BASIC FACTORS AFFECTING THE STRENGTH AND SINKAGE OF TILLABLE SOILS

By

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AN ABSTRACT

Submitted to the College of Agriculture of Michigan
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Approved Wesley F. Buchele

ABSTRACT

Soil compaction due to vehicular traffic is becoming an important agricultural problem. Yet farming operation must be mechanized to meet the future demand for agricultural products and reduce the cost of production.

Basic factors affecting the strength of agricultural soil must be studied so vehicles can be designed to perform the farming operation without deteriorating soil structure. The Bekker soil values, and other soil physics measurements were determined and used to investigate the vehicle-soil interaction.

Moisture and density play an important role in determining soil strength. Experiments, therefore, were conducted to determine the effects of moisture and bulk density on soil strength as measured by the Land Locomotion soil values.

A bevameter (an instrument used to obtain the soil values) was modified for agricultural use. A three point hitch and hydraulic motor were added to the bevameter to facilitate field testing. A large double tank soil handling apparatus was designed and constructed to investigate the effects of moisture and density on soil strength under controlled conditions.

Field and laboratory tests were conducted on Brookston sandy loam soil. Field tests determined the effects of

tillage operations, vehicle traffic and weather on the land locomotion soil values. Laboratory tests determined the effects of moisture and bulk density on the soil values.

Soil strength is greatly decreased by plowing and only slightly decreased by disking. Vehicle traffic increases the soil strength by compacting the soil. Weather and time increase the soil strength by returning the soil to its original consolidated state. When the moisture content is in the 10-24 percent range, bulk density has a greater effect on soil strength than moisture content. Certain bulk density depth relationships make it impossible to measure the sinkage soil values with the present Land Locomotion theory. Results from the field tests indicate that circular plates with diameters less than 2 inches should not be used in the penetration tests on plowed soil.

Application of the land locomotion soil values to the calculation of sinkage of a tractor in tillable soils is presented.

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INTRODUCTION

Soil is man's oldest and least understood engineering material. The ancient Egyptians learned how to construct roads in order to transport materials for their pyramids. The remains of various types of structures which involved the application of soil mechanics have been discovered at sites of other early civilizations.

Soil is the most common and important material that we can study. The rise and fall of civilizations have depended to a large extent on the fertility and management of soil.

Today, American agriculture is faced with the problem of soil compaction. As the mechanization of agriculture has progressed, the problem of soil compaction has increased. Certain areas of California have been removed from crop production due to soil compaction (Edminster, 1956). The physical environment of the soil is as important to plant growth as the chemical environment of the soil.

Developments in the science of soil engineering have taken place in recent years that enable us to better understand today's soil problems. Since 1925, the contributions by Terzaghi (1925), "the father of modern soil mechanics" have greatly increased man's knowledge of the soil.

Presently we are at the threshold of developing new theories and techniques to solve the problem of soil compaction.

The soil value system developed by Bekker (1950) is one new technique that offers possibilities in the study of soil compaction.

The soil value system attempts to describe the soil strength necessary for the movement of vehicles over the soil by use of the following quantities and equations:

K_c The cohesive moduli of deformation

K_ϕ The frictional moduli of deformation

n The rate of strain change with load.

These quantities apply to the sinkage equation:

$$P = \left(\frac{K_c}{b} + K_\phi\right) Z^n$$

where P = normal ground pressure in pounds per square inch

b = width of contact area in inches

Z = depth of sinkage in inches.

This formula is used to determine vehicle sinkage.

The ability of the soil to sustain thrust is determined from these soil values:

C The soil cohesion

ϕ The internal friction angle of the soil

These quantities apply to the Coulomb-Mohr formula:

$$S_s = C + P \tan\phi$$

where S_s = the soil sheering stress in pounds per square inch

P = normal ground pressure in pounds per square inch.

As most soil compaction problems are caused by the movement of farm implements across the soil, there should exist a relationship between the soil values and soil compaction.

Today's farm mechanization trend is toward heavier tractors and larger implements. The ability of these machines to travel over the soil without damaging it by compaction is an important design problem. Also of importance, when attempting to accomplish mechanized operations is, whether the prime mover can pull the implement in the soil without becoming mired. As the information necessary to solve these problems might be obtained from the soil value system, it is important that the adaptability of the soil value system to tillable soils be investigated.

The purposes of this investigation were to determine the applicability of the soil value system to tillable soils and the effects of tillage, soil moisture, bulk density, and weather on the soil values.

REVIEW OF LITERATURE

Micklethwait (1944) was one of the first to determine the ground strength necessary to propel land vehicles and relate the problem of vehicle mobility to Terzaghi's methods of soil mechanics. Terzaghi (1943) divided the soil mechanics problem into two groups--stability problems and elasticity problems and wrote "Stability problems deal with the conditions for the equilibrium of ideal soils immediately preceding ultimate failure by plastic flow. Elasticity problems deal with the deformation of the soil due to its own weight or due to external forces." Soil studied by Terzaghi is defined to be what the geologists call mantle or regolith. The decomposed upper layer of the earth which supports plants is not considered. Thus only problems in civil engineering are discussed by Terzaghi.

Bekker (1950) developed a detailed solution to the problem of vehicle mobility which defined the relationship between the size, weight and thrust of a vehicle and specific physical soil properties. A new approach was outlined (1955) for the solution of the plastic deformation of the soil under vehicle and implement action. Methods outlined by Terzaghi are used by Bekker (1956) to solve the soil stresses caused by vehiclular loads.

Two basic formulae are used in the Soil Value System. The ability of a vehicle to develop draw bar pull is determined from the Coulomb-Mohr equation which is widely used in soil mechanics. This equation states that shearing resistance of the soil is composed of two components, cohesion and friction.

$$S_s = C + P \tan\phi$$

The ground pressure is represented by P, C is cohesion and ϕ is the internal angle of soil friction. C and ϕ are the two physical soil values obtained from the ground area under study.

Vehicle sinkage is determined from the equation:

$$P = \left(\frac{Kc}{b} + K_\phi\right) Z^n$$

where P is the ground pressure, Z vehicle sinkage, b width of the ground contact area, and Kc, K_ϕ, and n are the physical soil values. This equation was developed by Bekker (1955) from Bernstein's (1913) equation $P = K\sqrt{Z}$ and the load sinkage relationship of a footing used by civil engineers $P = \left(\frac{Kc}{b} + K_\phi\right) Z$

Since the advent of the Land Locomotion soil value system some attempts have been made to study the effects of soil moisture on the soil values.

Trask, Skjei, and Klehn (1958) studied the effect of moisture, type of clay, percentage of sand and clay in the soil, and the grain size of the admixed sand on the sinkage soil values of Kc, K_ϕ and n. Tests were conducted in the laboratory using a penetrometer employing a strain gage transducer to measure forces for 0 to 1 inch sinkage of plates with 1-1.5-and 2-inch diameters. Circular plates were found to give better soil values than rectangular plates. Results of the tests showed that "Kc and K_ϕ decrease in magnitude as water content increased. This relationship holds true for all clay-sand ratios and all grain sizes tested. The steepness of the line showing this inverse relationship between Kc, K_ϕ and water increases as clay-sand ratio increases with the exception of mixtures of 20 percent benonite--80 percent silica for grain sizes of 1.2 and 74 microns. For a given K_ϕ or Kc, the water content increases regularly as the grain size decreases logarithmetically. As a general rule the relationship between water content and grain size becomes less sensitive as the grain size becomes smaller. The exponent, n, has been found to be essentially constant for all water contents and grain sizes tested for given clays and given clay-sand ratios." The soils used in this investigation were artificial soils consisting of the following clays: kaolin, illite, and montmorillonite. These clays were mixed with different sands and silts of 1.2, 74, 130 and 210 microns grain sizes. The composition of 20%, 50% and 100% clays at four different moisture concents in the plastic range of the soils were used for the tests.

Field tests conducted by Hanamoto and Hegedus (1958) show that Kc and K_ϕ decrease as the moisture content increases. Tests were conducted on a 200'x50' plot at 48 randomly selected test sites inside this area. Moisture contents of less than 10 to greater than 60% were found to exist at the test sites. Values of Kc and K_ϕ were obtained with a Bevameter (Figure 1). Graphs of Kc and K_ϕ versus moisture content have quite a wide variation but show a definite averaging trend. The values of K_ϕ range from 50 at 22% moisture to 1 at 42% moisture. Kc has a value of 100 at 22% moisture and a value of 3 at 44% moisture.

Investigations conducted by Cameron and Gallagher (1908) show that the force of penetration of a steel cone, 10.5-cm. long and 1-cm. in diameter at the thickest part, decreased as a optimum moisture content was reached and then increased. The soil was placed in a cup 12.5-cm. in diameter x 9-cm. in height during the tests. "One of the most serious difficulties encountered was to control the handling of the soil sample and its packing so that an agreement in results could be obtained between duplicate experiments." To overcome this problem the soil was screened with a 3 mesh screen placed at a fixed height above the test container and shaken with an eccentric mechanism. Only by mechanical methods could a loose, uniform sample be obtained. Tests on Podunk sandy loam show a moisture content for optimum penetration of 4 to 6%. The force of penetration varied from 112 grams at 0.36% moisture to 28 grams at 3.9% moisture. It then increased to 42 grams at 13.4% moisture. For

Miami black clay loam force of penetration decreased from 40 grams at 12% moisture to 28 grams at 32% moisture. Leonardtown loam had penetration values of 115 grams at 1.7% moisture to 66 grams at 15.2% moisture and then increased to 150 grams at 25.9% moisture. The investigators theorized that the force of penetration was related to cohesion and therefore the penetration values gave an indication of how moisture affects the cohesion of a soil.

Terzaghi (1943) states that for sand "the shearing resistance depends solely on the normal stress on the potential surface of sliding." Therefore $S_s = P \tan\phi$ which gives a value for C of zero in sand. The value of ϕ varies between the extreme limits of 30° to 50° with a difference between the densest and loosest state as high as 15°.

In cohesive soils the term $P \tan\phi$ sometimes is affected by preconsolidation of the soil. Terzaghi points out that "If the values of S_s increases for a given soil due to compaction then $P \tan\phi$ represents the sum of a frictional resistance and some other resistance which is independent of P. When this takes place we always find the water content has decreased due to compaction. We know from experience that the value of C increases for a given clay with decreasing initial water content. If S_s is appreciably greater on a preconsolidated soil $P \tan\phi$ consists of two parts with different physical causes." The first part is the friction produced by the normal stress P and the second part is the increase of the cohesion due to the reduction of the water content which occurred while the pressure on the specimen was increased from zero to P. For clays the shearing stress is always greater for a preconsolidated sample. Hence the value ϕ is not a constant nor does it represent the angle of internal friction.

Nichols (1932) when conducting shear tests of agricultural soils at different normal pressures, found that shear strength of plastic soils is proportional to pressure and increases and decreases linearly with moisture content, a maximum value being obtained near the lower plastic limit and proportional to the plasticity number. Shear strengths of non-plastic soils were found to be similar to those of plastic soils when the soil contained appreciable amounts of coloidal material. "Pure sand showed no increase in shear strength with increased moisture content." Shear values of non-plastic soils depend to a large degree on the size, shape and smoothness of the large particles. He proposed the following formula for shear strength of plastic soils.

$$S_s = \frac{(Pu - M)}{Pn} (0.06\ Pn + P + 1.8) \text{ where}$$

Pu is the upper plastic limit, M the moisture content in percentage, Pn the plasticity number, and P the pressure in pounds per square inch.

The shear strength of saturated clay was defined by Hvorslev (1937) to be $S_s = aP + b\exp(BE)$ where P is the effective compression load and E the voids ratio at the moment of failure. When the soil is saturated E is also the water content. The values a, b and B are soil constants. For a clay straining at equilibrium there is a unique pressure and shear strength depending on the water content. In a saturated clay, shear strength is determined by two factors, the effective normal load which with the coefficient of friction gives the frictional shear strength and the void ratio which determines the cohesion component of shear strength.

Considerable work has been done by Greacen (1960) in determining the effects of water content on soil strength. He used a ring shear machine capable of measuring shear strength, void ratio, and pore water suction. Tests were conducted on 7-14 mm aggregate fractions of two clays, one having a weak structure and referred to as a plastic clay, and the other a very strong structure with high aggregate stability. He was able to verify Hvorslev's equation for shear strength in a loose soil compressed and sheared in the saturated condition. For unsaturated soil he found the internal angle of friction ϕ to be 45° irrespective of soil type or water content over the wet range. The shear strength of unsaturated soil was found to be $S_s = (P + s) \tan\phi\ (1 - E)$ where P is the applied load, S the suction in the soil water, $\tan\phi$ the coefficient of friction, and E is the fractional air filled porosity.

He wrote "For both the saturated and unsaturated state, agricultural soil compresses under normal load to a density which appears to be a function of aggregate strength and the initial state of the bed. When a shear force is subsequently applied, the soil compresses further to what has been called the 'ultimate voids ratio', after which there is only negligible change." He also proposed a rheological model to explain the situation existing in soil when compressed with and without shear, and the effects of water content on strength.

MATERIALS AND APPARATUS

A bevameter developed and loaned by the Land Locomotion Laboratory was used to obtain the data used in the calculations of the soil values. The bevameter consists of a penetrometer, a shear vane, and a recording device. These components are mounted on a rigid frame as shown in Figure 1.

