PENETRATION OF PARTICLES INTO SOILS

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CHAPTER I

INTRODUCTION

Agricultural machinery is, in many respects, the most difficult class of machinery to design. These machines must function under a very wide variety of operating conditions, be simple, have a high degree of reliability, and be economical to operate.

Many types of agricultural machinery have been designed and developed. The use of these machines has resulted in reduced labor requirements by partial, and in some cases, complete mechanization of diverse agricultural processes. Many agricultural operations, however, are still not mechanized. Existing machinery needs refinement and new machines are needed to perform tasks not now mechanized.

Among the agricultural machines developed and widely used are the seeding machines that perform crop planting operations.

Crop planting operations may involve placing of seeds or tubers (such as potatoes) in the soil at a predetermined depth, or random scattering or dropping of seeds on the field surface (broadcasting), or setting of plants in the soil. The following methods are widely practiced:

1. Broadcasting
2. Drill seeding
3. Precision drilling
4. Hill dropping
5. Checkrow planting

Many factors affect the emergence of seedlings. Some of these factors are:

1. Type and quality of seeds.
2. Soil moisture conditions.
3. Physical condition of the seedbed.
4. Intimacy of contact between the soil and seed.
5. Depth of planting.
6. Planter performance.
7. Soil temperature.

All the seeding machines presently available, with the exception of broadcasters, perform the following mechanical functions (1, pp. 221-225):

1. Open the seed furrow to the proper depth.
2. Meter the seed.
3. Deposit the seed in the furrow in an acceptable pattern.
4. Cover the seed and compact the soil around the seed to the proper degree for the type of crop involved.

Most seeding machines disturb the seedbed during the planting operation. Seeds are deposited at irregular depths due to irregularities of the seedbed. The soil moisture content may be changed during planting. Weeds and plant residues contravene the optimum conditions needed for perfect germination. The adverse effects of these factors could be eliminated if a new method were devised whereby seeds could be injected into the seedbed from above. The seed would require sufficient energy at the soil surface to enable it to penetrate a predicted distance into the soil.

CHAPTER II

OBJECTIVES

The objectives of this study were: to design an apparatus that would characterize soil resistance, to design an apparatus that would inject particles, at varying velocities, into the soil, and to determine the effect of soil type and moisture content on the depth of penetration of particles.

This study was primarily concerned with determining the feasibility of designing a new type of seeding machine that will shoot seeds, needing precision planting, into the soil to a specific depth.

Another study would be required to answer a second question, namely, if it is feasible to give a seed enough energy to penetrate a certain vertical distance into the soil, would the rate of energy extraction required to penetrate the soil surface impair the germination of the seed?

Pertinent Factors

The pertinent factors involved with the penetration of a geometrical figure (particle) into the soil are:

1. The energy of the particle at the surface of the soil which is in turn a function of the mass and the velocity of the particle in question.
2. Shape and condition of surface of the geometrical figure.

3. Class of soil.
4. Moisture content of the soil.
5. Bulk density of soil.

Parameters

The following parameters were set in conjunction with the factors affecting depth of penetration of a geometrical figure:

1. No actual seeds were injected into the soil. Spherical nylon particles having a smooth surface were used in these tests.
2. Three distinct classes of soil were considered.
3. Three levels of moisture content for every soil were investigated.
4. Soil compaction was not a controlled variable.
5. The particles were injected vertically from a point above the surface of the soil under consideration.

CHAPTER III

REVIEW OF LITERATURE

In making this study, two primary factors were involved. One was the soil resistance to the penetration of a probe. The other was the resistance to penetration of soil by particles at different adjustable velocities. Each factor will be discussed and information on each, thought to add to the meaning of this study, will be presented.

Soil Resistance to Penetration

In reading the literature written since 1928 on the resistance of soil to penetration, it was noticed that most of the literature was directed to find the effect of tractor wheels and implements on the soil surface and sub-soil resistance. Much research has also been reported to answer the questions raised as to the effects of plowing in loosening the soil and how the shapes of plows affected soil conditions. Some of the studies were made to find the relationships between soil compaction, moisture content, and class of soil.

A. A. Stone and I. R. Williams (12, pp. 25-26) developed a soil hardness gage that consisted of a cylindrical tube or barrel 55 inches in height and 1-1/2 inches in diameter. This barrel was mounted on a 10 inch square plate of 3/16 inch steel. The penetrator was a piece of round steel 24 inches long, 1-1/2 inches in diameter at the top and tapered to 1/4 inch diameter at the tip which was rounded. It was divided into one inch and 1/4 inch graduations. At the lower end, narrow slots extended upward from the base on opposite sides of the barrel. A retainer was mounted at the upper end of the barrel, with a pin for suspending the penetrator at a fixed height of 36 inches above ground level. The retaining pin could be withdrawn manually by the operator to drop the penetrator. According to this study, many factors affect soil resistance, the most important of which are soil class, moisture content, and bulk density. A soil rated as sandy had a resistance of 3-lb/in^2 whereas a moist prairie sod had a resistance of 15-lb/in^2.

C. W. Terry and H. M. Wilson (13, p. 425 and 4, pp. 831, 834) designed a simple apparatus to determine the degree of compaction of soils. The unit was self-recording. It had a recording pointer which was positioned by the depth of penetration of the probe and by the downward force required to overcome resistance to penetration. When the point was pushed into the ground, a curve was drawn showing force versus penetration from the surface of the ground to the maximum depth of penetration. The force measurement was based on the fact that deflection of a spring below its elastic limit was directly proportional to the force applied. Force was applied to the probe through a calibrated spring. The depth of penetration was measured by means of a chart board supported on a foot that rested on the top of the ground, while a pointer, attached to the probe, moved down a distance equal to the depth of penetration.

The best and most accurate results of this penetrometer were obtained when used in soils of 20 percent moisture content.

For a soil with a volume density of 1.35, 25 pounds of force were required to force the probe to a depth of 13 inches. The projected frontal area of the probe was 0.20 in^2.

J. H. McCleland (9, pp. 480-481) devised a soil probe or continuous recording horizontal penetrometer for evaluating mechanical properties of soils including resistance to vertical penetration.

SR-4 strain gages were used by R. J. Hanks and K. A. Harkness (5, pp. 553-554) to measure soil-crust strength in connection with an investigation of wheat-seedling emergence. A penetrometer with a probe about the size of a wheat seedling was selected. Figure 1 shows a schematic diagram of the force detecting components.

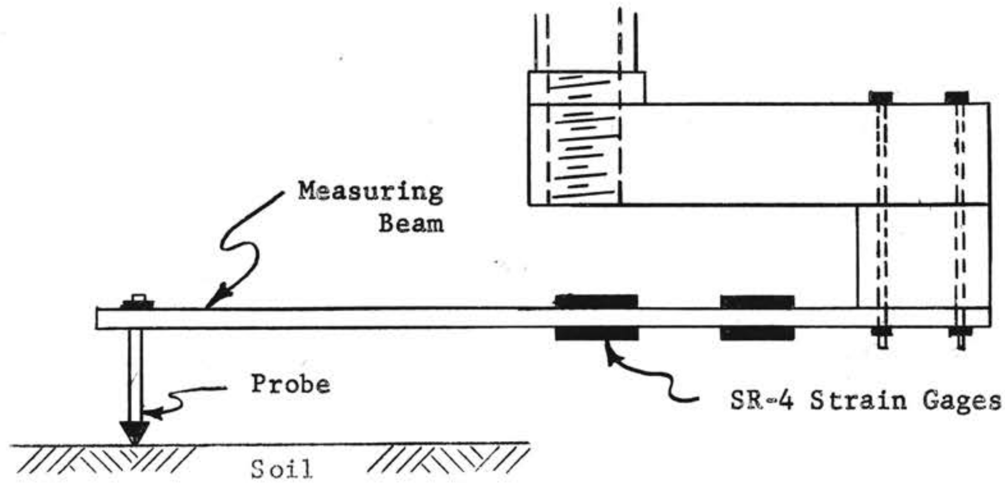

FIGURE 1. Schematic Diagram of the Strain-Gage Penetrometer Components

Preliminary trials showed that the penetrating force involved with the probe used ranged up to above four pounds. Their results also indicated that the friction of mechanical devices, similar to those used by other workers, caused large relative errors in this force range.

When the probe comes in contact with the soil, the resulting force of the soil is reflected by an accompanying strain of the beam supporting the probe. The magnitude of this force is indicated electrically by means of strain gages bonded to the beam. The linear relationship of strain, to applied force was determined by calibration with known forces. Using four SR-4-500 ohm strain gages allowed for automatic temperature compensation.

The soil resistance, according to Claude Culpin (2, pp. 22-35), is due to soil cohesion, soil plasticity, and surface friction between the soil and the metal.

Culpin (4, pp. 432-446) designed an apparatus to measure the soil resistance consisting mainly of a probe, two springs, attached to the probe by a rocker arm and a recording chart. This instrument used three sets of springs according to the soil condition and it was calibrated by use of known weights. It was noted that the speed of penetration of the probe--varied by means of a special gearing--has a pronounced effect on the resistance value obtained; the average resistance for a speed of one inch per second was 32.6 pounds, for a speed 1/8 inch per second was 30.6 pounds and for 1/4 inch per second was 30.7 pounds for the same soil. It was concluded that large increases in speed of penetration would give appreciable increases in the resistance to penetration.

The soil resistance tests showed that the resistance to penetration was less at a higher moisture content. Roughly the resistance of the soil was inversely proportional to its moisture content keeping other factors constant.

Also, it was shown that more force was needed to accomplish probe penetration for the first inch below the soil surface than for the depths below the first inch. On one gyrotilled plot the relationships shown in Table I were obtained.

TABLE I. Force Required for a 1-Inch Probe Penetration at Different Soil Depths

Depth	Average Force Pounds per Inch
1st inch	20.0
2nd inch	12.2
3rd inch	10.0
4th inch	9.5
5th inch	8.2
6th inch	7.6
7th inch	7.1
8th inch	6.3
10th inch	6.0
12th inch	5.1

Another type of penetrometer utilizing dead weights was designed by O. Heath (6, pp. 205-212). It consisted of a wooden tripod that supported an iron rod having at its lower end a steel cone. The length of steel pipe which surrounded the rod and rested on the upper end of the cone, served to carry the force of the impact direct to the cone; the rod serving only as a guide. A cylindrical weight was lifted to a certain height and allowed to fall freely on the top of the cone. This distance could be measured after each drop.

The energy of a single impact was 69.9 Kg.-Cms.

The following set of data, Table II, were obtained in plowed soil between a depth of 9 to 17 Cms. An average of four readings were taken. The moisture content was 17.82 percent.

TABLE II. Effect of Soil Condition on the Number of a 69.9 Kg.-Cms. Impacts to Obtain a Probe Penetration of 1 Cm.

Condition of Soil	Impacts per Cm.
Compressed	0.973
Normal	0.970
Grubbed	0.660

According to B. A. Keen and G. H. Cashen (7, pp. 126-134), equal energy increments produce progressively decreasing increments of descent of the probe driven into the soil by dead weights set at a vertical distance above the ground level. For a 10 Cms. penetration of the probe, the energy required was above 200 Kg.-Cm. at the soil surface; for a 20 Cms. depth of penetration about 350 Kg.-Cms. were required.

Depth of Penetration of Seeds or Particles Into Soil

No direct study has been made to determine the depth of penetration of seeds or particles into soils under any specific condition or set of parameters.

Claude Culpin (4, pp. 432-446) shot bullets from a revolver and a rifle in order to determine the resistance of soil to penetration; the depth of penetration of the bullets was about 30 Cms.

A recent study was made by Ivan W. Kirk and H. E. McLeod (8) on cotton seed rupture from both static force and impact velocity. An apparatus was designed that accelerated a single cotton seed to a given velocity and impinged it against a flat steel plate. The apparatus consisted of an air-pressure regulator and gage, a seed drop chamber, a blow-pipe and a 1/2 inch brass pipe 12 feet long. The blow-pipe was connected to an air line from an air compressor. An air pressure regulator with a pressure gage on the outlet was used to regulate air flow through the pipe. The system was under pressure at the pipe inlet so it was necessary to use an air tight chamber in order to drop the seeds, one at a time, into the air stream.

The blow-pipe was first calibrated for pressure gage reading versus air velocity. Stroboscopic pictures of a seed after it left the blow-pipe outlet were used to obtain a calibration of pressure gage reading versus seed velocity.

Cotton seeds were subjected to direct impact on a steel plate to determine the percent of seed rupture at seed velocities of 3000, 4000, 5000, 6000, and 8000 feet per minute. Three replications were made at each of three moisture contents, 6, 10, and 14 percent.

The average percent seed rupture for each velocity at the three moisture contents is presented in Table III.

The conclusions obtained from these experiments are the following:

1. The average percent seed rupture was found to be independent of moisture content and had, due to impact velocities, values of 1.22, 2.89, 7.44, 17.00 and 55.55 percent for seed velocities of 3000, 4000, 5000, 6000, and 8000 feet per minute, respectively.
2. Throughout the range of velocities tested in this investigation, the percent seed rupture is expressed by the following equation:

$$\text{Percent Seed Rupture} = 4.77 \times 10^{-16} (\text{Seed Velocity})^{4.38}$$

where seed velocity is given in feet per minute.

3. The relationship of seed velocity to air velocity is represented by:

$$\text{Seed Velocity} = 0.71 \text{ Air Velocity}$$

4. The average static energy absorption for cotton seed at a dry-basis moisture content of 10 percent and an average seed weight of 0.11 gms. was 0.969 inch-pounds at a seed velocity of 7460 feet per minute which produced a median rupture of 50 percent.

TABLE III. Average Percent Cotton Seed Rupture Due to Direct Impact for Five Seed Velocities and Three Moisture Contents

Seed Velocity Feet/Minute	Dry-Basis Seed Moisture Content, % 6	10	14
3000	0.67	2.00	1.00
4000	3.00	2.00	3.67
5000	8.80	8.33	6.00
6000	18.67	15.00	17.33
8000	58.00	52.33	57.33

CHAPTER IV

EXPERIMENTAL EQUIPMENT

Penetrometer

Although there are some available designs for penetrometers, (5, 12, 13, 14), it was felt that the available designs would be somewhat complicated and that the probes used, being conical at their points, would make the task of calculating the resistance of the soil to penetration impossible. The soil resistance would be divided between skin friction resistance and bearing resistance in unknown proportions.

The penetrometer used in the study consisted of a frame built out of angle iron in a box shape. Figure 2 shows a schematic diagram of the components of the penetrometer. The vertical members of the frame (A) are two feet long and made of 1-1/4 x 1-1/4 x 3/16 inch angle iron. The top of the frame (B) is made of similar angle iron with a rectangular shape of 2 feet by 1.5 feet. The bottom of the box (C) has only three 1-1/4 x 1-1/4 x 1/16 inch angle iron members, the fourth (2 feet) member was left out so that the sample box placed underneath the probe could be moved within the frame to any desired position.

The support members of the probe-rod were two, 2 x 2 x 1/4 inch angle iron, members (D) welded to the center of members B; the spacing between the two sides of these angle irons was 2-3/16 inches.

