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Methods of Research in Soil Dynamics as Applied to Implement Design

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TILLAGE is the greatest power-consuming operation on the farm. To date the design of equipment for this purpose has been largely empirical and, for this reason, is subject to question. Moreover, there seems to be little practical connection between the vast amount of miscellaneous information accumulated by soil technologists and the practical problems involved in soil preparation which face the designing engineer. The object of the work in soil dynamics described in this bulletin is to find a basis for design of tillage implements. Therefore, in attacking this problem, it appeared necessary that the properties of soils which affect their reactions to tillage implements be determined and methods for studying them evolved. This has been done and the following pages describe the methods and apparatus used. A sufficient amount of data obtained by these methods are included to allow the reader an opportunity for appraisal of their value.

It is quite evident that the soil is a constantly varying material. It varies both in physical structure and in chemical composition in different localities, and even within a field itself. Any given soil varies from time to time in response to the various forces acting upon it. If progress is to be made in implement design these facts must be recognized and the solution sought by the isolation of general or fundamental laws, rather than by attempts at empirical measurement of unknown complexes by the so called "practical" field trial method. This conception is of the greatest importance for only by understanding the cause of a soil's reaction to given force application can the results of any operation be accurately predetermined. Accurate knowledge of reaction to force application is, of course, the essential basis of engineering design. While apparently little attention has been paid to the general principles of a soil's reaction as such, it is quite evident that such principles exist, else there would be no basis for the judgment evidenced by experienced handlers of the soil. Moreover, extensive experimentation has developed certain facts which give a means of approach to these problems. The most

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The writer wishes to express his appreciation for the assistance of Dr. F. W. Parker and Dr. W. H. Pierre of the Soil's Laboratory of the Alabama Polytechnic Institute for chemical analysis of soils and for many valuable suggestions; and to Mr. R. W. Trullinger of the office of Experiment Stations, Washington, D. C., for valuable assistance in organizing the attack on the problem of Soil Dynamics.

important of these is the explanation of the physical properties of the soil on the basis of soil moisture films (1) and the effect of colloidal material (2). While chemical composition is important from a crop's standpoint, in general its physical effect is relatively unimportant when compared to such factors as particle size and moisture content. This appears to be quite generally agreed upon by soil technologists, except in the case of the smallest sized particles where chemical forces are more evident. Even here, in our common field soils, the quantity of colloidal material appears to be of more importance than the composition of the colloid. The most notable exception to this general viewpoint appears to be with colloidal materials which vary widely in their ratio of silica to aluminum and iron.

DETERMINATION OF SOIL PROPERTIES AFFECTING TILLAGE

The determination of physical properties entering into implement design was made by the following method: A small, nickel plated plow was mounted in a box (Figure 1) so that its point, shin, and heel ran beside a piece of heavy plate glass. The movement of the soil could be observed through the glass and measurements taken where desired. A prismatic binocular microscope, mounted to move with the plow, made it possible to observe the soil's action at any point desired. The plow was drawn by a cord which wound around a spool so arranged that a wide variation in speed could be obtained. Slow speeds were used for microscopic studies. Various soils were used and with each soil the plowing was done at different depths. It was found that the reactions to the plow were similar in all cases which permitted a general classification of properties. For different soils, moisture percentages, and structures, the different soil properties varied in importance.

The theory of plow action, generally used as an explanation

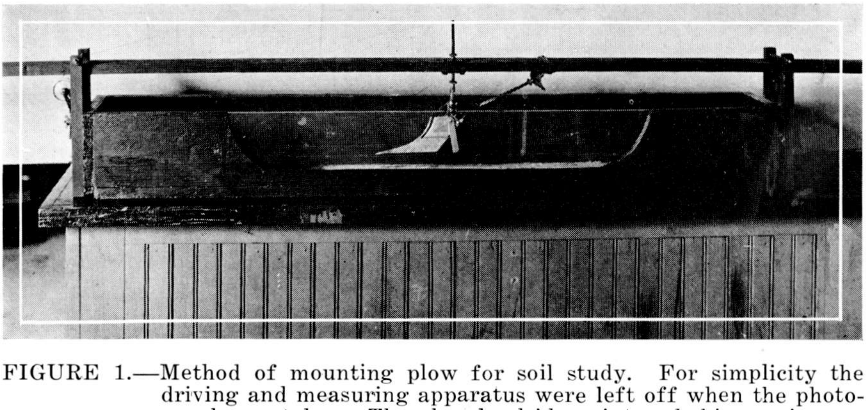

FIGURE 1.—Method of mounting plow for soil study. For simplicity the driving and measuring apparatus were left off when the photograph was taken. The plow landside point and shin are in contact with the glass side of the soil box.