Force vs. depth of penetration and shear are recorded. Force is measured by a linear spring having a 240 lb. capacity, with a 4.8 inch deflection. Distance is measured by the travel of the movable chart holder. The travel of the chart holder is determined by the position of the spring housing and spring deflection. Deflection of the spring subtracts from the travel of the chart holder so only actual distances of penetration and shear are recorded. Details of the chart drive mechanism are shown on Figure 2.

The penetration probe is forced into the soil by the downward travel of the spring housing. Deflection of the spring records the force of penetration on the chart.

The bevameter is equipped with circular probes having diameters of 1 to 3-1/2 inches at 1/2 inch intervals and 4 to 6 inches at 1 inch intervals. Rectangular probes available are 3/4 x 4 - 1 x 4 - 3/4 x 5 - 1 x 5 - 1-1/4 x 4 - 1-1/4 x 5 - 2 x 8-3/32 - 7 x 3/4 and 7 x 1. The shear

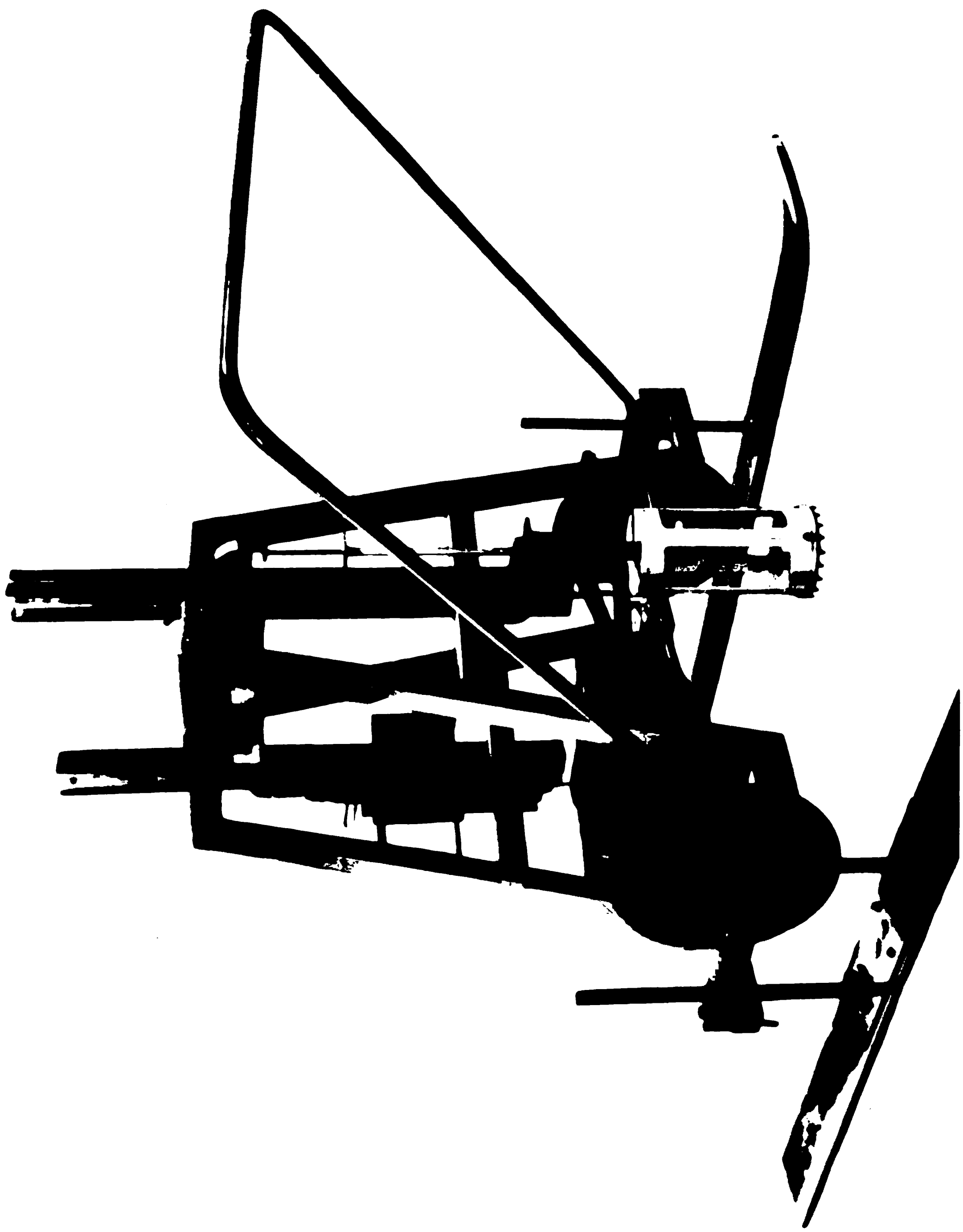

Figure 1. Bevameter

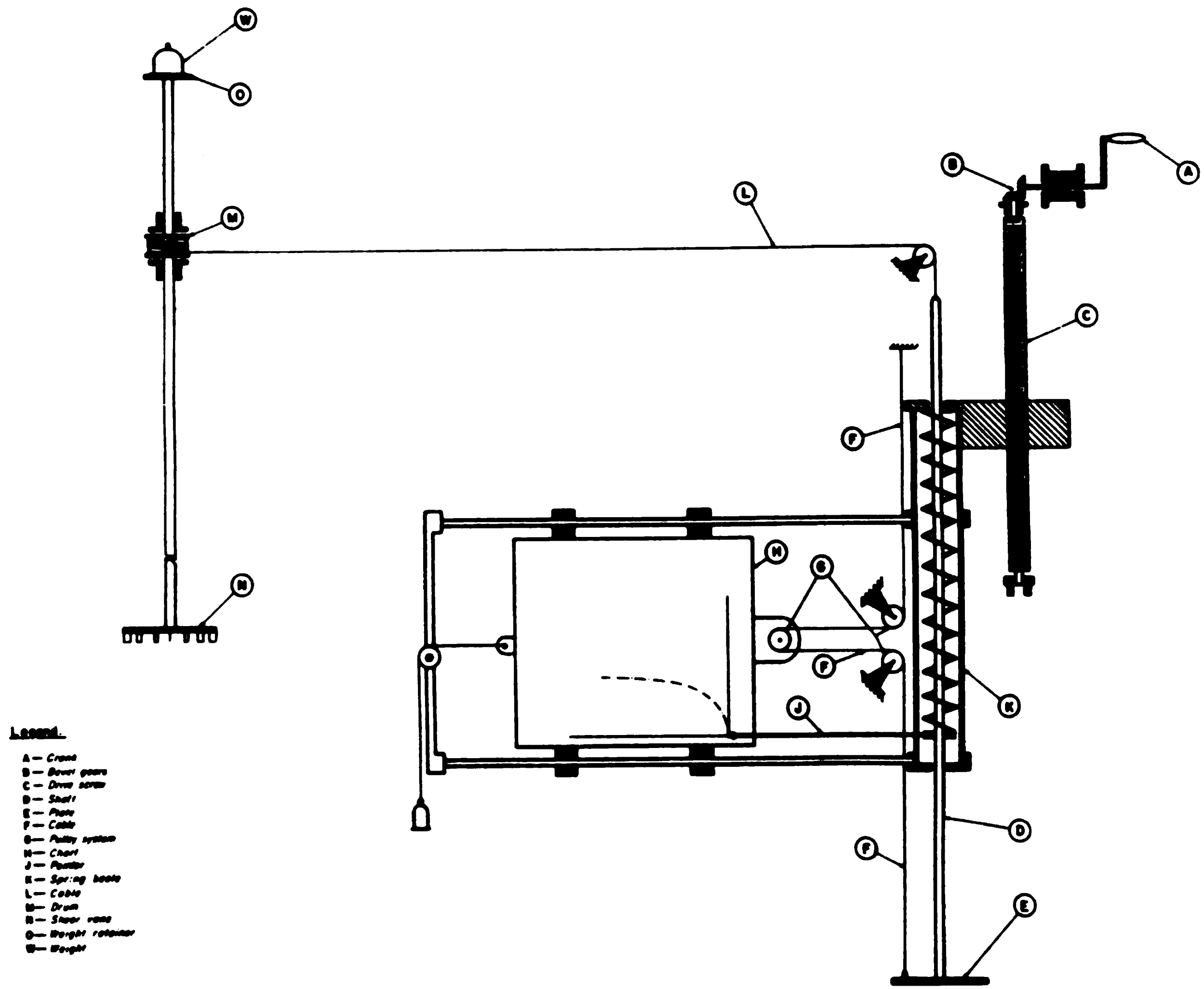

Figure 2. Schematic diagram of the bevameter recording chart drive mechanism.

vane is placed on the surface of the soil and loaded with lead weights to give a known normal force. It is rotated by a wire cable attached to the top of the penetration probe. To rotate the shear vane the spring housing is moved in the downward direction. The force required to shear the soil is measured by spring deflection and recorded on the chart.

Movement of the spring housing is caused by rotation of a hand crank which drives a threaded shaft by means of bevel gears.

A three-point hitch was added to the bevameter so it could be moved with a tractor. To provide power to drive the spring housing, a 1-1/2 HP hydraulic motor was installed on the bevameter and operated by the tractor's hydraulic system. The modified bevameter is shown in Figure 3.

Soil samples were taken with the Buchele soil sampler (1960). The sampler obtained undisturbed 3 x 3 inch cores to a depth of 18 inches. A chain saw engine provides power to drive an auger into the soil (see Figure 4). From these core samples moisture and bulk density were determined.

During one series of tests a Nuclear-Chicago gamma density gauge was used to measure bulk density. This instrument consists of a cesium source to supply gamma radiation and a Geiger counter which is placed on the surface of the soil. The reading from the Geiger counter is fed to an electronic counter which records the radiation reflected by the soil (see Figure 5).

Figure 3. The modified bevameter used in the study.

Negative No. 22376-2

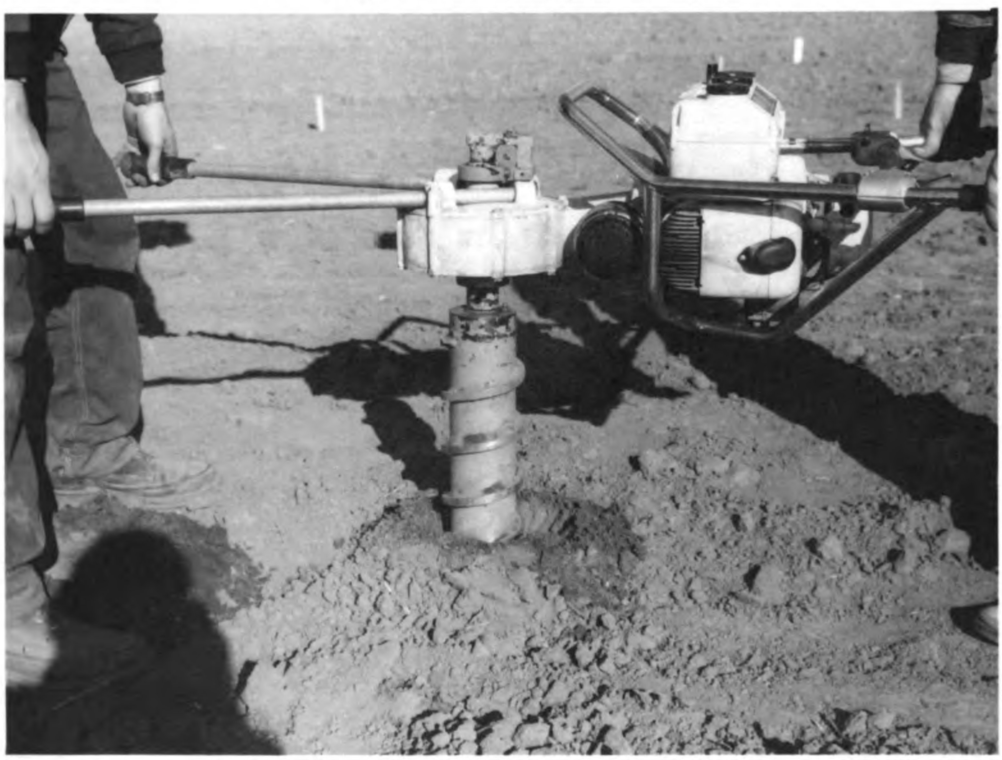

Figure 4. The Buchele soil sampler used to obtain undisturbed soil samples.

Negative No. 22192-27

The amount of radiation reflected depends on the density of the soil. Higher densities will reflect more radiation than lower densities.

A soil bin with soil moving equipment was constructed so tests could be conducted under laboratory conditions (Figure 6). The soil bin consisted of a tank 5' in diameter by 40" in height. The bevameter is mounted on rails over the top of the bin (see Figure 7). Two Syntron V-75 Electro Magnetic vibrators are attached to the tank bottom to provide vibration for soil compaction, and to assist in removing the soil from the tank. Two swinging doors permitted the soil to fall from the tank onto an 18-inch belt conveyer which transported the soil to the hopper of an inclined bucket elevator (Figure 8). The soil is then elevated to a height of ten feet where it falls onto an 18-inch belt conveyer which carries it to the soil storage tanks.

