

DEVELOPMENT OF NEW METHODS TO DETERMINE THE RELATIONSHIPS
BETWEEN THE DRAFT REQUIREMENT, AND THE FUNDAMENTAL FACTORS
AFFECTING THE DRAFT REQUIREMENTS, OF TILLAGE TOOLS

By

Baba-Telischi

AN ABSTRACT

Submitted to the School of Graduate Studies of Michigan
State College of Agriculture and Applied Science
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Agricultural Engineering

Year 1954

Approved by Howard F. McColl

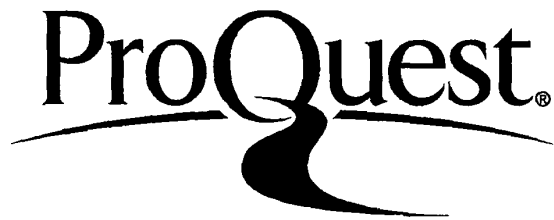
ProQuest Number: 10008439

All rights reserved

INFORMATION TO ALL USERS

The quality of this reproduction is dependent upon the quality of the copy submitted.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if material had to be removed, a note will indicate the deletion.



ProQuest 10008439

Published by ProQuest LLC (2016). Copyright of the Dissertation is held by the Author.

All rights reserved.

This work is protected against unauthorized copying under Title 17, United States Code
Microform Edition © ProQuest LLC.

ProQuest LLC.
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106 - 1346

The problem of tillage is one of the most basic of agricultural problems. From the early days when a piece of crooked wood was pulled in the ground to prepare seed beds, until now, when big steel plows stir and turn the soil many inches deep and wide, the question of "how to till the soil at the best and most economical time" has existed.

Many scientists and engineers have studied this problem and have reached some very interesting conclusions; more work needs to be done to be able to obtain adequate information at least to answer some basic questions on this subject. The problem of the force of soil resistance to the various implements of tillage and the factors that affect this force of resistance will be the phase of tillage discussed here.

The investigation in the field of tillage is being done mostly in two associated fields: soil science and agricultural engineering.

In soil science, soil physicists did basic work on soil characteristics and their effect on tillage operation. Agricultural engineers attempted to build different measuring devices either for laboratory or field work to evaluate those effects.

The work of the author consists mostly of the introduction of new experimental and theoretical methods to indicate the relationship between different factors and the draft requirement of tillage tools.

A preliminary field test was run in three different kinds of soils with five different tilling methods. The laboratory method consisted of running different tests in a soil box under controlled conditions. For the theoretical method, the theory of dimensional analysis was employed.

The field tests were considered insufficient and inaccurate to measure the draft requirement of tillage tools. The results obtained from the laboratory method, though qualitative, were very useful and encouraged the continuation of the investigation. The theoretical method was the best way to obtain the basic relationships between the draft requirement and the factors that affect the required draft.

DEVELOPMENT OF NEW METHODS TO DETERMINE THE RELATIONSHIPS
BETWEEN THE DRAFT REQUIREMENT, AND THE FUNDAMENTAL FACTORS
AFFECTING THE DRAFT REQUIREMENTS, OF TILLAGE TOOLS

By
Baba-Telischi

A THESIS

Submitted to the School of Graduate Studies of Michigan
State College of Agriculture and Applied Science
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Agricultural Engineering

1954

ACKNOWLEDGMENT

The author acknowledges the help and guidance of Professor Howard F. McColly, under whom this project was conducted. He also expresses his thanks to Dr. A. Earl Erickson, Soil Science Department, for his sincere cooperation and help in using the Soil Physics laboratory for all the soil tests.

The author is grateful to Dr. Charles O. Harris, head of the Department of Applied Mechanics, for his help in setting up the equation of the dimensionless products for the theoretical solution.

Sincere thanks are due to the following for their assistance and useful suggestions in different phases of the project:

Professor Arthur W. Farrall, head of the Agricultural Engineering Department;

Dr. Walter M. Carleton of the Agricultural Engineering Department;

Dr. Rolland T. Hinkle, Mechanical Engineering Department; and

Mr. James B. Cawood, Research Laboratory, Agricultural Engineering Department.

The author also wishes to extend his appreciation to other members of the Agricultural Engineering, the Civil Engineering, and the College Farms departments, who helped in accomplishing the field and laboratory experiments.

TABLE OF CONTENTS

	Page
I. INTRODUCTION	1
A. General	1
B. The Effects of Tillage	1
C. The Objects of Tillage	3
D. Energy Analysis of Tillage	4
E. Some Physical Properties of Soil	5
1) Texture	5
2) Structure	6
3) Consistency	6
a) Atterberg's Constants	7
b) Cohesion	8
c) Adhesion	8
d) Plasticity and Its Significance	8
II REVIEW OF LITERATURE	10
A. The Work of Agricultural Engineers	10
B. The Cooperative Work of Soil Physicists and Agricultural Engineers	17
III. OBJECTIVES	32
IV. GENERAL INVESTIGATION OF THE PROBLEM	33
A. Factors That Affect The Draft	33
V. METHODS OF PROCEDURE	37

Table of Contents (Cont.)

	Page
A. Field Work	37
1) Field Tests	37
2) Results and Conclusions	47
B. Laboratory Method	49
1) Objective of the Experiment	49
2) Soil Box	50
3) Tools and Equipment	54
4) Soil	61
5) Test Procedure	62
6) Results	62
7) Conclusions	75
a) The effect of speed	75
b) The effect of clay content	80
c) Effect of moisture	88
d) Effect of packing force	94
C. Theoretical Study	95
1) Reasons for Study	95
2) General Remarks on Dimensional Analysis.	95
3) Assumptions and the Solution of the problem	97
4) Conclusions	100
VI. SUMMARY	102
VII. SUGGESTIONS FOR FURTHER STUDY	103
A. Changes in Laboratory Tests	103

Table of Contents (Cont.)

	Page
1) Proposed Changes in Building Experimental	
Soil Box	103
2) More Tests With Different Conditions . . .	104
B. More Theoretical Study	104
C. Application of Theoretical and Laboratory	
Results to Field Conditions	104
VIII. REFERENCES	137

LIST OF TABLES

Table	Page
I. The result of preliminary field tests	43
II. The result of field tests (long strips) in sandy soil	44
III. The result of field tests (long strips) in clay soil.	45
IV. The result of field tests (long strips) in sod soil .	46
V. Some physical properties of experimental soils used for the laboratory tests	64
VI - XXX. The result of laboratory tests	106
XXXI. The friction determination of the tool carrier in the soil box	131

LIST OF FIGURES

Figure	Page
1. Relationship between cohesion and colloidal content .	21
2. Relationship between compression and colloidal content	21
3. Relationship between maximum force of adhesion and colloidal content	21
4. Relationship between lower plastic limit and the activity of soil moisture	23
5. Relationship between colloidal content of soil and plasticity number	24
6. Relationship between the metal friction and percent of soil moisture	24
7. Reaction of soil as a plow advances through it . . .	29
8. Dynamometer for field tests	40
9. Field test with two-bottom, 14-inch plow	41
10. A sample of dynamometer graph	42
11. Soil box, the general view	56
12. Soil box, grading and packing	57
13. Soil box, the moving section	58
14. Tools and implements used in soil box experiment . .	59
15. Attachment to the soil box to measure the friction of the tool carrier	60
16. Moisture release curve for the experimental soils . .	63
17 - 25. The curves of speed versus draft	66
26 - 29. The curves of clay percent versus draft	76
30 - 36. The curves of moisture percent versus draft . .	81

List of Figures (Cont.)

	Page
37 - 41. The curves of packing forces versus drart . .	89
42 - 46. The drawings of the soil box	132

INTRODUCTION

General

Tillage refers to all the mechanical operations and practices on the top layer of soil which are necessary to provide a favorable seed bed. In general, a good tillage practice always improves the yield of the crop although there are certain crop and soil conditions that cause the tilling action to be somewhat unimportant.

Despite the improvement of the shape, material, and the operation of tillage tools in recent years, the tillage operation continues to consume a large percentage of farm power. Statistics show (74) that field operations constitute about 48 percent of farm draft work, and that tillage work makes up approximately 58 percent of field work (or 29 percent of the total). Over half of the power consumed in tillage work is used in the basic operations of plowing and disking (5). So, any improvement in the method of tillage is a big contribution to the power requirement in farming.

The Effects of Tillage

Tillage results in the change of structure by changing the arrangement of secondary particles, conservation of moisture, and control of weeds.

The main duty of tillage is the building of a structure profile. J. A. Slypher (71) describes the specification of this structure profile as model profile. A vertically graduated structure and consistency is needed, the lower zone to consist of fine granules and the firmest degree of consistency. In successively higher zones, granulation should coarsen while the consistency loosens. The whole is to be topped by distinctly coarse granules forming a loose layer immediately above the seed level. Added organic matter to be intermixed with the lower half to two-thirds of the plow layer.

"The old order consisted of a thin veneering of dust on the surface, produced by overworking and reducing to a structureless condition. Beneath this and extending to the subsoil, the mass remained crude and undisturbed. A dust veneer is a barrier to ready intake of rainfall, an encouragement to evaporation, and fatal to ultimate good tilth. The new order would supplant dust with clods on the surface; and within limits clods are useful. The size of surface clods is necessarily subject to limitation, as it depends on the kind of crops and soils."

Slypher then suggests that a standard should be established by experiment and explains: "Since the object is to fully structuralize the full plow layer, the design of tillage tools should be changed to produce the above mentioned model profile. The problem is not the deep or shallow tilling, it is rather, the manner of manipulation. However, before the

design of tillage tools, the soil technologist must first establish experimentally the standard profile. Equally important is the necessity of a measuring-stick for structure applicable to field use."

Slypher finally discusses the particular cases of plow actions with different soil conditions as: "Old plows were compressing unduly the soil but gradually it is changing to cutting and lifting action. Type of soil has effect on that. Sandy soils should receive more compression and less lifting, because they don't have good structure and should be left in contact with subsoil."

The Objects of Tillage

Until rather recently all soil manipulations have been performed without knowledge of the effect of these manipulations upon soil physics and plants. On this basis the design of implements were based entirely on the empirical results; and practical experience was the main source of knowledge to the selection of tillage tools and the degree of tillage practice.

In 1730 Jethro Tull, an English farmer explained that the effect of tillage is only the breaking down of large soil particles into the fine ones which increase the particle's surface from which plant roots obtain their food. (40).

Today there is a need for a more adequate concept, and the concept of Tull is not satisfactory anymore.

4

The modern approach to the problem of soil tillage is by two methods (74, 71). One involves an approach based upon fundamental physical laws, while the second calls for an analysis involving the application and measurement of both physical and biological phenomena. It should be mentioned that the biological objective of the soil is different for different crops, and each type of soil has a special mechanism peculiar to itself.

Of these two approaches, the first one is probably the more attractive to engineers. It is simpler because it involves less variables. The second method needs the cooperation of physical and biological science.

Energy Analysis of Tillage

The approach of tillage problems through the physical method must be based upon energy input in the field. The operations should be evaluated primarily on that energy basis and the results should be correlated with the yield of crops. This involves three groups of variables, namely,

- 1) The energy input in the operation;
- 2) The character of the field operations including types of equipment;
- 3) The economic relationship.

The efficient application of energy to any operation is an engineering problem, and the amount of the applied energy is directly related to the physical condition of the soil,

the kind and the condition of implement, and finally, the management. In this research we are concerned with the first two, especially the physical condition of the soil.

Some Physical Properties of Soil

There are many factors which could be mentioned in connection with the physical properties of soil. Only those properties which are essential in the problem of tillage will be discussed in this section. Those properties are: texture, structure, and soil consistency.

Texture

Texture refers to the size of individual primary particles which constitute the soil mass. These particles have been classified according to their sizes. The finest particles are called clay. The next larger are silt, then sand, and the largest is gravel.

Any particle larger than 2 m. m. is called gravel. The particles between 2 m. m. and .02 m. m. (according to Atterberg's classification) are sand, between .02 and .002 is silt, and any particle smaller than .002 m. m. is clay. Gravel, sand, and silt build the frame of soil body, and clay and silt, especially clay, will act as binding materials. The large surface area per unit mass of clay is responsible for its activity chemically and physically. Clay and organic matter are the most active portions of the soil.

Structure

Bauer says (29) that the structure of a soil is the arrangement of its particles. These particles can be primary particles like sand, silt, clay, or they can be aggregates that have formed from groups of primary particles. Thus there are primary and secondary particles and their arrangements in the structural make-up of the soil.

Mechanical manipulation changes the structural condition of the surface layer of soil. Most of these manipulative operations are designed to break up the large secondary particles into smaller ones, and also rearrange the secondary particles to a more porous mass which may settle or completely disintegrate on wetting, depending on the stability of the secondary particles. The amount of manipulation varies with the kind of soil. It is also possible to destroy the original granulation of the soil by too much manipulation.

Consistency

Soil consistency is a term used to designate the manifestations of the physical forces of cohesion and adhesion acting within the soil at various moisture contents. These manifestations include the behavior toward gravity, pressure, thrust, pull and the tendency of the soil mass to adhere to foreign bodies or substances and the sensations which are evidenced by feel of the fingers of the observer. (71). Consistency of soil varies with the texture, structure of the

soil and especially with the colloidal and moisture. The clay might flow easily if enough moisture existed. By decreasing the moisture content it will become sticky, and as water continues to evaporate it becomes more sticky and tough. When it becomes air dry, the clay will be harsh to the touch, and finally, when it is oven-dried, it will reach its maximum hardness.

Atterberg's Constants. Lower and upper plastic limits, and plasticity number are called the Atterberg's constants.

Upper plastic limit (or liquid limit) of a soil is that moisture content, expressed as a percentage of the weight of the oven-dried soil, at which the soil will just begin to flow when lightly jarred ten times.

Lower plastic limit of a soil is the lowest moisture content, expressed as a percentage of the weight of the oven-dried soil, at which the soil can be rolled into threads one-eighth inch in diameter without the threads breaking into pieces.

Plasticity number is the difference between the above moisture limits.

With some moisture less than plastic range, the soil is soft and with very low moisture, soil is harsh. There is a fourth form of consistency which might overlap the plastic consistency. This is the sticky form. The four consistency forms of soil are then: sticky, plastic, soft, and harsh. The extent of each form of consistency in a soil depends on

its kind. A loamy soil might have a very small plasticity number. A clay soil, according to the kind and amount of colloidal content, can have a large plasticity number.

Cohesion. Cohesion in a moist soil is attributed in a large degree to the surface tension, forces which arise from the water films distributed through the soil mass.

Adhesion. When the moisture content of soil exceeds that for maximum cohesion, the adhesion of the soil to foreign material will take place. At a high moisture percentage the water film is held less tightly by the particles, and will be attracted to the surface of the foreign objects. This film of water will connect the soil to the object.

Nichols has indicated the force of adhesion of colloids with different amounts (54) of colloid content, and observed that their relation is a linear function. He also found that for any percent of colloids in the soil the moisture percentage needed for maximum adhesion is larger than the one for maximum cohesion. The curves of both adhesion and cohesion with respect to moisture percentage are S-shaped and the one for adhesion is slightly higher than the one for cohesion.

Plasticity and its significance. Atterberg studied the plasticity from the point of view of the moisture range and for the first time suggested the use of upper and lower plasticity limits and plasticity number. Apparently, he conducted his original work with the hope of finding some physical criterion for the classification of Swedish soil. Terzaghi (4)

has also suggested that the plasticity limits may serve as an index for the physical classification of soils. Soil with high upper plastic limit has either a high percent of fine-grain fraction or is rich in plate-shape particles. Soil having a high upper plastic limit and a low plasticity number should be in a finely divided state. A high plasticity number shows a sign of having a large quantity of scale-like particles. Terzaghi (4) has related the lower plasticity limit to the permeability of clays and the rate of evaporation of water films from soils. He states that the coefficient of permeability of a homogenous clay decreases rapidly with decreasing water content until, at lower plastic limit, it becomes practically zero, regardless of the value of the plastic limit. He also states that the rate at which water evaporates from the surface of a clay sample is four percent greater than the free water surface, provided the moisture content is higher than the lower plastic limit. Wehr (4) has reported that cultivating a soil with a moisture content above the lower plasticity number will cause puddling of the soil. The small plasticity number indicates the ease of tilth without puddling. If this number is large, a danger of puddling exists when cultivated above the lower plasticity limit. Although there exists some relationship between these constants and the soil tilth, sufficient evidence does not exist to draw a more specific conclusion.

REVIEW OF LITERATURE

The study of draft requirement of tillage implements and the factors that have an effect on the draft started long ago. Although different investigators have worked on this problem under different soil conditions, until rather recently there was very little basic research done. Most of the early investigators confined their studies to their local soil conditions.

The study of force and energy measurement in tillage can be divided into two sections: the work of agricultural engineers, and the cooperative work of agricultural engineers and soil physicists.

The Work of Agricultural Engineers

The work done by engineers consists of studies of the forces exerted by different tillage tools, design and development of instruments to measure these forces and the energy required to operate those tools.

Davidson (18) is among this group, who built the first integrating drawbar dynamometer with which he measured the draft of a plow at Ames, Iowa. He also ran tests to determine the effect of speed and other factors on the draft. He reported that an increase of speed from 2 to 4 miles per hour will increase the draft from 16 to 25 percent.

Collins (19) also ran tests at Iowa State College and states that: 1) type of bottom does not materially influence the draft; 2) an increase in speed will produce about the same increase in draft with any type of bottom; 3) the increase in draft due to speed is confined to that part of the total which is required for turning and pulverizing. This varies with speed from less than one-third to about one-half the total draft of a plow within a speed range of two to four miles per hour; 4) variation in depth is probably the greatest source of error in plow tests of a comparative nature; 5) under some conditions of plowing, a sharp cutting edge is of little importance; and 6) under certain conditions high speeds may cause failure to scour.

I. F. Reed and John W. Randolph (61) have studied the effect of speed on the draft and noted that for most cases in higher speed, their relationship is a parabola as

$$y = a + bx + cx^2$$

They also studied the effect of depth, width, and landside on the draft of implements. Data showed the effect of the depth changes with the kind of soil, and generally increasing depth will increase the draft.

Keen and Haines (40) state that the relationship between draft and speed is a straight line. Tests by the Bureau of Agricultural Engineering reported in part by Ashley, Reed and Glaves show that the relation between draft and speed of plowing may be expressed by the formula

$y = a + bx$ in which y is draft in pounds per square inch of furrow-slice cross section, x is the speed in miles per hour, and a and b are constants depending upon type and condition of soil.

Keen (32, 38) states that change in the setting of the plow or hitch have little effect on the draft, except in so far as the depth of plowing is affected. He also found that slope of the field affects the draft very little. Keen and Haines (34) were experimenting at Rothamsted experimental station in England. They studied the resistance of the soil in a comparatively uniform plot. The result was that there were large variations over short distances. They represented the differences by means of isodyne contours, drawn on a map. They repeated this experiment on the same plot for several seasons carrying wheat, barley and oats, respectively, and their conclusion was that the effect of crop and fertilizer was much less than natural variations in the soil. They also stated that there is close relationship between clay content in the plot and the draft of the plow.

The effects of crop cover, fertilizer, lime and manure have been studied by the Ohio, Missouri, Rothamsted stations and the Bureau of Agricultural Engineering. These studies show little or no measurable effect due to ordinary application of lime, fertilizer, or manure, but a marked effect due to cover crop (62). D. B. Lucas (49), in New Jersey,

used a hydraulic drawbar dynamometer, made in Cornell University, to measure the effect of the lime in the draft of tillage tools. He used a plow as the tillage tool, and found out that in limed plots draft decreases, but because of higher yield and good root development the result might become opposite.

Some rather classical studies have been done in analyzing the forces exerted on tillage implements, and also in expressing the shape of plow mathematically on the basis of the soil dynamic properties.

Theodore Brown (9) studied some fundamentals of plow design, and found that the surface of the most successful plow bottom has a hyperboloid equation like

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1$$

E. G. McKibben (51) studied the dynamics of the disk harrow by analyzing the different forces and moments existing in single and multiple gangs. Sjogren (70) studied the development of the offset disk harrow. E. D. Gordon (31) studied the reaction of soil on a disk in relation to different factors. His studies were with controlled soil conditions. He found that draft will increase 67 percent in a sandy loam soil with the increase of speed from 2.5 to 5 miles, a disk angle setting of 45° will cause the minimum draft, and the upward thrust will increase with the increase of disk angle. The increase of angle of penetration will increase the upward thrust and cut down the depth. With the

increase of concavity, the draft and the upward thrust increased. The larger disk would tend to penetrate better, due to reduced upward thrust. In an inclined form from vertical position, draft and penetration is in favor of smaller disks.

Clyde has analyzed the forces acting on tillage tools and their effect in the amount of draft. He has presented his work in several papers, in one of which (13) he indicated the importance of knowledge of the position, direction and magnitude of the useful soil force on tillage tools under conditions from easy to hard. He then expressed the usefulness of this knowledge as an aid to judgment in designing for strength or applying the pulling force to the best advantage, and for selecting the best shape of tool for a certain kind or degree of tillage.

Clyde also explained the two methods, the pulling method and the tillage meter method, of measuring the soil forces. Finally he discussed the results of his tests with different implements. In his later work (14) he discussed the way of finding the useful force in a tillage tool, and mentioned that this useful force in a plow and disk usually can be combined into a resultant force and a couple.

Clyde found that a "speed type" plow bottom requires less draft in higher speeds (2.5 to 4.5 m.p.h.) and covers better. He gave examples of using soil force measurements for computing the load on the bearings of a disk plow and

reported that wide spacing of the bearings reduces the loads because of the overhanging nature of the forces. Finally he stated that by knowing the soil forces one can plan for a shop test in a manner similar to its field loading. He has also studied plow tractor hitches and analyzed the forces on mounted and separate plows, the discussion of which will not be taken up in this section.

Finally, the work of the U.S.D.A. Bureau of Agricultural Engineering Tillage Laboratory at Auburn, Alabama, should be mentioned together with their complete tillage laboratory and extensive experimental works (59). The Auburn Laboratory has 11 soil plots, seven of them 20 x 250 feet while four are 20 x 125 feet. The depth of plots is two feet. They are filled with different type soils with a known mixture. They have tracks on the walls on each side and a trolley car can ride on these tracks the whole length of the plot. The tools and testing equipment are all on that car, and nothing can touch the soil except the experimental tools. The tool carrier on the frame can move cross-wise on the car. The equipment used for preparing the soil consists of a grader blade, subsoiling unit, disk, subsurface packer, surface roller and a sprinkling unit, all of which have been mounted on a car except the sprinkler unit which mounts on the front of the car. A cover car is provided to place over the plow whenever necessary. Testing equipment consists of two major units: the

power car with special dynamometer and the plow test unit. The power car unit furnishes the motive power and measures and records the components of draft necessary to handle the job. The plow test unit measures and records the forces necessary to hold the rear of the plow in its working position.

The three components of draft are recorded on the same chart with distance and time, thus making it possible to check the speed and draft at any time.

The plow bottom, in its working position, is held entirely by hydraulic units. The plow beam is carried on the front end by the dynamometer, and the rear end is mounted on two hydraulic units. These three hydraulic units, with the power car dynamometer, will enable one to measure the reactions of plow bottom continuously.

J. W. Randolph and I. F. Reed have run different tests in this laboratory and have obtained good results. They used a 14 inch plow to indicate its reaction to different factors. Then they tested several 14-inch plow bottoms (63, 64) with different shapes and found that the shape of the plow bottom affects draft markedly. They showed the different effects of major shapes which cause the bottoms to be classed into different types, and also the effects of shape variations within a class.

The Cooperative Work of Soil Physicists And Agricultural Engineers

The work of agricultural engineers and soil physicists covers the study of physical properties of soil and their effect on the draft requirement of the tillage tools.

In the study of the dynamic properties of soil affecting tillage, there has been a considerable amount of work done in some foreign countries and here in the United States.

In the United States, McKibben (50) has made an outline of the factors that enter into soil characteristics. After giving the outline in eight sections, he names three major problems in the soil dynamic situation.

- 1) The determination of the dynamic properties of soil, their changes, and the standard methods of measuring them;

- 2) Determination of what should be done and when, to get favorable results; and

- 3) Determination of best methods and implements to get those results.

M. L. Nichols has made extensive research on the dynamic properties of soil, their effect on the design of tillage tools, and the force that is necessary to pull them in the soil. His works have been published in six papers, which will be reviewed here very briefly.

In his first paper (54) he introduces the classification of variables that enter the design of implements and completes his discussion in subsequent papers (54, 56). His

classification is:

- 1) Primary soil factors: particle size, colloidal content, moisture percentage, state of compaction, organic matter and chemical composition of colloid.
- 2) Design variables: kind of metal, polish, bearing area, curvature of surface applying force.
- 3) Dynamic properties of soil: shear value, friction, compression, cohesion, moment of inertia.
- 4) Dynamic resultants: fragmentation, arch action, compaction, shear.

The assumption was made that the structure of soil is uniform and cementation is zero. Each soil has a normal structure which would afford a basis for quantitative studies of force reactions.

He expresses that some of the soil properties are inter-related and also all soil properties are related to the factors listed as "primary soil factors." Then, he discusses the relation between the primary soil factors and dynamic properties of soils. Colloid content and the percentage of moisture content are two important factors in the study of soil conditions.

He also obtained a quantitative relationship between soil colloidal and physical properties of soil in non-plastic soil (soil having less than 16 percent clay).

In his second paper (54) he discussed the work on non-plastic and plastic soils: the soils for this experiment

were made synthetically by mixing clay with different amounts of sand. In the study of non-plastic soils, he discussed the moisture content of soil for maximum reactions, and the relation of the force of reaction with the colloid content.

Moisture content of soil for maximum reactions: as the variations of the physical reaction of any soil are due to the moisture films of the colloidal content, it follows that the moisture percentage at which maximum reactions occur would be proportional to the colloidal content. This would hold only for soils having colloids of the same chemical or absorptive activity.

Nichols ran the tests and then indicated quantitatively the relationship between M, the moisture percent content at which maximum activity occurs, and C, the percent of colloid content.

For cohesion, $M = .293C \neq 6.94$

For adhesion, $M = .183C \neq 10.10$

For compression, $M = .395C \neq 2.1$

For shear, $M = .297C \neq 4.35$

also $M = \frac{DC}{100} \neq b$ where M and C are as explained before, b is the intercept of the equation, and D is a constant film thickness.

Force of reaction and colloid content: cohesion and adhesion, being simple reactions which involve merely the breaking of films, should vary directly as the number of

colloidal films being broken. Compression and shear, both of which involve orientation of particles, should show a definite relation to colloidal content, but the reactions would not be expected to show a simple, straight line relationship.

$F_a = .0044 C \div .48$, where F_a is the maximum force of adhesion and C is the percentage of colloid.

$F_c = .049 C^2 \div 5$, where F_c is the force of cohesion in grams per square inch.

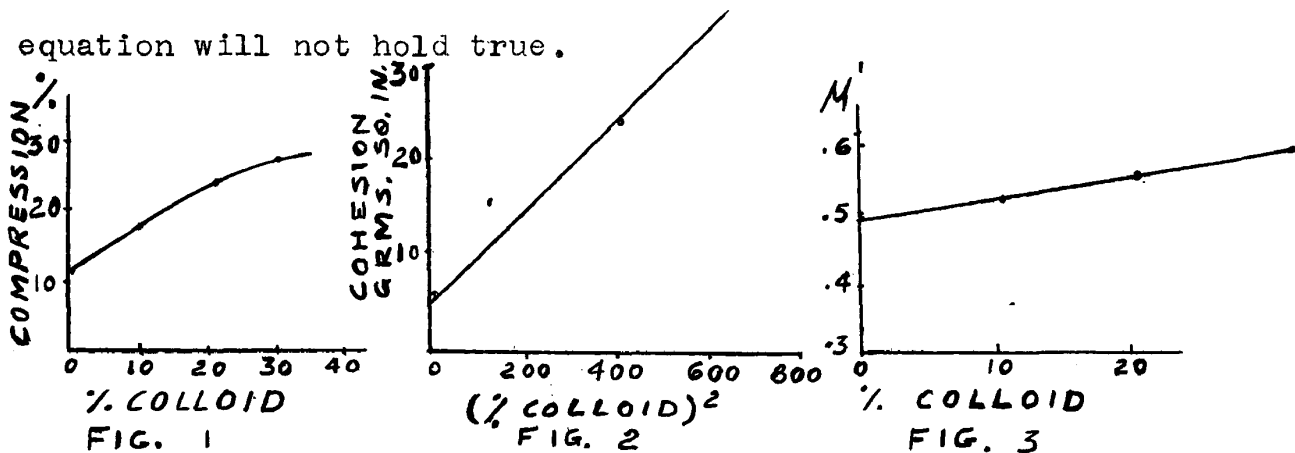
The agreement of this formula (the square of clay percentage) with the colloidal film hypothesis can be noticed. To measure the force of cohesion, a given cross-section of soil must be pulled apart. A pressure of more than ten psi was necessary to apply to a soil sample to get a constant number of films per unit cross-section area.

With the synthetic soils the apparent specific gravity did change with the square of the colloid as $D = .0012 C^2 \div 5$, where D is the gram increase in density per cubic inch with a given pressure regardless of moisture percentage. It will be seen therefore, that when the force formula is corrected for the amount of colloid, the variation of the force of cohesion is proportional to the amount of colloid present.

$F_c = -.625C \div 12$ The amount of F_c , force of compression, varies directly with the colloidal content up to a point near where plasticity occurs; from this point the

amount of compression varies inversely as the colloidal content. $F_c = -.625 C \sqrt{12}$ where F_c is the resistance force against compression and C is colloidal content.

Forces producing shear are not confined in their action to a single plane. The interlocking of particles and the cohesive action of moisture films cause the reaction to spread throughout a considerable mass of soil on each side of what is usually considered the shear plane. Under these conditions it can be expected that shear is the resultant of compression and cohesion. The maximum shear value of non-plastic soil is $S = .013 C \sqrt{.5}$; with the increase of colloid beyond the plastic limit this equation will not hold true.



Figures 1 and 2 show the relation of cohesion and compression with the colloidal content. Figure 3 shows the relation of colloid to maximum force of adhesion. Adhesion is measured by determining the increased friction due to the "sticking" of a soil to a metal slider.

Nichol also has found an equation indicating the amount of maximum value of shear is a function of colloidal percent and the pressure exerted on soil.

$$F_{ms} = .2 C / .7P$$

where

F_{ms} = shear value in psi

C is the colloidal content (percent)

P is the pressure in psi

This equation is for a soil with large quantity of coarse sand, but for those composed largely of fine sand or silts, the indicated shear value is low.

Plastic soils: The classification of soil as plastic and non-plastic is arbitrary. However, by increasing the colloidal content of soil there will be a point where the reaction to soil will change and evidence of plasticity will appear. Atterberg's constants have close relations with the properties of the plastic soil. It was found that within the range of forces entering into the tillage operations that

- 1) Maximum adhesion occurred at a moisture content fairly close to the upper plastic limit;
- 2) The moisture range over which adhesion took place and moisture content at which maximum adhesion occurred were functions of the plasticity number;
- 3) The range of maximum compressibility of a soil is approximately the same as the plasticity range on the moisture scale;
- 4) The maximum compressibility of a soil is a logarithmic function of the plasticity number;

5) The maximum resistance offered by a soil to the passage of chisels is a logarithmic function of the plasticity number; and

6) A double logarithmic relationship exists between the plasticity number and that moisture content at which the resistance of a soil to a chisel or implement being forced through it begins to increase rapidly.