of its pulverizing qualities, is that the lower soil in passing over a curved plow surface traveled farther than the surface soil. It was thought that the soil dividing into different layers, which traveled at different speeds, accounted for the pulverizing action of the plow. This action is shown diagrammatically in Figure 2. Under these conditions steeper curvatures of the plow would produce greater pulverization. The observed action of the plow is quite the opposite of this theoretical action in that the pulverization is at right angles to the tangents of the curve, instead of parallel to them. This is shown diagrammatically in Figure 3. The following description of the soil movements will explain this and show the basis for the selection of soil qualities for study.

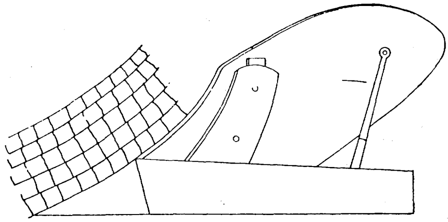

FIGURE 2.—Theoretical soil movement by plow.

As the point of the plow advances in the soil its bluntness (compared with soil particles) catches a part of the soil which it drives ahead in the form of a wedge. This soil wedge is compressed until its resistance to compression equals the resistance encountered in driving it into the soil. As this wedge advances through the soil there is a constant rolling motion of the soil along its sides due to the interlocking of particles. This brings into account the force required to roll or slip soil over soil, which may be termed internal frictional resistance or "shear". "Shear" is usually preceded by a compression of the soil when the soil moisture is within what is ordinarily considered the plowing range. Obviously, a determination of the coefficient of internal resistance, compression values of the soil and the friction of soil on particular metal would make it possible to determine the value of sharp points on a plow.

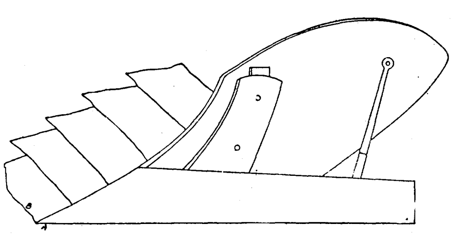

FIGURE 3.—Actual soil movement by plow.
A. Soil wedge at point of plow.
B. Shear plane.

As the point of the plow advances through the soil the inclined plane following it compresses the soil upward and forward. When the resistance to compression exceeds the shear value, the block of soil is sheared off and moves upward and forward as a solid unit.* The force required for this action depends upon the pressure of the soil and the friction of the metal and the soil. The forward movement of this block of soil is, of course, due to

*The lateral and twisting movements enforced on the soil by the various curve combinations of common plows are not mentioned as this discussion of soil movements is limited to those which may be observed by the use of the apparatus described.

the friction of the soil and metal and continues until the resistance of soil ahead of the block becomes equal to, or greater than, the friction between it and the metal when the soil is moved upward. When the plow shin is in the form of a curve, constantly increasing in steepness, the force required to move the soil up the plane is constantly increasing and the forward resistance of the soil must be greater to cause this more rapid movement. As the shin becomes more nearly perpendicular it will be noted that the surface applying force is nearly at right angles to the surface at the point. The pulverizing action of the plow is then due to the angles of the surface applying force being changed through the entire range of the curve of the plow from the nearly horizontal point to the vertical upper shin. This may be more clearly explained by calling attention to the amount of forward travel in relation to the upward movement enforced on the soil by the plow's curvature. As the soil passes over various parts of this curve it is forced to slip over itself at a constantly varying rate. It should be noted that these force applications and resulting reactions are vastly different from, in fact being almost at right angles to, the forces of inversion to which is commonly attributed the pulverizing action of the plow. When the soil particles are cemented together by drying, this wave of shearing forces is still generally apparent, but due to areas of high and low bondage, the soil breaks into irregular lumps which grind over one another producing the same general result. However, in a cemented or dried soil the resistance to compression is high in proportion to the shear value and the pulverizing effect is limited to the fragmentation of the lumps. When a soil is in proper condition for tillage the stresses flow through the entire soil mass. On the other hand when a soil is so filled with moisture that there is free water present, or where the films are large enough to be easily broken, the waves of compression and shear produce the injurious puddling effect shown by the shining furrow slice.