Water can be sprayed on the soil as it enters the storage tanks or the hopper of the elevator. About 1% moisture can be added to the soil in this manner each time the soil is renovated. Moisture changes in the tank were prevented by covering the soil with a plastic sheet during off work periods.

When the storage tanks are filled the soil is then returned to the testing tank by repeating the above process. As the soil enters the testing tank it passes through a 3/4 x 2 inch expanded metal screen (Figure 9). This

Figure 5. The gamma density gauge used to locate areas of uniform density for penetration tests. Negative No. 22376-5

Figure 6. The soil bins and soil handling equipment used for the laboratory study. Negative No. 23340-3

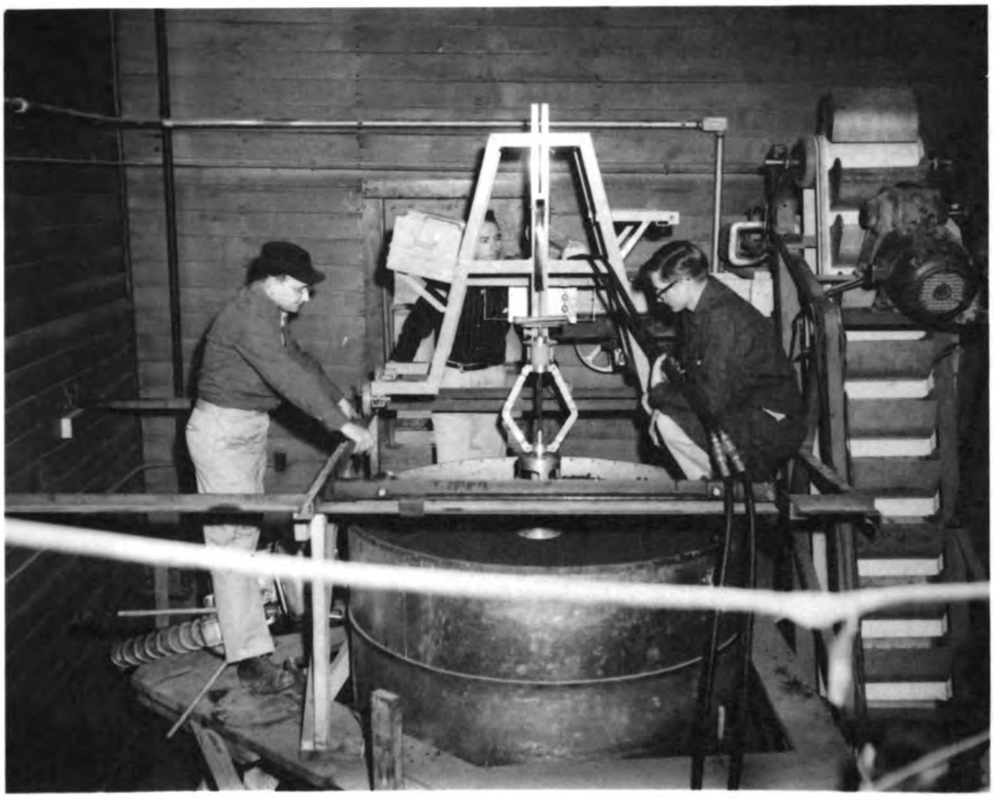

Figure 7. The bevameter mounted on rails over the top of the test tank.
Negative No. 23290-2

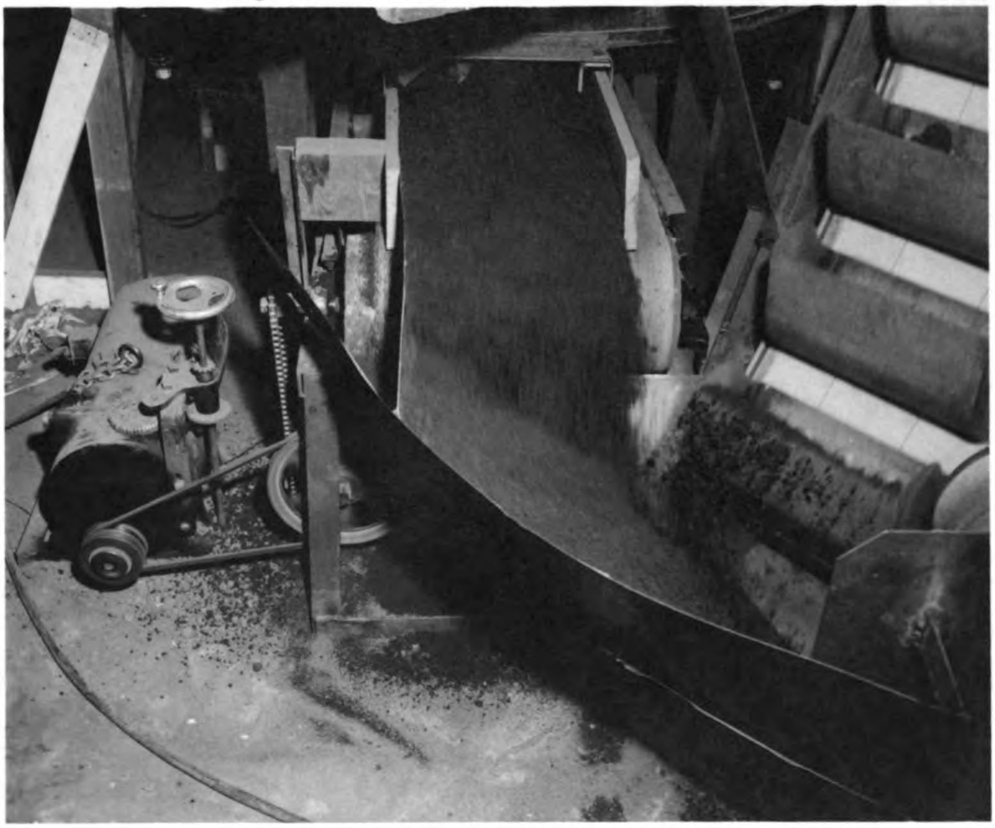

Figure 8. The horizontal conveyer and hopper of the inclined bucket elevator that was used to transport the soil.
Negative No. 23340-4

screening process insures a uniform soil density as it permits the soil to fall from the same height and be uniformly distributed in the tank.

The time required to renovate the soil was approximately 30 minutes. Soil below 18% moisture was the easiest to handle, as at higher moistures the screening process required additional time.

When removing the soil from the testing tank after the compaction tests, large blocks of soil were formed when breaking the soil loose from the tank. These large clods were completely destroyed during the handling and screening process.

The few remaining small clods which pass through the screen roll to the sides of the tank due to the cone of soil initially formed when filling the tank. The uniformity of the penetrometer tests showed that the resulting soil mass was at uniform density.

The soil when placed in the testing tank has a bulk density of approximately 0.9 (dry wt.) in the 0 to 3 inch zone. To increase the bulk density two methods were employed. For bulk densities in the range of 0.9 to 1.0 the tank vibrators were used. About 15 minutes of vibration were required to obtain bulk densities of 1.0. Higher bulk densities were obtained by use of an air tamper (Figure 10). By careful use of the tamper uniform bulk densities as high as 1.44 were obtained.

Figure 9. The 3/4 x 2 inch screen used to insure uniform soil density.
Negative No. 23340-5

Figure 10. The air tamper used to increase soil density.
Negative No. 23340-1

The Buchele soil sampler was used to obtain soil samples to determine moisture and density of the compacted soil tests. When the soil was in the loose condition a tin can with known dimension was used to obtain soil samples.

The soil used for the field and laboratory tests is a Brookston sandy loam. The field test plot was located at the Michigan State University campus on a field of the Farms Crops Department. The test site was especially selected because it contained soil of a known type and description. Soil from the test plot was also used in the laboratory tests and is described in Table I.

TABLE I.

PHYSICAL DESCRIPTION OF THE BROOKSTON SOIL USED IN THE TESTS

Mechanical Analysis		
Fine Gravel		1.2%
Coarse Sand		3.6%
Medium Sand		6.1%
Fine Sand		26.8%
Very Fine Sand		27.7%
50 Micron		13.4%
5 Micron		5.6%
2 Micron		15.6%
Hygro. Coef.	1.6%	
Moist. Equ.	14.3%	
Max. Water Holding Capacity	63.8%	
Soil Saturated	37.1%	
60 cm. Tension	25.4%	
Permanent Wicting Point	8.7%	
Lower Plastic Limit	21 %	
Upper Plastic Limit	25.5%	
Plastic Range	4.5%	
Density	2.6	

METHOD OF PROCEDURE

The procedure used for the field tests was similar to that recommended by Hanamoto and Hegedus (1958).

The 48' x 50' test site was divided into fifteen 16' x 10' plots. In each plot a complete series of soil value tests were conducted and at least two 18 x 3 inch core soil samples were obtained.

A complete soil value test consisted of penetration and shear tests. Two different sized circular plates were used for the penetration tests. At least three force vs. depth curves were obtained for each plate. Two shear curves of forces vs. deformation were obtained for normal forces of 1.01, 2.02, 3.03, and 4.05 psi. If there was a wide variation in the shape of these curves, additional tests were conducted to obtain a representative curve of the test site.

In testing a plot the following procedure was followed. The tractor was backed into the plot with the outside wheels 1/2 ft. inside the 10 foot plot boundary. As soon as the bevameter was inside the plot it was lowered to the soil and a penetration and shear test obtained. Penetration and shear tests were taken at 2 foot intervals until the 16 foot plot boundary was reached, the tractor was then driven ahead and backed into the plot 1/2 foot inside the other 10 foot plot boundary and the remaining tests taken as described above. Using this procedure at least four shear and penetration tests could be taken on each side of the plot, if additional tests were needed to obtain identical curves the distance between the tests were reduced to 1 foot. Using this method no difficulty was encountered in obtaining the required tests to obtain a complete set of soil values for each plot.

For the penetration tests, the tractor engine speed was set at 1600 RPM which gave a penetration speed of approximately 2.32 ft/min. During the shear tests the engine speed was set at 500 RPM which gave the spring housing a speed of 0.913 ft/min. Upon completion of these tests two or more soil samples were taken with the Buchele soil sampler (1960). The number of soil samples obtained depended on the amount of variation in the penetration curves. If the curves were quite variable then one or two additional soil samples were taken. The samples were taken close to the locations of the penetration tests.

In the laboratory a different procedure was used as the testing area was smaller and the soil condition controlled. When the soil was in the condition to be tested penetration tests were taken first. This consisted of two penetration tests with each of the two different sized circular plates. In a few cases there was a minor variance in the shape of the curves so an additional test was taken.

The hydraulic motor of the bevameter was operated by an electric driven hydraulic pump. The rate of penetration was 2.9 ft/min. When plates having diameters smaller than 3 inches were used the bevameter was positioned so that the probe center was 18" from the tank sides. With plates larger than this used, the probe center was located 15 inches from the tank sides. These distances proved to be adequate to eliminate tank side effects and the effects of the other penetrations.

Upon completion of penetration tests shear tests were taken on the remaining undisturbed soil. One value was obtained for each normal force of 1.01, 2.02, 3.03, and 4.05 psi.

Moisture and bulk density samples were obtained in the loose soil with a tin can of known dimensions, at two locations to a depth of nine inches. When the soil was compacted one sample was taken with the Buchele (1960) sampler.

The information from the penetration and shear tests were used to find the soil values which are the constants in the sinkage and shear formulas.

The constants Kc, K_ϕ and n in the sinkage formula

$$P = \left(\frac{Kc}{b} + K_\phi\right) Z^n$$

are obtained by the following solution:

$$P_1 = \left(\frac{Kc}{b_1} + K_\phi\right) Z_1^{\,n}$$

$$P_2 = \left(\frac{Kc}{b_2} + K_\phi\right) Z_2^{\,n}$$

Where the subscripts 1 and 2 refer to the values obtained from the sinkage of plates with radius b_1 and b_2.

Taking logarithms of the above equations:

$$\log P_1 = \log \left(\frac{Kc}{b_1} + K\phi\right) + n \log Z_1$$

$$\log P_2 = \log \left(\frac{Kc}{b_2} + K\phi\right) + n \log Z_2$$

When $Z_1 = Z_2 = 1$ inch then $n \log Z_1 = n \log Z_2 = 0$ for sinkage of 1 inch.

$$\log P_1 = \log \left(\frac{Kc}{b_1} + K\phi\right)$$

$$\log P_2 = \log \left(\frac{Kc}{b_2} + K\phi\right)$$

Now there are two equations and two unknowns so we can solve for Kc and $K\phi$.

Let $P_1 = a$ $P_2 = a_2$

then $a_1 = \frac{Kc}{b_1} + K\phi$

$$a_2 = \frac{Kc}{b_2} + K\phi$$

Solving for Kc and $K\phi$

$$K\phi = \frac{a_2 b_2 - a_1 b_1}{b_2 - b_1}$$

$$Kc = \frac{(b_1 b_2)(a_1 - a_2)}{b_2 - b_1}$$

To obtain a_1 and a_2 the values of P vs. depth are plotted on log-log paper. If sinkage follows the proposed equation then two parallel lines should be obtained on the log-log plot. The values of a_1 and a_2 are read from the plot at the 1 inch depth; the value of n is the tangent of the slope of the lines. The straight line plot of the smaller probe should be above the plot of the larger probe. When circular plates are used b is the radius in inches.