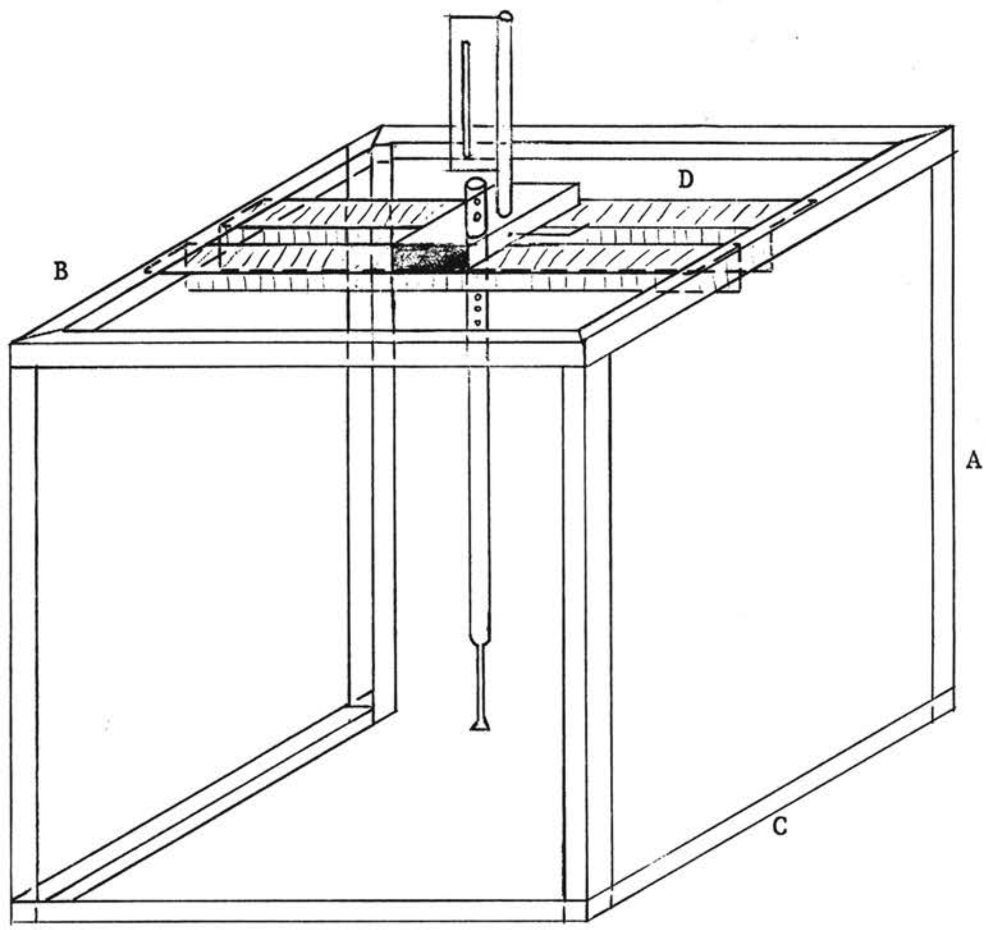

FIGURE 2. Schematic Diagram of the Component Parts of Penetrometer

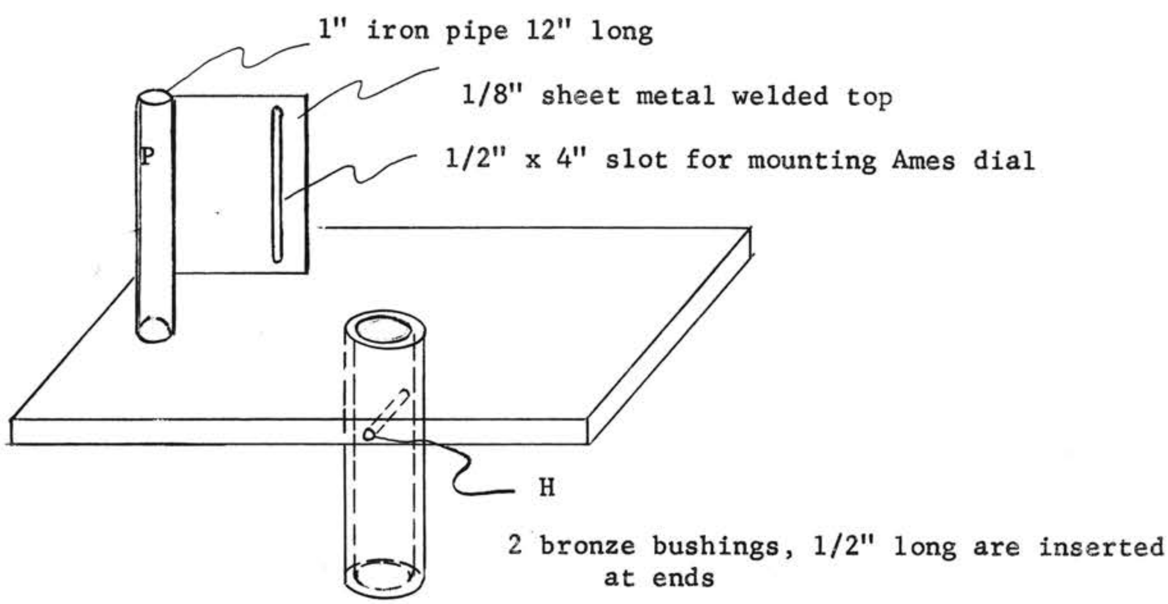

FIGURE 3. Schematic Diagram of Probe-Rod Guide and Support

The probe-rod guide and support is shown in Figure 3. Two bronze bushings with an inside diameter of 1.0625 inches and 1/2 inch length were inserted in the center of the guide. Two holes 17/64 inch in diameter (H) were provided at the sides for two pins to lock the probe-rod at a certain height. This element was bolted with 1/2 inch bolts at the center of the 2 x 2 x 1/4 inch angle iron members.

The probe-rod, Figure 4, was a steel bar one inch in diameter, 18 inches long, and weighing 3.93 pounds. At the sides of one end of the rod were seven 17/64 inch diameter holes, 0.25 inch deep, and spaced on 1/2 inch centers on opposite sides of the rod to provide for coarse height adjustment of the probe. At the other end of the rod a 1/4 inch diameter, one inch deep hole was drilled and threaded with 28 NF threads to provide for fine height adjustment of the probe. A 17/64 inch diameter hole was drilled, through the rod at a distance of two inches from the threaded hole end, to provide for holding the cylindrical weights by means of a 1/4 inch diameter pin.

Two steel probes Figure 5 (A) were made. The first was one inch in diameter and five inches long with the last inch of its length reduced to 1/4 inch diameter and threaded with 28 NF threads. The second probe, Figure 5 (B), was one inch in diameter at one end. Above this end was a conical shape starting with the lower edge and reduced to 1/2 inch diameter 1/2 inch above the base. The 3-1/2 inches next to the conical section were 1/2 inch in diameter. The last one inch of the probe was 1/4 inch in diameter and threaded with 28 NF threads.

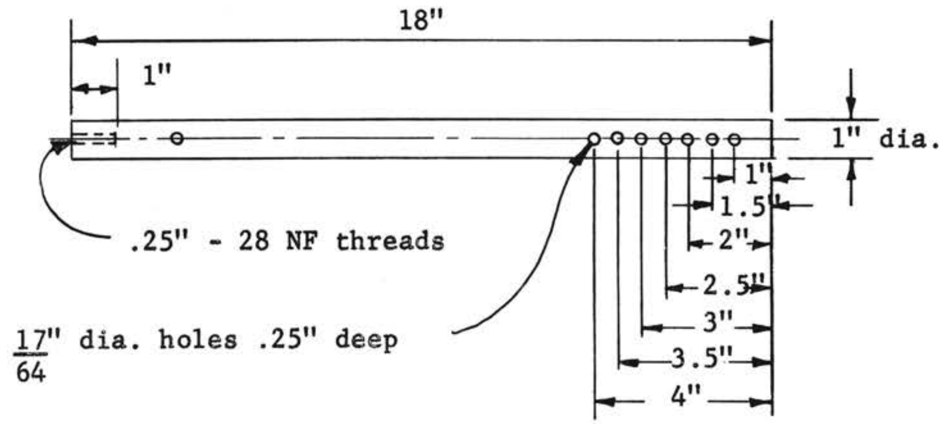

FIGURE 4. Schematic Diagram of Steel Rod

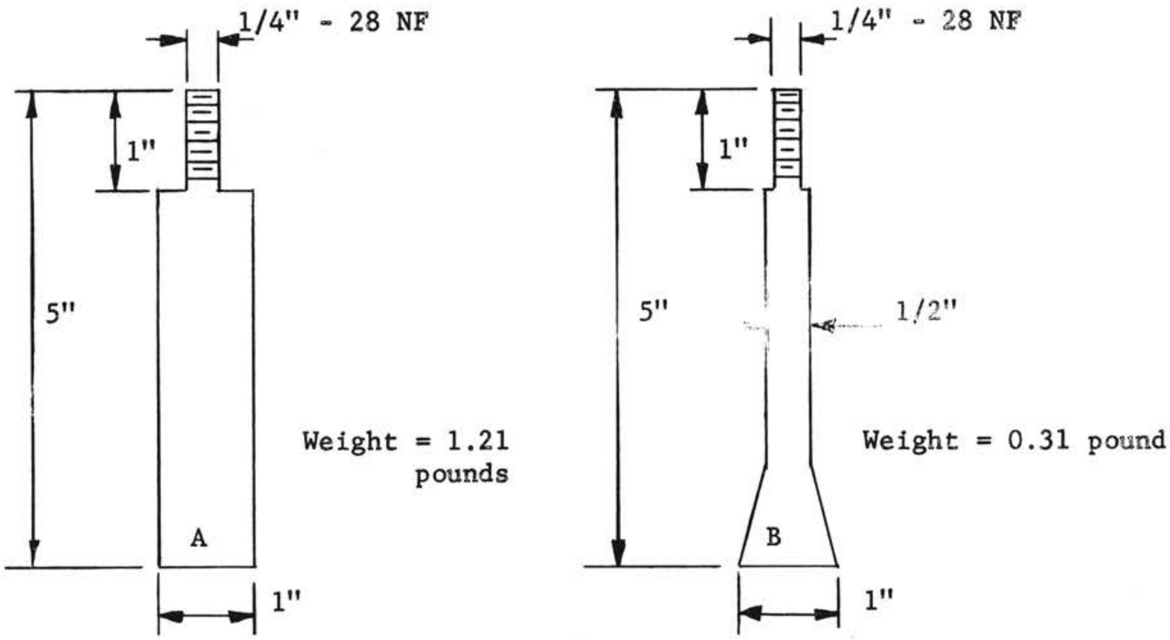

FIGURE 5. Schematic Diagram of Cylindrical and Conical Probes

The pins were made of 1/4 inch steel rod 6 inches long. The pins were bent as shown in Figure 6.

An Ames dial support was bolted to the rod guide above its center. The dial support had a vertical slot 1/2 x 4 inches to provide for zero dial adjustment.

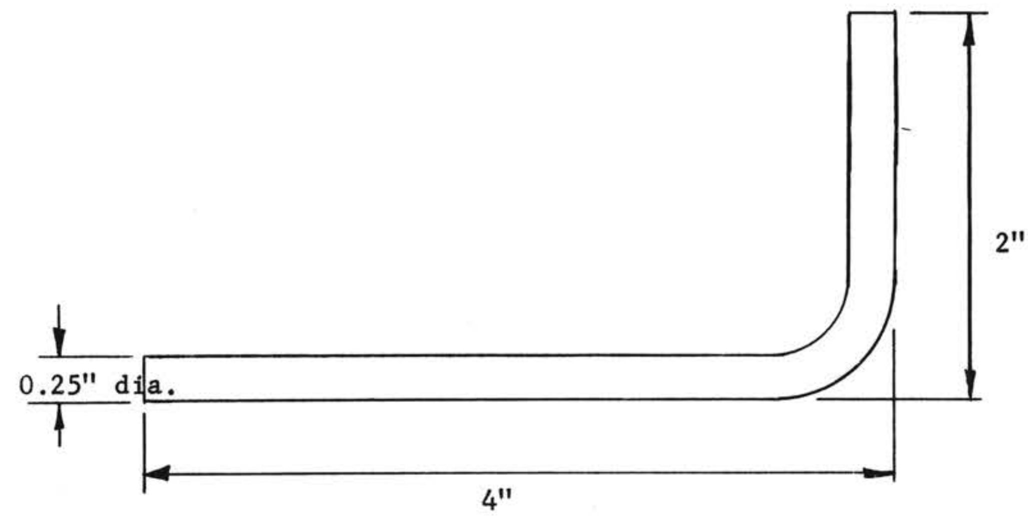

FIGURE 6. Schematic Diagram of Lock Pin

Figure 7 shows the penetrometer with the sample box placed underneath the one inch diameter conical probe.

Weights

The weights were made of iron cylinders drilled at the center with a hole diameter of 1.0625 inches. The weights were made in 5, 10 and 20 pound units. The cylindrical shape of the weights was chosen to give the probe a balanced loading with no eccentricity.

Sample Boxes

Two sample boxes were made of 1/16 inch sheets of iron with inside dimensions of 12 inches in length by 12 inches in width by 6 inches in height. Two 1-1/2 x 1-1/2 x 1/16 inch angle iron members were welded to opposite sides of the boxes 1/16 inch below the top edges. These angle irons were slotted to provide for adjustable bolting of the depth measuring device. Each slot was 1/2 inch wide and 11 inches long. The weight of one box was 16.10 pounds and the other was 14.78 pounds.

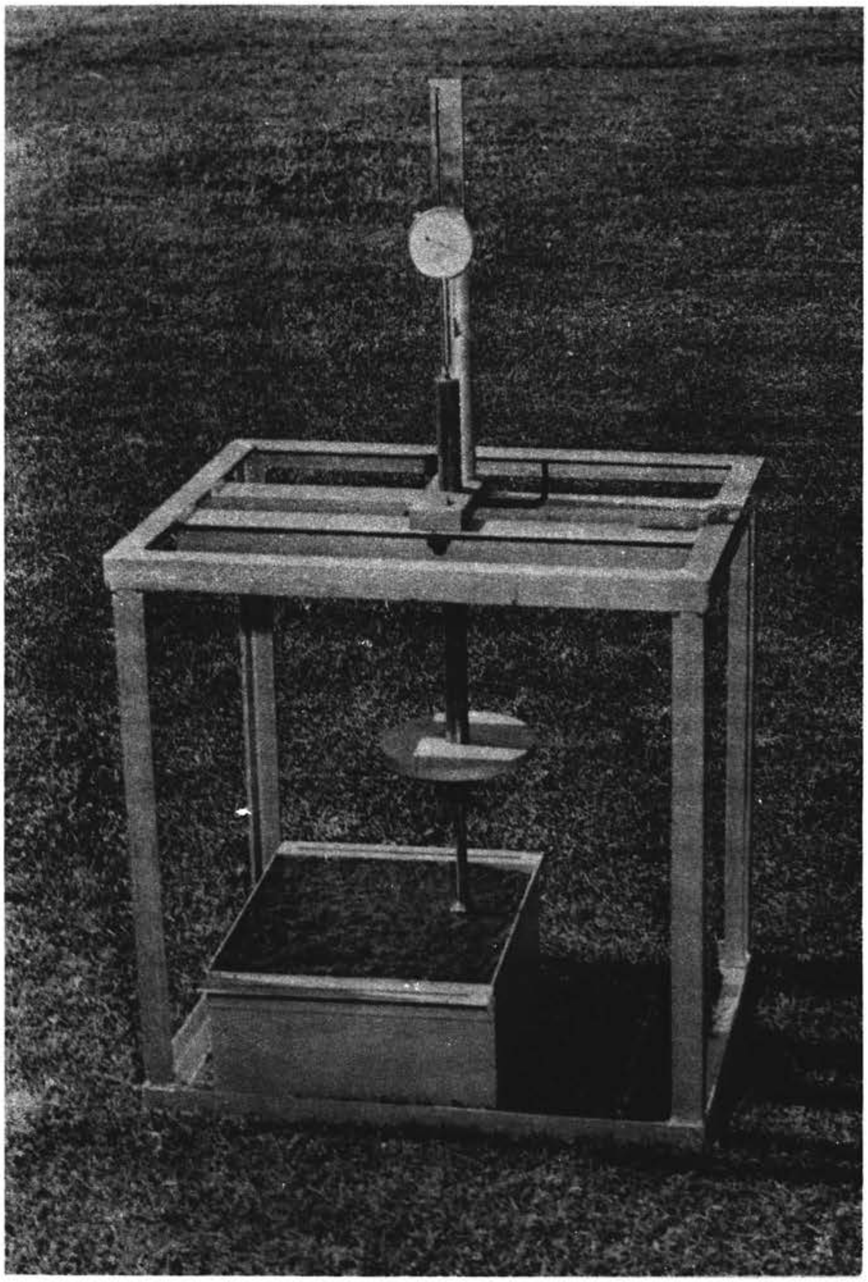

Figure 7. Penetrometer with sample box placed underneath the conical probe.

Air-Gun

Figure 8 shows a schematic diagram of the device used to shoot the particles into the soil. It consisted of an air tank (A) made out of two inch black iron pipe with an air check valve, similar to those used on tractor tires, at one end and threaded at the other end to fit a two inch quick-opening valve. Attached to the other end of the valve was a two inch pipe plug drilled in the center to a hole diameter of 0.2625 inch. A 1/4 inch inside diameter aluminum tube was welded to the pipe plug, after being inserted into the hole in the pipe plug. The tube was flanged at one end and slightly constricted.