The accompanying chart of the variables entering into these reactions was prepared from the above and similar studies. It is apparent that a knowledge of the interrelations of these elements is what is sought for they constitute a cause and effect relationship. The general procedure consists of measuring and evaluating the results obtained by the various elements of implement design on soils of known composition whose dynamic properties have been determined by the methods which follow.

CLASSIFICATION CHART

Variables entering into soil dynamic studies.

Soil structure uniform; cementation zero.

Primary Soil Factors (Measurable or controllable)	Design Variables (Controllable)	Dynamic Properties of Soil (Measurable)	Dynamic Resultants (Measurable)
Particle size	Kind of metal	Coefficient of internal resistance (or shear value)	Fragmentation
Colloidal content	Polish	Friction	Arch Action
Moisture (percentage)	Bearing area	Resistance to compression	Compaction
Apparent specific gravity (State of compaction)	Curvature of surface applying force	Cohesion	Shear
Organic matter		Adhesion	
Chem. composition of colloid		Moment of inertia	

EXPERIMENTAL SOILS AND METHODS OF ADJUSTING MOISTURE CONTENT

As previously stated, the soil's reaction is largely due to particle size and moisture content. These properties may either be varied in synthetic soils or determined in natural field soils. Experiments at this laboratory indicate that practically the same results are obtained by either method but the use of synthetic soils is preferred as a desirable range of variation can be more easily obtained. These synthetic soils are prepared by drying and mixing a heavy colloidal clay (amount and composition of colloid known) with sand. The general plan of procedure being followed is to determine the physical reactive forces from a series of soils ranging from heavy colloidal clays to coarse sands at different moisture percentages. The mixtures of ⅓ clay: ⅔ sand, and ⅔ clay: ⅓ sand, when taken with pure sand and pure clay, gives a satisfactory range of variation for most work.

One of the most difficult tasks in physical studies of this kind is bringing soil to a desired uniform moisture content. After much experimentation a method was evolved which is rapid and satisfactory. The dry soil is placed in a box or large container where it can be stirred continuously. As this stirring proceeds (See Figure 4) the soil is sprayed with a steam jet which passes over an atomizer filled with water. The steam jet and atomizer are so adjusted that the steam will vaporize the spray it throws from the atomizer and as a result the vapor is at so low a temperature that it condenses on the soil particles giving a very uniform moistening. As the moistening goes on the soil's temperature is slightly raised which materially decreases the danger of puddling. The slow, almost imperceptible, and uniform change in soil color gives an indication of the success of this method of moistening. Moreover, soils can be brought to a rather high moisture content and remain unpuddled in spite of the continued stirring. A handful of soil so moistened, which has been compressed into a ball, can again be crumpled into its fluffy, finely divided state without the formation of lumps or puddled particles.

