to the direction of soil movement over the chisel face. The leading edge of each tool was sharpened to an angle of 30°. Thus, a clearance of 15° was formed between the chisel under surface and the soil.

The 0.75 inch wide chisel was operated at 10% of the potential speed of the Servo-Tek motor while the 1.50 inch chisel was operated at 14.14% and the 2.25 inch chisel at 17.32%. These values were chosen to maintain model-prototype similitude as the velocities of each prototype chisel are determined by the ratio:

$$V_p = V_m \sqrt{n} \qquad [1]$$

when V_p = velocity of prototype chisel
V_m = velocity of model chisel
n = model-prototype scale factor.

Although not a requirement for similitude based prediction equations, each chisel was operated at all three velocities in order to develop a more complete understanding of velocity as a factor affecting soil-machine reaction forces.

Soil variables

Each chisel variable was tested in both the loose and compacted states for each soil at each of three different water contents. For Ottawa sand, the water contents were 0, 2 and 4 percent with the dry bulk density varying between 0.051 and 0.057 pounds per cubic inch. Haney clay was tested at water contents of 0, 8.7 and 13.9 percent while the dry bulk density varied between 0.043 and 0.047 pounds per cubic inch. Prior to each trial, samples were taken for water content determination and fixed volumes of soil were removed by a sampling core and weighed for bulk density determination.

ANALYTICAL PROCEDURES

Shear strength

During each test, stress and deformation were read from dial gauges and recorded manually and were then related graphically. Both the peak shear stress value and the steady shear stress value were derived from these graphs. For both soils, each of these values was related to soil water content, dry bulk density and normal pressure for each trial. This step was completed by analyzing these variables with the multiple linear regression and stepwise linear regression package available on an IBM 360/67 electronic computer at the University of British Columbia as was all regression analysis for this study. The significance of each factor's contribution to the regression equation was provided in the computer printout during this analysis.

Soil-metal friction

As for most friction studies, both static and kinetic friction forces were determined. Static friction is the peak resistance to sliding which occurs when motion is imminent. Kinetic friction is the resistance which occurs during movement at a relatively uniform rate. Both values were recorded by a chart recorder and measured by manually measuring the resulting deflections on the chart and comparing them to previous calibrations. Each friction force was then related to soil water content, dry bulk density, normal pressure and chisel width by multiple linear regression and stepwise linear regression.

Tillage analysis

Draft force (F_x), vertical force (F_z) and the moment about the horizontal axis running parallel to the chisel face (M_y) were continuously monitored on chart recorders during the entire length of each trial. F_z and M_y were then read directly from the Brush chart at 5 mm. intervals on the chart, while F_x was determined by measuring the deflections on the Mosely chart to the nearest 1/100 inch at 1/10 inch longitudinal intervals on the chart. The data for each test was then averaged for the duration of the specific trial and the forces converted to pounds and the moments to foot-pounds by comparison with previous calibrations. The resultant force (R) and the normal pressure (N) exerted on the chisel were calculated for each trial. Multiple linear regression and stepwise linear regression were then used to relate each force to the water content and dry bulk density of each soil as well as to chisel width and velocity. The forces were then related to the calculated weight of soil disturbed, velocity, shear strength and soil-metal firction by the same process. Using the Buckingham π theorem, dimensionless ratios, which included the variables and their corresponding dimensions as shown in Table 1, were developed.

TABLE 1
Variables and Corresponding Dimensions

Variable	Symbol	Dimensions
Dry bulk density	B	ML^{-3}
Chisel velocity	V	LT^{-1}
Water content	W	-
Chisel area	TL	L^2
Tillage forces	F_x, F_z, R	MLT^{-2}
Shear strength	S	$ML^{-1}T^{-2}$
Soil-metal friction	F	$ML^{-1}T^{-2}$
Gravity	G	LT^{-2}

Using B, V and TL as the repeating variables, the following π terms were developed.

$$\pi_1 = W$$

$$\pi_2 = \frac{F_x}{BV^2TL}, \frac{F_z}{BV^2TL}, \frac{R}{BV^2TL}$$

$$\pi_3 = \frac{S}{BV^2}$$ (S may be either the peak or the steady value)

$$\pi_4 = \frac{F}{BV^2}$$ (F may be either the static or the kinetic value)

$$\pi_5 = \frac{(TL)^{1/2}G}{V^2}$$

The π_2 terms were then related to the remaining π terms by multiple linear regression and stepwise linear regression. The π terms for each chisel were first analyzed separately so that regression equations were developed for each chisel in each soil. The next procedure involved determining the regression equation relating the π terms formed for all chisels operating at their respective velocities as determined by equation [1]. This step determined the effectiveness of similitude in model-prototype predictions for tillage studies. The results, for each equation, were then displayed in both tabular and graphical form in order to allow optimum comparisons. The results for each equation were compared graphically with the predicted results.