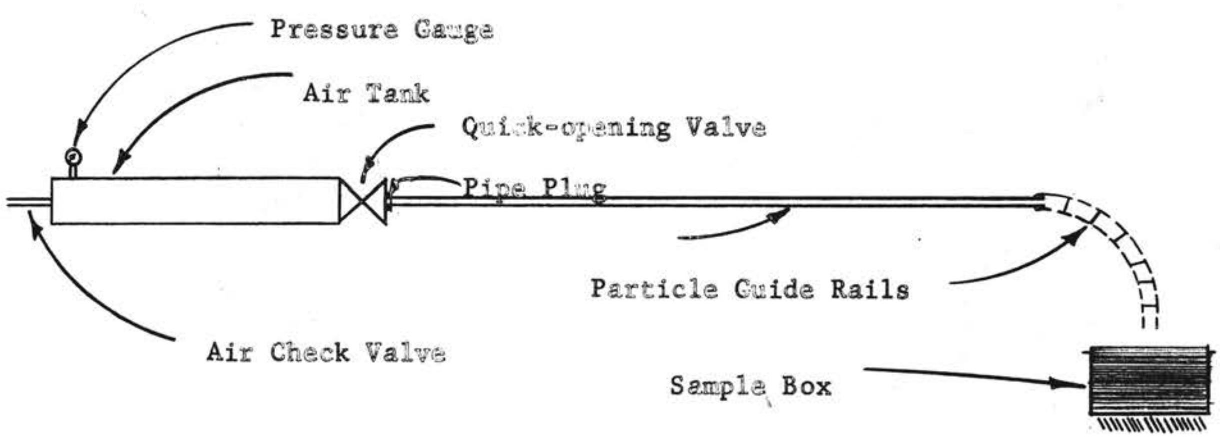

FIGURE 8. Schematic Diagram of Air-Gun

An air pressure gage having a range of 200 psi and 5 psi graduations was attached to the air tank.

A particle-guide rail made from four 1/8 inch wires was inserted at the outer end of the aluminum tube. A 5/16 inch spacing was provided between the wires. The wires were welded at two-inch intervals. The guide rails were twisted to form a quarter circle having a radius of one foot to provide for directing the horizontally shot particles into the soil at a right angle to the soil surface. The particle guide was made of four rails so that the air coming after the particle would take a horizontal path and therefore leave the ball deviate 90 degrees through the curved rail without any air following. Air would cause a disturbance of the soil surface.

A pressure drop of five percent or less was achieved between the air tank and the end of the aluminum tube when the valve was opened. To provide for this condition, a two feet long air tank was built with a six feet long aluminum tubing.

Figure 9 shows a picture of the complete setup of the shooting mechanism.

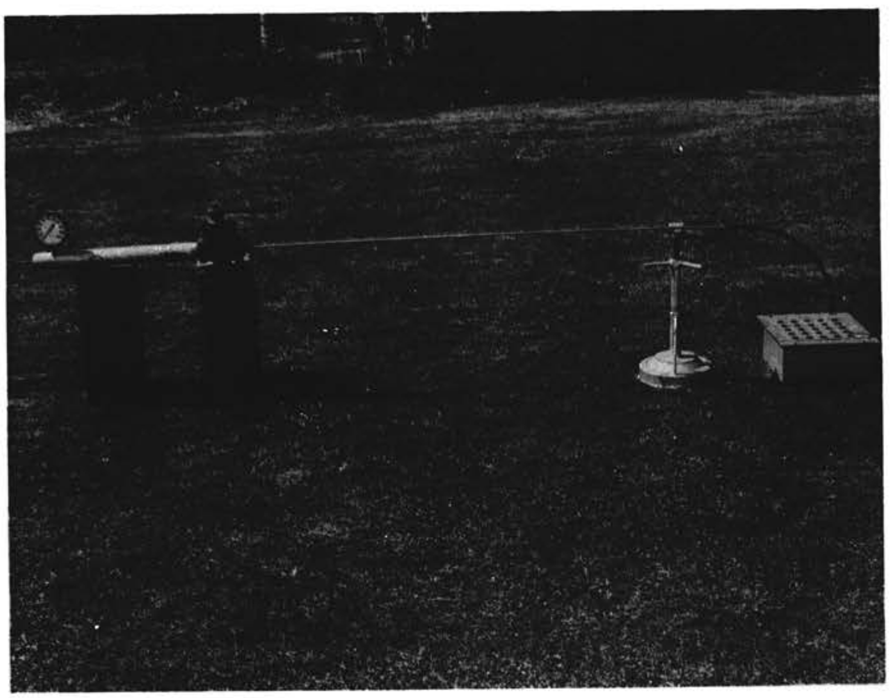

FIGURE 9. Air-Gun

Ballistic Pendulum

Figure 10 shows a schematic diagram of the ballistic pendulum. An oak block weighing 123.37 grams was used. Attached to its four corners were four strings. The block was suspended vertically 189.60 cms. below a fixed support. Padding weighing 31.51 grams was pressed on one end of the block to catch the particles and thus make the impact of the particle with the block inelastic.

A metal stick with a metal rider was placed below the block to measure the displacement of the block after the impact.

Depth Measuring Gage

To the center of a 1-1/2 x 1-1/2 x 3/16 inch angle iron, 28 inches long, a one inch pipe was welded at right angles.

Figure 11 shows a schematic side-view of the device.

Figure 12 shows a picture of the depth measuring gage placed on the edges of the sample box. One uncovered particle is also shown.

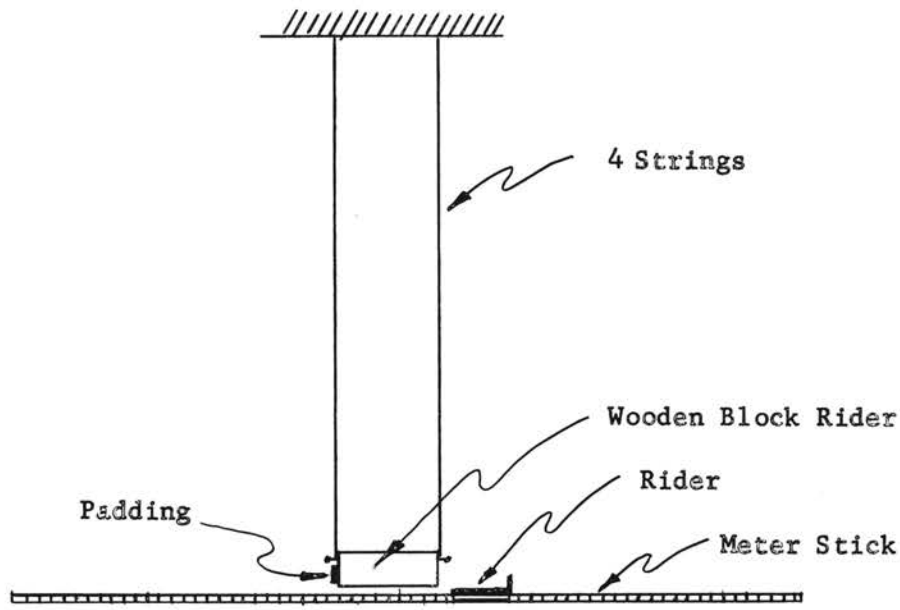

FIGURE 10. Schematic Diagram of Ballistic Pendulum

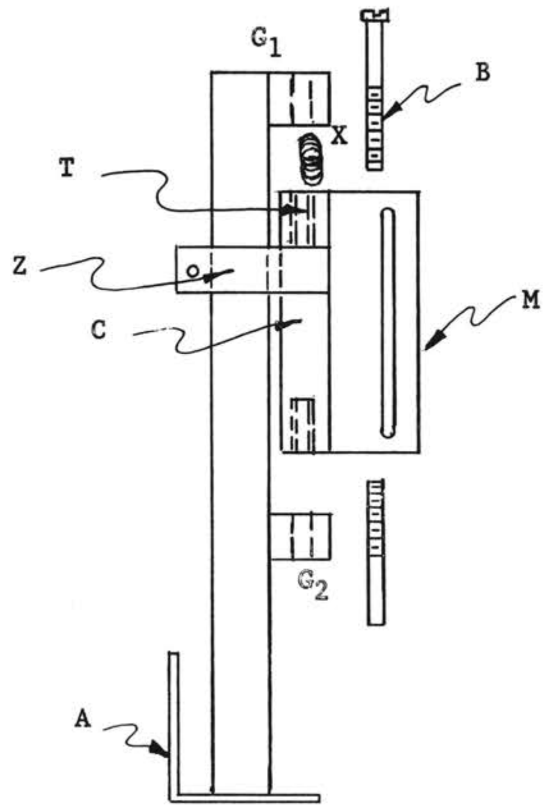

FIGURE 11. Schematic Side View Diagram of Depth Measuring Device

To the one inch pipe was welded two guide bushings (G_1 and G_2) 0.2506 inches in diameter and one inch thick. A 1/2 inch steel rod (C), having a length 1-1/2 inches less than the distance between G_1 and G_2, was drilled at each end with a 1/4 inch drill to a depth of 1-1/2 inches and threaded with 28 NF threads. This was to provide for vertical movement of the unit. One hole accommodated a 1/4 inch by 2-1/2 inch bolt at the top end. This bolt had 1-1/2 inches of 28 NF threads. At the lower end was a three inch brass rod 1/4 inch in diameter with 1-1/2 inches of 28 NF threads. A spring (X) was provided between the top of (C) and the bottom of (G_1) to keep (M) pushed down when the bolt (B) and the brass rod (P) were positioned in (T).

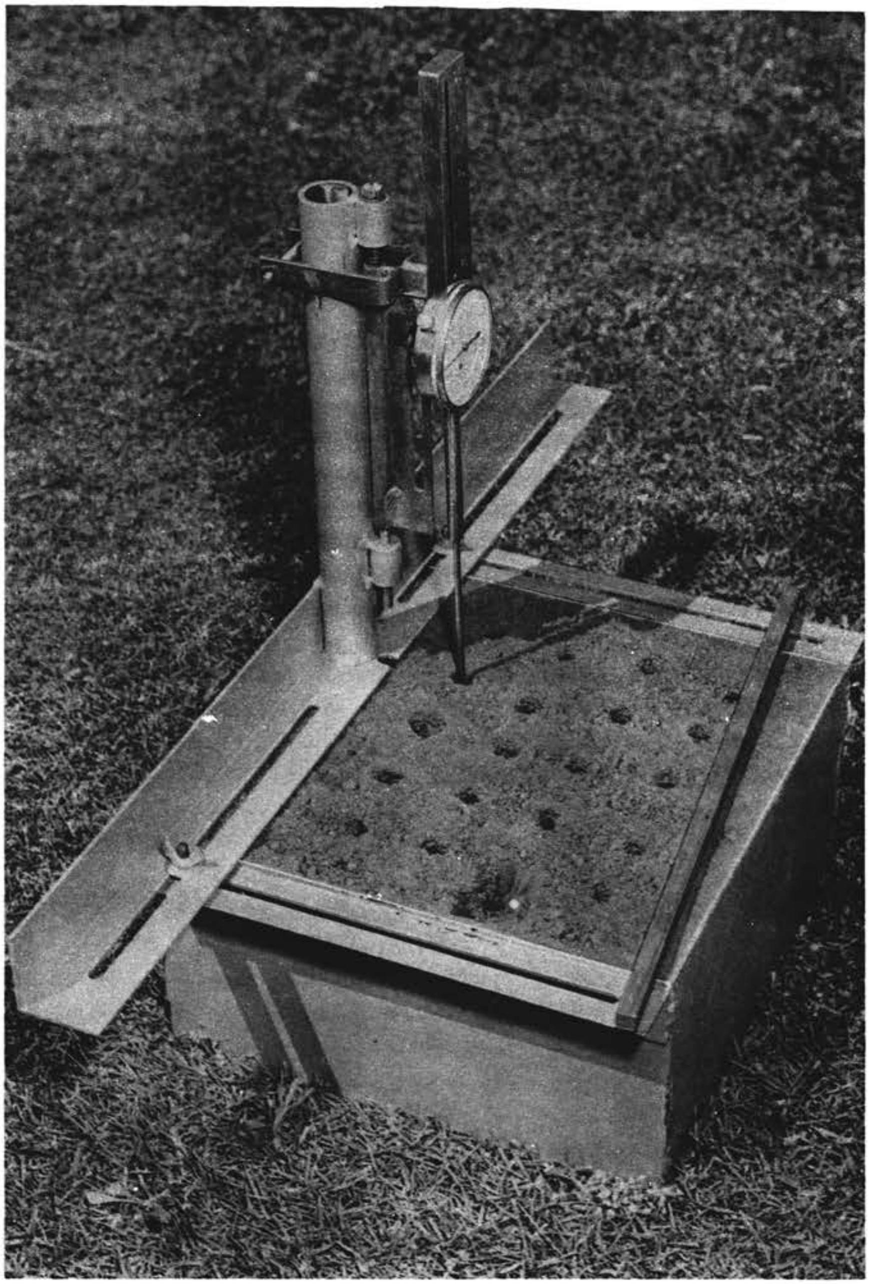

Figure 12. Depth Measuring Gage.

A metal guide, 1/16 inch thick and one inch wide, was welded to (C) two inches below its top. This guide surrounds the iron pipe by means of a 3/16 x 1.5 inch screw from the other side so that (M) moves only vertically.

The angle iron had two 5/16 inch slots extending both ways from the pipe at the center. These slots provided for the positioning of the Ames dial over the particle within the soil.

The Ames dial was bolted to the slot in the metal sheet (M) that was in turn welded to (C). The four inch slot in (M) provided for coarse adjustment of the dial whereas screwing and unscrewing bolt (B) provided for fine adjustment of the dial.

A 14 inch length of square key stock with a thickness of 0.438 inch was used to position the point of the dial.

Templet

A 24 gage galvanized metal sheet 13 inches square was drilled according to the pattern shown in Figure 13. The holes were one inch in diameter. This templet was used to divide the sample box area into 25 (two square inches each) divisions to run a latin square experiment with five replications for each one of the five treatments. It was also used as a cover to protect the soil from losing moisture. All 25 holes were covered except for the one where the particle was to be injected. The templet was attached to the sample box by means of four 1/4 x 1/2 inch bolts and wing nuts placed at the corners.

Air-Compressor

An air-compressor capable of delivering air at 150 psi was used. It was equipped with an air filler hose and attachment for filling the air tank to the desired pressure through the air-check valve.

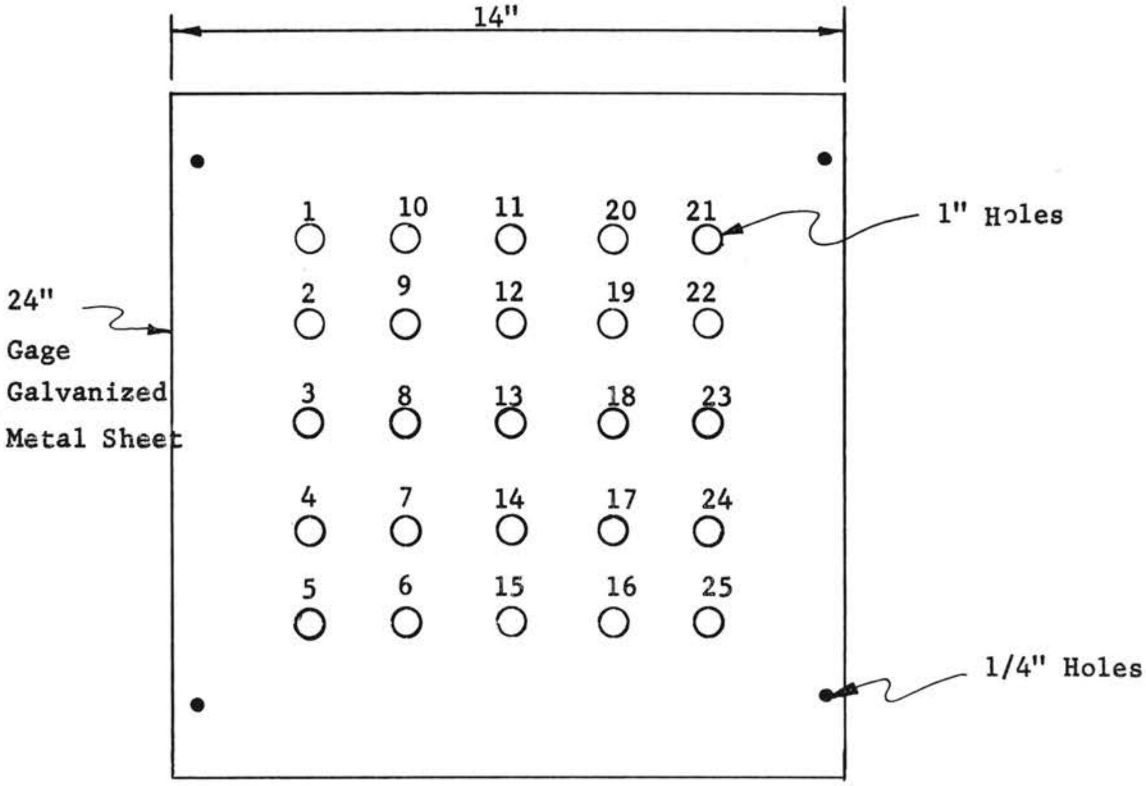

FIGURE 13. Schematic Diagram of Templet

CHAPTER V

PROCEDURE

Determination of Particle Velocity

The particles used in this study were made of nylon and had a very smooth surface. The shape of the particles was spherical. The particles used, 35 in number, were selected to have a diameter of 0.238 inch and a weight of 0.155 gram.