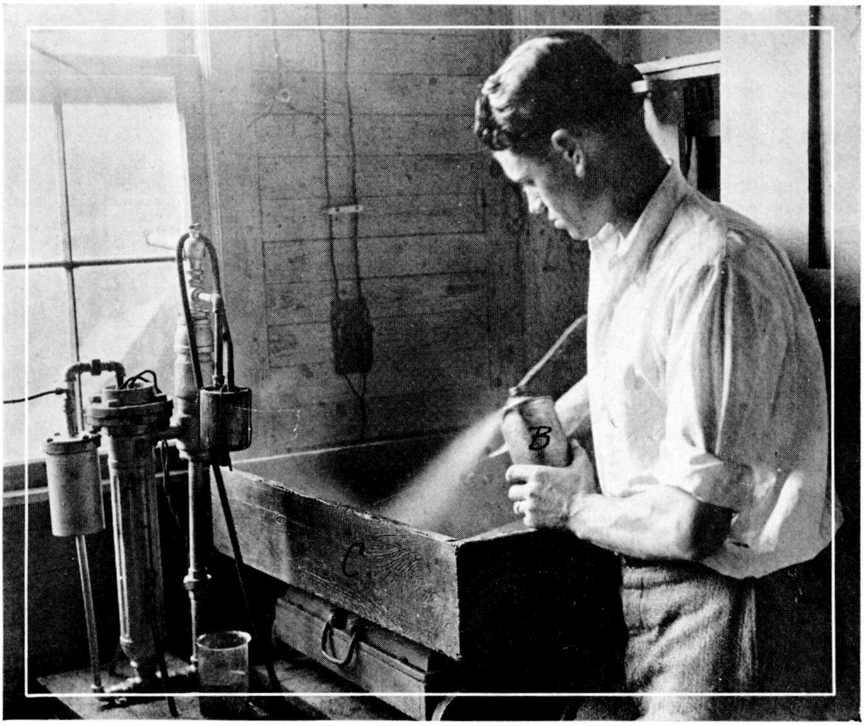

FIGURE 4.—Moistening Soil by Condensation Method.
A. Steam generator
B. Atomizer
C. Soil mixing box mounted on scales to give approximate amount of moisture added.

EXPERIMENTAL METHODS FOR STUDYING SOIL PROPERTIES

Resistance To Compression

Practically all of our tillage implements are simply devices for applying pressure in different ways. It has been shown that the reactions of soil to forces applied by a plow surface consist of a resistance to compression and, at the end of this compression, a shear. It was also suggested that each of these reactions under conditions of uniform soil structure indicated constant properties of a soil at any given moisture percentage. This is to be expected as these reactions are due to size of particle and moisture content. The reaction to pressure, therefore, is of the greatest importance in studies of the dynamic properties of the soil.

The equipment designed for determining resistance to compression consists of a two-inch cylinder (Figure 5) in which moves an air tight piston (A); to this cylinder is attached a rod which passes through guides to a brass plunger two inches in diameter (B). This plunger compresses the soil in a brass ring (C) or container $2\frac{1}{8}$ inches in diameter and .984 inches (250 MM.) deep. Compressed air is used in applying the pressure, which can be read directly from the gauges in pounds per square inch as the plunger and piston are of the same diameter. The pressure is controlled through a pressure regulator valve (D) between the piston and the air pump tank. Measurements of the amount of compression are made by means of a micrometer screw (E) reading to the hundredth part of a millimeter. The micrometer is attached to an Ames dial (F) indicator in contact with the upper surface of the plunger so that the amount of compression can be accurately measured.

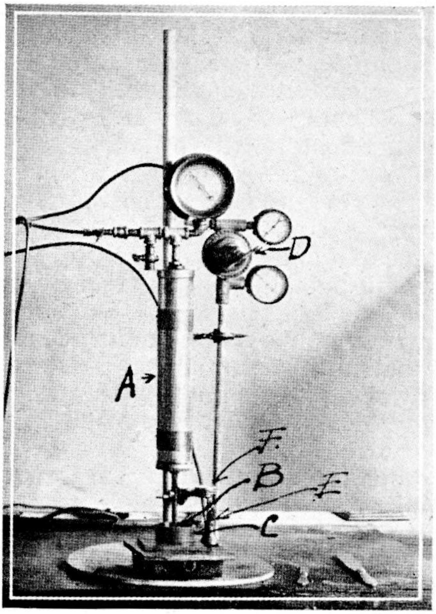

FIGURE 5.—Apparatus for Determination of Resistance to Compression
A. Air piston cylinder
B. Plunger same diameter as piston
C. Soil container
D. Pressure regulator
E. Micrometer screw
F. Ames Dial.

Micrometer readings are taken at intervals of five pounds pressure and the weight of the soil is taken before or after the series of tests. The apparent specific gravity can be determined at any step in the compression as the volume and weight of the soil mass is known.