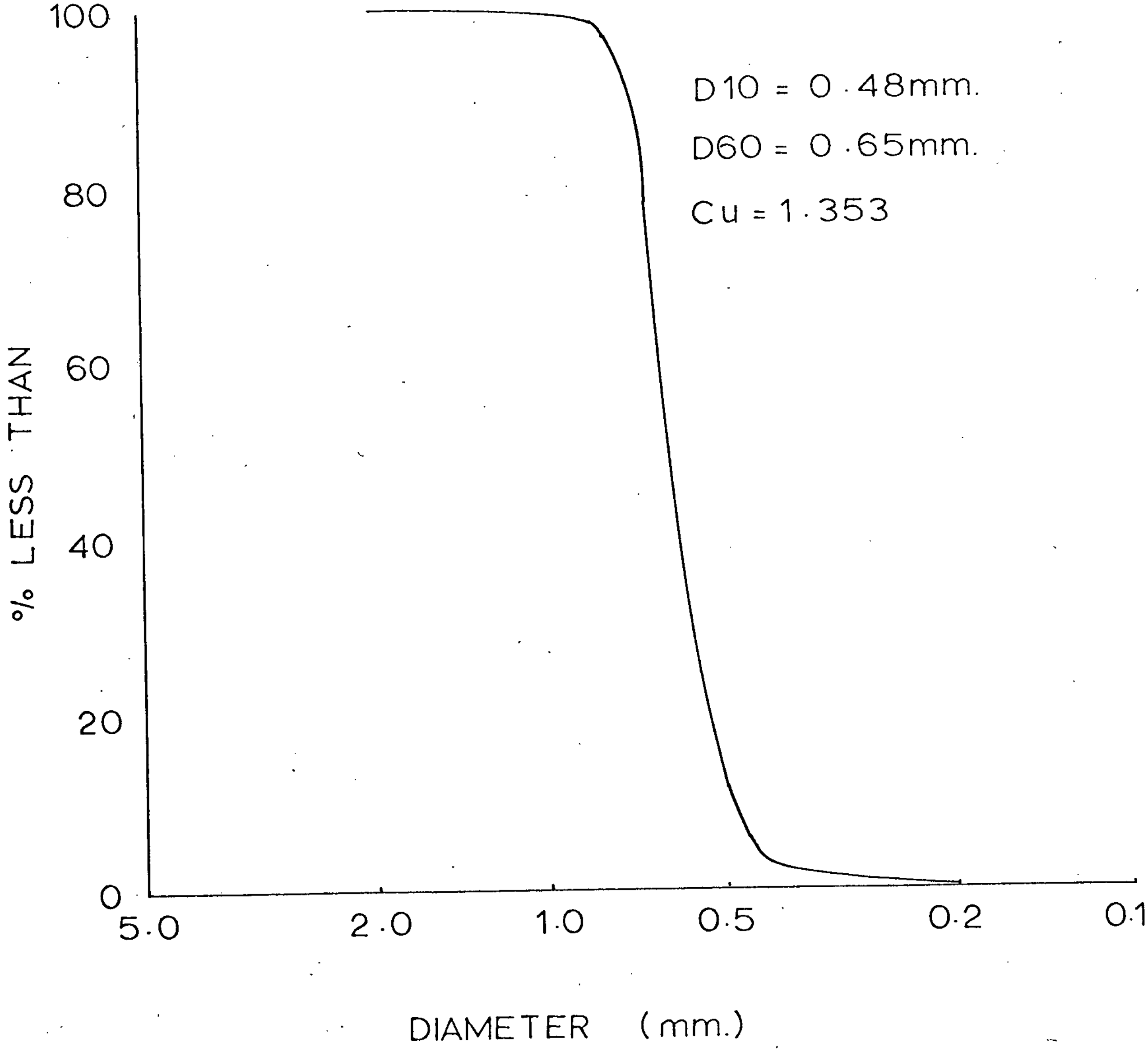

FIGURE 1. PARTICLE SIZE DISTRIBUTION FOR OTTAWA SAND

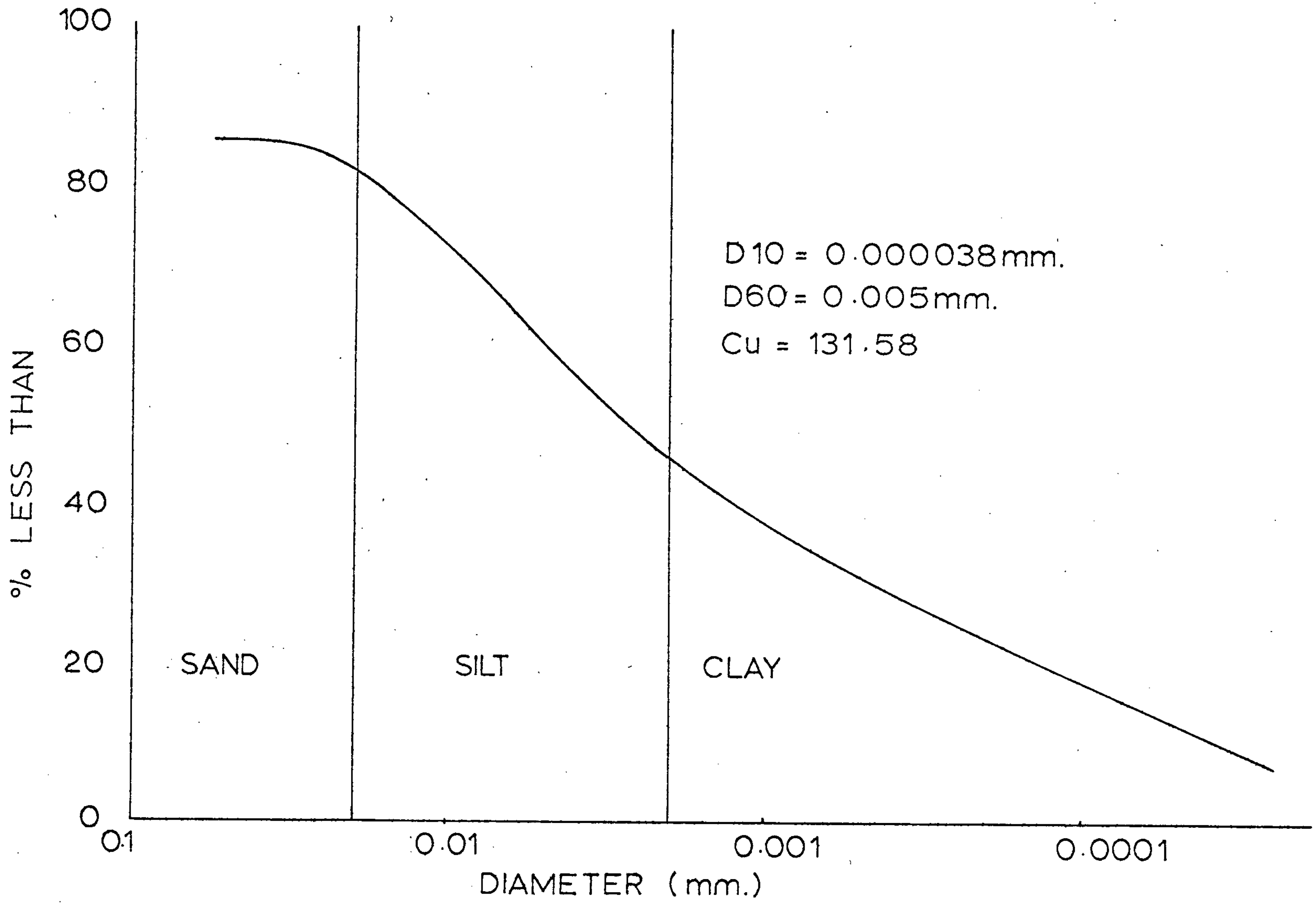

FIGURE 2. PARTICLE SIZE DISTRIBUTION FOR HANEY CLAY

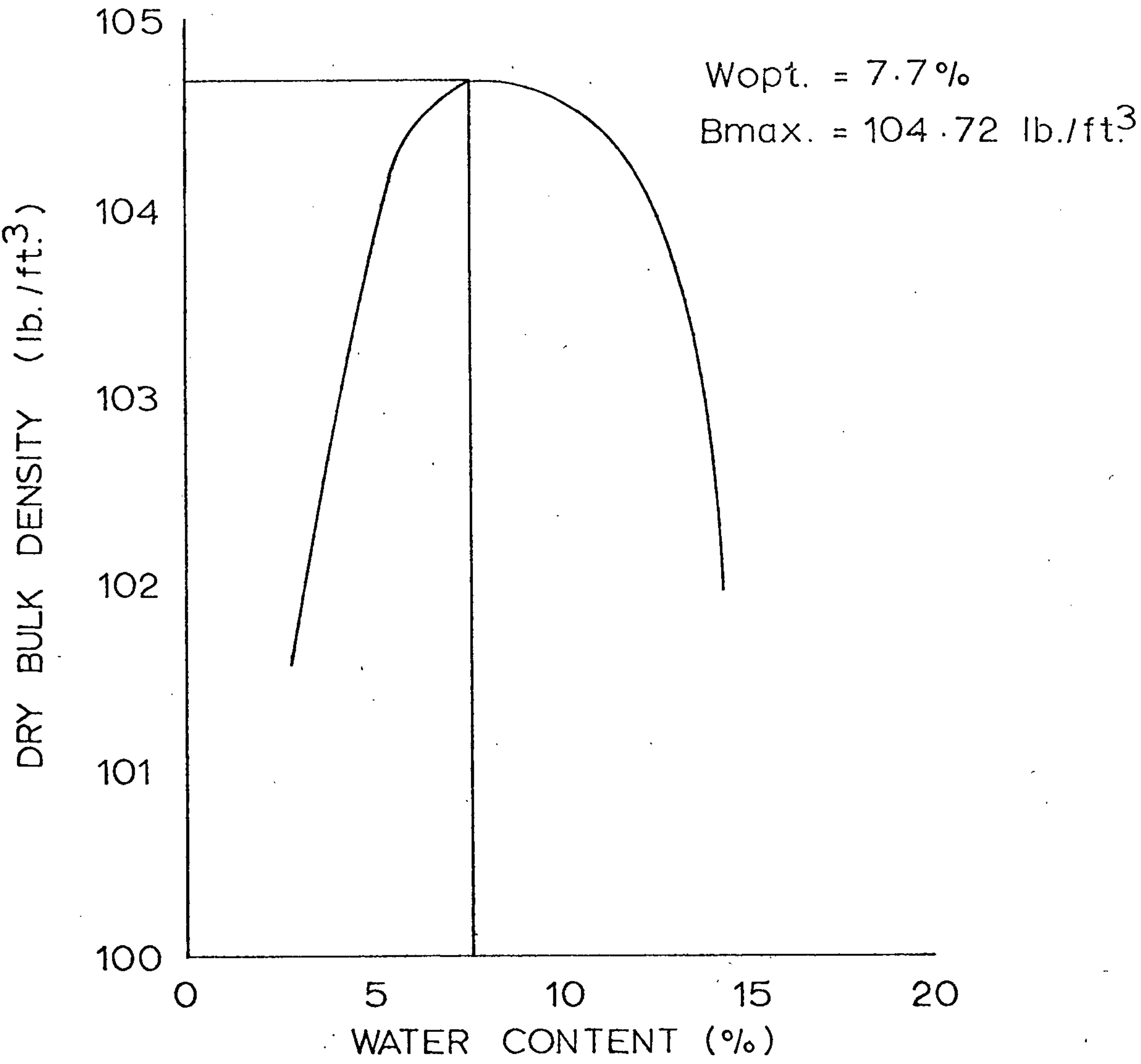

FIGURE 3. RESULTS OF STANDARD PROCTOR TEST FOR OTTAWA SAND.

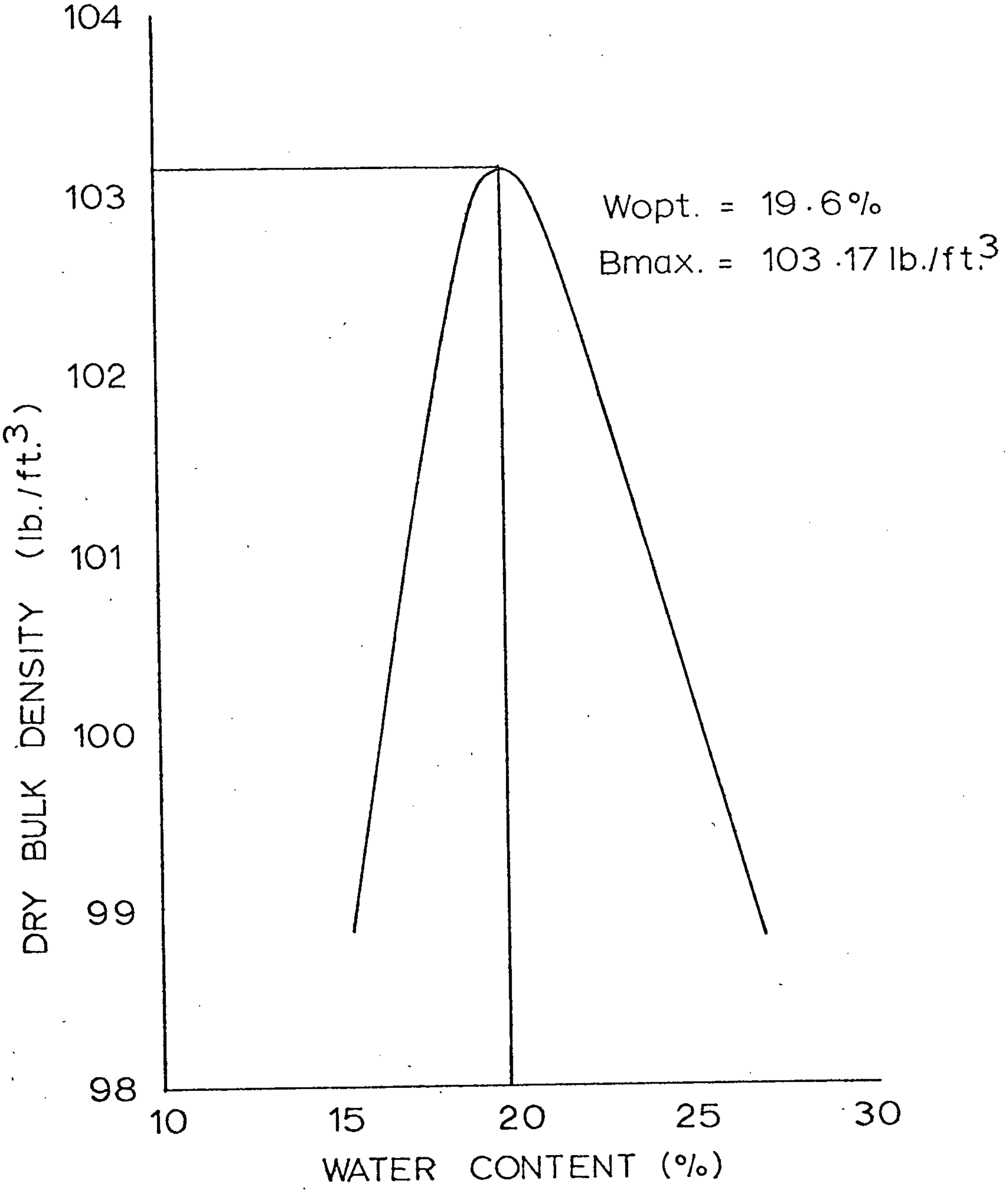

FIGURE 4. RESULTS OF STANDARD PROCTOR TEST FOR HANEY CLAY.

RESULTS AND DISCUSSION

Soil physical properties

The results of tests involving the basic physical characteristics of Ottawa sand and Haney clay are depicted in Table 2 below.

TABLE 2.

Comparison of Soil Physical Characteristics

Test	Factor	SOIL	
		Ottawa sand	Haney clay
Particle size analysis	D_{10} (mm.)	0.48	0.000038
	D_{60} (mm.)	0.65	0.005
	C_u	1.353	131.58
Compaction	Wopt (%)	7.7	19.6
	B max(lb/ft^3)	104.72	103.17
Plasticity	UL (%)	-	47.9
	LL (%)	-	19.85
	PI	-	28.05

The detailed results of the particle size analysis may be observed in Figures 1 and 2 while the results of the compaction tests are depicted in Figures 3 and 4. All particle sizes for Ottawa sand were within the range for sand whereas the Haney clay contained 18% sand, 37% silt and 45% clay.

For Ottawa sand, the shear strength values were found to be related to the soil variables and normal pressure as is depicted in equations 2 and 3.

$$PS = 6.153 - 14.2267\,E + 0.0133W + 7.9962E^2 + 0.5848N \qquad [2]$$

$$SS = 1.9113 - 4.8335E + 2.8998E^2 + 0.0004203W^2 + 0.5449N \qquad [3]$$

For Haney clay the corresponding relationships were as depicted in equations 4 and 5.

$$PS = 0.9066 + 0.1701W - 0.3006E^2 - 0.007139W^2 + 0.6575N \qquad [4]$$

$$SS = 0.6213 + 0.1720W - 0.2521E^2 - 0.006943W^2 + 0.6541N \qquad [5]$$

when PS = peak shear strength (lb/in^2)
SS = steady shear strength (lb/in^2)
W = soil water content (%)
E = void ratio
N = normal pressure (lb/in^2)

Equations 2 to 5 inclusive were all significant at $F \leqslant 0.0002$ and by comparison with the Mohr failure envelope equation, may be used to indicate the cohesive strength and the angle of internal friction of the soil by

$$S = C + \sigma \tan \phi \qquad [6]$$

when S = soil shear strength (lb/in^2)
C = cohesive strength (lb/in^2)
σ = normal stress (lb/in^2)
ϕ = angle of internal friction (°)

As may be noted from equations 2 and 3, the cohesive strength of Ottawa sand is very low ($C \rightarrow 0$) while for Haney clay, equations 4 and 5 indicate that the cohesive strength is, as expected, a much larger value. Also, equations 2 to 5 inclusive indicate that the angles of internal friction depicted in Table 3 are relatively constant values for each soil.

TABLE 3

Internal Friction Angles for Ottawa Sand and Haney Clay

Soil	Tan Friction Angle		Friction Angle (ϕ)	
	Peak	Steady	Peak	Steady
Ottawa sand	0.5848	0.5449	30° 18'	28° 36'
Haney clay	0.6578	0.6541	33° 20'	33° 12'

Soil-machine interaction

For both Ottawa sand and Haney clay, static and kinetic values of soil-metal friction were found to be related to chisel width, normal pressure and soil water content. These relationships are described in equations 7 and 8 for Ottawa sand

$$SF = 0.009176 - 0.01T + 0.00281T^2 + 0.2457N \qquad [7]$$

$$KF = -0.001471 + 0.003388W + 0.2433N \qquad [8]$$

Equations 9 and 10 describe the corresponding relationships for Haney clay

$$SF = 0.001801 - 0.006722W + 0.00005255W^2 + 0.3689N \qquad [9]$$

$$KF = 0.002441 + 0.3151N \qquad [10]$$

when

SF = static friction (lb/in^2)

KF = kinetic friction (lb/in^2)

W = soil water content (%)

T = chisel width (in)

N = normal pressure (lb/in^2)

Equations 7 to 10 inclusive were all found to be significant at F 0.0. The soil bulk densities at which the soil-metal friction tests were conducted included no values in the compression phase described by Nichols (17). Consequently, soil bulk density was not a significant factor in the relationships described by equations 7 to 10 inclusive.

Tillage forces

Direct relationships

During each tillage test, the measured forces resulted from the interactions between the chisel involved, its velocity and the soil conditions at the time of testing. For Ottawa sand, these relationships are indicated by equations 11, 12 and 13.

$$F_x = -175.7441 + 3.5582T + 3.6683W + 4983.5552B - 0.0819V - 0.5359W^2 - 42580.0B^2 \quad [11]$$

$$F_z = -233.9427 + 4.8502T + 4.0905W + 8116.0604B + 0.0465V - 0.5715W^2 - 70650.0B^2 \quad [12]$$

$$R = -275.9427 + 6.0246T + 5.4603W + 9536.4463B - 0.011V - 0.7783W^2 - 82590.0B^2 \quad [13]$$

The corresponding relationships for Haney clay are described by equations 14, 15 and 16.

$$F_x = 53.549 + 2.9051T + 0.1368W - 3731.8906B + 0.2295V + 0.0212W^2 + 56420.0B^2 \quad [14]$$

$$F_z = 158.3130 + 5.0347T + 0.2797W - 9414.6966B + 0.3920V + 0.0337W^2 + 128800.0B^2 \quad [15]$$

$$R = 158.8711 + 5.7662T + 0.3062W - 9774.0242B + 0.4536V + 0.0396W^2 + 136900.0B^2 \quad [16]$$

when F_x = draft force (lb)
F_z = vertical force (lb)
R = resultant force (lb)
T = chisel width (in)
W = soil water content (%)
B = soil dry bulk density (lb/in^3)
V = chisel velocity (in/sec).

The relationships described by equations 11 to 16 inclusive were all significant at F 0.0.

Comparison of equations 11 to 13 with equations 14 to 16 indicates that each soil type presents unique tillage relationship characteristics which must be recognized and understood on a quantitative basis before complete soil tillage relationships can be developed. For the two soils studied, the effects of chisel velocity, soil water content and dry bulk density were almost completely opposite. However, the negative velocity effect attributed to Ottawa sand by these equations must be considered to be exaggerated. A possible explanation for this effect might be that a slight vibration and corresponding draft reduction, may have been imparted to the chisels operating at higher velocities. However, the overall effect of chisel velocity indicates that the shear strength of cohesionless soils tends to be negligible while the shear strength of cohesive soils is definitely rate dependent.