The lower plastic limit is the place of maximum activity, or the percentage of water at which activity occurs. With different soils, the physical activity per unit of water will vary depending upon the amount required to satisfy the surface demands of the individual colloidal particles and the amount of colloid present. The physical activity of water would be inversely proportional to surface demands and directly to colloidal content. It is then expected that the greater the activity of water the lower the lower plasticity limit.

$P = \frac{KC}{M} \neq b$ or from the Parker and Pate data (54) the approximate quantities for b and K were evaluated and $P_1 = .361 - \frac{C}{10M}$ where P_1 is the lower plasticity limit, C the percent of colloidal and M is percent of moisture.

Figure 4 shows the relation of the place where lower plastic limit occurs to the activity of the soil's moisture.

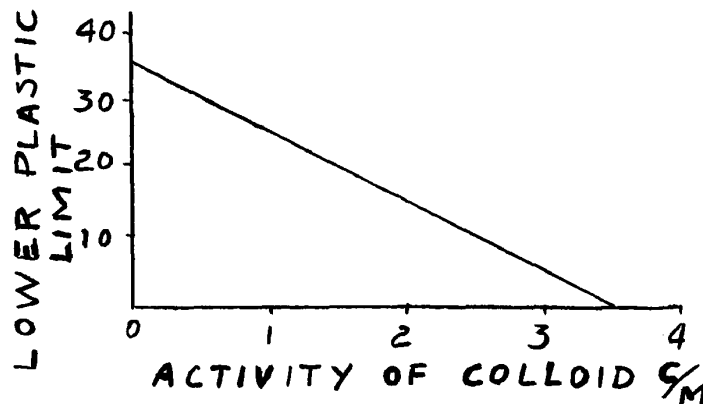


FIG. 4

Plasticity number: At lower plasticity, colloidal film action first became evident, and at the upper plastic limit the film expands so much that its activity is materially reduced. The plasticity number is an arithmetic difference of the percent moisture content at upper and lower plastic limit. This number is a function of colloidal content; an approximate equation is $P_n = .00489 c^{2.67}$. Since colloidal content is a mass and the film theory expresses a surface relationship, the equation describes a mass-surface relation which is exponential. The exponent 2.67 is close to e .

Figure 5 shows the relation between colloidal content and plasticity number.

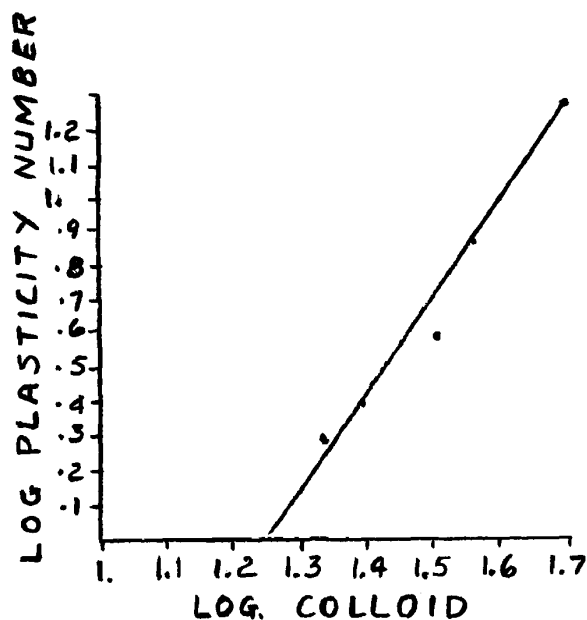


FIG. 5

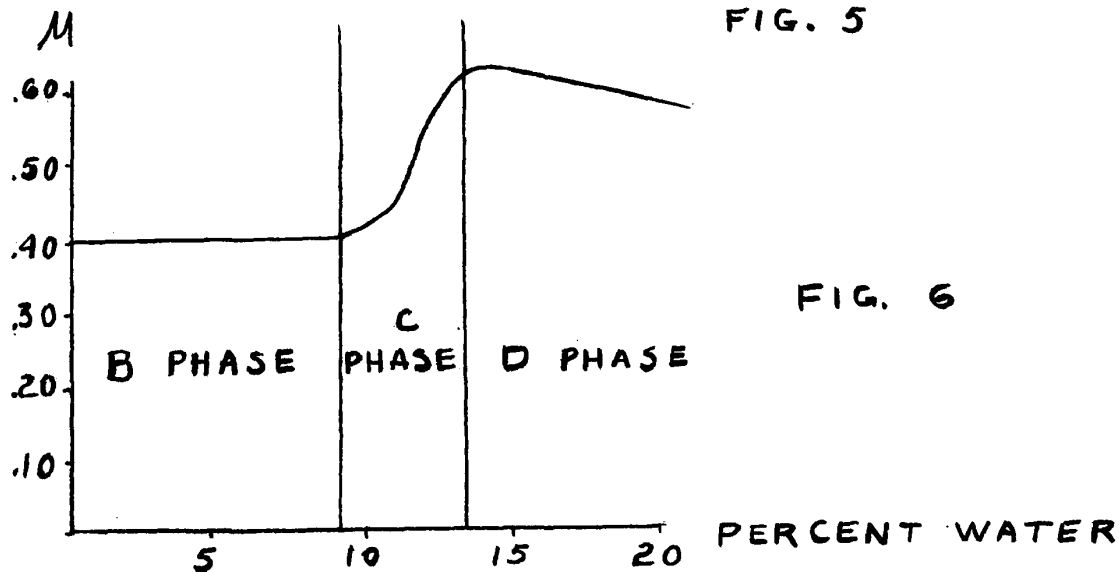


FIG. 6

In his third paper, Nichols discusses "Soil and Metal Friction" (54). Tests were run with synthetic soils and various known metals. The conclusions were drawn from the average of the data obtained from the tests. According to the structure and moisture of soil, and the pressure of metal surface, the frictional resistance was divided into four phases:

Compression phase (A): when water does not adhere to the metal, and when the bearing power of a soil is less than the pressure per unit area. Factors affecting M' are: speed, pressure, smoothness of the surface of metal and soil. To indicate these relationships mathematically, Nichol ran tests with sand and chose a slider with the weight just enough to cause slight rolling of the surface particles. He found out that $M' = .010S / .33$, where M' is the coefficient of sliding friction and S is the speed in feet per minute.

Friction phase (B): (B) phase occurs when the bearing power of soil is more than the pressure per unit area, and moisture does not adhere to metal. Factors affecting in this phase are: total pressure between the two surfaces, and the roughness of the surfaces; contact area and speed have no effect. An approximate equation for this relationship is $M' = .0076C / 28$; where M' is the coefficient of friction of chilled iron and C a colloid content. By introducing the hardness of metal in this relationship it was found:

$M' = .24 \times .005 C - .0001H$, where H is the hardness of metal determined by the Brinell number, and C and M' are as explained before. It was found that 32 percent clay is almost the limit beyond which the friction will not change appreciably.

Adhesion phase (C): In (C) phase, there is enough moisture present to cause the soil to adhere to metal, but not enough to appear on the surface of the metal. The affecting factors in this phase are: speed, area of contact, psi, surface and kind of metal, surface tension (i.e. amount of colloidal material, water percentage, temperature and viscosity). An approximate formula for the moisture content of maximum adhesion for a nickel slider on non-plastic soil, is

$$M = .2C \times 10$$

and moisture content at which first adhesion appears is

$$M = .13 C \times 4.77$$

M' in this case is;

$M' (MAX.) = .0044 C \times .48$ when C is the colloidal content, and M' is the coefficient of kinetic friction. For plastic soil $M = .7 PL$, where M is the percentage of moisture at which adhesion begins, and PL is the lower plasticity limit. Also $M' = .06 P_n \times .42$, where M' is the maximum coefficient of sliding friction and P_n is the plasticity number.

The effect of kind of metal on the coefficient of friction has not been determined very clearly; hardness and polish have some effect but the angle of wetness is the main factor that changes the μ' .

In the study of the friction between metal and soil in general, the phenomenon of adhesion should be investigated. Adhesion is related to the wetting power of the metal. A conception that is generally accepted is that the wetting power is a function not only of the surface tension of a liquid, but also of the specific attraction operative between the solid and liquid.

Parker has developed a method to get soil solution. F. A. Kummer and M. L. Nichols (42) used soil solution in indicating the adhesion between soil and metal. After studying the principles of adhesion, Kummer (43) tested different plow shapes and materials on scouring in heavy clays. He used four kinds of plows: 1) alloy-steel moldboard covering; 2) endless belt type moldboards; 3) wooden rollers replacing solid moldboards; 4) wooden slats, impregnated with paraffin or linseed oil, replacing steel slats. The plowing tests showed that wood slat bottoms produced considerably better scouring than steel slat bottoms, especially in the higher moisture ranges.

Lubrication phase (D): When there is enough moisture in the soil, it will give a lubrication effect. The effecting factors in the coefficient of sliding friction are: speed,

psi, amount of moisture and the viscosity, nature of metal and the surface. The exact relationship has not been found in this phase because of puddling of soil, but the clay percentage is the main factor in this case.

In the fourth paper (41), Nichols did work on the soil reactions in the specific case of moldboard plow. As their work consists mostly with the soil properties which is common in all others. A short discussion of his work will be reported here.

M. L. Nichols and T. H. Kummer (41, 55) have expressed the shape of the curvature of the moldboard plow mathematically, and discussed the relationship of these curvatures to the dynamic properties of soil.

First they classified the functions of the plow into:

- 1) the breaking or cutting loose of the furrow slice;
- 2) the pulverizing of the furrow slice; 3) the inversion of the furrow slice; and 4) the covering of trash and weeds. Eliminating such factors as landside pressure, wing, point, and heelbearings, suction, and other features of stability and smooth running, this classification centers attention on the moldboard, shin and share action.

As the plow moves forward it compresses the soil forward and upward. When the shear resistance exceeds the compression a block of soil is sheared off at an angle of 45° with the horizontal and slides up the shear plane as a solid unit. The blocks A, B, C, also will form as shown

in the picture. With the movement of the plow forward the soil slips over itself on shear plane "a"; to keep the soil slipping over itself in plane "b" at the same rate; the block B should travel at the same rate as A plus an additional amount equal to the movement of A.

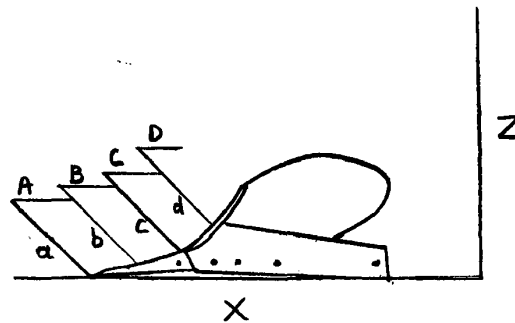


FIG. 7 REACTION OF SOIL AS A PLOW ADVANCES THROUGH IT

In the same way the plane "c" will move with the amount equal to the movement of A. Also, in the same way the plane "c" will move with the amount equal to the movement of A and B plus the movement of A.

The curvature of a vertical differential section of a moldboard which keeps the soil slipping on all shear planes simultaneously and uniformly must be constantly increasing at a rate which is proportional to the distance traveled up the curve. A mathematical expression for the increase rate in Z direction to X direction is

$$\begin{aligned} \frac{dz}{dx} &= a b e^{bx} & \text{OR} \\ bz &= a b e^{bx} \\ \text{OR FINALLY} \quad z &= a e^{bx} \end{aligned}$$

where Z and X are coordinates and a and b are constants. The constant a indicates the location of the differential section, and the constant b denotes the steepness of the slope of the section. The upper part of the moldboard inverts the soil and throws it into the preceeding furrow. It is necessary that for uniform scouring the inversion area also have a uniform pressure. A mathematical expression for the change of angle in this area have been found to be $\phi = \rho e^{Kt}$ where ϕ and t are angle and distance of travel, and ρ and K are constants governing the rate of turning or throw of the plow. Also the paths of soil particles were found to be sections of logarithmic or equiangular spirals of the general formula

$$R = a e^{m\omega}$$

where R is the radius, ω the angle through which the radius has turned, and a and m constants.

Nichols and Doner (26), after finding the equation of plow surface which indicates uniform pressures for pulverization and inversion, discovered another force which they called "buckling effect." Through mathematical studies of forces acting along the path of travel of soil particles, they showed that this effect at certain points increases the forces normal to the moldboard, thus materially affecting scouring. By developing a mathematical equation they found the tangential force necessary to maintain motion in terms of friction, length, curvature of the moldboard, and weight

of the soil at any point along the path of travel. They showed that high curvature in the path near the shear results in increased tendency for the soil to stick to the moldboards. If the curvature is shifted towards the wings of the moldboard, this tendency is materially reduced.

M. L. Nichols and I. F. Reed in their field study (58), discussed the physical reactions of soils to moldboard surfaces. They classified the soil according to their physical conditions as: hard cemented soils, heavy sod, packed or cemented surface, freshly plowed soil, push soils, and finally normal condition. The reaction of soil in good plowing condition is described from field studies. They found that the pulverization of the slice is produced by two sets of shear planes. The primary planes were formed by the wedge action of the point of the plow and extended upward and forward from the shin at an angle of 45 degrees to the direction of travel. The secondary planes were formed at right angles to the primary planes, and sheared the soil in two directions which produced pulverization.

Nichols states that the so-called "tension" effect of the plow is found to be due to variations in directional acceleration.

OBJECTIVES

The objectives of this study were

- 1) To run some field tests for the indication of the draft requirement of different tilling methods.
- 2) To run laboratory tests in a soil box to find the relationship between the draft requirements of tilling implements and the different effective factors.
- 3) To introduce a theoretical method to check the result of the laboratory work and to find a single equation to show the relationship between the force of soil resistance against the tillage tools, and the effective factors.

GENERAL INVESTIGATION OF THE PROBLEM

Factors That Affect The Draft

As has been mentioned previously, the problem of tillage is one of the oldest and most complicated ones in the field of agriculture. Different investigators have tried to approach this problem from different points of view, but because of the complexity of the nature of the problem no definite solution has been found.

In the study of the draft requirement the first step is to investigate the variables that enter into the problem; then, find out which of those variables have any effect and in the event they do have an effect, determine the relationships between them.

The variables that exist in the tillage operation can be divided into three sections:

Soil variables (primary soil factors)

1. Particle size and percent of colloidal
2. Chemical composition and the effect of organic matter and fertilizer
3. Moisture percentage
4. State of compaction or apparent specific density, a means of indicating the structure
5. Effect of vegetation and crops residue
6. Effect of slope and non-uniformity of soil

Implement variables

1. Kind of implement
2. Kind of metal
3. Surface condition and the sharpness of the implement
4. Bearing area
5. Curvature and the shape of surface applying force

Factors outside of soil and implement

1. Speed
2. Width and depth of the furrow

Some of these factors cannot be evaluated at present and though their effects have been proved by several investigators, the determination of any mathematical relationships have not yet been found, e. g. the effect of vegetation or fertilizer. There are also some other factors affecting the draft which have proved to be negligible, such as the slope of the field. Therefore, in indicating any draft functions only the variables that have significant effect will enter into the discussion.

In the design of tillage tools, attempts have been made to specialize the implements to work in particular conditions. This not only will improve the quality of tilth, but also decrease the draft and eliminate some of the above-mentioned design variables, for example, making cast iron plows for sandy soil; or selection of the optimum curve of moldboard plow for sod, sandy and clay soils.

Major Factors Affecting the Draft

Nichols (55) in the study of plow shapes has analyzed these functions as cutting loose and pulverizing the furrow slice by the action of compression and shear; then inversion and covering, by pushing up the soil over the moldboard curve which inverts, and throws the soil into the furrow. On the basis of this analysis the variables that affect the draft are: resistance to compaction, shear friction, compression and adhesion, and also speed which indicates the rate of those actions.

Nichols, in the study of dynamic properties of soil which have been discussed previously, has indicated that the above mentioned properties are functions of the following factors: composition and the percentage of colloidal content, moisture percentage, apparent specific gravity, and the speed of implement.

The indication of a single equation covering the effect of all these variables experimentally is at present next to impossible, though the relationship between the soil properties and the above mentioned factors has been indicated experimentally.

Thus in the present experiments, only the following factors have been considered for study:

- 1) the percent of clay;
- 2) the percent of moisture;
- 3) the apparent density; and
- 4) the speed of implement.

In the laboratory experiments the other factors could be controlled or kept constant. In the field test, attempt was made to select plots with the apparent uniform conditions, though there were some differences which could not be measured because of lack of means and methods of measurement.

The biggest problem in the field test is the non-uniformity of soil and the non-controllability of the factors. The U.S.D.A. tillage laboratory at Auburn, Alabama is able to run tests with controlled conditions. They have obtained very useful data on draft under different conditions.

The Auburn type of experiment station, though very useful, has the following handicaps: 1) high initial investment which makes it very difficult in other states to duplicate the investigation; 2) only 11 kinds of soil which are common in the south have been tested in the plots. To change the soil of each bin to different types requires a tremendous amount of labor and time. There are some other difficulties, e.g. the need of a long time to obtain a uniform moisture, controlling the bacteriological action, the accumulation of salts in the plot soils by drying and wetting process when the non-distilled water is used, etc.

To overcome the above-mentioned difficulties, the author decided to investigate the possibility of finding a new and better method of experimenting and also to find out the relationship between the draft and the affecting factors.

METHODS OF PROCEDURE

Three methods have been employed to complete the investigation of the subject: field work, laboratory work, and finally, mathematical solution with the help of dimensional analysis.

Field Work

Field Tests

The field work consisted of indicating the draft required to pull different implements in three plots of soil. The types of soil selected for the experiment were clay, sand, and sandy loam. The clay soil was Conover clay loam, without any crop and with very little vegetation. The Hillsdale sandy soil was covered with clover and oats; the Hillsdale sandy loam was under sod for several years. The experimental plots were located to the south of the campus. Although attempts have been made to find a comparatively uniform soil, the transportation, weather, and time were problems which prevented the selection of plots away from Lansing. For preliminary tests, the plots were arranged in the form of a square with 36 sections. The size of each section was 60 by 20 feet with a 15-foot alley on each side to provide space to maneuver the tractor and implement for return trip. Each of five methods of

tilling were practiced in six randomly selected sections. Six of the sections were not used. The results of this test were not satisfactory because of the short period between start and stop, and the packing of the soil by tractor and implement wheels caused by inadequate space for moving them within sections. To eliminate these difficulties the second time, long strips of 300 by 10 feet were selected and divided in five sections of 60 by 10 feet. Each of these strips was tilled in one run with a different implement and then the average of the draft required for each section was computed separately.

The methods of tilling were

- 1) Conventional plowing (plowing, disking, harrowing)
- 2) Plow with plow packer
- 3) Plow with cultimulcher
- 4) TNT plow (sub-base plow)
- 5) Disk tiller

The selected implements were the ones that were used in previous tillage experiments conducted jointly by the agricultural engineering and soil science departments to determine the effect of tillage method in the yield of crops. The implements consisted of:

plow: a two-bottom, 14-inch plow made by International Harvester, the trade name is "Little Genius No. 8";

disk harrow: John Deere tandem disk, seven feet wide;

harrow: spring tooth harrow;

packer: a plow packer, made by International Harvester with six wheels. The diameter of the wheels was twenty inches;

cultimulcher: made by Dunham. It consisted of two rows of notched disks at the ends and two rows of spring tooth harrows in the middle. Its size was 3 by 6 feet;

TNT plow: made by Oliver. Has two nine-inch plow bottoms and two smaller bottoms connected to the same beams with three inches more depth which gave a total of 2 by 14 inch furrows;

disk tiller: a "256-A" John Deere tiller with five disks and spacing of 10-2/3 inches between disks. The diameter of the disks was 22 inches and concavity was two and one-half inches. All the implements were the trailing type. The draft was measured by a hydraulic dynamometer made by Messrs. H. Fish and Garth Hall in the department of Agricultural Engineering at Michigan State College. Some minor changes were suggested by the author in order to improve performance.

The following data were taken for each section of the plots:

- 1) The draft requirement of different implements in indicated sections;

- 2) The mechanical analysis of the soil (average of three samples in each section); (7)



Fig. 8. Dynamometer for field tests



Fig. 9. Field test with two-bottom, 14-inch plow.

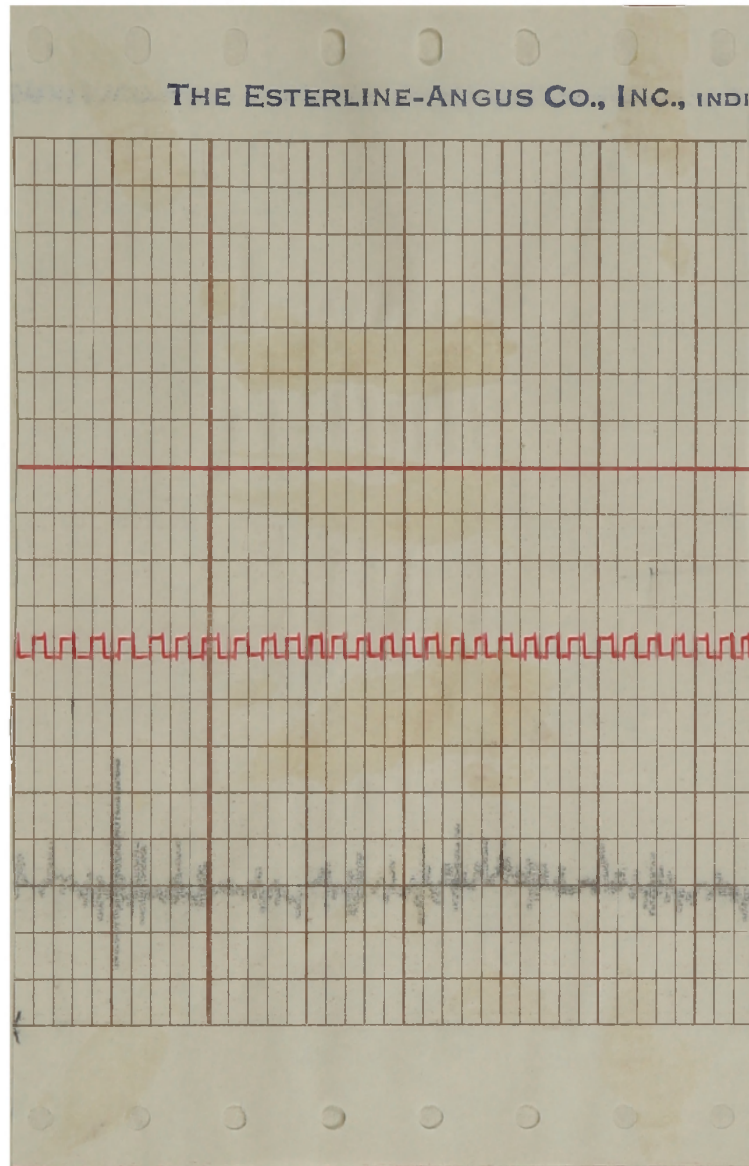


Fig. 10. A sample of dynamometer graph

TABLE I

THE RESULT OF PRELIMINARY FIELD TESTS

The average of 6 sections for each tilling method, in three soil types.

Method of Tilling	Mechanical Analysis			Percent Moisture	Apparent Density	Depth in.	Speed m.p.h.	Draft Req.* lbs.	Draft Req.* p.s.i.	
	SAND %	SILT %	CLAY %							
Conventional Plow	Sod	66.5	21.5	12.0	8.27	1.26	5.5	2.85	2753.3	17.88
	Sand	72.1	17.9	10.0	5.75	1.48	5.8	1.7	2351.	14.49
	Clay	55.3	28.0	16.7	14.80	1.51	6.2	3.4	1888.	10.8
Plow Packer	Sod	67.5	20.8	11.7	6.55	1.19	6.	3.14	1182.1	7.05
	Sand	72.2	16.7	11.1	5.58	1.45	6.6	1.19	1340.	7.25
	Clay	51.3	27.1	21.6	17.19	1.46	6.2	3.14	1610.	9.29
Plow With Mulcher	Sod	67.3	20.4	12.0	9.40	1.24	6.	1.93	1394.8	8.31
	Sand	72.0	17.7	9.5	5.63	1.43	5.8	1.57	1561.	9.63
	Clay	49.7	29.9	20.4	15.32	1.43	6.	2.45	1458.	8.7
T.N.T.	Sod	69.1	19.5	11.4	9.14	1.22	7.	2.75	1393.1	8.4
	Sand	73.0	16.9	9.3	4.80	1.38	7.6	1.59	1810.	9.91
	Clay	46.5	34.7	16.5	12.40	1.47	7.7	3.32	2050.	10.98
Disk Tiller	Sod	69.3	19.4	11.3	8.46	1.22	6.	1.84	5077.5	21.1
	Sand	72.7	15.9	11.4	5.05	1.38	4.6	1.27	2185.	11.73
	Clay	49.6	29.9	20.5	15.97	1.40	6.	2.08	1963.	8.2
** Draft Requirement										

TABLE II

THE RESULT OF FIELD TESTS (LONG STRIPS) IN SANDY SOIL

Method of Tilling	Run No.	Mechanical Analysis		Percent Moisture	Apparent Density	Depth in.	Speed m.p.h.	Draft Req. lbs.	Draft Req.* p.s.i.
		SAND %	SILT %	CLAY %					
Conventional Plow	1	69.4	20.6	10.	1.41	7.33	1.76	1645.	8.
	2	64.4	21.6	14.	1.50	7.1	1.57	1604.	8.06
	3	72.5	16.2	11.3	1.51	7.8	1.70	1644.	7.53
	4	75.4	15.9	8.7	1.45	8.1	1.57	1714.	7.55
	5	77.4	13.6	9.0	1.5	7.33	1.61	1540.	7.5
Plow With Mulcher	1	71.4	17.0	11.	1.45	6.6	2.01	1375.6	7.43
	2	67.3	20.5	11.7	1.51	6.17	1.91	1275.3	7.37
	3	75.4	12.6	12.	1.51	6.5	1.91	1273.2	7.67
	4	77.3	13.9	8.8	1.49	7.1	1.77	1328.3	6.67
	5	73.4	17.6	9.0	1.43	6.6	1.95	1250.5	6.78
T.N.T.	1	66.0	21.0	11.	1.51	7.66	1.72	1026.	5.57
	2	67.4	20.6	12.	1.53	5.83	1.64	980.	7.36
	3	71.7	15.9	12.2	1.47	5.83	1.65	939.	7.05
	4	77.4	14.0	8.6	1.54	8.33	1.62	1118.	5.5
	5	74.4	15.6	10.	1.44	6.5	1.61	925.	6.08
Disk Tiller	1	63.4	21.6	10.	1.49	5.	1.48	1111.	5.56
	2	57.5	20.5	11.7	1.46	4.83	1.30	1185.	6.14
	3	75.4	15.0	8.	1.55	5.33	1.38	1221.	5.73
	4	72.3	17.8	10.8	1.50	6.16	1.38	1291.	5.24
	5	69.4	20.6	10.	1.48	5.	1.42	1049.	5.24
Plow Packer	1	69.4	20.6	10.	1.41	7.33	1.76	1151.	5.61
	2	64.4	21.6	14.	1.50	7.1	1.57	1021.	5.13
	3	72.5	16.2	11.3	1.51	7.8	1.70	1018.	4.67
	4	75.4	15.9	8.7	1.45	8.1	1.57	1049.	4.62
	5	77.4	13.6	9.	1.5	7.33	1.61	1092.	4.88

* Draft Requirement

TABLE III

THE RESULT OF FIELD TESTS (LONG STRIP) IN CLAY SOIL

Method of Tilling	Run No.	Mechanical Analysis			Percent Moisture	Apparent Density	Depth in.	Speed m.p.h.	Draft Req.* lbs.	Draft Req.* p.s.i.
		SAND %	SILT %	CLAY %						
Conventional	1	29.4	41.6	29.	15.2	1.42	6.8	3.68	1871.5	9.72
	2	27.4	58.6	14.	16.2	1.49	6.7	3.69	1925.5	10.15
	3	32.4	45.6	22.	15.9	1.40	8.	3.69	1978.	8.82
	4	36.4	39.6	24.	14.1	1.41	7.3	4.65	1846.	9.01
	5	49.9	33.3	16.8	11.35	1.48	7.7	3.07	1918.	8.83
Plow With	1	55.4	26.6	18.	15.18	1.38	6.6	2.78	1262.	6.82
	2	42.4	35.6	22.	14.	1.47	7.5	3.1	1239.	5.9
	3	35.8	39.4	24.8	17.12	1.42	7.	1.44	1349.	6.87
	4	40.4	35.6	24.	12.65	1.44	7.5	2.84	1152.	5.5
	5	46.4	33.6	20.	11.82	1.39	7.4	1.93	1200.	5.78
T.N.T.	1	52.6	30.4	17.6	14.45	1.40	7.5	2.84	1757.	9.75
	2	45.4	33.6	21.	14.5	1.39	7.8	2.82	1784.	9.43
	3	37.4	35.6	24.	13.8	1.50	8.	3.01	1709.	8.82
	4	41.4	35.6	23.	15.75	1.48	7.8	2.84	1709.	9.03
	5	52.4	29.6	18.	12.15	1.49	8.	2.88	1575.	8.12
Disk	1	55.4	27.6	17.	14.72	1.44	6.3	2.9	1676.	6.65
	2	47.4	32.6	20.	15.7	1.44	6.3	2.82	1685.	6.63
	3	31.4	40.6	22.	14.1	1.46	6.6	2.92	1612.	6.1
	4	42.4	35.6	22.	12.02	1.50	6.	3.07	1569.	6.5
	5	54.2	28.3	17.5	9.42	1.62	6.	2.07	1432.	5.98
Plow with	1	57.4	26.6	16.	13.52	1.44	5.9	2.2	912.	5.5
	2	30.4	43.6	20.	15.	1.45	7.1	3.28	1063.	5.35
	3	34.4	42.6	23.	16.2	1.41	6.8	3.3	974.	5.22
	4	42.4	36.6	21.	16.55	1.42	6.8	3.41	1049.	5.5
	5	50.4	29.6	20.	13.09	1.48	6.6	3.29	1082.	5.86
Packer										

* Draft Requirement

TABLE IV
THE RESULT OF FIELD TESTS (LONG STRIPS) IN SOD SOIL

Method of Tilling	Run No.	Mechanical Analysis		Percent Moisture	Apparent Density	Depth in.	Speed m.p.h.	Draft Req. lbs.	Draft Req. p.s.i.
		SAND %	SILT %	CLAY %					
Conventional Plow	1	71.8	18.0	10.2	1.21	5.5	2.06	2685.	17.43
	2	56.8	28.0	15.2	1.10	5.5	2.06	2745.	17.82
	3	63.8	23.0	13.2	1.34	5.5	2.2	2655.	18.51
	4	58.8	27.0	14.2	1.34	5.5	2.37	2595.	16.81
	5	70.8	17.0	12.2	1.27	5.5	2.42	2845.	18.48
Plow With Mulcher	1	60.8	23.0	16.2	1.12	6.	2.27	1405.	8.37
	2	62.8	24.0	13.2	1.07	6.	2.62	1455.	8.67
	3	66.8	21.0	12.2	1.26	6.	2.53	1276.	7.6
	4	64.8	20.0	15.2	1.24	6.	1.6	1330.	7.92
	5	74.8	17.0	7.6	1.36	6.	1.87	1428.	8.5
T.N.T.	1	71.8	17.0	11.2	1.33	7.	2.29	1447.	8.72
	2	70.4	20.4	9.2	1.18	7.	2.4	1321.	7.97
	3	68.8	18.0	13.2	1.15	7.	3.08	1329.	8.
	4	62.8	25.6	11.6	1.20	7.	2.9	1380.	8.31
	5	70.8	15.0	14.2	1.18	7.	2.98	1312.	7.91
Disk Tiller	1	62.8	22.0	15.2	1.18	6.	2.09	5145.	21.4
	2	67.8	22.0	10.2	1.26	6.	2.08	4985.	20.75
	3	66.8	22.0	11.2	1.38	6.	1.83	4650.	19.35
	4	68.8	19.0	12.2	1.14	6.	1.89	5050.	21.
	5	76.8	13.0	10.2	1.34	6.	1.61	5260.	21.9
Plow With Packer	1	68.8	18.0	13.2	1.06	6.	3.56	1390.	8.28
	2	66.8	22.0	9.2	1.12	6.	2.87	881.	5.24
	3	62.8	27.0	10.2	1.28	6.	3.4	1291.	7.69
	4	70.8	14.0	15.2	1.25	6.	3.15	868.	5.16
	5	60.8	26.0	13.2	1.03	6.	2.96	1384.	8.25

* Draft Requirement

3) The moisture percentage of the soil immediately after tilling;

4) The apparent density of the soil before tilling (three core samples from each section);

5) Depth of the furrow (depth readings were taken every ten feet in the furrow);

6) Indication of speed for each run.