To determine C and ϕ in the Coulomb-Mohr equation an annulus with an inside and outside diameters of 5-3/8" and 7 inches is placed on the surface of the soil and rotated at various normal pressures. The force required to shear the soil is recorded by the bevameter. From the following formulas the shear stress, S_s, is calculated.

The moment resisted by the soil can be described as

$$dM = 2\pi r \times r dr S_s$$

$$M = S_s \int_{r_1}^{r_2} 2\pi r^2 dr$$

$$M = 2/3\, \pi\, S_s (r_2^3 - r_1^3)$$

$$S_s = \frac{3M}{2\pi (r_2^3 - r_1^3)}$$

$r_2 = 3.5$ inches and $r_1 = 2.687$ inches, $\therefore$

$$S_s = .02025\ M$$

The point where the shear vane is rotated by the flexible cable has a radius of 2.51 inches; therefore

$$S_s = .02025 \times 2.51 \times \text{Force}$$

$$S_s = .0508 \times \text{Force}.$$

As the flexible cable passes over two pulleys in order to connect to the top of the penetration probe the recorded maximum force is divided by 1.2 to get the corrected force for use in the above formula.

The normal stress P is obtained by placing lead weights on a loading plate attached to the shear vane. Each weight weighs 8# and as the surface of contact with the soil is

$$\pi r_2^2 - \pi r_1^2 = 15.85 \text{ sq. in.}$$, 2 - 4 - 6 and 8 weights are required for the normal stress of 1.01, 2.02, 3.03 and 4.05 used in the tests.

Shear stress vs. normal stress is plotted to obtain C and ϕ . C is the value of the shear stress at zero normal stress and ϕ is the angle of the straight line obtained from the plotted values of S_s vs P.

The force vs. depth curves from the bevameter penetrometer were analyzed in the following manner. The force scale used was 50# per inch and the depth scales used were 1 to 1 and 2 to 1. The 1 to 1 scale is preferable. A plastic template was used to read the force for depths of 1,-2 - 3 and 4 inches from the penetration curves.

The forces obtained from the curves were multiplied by .94 to obtain the corrected value as the measuring spring had a 6 percent error. From the three or more curves obtained with each sized plate only the force values from the similar curves were averaged to obtain P. The dissimilar curves were neglected as they were thought to be caused by irregularities in the soil.

In analyzing the shear curves the maximum shearing force from the similar curves were averaged and then multiplied by the correction factor, 1/1.2, which corrects for the spring error and the pulley friction losses. Dissimilar shear curves were neglected as they were caused by improper contact of the shear vane with the soil and soil irregularity.

In drawing the parallel lines through the log-log plots of P vs. depth the points at the 1 inch depth were sometimes neglected as past experience (Trask 1958) has shown that at the shallow depths the Bekker sinkage equation does not hold.

PRESENTATION AND DISCUSSION OF EXPERIMENTAL RESULTS

Tests were conducted in the field and laboratory and are presented in chronological order.

Field Tests

Field tests were conducted during the period 30 July-12 November 1959 and on 23 April 1960. The following points were investigated.

a. Effect of plowing on soil values

b. Effect of disking on soil values

c. Effect of wheel traffic on soil values

d. Effect of a freezing and thawing cycle on soil values

e. Effect of weather on soil values.

The Effects of Plowing on the Soil Values

Soil values were obtained on unplowed fallow soil having a sparce weed cover. The soil is classified as an Metamora fine sandy loam. Immediately after these values were obtained the area was plowed to a depth of 5 inches and soil values were then obtained for the plowed ground.

As can be seen on Figures 11 and 12 and Table II, plowing reduces the soil strength by decreasing C, and K_ϕ , and increasing n. By observing the changes in moisture and density due to plowing, Figures 13 and 14, it becomes apparent that a plowed soil should have a lower strength. The change in cohesion due to the decreased density indicates that the shear strength of this soil is affected by preconsolidation.

Tests were conducted on alfalfa sod adjacent to the above test site. This sod had not been disturbed for five years. After obtaining the sod soil values the test area was plowed to a depth of 12 inches and soil values were again taken, Figures 15 and 16. Again we see that K_ϕ and C are decreased while n increases (Table II). The sod had a higher bulk density than the fallow ground, Figures 17 and 18, and this accounts for the larger value for K_ϕ.

TABLE II

SOIL VALUES OBTAINED FOR UNPLOWED AND PLOWED SOIL

		Kc	K_ϕ	n	C	ϕ
					Psi	Degrees
Weed Cover	Unplowed	10.5	37.2	.61	1.63	42.5
	Plowed	1.65	1.32	1.1	1.02	20.5
Sod	Unplowed	15	64	.05	4.65	28.5
	Plowed	0	3.8	.95	1.45	27.5

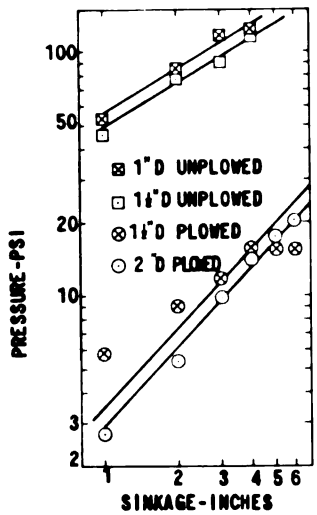

Figure 11. Logarithmic plot of pressure versus sinkage for plowed and unplowed soil having a week cover.

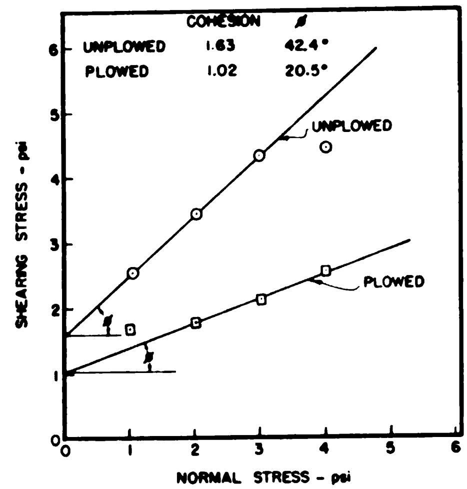

Figure 12. Normal stress versus shearing stress for plowed and unplowed soil having a weed cover.

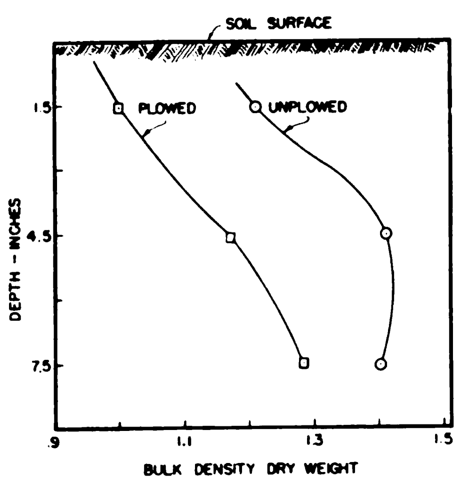

Figure 13. Bulk density versus depth for plowed and unplowed soil having a weed cover.

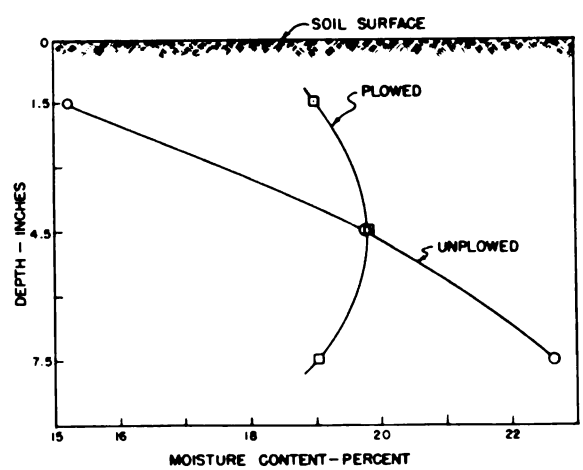

Figure 14. Moisture content versus depth for plowed and unplowed soil having a weed cover.

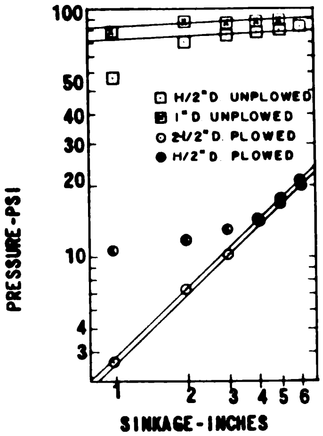

Figure 15. Logarithmic plot of pressure versus sinkage for plowed and unplowed sod.

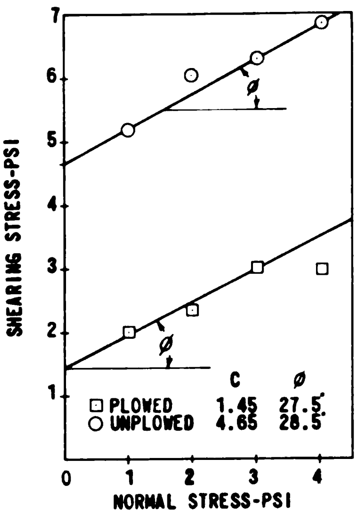

Figure 16. Normal stress versus shearing stress for plowed and unplowed sod.

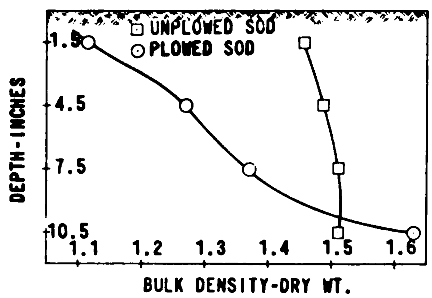

Figure 17. Bulk density versus depth for plowed and unplowed sod.

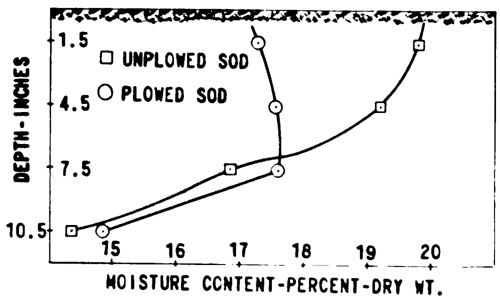

Figure 18. Moisture content versus depth for plowed and unplowed sod.

The Effects of Disking on the Soil Values

Soil values were obtained on Brookston soil that had been plowed and disked once and then remained undisturbed for a period of approximately 16 days. The field was then disked and soil values taken immediately after disking.

The effects of disking are to decrease K_ϕ and n and increase Kc, Table III. C and ϕ were not appreciably affected, Figures 19, 20, 21 and 22.

TABLE III

SOIL VALUES OBTAINED FOR SOIL BEFORE AND AFTER DISKING

	Kc	K_ϕ	n	C	ϕ
				Psi	Degrees
Before Disking	11.25	19.2	.95	.7	20
After Disking	36	6	.57	.5	22.5

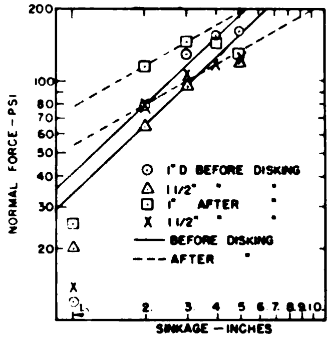

Figure 19. Normal stress versus shearing stress for soil before and after disking.

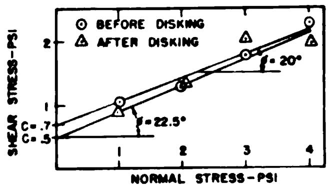

Figure 20. Logarithmic plot of pressure versus sinkage for soil before and after disking.

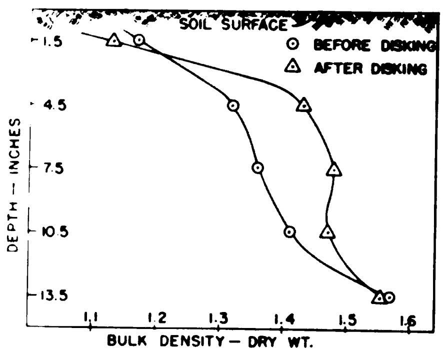

Figure 21. Bulk density versus depth for soil before and after disking.

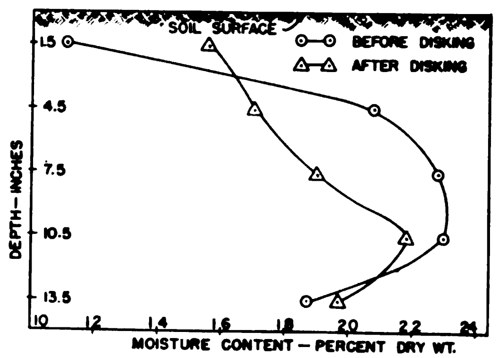

Figure 22. Moisture content versus depth for soil before and after disking.

The Effects of Wheel Traffic on the Soil Values

The effect of wheel traffic was observed on Brookston soil that had been plowed nine days prior to this test. Soil values were obtained and then a Ford Model 660 Tractor was driven back and forth in the same track until a sinkage of approximately four inches was obtained. Soil values were then measured in the tracks.