The ballistic pendulum apparatus was set as shown in Figure 11. The guide rails were turned to a position perpendicular to the block, and two inches away from it. The padding was placed on the end of the block and the rider was placed at a zero position on the reference scale. The particle was placed in the aluminum tubing next to the air tank. The quick opening valve was closed. The air tank was inflated to the desired pressure; the valve was then opened and a preliminary shot, not recorded, was made to learn approximately how far would the rider move. Then, before each succeeding shot, the rider was returned only a few millimeters toward its zero position. In this way the rider moves only a small distance and the effect of friction between it and its support was largely eliminated.

A preliminary shot and three other shots at each pressure level were made and readings of the corresponding displacement of the rider were taken.

General Procedure for Conducting Experiments

Soil Resistance to Penetration:

The three soils used in connection with this study belonged to three distinct classes. The soils were designated as I, II, and III. Preliminary experiments were performed on uniform sand designated as 0.

The Agronomy Department at Oklahoma State University ran a particle-size distribution analysis for the three soils. Corresponding moisture content levels at the permanent wilting point (15 Atm.) and at the field capacity (1/3 Atm.) were obtained. The results are shown in Tables IV and V.

TABLE IV. Particle Size Distribution of Soils

Soil Number	% Sand	% Silt	% Clay	Class of Soil
I	48.0	42.0	10.0	Loam
II	50.2	24.3	25.5	Sandy Clay Loam
III	26.4	45.6	28.0	Clay Loam

TABLE V. Moisture Contents of Soils at Field Capacities and Permanent Wilting Points

Soil Number	Moisture Percent at Field Capacity (1/3 Atm.)	Moisture Percent at Permanent Wilting Point (15 Atm.)
I	16.94	5.55
II	22.00	7.13
III	31.52	12.78

The soils used were crushed and plant residues removed. Only that portion passing through a No. 4 sieve was used for test purposes. About one cubic foot of each soil was prepared in this manner.

Planting operations generally take place when the soil moisture content lies between the field capacity and the permanent wilting point. It was, however, decided to conduct the experiments at three moisture levels for each soil. The first run was conducted at a moisture content that was less by 10 percent than the moisture content at field capacity, the second run at a moisture content that was higher by 10 percent than the moisture content at wilting point and the third run at a moisture content that was half way in between those of the first and second runs. The experimental runs with their desired moisture contents are listed in Table VI.

TABLE VI. Experimental Runs at Different Levels of Moisture Contents

	Moisture Content Used - Percent		
Soil Number	Run: 1	2	3
I	6.50	10.74	15.25
II	7.85	13.82	19.80
III	11.50	19.94	28.37

A sample box, described previously, was filled with the soil, that had been prepared and adjusted for moisture to a desired percentage. When the soil was about two inches below the top edge of the box, the box was tapped on the floor by raising it about two inches above the floor and then letting it drop freely. This procedure was repeated three times. The box was then overfilled with the soil and tapped twice more. The excess of soil was then removed by stroking the container with a 2 x 2 x 1/16 inch angle iron from one edge of the box to the opposite edge, thus leaving the soil flush with the top edges of the box.

The soil was then weighed and placed under the penetrometer. The probe of the penetrometer was set, by locking it with the pin. Using the fine adjustment, the probe was caused to just touch the soil surface. The Ames dial was then set to read zero. The soil box was divided into nine equal squares to provide for three loading treatments of 4.24, 9.24, and 14.24 pounds with three replications of each according to a latin square design described elsewhere. The probe was unlocked and the depth of penetration was read from the Ames dial. The probe was raised and locked at its original position, the box was then moved to another of the nine squares according to the latin square design and the procedure repeated until nine readings were obtained with three replications at each loading.

The latin square design was chosen in performing these experiments since it was found, after a preliminary experiment, that there was variations in the soil properties along two directions of the soil in the box and therefore the latin square design was suitable to remove the differences encountered.

Shooting Particles Into Soil:

The box was filled with soil as described elsewhere. The weight of the soil was brought to the same weight as in the run performed for the determination of the soil resistance to penetration. The templet was placed on top of the box containing the soil by means of four bolts and wing nuts attached to the slotted angle irons welded to the sides of the box. The box was placed under the end of the particle-guide rails two inches below the end of the rails which were aimed at hole one shown in Figure 13. The guide rails were removed and a particle was placed into the tube at the end near the quick-opening valve. The guide rail was placed again in position, the valve closed and compressed air was admitted into the air tank until the desired pressure, as read in the pressure gage, was reached. The valve was opened and the particle was thus injected into the soil. The box was moved until it was under hole two of the templet and the procedure of placing the particle and shooting just described was repeated.

Holes 3 through 25 were shot at according to the numerical sequence shown in Figure 13. Five pressures--20, 40, 60, 80, and 100 pounds per square inch--with five replications at each pressure were used. The 25 holes were set in a latin square design to remove the differences, found through running a preliminary experiment, existing along the two directions of the soil.

After the 25 particles had been shot, the templet was removed. The soil covering the particles was then removed carefully by means of a steel marker and a screw driver so that the particle was not disturbed. The depth measuring device was then placed on top of the box after the four-inch Ames dial was bolted in such a position that its probe was placed over but not touching the particle. The angle iron carrying the Ames dial was then bolted to the slotted angle irons, welded to the sides of the box, by means of two bolts and wing nuts. The probe of the Ames dial was then lowered--by means of the fine adjustment screw (B), Figure 11,--until the dial showed a slight deflection indicating that the end of the dial stem was in contact with the top of the particle. The dial stem was then raised and placed over the square key that had been placed on the top of the two opposite edges of the box and the dial's reading was taken. A constant, 0.198 inch, was subtracted from the reading to obtain the net depth of the particle. This constant, 0.198 inch, is the thickness of the square key minus the diameter of the particle, therefore the depth reading obtained included the thickness of the particle. The above procedure was repeated for all 25 particles.

Moisture Content Determination

A soil sample weighing between 150 and 200 grams was placed in a small can. The can was covered and the sample weighed by means of a sensitive balance. The cover was removed and the can was then placed in an oven and left for about 24 hours at a temperature of 105 degrees centigrade. The can was then weighed and the loss of weight, being the weight of the water, was determined. The can was then placed in the oven until there was no further loss in weight; the weight of the soil sample at this point was recorded and the moisture content calculated according to the following formula:

$$\text{Moisture Content (Percent)} = \frac{\text{Net Weight of Water in Sample}}{\text{Weight of Dry Soil Sample}} \times 100$$

Moisture Content Adjustment

After determining the moisture content of the sample soil as previously described, dry weight (M_d) of the soil to be used was calculated according to the formula:

$$W_o \text{ (decimal)} = \frac{X_1}{M_W - X_1}$$

where, X_1 = Net weight in pounds of water contained by the soil

$M_W - X_1 = M_d$ = Dry weight of the soil, pounds

W_o = Original soil moisture content, percent

M_W = Weight of wet soil, pounds

After knowing M_d, the quantity of water that is to be added to bring the soil to a desired moisture content was calculated according to the following formula:

$$W_d \text{ (decimal)} = \frac{X_2}{M_d}$$

where, X_2 is the pounds of water to add to bring the dry soil of weight M_d to the desired moisture content level W_d.

The net quantity of water to add was determined by subtracting X_1 from X_2.

Bulk Density and Dry Weight

The bulk density is the mass of the oven dry solids per unit volume and is determined in grams per cubic centimeter.

There are 453.6 grams in one pound and 27210 cubic centimeters in one cubic foot.

Dry volume weight is the weight of the oven dry solids, in pounds, per one cubic foot volume.

The Latin Square Design for Randomization of Treatments

According to G.W. Snedecor (11, pp. 304-308), the latin square design is effective in controlling two independent variables of which the experimeter has predictive knowledge.

The sample soil within the box was divided into three blocks and each of these three blocks was divided into three plots in the case of the soil resistance to penetration experiments and thus yielding nine equal areas within the box. The area of the box was divided into five blocks and five plots per block for the depth of particle penetration experiments and thus yielding 25 equal areas within the box.

The blocks were designated as rows and the plots as columns. Every treatment was assigned once to each column as well as to each row. This required as many columns and rows as treatments.

The treatments were designated by A, B, C, D, and E which were assigned at random to the treatments. Every letter appeared once in every column and once in every row. After a schematic arrangement of the letters was written, the rows were interchanged and the columns were also interchanged at random and thus allowing for randomization.

To apply the rules mentioned above, consider the three by three latin square for one of the soil resistance to penetration experiments:

1. Write at random a basic latin square.

1.	A	B	C
2.	C	A	B
3.	B	C	A

2. Randomize rows in 1:

	1.	2.	3.	
1.	B	C	A	Row 3 becomes 1
2.	A	B	C	Row 1 becomes 2
3.	C	A	B	Row 2 becomes 3

3. Randomize columns in 2:

	1.	2.	3.	
1.	A	C	B	Column 3 becomes 1
2.	C	B	A	Column 2 remains 2
3.	B	A	C	Column 1 becomes 3

4. Randomize treatments to the letters:

A for 9.24 pounds

B for 4.24 pounds

C for 14.24 pounds

The model for latin squares is:

$$Y_{ijk} = M + R_i + C_j + T_k + E_{ijk}$$

where, M = Overall mean

R_i = Row effect

C_j = Column effect

T_k = Treatment effect

E_{ijk} = Random error

It is assumed in this model that R, C, T, and E are independent and that no interaction among rows, columns, and treatments exists.

CHAPTER VI

ANALYSIS OF DATA

Calculation of Particle Velocities

The velocity of a bullet or particle could be measured within two percent accuracy utilizing a ballistic pendulum according to an outlined experiment by D. L. Rutledge (10, pp. 23-24).

The ballistic pendulum used was made of a block of wood suspended by four cords in such a way that, as the pendulum swings, the block of wood remains parallel to its initial position. In Figure 14 the heavy lines show the position of the pendulum before the particle, which was shot from the left, strikes it. Before the impact of the particle on the block, the momentum of the system is mV. After the particle has struck, the momentum becomes (m + M)v. These momenta are equal:

$$(1) \quad mV = (m + M)v$$

where, m = Mass of particle, gms.

M = Mass of block, gms.

V = Velocity of particle, cms/sec.

v = Velocity of block and particle, cms/sec.

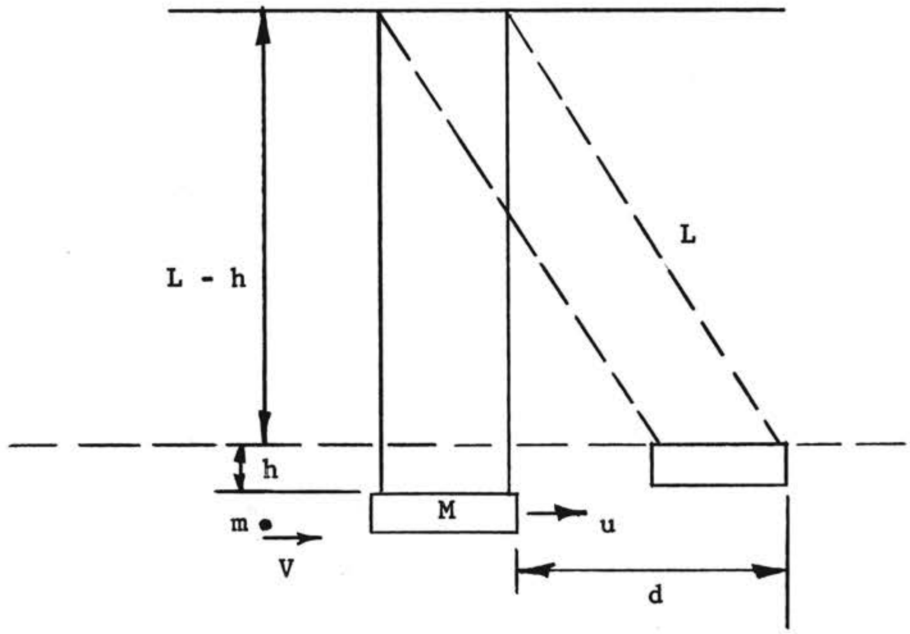

FIGURE 14. Definition Sketch of Ballistic Pendulum

The kinetic energy in the lowest position is equal to the potential energy at the highest point. Thus:

(2) $1/2\ (m + M)v^2 = (m + M)\ gh$

where, g = Acceleration due to gravity, 980 cms/sec^2

h = Vertical displacement of block, cms.

Solving equation (2) for v:

(3) $v = \sqrt{2\ gh}$

Equation (3) indicates that v is known if h can be measured. h is determined from the geometry of the system since:

(4) $d^2 = L^2 - (L - h)^2 = 2\ Lh - h^2$

h^2 is so small that it may be neglected, therefore, upon solving for h in (4), we get:

$$h = \frac{d^2}{2L}$$

where, d = Horizontal displacement of block, cms.

L = Length of cord, cms.

Equation (1) will enable us to determine V, the velocity of particle.

In determining the velocities of the particles at different pressures, the length of the pendulum's string was 189.60 cms., the weight of the block 123.37 gms., the weight of padding 31.51 gms., and the weight of each particle 0.155 gms.

The average of three readings of the rider's displacement was taken in determining the velocity of the particles at each pressure level.

As an example, consider the calculation of the velocity of the particle at a pressure of 30 pounds per square inch:

$$h_{30} = \frac{d^2}{2L} = \frac{(5.52)^2}{2\ (189.60)} = 0.08035 \text{ cms.}$$

$$v_{30} = \sqrt{2\ gh} = \sqrt{2 \times 980 \times .0835}$$

$$= \sqrt{157.486} = 12.55 \text{ cm./sec.}$$

$$V_{30} = \frac{(m + M)v}{m} = \frac{(155.035)(12.55)}{0.155}$$

$$V_{30} = 12553 \text{ cms/sec} = 411.9 \text{ ft/sec}$$

Similarly, the velocities at different pressure levels were calculated and tabulated in Table VII. The velocities were converted to feet per second and the corresponding kinetic energies were also included.

Figure 15 shows a plot of pressure versus velocity.