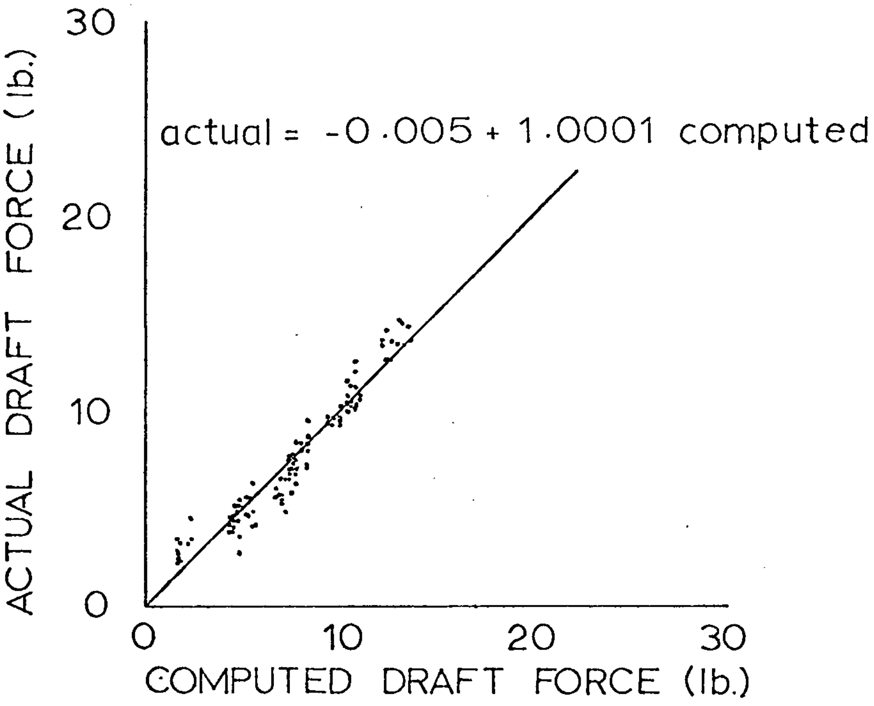

FIGURE 5. OTTAWA SAND - ACTUAL DRAFT FORCE VS. VALUE COMPUTED FROM EQUATION 11.

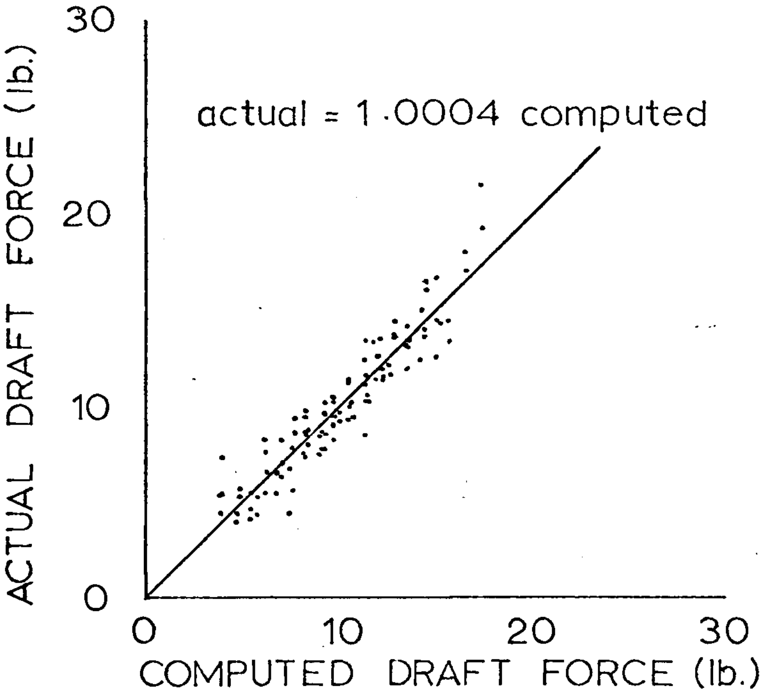

FIGURE 6. HANEY CLAY - ACTUAL DRAFT FORCE VS. VALUE COMPUTED FROM EQUATION 14.

Attempts tp develop satisfactory equations relating tillage forces to chisel velocity, soil-metal friction, soil shear strength and weight of soil disturbed were unsuccessful due to the low level of significance of each contributing factor. Consequently, no comparisons with theoretical force-reaction equations as proposed by Gill and Vanden Berg (10) were possible.

Dimensionless equations

Attempts have been made to develop dimensionless tillage relationships using the cohesive strength plus the angle of internal friction of the soil to describe the soil shear strength value. However, cohesion and friction angle were shown in equations 2 to 5 inclusive (by comparison with equation 6) to be determined by the soil and its condition at the time of testing, and bear no relationship to tillage variables. Consequently, the normal pressure applied to the failure surface must be known in order for soil shear strength to make a meaningful contribution to a soil tillage relationship equation. Similarly, the normal pressure value is required for studying soil-metal friction in relation to soil tillage. Since the chisels were inclined at an angle of 45° to the soil surface and this value is very similar in magnitude to the angle of the shear failure planes formed during tillage, the same equations were used to indicate normal pressure for calculating both soil shear strength and soil-metal friction. For Ottawa sand, the normal pressure is indicated in equation 17.

$$N = 3.4248 - 1.1366T + 0.9807W + 0.2106T^2 - 0.1379W^2 - 2.0957E^2 \qquad [17]$$

For Haney clay, normal pressure is indicated by equation 18.

$$N = 32.1408 - 2.8869T - 36.4914E + 0.00122V + 0.5836T^2 + 0.0115W^2 + 10.9012E^2 \qquad [18]$$

when N = normal pressure (lb/in^2)

T = chisel width (in)

W = water content (%)

E = void ratio.

The normal pressures derived from equations 17 and 18 were included in the appropriate soil-metal friction and soil shear strength equations to yield the numerical values of soil-metal friction and soil shear strength values for each test. These values were then included in the previously developed dimensionless ratios and regression equations developed for tillage reactions. For Ottawa sand, the 0.75 inch wide chisel's reactions are described by equations 19, 20 and 21; the 1.50 inch wide chisel's reactions by equations 22, 23 and 24; and the 2.25 inch wide chisel's reaction by equations 25, 26 and 27. When each chisel is operated in Ottawa sand at its proper similitude based velocity (as determined by equation 1, the interactions were as depicted by equations 28, 29 and 30.

$$\frac{F_x}{BV^2TL} = -0.0553 + 0.0127W + 0.6634\,\frac{PS}{BV^2} + 1.0308\,\frac{SF}{BV^2} \qquad [19]$$

$$\frac{F_z}{BV^2TL} = -0.0276 + 0.0118W + 0.9189\,\frac{PS}{BV^2} + 1.0169\,\frac{SF}{BV^2} \qquad [20]$$

$$\frac{R}{BV^2TL} = -0.0514 + 0.0161W + 1.1065\,\frac{PS}{BV^2} + 1.4871\,\frac{SF}{BV^2} \qquad [21]$$

$$\frac{F_x}{BV^2TL} = -0.007588 - 0.001506W - 0.2736\,\frac{PS}{BV^2} + 3.0657\,\frac{SF}{BV^2} \qquad [22]$$

$$\frac{F_z}{BV^2TL} = 0.004433 + 0.00152W - 0.1676\,\frac{PS}{BV^2} + 3.4876\,\frac{SF}{BV^2} \qquad [23]$$

$$\frac{R}{BV^2TL} = -0.0004752 + 0.0001727W - 0.2994\,\frac{PS}{BV^2} + 4.6332\,\frac{SF}{BV^2} \qquad [24]$$

$$\frac{F_x}{BV^2TL} = 0.0111 - 0.0101W - 0.3835\,\frac{PS}{BV^2} + 3.2361\,\frac{SF}{BV^2} \qquad [25]$$

$$\frac{F_z}{BV^2TL} = 0.043 - 0.011W - 0.3719\,\frac{PS}{BV^2} + 3.65\,\frac{SF}{BV^2} \qquad [26]$$

$$\frac{R}{BV^2TL} = 0.0419 - 0.0153W - 0.5427\,\frac{PS}{BV^2} + 4.9038\,\frac{SF}{BV^2} \qquad [27]$$

$$\frac{F_x}{BV^2TL} = -0.0393 + 0.005241W + 0.4985\,\frac{PS}{BV^2} + 1.4391\,\frac{SF}{BV^2} \qquad [28]$$

$$\frac{F_z}{BV^2TL} = -0.0309 + 0.008054W + 0.7783\,\frac{PS}{BV^2} + 1.3964\,\frac{SF}{BV^2} \qquad [29]$$

$$\frac{R}{BV^2TL} = -0.046 + 0.008841W + 0.9012\,\frac{PS}{BV^2} + 2.0249\,\frac{SF}{BV^2} \qquad [30]$$

The corresponding relationships for Haney clay are described by equations 31, 32 and 33 for the 0.75 inch wide chisel; equations 34, 35 and 36 for the 1.50 inch wide chisel; and equations 37, 38 and 39 for the 2.25 inch wide chisel. When each chisel was operated in Haney clay at its proper similitude based velocity (as determined by equation 1) the interactions were as depicted by equations 40, 41 and 42

$$\frac{F_x}{BV^2TL} = 0.0135 - 0.00626W + 0.5038\,\frac{PS}{BV^2} + 0.5091\,\frac{SF}{BV^2} \qquad [31]$$

$$\frac{F_z}{BV^2TL} = -0.0241 - 0.001027W + 0.0694\,\frac{PS}{BV^2} + 1.9370\,\frac{SF}{BV^2} \qquad [32]$$

$$\frac{R}{BV^2TL} = -0.008109 - 0.004942W + 0.3872\,\frac{PS}{BV^2} + 1.7879\,\frac{SF}{BV^2} \qquad [33]$$

$$\frac{F_x}{BV^2TL} = 0.0602 - 0.005017W + 0.2557\,\frac{PS}{BV^2} + 0.7783\,\frac{SF}{BV^2} \qquad [34]$$

$$\frac{F_z}{BV^2TL} = 0.0549 - 0.005742W + 0.3453\,\frac{PS}{BV^2} + 1.0868\,\frac{SF}{BV^2} \qquad [35]$$

TABLE 4

Calculated Reaction Forces for Ottawa Sand when Velocity is varied and B = 0.057 kb/in^3 and W = 1.99%.

Chisel Width (in.)	Equation Numbers	F_x (lb)	F_z (lb)	R (lb)	V (in/sec)
0.75	19,20,21	6.80	8.59	10.94	6.820
		6.44	8.55	10.73	10.725
		6.09	8.51	10.51	13.435
	28,29,30	6.91	8.68	11.08	6.820
1.50	22,23,24	12.11	15.25	19.25	6.820
		11.46	15.42	19.27	10.725
		11.22	15.63	19.30	13.435
	28,29,30	11.22	14.64	18.41	10.725
	19,20,21	11.70	14.83	18.89	6.820
		10.97	14.72	18.42	10.725
		10.21	14.60	17.80	13.435
2.25	25,26,27	15.15	19.03	24.45	6.820
		14.93	19.84	24.85	10.725
		14.58	20.50	24.25	13.435
	28,29,30	15.51	21.50	26.45	13.435
	22,23,24	15.90	21.05	26.40	6.820
		15.60	21.40	26.45	10.725
		15.24	21.65	26.40	13.435
	19,20,21	17.65	22.60	28.90	6.820
		16.55	22.65	27.90	10.725
		15.48	22.35	27.30	13.435