Due to the high density of the soil the foot was removed from the penetrometer and the 3/4 inch penetrometer rod was used as the foot. With a plate size larger than one inch the capacity of the bevameter force measuring spring was exceeded.

Wheel traffic increased K_ϕ and ϕ while decreasing Kc and n, (Table IV). The penetration log-log curve of the compacted soil seemed to indicate two sets of soil values (Figure 23). The force required for penetration reaches a maximum at 1-1/2 inch and 230 psi. for both sized probes and then decreases giving a negative n for the 1-1/2 to 4 inch range. A similar phenomenon was observed for surface compacted soil in the laboratory tests (to be discussed later). This indicates that for soil compacted in this manner sinkage is determined by two sets of constants. One set holds true until a certain sinkage is reached and then the second set of soil values applied to deeper sinkages.

Cohesion is decreased and the internal angle of soil friction increased by the action of wheel traffic (Figure 24). Laboratory test B on surface compacted soil gave similar values of C and ϕ.

Bulk density is greatly increased by wheel traffic (Figure 25). This shows that wheel traffic can produce high bulk densities on soil recently plowed. It is interesting to note the large increase in surface bulk density since plowing due to rainfall.

Compaction by wheel traffic tended to decrease the surface moisture content and increase the moisture content at lower depths (Figure 26). The surface soil was pulverized by wheel action which would cause it to be dryer. The increased compaction at the subsurface caused an increase in moisture content at this level.

TABLE IV

SOIL VALUES FOR UNCOMPACTED SOIL AND SOIL COMPACTED BY WHEEL TRAFFIC

	Kc	K_ϕ	n	C	ϕ
				Psi	Degrees
Uncompacted Soil	5	7	.78	1	29.5
Compacted Soil	0	217.5	.12	0	46

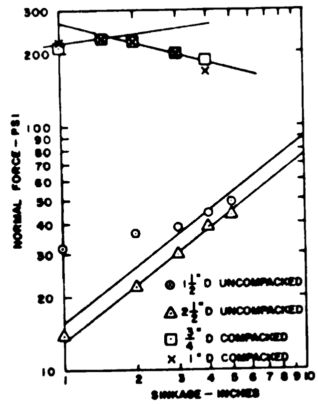

Figure 23. Logarithmic plot of pressure versus sinkage for compacted and uncompacted soil.

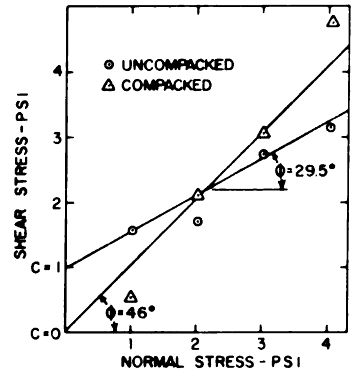

Figure 24. Normal stress versus shearing stress for compacted and uncompacted soil.

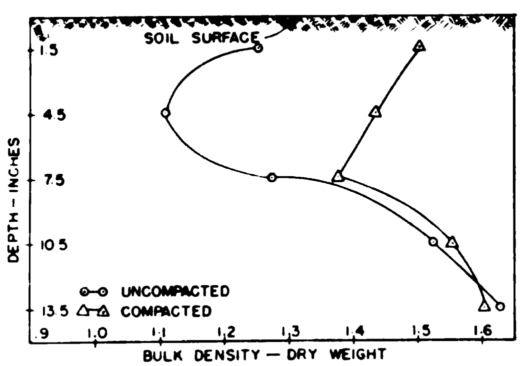

Figure 25. Bulk density versus depth for compacted and uncompacted soil.

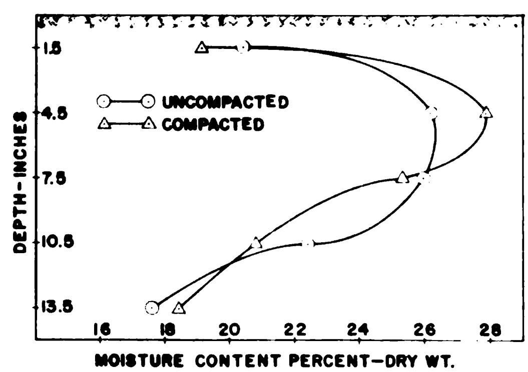

Figure 26. Moisture content versus depth for compacted and uncompacted soil.

The Effects of Freezing and Thawing on the Soil Values

Moisture and density measurements showed almost identical field conditions on 12 November 1959 and 23 April 1960 (Figures 29 and 30). Penetration tests showed minor changes in the sinkage soil values (Table V). From the log-log plot of the penetration curve of 23 April (Figure 27) it can be seen that two sets of soil values can be obtained indicating that for sinkages over approximately 2-1/2 inches another set of soil values should be used in the sinkage formula.

The large increase in C and decrease in ϕ (Figure 28) was probably caused by puddling of the soil which took place upon thawing due to the very high moisture content that existed for a long period of time due to poor drainage.

TABLE V

SOIL VALUES FOR 12 NOVEMBER 1959 AND 23 APRIL 1960

	Kc	K_ϕ	n	C	ϕ
				Psi	Degrees
12 November 1959	21	31.2	.42	1.0	37
23 April 1960	13.5	38.8	.4	2.6	22.3

Soil samples were obtained with the Buchele soil sampler (1960) on 15 March and 29 March 1960 to study the effects of freezing and thawing on moisture content and bulk density. On 15 March the soil was frozen to a depth of 15 inches and on 29 March the soil had thawed to a depth of 6 inches.

As can be seen on Figures 29 and 30 freezing lowers the bulk density considerably and increases the moisture content. The bulk density is decreased due to the expansion caused by freezing of the soil water. Upon thawing this expanded structure collapses and the bulk densities return to their original values. Surface moisture content is high for several days after thawing as the soil remains frozen at the lower depth for several days preventing drainage. Soil samples obtained on 11 April showed the soil to still be frozen at the 12 to 15 inch depth and surface moisture to be 26%.

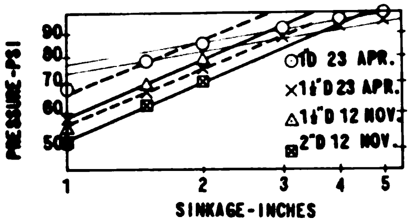

Figure 27. Logarithmic plot of pressure versus sinkage for 12 Nov. 1959 and 23 April 1960.

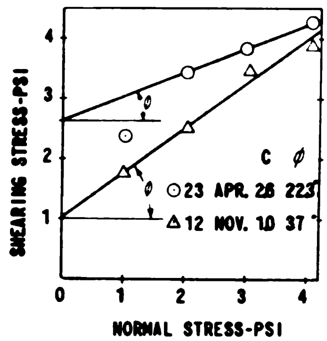

Figure 28. Normal force versus shearing stress for 12 Nov. 1959 and 23 April 1960.

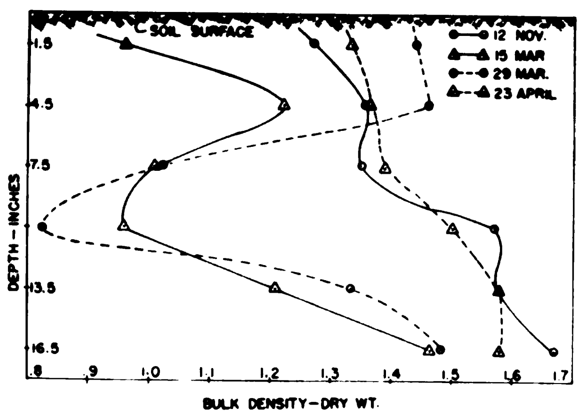

Figure 29. Bulk density versus depth for Fall, Winter and Spring 1959-60.

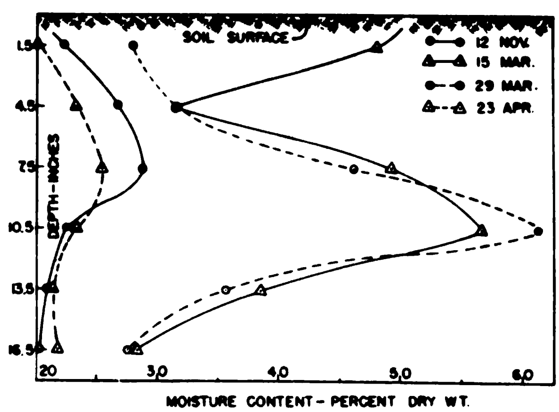

Figure 30. Moisture content versus depth for Fall, Winter and Spring 1959-60.

Effect of Weather on Soil Values

The soil values obtained on the test site containing Brookston soil are plotted vs. time from 30 July 1959 to 23 April 1960.(Figures 31 and 32). Changes in moisture content and bulk density from 12 August to 23 April are plotted on Figure 33. Moisture and bulk density were not obtained on 30 July and 4 August. It is observed that on 22 September and 29 October the moisture content remained the same while the bulk density increased from 1.17 to 1.29, and the soil values Kc, K_ϕ and ϕ increased while n and C decreased. This shows the possible effect of bulk density on the soil values.

The slight decrease in bulk density and moisture content on 12 November increased n, Kc, K_ϕ, and ϕ while decreasing C which shows the effect of decreasing moisture on the soil values. It is interesting to note that Kc increases when C decreases and vice versa which indicates an inverse relationship between these values. In the moisture range of these tests bulk density has a greater effect on the soil values than moisture content.

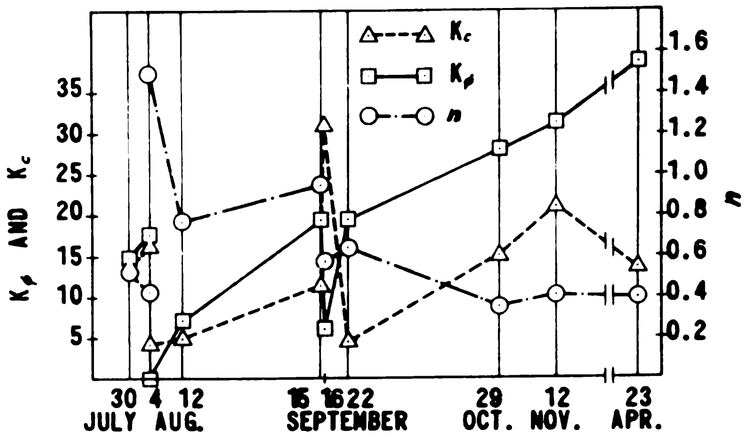

Figure 31. Sinkage soil values versus time from 30 July 1959 to 23 April 1960.

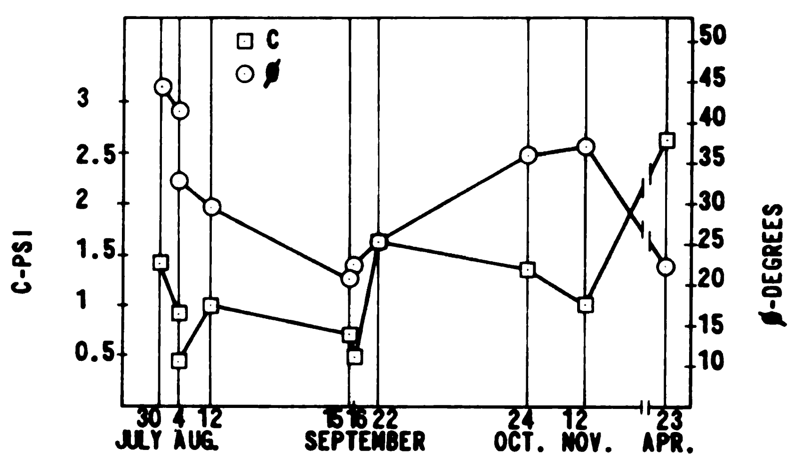

Figure 32. C and Ø versus time from 30 July 1959 to 23 April 1960.

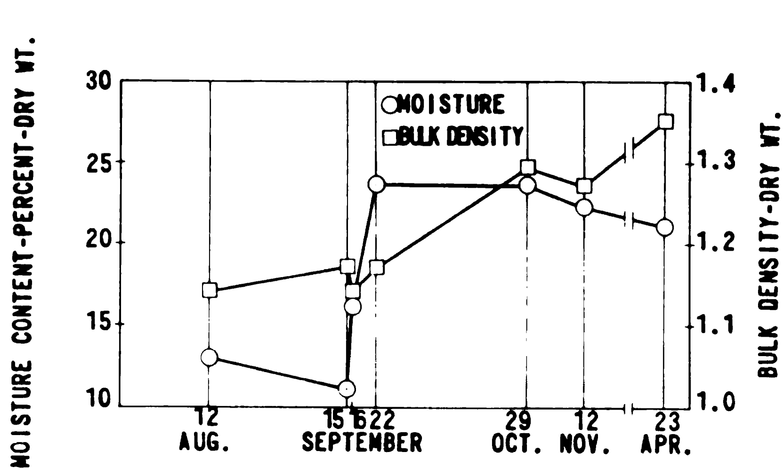

Figure 33. Moisture content and bulk density versus time from 12 Aug. 1959 to 23 April 1960.