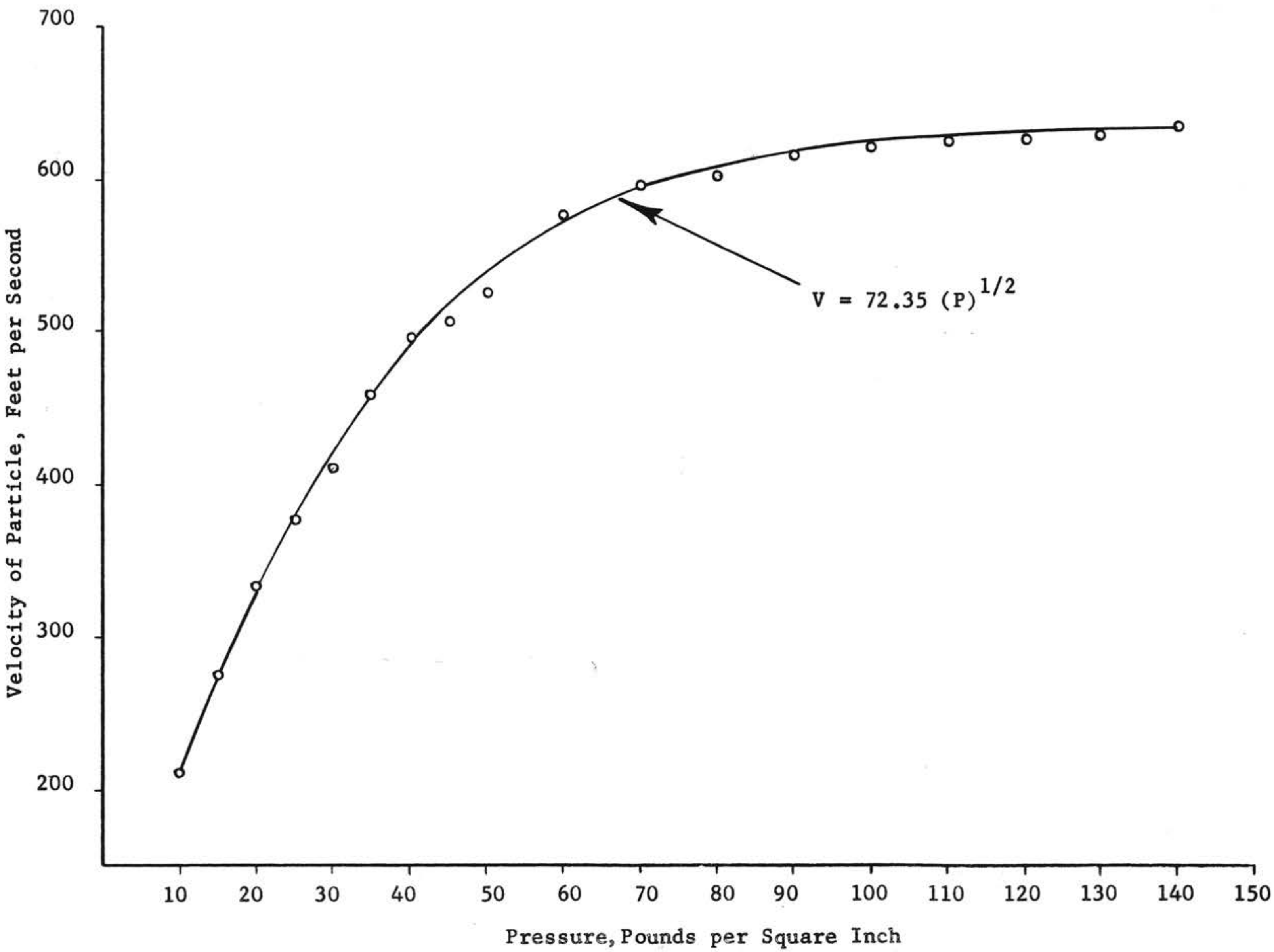

FIGURE 15. Applied Pressure Versus Velocity of Particle

TABLE VII. Velocities of Particles at Different Pressure Levels

Pressure PSI	Rider's Displacement (Cms.) 1	2	3	Avg.	Velocity Cm/Sec	Velocity Ft/Sec	K.E. Ft. Lb.
10	2.80	2.90	2.85	2.85	6479	212.6	0.479
15	3.70	3.70	3.70	3.70	8412	276.0	0.807
20	4.50	4.50	4.45	4.48	10179	334.0	1.182
25	5.20	5.15	5.15	5.17	11546	378.8	1.515
30	5.50	5.55	5.50	5.52	12553	411.9	1.798
35	6.10	6.05	6.05	6.17	14023	460.1	2.244
40	6.70	6.65	6.75	6.70	15228	499.6	2.646
45	6.85	6.80	6.85	6.82	15523	509.3	2.749
50	7.05	7.10	7.10	7.07	16076	527.4	2.948
60	7.75	7.80	7.70	7.75	17623	578.2	3.544
70	7.95	7.90	7.95	7.93	18124	594.6	3.747
80	8.10	8.05	8.05	8.07	18354	602.2	3.844
90	8.25	8.30	8.30	8.28	18830	617.8	4.046
100	8.35	8.30	8.35	8.33	18944	621.7	4.097
110	8.35	8.40	8.40	8.38	19053	625.1	4.142
120	8.40	8.45	8.45	8.43	19162	628.7	4.189
130	8.40	8.50	8.50	8.47	19261	631.9	4.235
140	8.55	8.60	8.60	8.58	19504	639.9	4.340

Calculations of Soil Resistance to Penetration

Using the observed depth readings of the probe obtained from the experiments, the corresponding soil resistance in pounds per inch was determined by dividing the load used by the depth in inches through which the probe penetrated. The probe used in all experiments was conical in shape, Figure 5, and had a one-inch diameter which corresponds to a 0.785 square inch of bearing area. The average of three depth readings was taken into consideration. Three weight increments of 4.24, 9.24, and 14.24 pounds were applied.

The load in pounds was plotted against the corresponding depth of penetration for the three soils under consideration. Three graphs for each soil were plotted, each representing a moisture content level at which the experiment was performed.

Statistical Analyses

Statistical analyses of variance, as outlined by Snedecor (11, pp. 304-308), were applied to the data obtained from the experiments. The variance ratios and significance levels were calculated for the soil resistance to the penetration of the probe (R) and for the depth of penetration of the particle (D). The variance ratios and significance levels for differences in R are summarized in Table VIII and for the differences in D in Table IX. Two examples of the analyses of variance for R and D are presented in Appendix B.

TABLE VIII. Summary Table of the Variance Ratios (VR) and Significance Levels (SL) Associated with Differences in R

Soil	Moisture Content, %	Resistance of Soil to Penetration (R), Pounds/Inch	ANALYSES Variance Ratios	Significance Levels
I	5.87	2.19 2.60 3.38	47.150	> 95.00
	10.65	2.72 2.53 3.08	58.576	> 95.00
	14.80	3.06 3.28 3.65	53.772	> 95.00
II	7.81	5.13 5.11 6.11	814.230	> 95.00
	13.50	4.96 4.85 5.64	83.070	> 95.00
	19.87	4.50 4.57 4.71	111.200	> 95.00
III	11.28	7.48 6.34 6.58	707.970	> 95.00
	19.45	4.80 4.14 4.39	770.680	> 95.00
	27.65	5.22 2.18 2.78	175.099	> 95.00

TABLE IX. Summary Table of the Variance Ratios (VR) and Significance Levels (SL) Associated with Differences in D

Soil	Moisture Content, %	Depth of Penetration of Particles (D), Inches	ANALYSES Variance Ratios	ANALYSES Significance Levels
		1.130		
		1.213		
	5.87	1.334	10.588	> 99.00
		1.381		
		1.388		
		1.128		
		1.285		
I	10.65	1.359	3.562	> 95.00
		1.403		
		1.464		
		1.154		
		1.284		
	14.80	1.342	49.288	> 99.00
		1.393		
		1.440		
		0.653		
		0.778		
	7.81	0.839	6.342	> 99.00
		0.866		
		0.887		
		0.884		
		0.982		
II	13.50	1.112	21.743	> 99.00
		1.146		
		1.192		
		1.158		
		1.274		
	19.87	1.396	18.890	> 99.00
		1.470		
		1.485		
		0.680		
		0.777		
	11.28	0.834	14.829	> 99.00
		0.865		
		0.879		
		1.041		
		1.201		
III	19.45	1.272	37.460	> 99.00
		1.391		
		1.435		
		1.392		
		1.437		
	27.65	1.673	6.370	> 99.00
		1.821		
		1.762		

CHAPTER VII

DISCUSSION OF RESULTS

Soil Resistance to Penetration

One objective of this study was to design a simple apparatus that would measure the soil resistance to the penetration of a probe of known bearing area. The penetrometer designed proved to be adequate.

The experiments were designated by assigning Roman numerals I, II, and III for the loam, silt clay loam, and clay loam, respectively. Zero was assigned to uniform sand. The Roman numerals are followed by Arabic numerals indicating the run number. The lowest moisture contents at which the experiments were run was assigned number 1, the highest moisture contents at which the experiments were run was assigned number 3, and the moisture content that was in between the highest and lowest was assigned number 2. Experiment I3 can be decoded as that experiment ran on the loam soil at the highest moisture content. Two side experiments were performed with a conical probe of a one-inch diameter and a bearing area of 0.785 square inches and a cylindrical probe of the same diameter and bearing area. The two experiments were performed on the same soil (I) keeping the bulk density and the moisture content at the same levels in both experiments. The results of the two experiments are summarized in Table X.

TABLE X. Effect of Skin Friction on Probe's Penetration

Load, Pounds	Depth of Penetration of Cylindrical Probe, In.	Depth of Penetration of Conical Probe, In.
4.24	1.304	1.376
9.24	2.488	2.654
14.24	3.640	3.871

From Table X, it is noted that the depth of penetration of the cylindrical probe was lower at all loading levels than the corresponding depth of penetration of the conical probe. This was due to the skin friction of the metal surface with the soil which was of an unknown value. Therefore the conical probe was used in all experiments to eliminate the effect of skin friction.

Table XI shows a summary of the results of the experiments performed in connection with soil resistance to penetration of three classes of soil at three moisture content levels.

Plots of load versus depth of penetration are shown in Figures 14, 15, and 16 for the three soils.

From Table XI and Figures 14, 15, and 16, it is observed that the resistance of soil per unit depth increased as depth increased. The least soil resistance to the penetration of the probe for soil I was at the moisture content between that of field capacity and wilting point. This was not the case with soils II and III since the greatest depth of penetration of the probe occurred at the highest moisture content. This was due to the formation of big clods of the plastic clay soils thus leaving large voids within the soil that lowered the soil resistance to penetration.

TABLE XI. Depth of Penetration of the 0.785 Square Inch Conical Probe in Soils I, II, and III at Three Moisture Content Levels

Soil	Load Lbs.	Moisture Content Percent	Depth of Penetration of Probe, Inches	Resistance of Soil to Penetration Lbs/Inch
	4.24	5.87	1.671	2.19
	9.24	5.87	3.284	2.60
	14.24	5.87	4.210	3.38
	4.24	10.65	1.554	2.72
I	9.24	10.65	3.645	2.53
	14.24	10.65	4.633	3.08
	4.24	14.80	1.382	3.06
	9.24	14.80	2.812	3.28
	14.24	14.80	3.902	3.65
	4.24	7.81	0.829	5.13
	9.24	7.81	1.805	5.11
	14.24	7.81	2.314	6.11
	4.24	13.50	0.855	4.96
II	9.24	13.50	1.908	4.85
	14.24	13.50	2.663	5.64
	4.24	19.87	0.940	4.50
	9.24	19.87	2.197	4.57
	14.24	19.87	3.037	4.71
	4.24	11.28	0.566	7.48
	9.24	11.28	1.456	6.34
	14.24	11.28	2.178	6.58
	4.24	19.45	0.884	4.80
III	9.24	19.45	2.234	4.14
	14.24	19.45	3.253	4.39
	4.24	27.65	0.812	5.22
	9.24	27.65	4.237	2.18
	14.24	27.65	5.133	2.78