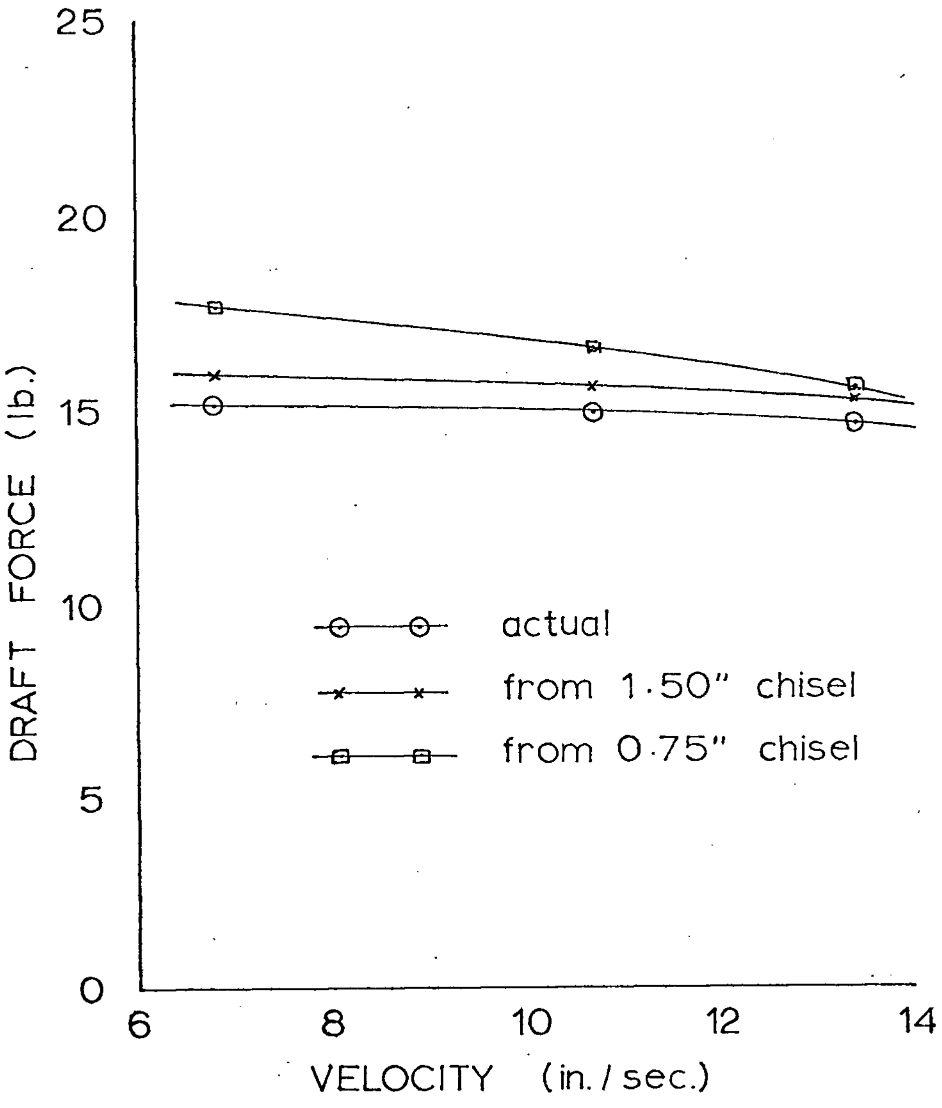

FIGURE 7. COMPARISON OF PREDICTED DRAFT FORCES FOR 2.25 INCH WIDE CHISEL IN OTTAWA SAND WHEN VELOCITY IS VARIED AND B = 0.057 lb/in^3 AND W = 1.99%.

TABLE 5

Calculated Reaction Forces for Ottawa Sand when Water Content is varied and B = 0.0541 lb/in^3 and V = 10.725 in./sec.

Chisel Width (in.)	Equation Numbers	F_x (lb)	F_z (lb)	R (lb)	W (%)
0.75	19,20,21	1.64	2.76	3.28	0
		5.00	6.75	8.44	1.994
		6.17	8.05	10.13	3.967
1.50	22,23,24	3.82	5.27	6.54	0
		8.88	12.00	14.94	1.994
		9.94	13.65	16.49	3.967
	19,20,21	1.25	2.98	3.31	0
		8.03	11.03	13.69	1.994
		10.42	13.69	17.20	3.967
2.25	25,26,27	4.98	7.72	9.24	0
		12.78	16.60	18.97	1.994
		16.29	20.95	24.50	3.967
	22,23,24	4.11	6.16	7.41	0
		11.65	16.25	19.98	1.994
		16.20	21.35	27.30	3.967
	19,20,21	2.45	5.32	5.96	0
		12.13	16.85	20.80	1.994
		16.63	21.70	27.40	3.967

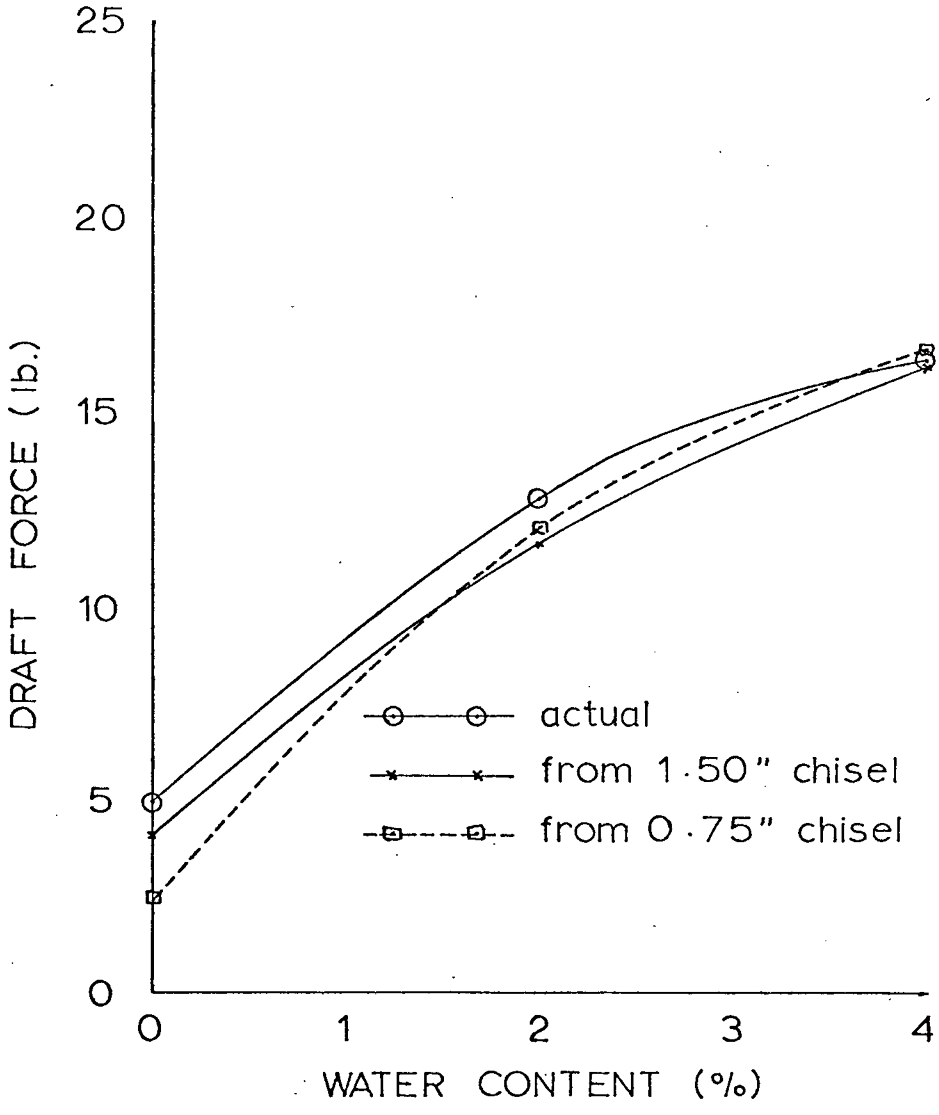

FIGURE 8. COMPARISON OF PREDICTED DRAFT FORCES FOR 2.25 INCH WIDE CHISEL IN OTTAWA SAND WHEN WATER CONTENT IS VARIED AND B = 0.054 lb/in^3 and V - 10.72 in/sec.

TABLE 6

Calculated Reaction Forces for Ottawa Sand when Dry Bulk Density is Varied and W = 1.99% and V = 10.72 in./sec.

Chisel Width (in.)	Equation Numbers	F_x (lb)	F_z (lb)	R (lb)	B (lb/in^3)
0.75	19,20,21	4.17	5.65	7.06	0.0514
		5.00	6.75	8.44	0.0541
		6.44	8.55	10.73	0.0573
1.50	22,23,24	7.85	10.57	13.20	0.0514
		8.88	12.00	14.94	0.0541
		11.46	15.42	19.27	0.0573
	19,20,21	6.44	8.95	11.12	0.0514
		8.03	11.03	13.69	0.0541
		10.97	14.72	18.42	0.0573
2.25	25,26,27	9.61	13.45	16.58	0.0514
		12.78	16.60	18.97	0.0541
		14.93	19.84	24.85	0.0573
	22,23,24	10.09	14.15	17.30	0.0514
		11.65	16.25	19.98	0.0541
		15.60	21.40	26.45	0.0573
	19,20,21	9.79	13.82	17.00	0.0514
		12.13	16.85	20.80	0.0541
		16.55	22.65	27.90	0.0573

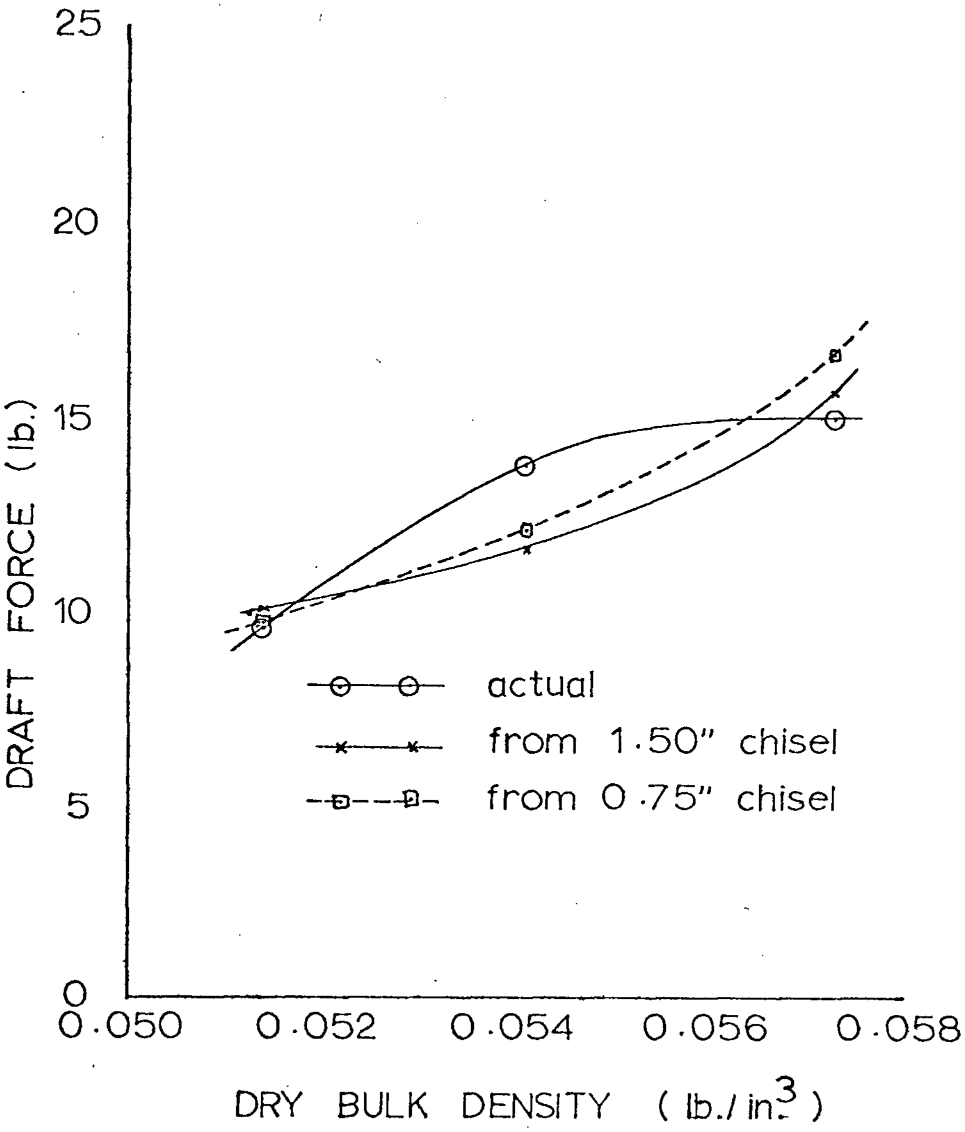

FIGURE 9. COMPARISON OF PREDICTED DRAFT FORCES FOR 2.25 INCH WIDE CHISEL IN OTTAWA SAND WHEN DRY BULK DENSITY IS VARIED AND W = 1.994% AND V = 10.725 in/sec.

$$\frac{R}{BV^2TL} = 0.0812 - 0.007683W +).4302\ \frac{PS}{BV^2} + 1.3355\ \frac{SF}{BV^2} \qquad [36]$$

$$\frac{F_x}{BV^2TL} = 0.0949 - 0.008653W + 0.4779\ \frac{PS}{BV^2} - 0.0691\ \frac{SF}{BV^2} \qquad [37]$$

$$\frac{F_z}{BV^2TL} = 0.1157 - 0.008815W + 0.6063\ \frac{PS}{BV^2} + 0.0536\ \frac{SF}{BV^2} \qquad [38]$$

$$\frac{R}{BV^2TL} = 0.1497 - 0.0122W + 0.7722\ \frac{PS}{BV^2} + 0.0008708\ \frac{SF}{BV^2} \qquad [39]$$

$$\frac{F_x}{BV^2TL} = -0.0327 - 0.005457W + 0.5968\ \frac{PS}{BV^2} + 0.319\ \frac{SF}{BV^2} \qquad [40]$$

$$\frac{F_z}{BV^2TL} = -0.007707 - 0.001265W + 0.2309\ \frac{PS}{BV^2} + 1.4872\ \frac{SF}{BV^2} \qquad [41]$$

$$\frac{R}{BV^2TL} = -0.0259 - 0.004571W + 0.5689\ \frac{PS}{BV^2} + 1.3260\ \frac{SF}{BV^2} \qquad [42]$$

when

F_x = draft force (lb)
F_z = vertical force (lb)
R = resultant force (lb)
B = soil dry bulk density (lb/in^3)
V = chisel velocity (in/sec)
T = chisel width (in.)
L = chisel depth (in.)