Laboratory Tests

Laboratory tests were conducted during the period 3 March to 21 April 1960 to study the effect of moisture and density on the soil values. Soil values were determined for the following soil conditions and are reported in this order:

1. Uncompacted soil
2. Surface compacted soil
3. Uncompacted soil over a compacted layer
4. Compacted at surface and subsurface

Soil Values of Uncompacted Soil

Soil values were obtained on soil with bulk densities ranging .90 to 1.0 and moisture contents from 14 to 17.9 percent. The results of a typical test are shown in Figures 34, 35 and 36. Figure 34 shows the type of force vs. sinkage curve obtained for the bulk density profile of an uncompacted soil.

The log-log plot of this force-sinkage curve gives two parallel lines (Figure 35) which indicates that sinkage in soil with a fairly constant bulk density vs. depth relationship is determined by Bekker's sinkage formula. The soil values of this test are $Kc = 2.$, $K_\phi = 0.7$, $n = 0.9$, $C = 0.2$ and $\phi = 24^\circ$.

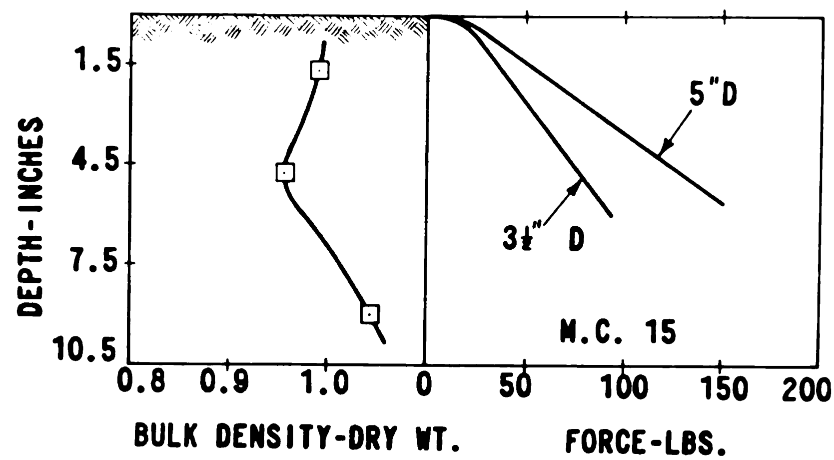

Figure 34. Bulk density and force of penetration versus depth for an uncompacted soil.

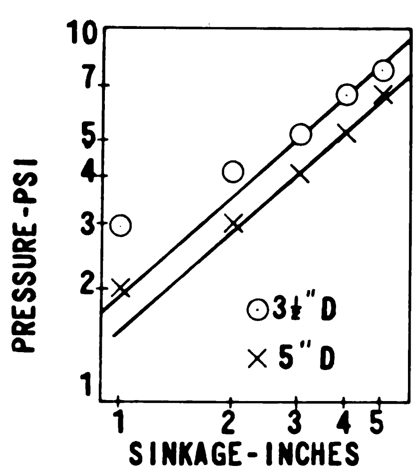

Figure 35. Logarithmic plot of pressure versus sinkage for an uncompacted soil.

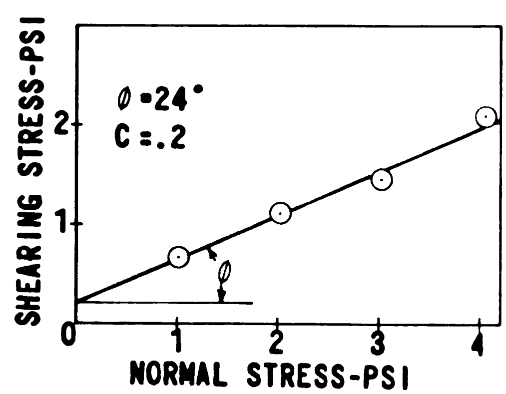

Figure 36. Normal stress versus shearing stress for an uncompacted soil.

Soil Values of Surface Compacted Soil

The soil was compacted on the surface with an air tamper and soil values were taken to determine the effects of surface compaction. The effects of different depth vs. bulk density curves on pressure-sinkage relationships are shown on Figures 37, 38 and 39. Soil of Test A had a higher moisture content and bulk density than the soil of Test B. The shape of the log-log plot of pressure vs. sinkage for Test A is identical to pressure sinkage curve in Figure 23, obtained on soil compacted by wheel traffic. This indicates that surface compacted soil requires two sets of soil values to determine its trafficability, Table VI. The difference in the soil values between Test A and B caused by a higher surface bulk density in Test A is quite pronounced and indicates that bulk density is one of the major factors affecting the soil values.

TABLE VI

SOIL VALUES FOR A SURFACE COMPACTED SOIL

	Kc	K_ϕ	n	C Psi	ϕ Degrees
Test A					
0-2-[illegible] sinkage	0	100	.21	.6	27
[illegible]age	0	182	-.42	.6	27
[illegible]					
[illegible]	21	0	.12	.1	41
[illegible]	33	1	-.13	.1	41

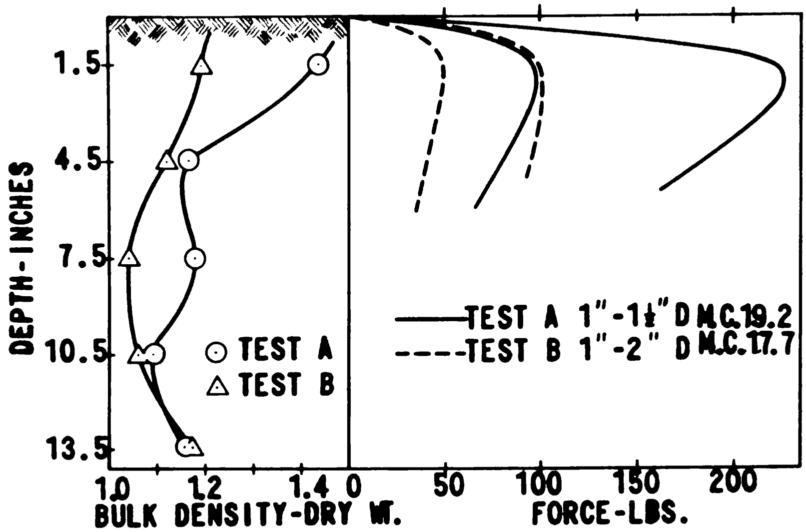

Figure 37. Bulk density and force of penetration versus depth for a surface compacted soil.

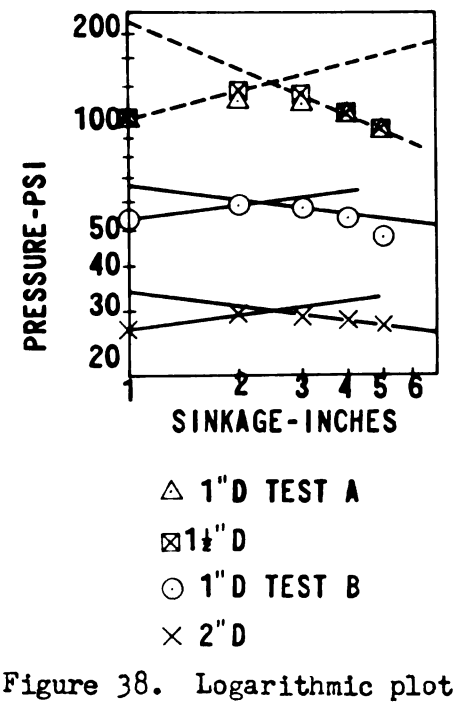

Figure 38. Logarithmic plot of pressure versus sinkage for a surface compacted soil.

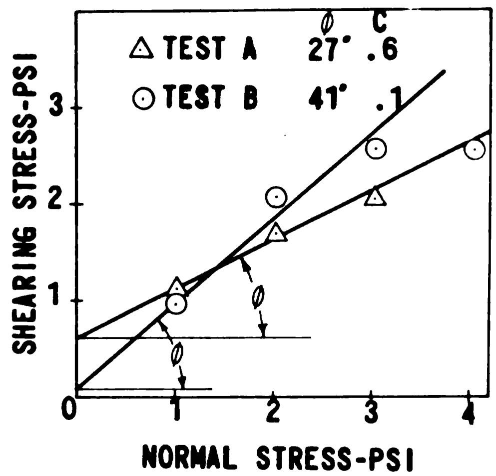

Figure 39. Normal stress versus shearing stress for a surface compacted soil.

Soil Values of Compacted Subsurface Soil

After the soil was compacted with the air tamper, a layer of loose soil was placed on top of this dense layer. Soil values were determined on this soil structure to investigate the effects of plow sole on the soil values. Figures 40, 41 and 42 show the results of two tests of this type. Tests C and D were conducted on 4 and 6 inch layers of loose soil respectively. The higher values of the force-depth curve of Test C, Figure 40, is a result of the shallower layer of loose soil. The log-log plot of Test C yields two sets of soil values (Table VII). From the force-depth curve of Test D it is impossible to obtain two parallel lines on the log-log plot, therefore sinkage soil values cannot be obtained for this test.

The force-depth curve has a point of inflection above the compacted layer. This indicates that a cone of soil forms under the penetrometer foot. The base angle of such a cone is given by Terzaghi (1943) as $45^{\circ} + \frac{\phi}{2}$. During Test C the point of inflection occurred at depths of 2.125" and 1" for the 2" and 3-1/2" diameter probes respectively. As the cone base angle = $45^{\circ} + \frac{23^{\circ}}{2} = 56.5^{\circ}$, the height of the cones should be 1.56" and 2.74" for the 2" and 3-1/2" diameter probes respectively. Therefore the compacted layer should be at approximately:

using figures for 2' diameter probe

2.125 + 1.56 = 3.7" depth

or for the 3-1/2" diameter probe

1 + 2.74 = 3.7" depth.

Using the same procedure the calculated depth of the compacted layer for Test D is 6.8 and 7.3 inches for the 2-1/2" and 3-1/2" diameter plates respectively. As the actual depth of this compacted layer is 4 and 6" for Tests C and D respectively, the cone theory of Terzaghi seems to be true in this case and shows that densities at lower depths have an influence on penetration forces.

TABLE VII

SOIL VALUES FOR A SUBSURFACE COMPACTED SOIL

	Kc	K_ϕ	n	C	ϕ
				Psi	Degrees
Test C					
0 to 2" Sinkage	2.03	1.25	1.45	0	23
> 2" Sinkage	.77	.35	2.45	0	23
Test D	--	--	--	.1	24

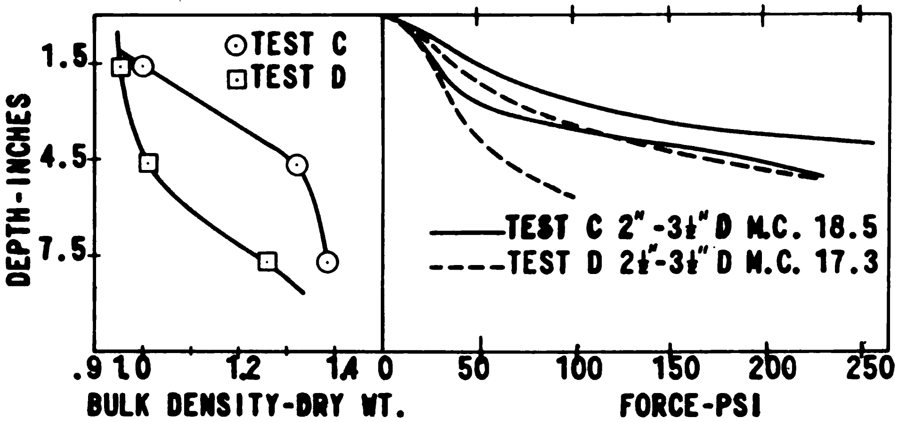

Figure 40. Bulk density and force of penetration versus depth for a subsurface compacted soil.

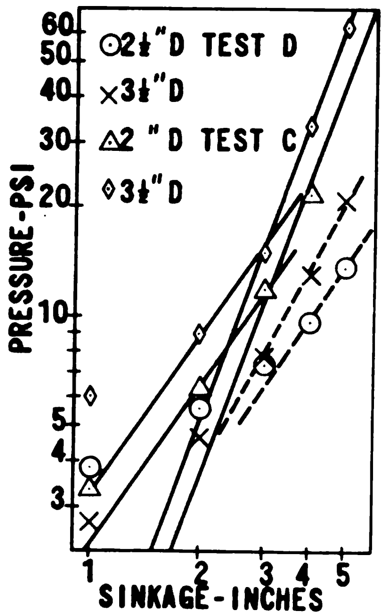

Figure 41. Logarithmic plot of pressure versus sinkage for subsurface compacted soil.

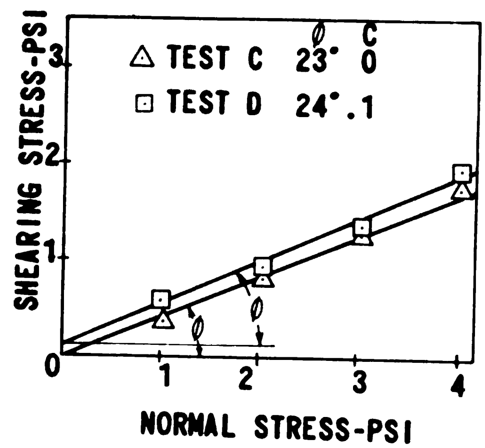

Figure 42. Normal stress versus shearing stress for a surface compacted soil.