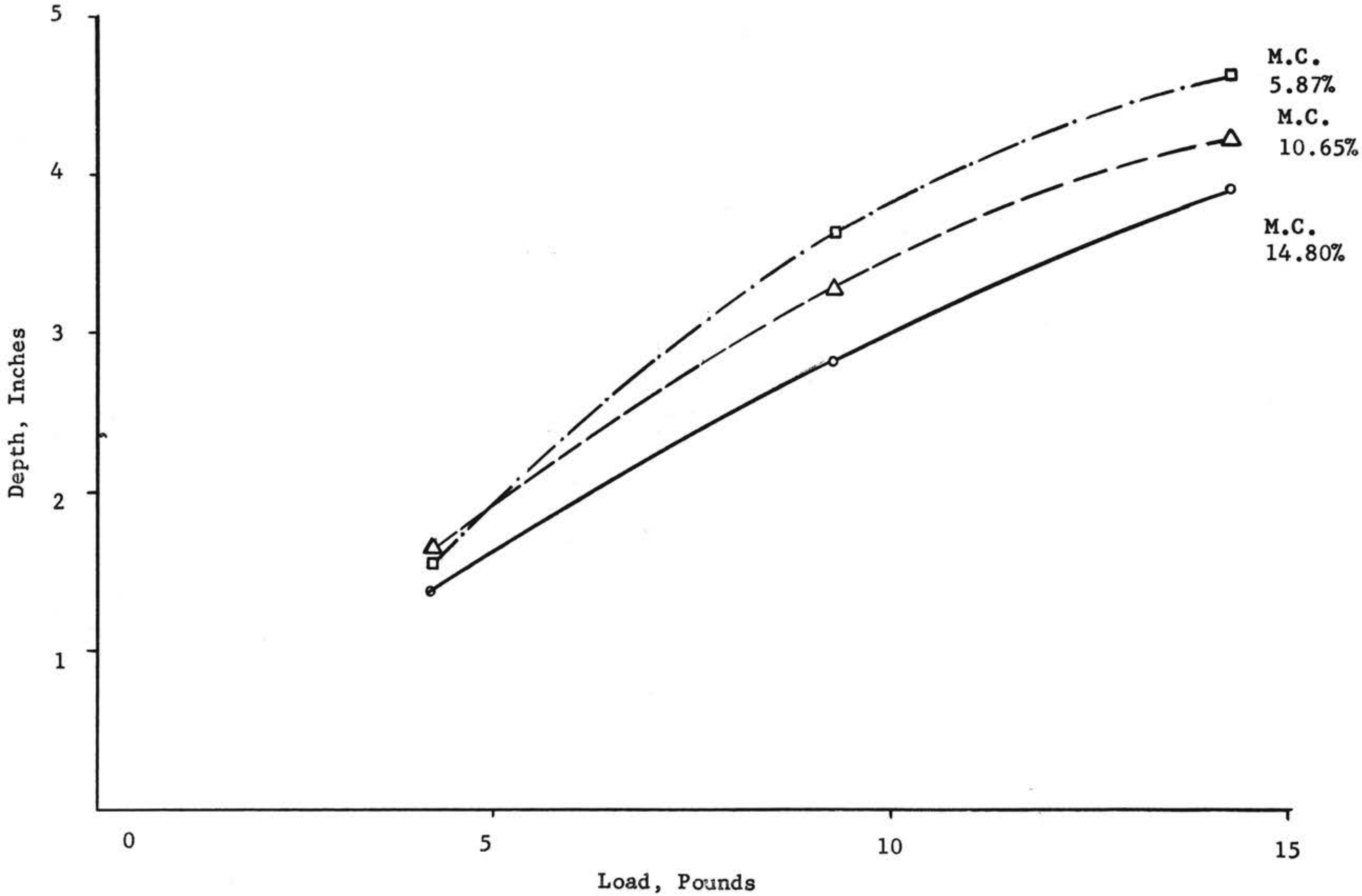

FIGURE 16. Load Versus Depth of Penetration for Soil I

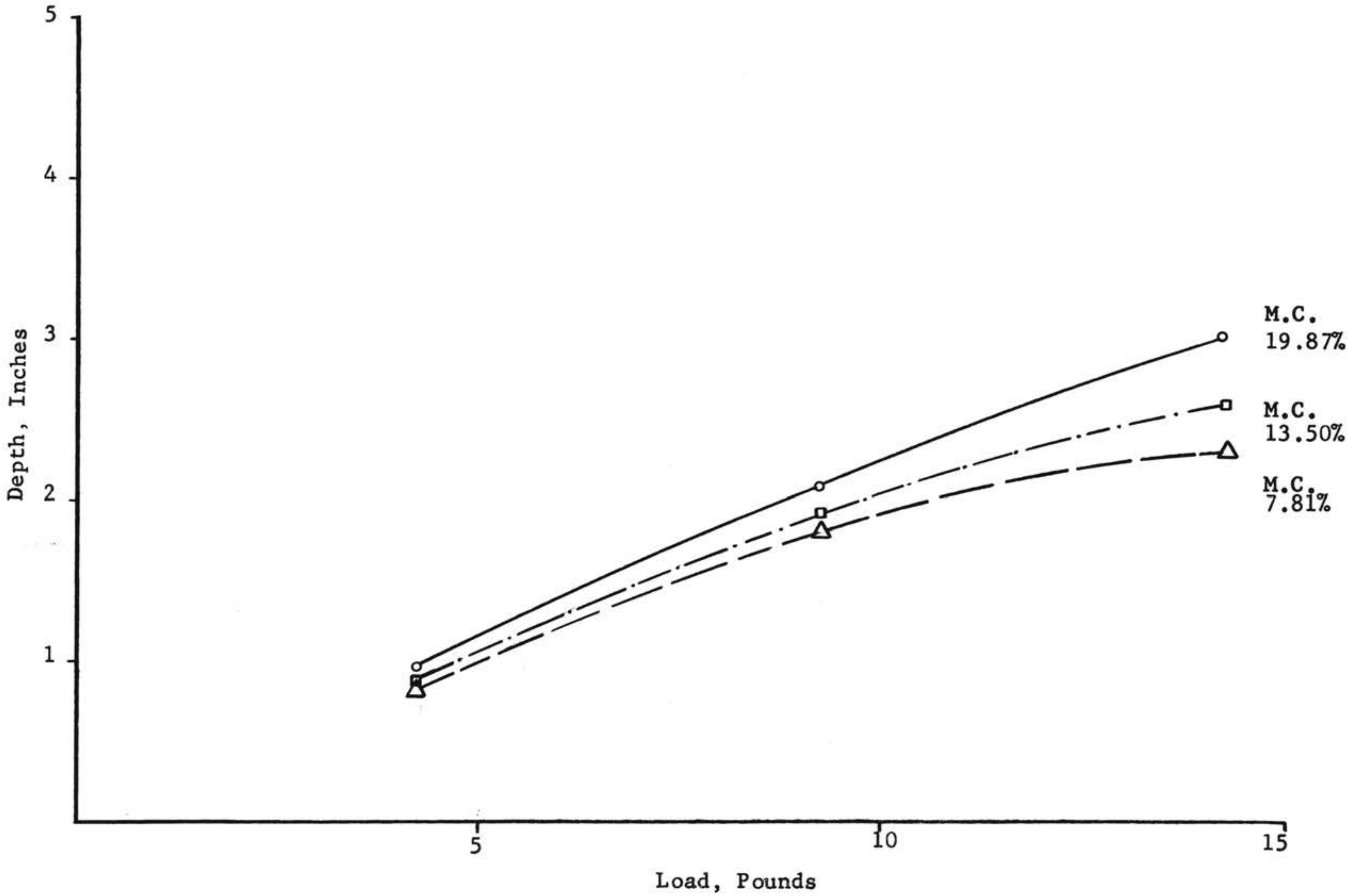

FIGURE 17. Load Versus Depth of Penetration for Soil II

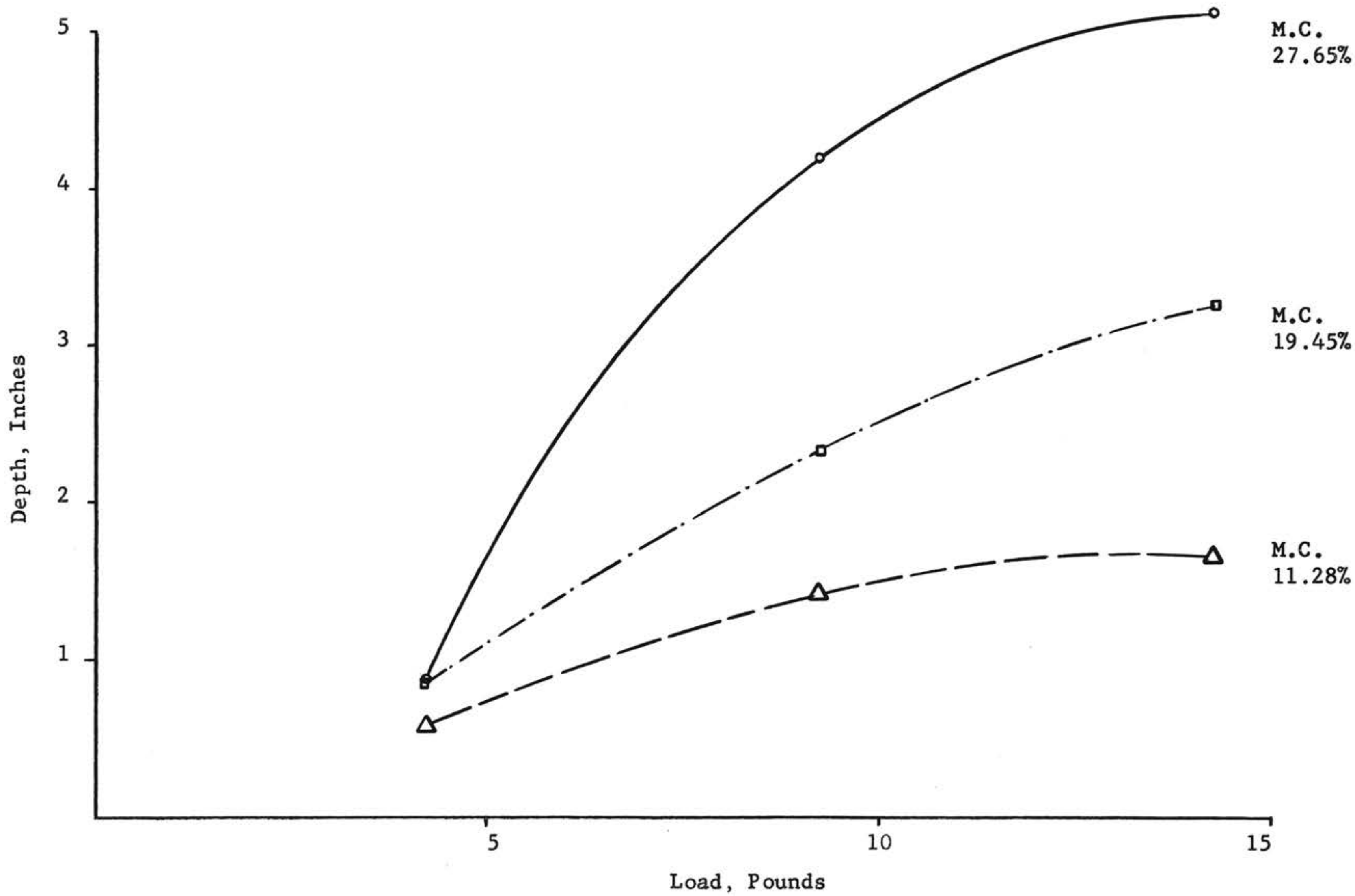

FIGURE 18. Load Versus Depth of Penetration for Soil III

No attempt was made to compact the soil to observe the effect of compaction on penetration of the probe. It was assumed that with higher compaction lower penetrations will be obtained since less voids are present and since the individual particles of the soil are in closer contact with each other.

The results obtained from using this penetrometer proved to be in accordance with the results obtained by other investigators, (2).

According to the experimental results obtained, the soil resistance to penetration increased with increasing depth; this was expected since the soil under the probe was pushed to the sides and at the same time packed under it. This packing actually brought the probe to a stop. With soil I at all levels of moisture contents, the probe came to a sudden stop whereas with soils II and III the probe continued to move slowly for some time after the lock pin was released. For soils II and III the probe took between two and five minutes to come to a complete stop. This is attributed to the plastic properties of soils II and III.

A complete set of the data obtained is presented in Appendix A.

Penetration of Particles Into Soils

Table XII is a summary of the results obtained through the experiments performed with the penetration of particles into soils. Figures 19, 20, and 21 show plots of the velocity of particle versus its depth of penetration into soils I, II, and III, respectively, at three moisture content levels.

The velocities of the particles at different pressures was obtained by means of a ballistic pendulum.