The draft at each instant was recorded on the dynamometer chart. By indicating the area of the draft curve with planimeter, and multiplying by the spring factor, then dividing by the distance traveled, the average draft requirement for each run was calculated. The speed of the tractor was calculated by dividing the distance traveled by the time. This distance and time was measured from the chart. Figure 10 shows a sample of the dynamometer chart. Each notch indicates one second time and the length of notches is proportional to the distance traveled by the implement (one inch on the chart corresponds to twenty feet on the field).

Results and Conclusions

Data taken from the field tests were recorded and the results can be seen in Tables 1 through 4. In general, the result of the field test was not accurate and satisfactory though some general conclusions can be obtained. The conventional plow method required more pulling force per inch of furrow section; the disk tiller has the least pulling force in sandy soil; in sod, the draft requirement of the disk

tiller was the highest among all. The effect of the pull of the packer on the draft of the plow was negligible; the plow packer combination is the lowest energy consuming method in all three kinds of soils.

As the soil factors in the field condition could not be controlled, a more specific conclusion could not be obtained. Although the soil in each plot appeared to be uniform, the mechanical analysis in each section differed from the others considerably. The moisture content also varied in different sections of the plot. Speed varied in some sections although an attempt was made to keep the tractor speed constant. The effect of root, vegetation and organic matter, especially in sod and sandy soil, were of importance; but no satisfactory method exists to evaluate that factor. The indirect effect of organic matter will appear in the moisture content, soil aggregate analysis, and the apparent density of the soil.

In conclusion one can say that the field test is good only for an approximate indication of the draft requirement of different tillage methods under a normal tillage condition. For any specific results the laboratory and theoretical methods should be employed.

Laboratory Method

The field tests not only do not give satisfactory results, they also require a special season of the year, with good weather and workable soil condition. It is also time-consuming, expensive and difficult. To overcome some of the above mentioned difficulties, the author decided to work on the possibility of some laboratory tests.

In reviewing literature, the author noted an article (25) by A. W. Clyde in which was suggested the possibility of using a soil box and small tools to determine the effect of soil factors in the draft requirement of tillage tools. Although the article was published in 1939, the idea never materialized.

To continue the study of tillage problem the author decided to design a soil box with reasonable dimensions, which could be constructed in an agricultural engineering laboratory and to run the tests.

Objective of the Experiment

The objective of the tests in the soil box was to determine the effect of any individual factor in the draft requirement by keeping the other factors constant and changing this specific factor. Effects of speed, moisture, percent clay, packing the soil, were investigated. In this test all other factors, such as organic matter of the soil, cementation, vegetation, etc., were eliminated or controlled with reasonable accuracy.

Soil Box

The experimental soil box consisted of three sections: the stationary part that held the soil, the moving section which carried tillage tools and a spring dynamometer to measure the pulling force, and the power section which consisted of a three-quarter horsepower electric motor and the transmission.

Stationary section: This section consists of the body of the box. The box was twenty feet long, three feet wide, and one foot deep. The whole box was made from a steel frame with two removable end gates. The interior of the box was covered with 20-gauge sheet steel. The steel sheets were attached to the steel frame with a few wire ties. Along the upper edges of the box, two rows of door-hanger tracks were bolted in each side to the main frame as is shown in Figures 43 and 44, Appendix. The box was thirty inches above the ground, and was supported by an adequate number of cement blocks. The entire frame was made with angle steel beams and, because of ample support at the bottoms and because of low-bending moments, the main beam of the frame was comparatively light. The detail of the design has been shown in Figures 41, 42, 43, 45 and 46, Appendix. A check of the strength was made wherever it was felt necessary. The removable end gates were to facilitate the loading and unloading of soil from the box. The box could be loaded by a tractor with a hydraulic lifting bucket or simply by

throwing the soil in the box with shovel. The capacity of the box was almost fifty cubic feet. Because of the comparatively low capacity of the box unloading or loading of soil did not take more than one and one-half to two hours.

The moving section: The frame of the moving section was made from two diagonal and two longitudinal 2 x 2 x 1/8 inch angle steel beams, bolted together in a rectangular shape. This frame was attached rigidly to four trolley door hangers, which rolled in the previously mentioned tracks. This provided a low friction motion of the frame along the length of the box. A third diagonal 2 x 2 x 1/4 inch angle steel beam was bolted almost in the middle of the frame to hold the tillage tools. A 3/8 inch wide slot was cut along the length of this beam to provide a location change of the tool anywhere along the width of the box. To the same beam was welded vertically another 2 x 2 x 1/8 inch beam to carry the dynamometer. This dynamometer was a spring scale which was graduated to one-pound divisions. A one-inch inside diameter and 4.5 inches long dashpot was made to dampen the vibration of the spring. The dashpot was bolted to the vertical beam underneath the scale. A one-half inch short horizontal rod was fixed with two nuts to the weighing loop hole at the lower section of the scale, and the force of forward movement was transferred to the scale by this rod. At each end of this rod there was one quarter-inch hole.

The necessary power to move this whole frame was supplied by two one-eighth inch flexible aviation cables. A quarter-inch bolt was brazed to the end of each cable, and the bolts were held with two nuts in the quarter-inch holes of the horizontal bar in the dynamometer scale. The cables were directed to the drum at the power end of the box with four rollers which bent the cables in reasonable angles to make them horizontal and parallel to each other.

The tools were attached to the frame by individual beams made especially to fit their shape. Several holes were drilled in the tool beams to obtain different furrow depths. Special arrangements were made on the moving frame to hitch the roller-packer behind, and to attach the scraper to the front diagonal steel beams.

The power section: A three-quarter horsepower capacity electric motor with 1750 r.p.m. furnished the required power. A variable speed reducer with V-belt was available to the r.p.m. of the motor from 1:2 to 1:5. Another set of pulleys with the reduction ratio of 1:5 was used to transfer the power to the drum. The drum was made of four-inch steel tubing welded with two steel plates to a three-quarter inch shaft in the center of the tube. Two self-aligning journal bearings at both ends of the drum shaft provided a free rotation of the drum. These bearings were located on two pieces of 2 x 2 x 1/8 inch angle steel beams which were bolted to the end of the box. A loop was made at the end

of each power cable, and two three-eighths inch bolts were screwed through these loops in the drum to hold the end of the cables tightly in place while the drum was turning. Turning the drum caused the steel rope to wind around it, and, in this way, to pull the moving section forward. Special arrangements were made to get a uniform winding on the drum to obtain an equal pulling effect in both cables. The length of the cables could be adjusted by screwing or unscrewing the $1/4$ inch bolts at the end of the cables. A double-pole, double-throw switch was used to run the motor forward and reverse directions. This forward movement of the tool cart was accomplished by the pulling force of the electric motor, but the reverse movement was by hand or by gravity force of a hanging weight at the other end. A second switch was installed at the opposite end to turn off the motor line when the tool cart reached that end.

To indicate the friction produced by moving the tool cart along the box with different speeds and loads, new additions were designed and built: a piece of one-eighth inch flexible aviation cable was connected to the rear end of the tool cart, and after giving a 90 degree bent around a six-inch pulley, it was drawn up 25 feet high, and after being bent again 180 degrees, around a 12-inch pulley, came down perpendicularly and connected to a weighing pan (a long pail). Different weights were added on the pan and the cart was pulled with different speeds. Each time the

pulling force was read on the dynamometer scale and recorded. Table 32, Appendix, shows the above mentioned data. In loading the tool cart, an attempt was made to repeat the same conditions that existed in actual tillage tests. As the results of the tests show, there were only two pounds friction with any test condition, which eliminated the introduction of a correction factor in the actual data.

Tools and Equipment

To prepare the soil in the box for testing, equipment was made to help bring the soil to the desired condition. Two sprayer heads were installed on a piece of pipe 18 inches apart to spray the water evenly on the surface of the soil. The pipe was connected to the water line with a long hose, and could be carried by hand from one end to the other of the box. Two heavy impermeable canvasses were used to cover the soil after spraying, to keep the moisture from evaporating, and also to homogenize the moisture in different soil sections by keeping the water vapor inside the soil.

A regular 20° short-tooth fork and a shovel were used to stir the soil and eliminate the effect of previous packing, tillage practice, and occasional cementation of the soil.

Scraper. This was used to level off the soil in the box and also bring it to the desired depth. The scraper was simply a piece of $1/4 \times 3 \times 30$ inch steel, sharpened on one side. Two $1 \frac{1}{4} \times 3/8 \times 1.5$ inch steel strips were used to attach the scraper rigidly to the front diagonal steel beam

of the moving cart. Several $3/8$ inch holes were drilled with $1/2$ inch intervals on the connecting steel strips to control the depth. Figure 14 shows the above mentioned scraper.

Packer. After leveling the soil surface, packing was necessary to give the soil a desired apparent density. To accomplish this, a hollow cylinder with 8.5 inch diameter and 24 inch length was made from 24 gauge steel sheet. Inside this cylinder two round wooden plates were fitted tightly. A $5/8$ inch rod was run through the centers of the wooden plates and tightly connected to them. This rod acted as a shaft of the hollow cylinder. A 28 x 8 inch rectangular steel frame was made to hold the packing weights, and this frame was attached to the bearings at the ends of the shaft as shown in Figure 45, Appendix. The weights on the frame were transferred to the cylinder and caused packing of the soil. The packer was trailed behind the moving cart with two hitch points.

A cement vibrator to vibrate the box was tested for uniform packing, but it did not work satisfactorily especially in clay and moist soils.

To measure the apparent density, a four inch long steel tubing with one and $13/16$ inside diameter was used with one sharpened end to facilitate the penetration. The Reinhart method to indicate the apparent density was examined; it was time consuming, and not satisfactory.

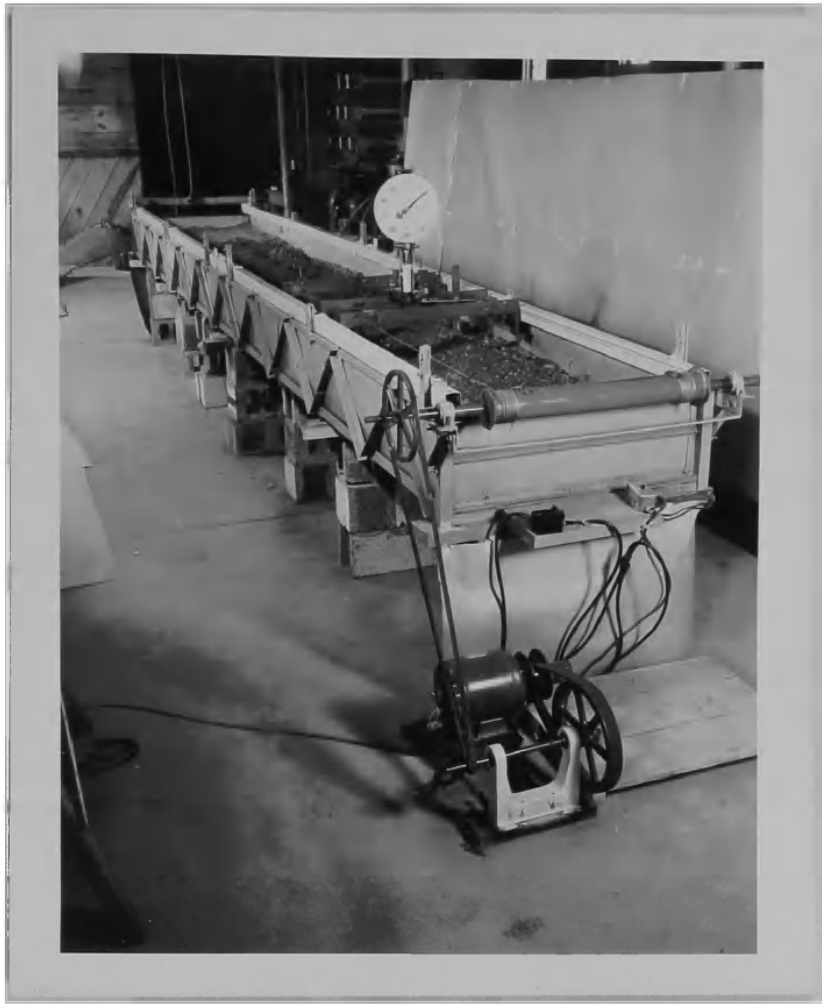


Fig. 11. Soil box, the general view.



Fig. 12. Soil box, grading and packing.



Fig. 13. Soil box, the moving section.



Fig. 14. Tools and implements used in soil box experiment.

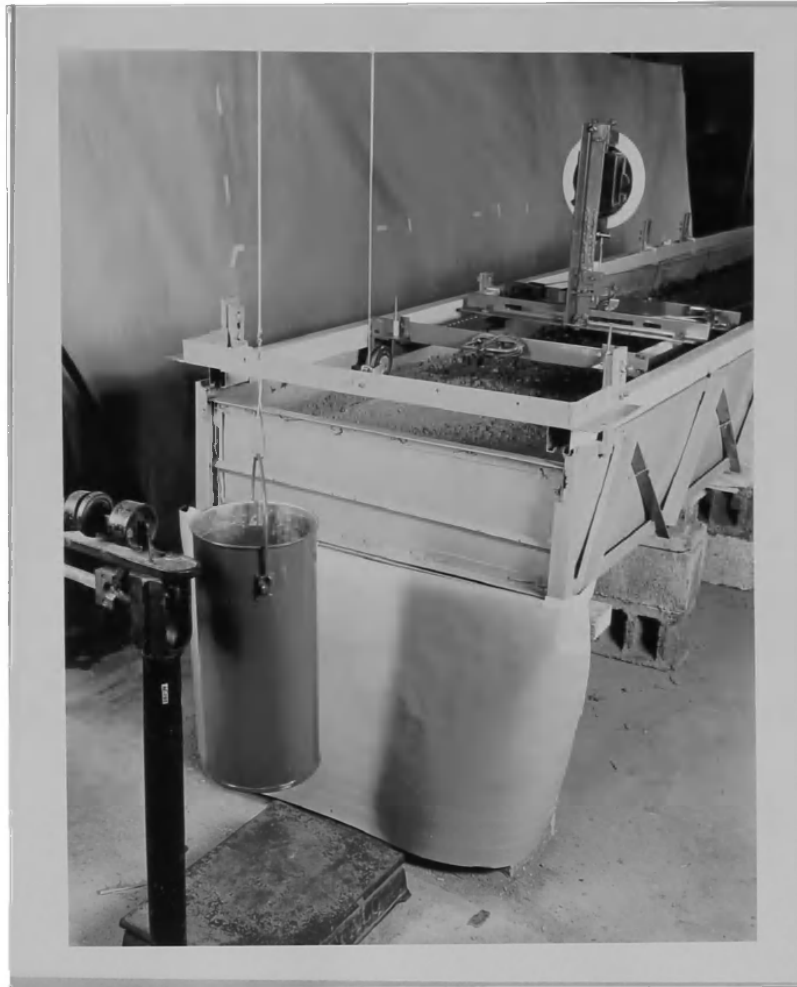


Fig. 15. Attachment to the soil box to measure the friction of the tool carrier.

Three different implements were used to determine the effect of previously mentioned factors. The implements were of miniature size which are used mostly in cultivating gardens; they were a four-inch plow, seven-inch disk, and a one-inch width cultivator tooth. To study the effect of the size of the implement, a 2.5 inch wide tooth was used to run the same tests and the results were compared with the ones obtained with the one-inch wide tooth.

Soil

The uniformity of the soil in the plot was of high importance. To obtain a uniform soil, five cubic yards of clean uniform washed sand (mortar sand) with almost four cubic yards fine bottom layer clay without organic matter (used in making tile and clay products) were used as main constituents of the synthetic soil. Sand and clay were mixed with a cement mixer to any ratio that was desired. To get the best uniformity, clay was ground with a feed grinder to the fine powdery form. In mixing the soil, sand was moistened but the clay was dry. Full shovels of clay and sand were thrown in the mixer while it was turning. The ratio of the shovels of clay to the shovels of sand gave the clay-to-sand ratio. After filling the box with this mixed soil, more mixing was done by shovels and then mechanical analysis of several points was made to ascertain the uniformity of the soil.

Test Procedure

After the box was filled with a known uniform soil, moisture was added by the condensation method (spraying and covering the soil). After 24 hours or longer the soil was ready for the experiment.

To break the soil clods, first it was thoroughly cultivated with a one-inch tooth. Then it was disturbed with a shovel by displacing the soil from one place to the other. To get a uniform fine particle, the fork was used which left the soil with narrow ridges on the surface. Later the scraper was run to level the surface of the soil. After the scraper, the packer was run twice over the soil to pack it to the desired conditions. After the packer, the scraper was run again to scrape the high spots (if any existed). At this time the soil was ready for running the test. The desired speed was set by the speed reducer, and then the tool was mounted on the tool cart at the desired depth. After each run the tool was moved along the width of the box to a new position for another run until the entire width of the box was used. To start another set of runs, the above mentioned procedure was followed to prepare the soil for the test.

Results

Three kinds of soil material were used in the experiment: washed fine sand with zero percent clay, 16.78 percent and 22.52 percent clay.

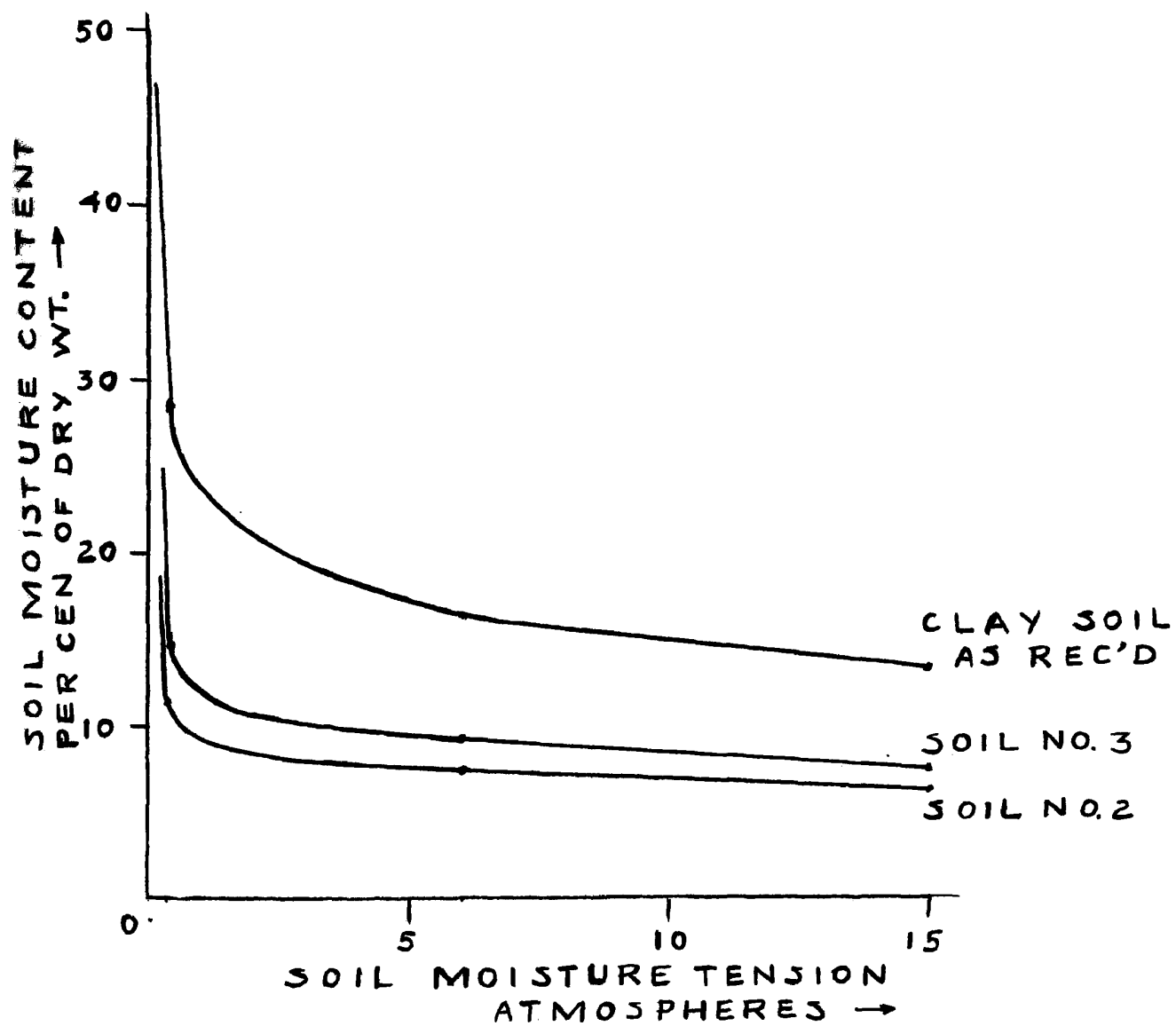


Fig. 16. Moisture Release Curve For The Experimental Soils.

TABLE V

SOME PHYSICAL PROPERTIES OF EXPERIMENTAL SOILS USED FOR THE LABORATORY TESTS

	Clay Soil as Received	Experimental Soil No. 3	Experimental Soil No. 2	Experimental Soil No. 1
Mechanical analysis percent				
Above 2 m.m.	.2	.4	.5	.7
2 - .053 "	25.2	57.1	68.5	99.
.053 - .002 "	35.2	20.	14.3	.3
Below .002 "	39.4	22.5	16.7	--
Atterberg's Constants				
Upper plastic limit	44.1	22.4	19.2	--
Lower plastic limit	25.1	15.7	13.8	--
Plastic number	19.	6.7	5.4	--
Maximum water holding capacity percent	61.8	41.7	38.	
Moisture equivalent percent	28.3	14.8	11.8	
Moisture at 6 atmospheres percent*	16.4	9.3	7.5	
Moisture at 15 atmospheres percent*	13.5	7.6	6.1	
Soil moisture at air dryness percent	1.56	.96	.64	

* The pressure membrane apparatus of Richards was used.

A higher clay percentage soil was also tried but because of difficulty of handling (easy puddling) the test was discontinued.

The mechanical analysis (7) of the soil was:

Particle size	Percentage
2 - .053 m.m.	31.3
.053 - .002 m.m.	34.1
below .002 m.m.	34.6

Four speeds of tool movement were selected and used throughout the experiment.

	r.p.m. of the drum	feet/min	miles/hour
1)	58	53.1	.604
2)	90	82.5	.938
3)	125	114.5	1.275
4)	170	155.5	1.77

With the limited selection of speed reducer, dynamometer scale, and the length of box, a higher speed was not practical.

The packing force was provided by adding pieces of channel beams, each weighing nine pounds. The three sets of weights were 36, 54, and 79 pounds; in the case of sand, one 18-pound packing force was used.

The moisture percentage could not be controlled as closely as the other factors. To obtain a particular moisture percentage the method of trial and error was used. After some experience the approximate amount of water necessary to bring a soil to a definite moisture content could be estimated.

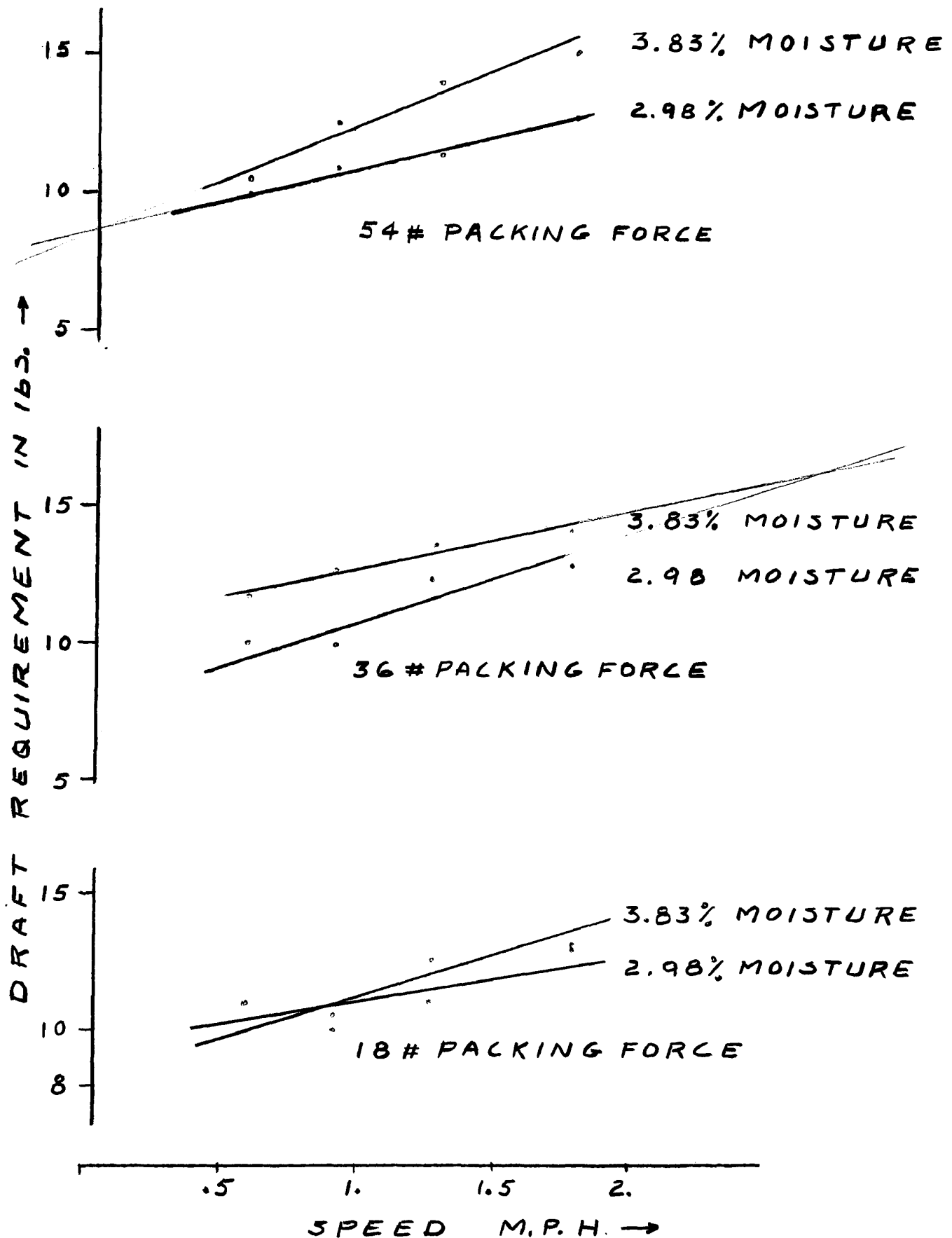


Fig. 17. Speed versus draft requirement of a one-inch tooth in soil No. 1 (99 percent silt) with two different moisture percents, three packing forces, at 4-inch depth.

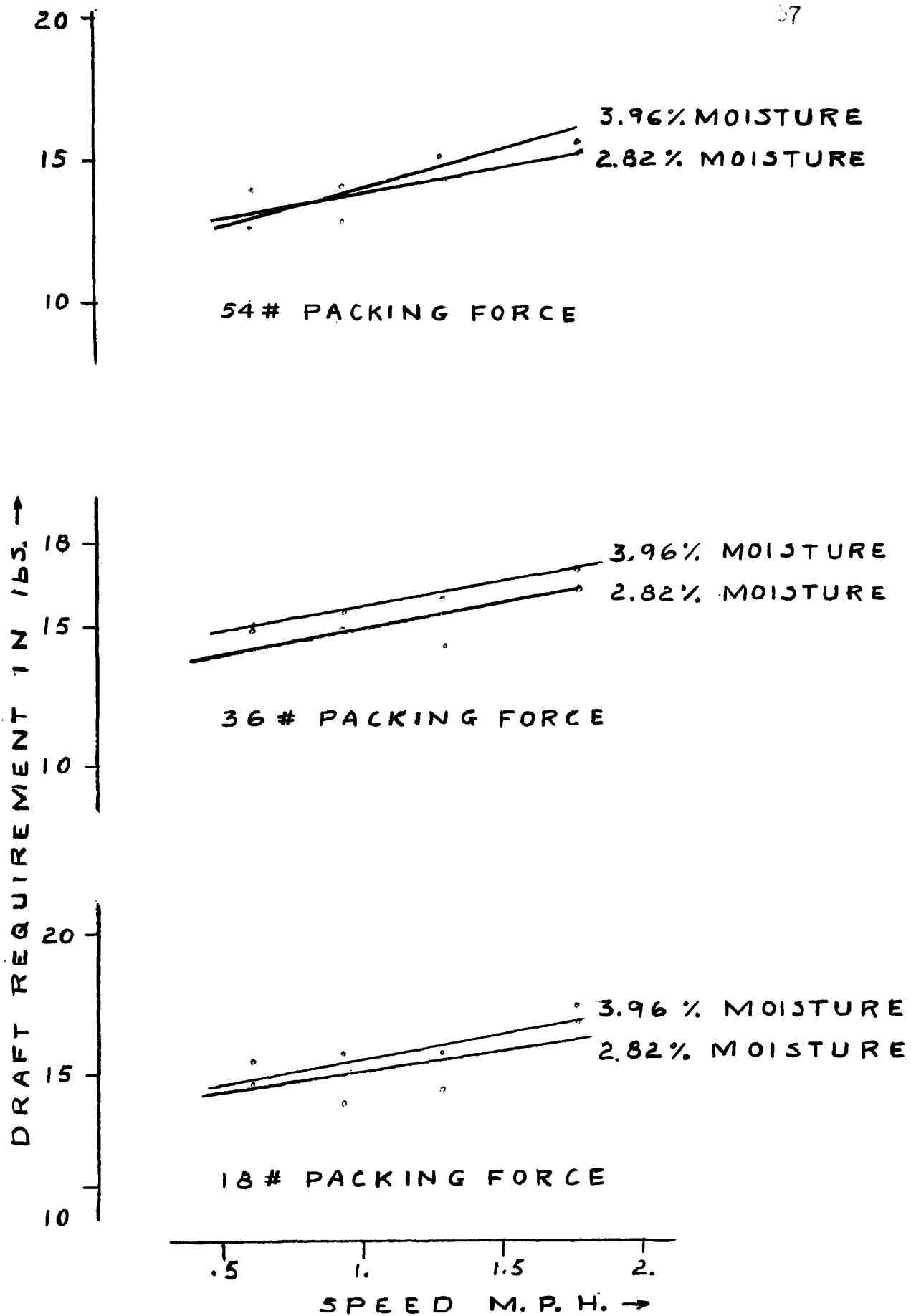


Fig. 18. Speed versus draft requirement of a four-inch plow in soil No. 1 (99 percent silt) with two different moisture percents, three packing forces, at 2.5 inch depth.