Soil Values of Subsurface and Surface Compacted Soil

For these tests the soil was compacted with the air tamper at the surface and subsurface by partially filling the test tank with soil and then compacting with the tamper. The tank was then filled with soil and compacted again. Figures 43, 44 and 45 show the results of two typical tests. Test F was compacted at a shallower depth than Test E as can be observed on the bulk density depth curve (Figure 43). Approximately 4" of soil were placed on the compacted layer before the final compaction of Test F, while for Test E approximately 6" of soil were added. The force-depth curve of Test F shows a decrease in force before the dense layer is reached which indicates that a soil cone was formed under the penetrometer and was forced through the dense layer ahead of the probe. The curves of Test E do not show this phenomena as the depth of penetration was not sufficient to break through the compacted layer. The log-log plot of Test E, Figure 44, does not yield parallel lines indicating that sinkage does not follow Bekker's formula. Soil values for these tests are presented in Table VIII.

TABLE VIII

SOIL VALUES OBTAINED FROM

SURFACE-SUBSURFACE COMPACTED SOIL

	Kc	K_ϕ	n	C	ϕ
				Psi	Degrees
Test E	--	--	--	.36	46
Test F	34.5	30	.31	1.17	43

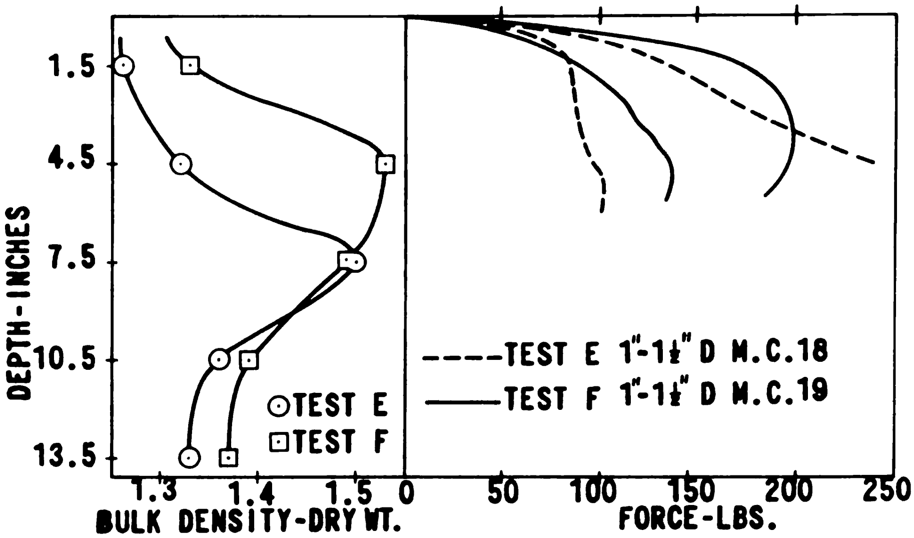

Figure 43. Bulk density and force of penetration versus depth for a surface-subsurface compacted soil.

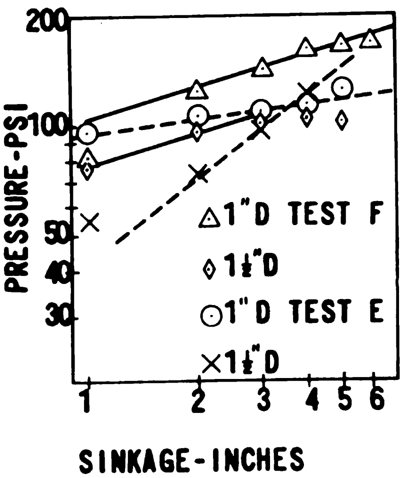

Figure 44. Logarithmic plot of pressure versus sinkage for surface-subsurface compacted soil.

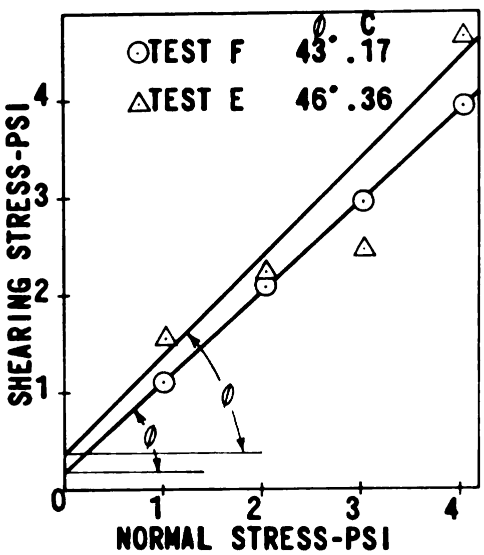

Figure 45. Normal stress versus shearing stress for surface-subsurface compacted soil.

Effects of Moisture on Soil Values

Soil values from laboratory tests with bulk densities of .9 to 1.0 were plotted vs. moisture content in percent. Figures 46, 47 and 48 show that relationships exist between Kc and Kϕ and moisture content. These curves are presented to show what the possible trend of these relationships might be but due to the lack of sufficient data they cannot be used to determine these relationships.

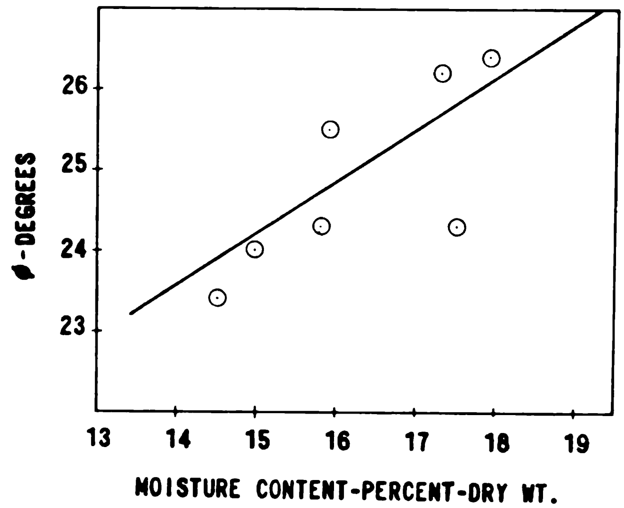

Figure 46. ϕ versus moisture content for soil having bulk densities of .9 to 1.0.

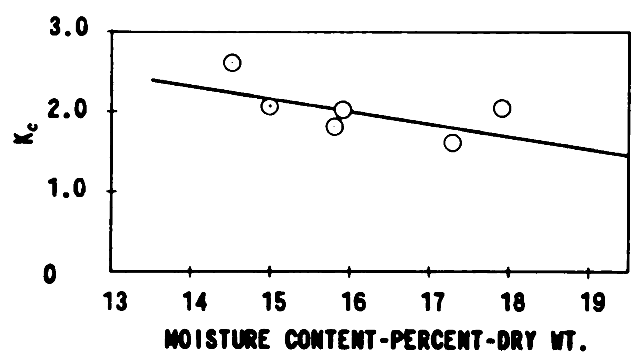

Figure 47. Kc versus moisture content for soil having bulk densities of .9 to 1.0.

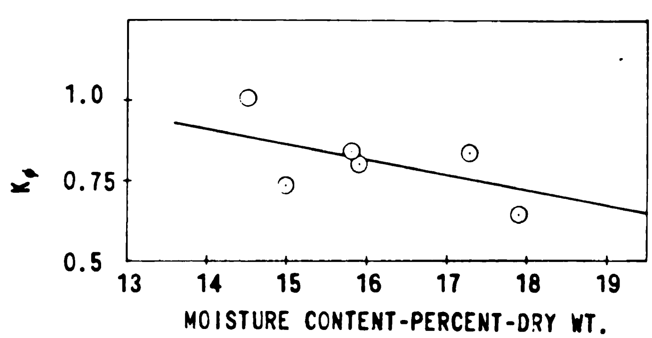

Figure 48. Kϕ versus moisture content for soil having bulk densities of .9 to 1.0.

DISCUSSION

The laboratory tests point out the limitation of the soil value system. When the soil mass contains certain nonuniform density-depth relationships, sinkage does not follow the sinkage formula and sinkage soil values cannot be obtained with the present equipment and methods.

During the month of September it was extremely difficult to obtain force-depth curves which would yield parallel lines on the log-log plot. The density-depth curves for this period are similar to the curves obtained for the laboratory tests of surface-subsurface compacted soil. In plowed soil the pressure-sinkage log-log plot obtained from circular probes with diameters smaller than 2 inches are not straight lines. The relationship between void size and probe area for plowed soil is probably critical for these small probes. Future work should be conducted with larger diameter probes.

Nineteen soil value tests were conducted during September from which 12 sets of soil values were obtained. Of these twelve successful tests, six tests produced two sets of soil values due to inflections of the force-depth curve caused by nonhomogeneous soil structures.

The reason for the lack of homogeneity in the density profile during this period is probably due to the effect of

tillage, wheel compaction and the swelling and drying cycles upon the soil. These factors tend to deteriorate the soil structure and cause it to return to the original consolidated state.

Before and after the field was plowed soil values could be easily obtained. Before plowing, the soil was consolidated giving a fairly uniform homogeneous structure. Immediately after plowing, the soil had a homogeneous loose structure in which soil values could be obtained. But a short time after plowing, the action of weather caused this loose homogeneous structure to collapse and the soil began to return to the consolidated state. The beginning of this consolidation produces non-homogeneity in the soil as some areas tend to be more active in consolidation than others because of the higher moisture content at these areas following periods of heavy rainfall (rainfall collects in the low spots). This condition is probably more severe in the Brookston type soil as it is poorly drained, which would easily produce nonuniform soil moisture conditions.

Another factor affecting the soil value tests is the lack of uniformity in the soil density profiles of the test sites. Different shaped force-depth curves were sometimes obtained for penetration tests located only 1 foot apart. This lack of uniformity was verified by use of a gamma density meter. Variation in bulk densities as large as .15 were recorded in the same test plot. For soil in the moisture range of 11 to 24 percent, bulk density has a greater effect on the soil values than moisture content.

The field tests showed it is difficult to obtain soil values for soil that is in the semi-consolidated state. This does not destroy the validity of the soil-value system as laboratory tests showed that for a uniform-bulk-density profile and for certain types of compacted soils, soil values can be obtained. This suggests that the soil value system can be used if certain limitations are considered.

APPLICATION OF RESULTS

The soil value system can be used to determine the strength of agricultural soils. Vehicle sinkage can be calculated from the soil values. An example of this type problem is given below:

Problem: Calculate sinkage of a Ford Model 660 tractor in unplowed and plowed soil.

Conditions: Soil Soil values from Table II will be used.

	Kc	Kø	n
Unplowed	10.5	37.2	.61
Plowed	1.65	1.32	1.1

Tractor

Total tractor weight = 4917* lbs.

Weight on rear wheels = 3580 lbs.

Weight on front wheels = 1337 lbs.

Diameter of rear wheels = 47.5 inches.

Diameter of front wheels = 26 inches.

Width of rear wheels = 12 inches.

Width of front wheels - 5 inches.

*These weights were taken from Nebraska tractor tests and include 332 lbs. of liquid and 579 lbs. of iron wheel weights for each rear wheel.

Solution: The sinkage formula of a rigid wheel given by Bekker (1956) is used to calculate sinkage.

$$z = \left(\frac{3W}{(3-n)\ (Kc + bK_\phi)\ \sqrt{D}} \right)^{\frac{2}{2n+1}}$$

where W = weight acting on the wheel in pounds

D = diameter of the wheel in inches

b = width of the wheel in inches

Kc, K_ϕ, n = soil values.

The weights on the tractor wheels are corrected to include the weight of the bevameter and the removal of the wheel weights. Weight of bevameter and balast, ≈ 500 pounds, is located 4 feet behind the rear axle.

Corrected weight on rear wheel = 1666 lbs.

Corrected weight on front wheel = 458 lbs.

Solving for sinkage using the above formula gives:

UNPLOWED SOIL

Front Wheels

W = 458 lbs.

D = 26 inches

b = 5 inches

$$z = \left(\frac{3 \times 458}{(10.5 + 5 \times 37.2)\ (2.39)\ \sqrt{26}} \right)^{0.9}$$

z = 0.6 inches.

Rear Wheels

W = 1666 lbs.

D = 46 inches

b = 12 inches

Using this to solve for sinkage gives z = 0.7 inches.

PLOWED SOIL

Front Wheels

$z = 5.9$ inches.

Rear Wheels

$z = 6.9$ inches.

Actual sinkages were measured for the tractor described above and are compared with the calculated values below:

		Calculated Sinkage-Inches	Actual Sinkage-Inches
Unplowed	Front Wheels	0.6	0-1/2
	Rear Wheels	0.7	0-1/2
Plowed	Front Wheels	5.9	2-1/2 to 2-7/8
	Rear Wheels	6.9	4

The calculated sinkages agree quite well for the shallow sinkages occurring on unplowed soil but show a variation on the plowed soil. This is probably due to the assumption that the pneumatic tire is a rigid wheel and slight errors in the soil values for the plowed soil. As can be seen in Figure 11, the plotted values of P vary somewhat from the parallel line relationship.

The variation between actual and calculated sinkage does not invalidate the theory but gives indication that refinements in techniques and formula are needed.

As rolling resistance is related to sinkage the power required to move a vehicle over the soil can be calculated from the sinkages calculated from the soil values.