These relationships are all significant at F 0.0 The dimensionless ratios involving gravity, steady shear stress, and kinetic soil-metal friction were not included in equations 19 to 42 inclusive as they made no significant contribution to the dimensionless relationships.

The effectiveness of prediction from the equations for Ottawa sand are displayed by Tables 4, 5 and 6 and by Figures

7, 8 and 9, while the predictions for Haney clay are displayed in Tables 7, 8 and 9 and Figures 10, 11 and 12.

As these graphs and tables indicate, prediction equations based on similitude may be developed successfully at some soil water content values and soil dry bulk density values. Thus, the values of dry bulk density and water content at which their tests were conducted may provide an explanation for the success of some of the studies referred to in the list of references included in this report. At the same time the failure of others is explained.

Comparisons of actual draft forces with those predicted by the dimensionless equations for Ottawa sand are presented in Figures 13 to 16 inclusive while the corresponding comparisons for Haney clay are presented in Figures 17 to 20 inclusive. Comparison of these graphs with Figures 5 and 6 yields an indication that the treatment of the directly measurable chisel and soil variables in the dimensionless equations does not indicate their true effect on the soil tillage relationship. Indeed by comparing the variable treatment in the dimensionless ratios with the treatment of these variables in equations 11 to 16 inclusive, the conclusion is reached that the effects of chisel velocity, chisel width, soil water content and dry bulk density are treated in a completely distorted manner during inclusion in dimensionless ratios. Also explained by this fact is that while the similitude based predictions are satisfactory at certain soil variable values, they are not for others.

TABLE 7

Calculated Reaction Forces for Haney clay when Velocity is Varied and B = 0.047 lb/in^3 and W = 8.68%

Chisel Width (in.)	Equation Numbers	F_x (lb)	F_z (lb)	R (lb)	V (in/sec)
0.75	31,32,33	9.09	10.55	13.95	6.927
		9.13	10.90	14.28	10.725
		9.57	11.05	14.35	13.572
	40,41,42	9.09	10.53	13.47	6.927
1.50	34,35,36	11.68	15.79	19.64	6.927
		12.79	16.96	21.25	10.725
		13.62	17.88	22.55	13.572
	40,41,42	13.72	16.75	21.70	10.725
	31,32,33	14.23	15.50	21.15	6.927
		14.45	16.18	21.75	10.725
		14.27	16.54	21.90	13.572
2.25	37,38,39	14.05	19.43	24.00	6.927
		15.38	21.65	26.70	10.725
		16.55	23.70	28.95	13.572
	40,41,42	15.68	22.45	27.95	13.572
	34,35,36	15.23	20.55	25.60	6.927
		16.95	22.35	28.10	10.725
		18.30	23.70	30.00	13.572
	31,32,33	18.94	19.46	27.15	6.927
		19.05	20,50	28.10	10.725
		18.79	21.00	28.30	13.572

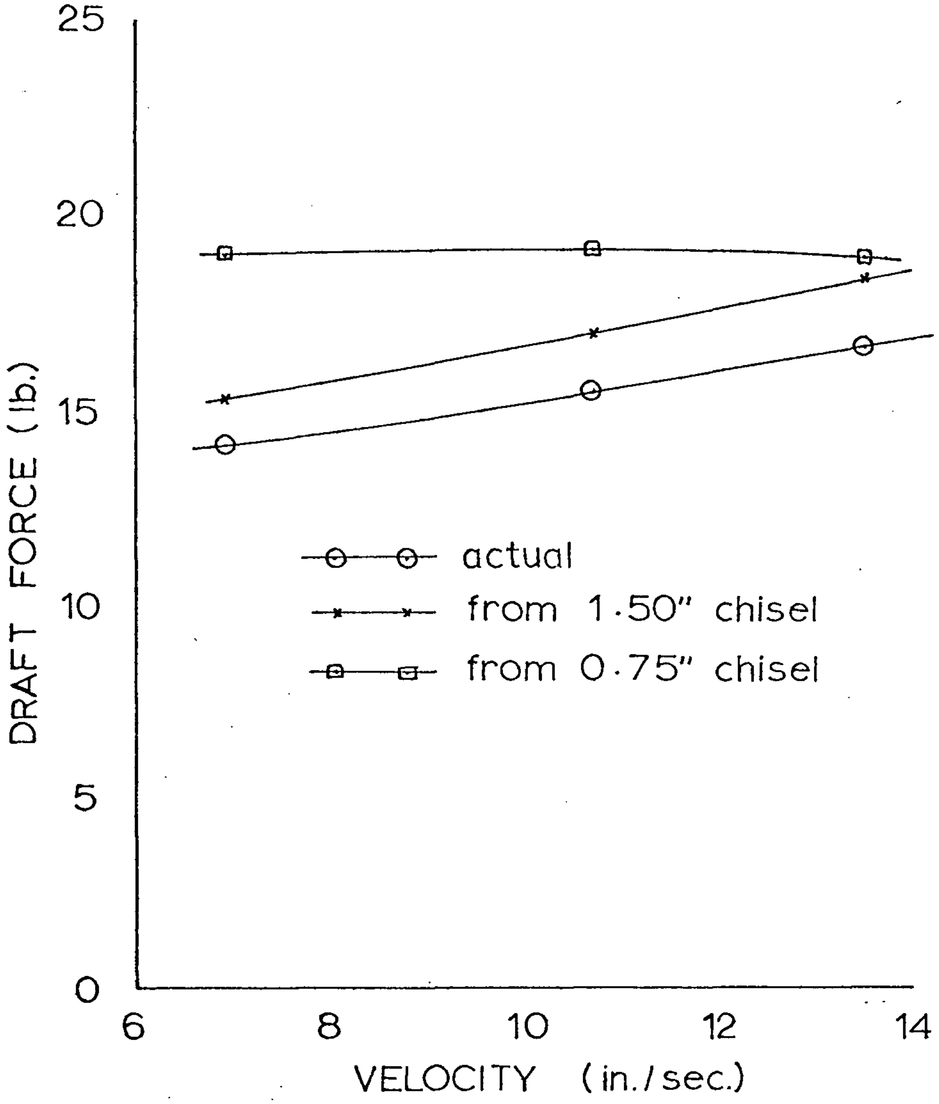

FIGURE 10. COMPARISON OF PREDICTED DRAFT FORCES FOR 2.25 INCH WIDE CHISEL IN HANEY CLAY WHEN VELOCITY IS VARIED AND B = 0.047 lb/in^3 AND W = 8.68%.

TABLE 8

Calculated Reaction Forces for Haney clay when Water Content is Varied and B = 0.045 lg/in^3 and V = 10.72 in/sec.

Chisel Width (in.)	Equation Numbers	F_x (lb)	F_z (lb)	R (lb)	W %
0.75	31,32,33	5.71	6.66	8.80	0
		7.77	8.99	11.93	8.679
		9.65	12.75	15.82	13.926
1.50	34,35,36	7.68	9.64	12.34	0
		10.40	13.68	17.20	8.679
		12.80	18.60	23.20	13.926
	31,32,33	7.57	7.69	10.80	0
		11.71	12.36	17.07	8.679
		15.42	19.45	24.85	13.926
2.25	37,38,39	10.40	13.10	16.50	0
		12.95	18.17	22.35	8.679
		15.10	21.55	26.10	13.926
	34,35,36	9.27	11.37	14.67	0
		13.34	17.40	21.95	8.679
		18.45	24.80	30.90	13.926
	31,32,33	8.71	7.79	11.68	0
		14.95	14.77	21.05	8.679
		20.70	25.45	32.70	13.926

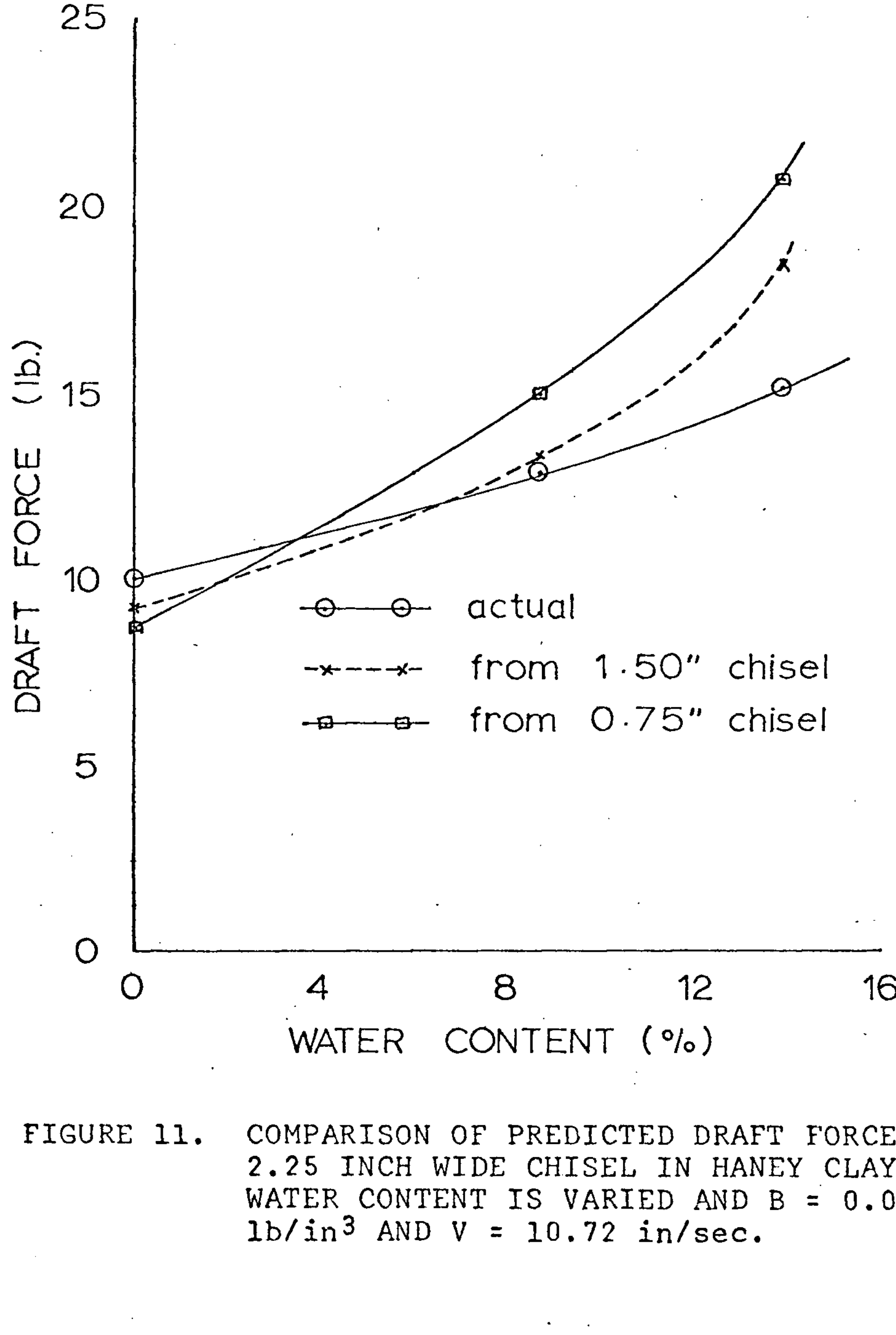

FIGURE 11. COMPARISON OF PREDICTED DRAFT FORCES FOR 2.25 INCH WIDE CHISEL IN HANEY CLAY WHEN WATER CONTENT IS VARIED AND B = 0.045 lb/in^3 AND V = 10.72 in/sec.

TABLE 9

Calculated Reaction Forces for Haney clay when Dry Bulk Density is Varied and W = 8.68% and V = 10.72 in/sec.