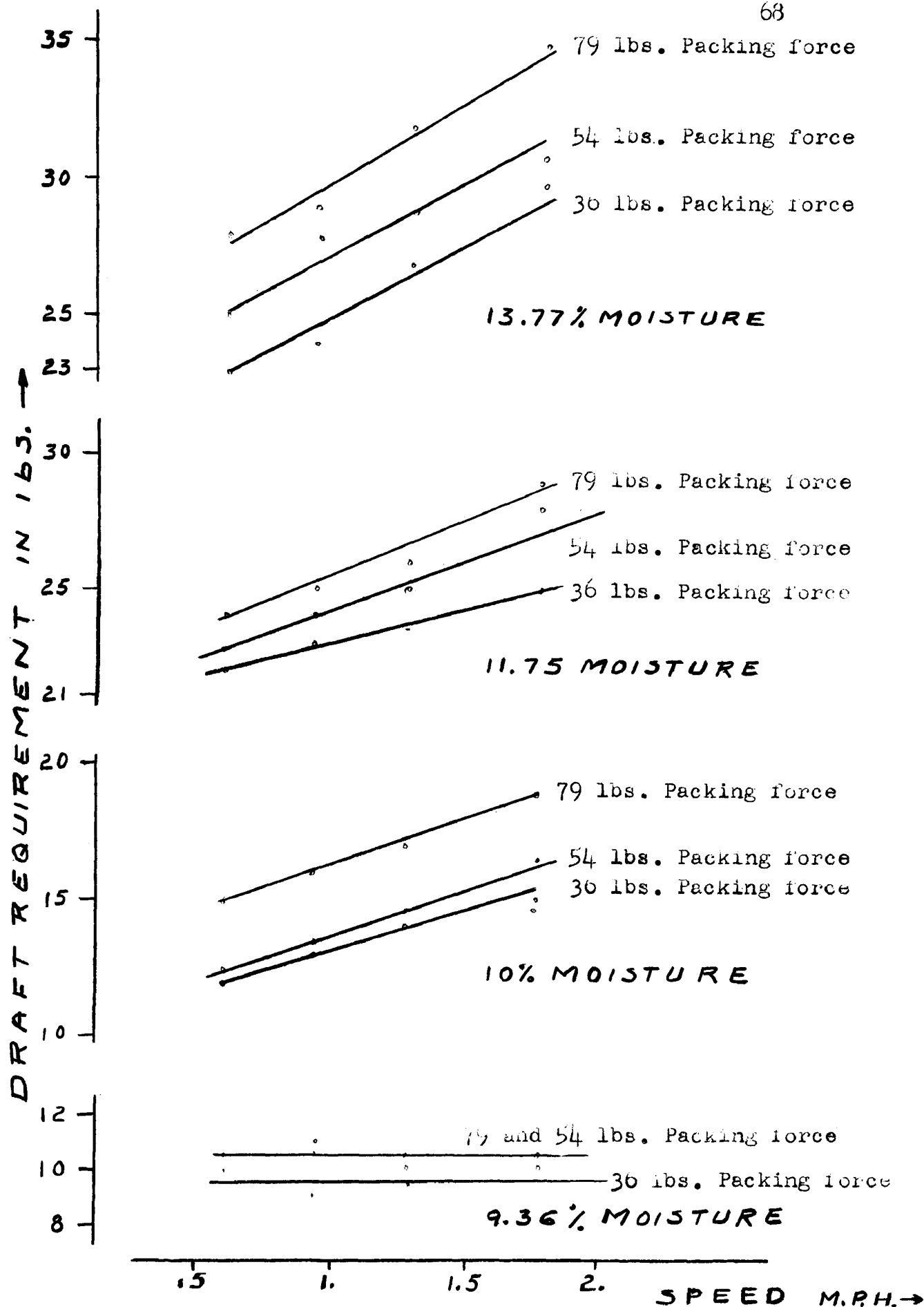


Fig. 19. Speed versus draft requirement of a one-inch tooth in soil No. 2 (10.7 percent clay) with four different moisture percents, three packing forces, at 4-inch depth.

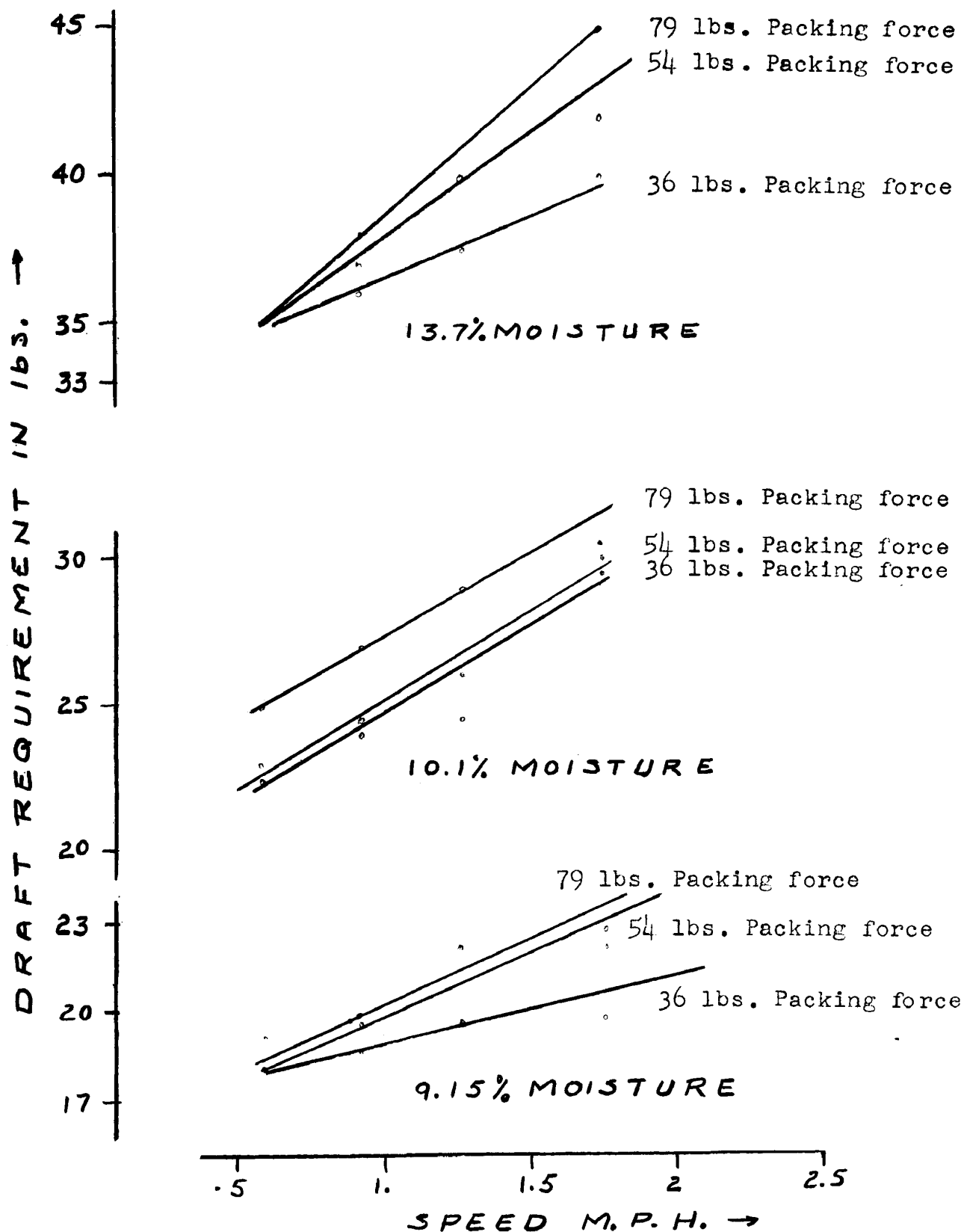


Fig. 20. Speed versus draft requirement of a four-inch plow in soil No. 2 (16.7 percent clay) with three different moisture percents, three packing forces, at 2.5-inch depth.

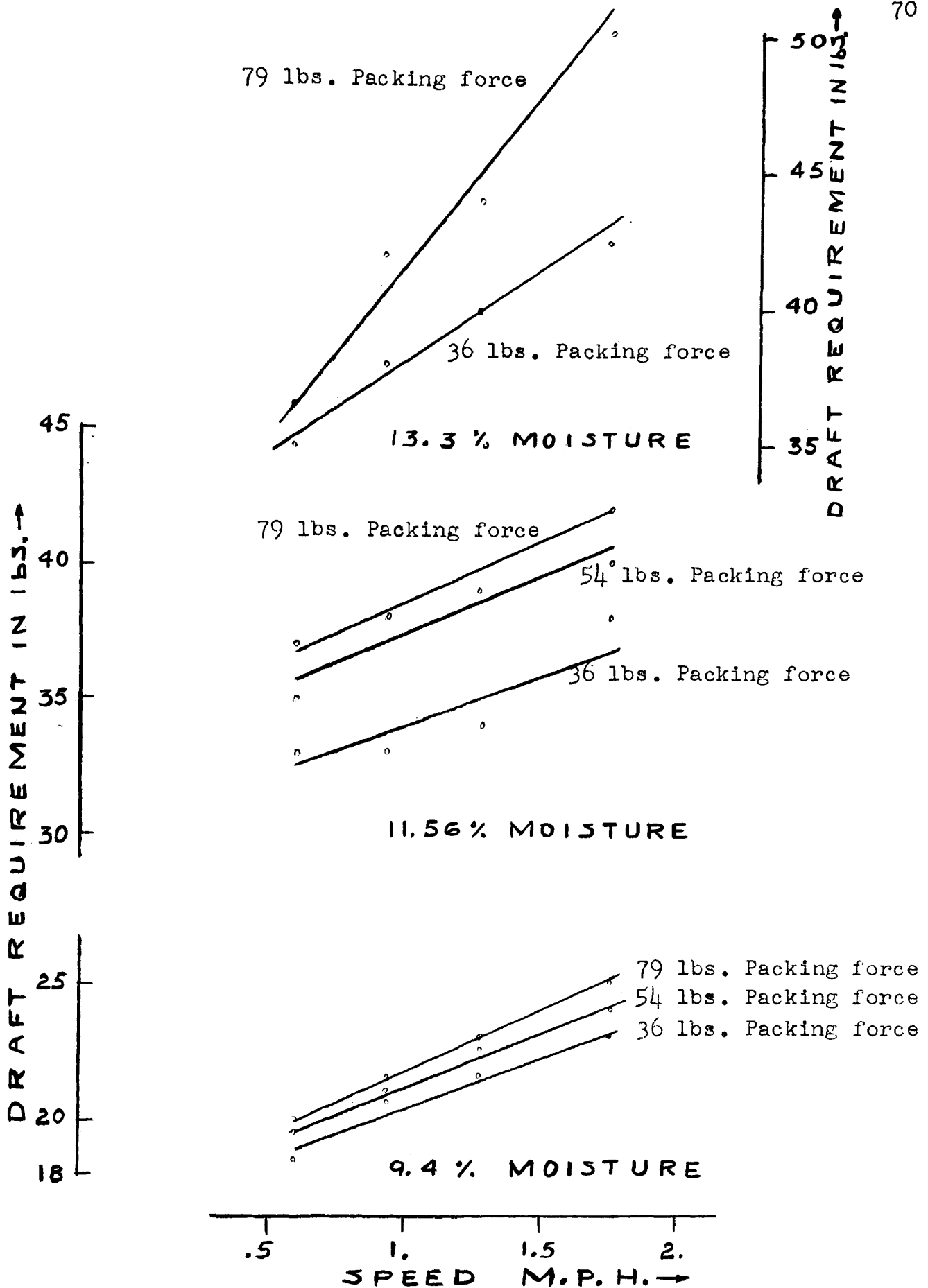


Fig. 21. Speed versus draft requirement of a 2.5-inch tooth in soil No. 2 (16.7 percent clay) with three different moisture percents, three packing forces, at 4-inch depth.

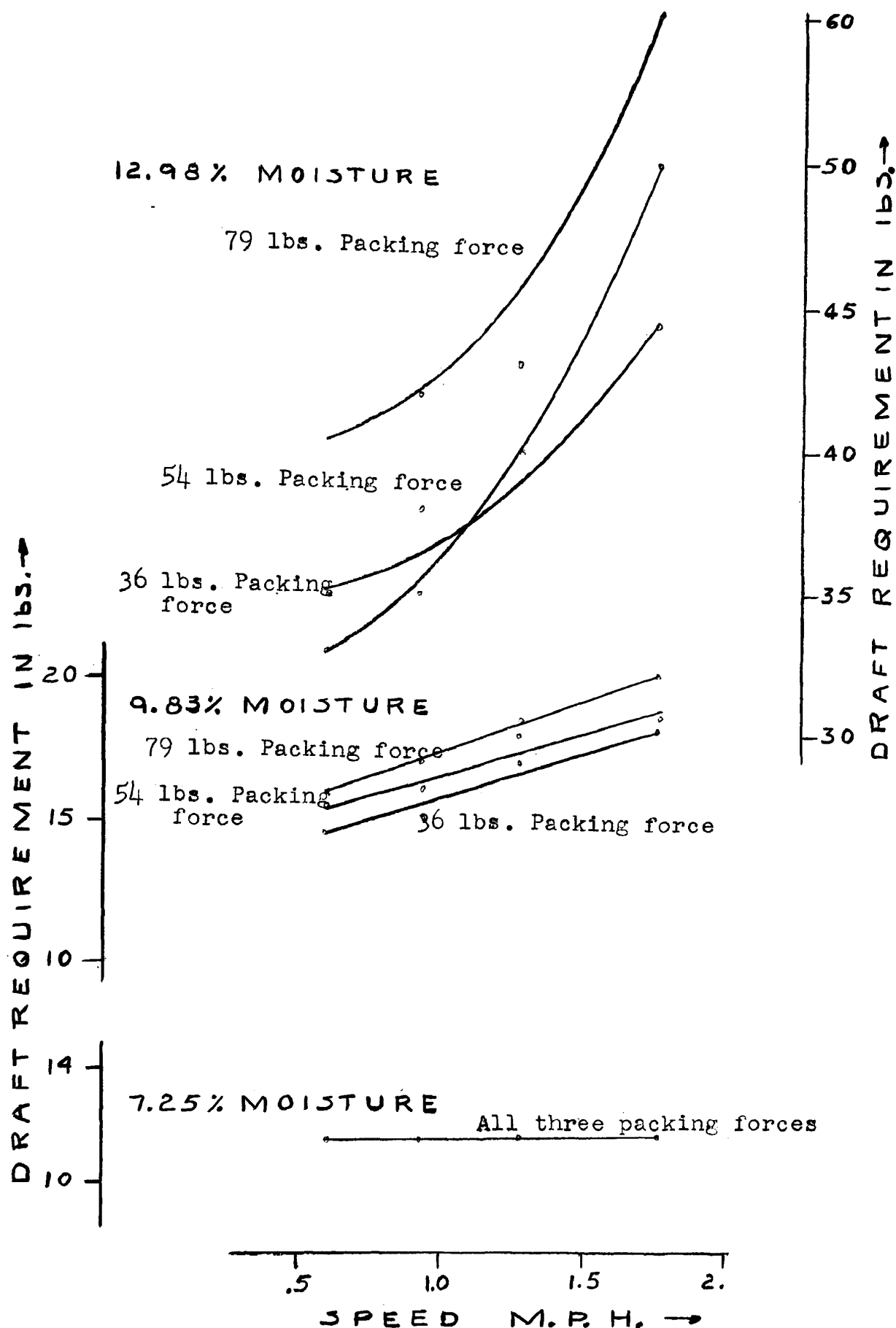


Fig. 22. Speed versus draft requirement of a one-inch tooth in soil No. 3 (22.5 percent clay) with three different moisture percents, three packing forces, at 4-inch depth.

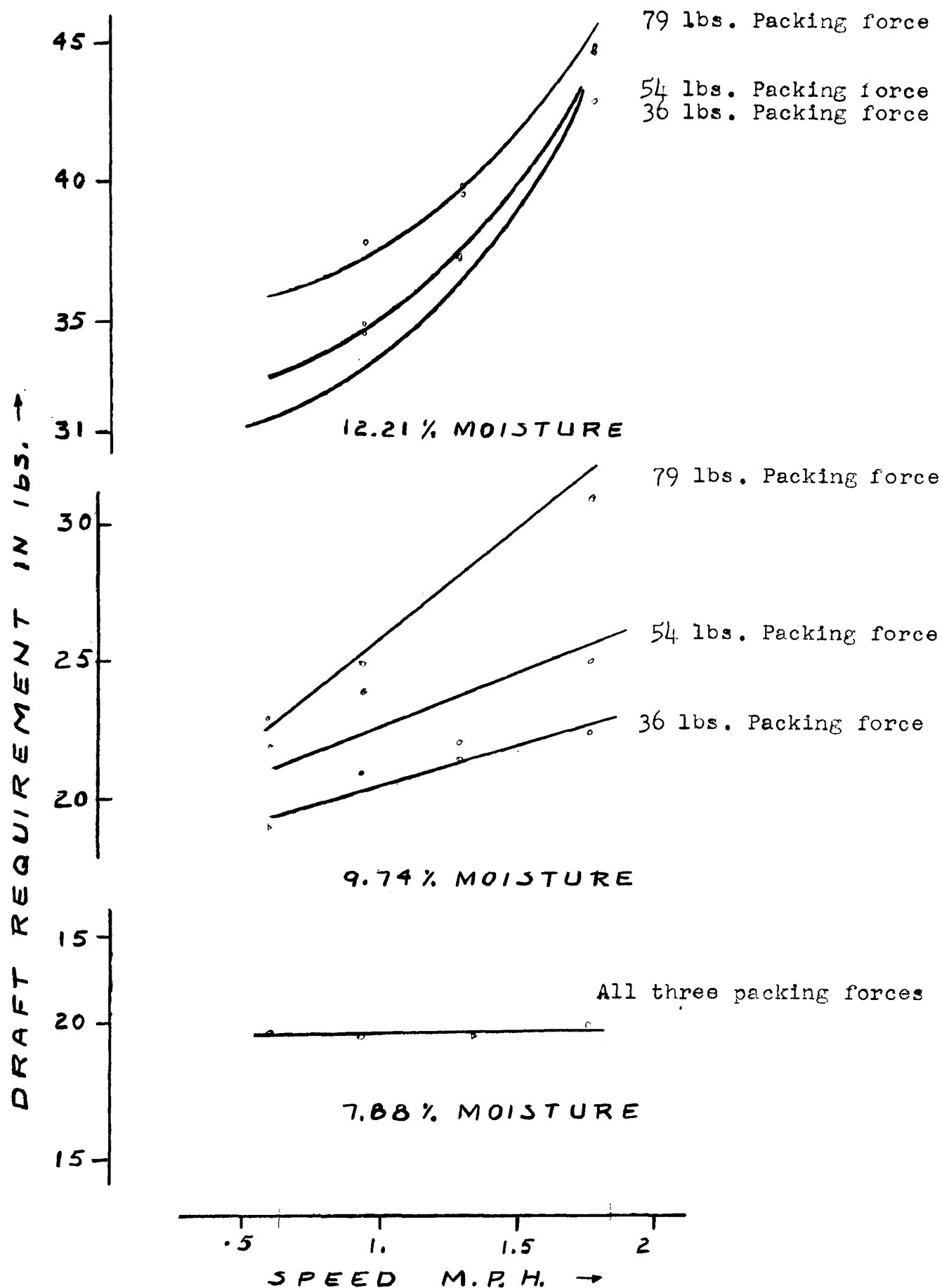


Fig. 23. Speed versus draft requirement of a four-inch plow in soil No. 3 (22.5 percent clay) with three different moisture percents, three packing forces, at 2.5 inch depth.

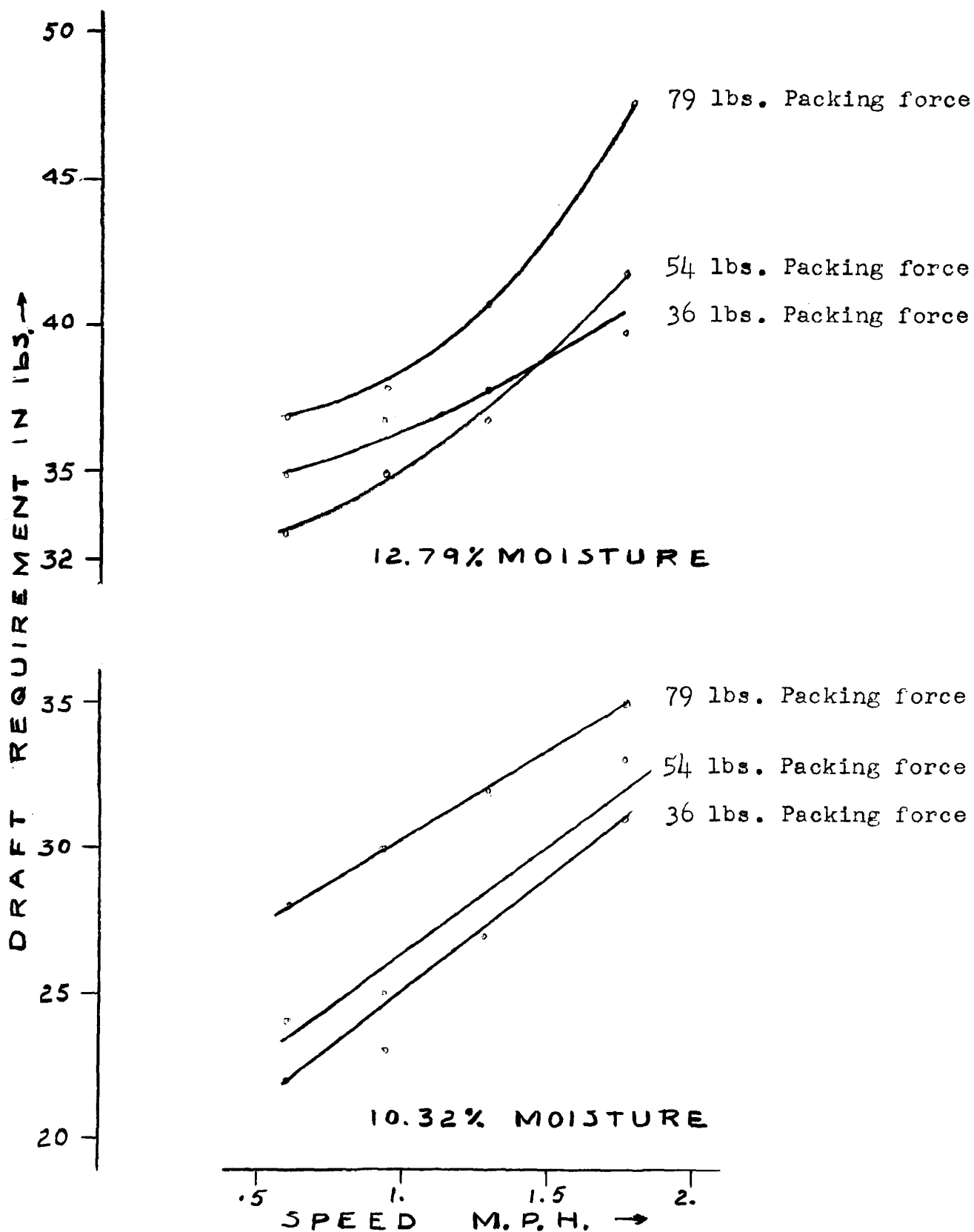


Fig. 24. Speed versus draft requirement of a 2.5-inch tooth in soil No. 3 (22.5 percent clay) with two different moisture percents, three packing forces, at 4-inch depth.

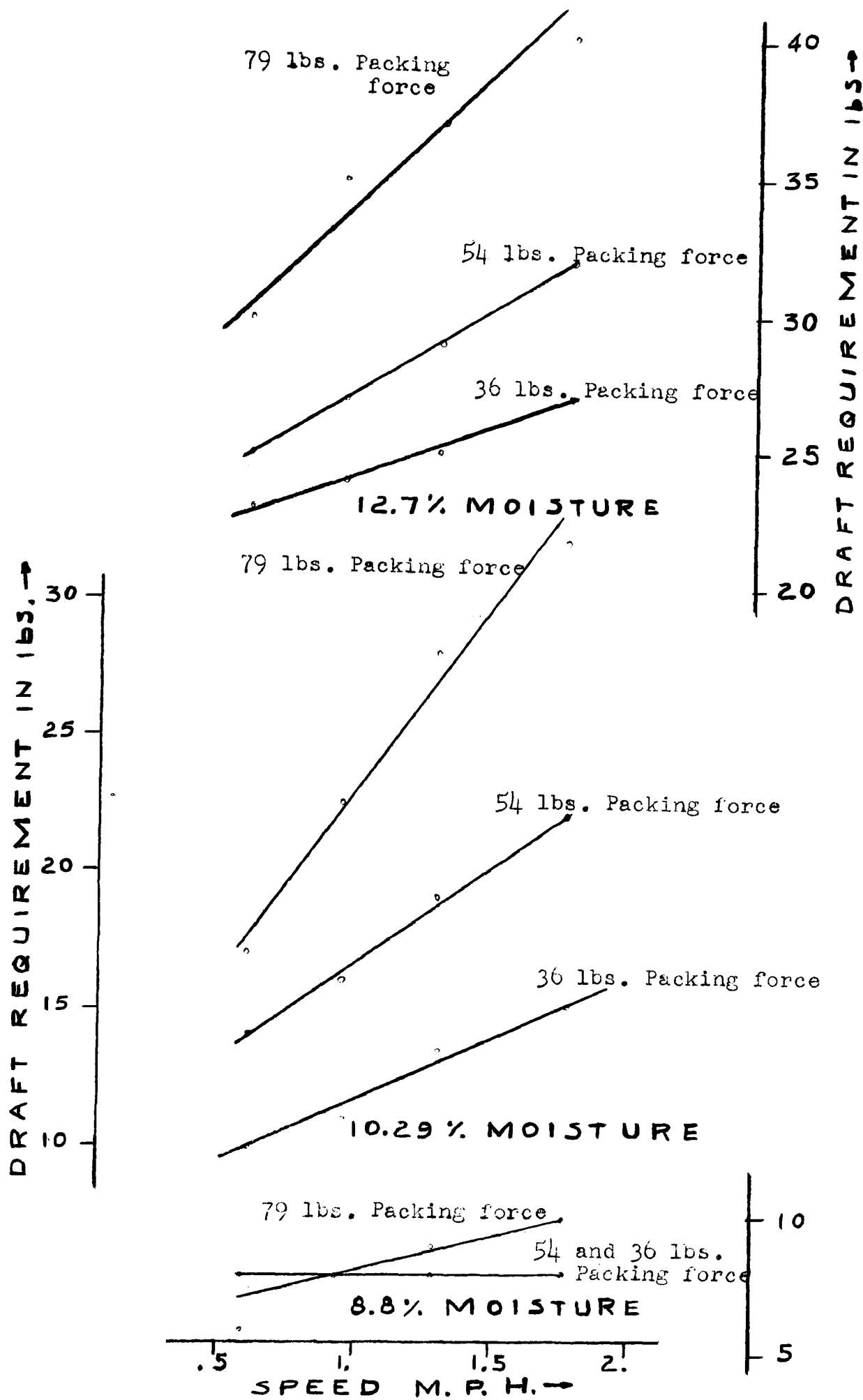


Fig. 25. Speed versus draft requirement of a seven-inch disk in soil No. 3 (22.5 percent clay) with three different moisture percents, three packing forces, at 2.5-inch depth.

With each soil mixture experiments were run for three different soil moisture contents. With each moisture content, three different packing forces of soil were selected to be tested. Four different speeds of the tools were run with each packing force of the soil. In this way a total of 108 readings were recorded with each implement, except in the case of sand where it was not necessary. The results are recorded and given in Tables 6 through 30, Appendix.

Conclusions

In general the results obtained were largely qualitative rather than quantitative. The readings of the scale in higher speeds and loads were not very accurate because of the vibration of the dynamometer needle. A hydraulic type dynamometer with a recording system would work better than the present spring dynamometer. Also, to get more accurate results more tests with different clay and moisture content were necessary. This, however, because of time and fund limitations, was not possible.

The introduction of the theory of "models and similarity" and its application to the soil box and miniature implements, to be discussed later, not only will prove the validity of these tests, but also will encourage the use of small laboratory methods in tillage problems.

The effect of speed. The general equation of $y = ax^b / c$ can represent the relationship between the speed and the draft requirement of tillage tools.