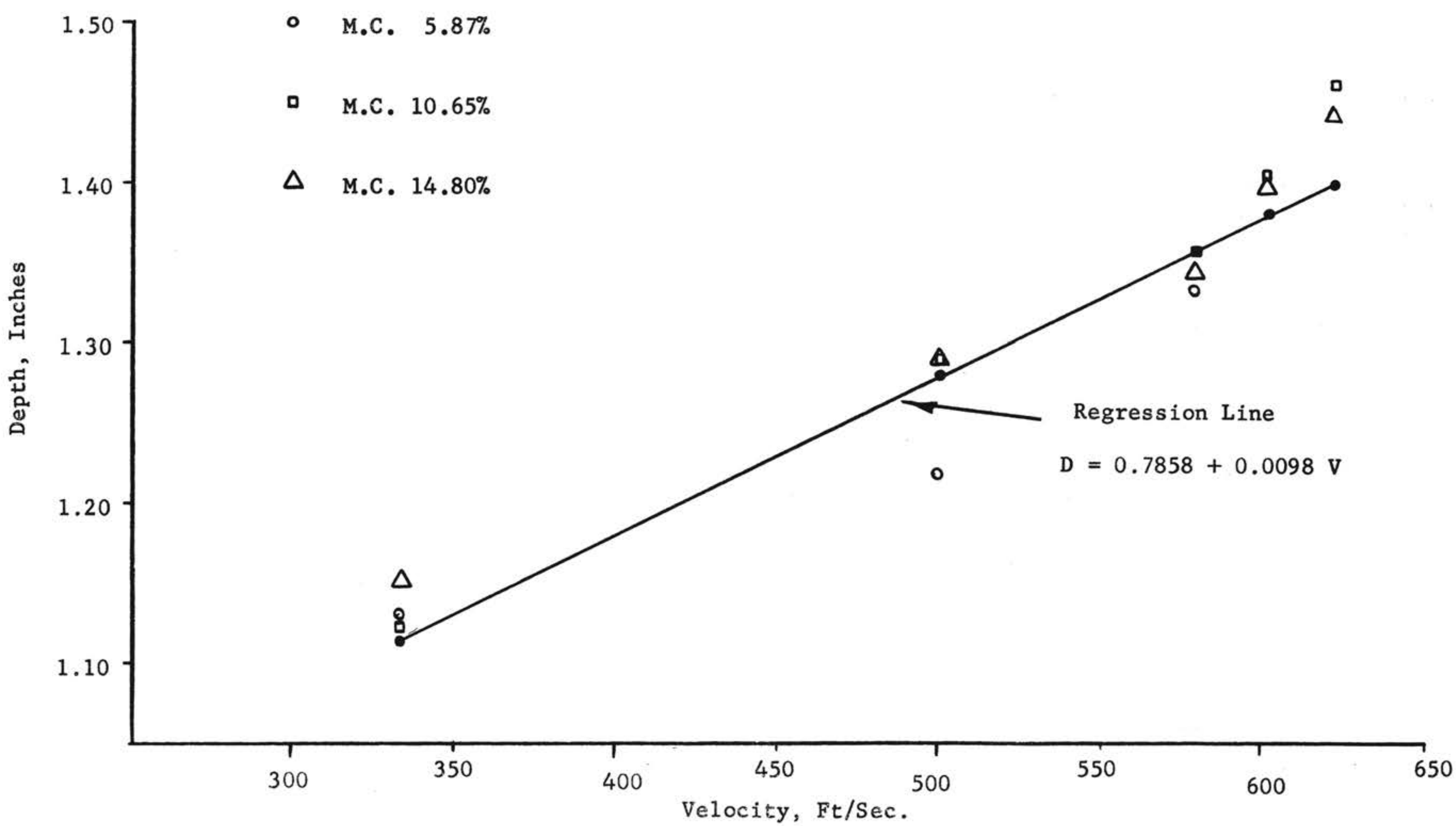

FIGURE 19. Velocity of Particle Versus Its Depth of Penetration for Soil I

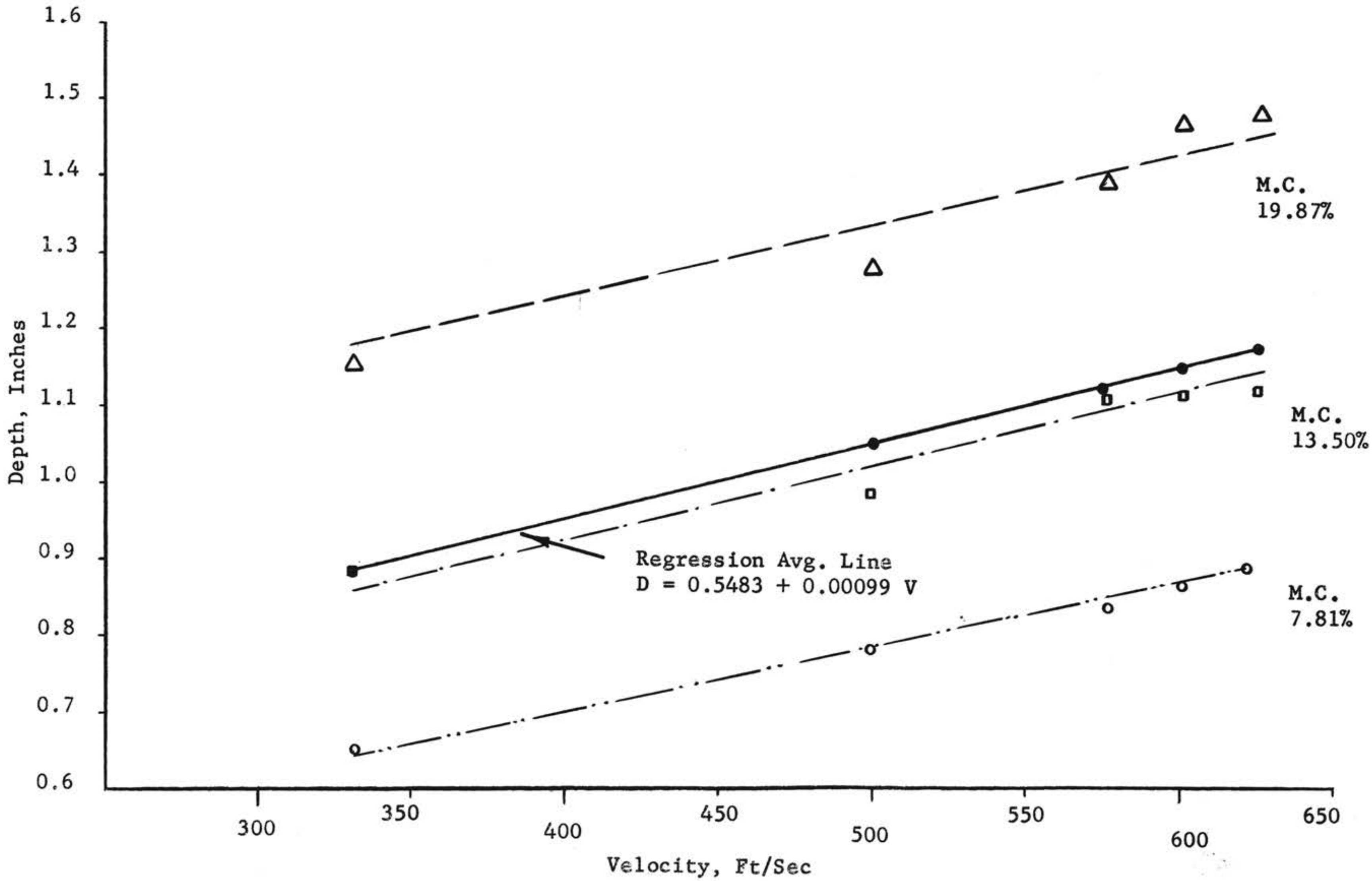

FIGURE 20. Velocity of Particle Versus Its Depth of Penetration for Soil II

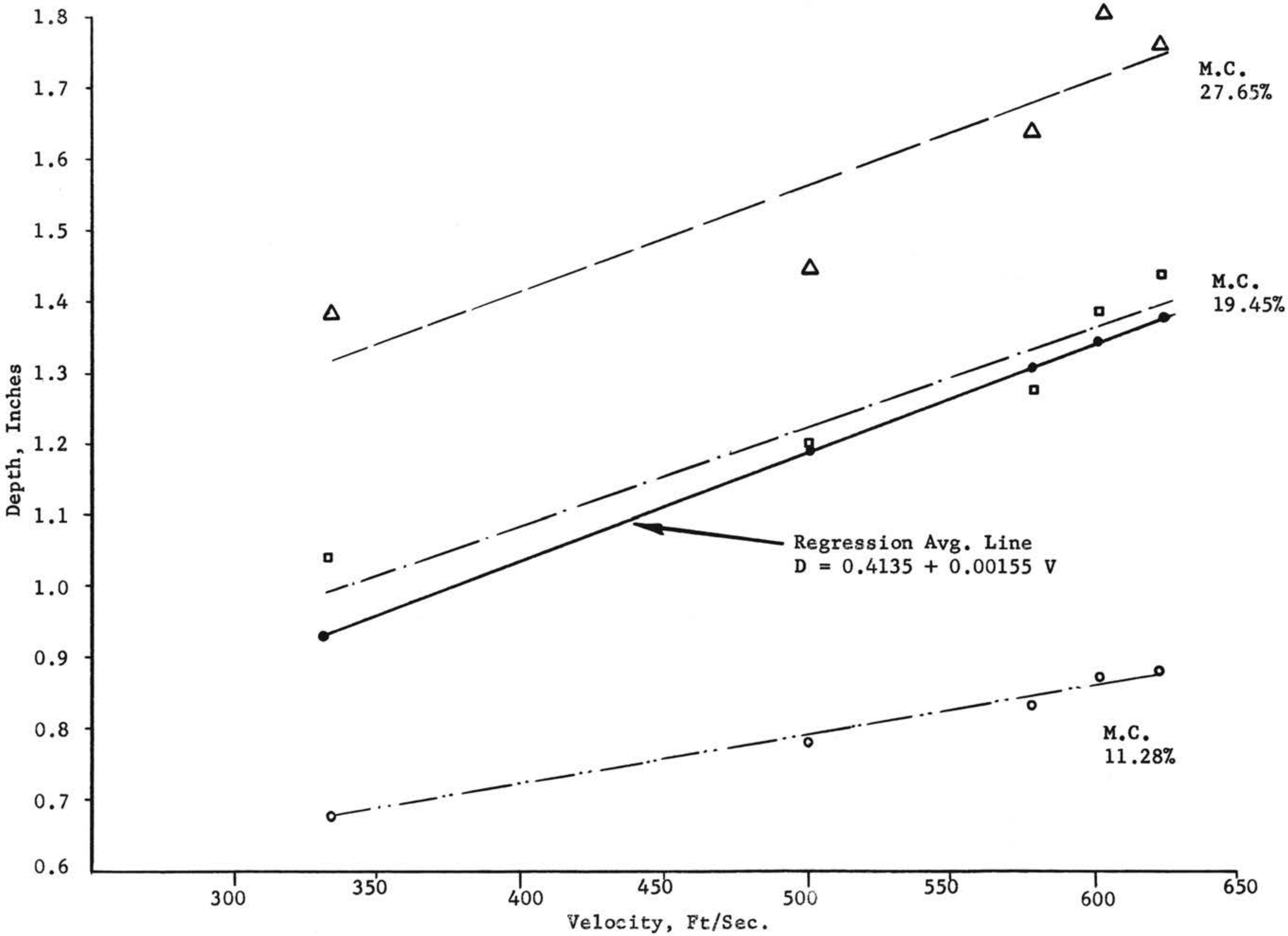

FIGURE 21. Velocity of Particle Versus Its Depth of Penetration for Soil III

Figure 15 shows that the velocity of the particle is not linearly proportional to the applied pressure. With increasing increments of pressures, corresponding decreasing increments of velocity were obtained. The kinetic energy of the particle, which is proportional to the mass and velocity of the particle (K.E. = $1/2\ mv^2$), followed the same relationship to pressure as did velocity.

It was of interest to find a general mathematical expression for the velocity of particle as a function of applied pressure. The Buckingham Pi theorem, a basic tool of dimensional analysis, was used. Buckingham's theorem is stated as follows (2, p. 345):

If an equation is dimensionally homogeneous, it can be reduced to a relationship among a complete set of dimensionless products.

The number of independent and dimensionless products required to express a relationship among the physical quantities is equal to the number of quantities involved minus the rank of the matrix for the quantities.

Figure 22 shows a schematic diagram of the system involved.

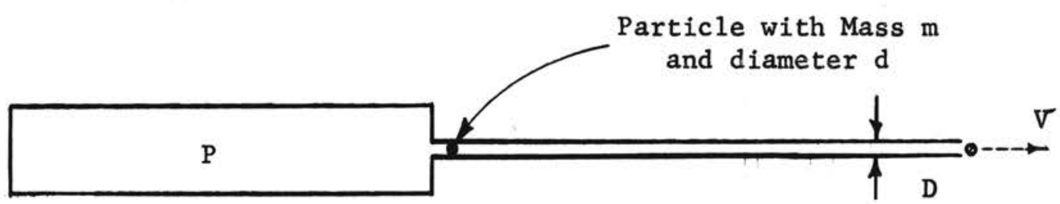

FIGURE 22. Definition Sketch of Shooting System

The pertinent quantities involved are presented in Table XII.

TABLE XII. Pertinent Quantities

No.	Symbol	Description		Dimensional Symbol
1	P	Tank Pressure	Lb./Sq. Ft.	FL^{-2}
2	m	Particle Mass	$Lb._{Mass}$	M
3	d	Particle Diameter	Ft	L
4	D	Tube Diameter	Ft	L
5	V	Particle Velocity	Ft./Sec.	LT^{-1}
6	k	Newton's Second Law Constant	Lb_{Force} / Lb_{Mass} x Ft./Sec^2	$FT^2\ M^{-1}\ L^{-1}$

There are six quantities involved in this system and expressed with a matrix of rank 2; therefore, we have two π terms. By inspection the two π terms are:

$$\pi_1 = \frac{V^2\ k\ m}{P\ d^3} \qquad \pi_2 = \frac{d}{D}$$

But $\frac{d}{D}$ is a constant throughout the experiments, then:

$$\pi_1 = f\ (\pi_2) = f\ (\text{Constant})$$

or

$$\frac{V^2\ k\ m}{P\ d^3} = C$$

Also, $\frac{km}{d^3}$ is a constant, therefore:

$$\frac{V^2}{P} = \text{Constant} = 5236$$

$$V = 72.35\ (P)^{1/2}$$

This is valid for a range between 10 psi and 140 psi.

A side experiment was first performed on moist uniform sand without any effort to randomize the treatments. The results of this experiment are tabulated in Table XIII. The sample box was divided into six blocks and treatments of 30 40,50,70,90,and 110 psi were assigned to the blocks; three replications of each treatment were made in each of the blocks and the average of these readings were considered. The complete set of data is presented in Appendix A. From this set of data it was noted that within a given treatment great variations existed. Moreover, it was hypothesized, that with higher pressures and consequently higher velocities and kinetic energies of the particle at the soil's surface, one should obtain greater depths of penetration. This was not the case as it is seen in Table XIII. The great differences in depth of penetration among the replications within the treatments was attributed to differences in the soil properties in two directions. A latin square design (pp. 33-34) was therefore adapted to remove the encountered differences. Only five pressure values (20, 40, 60, 80 and 100 psi) were applied.

TABLE XIII. Depth of Penetration of Particles Into Moist Uniform Sand. No Treatment Randomization

Pressure PSI	Depth of Penetration of Particles Inches
30	1.136
40	0.972
50	0.975
70	1.038
90	1.116
110	1.103

TABLE XIV. Depth of Penetration of Particles Into Soils I, II, and III at Three Moisture Content Levels

Soil	Moisture Content, Percent	Depth of Penetration of Particles (In.) at Indicated Velocities (Ft/Sec)				
		334	500	578	602	622
	5.87	1.130	1.213	1.334	1.381	1.388
I	10.65	1.128	1.285	1.359	1.403	1.464
	14.80	1.154	1.284	1.342	1.393	1.440
	7.81	0.653	0.778	0.839	0.866	0.887
II	13.50	0.884	0.982	1.112	1.146	1.192
	19.87	1.158	1.274	1.396	1.470	1.485
	11.28	0.680	0.777	0.834	0.865	0.879
III	19.45	1.041	1.201	1.272	1.391	1.435
	27.65	1.392	1.437	1.673	1.821	1.762

The experimental data obtained indicates that the three soils behaved differently with respect to their resistance to the penetration of the particles. Every soil will be discussed separately.

Penetration of Particles Into Soil I

This soil was classified as a loam soil. All the particles shot into the soil at five velocity levels penetrated to distances ranging from 1.130 inches to 1.464 inches. The particles had a poor contact with the soil at the 5.87 percent moisture content but good contact at the 10.65 percent and 14.80 percent moisture content levels. All particles for all runs were covered with about 1/2 inch of loose soil. The hole at the soil's surface on the top of the particles had a diameter of 3/4 inch.

From Figure 19 it is seen that moisture content has only a negligible effect on the depth of penetration; therefore, the depth of penetration of the particles was found to be a function of their velocities.

Calculating a linear regression on all the data obtained for this soil, the following mathematical expression for the depth of penetration was obtained:

$$D = 0.7858 + 0.00098 V$$

where, D = Depth of penetration of particle, inches

V = Velocity, Ft/Sec.

This expression is only valid for the velocity range used in this experiment and for moisture content levels that lie within 5.87 percent and 14.80 percent.

A sample calculation for the regression equation is presented in Appendix B.

Penetration of Particles Into Soil II

This soil was classified as a sandy clay loam soil. All the particles shot into the soil at five velocity levels penetrated to distances ranging from 0.653 inch to 1.485 inches. The particles had a good contact with the soil at all moisture content levels. All particles shot at velocities of 334, 500, 578, 602, and 622 ft./sec. at the 7.81 percent moisture content level were partially covered with about 1/3 inch loose soil. At higher moisture content levels the particles were not covered with soil. A conical hole was formed extending from the soil's surface to the particle with a base diameter of about

3/4 inch. At moisture content levels of 13.50 and 19.87 percent, clods were formed.

From Figure 20 it is seen that moisture content has a great effect on the depth of penetration of particles at different velocities. Therefore, since the straight lines representing velocity versus depth of penetration are almost parallel, a relationship among velocity, depth of penetration and moisture content was obtained by plotting the values of moisture content against D/V^m; where, D is the depth of penetration in inches, V is the velocity of particle in feet per second, and m is the average of the three slopes of the original regression lines (Figure 18).

Table XV shows the computed values of D/V^m for all the experiments performed with soil II.

Figure 23 is a plot of D/V^m versus moisture content. The straight line to best fit the points was found. The equation of this line is:

$$D = V^{0.099} \left[0.3580 + 0.0478 \ (M.C.) \right]$$

where, D = Depth of penetration of particle, Inches

V = Velocity of particle, Ft/Sec.

M.C. = Moisture content, Percent

This equation applies within the range of values of velocity and moisture contents used in this experiment.

Penetration of Particles Into Soil III

Soil III was classified as clay loam. All the particles shot into the soil had a very good contact with it, yet all the particles were not covered by loose soil after they had been shot. This was, as in soil II, due to the cohesive properties of clay soils. A cone with a 3/4 inch base was formed above the particle.

TABLE XV. Computed Values of D/V^m for Soil II

Moisture Content, %	V Ft/Sec.	D/V^m where, m = 0.0999
7.81	334	0.617
	500	0.731
	578	0.788
	602	0.813
	622	0.832
13.50	334	0.834
	500	0.922
	578	1.045
	602	1.074
	622	1.118
19.87	334	1.092
	500	1.197
	578	1.311
	602	1.446
	622	1.394

From Figure 21 it is seen that moisture content has an effect on the depth of penetration. Since the scatter of the points on the graph are similar to points representing the readings for soil II, the same analyses was done and the following equation, valid through the range of the values used in the experiments is obtained:

$$D = V^{0.0155} \left[0.2050 + 0.0462 \ (M.C.) \right]$$

Table XVI represents the computed values of D/V^m for soil III. Figure 24 is a plot of D/V^m versus moisture content for soil III.

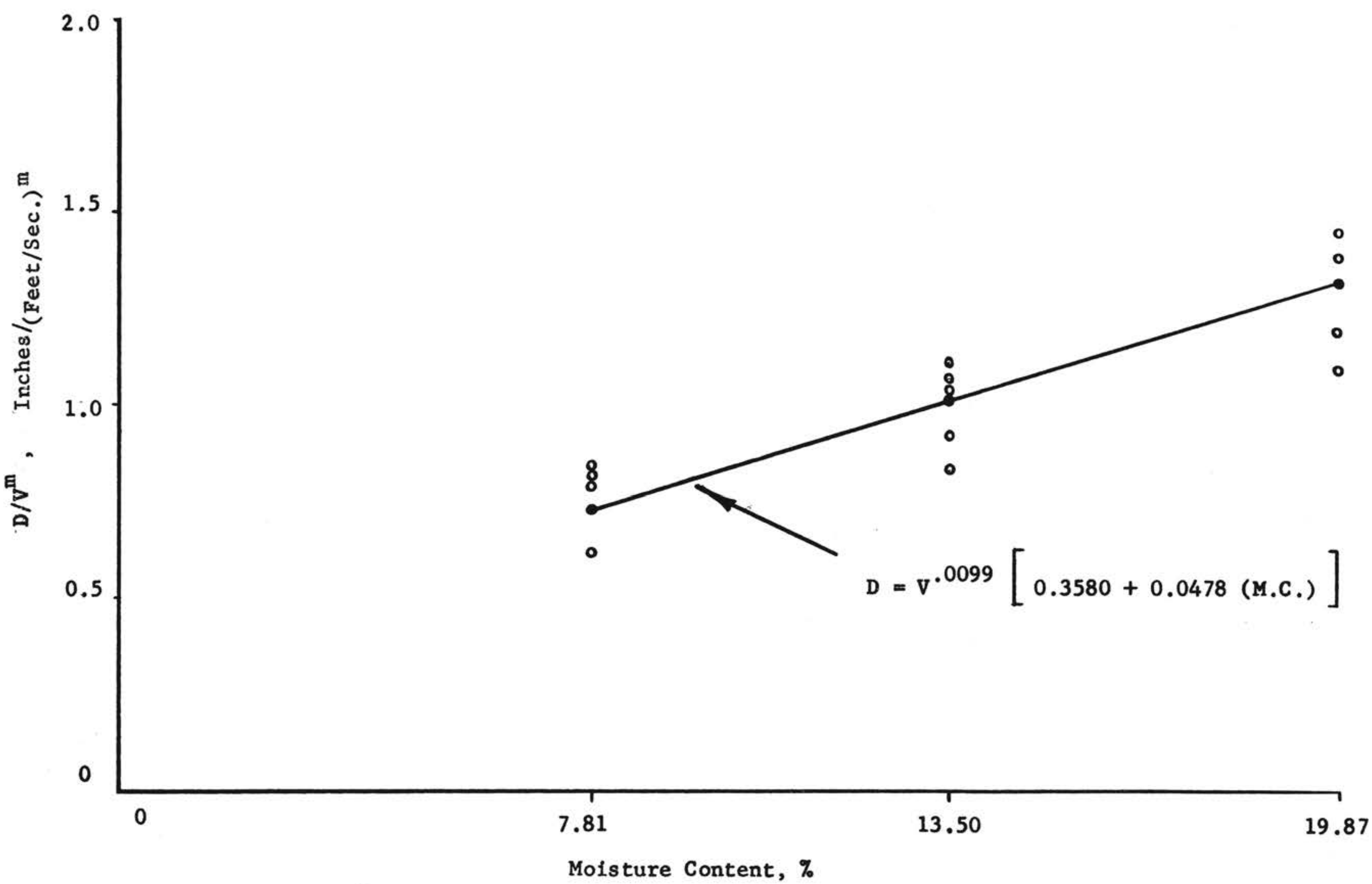

FIGURE 23. Depth of Penetration of Particle Versus Moisture Content for Soil II

TABLE XVI. Computed Values of D/V^m for Soil III

Moisture Content, %	V Ft/Sec.	D/V^m where, m = 0.0015
11.28	334	0.637
	500	0.723
	578	0.772
	602	0.803
	622	0.815
19.45	334	0.974
	500	1.118
	578	1.180
	602	1.293
	622	1.333
27.65	334	1.301
	500	1.337
	578	1.550
	602	1.691
	622	1.635