Chisel Width (in.)	Equation Numbers	F_x (lb)	F_z (lb)	R (lb)	B (lb/in^3)
0.75	31,32,33	5.87	6.44	8.75	0.0430
		7.77	8.99	11.93	0.0451
		9.13	10.90	14.28	0.0469
1.50	34,35,36	7.14	9.24	11.67	0.0430
		10.40	13.68	17.20	0.0451
		12.79	16.96	21.25	0.0469
	31,32,33	7.97	7.22	10.71	0.0430
		11.71	12.36	17.07	0.0451
		14.45	16.18	21.75	0.0469
2.25	37,38,39	9.56	13.28	16.40	0.0430
		12.95	18.17	22.35	0.0451
		15.38	21.65	26.70	0.0469
	34,35,36	8.47	10.74	13.70	0.0430
		13.34	17.40	21.95	0.0451
		16.95	22.35	28.10	0.0469
	31,32,33	9.37	7.08	11.54	0.0430
		14.95	14.77	21.05	0.0451
		19.05	20.50	28.10	0.0469

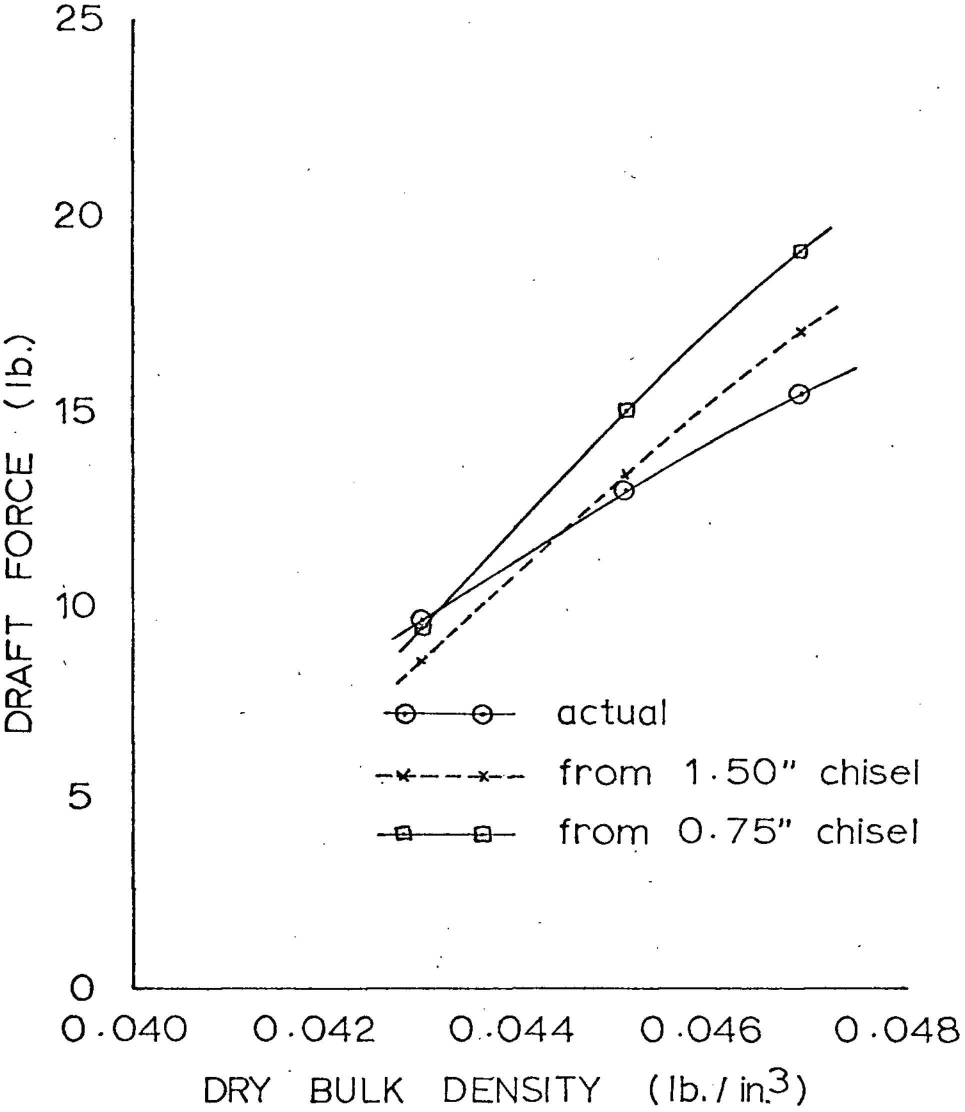

FIGURE 12. COMPARISON OF PREDICTED DRAFT FORCES FOR 2.25 INCH WIDE CHISEL IN HANEY CLAY WHEN DRY BULK DENSITY IS VARIED AND W = 8.68% AND V = 10.72 in/sec.

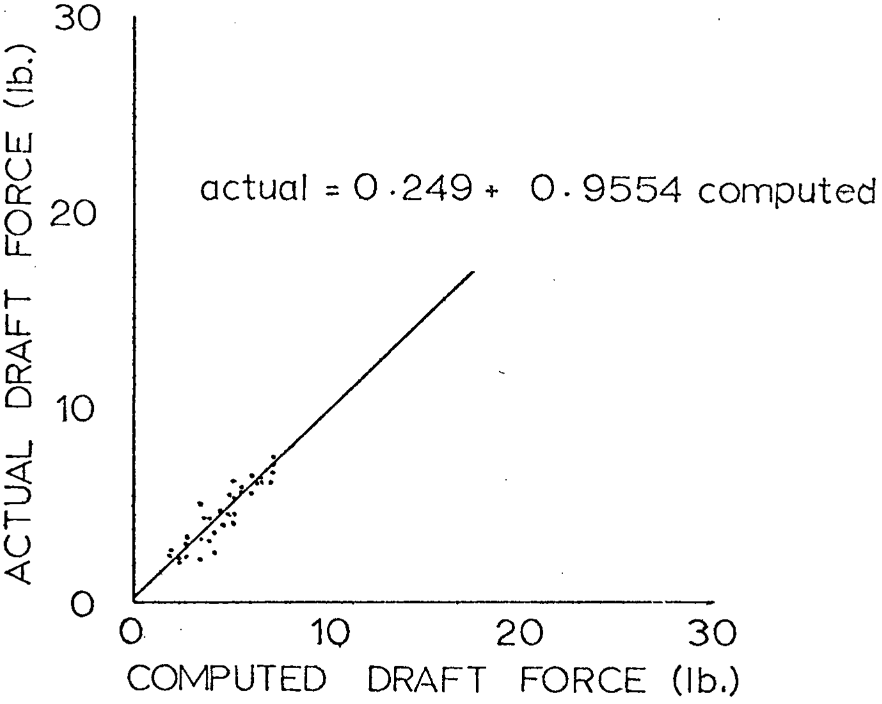

FIGURE 13. COMPUTED VS. ACTUAL DRAFT FORCE FOR 0.75 INCH WIDE CHISEL IN OTTAWA SAND.

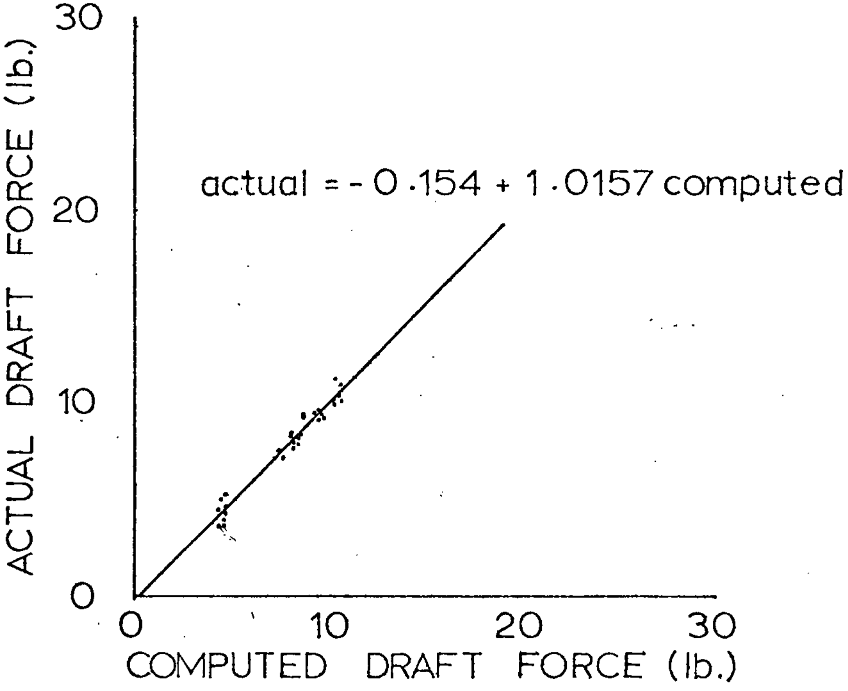

FIGURE 14. COMPUTED VS. ACTUAL DRAFT FORCE FOR 1.50 INCH WIDE CHISEL IN OTTAWA SAND.

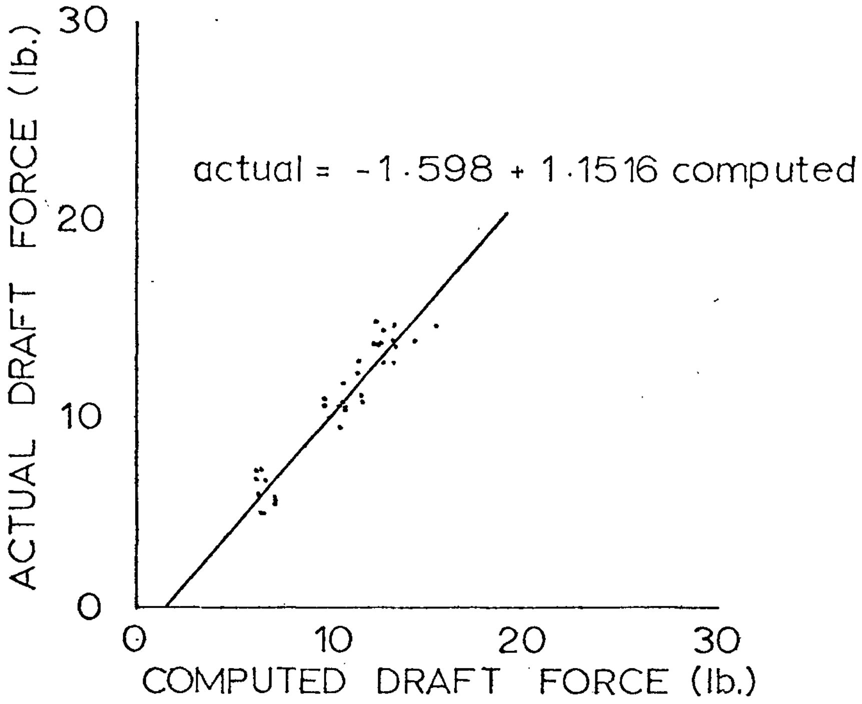

FIGURE 15. COMPUTED VS. ACTUAL DRAFT FORCE FOR 2.25 INCH WIDE CHISEL IN OTTAWA SAND.

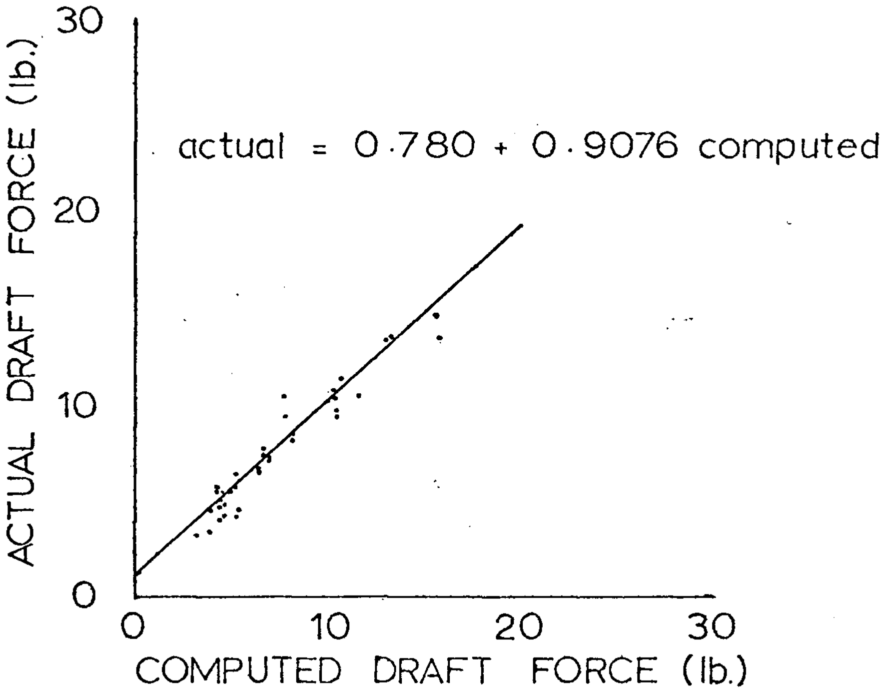

FIGURE 16. ACTUAL DRAFT FORCE VS. VALUE COMPUTED BY GENERAL (G) EQUATION FOR OTTAWA SAND.