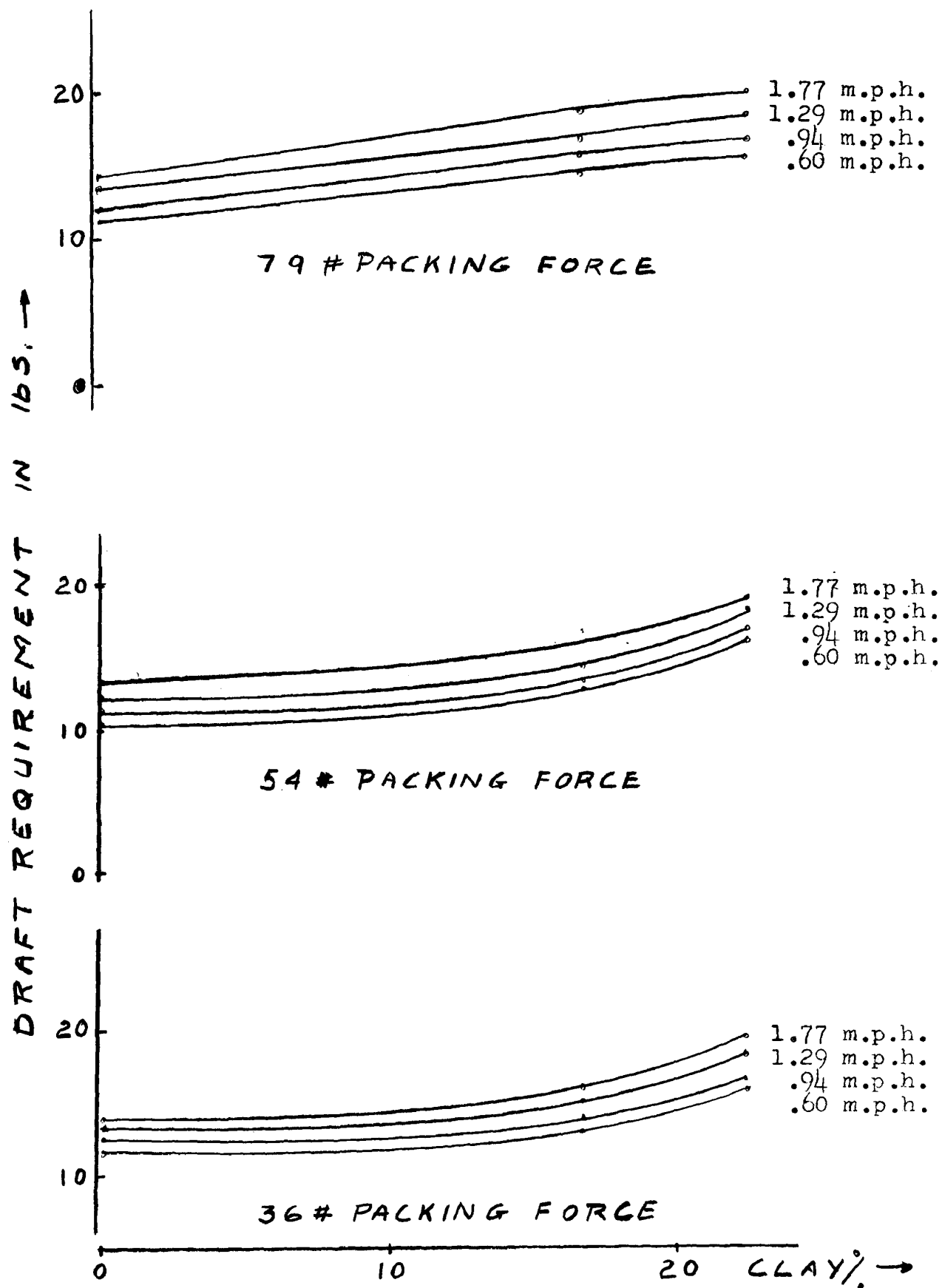


Fig. 26. Percent clay versus draft requirement of a one-inch tooth with 10 percent moisture, four speeds, and three packing forces, at 4-inch depth.

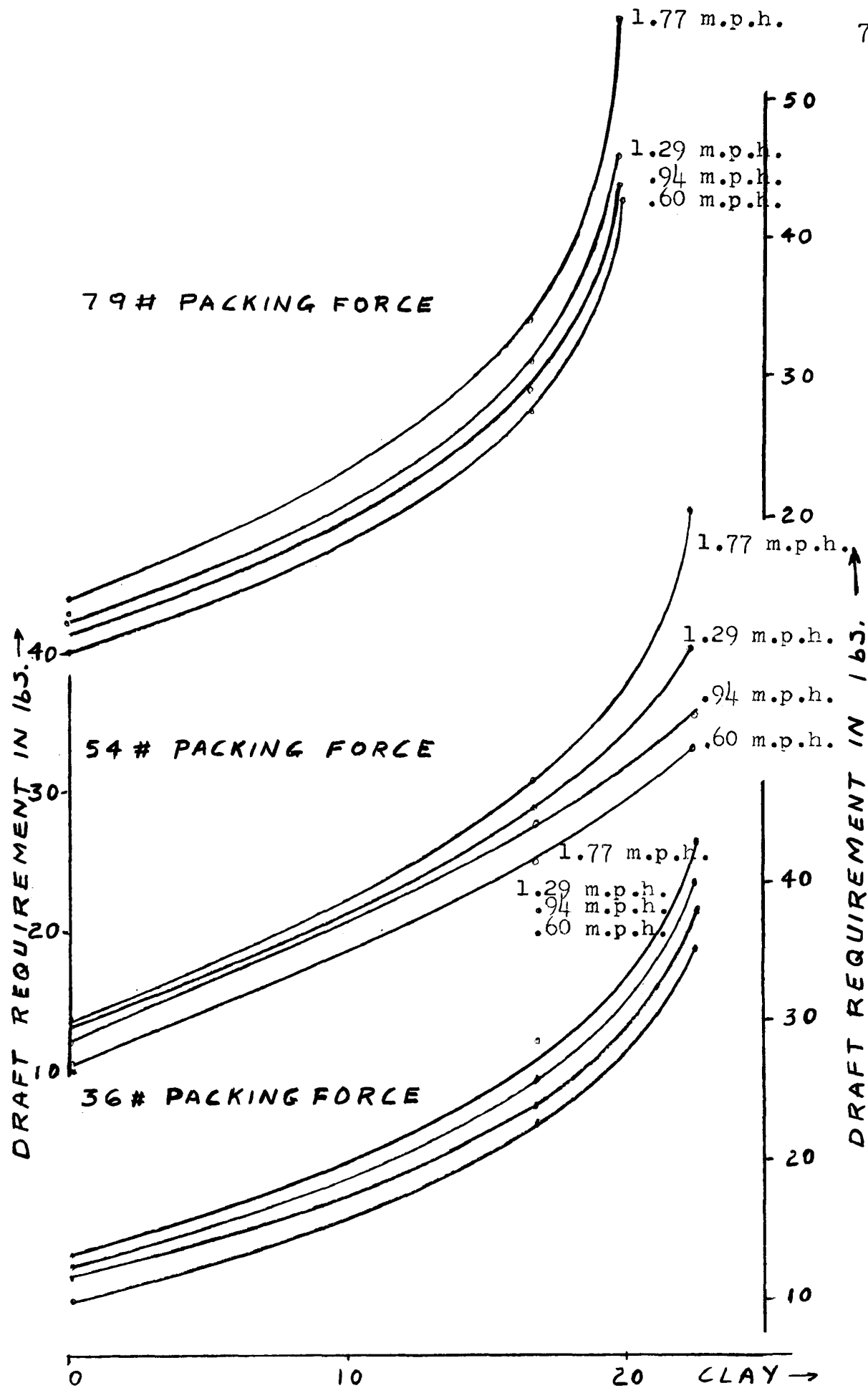


Fig. 27. Percent clay versus draft requirement of a one-inch tooth with 13 percent soil moisture, four speeds, three packing forces, at 4-inch depth.

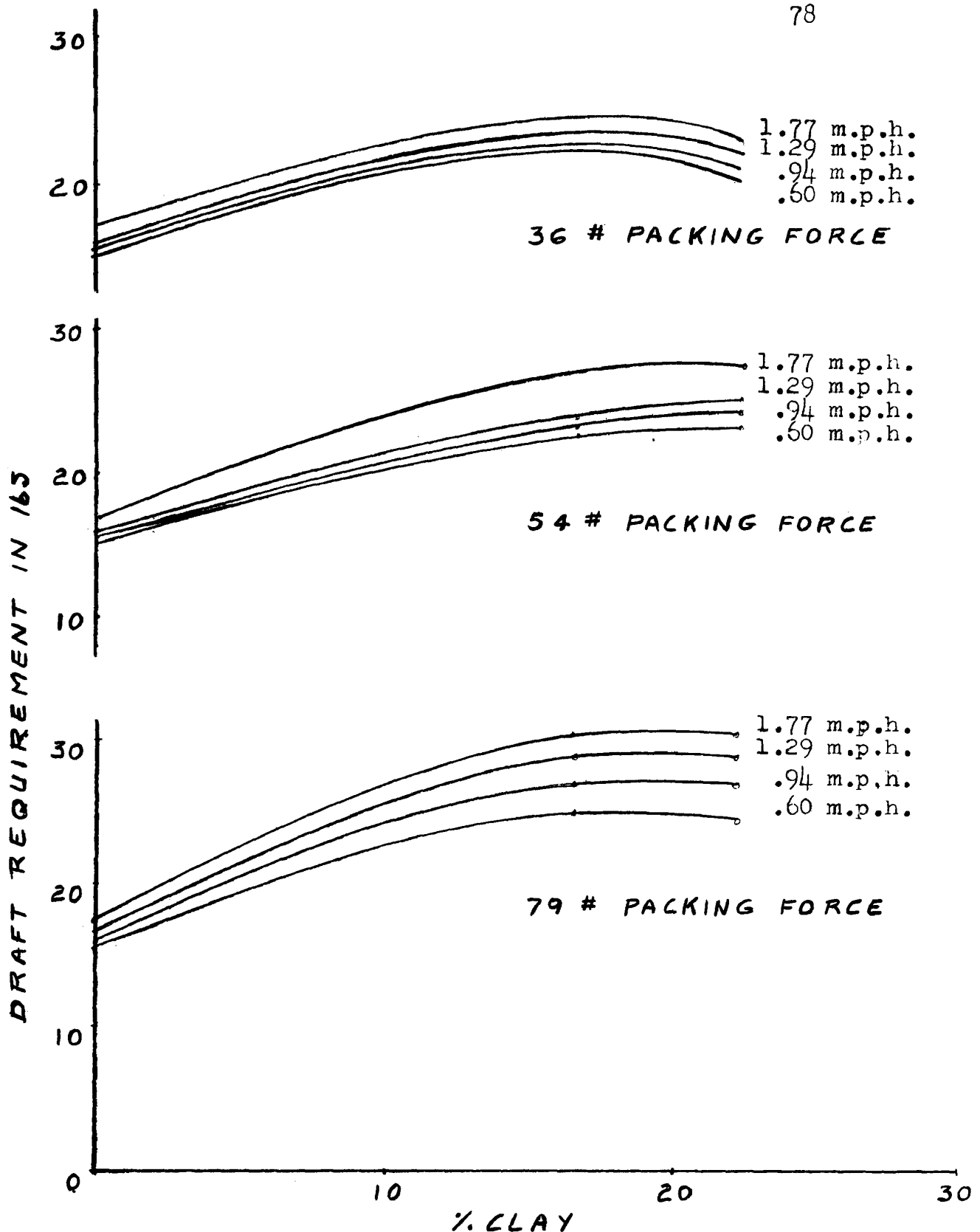


Fig. 28. Percent of clay versus draft requirement of a four-inch plow with 10 percent soil moisture, four speeds, three packing forces, at 2.5-inch depth.

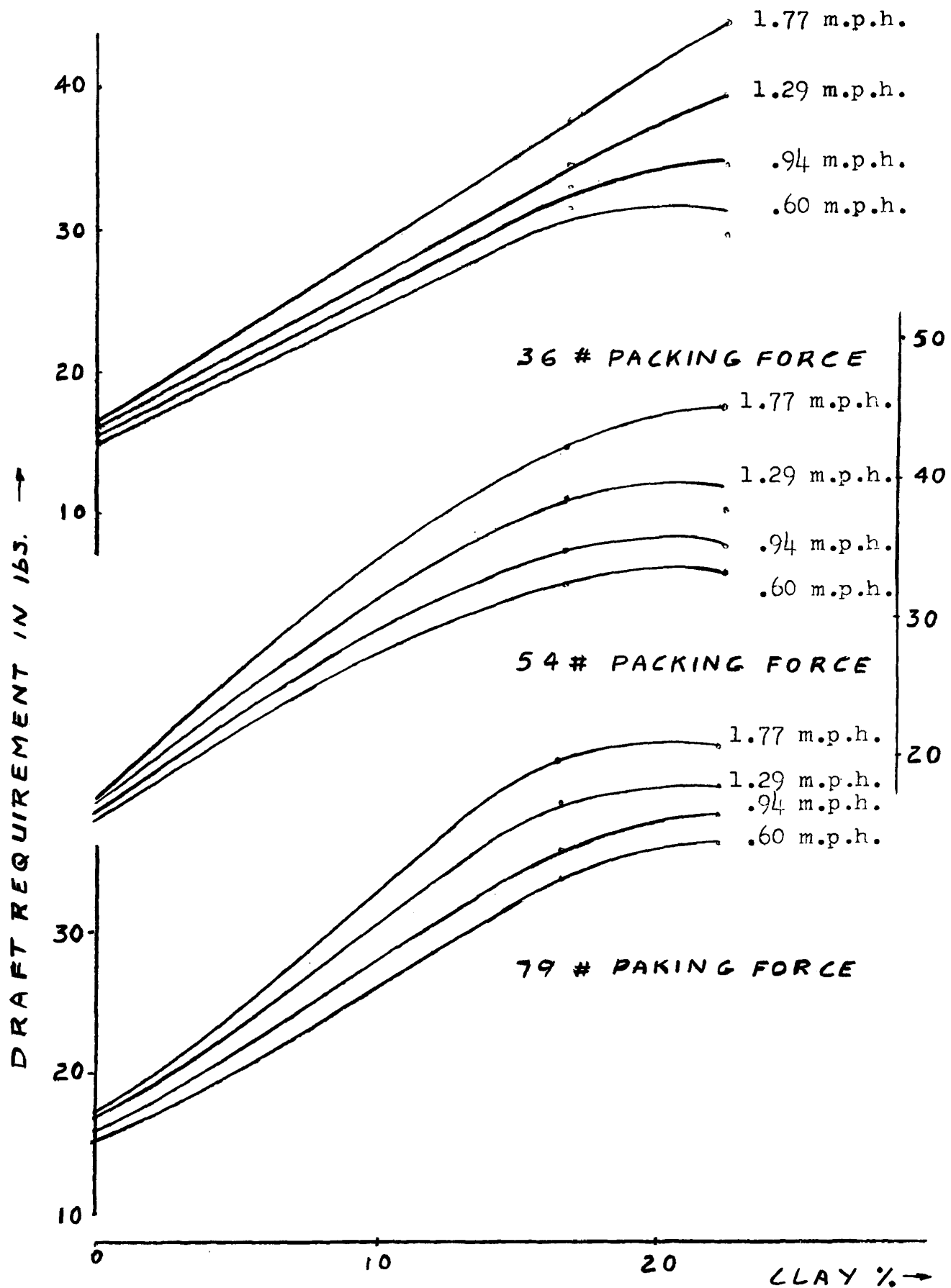


Fig. 29. Percent clay versus draft requirement of a four-inch plow with 12.2 percent soil moisture, four speeds, three packing forces, at 2.5-inch depth.

As the curves of draft versus speed indicate, this relationship is an almost horizontal line in sandy soil and in any other types of soil that have low moisture content and where the effect of cementation has been eliminated. The maximum moisture content at which the speed does not have appreciable effect is slightly above the wilting point, or moisture percent of almost 15 atmospheres. As the amount of moisture and clay increased, the slope of the line increased so that in very high clay and moisture contents the relationship changed from a straight line to a curve. This change can be shown in the general equation of $y = ax^b / c$ by the different number given to b . For example, $b = 0$, y is a straight horizontal line, and for $b = 1$, this will be a straight line with variable slope.

Also the kind of implement seems to have an effect on the relationship between the speed and draft. For example, with a disk the curves show straight lines even at 22.6 percent clay and 12.7 percent moisture content. Probably the change of curve will occur in higher clay and moisture percentage.

Effect of clay content. By clay content is meant the percentage of particles that are smaller than two microns. Figures 26 through 29 show the effect of clay percentage on the draft requirement with constant moisture, speeds and packing force. As the shape of the curves indicates, the clay content has very little effect in low moisture percentage,

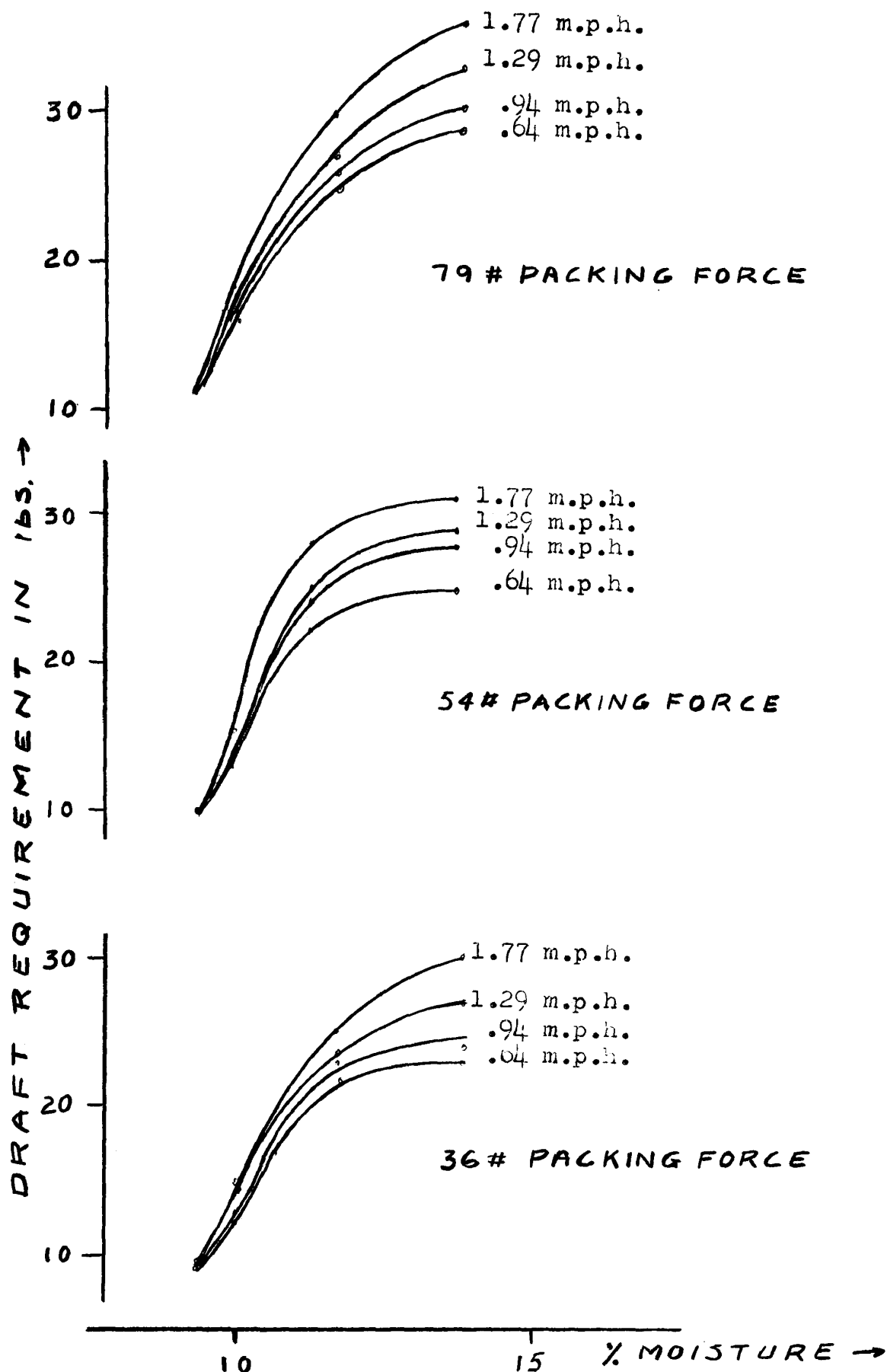


Fig. 30. Moisture percent versus draft requirement of a one-inch tooth in soil No. 2 (10.7 percent clay) with three packing forces, four speeds, at 4-inch depth.

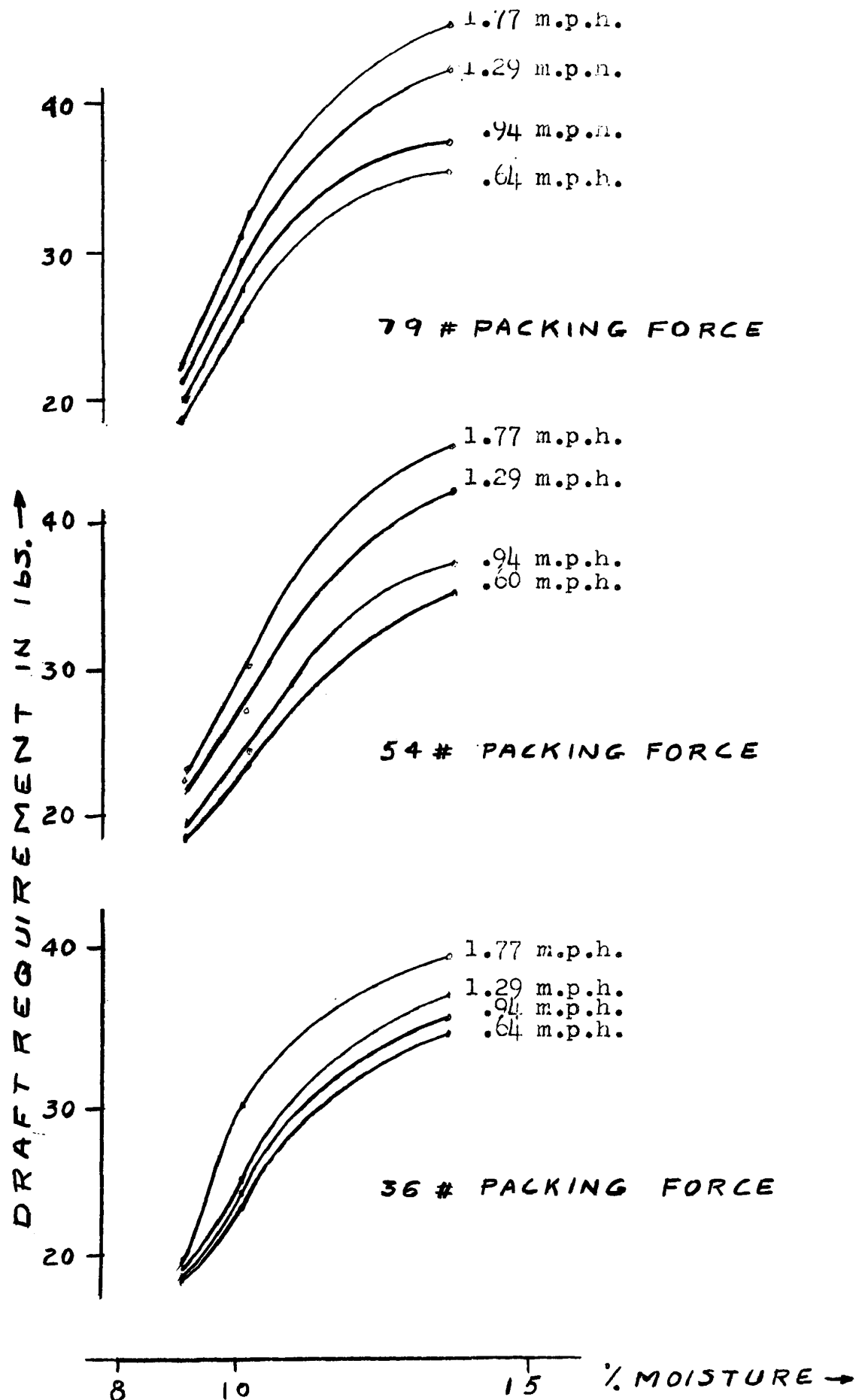


Fig. 31. Moisture percent versus draft requirement of a four-inch plow in soil No. 2 (16.7 percent clay) with three packing forces, four speeds, at 2.5-inch depth.

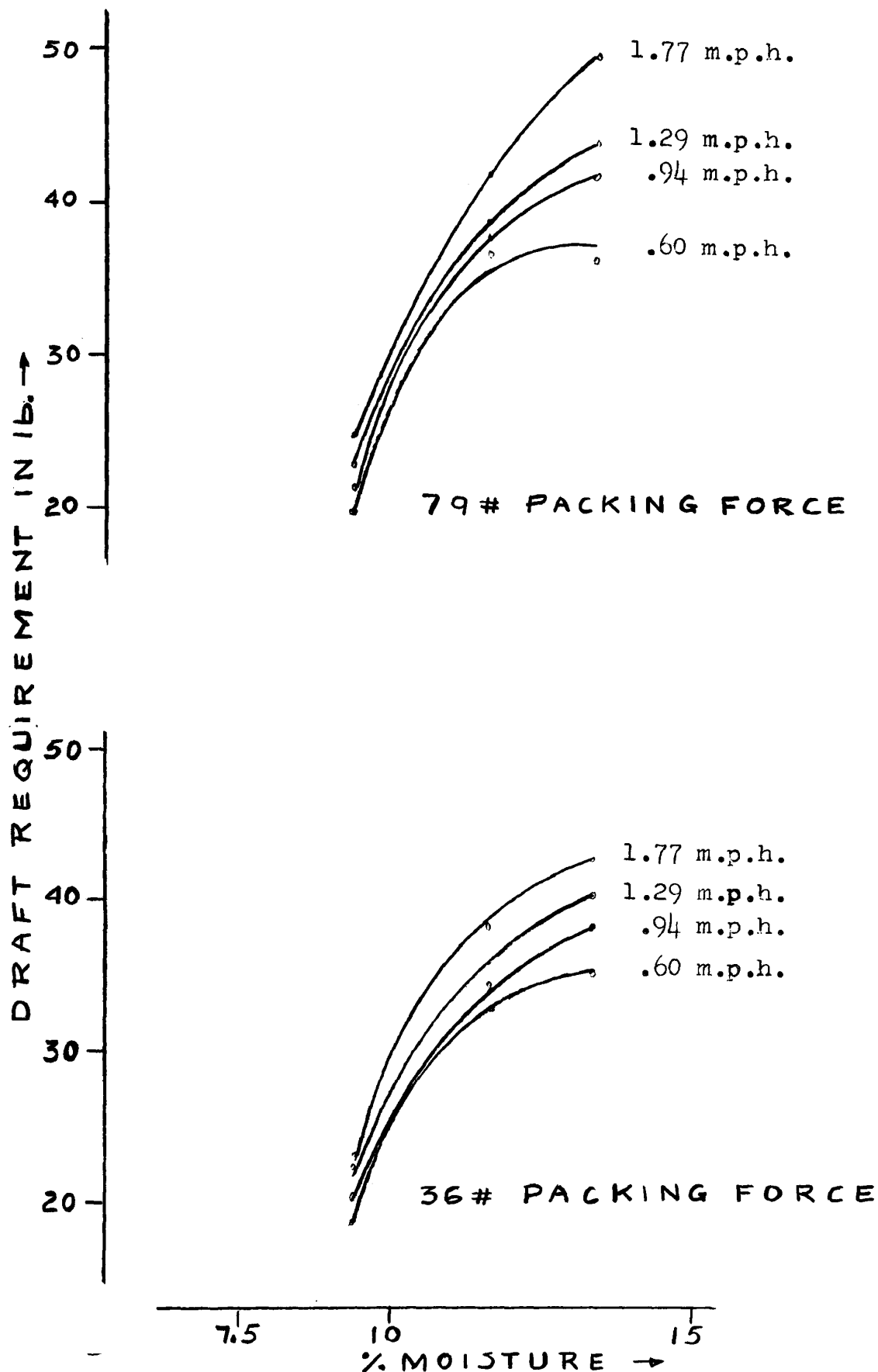


Fig. 32. Moisture percent versus draft requirement of a 2.5-inch tooth in soil No. 2 (16.7 percent clay) with two packing forces, four speeds, at 4-inch depth.

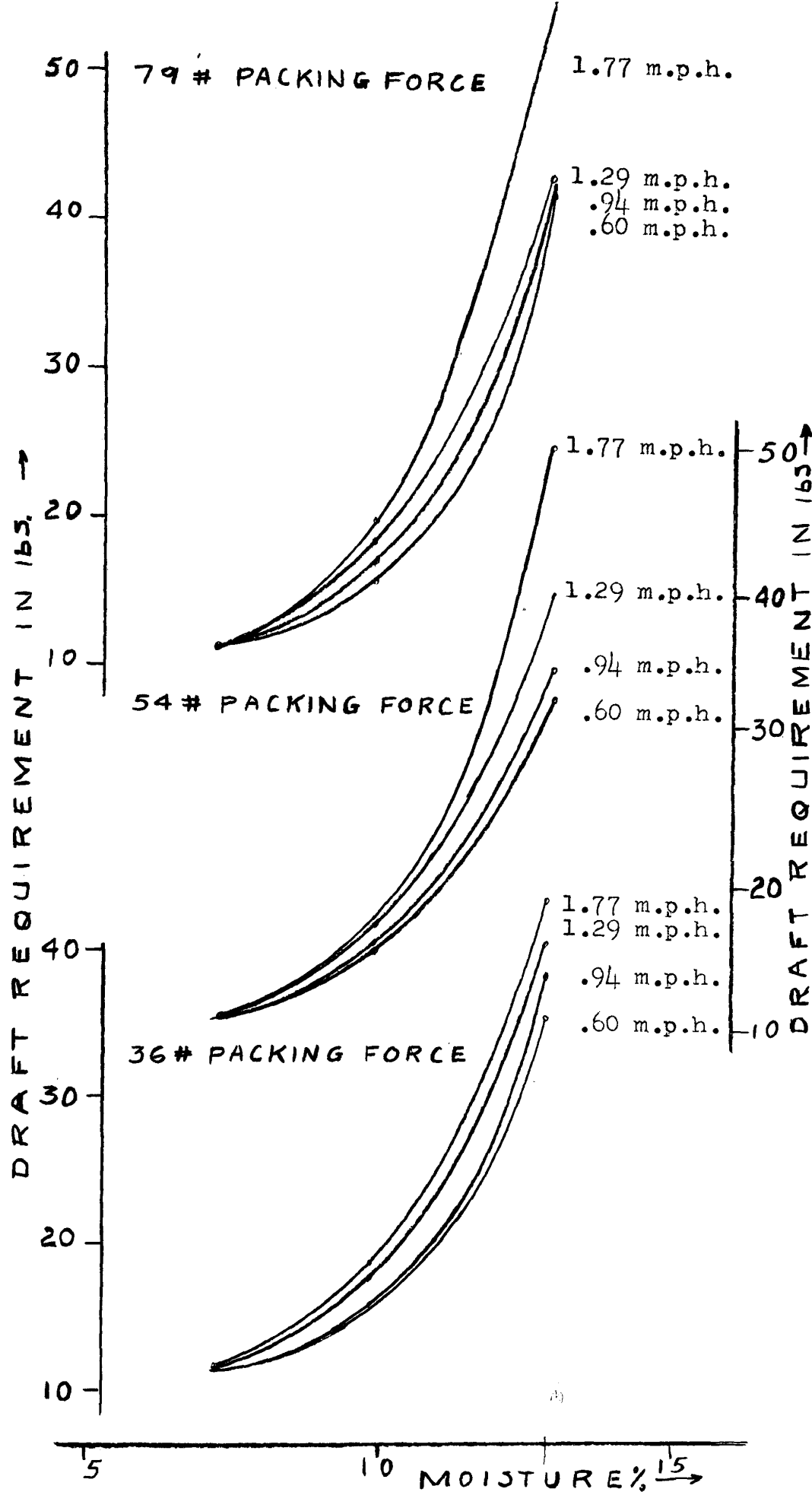


Fig. 33. Percent moisture versus draft requirement of a one-inch tooth in soil No. 3 (22.5 percent clay) with three packing forces, four speeds, at 4-inch depth.