With forces of the magnitude used in tillage the relation of force applied to compression may be shown by a smooth curve. (See Figures 6 and 7.) Since the state of compression of test samples vary, duplicates of the soil run for check will give similar curves but uniformly higher or lower due to varying masses of soil. It is quite important that curves of this kind be studied carefully to discover mathematical expressions for functional relations. Not only does the discovery of empirical formulas by "curve fitting" serve as a practical means of calculating approximations to other values of the variables but its form may suggest hitherto unknown laws connecting the variables which can be established by further investigation. While these studies have not been of sufficient scope to warrant the drawing of final conclusions, the following discussion of these curves with tentative conclusions is given as an illustration of method.

All of the curves obtained in these compression studies appear like hyperbolas in that the value of Y approaches a limit as the value of X increases. In attempting to fit a formula to these curves considerable difficulty was experienced in that hyperbola formulas would fit the upper part of the curves closer than those of any other curve considered but would not fit the lower part. This indicated that possibly there were factors other than the film moisture entering into the formation of these curves. Until the pressure had produced a certain maximum contact of particles where laws affecting the elasticity of the films would come into full effect, it was concluded that we should expect no definite law of reaction as the first reaction is due to structural rearrangement. Since soil structure in general is the result of action rather than an inherent property of the soil the lower part of the curve becomes of questionable value so far as general laws are concerned. From a practical viewpoint, however, this part of the curve is quite important, as pressures are far above the average pressure exerted by the plow. Apparently a plow running 6 inches deep and cutting 10 inches wide (60 sq. in. furrow slice) exerts a pressure sufficient to rearrange the structure to the extent of giving full film contact to only a small portion of the soil it turns over even in optimum plowing conditions. Therefore, tilth must be produced by breaking the soil up so that natural agencies can work on it.

The question of pressure as it affects design narrows itself into the following parts: (1) pressures should be applied to produce the maximum fragmentation with minimum total pressures, (2) pressures should be applied so as to minimize danger of rupture of moisture films in soils with a tendency to puddle. The first question has to do with sharp cutting edges and the arrangement of the plow curves to throw the forces applied into effect at the right time and in the most effective direction. The second question would seem to indicate limitations of these curvatures and definite relationships with soil types.

Further evidence of the value of these curve studies may be shown by comparing the curves obtained from field soils. The curve produced by a white coarse sand from Illinois (Figure 7, curve No. 1) rose rapidly at first and flattened off to practically horizontal at 8 per cent compression at a pressure of