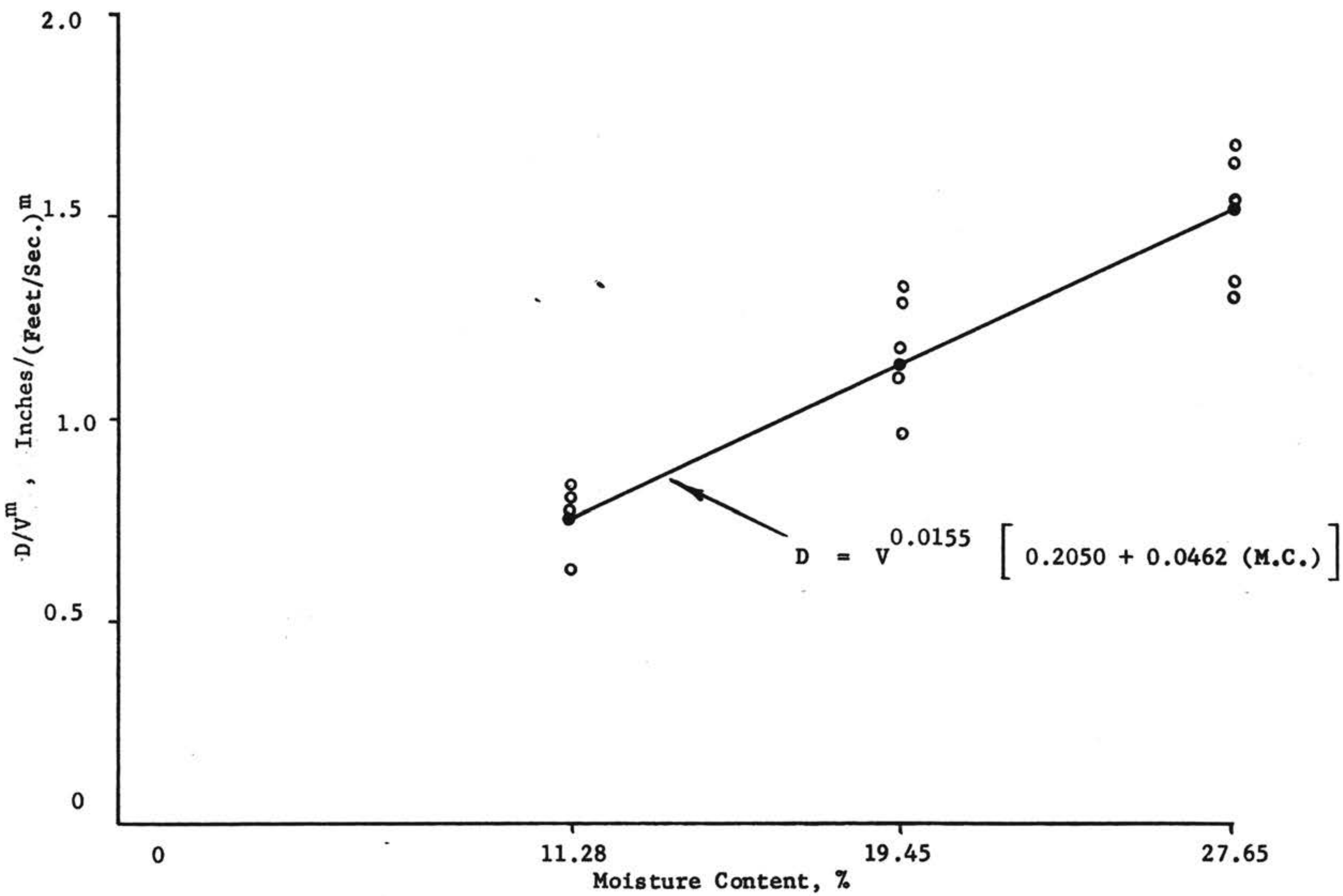

FIGURE 24. Depth of Penetration of Particle Versus Moisture Content for Soil III

CHAPTER VIII

SUMMARY AND CONCLUSIONS

An experimental investigation on the depth of penetration of particles was performed on three soils belonging to three classes at three moisture content levels for each soil. The effect of soil class, moisture content, and the velocity of particles was determined. A penetrometer, designed for this study, was used to characterize the soils by their resistance to the penetration of a conical probe having a bearing area of 0.785 square inches.

The followings are the main results obtained from this study:

1. The penetrometer designed gave more uniform results when used on the light soil and at moisture content levels tending towards the permanent wilting point moisture content values.
2. The resistance of soil per unit depth increased as depth of penetration of the probe into soil increased.
3. The least soil resistance to the penetration of the probe for the loam soil was at the moisture content between that of field capacity and wilting point.
4. The least soil resistance to the penetration of the probe for the sandy clay loam and the clay loam soils was at the highest moisture content.

5. Metal-to-soil skin friction increased appreciably the soil resistance values as measured by the cylindrical probe.
6. All loading treatments produced significantly different penetration.
7. The velocity of the particle was a function of applied pressure and is expressed by: $V = 72.35\ (P)^{1/2}$ for the range used in the experiments.
8. Depths of penetration of particles into the loam soil were not appreciably affected by moisture content. The depth of penetration of particles is expressed by: $D = 0.7858 + 0.00098\ V$, for the experimental velocity ranges used.
9. Depths of penetration of particles into the sandy clay loam soil was affected by moisture content and velocity according to the expression: $D=V^{0.0099}\left[0.3580 + 0.0478(M.C.)\right]$, for the experimental velocities and moisture contents ranges used.
10. Depths of penetration of particles into the clay loam soil was influenced by velocity and moisture content according to the expression: $D=V^{0.0155}\left[0.2050 + 0.0462(M.C.)\right]$, for the experimental velocities and moisture content ranges used.
11. The particles were partially covered by loose soil for the loam soil whereas they were mainly not covered for the sandy clay loam soil and the clay loam soil.

12. Contact between particle and soil was generally very firm.
13. All pressure and consequently velocity treatments gave significantly different penetration of the particles.

The following conclusions are drawn from the investigations:

1. Soil properties were different from one inch to the adjacent inch in the sample boxes. This made the penetrometer readings, for the same treatment, differ greatly. Also, the depth of penetration of the particles, for the same treatment level, varied greatly.
2. Planting by injecting the seeds into the soil is possible but has limitations. Variables such as the depth of planting the seeds, the resistance of seeds to rupture due to impact with soil, moisture content levels, giving the light-weight seed the required velocity at the surface of the soil to enable it to reach the desired depth, and finally the effect of the shape of the seed need further investigation.

Suggestions for Future Investigations

1. To find a relationship between the penetrometer reading for a given soil with the depth of penetration of particles into that soil.
2. Find the effect of particle diameter on depth of penetration.
3. Perform experiments, similar to the ones used in this study, with actual seeds.

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APPENDIXES

APPENDIX A

EXPERIMENTAL DATA

Soil Resistance to Penetration

Exp. No.	Load Pounds	Moisture Content, Percent	Bulk Density	Penetration of Probe, Inches Replication 1	2	3	Avg.	R, Lb/In
01 Non Random	5.14	8.78	1.44	1.528	1.321	1.487	1.445	2.94
	10.14	8.76	1.44	3.850	3.742	3.658	3.750	2.46
01 Random	5.14	4.75	1.67	0.824	1.153	1.058	1.012	5.04
	10.14	4.75	1.67	2.565	2.545	2.579	2.563	3.86
	15.14	4.75	1.67	3.973	3.790	3.948	3.903	3.88
I1 Conical Probe	4.24	6.62	1.11	1.322	1.435	1.372	1.376	3.09
	9.24	6.62	1.11	2.833	2.486	2.642	2.654	3.62
	14.24	6.62	1.11	3.873	3.765	3.975	3.871	3.68
I1 Cylindrical Probe	5.14	6.62	1.11	1.301	1.248	1.364	1.304	3.93
	10.14	6.62	1.11	2.600	2.525	2.338	2.488	4.10
	15.14	6.62	1.11	3.803	3.725	3.392	3.640	4.16
I1 Conical Probe	4.24	5.87	1.09	1.370	1.995	1.649	1.681	2.19
	9.24	5.87	1.09	3.048	3.142	3.661	3.284	2.60
	14.24	5.87	1.09	3.882	4.156	4.587	4.210	3.38
I2 Conical Probe	4.24	10.65	1.07	1.217	1.855	1.589	1.554	2.72
	9.24	10.65	1.07	3.958	3.287	3.689	3.645	2.53
	14.24	10.65	1.07	4.812	4.437	4.650	4.633	3.08
I3 Conical Probe	4.24	14.80	1.12	1.261	1.349	1.535	1.382	3.06
	9.24	14.80	1.12	3.205	2.426	2.805	2.812	3.28
	14.24	14.80	1.12	3.705	3.955	4.060	3.902	3.65
II1 Conical Probe	4.24	7.81	1.12	0.955	0.801	0.730	0.829	5.13
	9.24	7.81	1.12	1.811	1.880	1.724	1.805	5.11
	14.24	7.81	1.12	2.451	2.171	2.321	2.314	6.11
II2 Conical Probe	4.24	13.50	1.10	0.785	0.972	0.810	0.855	4.96
	9.24	13.50	1.10	1.855	1.895	1.975	1.908	4.85
	14.24	13.50	1.10	2.381	2.882	2.725	2.663	5.64
II3 Conical Probe	4.24	19.87	1.08	0.875	0.645	1.300	0.940	4.50
	9.24	19.87	1.08	1.890	2.210	2.475	2.197	4.57
	14.24	19.87	1.08	3.750	2.350	3.010	3.037	4.71

Exp. No.	Load Pounds	Moisture Content, Percent	Bulk Density	Penetration of Probe, Inches Replication 1	2	3	Avg.	R, Lb/In
III1	4.24	11.28	1.03	0.601	0.555	0.541	0.566	7.48
Conical	9.24	11.28	1.03	1.395	1.512	1.462	1.456	6.34
Probe	14.24	11.28	1.03	2.365	2.257	1.912	2.178	6.58
III2	4.24	19.45	1.05	0.948	0.965	0.739	0.884	4.80
Conical	9.24	19.45	1.05	2.221	2.256	2.225	2.234	4.14
Probe	14.24	19.45	1.05	3.318	3.415	3.028	3.253	4.39
III3	4.24	27.65	1.14	1.128	0.785	0.523	0.812	5.22
Conical	9.24	27.65	1.14	4.210	4.350	4.150	4.237	2.18
Probe	14.24	27.65	1.14	5.340	5.230	4.830	5.133	2.78

Depth of Penetration of Particles Into Soils

Exp. No.	Pressure Lbs/In^2	M.C. %	Bulk Density	Penetration of Particles, Inches Replication 1	2	3	4	5	Avg.
01 Non Random	30	8.78	1.44	1.236	1.176	0.998	—	—	1.136
	40	8.78	1.44	0.934	0.960	1.023	—	—	0.972
	50	8.78	1.44	0.979	0.924	1.023	—	—	0.975
	70	8.78	1.44	1.015	1.046	1.054	—	—	1.038
	90	8.78	1.44	1.128	1.024	1.198	—	—	1.116
	110	8.78	1.44	1.185	1.098	1.014	—	—	1.103
01 Random	20	4.75	1.67	0.782	0.614	0.434	0.538	0.584	0.600
	40	4.75	1.67	0.694	0.612	0.652	0.684	0.734	0.635
	60	4.75	1.67	0.740	0.718	0.654	0.706	0.818	0.741
	80	4.75	1.67	0.733	0.826	0.714	0.728	0.814	0.783
	100	4.75	1.67	0.804	0.778	0.768	0.794	0.792	0.787
I1	20	5.87	1.09	1.183	1.265	1.130	0.942	1.132	1.130
	40	5.87	1.09	1.224	1.272	1.218	1.104	1.245	1.213
	60	5.87	1.09	1.227	1.327	1.385	1.363	1.366	1.334
	80	5.87	1.09	1.362	1.415	1.389	1.396	1.342	1.381
	100	5.87	1.09	1.357	1.414	1.456	1.515	1.203	1.388
I2	20	10.65	1.07	1.081	1.167	1.178	1.127	1.085	1.128
	40	10.65	1.07	1.302	1.375	1.227	1.309	1.211	1.285
	60	10.65	1.07	1.305	1.360	1.357	1.464	1.311	1.359
	80	10.65	1.07	1.374	1.371	1.473	1.368	1.429	1.403
	100	10.65	1.07	1.412	1.486	1.469	1.505	1.449	1.464
I3	20	14.80	1.12	1.130	1.221	1.154	1.050	1.213	1.154
	40	14.80	1.12	1.290	1.310	1.260	1.245	1.317	1.284
	60	14.80	1.12	1.322	1.326	1.356	1.341	1.363	1.342
	80	14.80	1.12	1.386	1.385	1.441	1.386	1.368	1.393
	100	14.80	1.12	1.465	1.392	1.451	1.436	1.459	1.440

Exp. No.	Pressure Lbs/In^2	M.C. %	Bulk Density	Penetration of Particles, Inches Replication					
				1	2	3	4	5	Avg.
II1	20	7.81	1.12	0.650	1.176	0.998			1.136
	40	7.81	1.12	0.726	0.749	0.817	0.805	0.796	0.778
	60	7.81	1.12	0.851	0.816	0.877	0.856	0.794	0.839
	80	7.81	1.12	0.878	0.900	0.860	0.864	0.830	0.866
	100	7.81	1.12	0.890	0.920	0.870	0.873	0.885	0.887
II2	20	13.50	1.10	0.731	1.012	0.910	0.957	0.810	0.884
	40	13.50	1.10	0.918	1.016	0.937	1.041	1.002	0.982
	60	13.50	1.10	1.160	1.112	1.022	1.211	1.057	1.112
	80	13.50	1.10	1.070	1.129	1.169	1.192	1.170	1.146
	100	13.50	1.10	1.145	1.201	1.264	1.184	1.165	1.192
II3	20	19.87	1.08	1.302	1.221	1.059	0.915	1.291	1.158
	40	19.87	1.08	0.964	1.161	1.232	1.491	1.521	1.274
	60	19.87	1.08	1.129	1.591	1.049	1.533	1.677	1.396
	80	19.87	1.08	1.350	1.329	1.669	1.633	1.371	1.470
	100	19.87	1.08	1.147	1.539	1.685	1.518	1.518	1.485
III1	20	11.28	1.03	0.693	0.713	0.682	0.666	0.645	0.680
	40	11.28	1.03	0.738	0.814	0.779	0.820	0.733	0.777
	60	11.28	1.03	0.748	0.875	0.838	0.823	0.804	0.834
	80	11.28	1.03	0.953	0.779	0.970	0.785	0.900	0.865
	100	11.28	1.03	0.868	0.823	0.960	0.844	0.955	0.879
III2	20	19.45	1.05	1.013	1.052	0.937	1.192	1.010	1.041
	40	19.45	1.05	1.204	1.250	1.142	1.244	1.162	1.201
	60	19.45	1.05	1.282	1.714	1.262	1.292	1.210	1.272
	80	19.45	1.05	1.393	1.413	1.363	1.355	1.429	1.391
	100	19.45	1.05	1.411	1.491	1.383	1.436	1.455	1.435
IV3	20	27.65	1.14	1.579	1.418	1.512	1.201	1.248	1.392
	40	27.65	1.14	1.323	1.353	1.472	1.494	1.541	1.437
	60	27.65	1.14	1.473	1.848	1.554	1.703	1.585	1.633
	80	27.65	1.14	1.854	1.594	1.821	1.969	1.869	1.821
	100	27.65	1.14	1.462	1.772	1.582	2.050	1.942	1.762

APPENDIX B

SAMPLE ANALYSES OF VARIANCE TABLES

Soil Resistance to Penetration

AOV due to differences in R for experiment I1 with conical probe at 5.87 percent M.C.

Source	Degrees Freedom	Sum of Squares	Mean Square	Variance Ratio	Sign. Level
Total	8	10.5660			
Rows	2	0.0431			
Columns	2	0.4105			
Depth	2	9.9026	4.9510	47.150	> 95.00
Remainder	2	0.2100	0.1050		

Depth of Penetration of Particles Into Soils

AOV due to differences in D for experiment I1 at 5.87 percent M.C.

Source	Degrees Freedom	Sum of Squares	Mean Square	Variance Ratio	Sign. Level
Total	24	0.4045			
Rows	4	0.0254			
Columns	4	0.0503			
Depth	4	0.2562	0.0640	10.588	> 99.00
Remainder	12	0.0726	0.0061		

SAMPLE REGRESSION CALCULATIONS

Regression of Depth of Penetration of Particles on Velocity of Particle for Soil I

Heading		Treatment 1	2	3	4	5	Total	Mean
Velocity of Particle, Ft/Sec	X	334	500	578	602	622	2636	527.2
Depth of Penetration of Particles, In.	Y	1.137	1.261	1.345	1.392	1.431	6.566	1.313
Deviation from	x	-193.2	-27.2	50.8	74.8	94.8		
Mean	y	-.176	-0.052	0.032	0.079	0.118		
Squares of	x^2	37326.24	739.84	2580.64	5595.04	8987.04	55228.80	
Deviations	y^2	0.0398	0.0027	0.0010	0.0062	0.0139	0.0636	
Product of Deviations	xy	34.0032	1.4144	1.6256	5.9092	11.1864	54.1388	

$$b = \frac{\Sigma xy}{x^2} = \frac{54.1388}{55228.80} = 0.00098$$

$$a = \bar{Y} - b\bar{X} = 1.313 - 0.00098\ (527.2)$$

$$= 0.7850$$

$$Y = a + bx = 0.7858 + 0.0098\ X$$

$$D = 0.7858 + 0.00098\ V$$

VITA

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Biographical:

Personal Data: Born in Damascus, Syria, The United Arab Republic, March 31, 1936, the son of Joseph F. and Farida Dabbous.

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