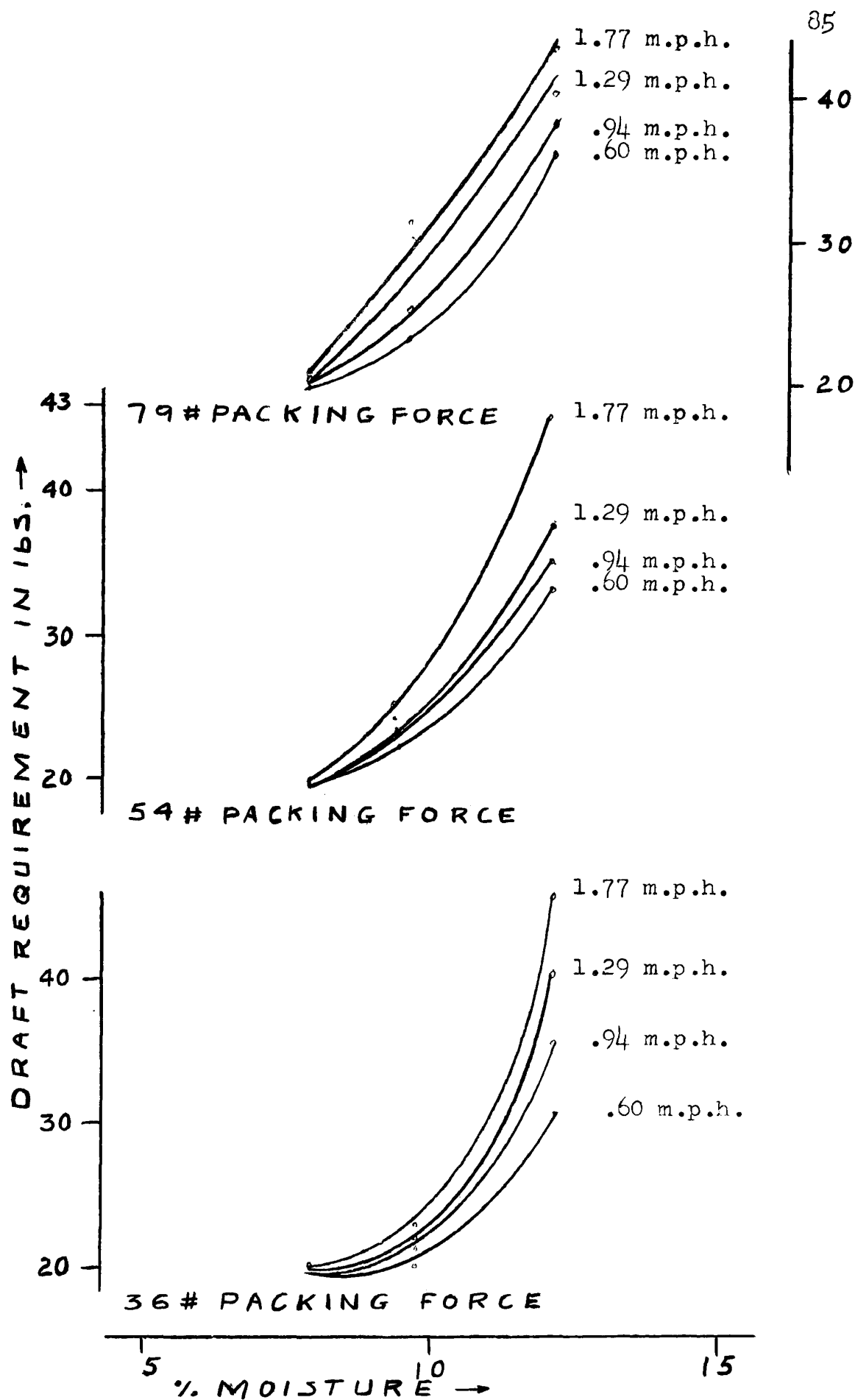


Fig. 34. Percent moisture versus draft requirement of a four-inch plow in soil No. 3 (22.5 percent clay) with three packing forces, four speeds, at 2.5-inch depth.

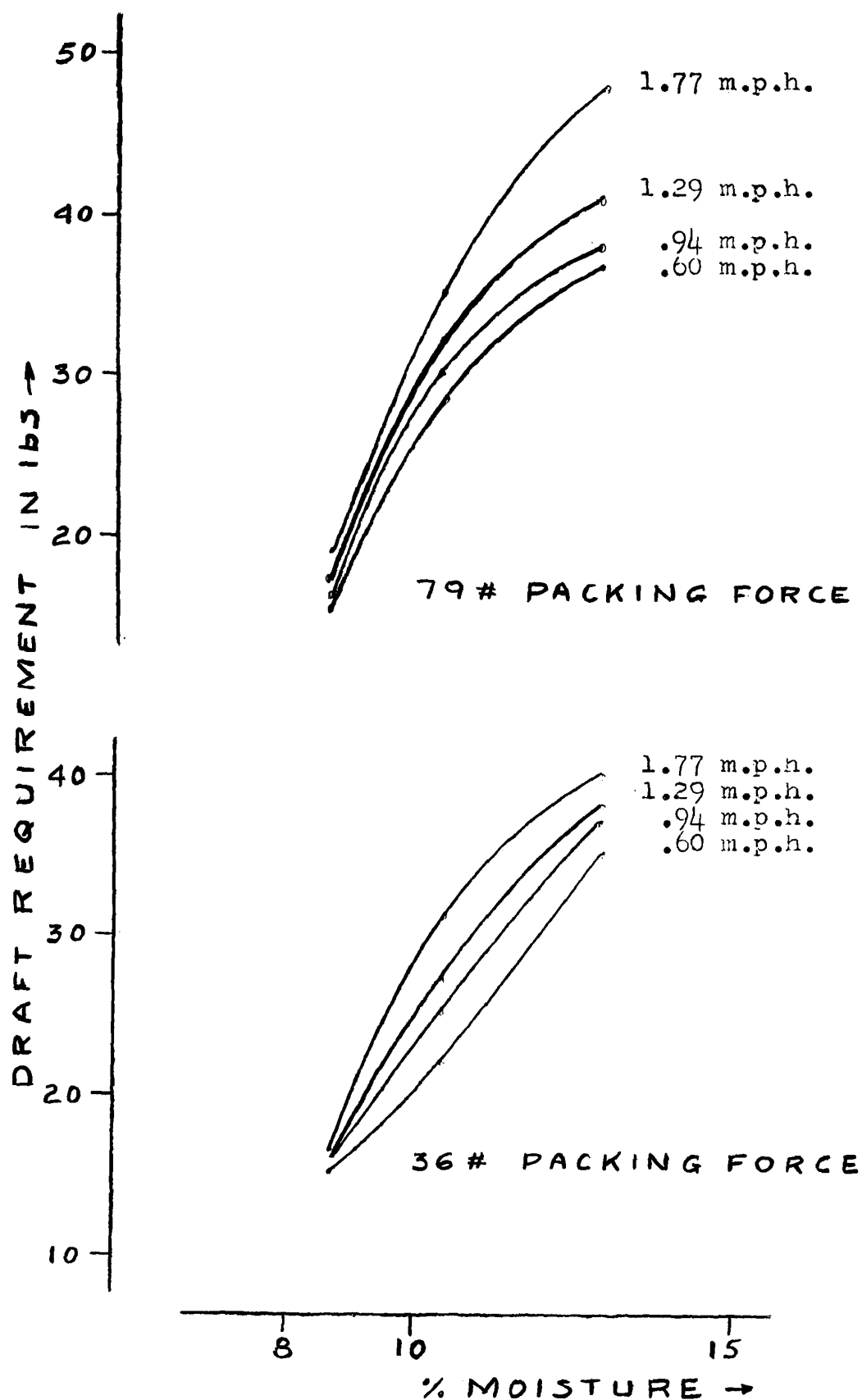


Fig. 35. Moisture percent versus draft requirement of a 2.5-inch tooth in soil No. 3 (22.5 percent clay) with two packing forces, four speeds, at 4-inch depth.

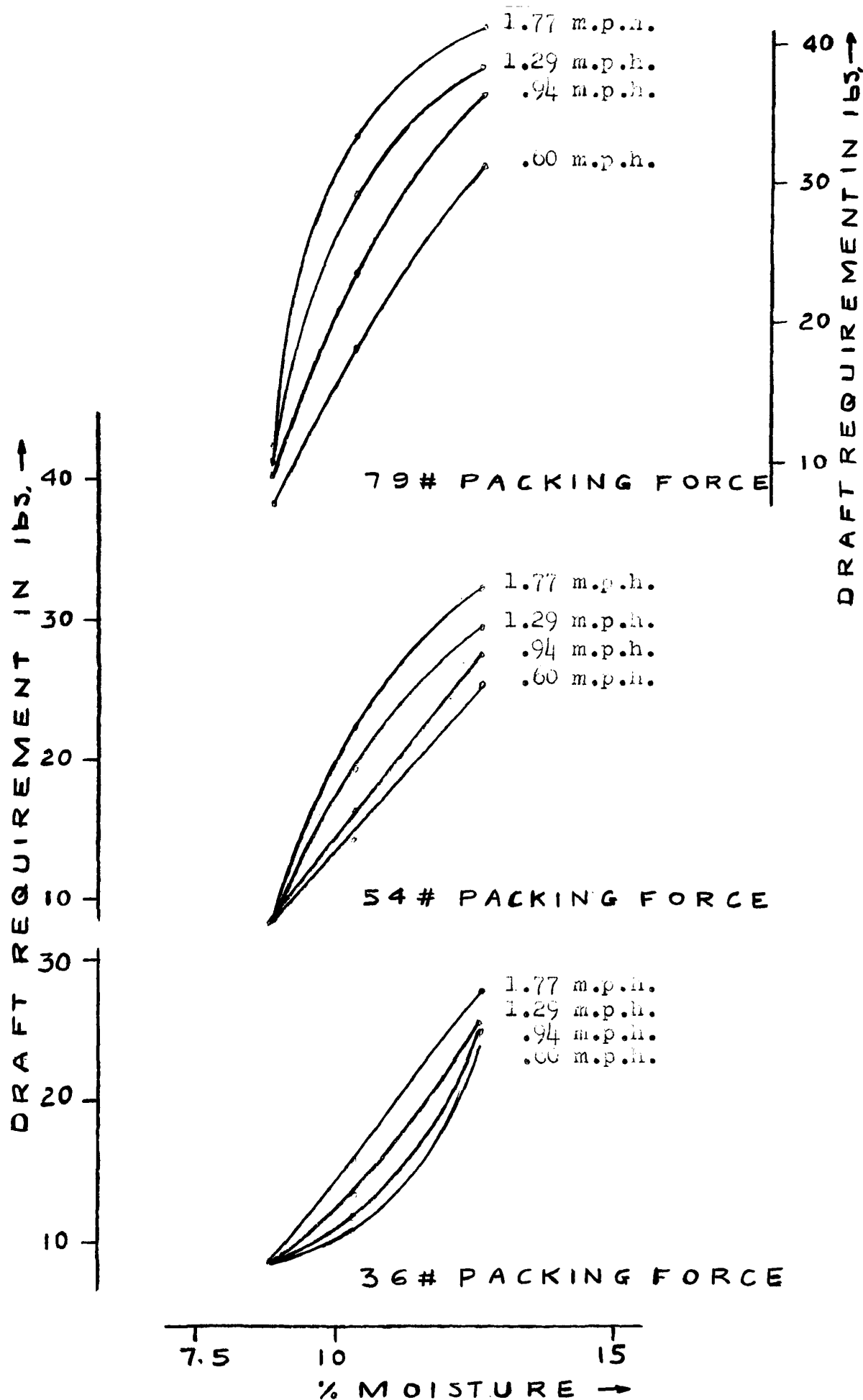


Fig. 36. Moisture percent versus draft requirement of a seven-inch disk in soil No. 3 (22.5 percent clay) with three packing forces, four speeds, at 2.5-inch depth.

but by increasing the moisture, the curves of draft versus clay rise rapidly. This increase will continue to a maximum which is around field capacity, and after that it will tend to a slight decline (refer to moisture curves). This is logical because the capillary activities of the clay particles will end at about moisture equivalent. Two sets of curves have been drawn for different implements under two different moisture contents. The above mentioned changes apply in all cases. The exact equation for the relationship between draft and clay content can not be given here because there were not enough points in the curve, but in general, they are of the type $y = ax^b / c$, where, in most cases, $c = 0$.

Effect of moisture. Moisture is one of the most important soil factors that have been observed in this experiment to affect the draft. However, in the sandy soil, because of the lack of effective soil particles, the change of moisture has little effect on the soil resistance, but by mixing some clay with it the effect of moisture was noticeable. In almost all cases the curves start with a sharp increase and then flatten around the moisture content of field capacity. The moisture equivalents for both clays have been indicated and can be noticed very distinctly on the curves. In higher clay contents, the increase of moisture caused a very bad puddling of the soil which made it difficult to work the soil. The limits of moisture variations within which soil

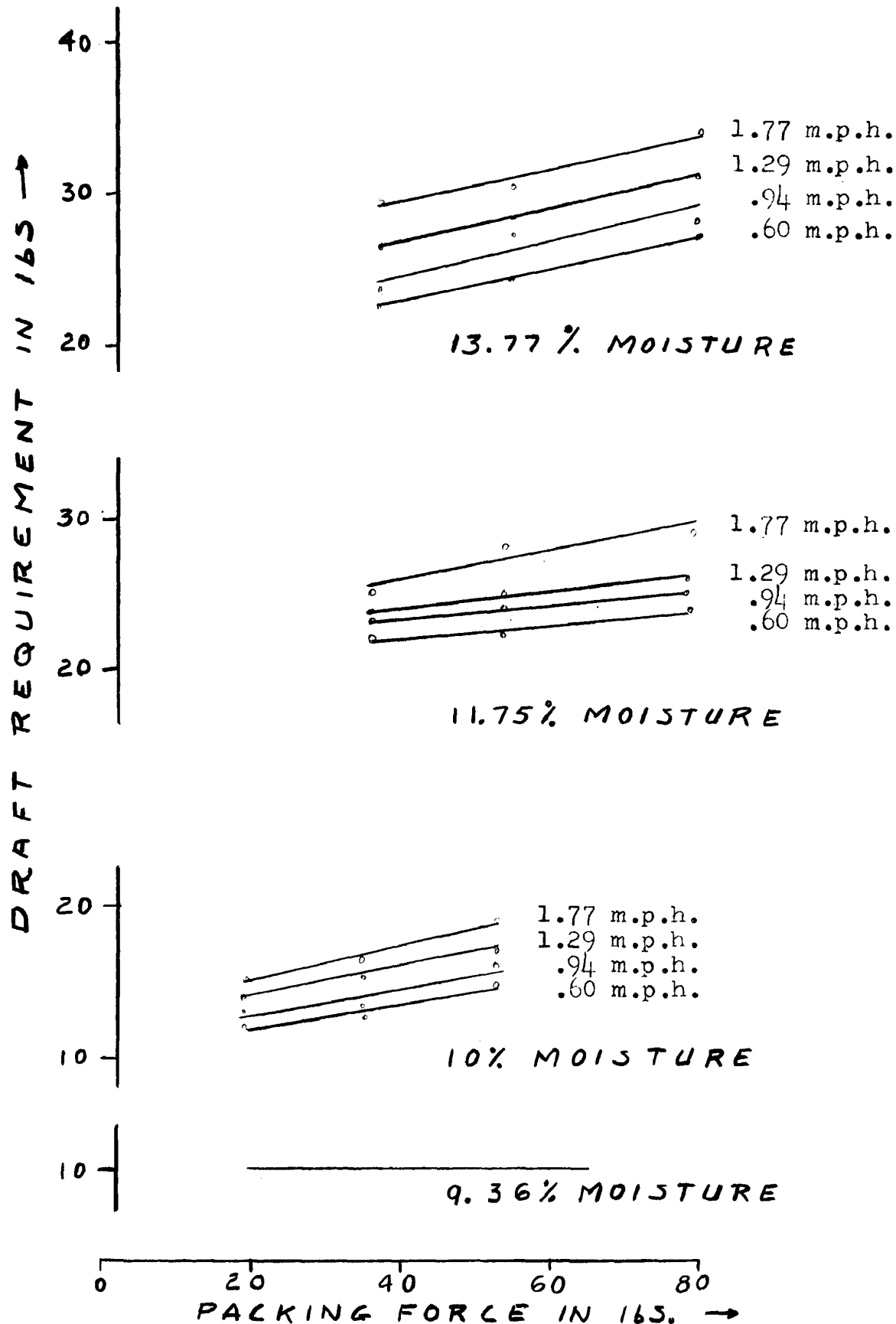


Fig. 37. Packing force versus draft requirement of one-inch tooth in soil No. 2 (16.7 percent clay) with four speeds, four different moisture percents, at 4-inch depth.

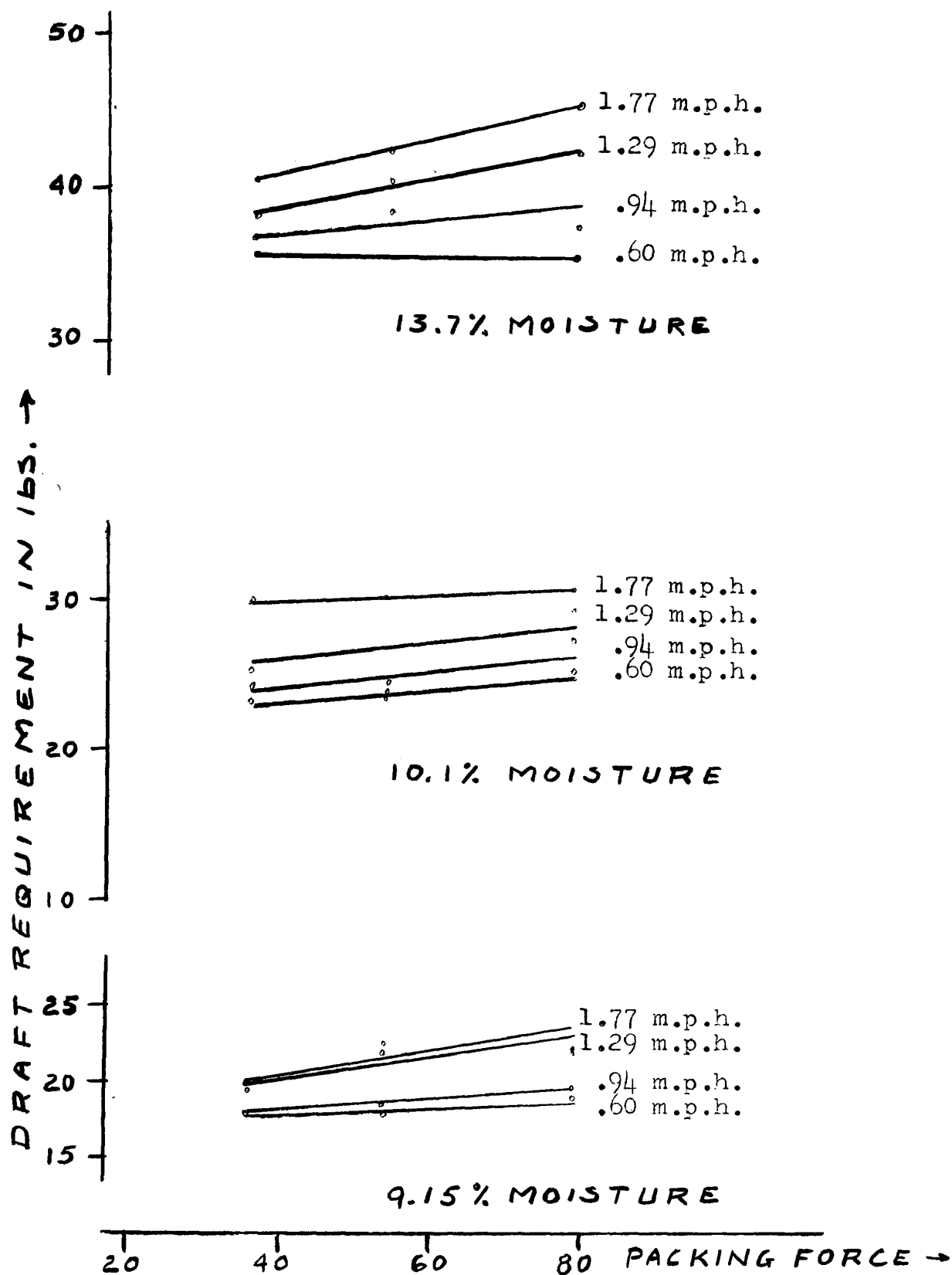


Fig. 38. Packing force versus draft requirement of a four-inch plow in soil No. 2 (16.7 percent clay) with three different moisture percents, four speeds, at 2.5 inch depth.

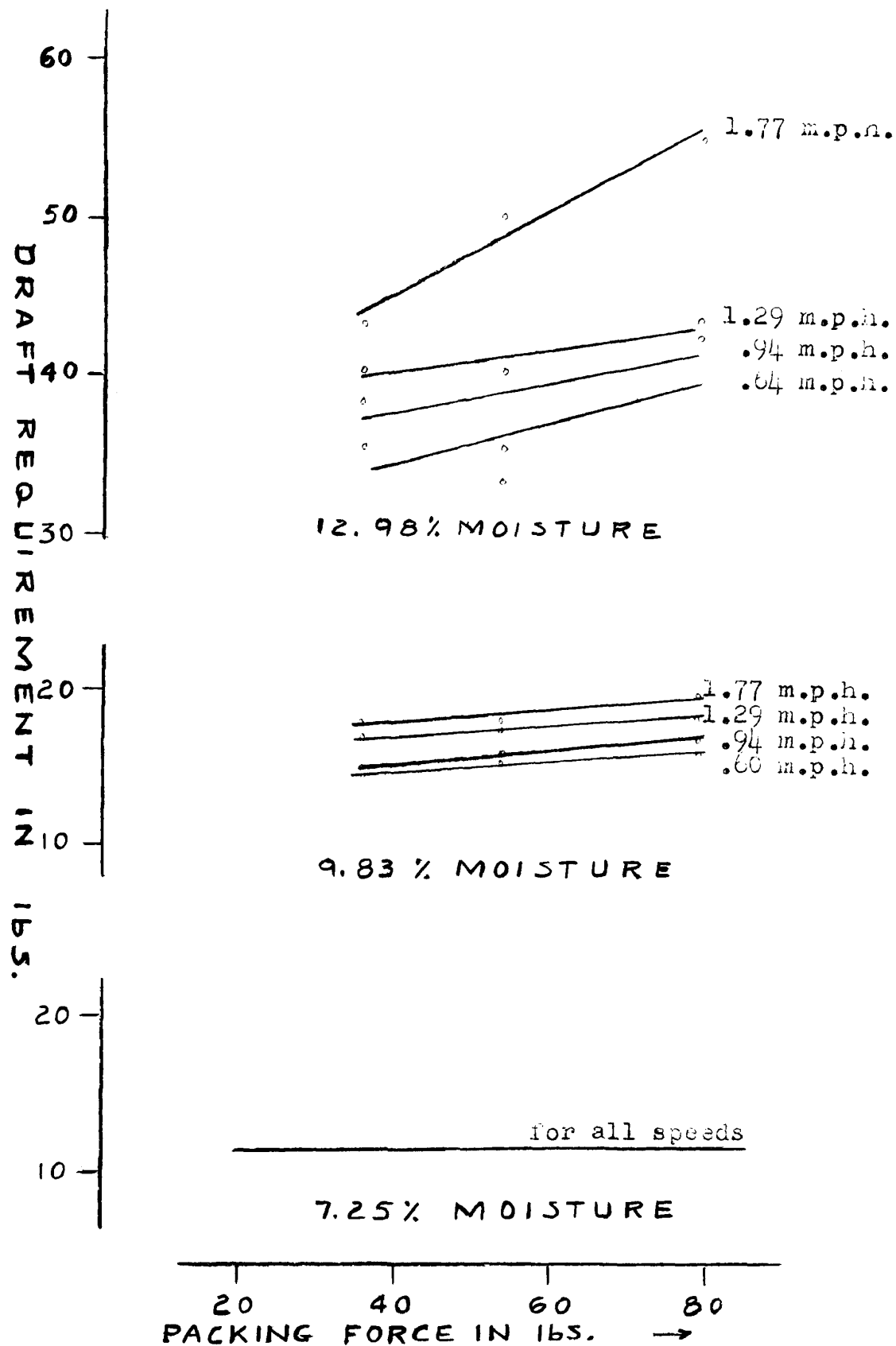


Fig. 39. Packing force versus draft requirement of a one-inch tooth in soil No. 3 (22.5 percent clay) with three different moisture percents, four speeds, at 4-inch depth.

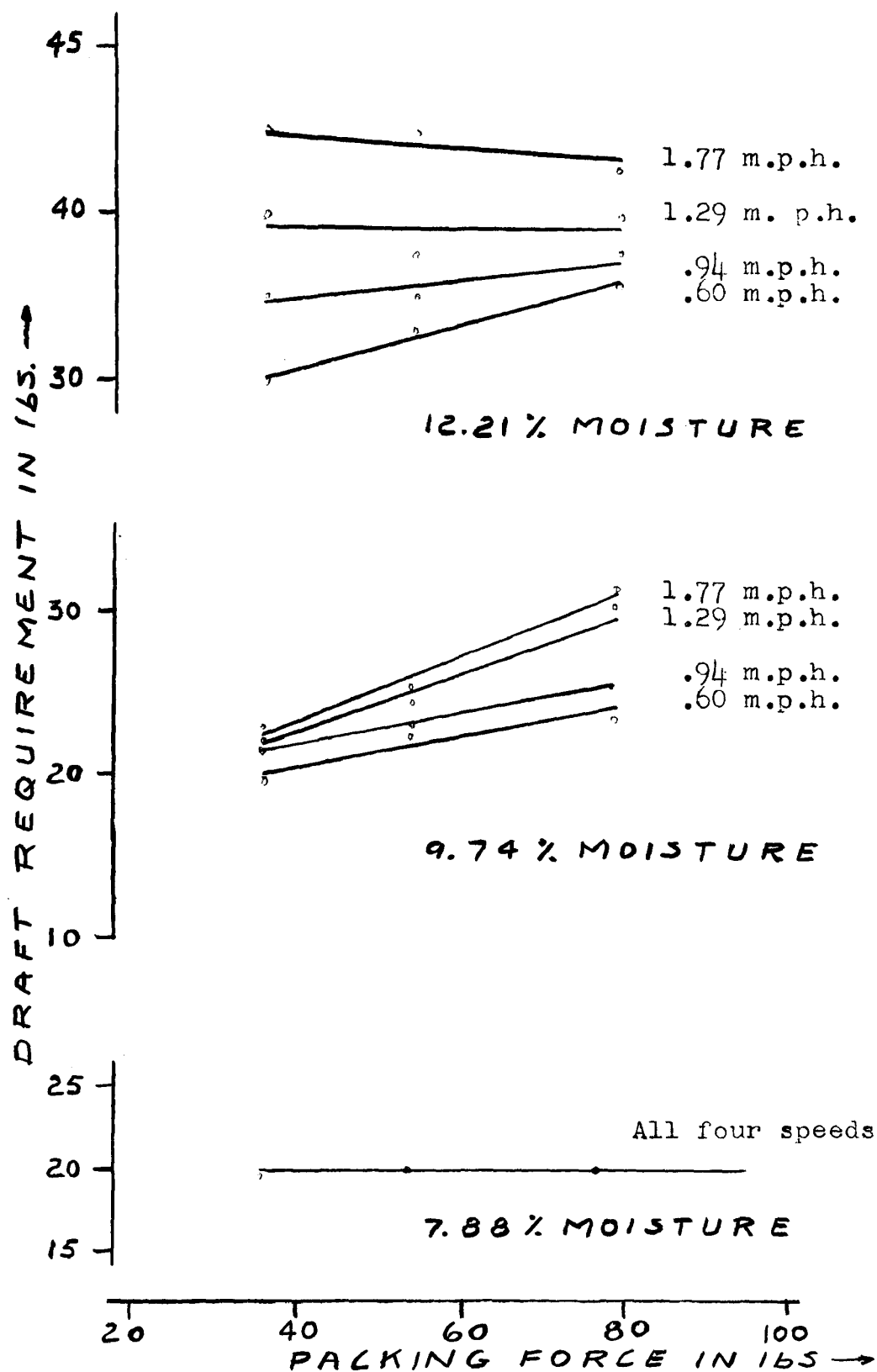


Fig. 40. Packing force versus draft requirement of a four-inch plow in soil No. 3 (22.5 percent clay) with different moisture percents, four speeds, at 2.5-inch depth.