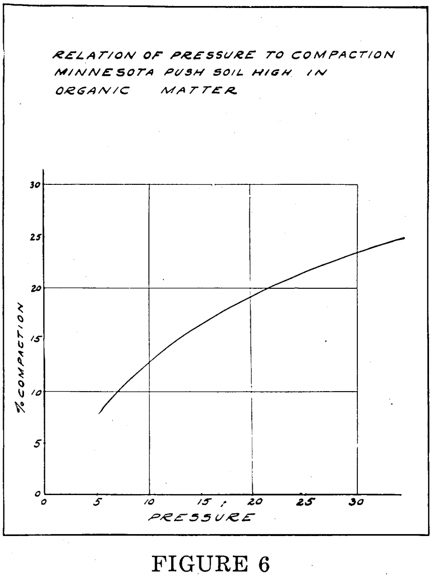

FIGURE 6

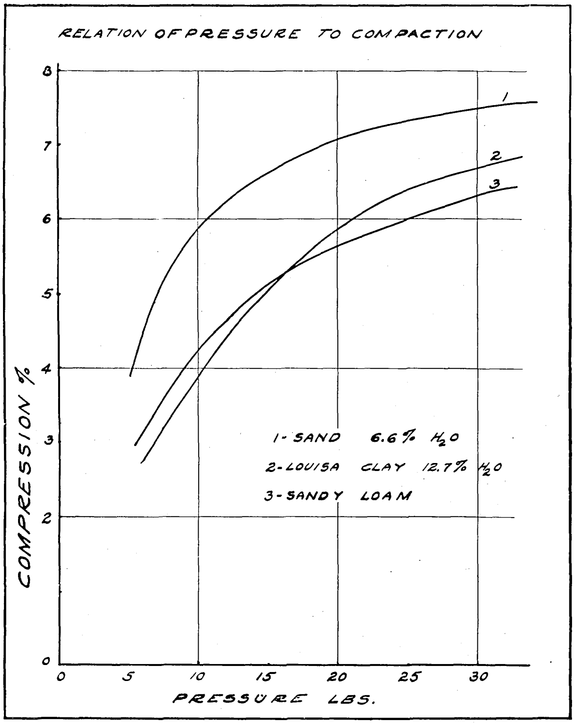

FIGURE 7

30 lbs. per square inch. With a "push" soil from Minnesota (Figure 6) which was very high in organic matter, 7 per cent compression was obtained at 7.5 lbs. pressure, and thirty pounds pressure had compacted the soil 24.5 per cent with no indication of the curve flattening. The sand will compact but little before it shears while the black mucky soil will "ball up" and compress considerably before shear takes place. The failure of the "push" soil curve to flatten out indicates that there is a third phase of compression to be considered: namely, that the soil material itself may be compressible.

The measurement of this property of compression resistance is, of course, of little benefit by itself but in studying soil movements and the reaction of soil to forces it is of the greatest importance. For example, in studies of stress distribution by the plaster cast method, the pressure exerted on any point in the soil can be determined by measuring the amount of compression and, as will be shown later, the arch action of a soil in the path of a lug or other moving body is greatly affected by this property.

Arch Action

The pressure exerted by a body being pushed into the soil, or resting upon it, is distributed out over a considerable area. This arch-like distribution of stress is quite an important consideration in tractor lug action, plowing, and all other soil operations. The resistance to the point and other cutting edges of the plow as previously shown is materially affected by this property. Before entering upon this discussion however, there should be a clear understanding of the difference between arch action and compressive action as used in this report. By arch action is meant the tendency of a soil to distribute or vector out a compressive force; by compression is meant the reduction in volume by a compressive force.

Two methods of studying this action have been developed at this institution, the plaster cast method (3) and a visual method. In the plaster cast method the soil is stratified into layers by means of aluminum leaf or other delicate material and a definite pressure applied—the effect of which is to be studied. The soil is then removed one layer at a time and a cast made of the distorted surfaces of the aluminum leaf. When the casts are removed their surfaces may be contoured and studied. A camera lucida is used for transferring the contours to coordinate paper for study. Figure 8 shows a series of casts made by this method. Two blocks of soil are shown divided into six layers each. The arching out of the soil is caused in this case by a small tractor lug sinking three-fourths of an inch into the soil block parallel to the surface shown.

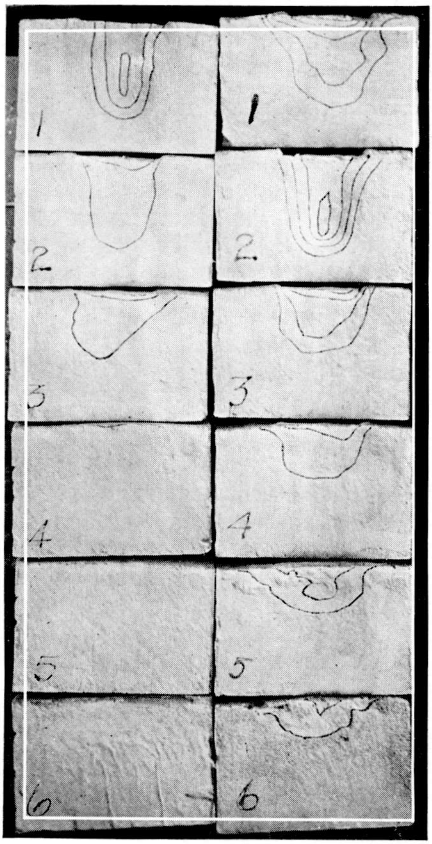

FIGURE 8.—Two series of plaster casts showing the distortion of soil at successive layers caused by a tractor lug.