Degree of soil compaction can also be determined from vehicle sinkage.

Soil has the lowest strength immediately after plowing and is therefore very sensitive to rutting and compaction at this time. Vehicle traffic on freshly plowed soil will develop high bulk densities in the wheel tracks. To avoid soil compaction vehicle traffic should not be permitted on plowed soil.

SUMMARY

Field and laboratory tests were conducted on Brookston soil to determine the effects of tillage and weather on the soil values.

A bevameter, an instrument used to measure the soil values, was modified to include a three point hitch so it could be transported with a tractor. A hydraulic motor was also added to the bevameter to provide power for operating the penetrometer.

The effects of plowing, disking, wheel traffic and weather on the soil values were determined from field tests. Data obtained in these studies shows that plowing has the greatest effect on the soil values while disking has only a small effect. Both tillage operations reduce the soil strength. Wheel traffic on plowed soil had a pronounced effect on the soil values. The increased bulk density caused by the traffic greatly increased the soil strength. Weather tends to increase the strength of tilled soil. Freezing and thawing cycles do not seem to affect the sinkage soil values but increased cohesion and the angle of internal friction.

Laboratory tests conducted under controlled density and moisture conditions explained the effects of density on the shape of the penetrometer curves. They verified the

field results obtained on soil compacted by wheel traffic and explained why soil values were not obtained during certain field conditions. The limiting factor of the soil value system is the non-homogeneous soil bulk density profile. Certain large variations in bulk densities in the 0-9 inch soil profile invalidate the sinkage formula.

CONCLUSIONS

1. The effect of tillage operations in decreasing soil strength were determined by the soil values.
2. Soil was in the weakest condition immediately after plowing but increased in strength due to weathering.
3. Freezing and thawing increased the strength of the soil, C and angle of the internal friction, without affecting, K_ϕ , Kc and n.
4. Sinkage soil values were not obtainable on soils having large bulk density variations in the 0-9 inch soil profile.
5. Under certain bulk-density-depth relationships two sets of sinkage soil values were obtained, one set applied to shallow sinkages and the other to deeper sinkages.
6. When moisture content ranged from 11% to 22%, bulk density had a greater effect on the soil values than moisture.
7. It was feasible to use natural soils in the laboratory to study the effects of moisture and density on the soil values.

PROPOSED FUTURE INVESTIGATIONS

Further studies should be conducted in the laboratory to determine the relationship between bulk density and the soil values. The possibilities of using a small model bevameter on small soil samples should be investigated as it would greatly facilitate the gathering of data for this study.

A new technique for obtaining soil values in the field should be developed. The present system requires too much time to permit the large number of tests required to obtain a statistical sample necessary for a nonuniform soil. One technique might be to measure sinkage of a wheel as it traverses the test area. In this way soil values for large areas could be quickly obtained.

APPENDIX

TABLE IX

AVERAGE PRESSURES AND SINKAGES RECORDED FOR THE FIELD TESTS

Sinkage Inches	18 Sept. Unplowed Soil		18 Sept. Plowed Soil		18 Sept. Sod Cover Unplowed		18 Sept. Sod Cover Plowed		15 Sept. Before Disking	
	1 in. D	$1\frac{1}{2}$ in. D	$1\frac{1}{2}$ in. D	2 in. D	1 in. D	$1\frac{1}{2}$ in. D	$1\frac{1}{2}$ in. D	$2\frac{1}{2}$ in. D	1 in. D	$1\frac{1}{2}$ in. D
	P-Psi	P-Psi	P-Psi	P-Psi	P-Psi	P-Psi	P-Psi	P-Psi	P-Psi	P-Psi
1	53.5	46	5.8	2.7	89.0	57.0	10.7	3.65	11.9	20.2
2	86.5	77	9.0	5.4	97.5	80.0	11.7	7.29	78.0	65.0
3	117	90	11.7	9.8	98.5	85.5	13.3	10.2	129	97.0
4	122	114	15.4	14.0	98.5	87.5	14.4	14.4	155	117
5			15.4	17.3	98.5	89.0	17.6	16.9	160	118
6			15.4	25.4		94.0	21.3	20.5		
7										

TABLE IX (Continued)

Sinkage Inches	16 Sept. After Disking		12 Aug. Uncompacted		13 Aug. Compacted		12 Nov.		23 April	
	1½ in. D	1 in. D	2½ in. D	1⅓ in. D	1 in. D	3/4 in. D	2 in. D	1½ in. D	1½ in. D	1 in. D
	P-Psi	P-Psi	P-Psi	P-Psi	P-Psi	P-Psi	P-Psi	P-Psi	P-Psi	P-Psi
1	13.8	26.0	13.9	32.0	318	212	51.6	55.7	48.5	68.0
					228*	230*	62.0*	69.0*	66.5*	78.0*
2	78.5	116.0	22.0	36.8	221	221	70.0	78.5	75.5	85.0
3	106	145.0	30.0	38.5	198	198			87.7	92.0
4	117	142.0	38.5	43.7	167	185			92.5	96.0
5	124	130.0	43.0	48.5					95.7	99.3
6									96.7	

*1½" depth

TABLE X

FORCES, PRESSURES AND SINKAGES RECORDED FOR THE LABORATORY TESTS

Sinkage Inches	Uncompacted				Surface Compacted Test A				Surface Compacted Test B	
	3½ in. D.		5 in. D.		1 in. D.		1½ in. D.		1 in. D.	
inches	Force pounds	P-Psi	Force pounds	P-Psi	Force Pounds	P-Psi	Force pounds	P-Psi	Force pounds	P-Psi
1	30	2.94	42	2.01	85	102	190	101	45	53.9
2	42	4.11	63	3.02	98	117	224	119	49	58.7
3	53	5.19	85	4.07	94	113	218	117	48	57.5
4	67	6.55	110	5.28	88	105	197	104	45	53.9
5	79	7.72	137	6.58	79	94.6	175	93.0	40	47.9

TABLE X (Continued)

Sinkage	Test B		Test C				Surface Compacted Test D			
	2 in. D.		2 in. D.		3½ in. D.		2½ in. D.		3½ in. D.	
inches	Force pounds	P-Psi	Force pounds	P-Psi	Force pounds	P-Psi	Force pounds	P-Psi	Force pounds	P-Psi
1	89	26.7	20	6.0	34	3.32	20	3.84	28	2.74
2	99	29.6	30	8.98	65	6.35	29	5.56	47	4.6
3	98	29.4	51	15.2	121	11.8	39	7.48	78	7.64
4	95	28.4	112	33.5	235	23.0	50	9.60	132	12.9
5	92	27.6	208	62.3			72	13.8	210	20.6

TABLE X (Continued)

	Surface-Subsurface Compacted							
Sinkage	Test E				Test F			
	1 in. D.		1½ in. D.		1 in. D.		1½ in. D.	
inches	Force pounds	P-Psi	Force pounds	P-Psi	Force pounds	P-Psi	Force pounds	P-Psi
1	80	95.9	102	54.3	69	82.5	148	78.5
2	89	107	140	74.5	104	124	182	96.7
3	90	108	179	95.3	118	141	196	104
4	95	114	228	121	134	160	198	105
5	105	126			139	166	192	102

TABLE XI

SHEARING STRESSES AND NORMAL STRESSES RECORDED FOR THE FIELD TEST

Normal Stress Psi	18 Sept. unplowed soil	18 Sept. plowed soil	18 Sept. sod cover unplowed	18 Sept. sod cover plowed	15 Sept. before disking	16 Sept. after disking	12 Aug. uncom- pacted	13 Aug. compacted	12 Nov.	23 April
	S_s-Psi	S_s-Psi	S_s-Psi	S_s-Psi	S_s-Psi	S_s-Psi	S_s-Psi	S_s-Psi	S_s-Psi	S_s-Psi
1.01	2.54	1.69	5.20	2.0	1.06	0.89	1.58	.528	1.183	2.38
2.02	3.47	1.78	6.05	2.33	1.27	1.31	1.69	2.11	2.71	3.44
3.03	4.25	2.12	6.3	3.0	1.78	2.03	2.74	3.07	3.81	3.82
4.05	4.45	2.54	6.85	2.98	2.29	2.12	3.16	4.83	4.02	4.24

TABLE XII

SHEARING STRESSES AND NORMAL STRESSES RECORDED FOR LABORATORY TESTS

Normal Stress Psi	Uncompacted	Test A Surface Compacted	Test B Surface Compacted	Test C Subsurface Compacted	Test D Subsurface Compacted	Test E Surface-Subsurface Compacted	Test F Surface-Subsurface Compacted
	S_s-Psi	S_s-Psi	S_s-Psi	S_s-Psi	S_s-Psi	S_s-Psi	S_s-Psi
1.01	0.68	1.10	0.98	0.38	0.51	1.52	1.10
2.02	1.10	1.69	2.03	0.80	0.93	2.20	2.12
3.03	1.44	2.03	2.54	1.22	1.31	2.45	2.96
4.05	2.04	5.38	2.54	1.74	1.95	4.66	3.94

TABLE XIII

MOISTURE AND BULK DENSITY AT DIFFERENT DEPTHS

OBTAINED FOR THE FIELD TESTS

Depth	18 Sept. Weed Cover Plowed		18 Sept. Weed Cover Unplowed		15 Sept. Before Disking		16 Sept. After Disking	
inches	Moisture %	Bulk* Density	Moisture %	Bulk Density	Moisture %	Bulk Density	Moisture %	Bulk Density
1.5	19.0	1.0	15.2	1.21	11.1	1.17	15.6	1.13
4.5	19.8	1.17	19.8	1.41	20.8	1.32	17.0	1.43
7.5	19.0	1.28	22.6	1.40	22.8	1.36	19.0	1.48
10.5					23.0	1.41	21.9	1.47
13.5					18.7	1.57	19.7	1.56

*Moistures and bulk densities are calculated on dry weight basis

TABLE XIII (Continued)

Depth	12 Aug. Compacted		13 Aug. Uncompacted		12 Nov.		15 Mar. 1960		29 Mar. 1960		23 Apr. 1960	
inches	Moisture %	Bulk Density	Moisture %	Bulk Density	Moisture %	Bulk Density	Moisture %	Bulk Density	Moisture %	Bulk Density	Moisture %	Bulk Density
1.5	19.10	1.505	20.40	1.255	22.25	1.27	48.25	.96	28.00	1.44	20.00	1.335
4.5	27.90	1.435	26.20	1.110	26.75	1.36	31.50	1.225	31.50	1.46	25.25	1.365
7.5	25.30	1.375	26.00	1.275	28.75	1.35	49.25	1.01	46.25	1.02	25.50	1.390
10.5	20.80	1.555	22.4	1.525	22.50	1.57	56.75	0.96	61.25	0.825	23.25	1.500
13.5	18.40	1.605	17.6	1.628	20.75	1.58	38.50	1.21	35.50	1.335	21.25	1.580
16.5					20.25	1.67	28.25	1.465	27.50	1.485	21.75	1.58

TABLE XIV

BULK DENSITIES AT DIFFERENT DEPTHS OBTAINED FOR THE LABORATORY TESTS

	Uncompacted	Surface Compacted		Subsurface Compacted		Surface-Subsurface Compacted	
		Test A	Test B	Test C	Test D	Test E	Test F
Depth inches	Bulk* Density	Bulk Density	Bulk Density	Bulk Density	Bulk Density	Bulk Density	Bulk Density
1.5	0.99	1.44	1.19	1.00	0.94	1.26	1.33
4.5	0.95	1.17	1.12	1.32	1.01	1.32	1.53
7.5	1.04	1.18	1.03	1.38	1.26	1.50	1.49
10.5		1.09	1.06			1.36	1.39
13.5		1.16	1.17			1.33	1.37

*Bulk density calculated on dry weight basis.

TABLE XV

Kc, K_ϕ AND ϕ AT VARIOUS MOISTURE CONTENTS

Moisture* %	Kc	K_ϕ	ϕ
			Degrees
14.5	2.6	1.0	23.4
15.0	2.045	0.73	24.0
15.8	1.8	0.84	24.3
15.9	2.0	0.80	25.5
17.3	1.6	0.84	26.2
17.9	2.04	0.64	26.4

*Dry weight basis

TABLE XVI

MOISTURE, BULK DENSITY AND SOIL VALUES FOR VARIOUS DAYS

FROM SUMMER 1959 TO SPRING 1960

Date	Moisture %	Bulk* Density	Kc	K_ϕ	n	C Psi	ϕ Degrees
30 July			14.0	14.5	0.52	1.45	44.3
Unplowed			16.5	17.4	.43	0.90	41.4
4 Aug. Plowed			4.22	0	1.5	0.43	32.8
12 Aug.	13	1.14	5.0	7.0	0.78	1.0	29.5
15 Sept.	11.2	1.17	11.25	19.2	0.95	0.70	20.6
16 Sept. Disked	15.2	1.14	36.0	6	0.57	0.50	22.5
27 Sept.	23.7	1.17	4.50	19.6	0.65	1.63	25.3
29 Oct.	23.7	1.29	15.0	28.0	0.35	1.33	36.0
12 Nov.	22.3	1.27	21.0	31.2	0.42	1.0	37.0
23 April	20.1	1.35	13.5	38.8	0.4	2.63	22.3

*Moisture and bulk density calculated on dry weight basis at 0-3 inch depth.

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