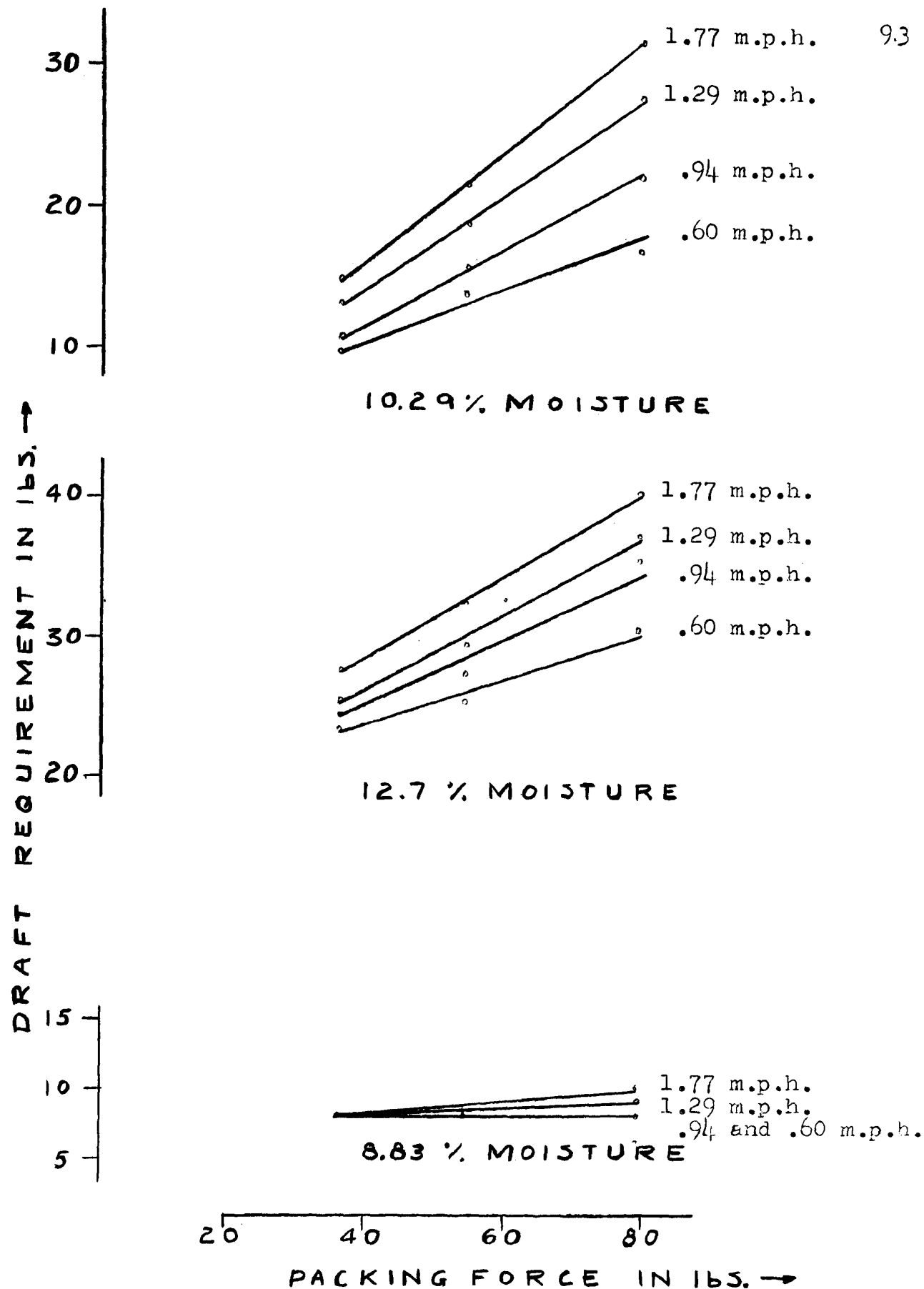


Fig. 41. Packing force versus draft requirement of a seven-inch disk in soil No. 3 (22.5 percent clay) with three different moisture percents, four speeds, at 2.5 inch depth.

was workable for tillage operation, narrowed down with the increase of clay percentage. For this reason, the tests with the soil having 34.6 percent clay were not feasible. The soil with 16.78 percent clay could be worked even after 11.78 percent moisture content which is the moisture equivalent of this soil, but in the other side, the soil with 22.52 percent clay was in a very bad shape with 12.7 percent moisture which is less than 14.83 percent, the moisture equivalent of that soil. The best equation that could represent the data obtained in all cases is

$$y = e^{a+bx} + c$$

Effect of packing force. The packing force of the soil changed the apparent density of the soil. The relationship between the apparent density and compression force has been studied by Nichols and was discussed previously. The density change in different tests has been shown in the tables given for each test. It seems to be more practical here to show the relationship between the draft and the force of packing soil. As the method of packing was the same throughout the experiment, it was decided to use the amount of weight applied over the packer as the abscissa and the draft of the implement as the ordinate. The change of draft was proportional to the change of packing force, and this relationship is a straight line in all cases.

Theoretical Study of Soil Factors Affecting The Draft Requirement of Tillage Tools

Reasons for Study

The problem of soil resistance against the pulling of a tillage tool should be studied by the method of dimensional analysis for two reasons:

1) Instead of running field tests to indicate the performance of a particular tillage tool, the performance can be found with small models in the soil box inside the laboratory. Then by the use of the theory of models, the results of laboratory tests can be applied to the actual field size.

2) The theory of dimensional analysis is a good method of finding an equation indicating the relationship between the soil resistance against the tillage tools and the different factors, or a dimensionless product of these factors.

General Remarks on Dimensional Analysis

An equation will be said to be dimensionally homogenous if the form of the equation does not depend on the fundamental units of measurement. Dimensionally homogenous functions are a special class compared to the general types of functions that are investigated in mathematical analysis. The theory of dimensional analysis, which is the mathematical theory of this class of functions, is purely algebraic.

The application of dimensional analysis to a practical problem is based on the hypothesis that the solution of the problem is expressible by means of a dimensionally homogenous equation in terms of specified variables. An unknown equation is dimensionally homogenous when the equation contains all the variables that would appear in an analytical derivation of the equation.

The first step in the dimensional analysis of a problem is to decide what variables enter the problem. If variables that are introduced do not affect the phenomenon, too many terms may appear in the final equation. If variables that may affect it are omitted, the calculations may reach an impasse, or an erroneous answer may be obtained.

Theorems: 1) A set of dimensionless products of given variables is complete, if each product in the set is independent of the others and every other dimensionless product of the variables is a product of powers of dimensionless products in the set.

2) Buckingham's Theorem. If an equation is dimensionally homogenous, it can be reduced to a relationship among a complete set of dimensionless products.

3) The number of dimensionless products in a complete set is equal to the total number of variables minus the maximum number of these variables that will not form a dimensionless product.

Assumptions and the Solution of the Problem

With the present knowledge of soil characteristics, the elements that have been considered effective in the resistance force against tillage implements are shear, acceleration of tool, velocity of tools, density of soil, a unit of length which is effective (it can be first, second or third power of length), and viscosity of soil solution or water in soil.

The dimensions of the above factors will be

$$\text{Shear strength} \quad S = \frac{F}{L^2}$$

$$\text{Acceleration} \quad A = \frac{L}{T^2}$$

$$\text{Velocity} \quad V = \frac{L}{T}$$

$$\text{Density} \quad = \frac{FT^2}{L^3}$$

$$\text{Force} \quad = F \quad \text{The force of soil resistance against tillage tools}$$

$$\text{Length} \quad D = L$$

$$\text{Viscosity} \quad = \frac{FT}{L^2}$$

According to the theory of dimensional analysis, it can be said that $f(S^a, A^b, V^c, \rho^d, \theta^e, D^f, M^g) = 0$.

According to Buckingham's theorem this can be reduced to a set of dimensionless products. The number of those products is equal to the total number of variables minus three (the number of independent variables). To find the dimensionless

products a few assumptions should be made so that each product contains only one of the required unknowns:

1) FIRST ASSUMPTION

$$b = c = d = g = 0$$

$$f(S^a \theta^e D^f) = 0$$

$$\text{OR } f\left[\left(\frac{F}{L^2}\right)^a (F)^e (L)^f\right] = 0$$

	S	θ	D
F	1	1	0
L	-2	0	1
T	0	0	0

$$a + e = 0 \quad \text{OR} \quad a = -e$$

$$-2a + f = 0 \quad \text{OR} \quad f = 2a$$

$$\text{FOR } e = -1 ;$$

$$a = 1 \quad \text{AND} \quad f = 2$$

$$\text{SO, } f\left(\frac{S D^2}{\theta}\right) = 0 \quad \text{IS A DIMENSIONLESS PRODUCT}$$

2) SECOND ASSUMPTION

$$a = b = g = 0$$

$$f(V^c \rho^d \theta^e D^f) = 0$$

$$\text{OR } f\left[\left(\frac{L}{T}\right)^c \left(\frac{F T^2}{L^4}\right)^d (F)^e (L)^f\right] = 0$$

	V	ρ	θ	D
F	0	1	1	0
L	1	-4	0	1
T	-1	2	0	0

$$d + e = 0$$

$$c - 4d + f = 0$$

$$-c + 2d = 0$$

$$\text{FOR } e = -1$$

$$d = 1 \quad c = -4 + f = 0 \quad \text{OR} \quad c + f = 4$$

$$\text{AND} \quad c = 2d = 2, \quad f = 2$$

$$\text{SO, } f(V^2 \rho \theta^{-1} D^2) = 0$$

$$\text{OR } f\left(\frac{V^2 \rho D^2}{\theta}\right) = 0 \quad \text{IS A DIMENSIONLESS PRODUCT}$$

3) THIRD ASSUMPTION

$$\alpha = b = d = 0$$

$$\text{OR } f \left[\left(\frac{L}{T} \right)^c \left(\frac{FT}{L^2} \right)^g (F)^e (L)^f \right] = 0$$

$$g + e = 0$$

$$c - 2g + f = 0$$

$$-c + g = 0$$

	V	M	Q	D
F	0	1	1	0
L	1	-2	0	1
T	-1	1	0	0

FOR $e = -1$; $g = 1$, $c = 1$ AND $f = 1$

$$\text{SO, } f \left(\frac{VM_D}{\rho} \right) = 0 \quad \text{IS A DIMENSIONLESS PRODUCT}$$

4) FOURTH ASSUMPTION.

$$\alpha = c = g = 0$$

$$\text{OR } f \left[\left(\frac{L}{T^2} \right)^b \left(\frac{FT^2}{L^4} \right)^d (F)^e (L)^f \right] = 0$$

$$d + e = 0$$

$$b - 4d + f = 0$$

$$-2b + 2d = 0$$

	A	P	Q	D
F	0	1	1	0
L	1	-4	0	1
T	-2	2	0	0

FOR $e = -1$, $d = 1$; $b = 1$ AND $f = 3$

$$\text{SO, } f(A \rho Q^{-1} D^{-3}) = 0 \quad \text{IS A DIMENSIONLESS PRODUCT}$$

FINALLY,

$$f \left[\left(\frac{Q}{\rho D^2} \right), \left(\frac{Q}{V^2 \rho D^2} \right), \left(\frac{Q}{V D_M} \right), \left(\frac{Q}{A \rho D^3} \right) \right] = 0$$

OR

$$A \left(\frac{Q}{S D^2} \right) + B \left(\frac{Q}{V^2 \rho D^2} \right) + C \left(\frac{Q}{V D_M} \right) + G \left(\frac{Q}{A \rho D^3} \right) = 0$$

OR

$$\frac{1}{Q} = A_1 \frac{1}{S D^2} + B_1 \frac{1}{V^2 \rho D^2} + C_1 \frac{1}{V D_M} + G_1 \frac{1}{A \rho D^3} \quad (1)$$

To find the amount of Θ which is a function of S , D , V , ρ and M , the coefficients of A , B , C , and G should be determined from practical data.

The relationship between shear and moisture and clay content has been indicated by Nichols, and has been discussed here previously. The acceleration of the implement is zero, if it will run with constant speed; when acceleration is zero, the last item will drop out. The effect of viscosity should be studied more and its relationship to the percent of clay and moisture should be determined. The velocity and the size of the implement also the density of soil can be measured directly and used in the above equation.

Conclusions

Equation (1) will indicate the amount of resistance force of the soil against the pulling of the implement. This will be justified only when the soil is uniform and under controlled conditions. As has been discussed before, some of the factors that it is not possible to control like organic matter, vegetation, etc., have been eliminated; some laboratory work is needed also to indicate the constants and the degree of effectiveness of the viscosity and its relationship with the other more easily measurable soil properties. In general, it could be mentioned that this is not a complete theoretical solution for the problem of measuring the draft requirement of tillage. It indicates only the possibility of the theoretical solution which should be investigated later.

Upon the completion of the above relationship for the uniform soil, it can be applied to field conditions by multiplying this relationship by certain factors which will be determined according to the field condition. This method has been used in many other fields of applied science, and will be discussed further in the section on "Suggestions for Further Study."

SUMMARY

The non-uniformity of soil, and the fact that the control of soil properties in the field is next to impossible, has made field tests of very little value. None of the field tests run in different localities could be duplicated, and no uniform plot existed to use for the experiments. Haines (34) in England, also recognized this non-uniformity of soils in field tests.

In order to study the problem of the draft requirement of tillage tools, the important factors were determined first. Then, with the help of laboratory methods, the relationships between the draft requirement and the effective factors were determined.

The theoretical method was the best way to determine the above mentioned relationships. The application of the theory of dimensional analysis to this problem seemed to be satisfactory, though more investigations are needed to obtain the final results. More detailed conclusions are given at the end of each section.

/

SUGGESTIONS FOR FURTHER STUDY

Changes in Laboratory Tests

Proposed Changes in Building Experimental Soil Box

A longer and wider soil box would make possible tests with higher speeds and also more runs with different speeds which could be done after each soil preparation. The depth of the box seemed to be adequate and no changes were needed. The length of the tool cart should be increased to have more stable smooth movement of the tool cart at higher speeds.

A hydraulic dynamometer with recording instrument would increase the accuracy of reading.

Change of the trolley door tracks to a stronger and more rigid type, would avoid the bouncing of rollers at higher speeds. It should also be designed so that it will always remain clean and save time by eliminating continuous cleaning.

Some other small changes which might be suggested are: providing a means of stirring the soil instead of using a hand fork, using a better method to measure the apparent density, in order to save time and increase the accuracy of the test.

More Tests With Different Conditions

Only three kinds of soils were used in the experiment. The above soils were made of only sand and clay. For better results the number of soil mixtures should be increased. Also organic matter, and vegetation can be added to the soil in known quantities, and their effect on the amount of draft determined.

More Theoretical Study

The theoretical method should be developed more completely and checked with the laboratory results. The method of dimensional analysis seems satisfactory, though some other methods might be found that are more adaptable. In the theoretical analysis, the conception of the main functions of tillage is very important. Any misassumption of the factors presenting those functions will end in a faulty result. Therefore, those function, the assumptions, and the solution of the equations should be studied carefully.

Application of Theoretical and Laboratory

Results to Field Conditions

As has been mentioned before, the main difficulty in field tests is the non-uniformity of the soil. To overcome this difficulty, the author suggests consideration of the following method:

- 1) Developing a method for the classical study of the

effect of some factors such as different organic matter, surface vegetation, root system, trash, etc., in the draft requirement of functionally different tillage implements.

2) Using a large sample of the non-uniform soil, mixing it thoroughly and running different tests in the soil box.

3) Running a few field tests and getting the average amount of the draft requirement.

4) Determining the ratio of the result of the field test to the laboratory test. This can be called the "field factor." Determining and recording the field factor in a few soil types.

5) Determining the soil type and the amount of various effective factors, as has been previously discussed, in order to discover the draft requirements in any field. This would require the use of the theoretical equations to evaluate the amount of theoretically required draft, and by multiplying by the field factor would give the actual draft requirement of the tool.

APPENDIX

TABLE VI
DRAFT REQUIREMENT OF A ONE-INCH TOOTH

Soil No. 1

Moisture percent 2.98

Run No.	Packing Force lbs.	Apparent Density	Speed m.p.h.	Draft Requirement lbs.
1	18	1.29	.60	11.
2	"	"	.93	10.5
3	"	"	1.29	11.
4	"	"	1.77	13.
1	36	1.35	.60	10.
2	"	"	.93	10.
3	"	"	1.29	12.5
4	"	"	1.77	13.
1	54	1.39	.60	10.
2	"	"	.93	11.
3	"	"	1.29	11.5
4	"	"	1.77	13.

TABLE VII
DRAFT REQUIREMENT OF A ONE-INCH TOOTH

Soil No. 1

Moisture Percent 3.83

Run No.	Packing Force lbs.	Apparent Density	Speed m.p.h.	Draft Requirement lbs.
1	18	1.31	.60	11.
2	"	"	.93	10.
3	"	"	1.29	12.5
4	"	"	1.77	13.
1	36	1.32	.60	12.
2	"	"	.93	13.
3	"	"	1.29	14.
4	"	"	1.77	14.5
1	54	1.37	.60	10.
2	"	"	.93	12.
3	"	"	1.29	13.5
4	"	"	1.77	14.5

TABLE VIII
DRAFT REQUIREMENT OF A ONE-INCH TOOTH
Soil No. 2
Moisture Percent 9.36

Run No.	Packing Force lbs.	Apparent Density	Speed m.p.h.	Draft Requirement lbs.
1	18	1.23	.60	10.
2	"	"	.93	9.
3	"	"	1.29	9.5
4	"	"	1.77	10.
1	36	1.26	.60	10.
2	"	"	.93	11.
3	"	"	1.29	10.
4	"	"	1.77	10.5
1	54	1.27	.60	10.5
2	"	"	.93	11.
3	"	"	1.29	11.
4	"	"	1.77	10.5

TABLE IX
DRAFT REQUIREMENT OF A ONE-INCH TOOTH
Soil No. 2
Moisture Percent 10.0

Run No.	Packing Force lbs.	Apparent Density	Speed m.p.h.	Draft Requirement lbs.
1	36	1.22	.60	12.
2	"	"	.93	13.
3	"	"	1.29	14.
4	"	"	1.77	15.
1	54	1.30	.60	12.5
2	"	"	.93	13.
3	"	"	1.29	14.
4	"	"	1.77	16.5
1	79	1.32	.60	15.
2	"	"	.93	16.
3	"	"	1.29	19.
4	"	"	1.77	17.

TABLE X
DRAFT REQUIREMENT OF A ONE-INCH TOOTH
Soil No. 2
Moisture Percent 11.75

Run No.	Packing Force lbs.	Apparent Density	Speed m.p.h.	Draft Requirement lbs.
1	36	1.42	.60	22.
2	"	"	.93	23.
3	"	"	1.29	23.5
4	"	"	1.77	25.
1	54	1.41	.60	22.
2	"	"	.93	24.
3	"	"	1.29	25.
4	"	"	1.77	28.
1	79	1.60	.60	24.
2	"	"	.93	25.
3	"	"	1.29	26.
4	"	"	1.77	29.

TABLE XI

DRAFT REQUIREMENT OF A ONE-INCH TOOTH

Soil No. 2

Moisture Percent 13.77

Run No.	Packing Force lbs.	Apparent Density	Speed m.p.h.	Draft Requirement lbs.
1	36	1.54	.60	23.
2	"	"	.93	24.
3	"	"	1.29	27.
4	"	"	1.77	30.
1	54	1.51	.60	25.
2	"	"	.93	28.
3	"	"	1.29	29.
4	"	"	1.77	31.
1	79	1.51	.60	28.
2	"	"	.93	29.
3	"	"	1.29	32.
4	"	"	1.77	35.

TABLE XII
DRAFT REQUIREMENT OF A ONE-INCH TOOTH
Soil No. 3
Moisture Percent 7.25

Run No.	Packing Force lbs.	Apparent Density	Speed m.p.h.	Draft Requirement lbs.
1	36	1.18	.60	11.
2	"	"	.93	11.5
3	"	"	1.29	11.5
4	"	"	1.77	11.
1	54	1.19	.60	11.
2	"	"	.93	11.
3	"	"	1.29	11.5
4	"	"	1.77	11.5
1	79	1.2	.60	11.5
2	"	"	.93	11.5
3	"	"	1.29	11.5
4	"	"	1.77	12.

TABLE XIII

DRAFT REQUIREMENT OF A ONE-INCH TOOTH

Soil No. 3

Moisture Percent 9.83

Run No.	Packing Force lbs.	Apparent Density	Speed m.p.h.	Draft Requirement lbs.
1	36	1.18	.60	14.5
2	"	"	.93	15.
3	"	"	1.29	17.
4	"	"	1.77	18.
1	54	1.19	.60	15.5
2	"	"	.93	16.
3	"	"	1.29	17.5
4	"	"	1.77	18.
1	79	1.2	.60	16.
2	"	"	.93	17.
3	"	"	1.29	18.5
4	"	"	1.77	20.

TABLE XIV

DRAFT REQUIREMENT OF A ONE-INCH TOOTH

Soil No. 3

Moisture Percent 12.98

Run No.	Packing Force lbs.	Apparent Density	Speed m.p.h.	Draft Requirement lbs.
1	36	1.32	.60	35.
2	"	"	.93	38.
3	"	"	1.29	40.
4	"	"	1.77	43.
1	54	1.50	.60	33.
2	"	"	.93	35.
3	"	"	1.29	40.
4	"	"	1.77	50.
1	79	1.36	.60	42.
2	"	"	.93	42.
3	"	"	1.29	43.
4	"	"	1.77	55.

TABLE XV
DRAFT REQUIREMENT OF A FOUR-INCH PLOW
Soil No. 1
Moisture Percent 2.82

Run No.	Packing Force lbs.	Apparent Density	Speed m.p.h.	Draft Requirement lbs.
1	18	1.34	.60	15.5
2	"	"	.93	14.
3	"	"	1.29	14.5
4	"	"	1.77	17.5
1	36	1.37	.60	15.
2	"	"	.93	15.
3	"	"	1.29	14.5
4	"	"	1.77	16.5
1	54	1.38	.60	14.
2	"	"	.93	13.
3	"	"	1.29	14.5
4	"	"	1.77	15.5

TABLE XVI

DRAFT REQUIREMENT OF A FOUR-INCH PLOW

Soil No. 1

Moisture Percent 3.96

Run No.	Packing Force lbs.	Apparent Density	Speed m.p.h.	Draft Requirement lbs.
1	18	1.35	.60	14.5
2	"	"	.93	15.5
3	"	"	1.29	15.5
4	"	"	1.77	16.5
1	36	1.37	.60	15.
2	"	"	.93	15.5
3	"	"	1.29	16.
4	"	"	1.77	17.
1	54	1.37	.60	12.5
2	"	"	.93	14.
3	"	"	1.29	15.
4	"	"	1.77	15.5

TABLE XVII
 DRAFT REQUIREMENT OF A FOUR-INCH PLOW
 Soil No. 2
 Moisture Percent 9.15

Run No.	Packing Force lbs.	Apparent Density	Speed m.p.h.	Draft Requirement lbs.
1	36	1.39	.60	18.
2	"	"	.93	19.5
3	"	"	1.29	19.5
4	"	"	1.77	19.5
1	54	1.41	.60	18.
2	"	"	.93	18.5
3	"	"	1.29	22.
4	"	"	1.77	22.5
1	79	1.42	.60	19.
2	"	"	.93	19.5
3	"	"	1.29	22.
4	"	"	1.77	22.

TABLE XVIII
DRAFT REQUIREMENT OF A FOUR-INCH PLOW
Soil No. 2
Moisture Percent 10.1

Run No.	Packing Force lbs.	Apparent Density	Speed m.p.h.	Draft Requirement lbs.
1	36	1.44	.60	22.5
2	"	"	.93	24.5
3	"	"	1.29	26.
4	"	"	1.77	29.5
1	54	1.42	.60	23.
2	"	"	.93	23.5
3	"	"	1.29	24.
4	"	"	1.77	30.
1	79	1.42	.60	25.
2	"	"	.93	27.
3	"	"	1.29	29.
4	"	"	1.77	30.5

TABLE XIX
 DRAFT REQUIREMENT OF A FOUR-INCH PLOW
 Soil No. 2
 Moisture Percent 13.7

Run No.	Packing Force lbs.	Apparent Density	Speed m.p.h.	Draft Requirement lbs.
1	36	1.57	.60	35.
2	"	"	.93	36.
3	"	"	1.29	37.5
4	"	"	1.77	40.
1	54	1.55	.60	35.
2	"	"	.93	38.
3	"	"	1.29	40.
4	"	"	1.77	42.
1	79	1.46	.60	35.
2	"	"	.93	37.
3	"	"	1.29	42.
4	"	"	1.77	45.

TABLE XX
DRAFT REQUIREMENT OF A FOUR-INCH PLOW
Soil No. 3
Moisture Percent 7.88

Run No.	Packing Force lbs.	Apparent Density	Speed m.p.h.	Draft Requirement lbs.
1	36	1.18	.60	19.
2	"	"	.93	19.
3	"	"	1.29	19.5
4	"	"	1.77	19.5
1	54	1.19	.60	19.5
2	"	"	.93	20.
3	"	"	1.29	20.
4	"	"	1.77	20.
1	79	1.2	.60	19.5
2	"	"	.93	20.
3	"	"	1.29	20.
4	"	"	1.77	20.

TABLE XXI
DRAFT REQUIREMENT OF A FOUR-INCH PLOW
Soil No. 3
Moisture Percent 9.74

Run No.	Packing Force lbs.	Apparent Density	Speed m.p.h.	Draft Requirement lbs.
1	36	1.2	.60	19.
2	"	"	.93	21.
3	"	"	1.29	21.5
4	"	"	1.77	22.5
1	54	1.21	.60	22.
2	"	"	.93	22.
3	"	"	1.29	24.
4	"	"	1.77	25.
1	79	1.23	.60	23.
2	"	"	.93	25.
3	"	"	1.29	30.
4	"	"	1.77	31.

TABLE XXII
DRAFT REQUIREMENT OF A FOUR-INCH PLOW
Soil No. 3
Moisture Percent 12.21

Run No.	Packing Force lbs.	Apparent Density	Speed m.p.h.	Draft Requirement lbs.
1	36	1.35	.60	30.
2	"	"	.93	35.
3	"	"	1.29	40.
4	"	"	1.77	45.
1	54	1.40	.60	33.
2	"	"	.93	35.
3	"	"	1.29	37.5
4	"	"	1.77	45.
1	79	1.47	.60	36.
2	"	"	.93	38.
3	"	"	1.29	40.
4	"	"	1.77	43.

TABLE XXIII
 DRAFT REQUIREMENT OF A 2.5 INCH TOOTH
 Soil No. 2
 Moisture Percent 9.41

Run No.	Packing Force lbs.	Apparent Density	Speed m.p.h.	Draft Requirement lbs.
1	36	1.27	.60	18.5
2	"	"	.93	20.5
3	"	"	1.29	22.5
4	"	"	1.77	23.
1	54	1.38	.60	19.5
2	"	"	.93	21.
3	"	"	1.29	21.5
4	"	"	1.77	24.
1	79	1.39	.60	20.
2	"	"	.93	21.5
3	"	"	1.29	23.
4	"	"	1.77	25.

TABLE XXIV
 DRAFT REQUIREMENT OF A 2.5 INCH TOOTH
 Soil No. 2
 Moisture Percent 11.56

Run No.	Packing Force lbs.	Apparent Density	Speed m.p.h.	Draft Requirement lbs.
1	36	1.47	.60	33.
2	"	"	.93	33.
3	"	"	1.29	34.
4	"	"	1.77	38.
1	54	1.52	.60	35.
2	"	"	.93	38.
3	"	"	1.29	39.
4	"	"	1.77	40.
1	79	1.51	.60	37.
2	"	"	.93	38.
3	"	"	1.29	39.
4	"	"	1.77	42.

TABLE XXV
 DRAFT REQUIREMENT OF A 2.5 INCH TOOTH
 Soil No. 2
 Moisture Percent 13.3

Run No.	Packing Force lbs.	Apparent Density	Speed m.p.h.	Draft Requirement lbs.
1	36	1.5	.60	35.
2	"	"	.93	38.
3	"	"	1.29	40.
4	"	"	1.77	42.5
1	79	1.54	.60	36.5
2	"	"	.93	42.
3	"	"	1.29	44.
4	"	"	1.77	50.

TABLE XXVI
DRAFT REQUIREMENT OF A 2.5 INCH TOOTH
Soil No. 3
Moisture Percent 10.32

Run No.	Packing Force lbs.	Apparent Density	Speed m.p.h.	Draft Requirement lbs.
1	36	1.19	.60	22.
2	"	"	.93	25.
3	"	"	1.29	27.
4	"	"	1.77	31.
1	54	1.22	.60	24.
2	"	"	.93	23.
3	"	"	1.29	25.
4	"	"	1.77	33.
1	79	1.22	.60	28.
2	"	"	.93	30.
3	"	"	1.29	32.
4	"	"	1.77	35.

TABLE XXVII
 DRAFT REQUIREMENT OF A 2.5 INCH TOOTH
 Soil No. 3
 Moisture Percent 12.79

Run No.	Packing Force lbs.	Apparent Density	Speed m.p.h.	Draft Requirement lbs.
1	36	1.37	.60	35.
2	"	"	.93	37.
3	"	"	1.29	38.
4	"	"	1.77	40.
1	54	1.38	.60	33.
2	"	"	.93	35.
3	"	"	1.29	37.
4	"	"	1.77	42.
1	79	1.43	.60	37.
2	"	"	.93	38.
3	"	"	1.29	41.
4	"	"	1.77	48.

TABLE XXVIII
 DRAFT REQUIREMENT OF A SEVEN-INCH DISK
 Soil No. 3
 Moisture Percent 8.83

Run No.	Packing Force lbs.	Apparent Density	Speed m.p.h.	Draft Requirement lbs.
1	36	1.26	.60	8.
2	"	"	.93	8.
3	"	"	1.29	8.
4	"	"	1.77	8.
1	54	1.21	.60	8.
2	"	"	.93	8.
3	"	"	1.29	8.
4	"	"	1.77	8.
1	79	1.28	.60	8.
2	"	"	.93	8.
3	"	"	1.29	9.
4	"	"	1.77	10.

TABLE XXIX
 DRAFT REQUIREMENT OF A SEVEN-INCH DISK
 Soil No. 3
 Moisture Percent 10.29

Run No.	Packing Force lbs.	Apparent Density	Speed m.p.h.	Draft Requirement lbs.
1	36	1.26	.60	10.
2	"	"	.93	11.
3	"	"	1.29	13.5
4	"	"	1.77	15.
1	54	1.30	.60	14.
2	"	"	.93	16.
3	"	"	1.29	19.
4	"	"	1.77	22.
1	79	1.31	.60	17.
2	"	"	.93	22.5
3	"	"	1.29	28.
4	"	"	1.77	32.

TABLE XXX
DRAFT REQUIREMENT OF A SEVEN-INCH DISK
Soil No. 3
Moisture Percent 12.71

Run No.	Packing Force lbs.	Apparent Density	Speed m.p.h.	Draft Requirement lbs.
1	36	1.41	.60	23.
2	"	"	.93	24.
3	"	"	1.29	25.
4	"	"	1.77	27.
1	54	1.48	.60	25.
2	"	"	.93	27.
3	"	"	1.29	29.
4	"	"	1.77	32.
1	79	1.49	.60	30.
2	"	"	.93	35.
3	"	"	1.29	37.
4	"	"	1.77	40.