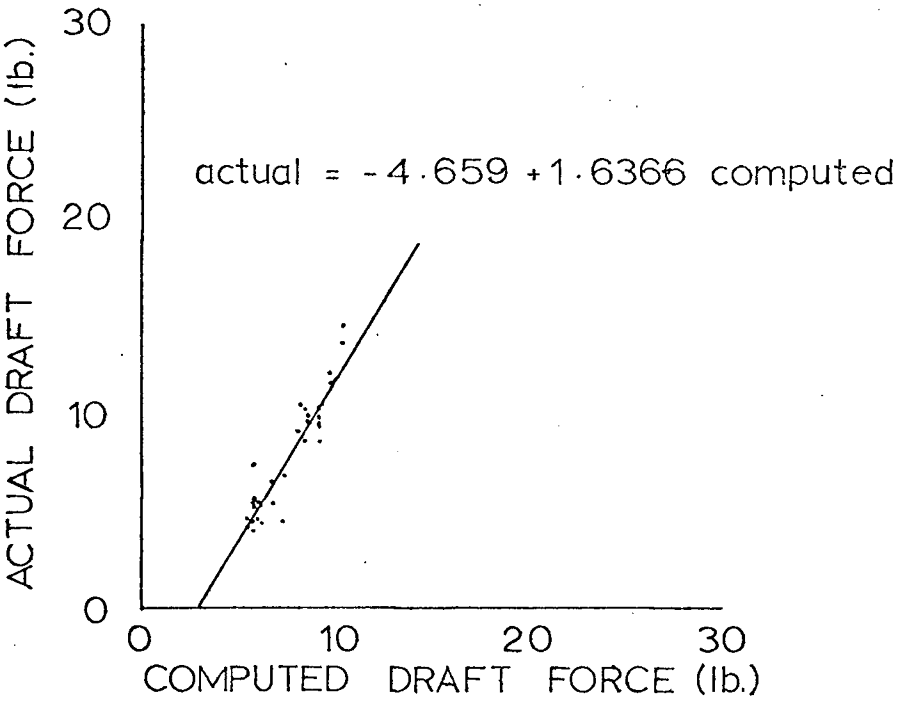

FIGURE 17. COMPUTED VS. ACTUAL DRAFT FORCE FOR 0.75 INCH WIDE CHISEL IN HANEY CLAY.

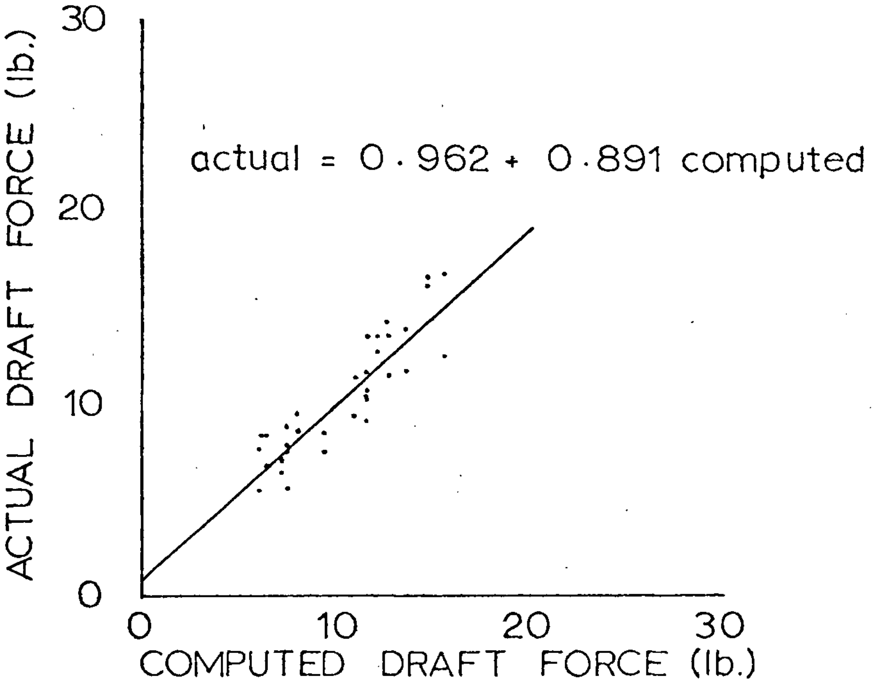

FIGURE 18. COMPUTED VS. ACTUAL DRAFT FORCE FOR 1.50 INCH WIDE CHISEL IN HANEY CLAY.

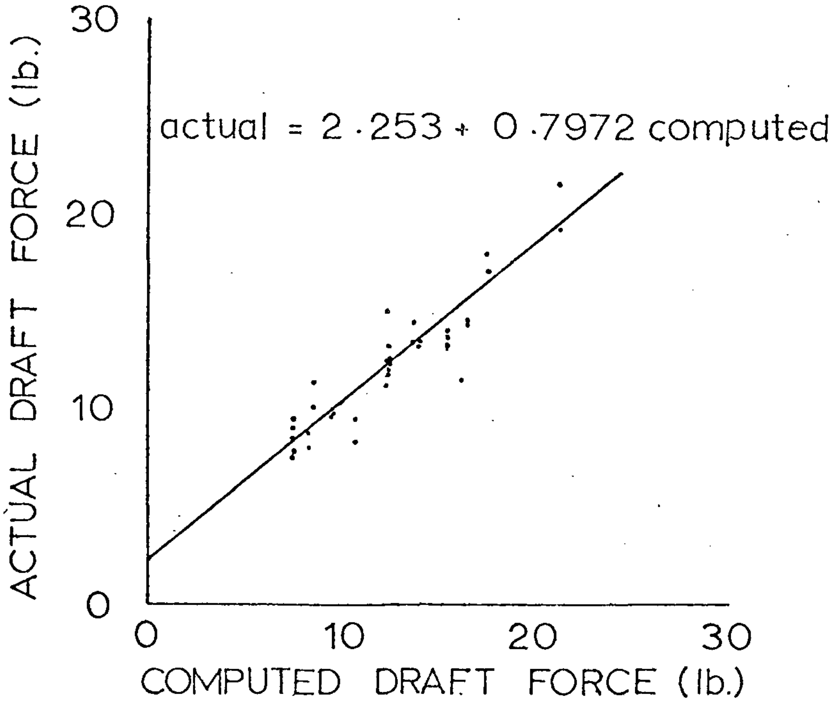

FIGURE 19. COMPUTED VS. ACTUAL DRAFT FORCE FOR 2.25 INCH WIDE CHISEL IN HANEY CLAY.

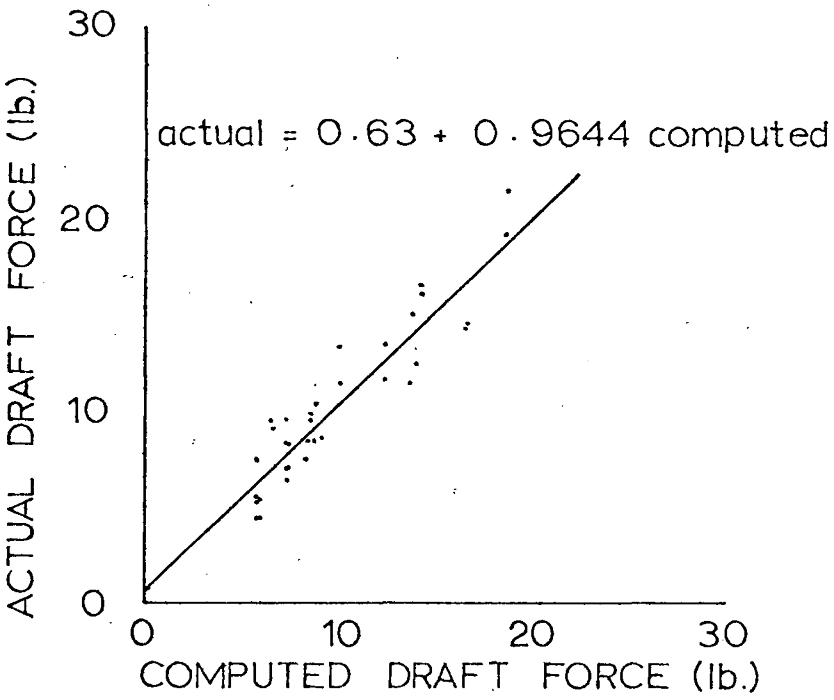

FIGURE 20. ACTUAL DRAFT FORCE VS. VALUE COMPUTED BY GENERAL (G) DIMENSIONLESS EQUATION FOR HANEY CLAY.

The different treatments of these variables will give close numerical results at some values but not at others. A careful re-evaluation of other studies available would lead one to conclude that the ojbective of most of these studies was to test the theories of similitude rather than the stated objective of developing a soil tillage mechanics.

A further disadvantage of restrickting a soil tillage study to similitude based models is that the effects of individual tool variables are not distinguishable from one another.

The main advantage to the use of dimensionless equations in tillage studies is the possibility of testing a single model machine and then predicting the results for larger prototypes. The results from this study indicates that the procedure has definite potential for use but requires further work so that the variables being studied are treated in a manner which reflects their actual effect on soil tillage interactions.

SUMMARY AND CONCLUSIONS

1) Ottawa sand is a cohesionless soil while Haney clay is definitely cohesive.

2) Soil void ratio, soil water content and normal pressure may be combined to predict the soil shear strength of either Ottawa sand or Haney clay.

3) Soil water content, area of contact and normal pressure may be combined to predict the soil-metal friction between either Ottawa sand or Haney clay and the soil machines studied.

4) Soil water content, dry bulk density, chisel width and chisel velocity may be combined to predict soil-chisel reaction forces for the soils and chisels studied.

5) The dimensionless ratios developed may be combined to predict soil-chisel reaction forces for scaled implements. However, large discrepancies do exist for certain soil conditions and the time required for preliminary testing is very extensive.

6) Since all measurements recorded during the course of this study were analyzed by statistical procedures, the resulting equations do not represent basic physical relationships. Caution should therefore be used if these equations are to be applied to values beyond the range of values analyzed in this report.

SUGGESTIONS FOR FURTHER WORK

The work initiated in this study should be expanded by adding an increased number of tillage tool variables and soil types and to determine their effects on soil-machine interactions. Possible machine variables to study would be depth of operation, angle of approach and machine shape. The other soil types would add to the body of knowledge developed to the possible extend that dimensionless ratios and consequently prediction equations might be developed by combining the soil and machine variables in such a manner as to indicate their effect on the force interactions involved.

The next step would be to determine the effects of tillage tool variables on the production of desired soil conditions.

An interesting note of great merit is that equations 11 to 16 inclusive are in such a form that velocity, chisel width and reaction forces are directly related in such a form as to indicate potential development of tillage energy relationships. The consequence of this relationship would be a very meaningful study on tillage cost minimization.

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APPENDIX A

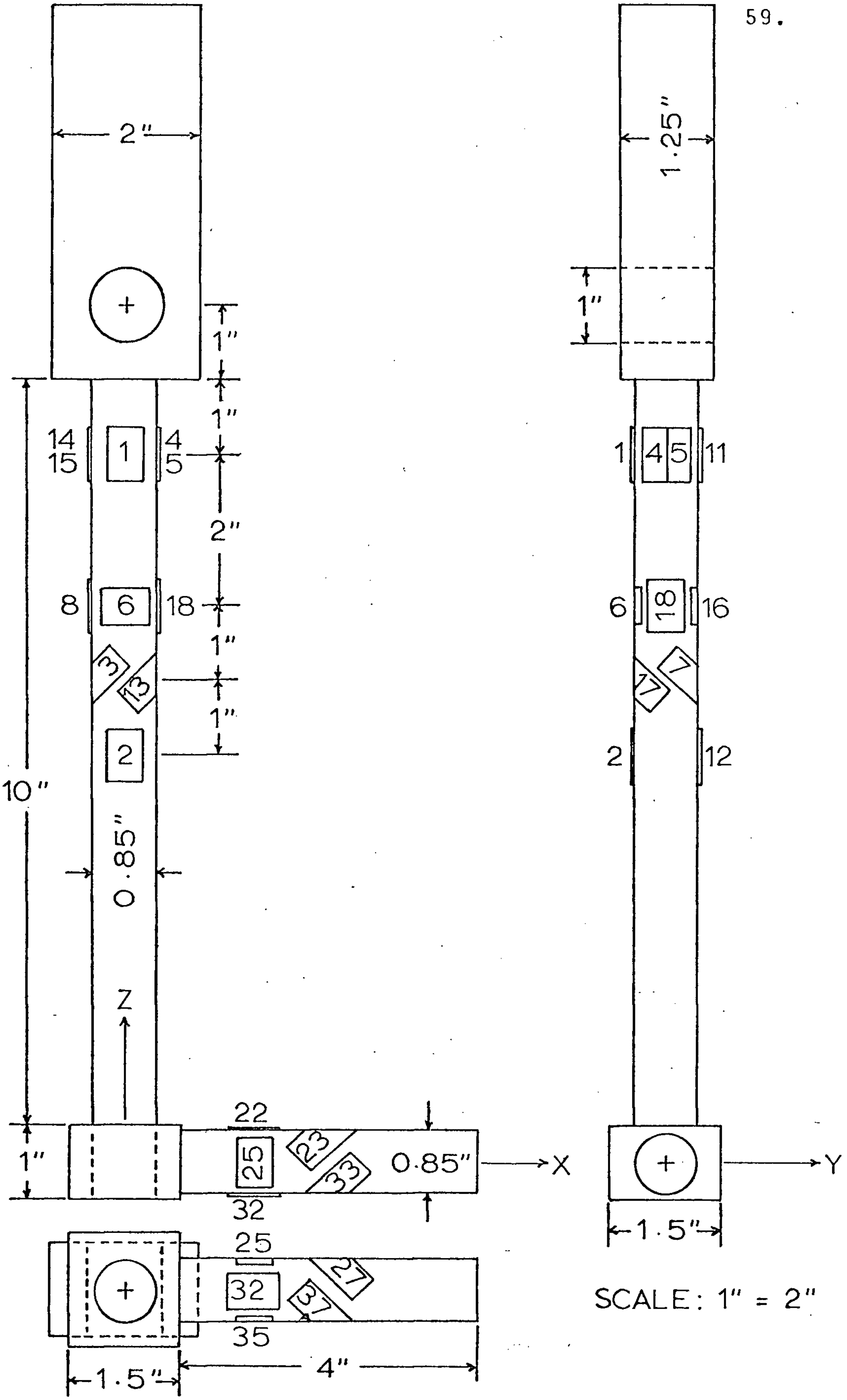

FIGURE A1. TRANSDUCER PLAN WITH STRAIN GAUGE LOCATIONS.