TABLE XXXI

THE FRICTION DETERMINATION OF THE TOOL CARRIER IN THE SOIL BOX

Speed m.p.h.	Load on the Tool Carrier lbs.	Dynamometer Reading lbs.
.60	10	12
.94	10	12
1.29	10	12
1.77	10	12
.60	20	22
.94	20	22
1.29	20	22
1.77	20	22
.60	30	32
.94	30	32
1.29	30	32
1.77	30	32
.60	39	41
.94	39	41
1.29	39	41
1.77	39	41
.60	47	49
.94	47	49
1.29	47	49
1.77	47	49

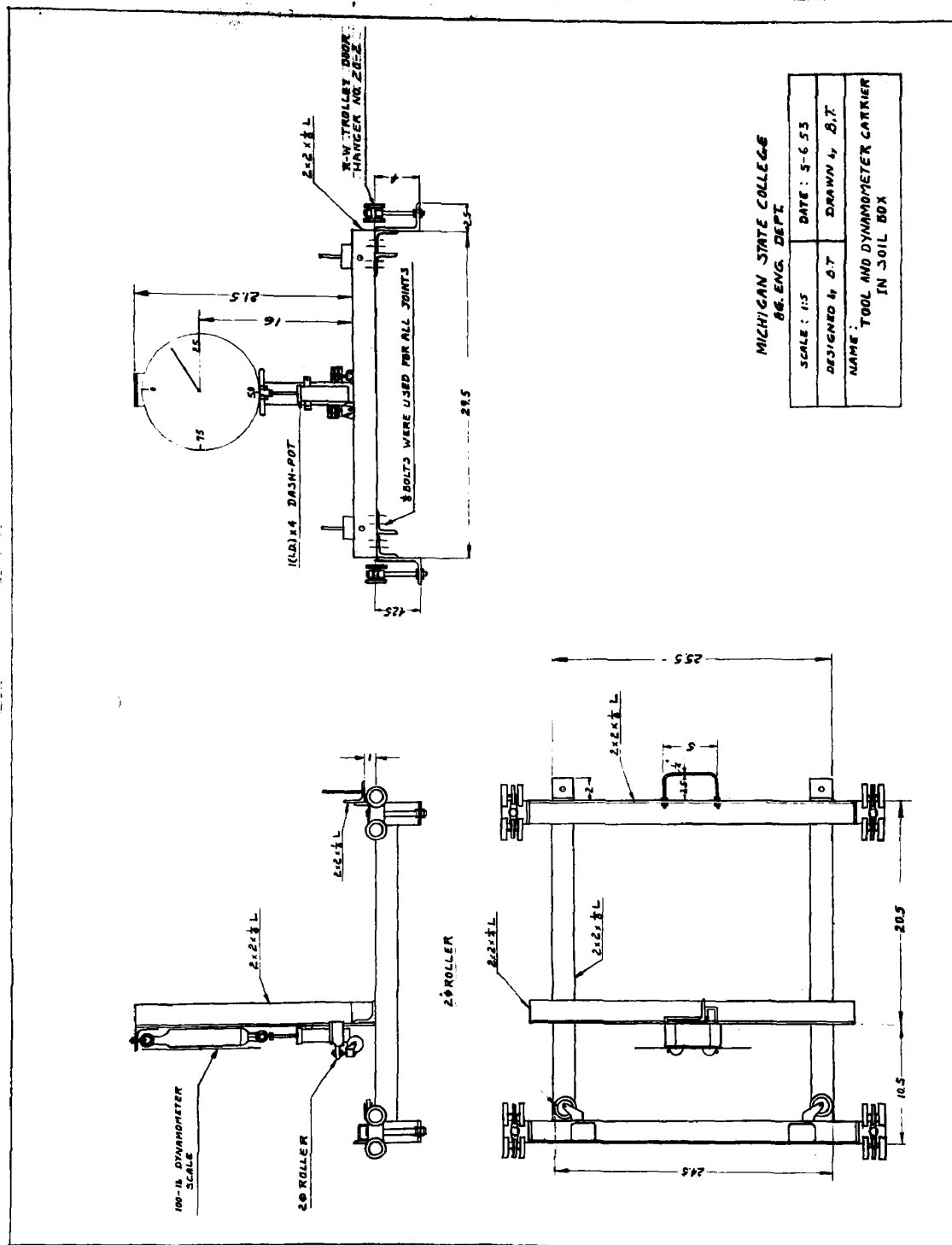


Fig. 42

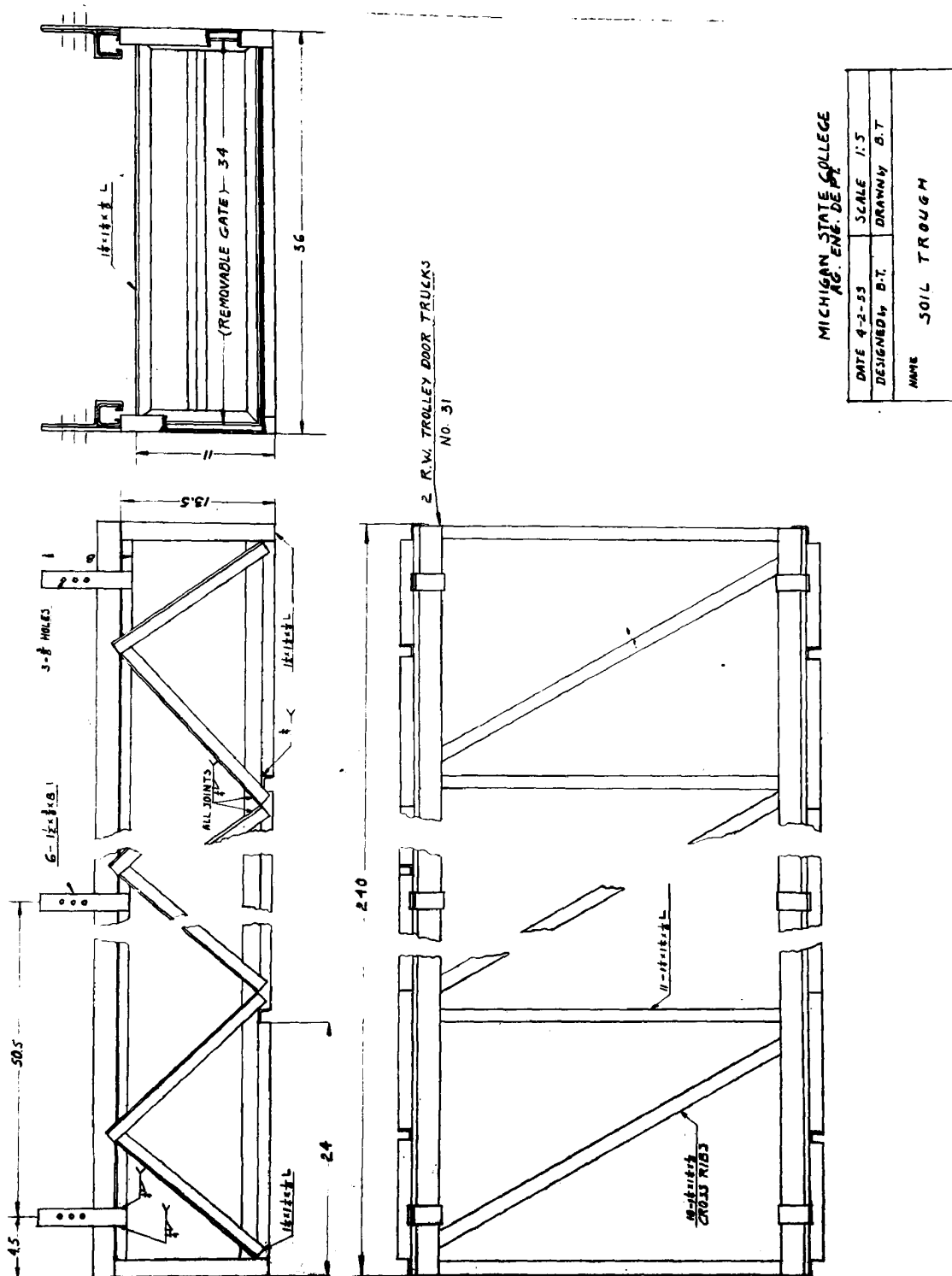


Fig. 43

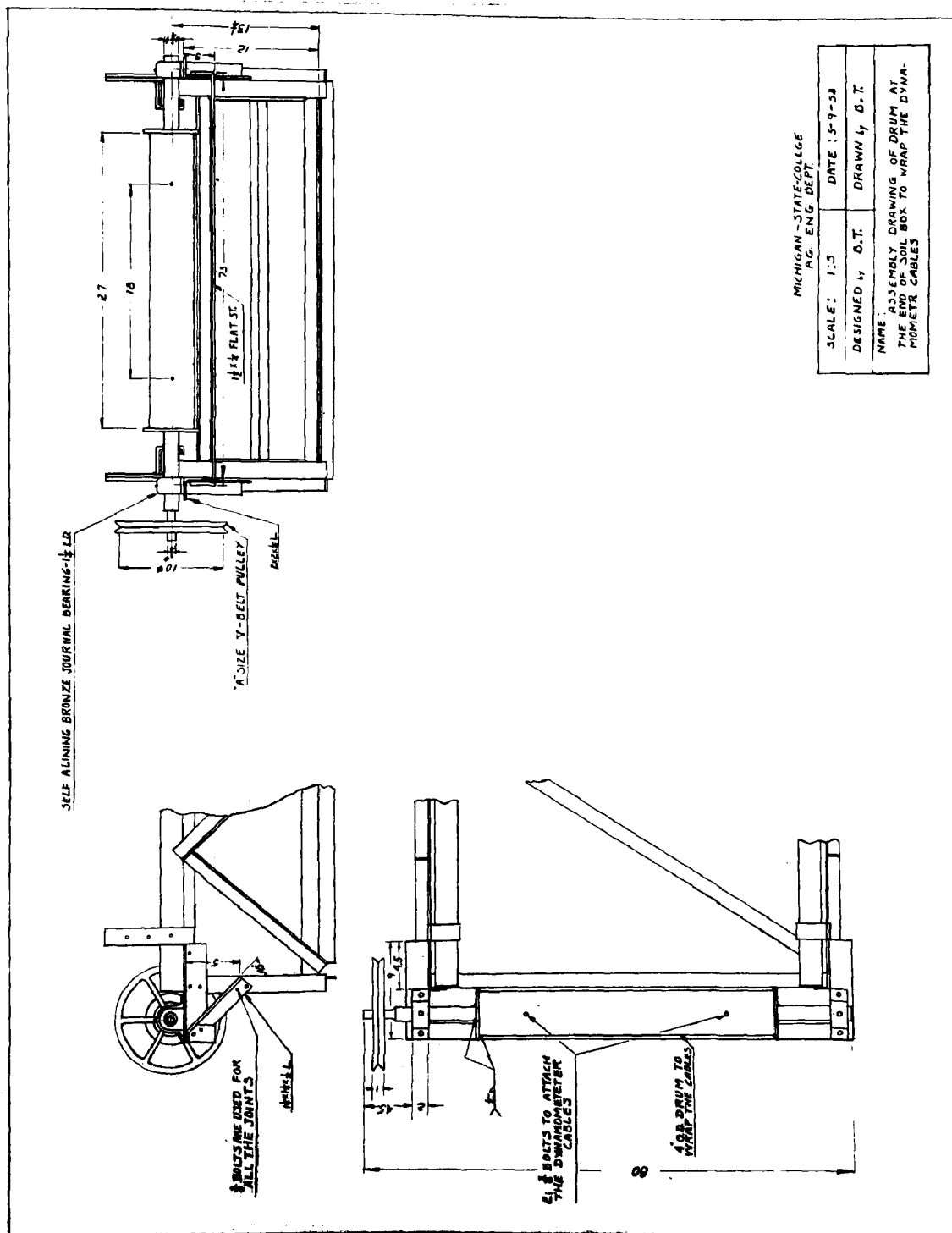


Fig. 44

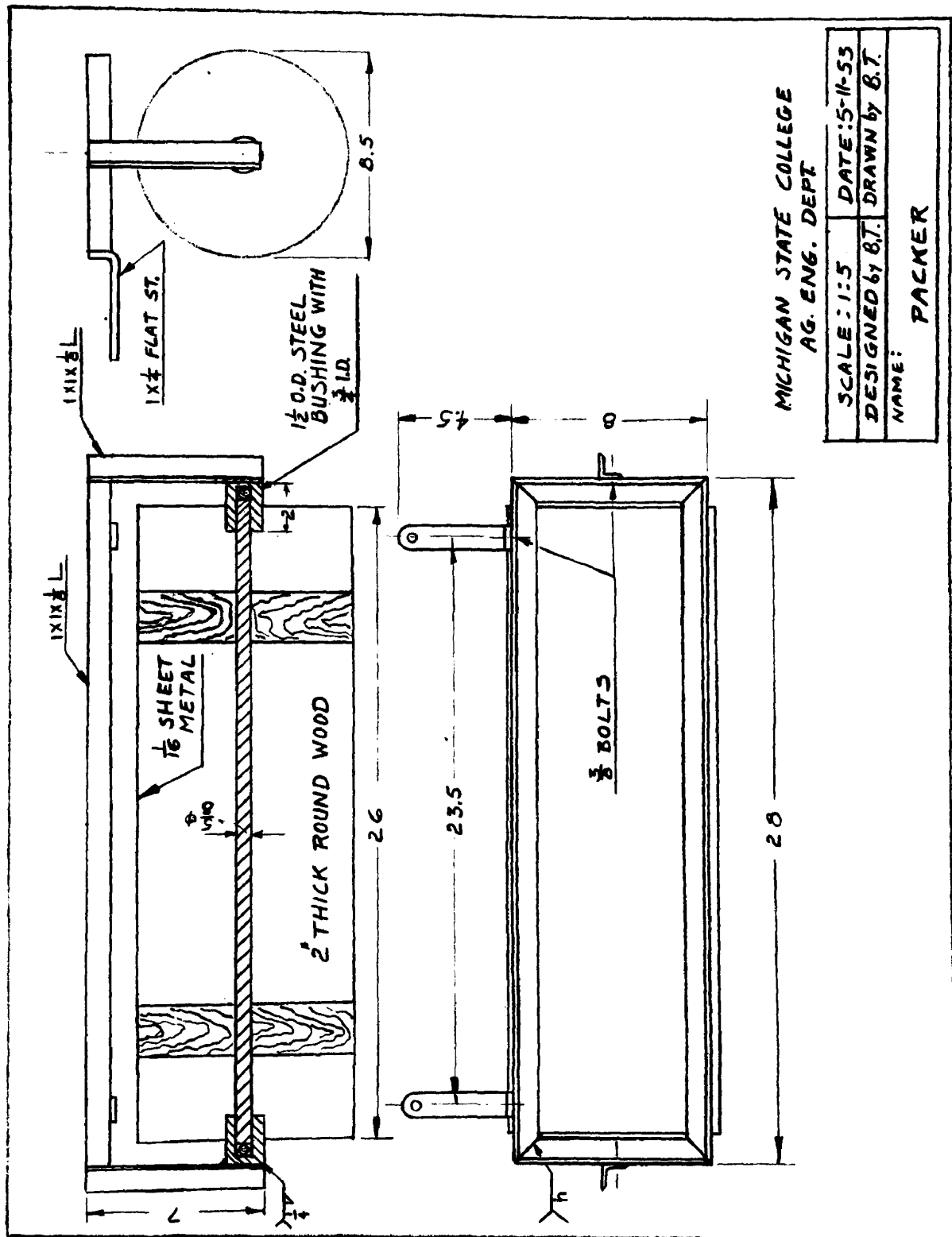


Fig. 45

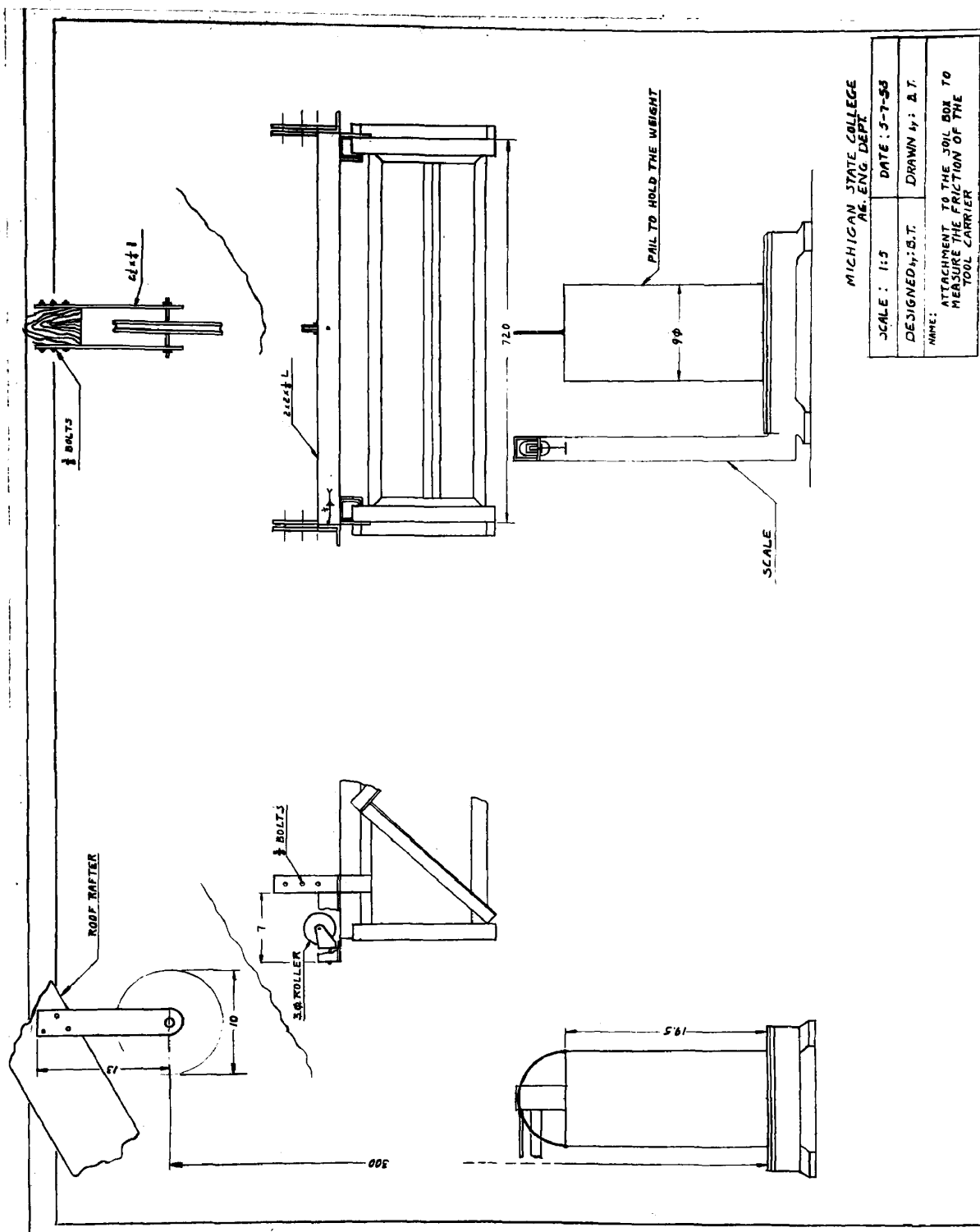


Fig. 46

REFERENCES

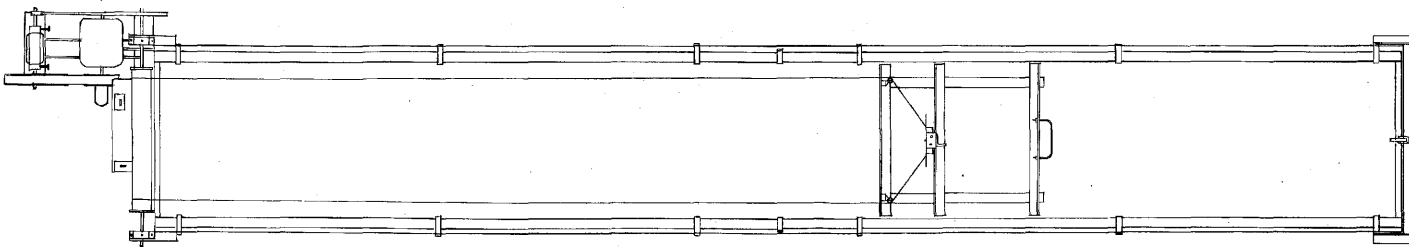
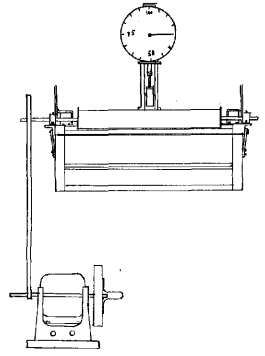
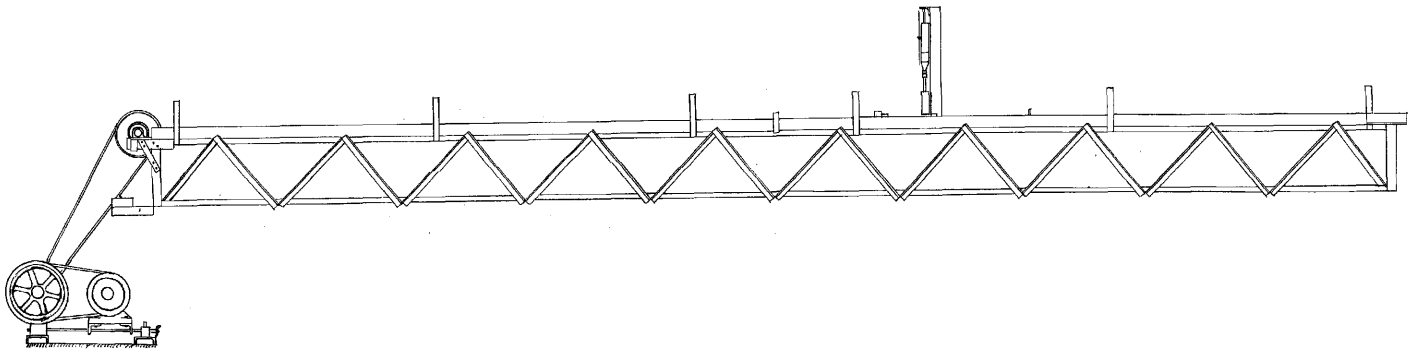
1. Ashley, Wallace. A method of comparing plow bottom shapes. Ag. Eng. J., Vol. 26:35, Jan. 1932.
2. Bacon, C. A. Plow bottom design. Ag. Eng. Transaction, Vol. 12:26, 1918.
3. BaVer, L. D. The physical properties of soil of interest to agricultural engineers. Ag. Eng. J., Vol. 13:324, Dec. 1932.
4. BaVer, L. D. The Atterberg consistency constants: Factors affecting their values and a new concept of their significance. J. Am. Soc. Agron., 22:935-948, 1930.
5. BaVer, L. D. Soil Physics, John Wiley and Sons, Inc., New York. Second edition, 1948.
6. Bouyoucos, G. J. A simple and rapid method for measuring the stickiness of soil. Soil Sc. 34, No. 5:393-410, 1932.
7. Bouyoucos, G. J. Recalibration of the hydrometer method for making mechanical analysis of soils. Agronomy Journal, Vol. 43:434-8, September 1951.
8. Brown, Theo. Engineering development of tillage equipment. Ag. Eng. J. Vol. 12:211, June 1931.
9. Brown, Theo. Some fundamentals of plow design. Ag. Eng. Transaction, Vol. 19:24, 1925.
10. Browning, G. M. Principles of soil physics in relation to tillage. Ag. Eng. J., Vol. 31:341, 1950.
11. Browning, O. A. Present status of the plow as a tillage implement. Ag. Eng. J., Vol. 25:7, 1944.
12. Clyde, A. W. Mechanics of plow and tractor hitches. Ag. Eng. Transaction, Vol. 28:28, 1934.
13. Clyde, A. W. Measurement of forces on soil tillage tools. Ag. Eng. J., Vol. 17:5, Jan. 1936.
14. Clyde, A. W. Load studies on tillage tools. Ag. Eng. J., Vol. 18:117, 1937.

15. Clyde, A. W. The problem of soil tilth. Ag. Eng. J., Vol. 18:320, 1937.
16. Clyde, A. W. Improvement of disk tools. Ag. Eng. J., Vol. 20:215, 1939.
17. Clyde, A. W. Mounted plows and their effects on the tractor. Ag. Eng. J., Vol. 2:167, 1940.
18. Collins, E. V. Factors influencing the draft of plows. Ag. Eng. Transaction. Vol. 14:39, 1920.
19. Collins, E. V. Making a tractor drawbar test. Ag. Eng. J., Vol. 2:19, Jan. 1921.
20. Collins, E. V. The direct application of mechanical power to soil tillage. Ag. Eng. J., Vol. 10:165, May 1929.
21. Cook, R. L. A comparison of tillage implements. Ag. Eng. J., Vol. 31:211, 1950.
22. Davidson, J. B. Influence of speed on the draft of plows. Ag. Eng. Transaction, Vol. 13:69, 1939.
23. Davidson, J. B. The manless plow. Ag. Eng. Transaction, Vol. 18:53, 1924.
24. Davis, Dale S. Empirical Equation and Nomography. McGraw-Hill Book Company, Inc., New York and London, 1943.
25. Dejuhasz, K. J. and Clyde, A. W. Model experiments on tillage tools. Pa. Exp. Sta. Instruments, 12, 1939, N.S.P. 144, Penn. Sta. Bul. 382, p. 19.
26. Dover, Ralph D. and Nichols, M. L. Dynamics of soil on plow moldboard surfaces related to scouring. Ag. Eng. Transaction, Vol. 28:9, 1934.
27. Duely, F. L. and Jones, M. M. Effect of soil treatment on the draft of plows. Soil Science, 21, No. 4:277-288, 1926.
28. Fletcher, L. J. The development of deep tillage in California. Ag. Eng. Transaction, Vol. 17:202, 1923.
29. Gray, R. B. A farm tillage machinery laboratory. Ag. Eng. J., Vol. 15:6, 1934.
30. Green, John M. Some rotary tillage applications. Ag. Eng. J., Vol. 27:175, 1946.
31. Gordon, E. D. Physical reactions of soil on plow disks. Ag. Eng. J., Vol. 22:205, 1941.

32. Haines, W. B. Studies in the physical properties of soils and mechanical properties concerned in cultivation. *J. Agr. Sci. (England)* 15, No. 2:178-200, 1925.
33. Haines, W. B. Studies in the physical properties of soils. *J. Agr. Sci. (England)* 15, No. 4:529-543, 1925.
34. Haines, R. G. Analysis and control of landslides. *Washington Engin. Exp. St. Bul.* 91:57, 1936.
35. Iyer, P. V. K. and Kao, P. S. Preliminary investigation into the influence of the fundamental dimensions of a plow and drawbar pull depth and resistance per unit area. *J. Agr. Sci.* 14:240-4, June, 1944.
36. Jennings, B. A. Plow adjustment. *Cornell Ag. Ext. Bul.* 381:1-36, 1942.
37. Keen, B. A. The use of the dynamometer in soil cultivation studies and implement trial. *J. of Royal Agr. Society of England* 36:30-43, 1925.
38. Keen, B. A. and Haines, W. B. Studies in soil cultivation I-III. *J. of Agr. Sci. (England)* 15, No. 3:375-406, 1925.
39. Keen, B. A. Physical research on problems of soil cultivation. *Tropical Agr.* 19:143, July, 1942.
40. Keen, B. A. *The Physical Properties of The Soil.* Longmans, Green and Co., New York, 1931.
41. Kummer, F. A. and Nichols, M. L. The dynamic properties of soil. IV - a method of analysis of plow moldboard design based upon dynamic property of soil. *Ag. Eng. J.* Vol. 13:279, Nov. 1932.
42. Kummer, F. A. and Nichols, M. L. A study of nature of physical forces governing the adhesion between soil and metal surfaces. *Ag. Eng. J.*, Vol. 19:73, 1938.
43. Kummer, F. A. The dynamic properties of soil. VIII - The effect of certain experimental plow shapes and materials on scouring in heavy clay soils. *Ag. Eng. J.*, Vol. 20:111, 1939.
44. King, F. H. *Physics of Agriculture.* F. H. King, Madison, Wisconsin, 1894.
45. Kummer, F. A. Dynamic properties of soils as applied to the elements of implement design (Experiment on wooden and metal plow). *Alabama Sta. Report*, 1938, pp. 1-8.

46. Kummer, F. A. The dynamic properties of soils. Ag. Eng. J., Vol. 26:21, 1945.
47. Langhaar, Henry L. Dimensional Analysis and Theory of Models. John Wiley and Sons, Inc., New York, 1951.
48. Lindgren, A. C. Coordination of theory and practice in plow design and operation. Ag. Eng. J., Vol. 15:150, 1920.
49. Lucas, D. B. Plowing draft tests on fertilizer plots. Ag. Eng. J., Vol. 9:335, Nov. 1928.
50. McKibben, E. G. The soil dynamic problem. Ag. Eng. J., Vol. 7:412, Dec. 1926.
51. McKibben, E. G. A study of the dynamics of the disk harrow. Ag. Eng. J., Vol. 7:92, March 1926.
52. Nichols, M. L. An analysis of soil dynamics: Factors affecting the operation of tillage and tractor machinery. Ag. Eng. Transaction, Vol. 17:174, 1923.
53. Nichols, M. L. Methods of research in soil dynamics as applied to implement design. Alabama Sta. Bul. 229-27, 1929.
54. Nichols, M. L. The dynamic properties of soil. Ag. Eng. J., Vol. 12:321, August, 1931.
55. Nichols, M. L. Methods of research in soil dynamics as applied to implement design. Ag. Eng. J., 13:279-285, 1932.
56. Nichols, M. L. The dynamic properties of soil; shear values of uncemented soils. Ag. Eng. J., Vol. 13:201, Aug. 1932.
57. Nichols, M. L. The dynamic properties of soils by means of colloidal films. Ag. Eng. Transaction, Vol. 26:37, 1932.
58. Nichols, M. L. and Reed, I. F. Physical reactions of soils to plow moldboard surfaces. Ag. Eng. Transaction, Vol. 28:14, 1934.
59. Nichols, M. L. and Doner, R. D. (V) Dynamics of soil on plow moldboard surfaces related to scouring. Ag. Eng. J., Vol. 15:9, 1934.
60. Randolph, John W. A method of studying soil stresses. Ag. Eng. J., Vol. 6:134, June 1925.

61. Randolph, John W. Tests of tillage tools. Ag. Eng. J., Vol. 19:29, 1938.
62. Reed, I. F. The status of research on plowing problems. Ag. Eng. J., Vol. 15:3, Jan. 1934.
63. Reed, I. F. Tests of tillage tools. I - Equipment and procedure for moldboard plows. Ag. Eng. J., Vol. 18:111, 1937.
64. Reed, I. F. Tests of tillage tools. III - Effect of shape on the draft of fourteen inch moldboard plow bottom. Ag. Eng. J., Vol. 22:101, 1941.
65. Reed, I. F. Some factors affecting design of tillage machinery and proposed approach to their evaluation. Soil Sci. Soc. Amer. Proc. 9:223-5, 45, 1944.
66. Richards, L. A. Pressure membrane apparatus - construction and use. Ag. Eng. J. 10:451-54, Oct. 1947.
67. Richards, L. A. Methods of measuring soil moisture tension. Soil Sci. Vol. 68, No. 1:95-112, July, 1949.
68. Russel, J. C. Report of committee on soil consistency. Amer. Soil Survey Assoc. Bul. 9:10-22, 1928.
69. Seaholm, J. P. Problems of plow bottom manufacture. Ag. Eng. J., Vol. 15:7, 1934.
70. Sjogren, O. W. Development of offset disk harrow. Ag. Eng. J., Vol. 17:503, 1936.
71. Slipher, John A. The mechanical manipulation of soil as it affects structure. Ag. Eng. J. 13:7-10, 1932.
72. Stirniman, E. J. Draft test of farm machinery. Ag. Eng. Transaction, Vol. 11:9, 1917.
73. Trullinger, R. W. The fundamental approach to tillage and traction research problems. Ag. Eng. J., Vol. 18:17, 1937.
74. Walker, H. B. The engineer and tillage research. Ag. Eng. J., Vol. 11:281, Aug. 1930.
75. Williams, Ira. L. Measurement of soil hardness. Ag. Eng. J., Vol. 20:25, 1939.
76. Yoder, R. E., et al. Report on the investigation of physical property of soil. Alabama Station Rpt. 1937, pp. 7-9.



MICHIGAN STATE COLLEGE AG. ENG. DEPT.	
DATE 12-30-53	SCALE 1"=1'
DESIGNED BY B.T.	DRAWN BY B.T.
ASSEMBLY DRAWING SOIL TROUGH FOR TILLAGE EXPERIMENTS	