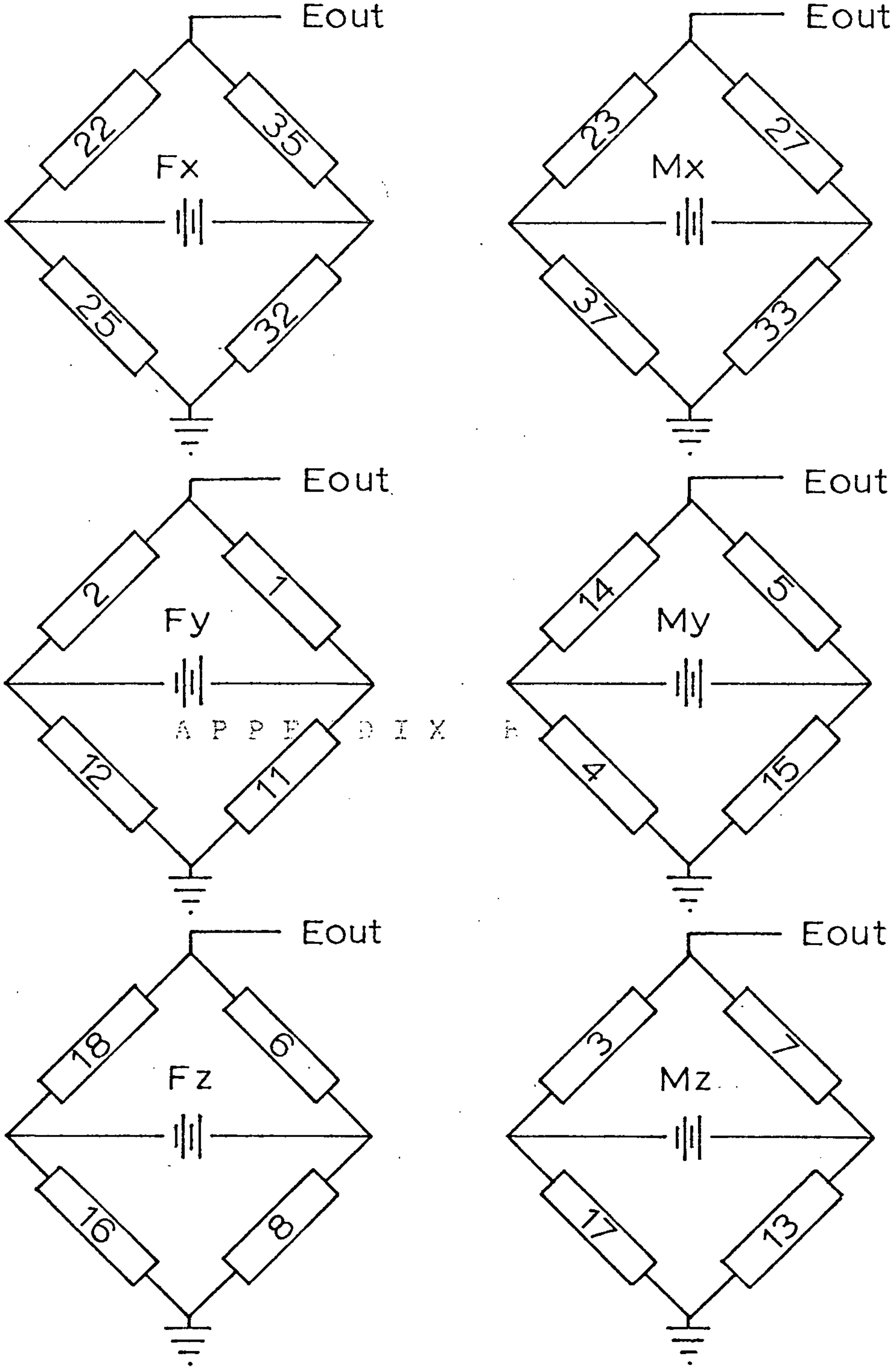

FIGURE A2. WHEATSTONE BRIDGE CONFIGURATIONS FOR FORCES AND MOMENTS TO BE MEASURED.

APPENDIX B

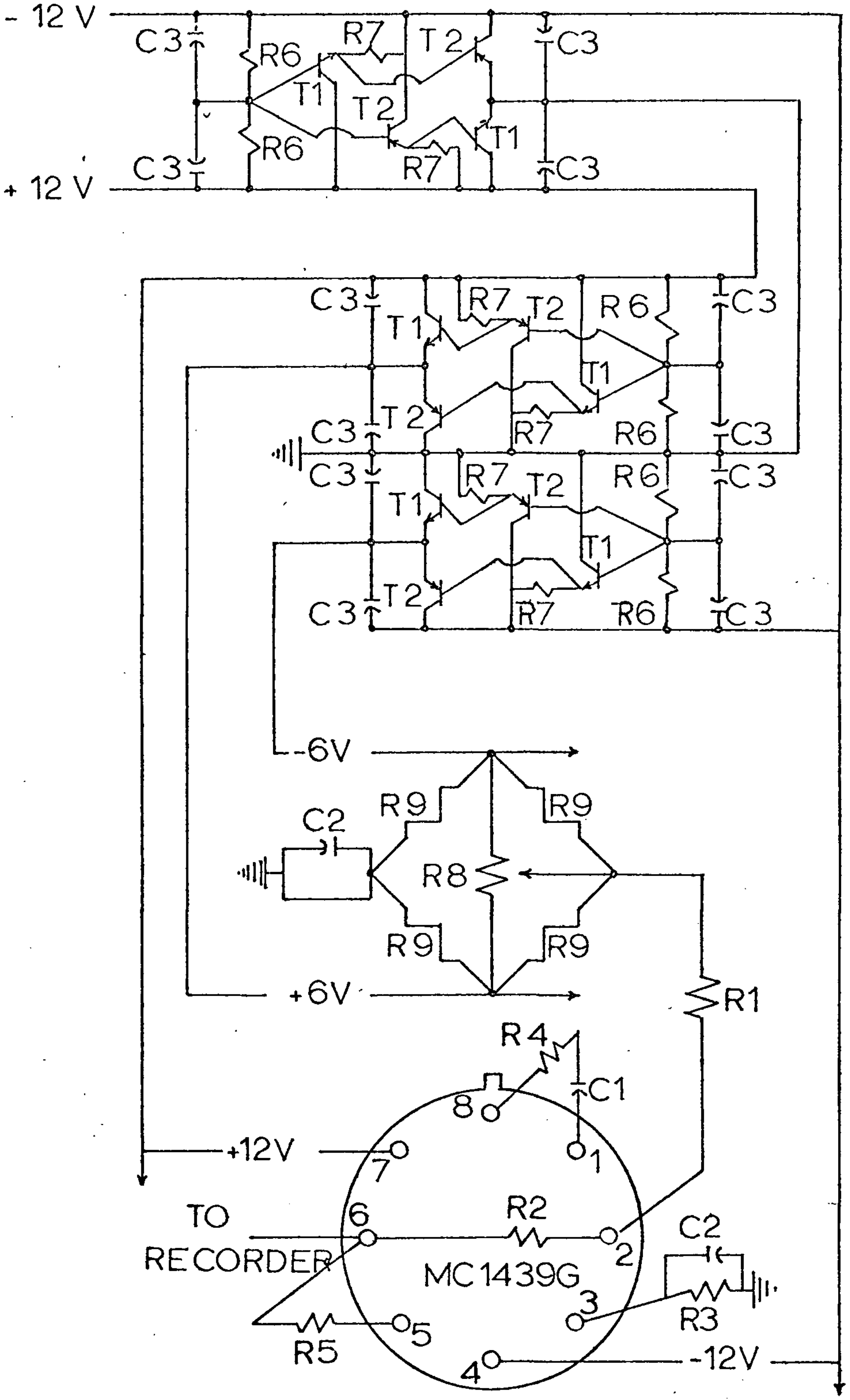

FIGURE B1. SCHEMATIC DIAGRAM OF STRAIN GAUGE AMPLIFIERS

PARTS LIST FOR STRAIN GAUGE AMPLIFIERS

R1 = 1 K ohms

R2 = switch allows choice of 1K, 1.5K, 2.2K, 4.7K, 10K, 22K, 47K, 100K, 2200K, 4700K, 10,000K ohms.

R3 = 1 K ohms

R4 = 10K ohms

R5 = 10K ohms

R6 = 1 K ohms

R8 - 10K ohms, 10 turn potentiometer

R9 = 500 ohms electrical resistance strain gauges

C1 = 2200 pF

C2 = 0.1 μF

C3 = 800 μF

T_1 = NPN Transistor) 2N4920
)
T_2 = PNP Transistor) 2N4923

NOTES:

1. Amplification = R_2/R_1

2. All grounds to be carried separately to a common ground.

3. C2 capacitors are used to eliminate crosstalk as 6 strain gauge bridges and 6 amplifiers were connected in parallel from the same power source.

4. Switch for R2 must be of make before break type.

APPENDIX C

TABLE C1

CORRELATION MATRIX FOR DIRECT SHEAR TESTS FOR OTTAWA SAND.

	W^2	W	E^2	E	Normal	Steady	Peak
Peak	0.062	0.061	-0.517	-0.527	0.964	0.970	1.000
Steady	0.080	0.062	-0.417	-0.423	0.982	1.000	
Normal	0.000	0.000	-0.405	-0.408	1.000		
E	0.133	0.250	0.997	1.000			
E^2	0.128	0.245	1.000				
W	0.960	1.000					
W^2	1.000						

TABLE C2

CORRELATION MATRIX FOR DIRECT SHEAR TESTS FOR HANEY CLAY

	W^2	W	E^2	E	Normal	Steady	Peak
Peak	-0.274	-0.160	-0.124	-0.115	0.767	0.994	1.000
Steady	-0.218	-0.102	-0.122	-0.118	0.769	1.000	
Normal	0.000	0.000	-0.259	-0.260	1.000		
E	-0.369	-0.305	0.994	1.000			
E^2	-0.326	-0.249	1.000				
W	0.963	1.000					
W^2	1.000						

APPENDIX D

TABLE D1

CORRELATION MATRIX FOR SOIL-METAL FRICTION TESTS FOR OTTAWA SAND.

	T^2	T	W^2	Water	Normal	Kinetic	Static
Static	-0.396	-0.426	0.069	0.065	0.978	0.985	1.000
Kinetic	-0.370	-0.393	0.114	0.112	0.982	1.000	
Normal	-0.339	-0.360	0.033	0.015	1.000		
Water	-0.108	-0.086	0.962	1.000			
W^2	-0.128	-0.105	1.000				
T	0.988	1.000					
T^2	1.000						

TABLE D2

CORRELATION MATRIX FOR SOIL-METAL FRICTION TESTS FOR HANEY CLAY

	T^2	T	W^2	Water	Normal	Kinetic	Static
Static	-0.352	-0.378	0.380	0.332	0.838	0.936	1.000
Kinetic	-0.358	-0.385	0.216	0.187	0.890	1.000	
Normal	-0.375	-0.396	0.000	0.000	1.000		
Water	0.000	0.000	0.952	1.000			
W^2	0.000	0.000	1.000				
T	0.990	1.000					
T^2	1.000						

APPENDIX E

TABLE E1

CORRELATION MATRIX FOR TILLAGE TESTS FOR OTTAWA SAND

	B^2	B	W^2	W	V	T
F_x	-0.165	-0.160	0.495	0.588	-0.082	0.656
F_z	-0.141	-0.136	0.473	0.555	0.012	0.708
R	-0.151	-0.146	0.483	0.570	-0.023	0.695
T	0.029	0.028	0.000	0.000	-0.002	1.000
V	0.016	0.013	-0.010	-0.011	1.000	
W	-0.573	-0.569	0.961	1.000		
W^2	-0.486	-0.484	1.000			
B	0.999	1.000				
B^2	1.000					

	F_x	F_z	R
R			1.000
F_z		1.000	0.996
F_x	1.000	0.969	0.988

TABLE E2

CORRELATION MATRIX FOR TILLAGE TESTS FOR HANEY CLAY

	B^2	B	W^2	W	V	T
F_x	0.648	0.644	-0.281	-0.308	0.178	0.504
F_z	0.591	0.584	-0.219	-0.252	0.188	0.541
R	0.613	0.607	-0.241	-0.272	0.187	0.532
T	0.000	0.000	0.000	-0.000	0.003	1.000
V	0.004	0.004	-0.010	-0.009	1.000	
W	0.805	-0.800	0.964	1.000		
W^2	-0.803	-0.802	1.000			
B	0.999	1.000				
B^2	1.000					

	F_x	F_z	R
R			1.000
F_z		1.000	0.997
F_x	1.000	0.971	0.986