The visual method (Figure 9) of studying arch properties of a soil consists essentially in stratifying the soil into layers by means of thin Italian aluminum foil in a glass faced box (A) and forcing a plunger (B) down into the soil beside the glass. The pressure of the plunger is measured by means of a calibrated spring (C) and the movement of the soil is shown by the distortion of the aluminum leaf layers. The aluminum leaf being very thin and fragile does not apparently affect the soil movement to any appreciable extent except in cases where it is very close and parallel to a shear area in which case its effect can be noted in fragmentation at a place of low bondage. The soil is placed in the box one layer at a time and compressed by means of a crank driven worm geared plunger (D). The compacting pres-

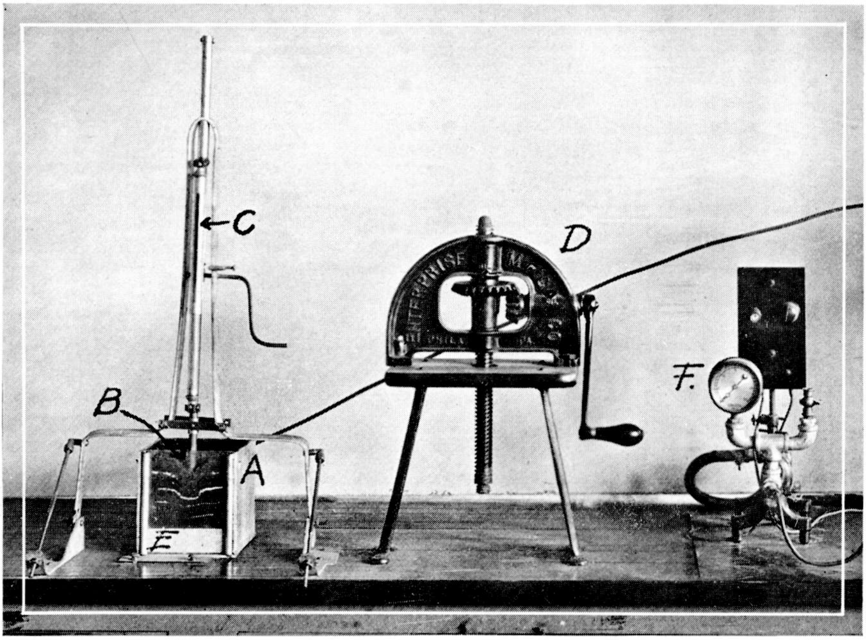

FIGURE 9.—Apparatus for Studying Arch Action of Soil.
A. Soil box
B. Plunger
C. Calibrated spring
D. Compression device
E. Location of Goldbeck Gauge
F. Compression air apparatus for measuring compaction.

sure is measured by means of a Goldbeck gauge (E) (4), air for which is supplied and controlled by means of needle valves and pressure regulators (F). Measurements are made of the sinking in of the plunger and width and depth of the arch. Some of the results obtained with the visible method apparatus follow and are given in order to allow an appraisal of the value of this method of observation.

Studies with the above described apparatus show that the full compressive force of the plunger is only exerted on a comparatively shallow area as the aluminum leaves are not moved far ahead of the plunger. This means that the force is vectored outward and distributed in all directions. This vectoring is apparently caused by the friction of soil on soil, by the interlocking of particles and by the cohesion of the moisture films. The lines of force vectoring outward are met by the compressive resistance of the soil and shear resistance. Since cohesion can be measured and the relation of pressure to compaction is known, and, as will be shown later, since the shear value of a soil is proportional to pressure, it is possible to determine with a reasonable degree of accuracy the amount of force being exerted on different parts of the soil as well as its direction. Magnitude and direction being all that is needed to define a force, it would seem possible then to predict the reaction of different soils to various force applications from the data obtained by these experiments.

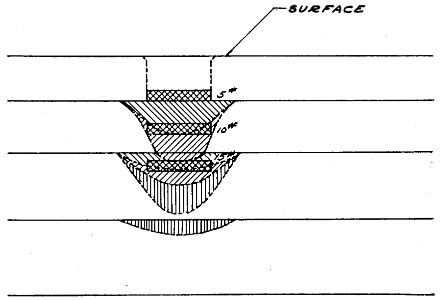

FIGURE 10.—Pure sand 6.6% H_2O compressed 10 lbs. per sq. in.

It was found that the soil is driven ahead of the plunger in the shape of a cone (See Figure 10) and that the lines of distortion of the soil caused by the advancement of the cone were in the form of an arch closely resembling parabolas in appearance. The soil movement was along the sides of this cone. Experiments were conducted with different widths of plungers and it was found that the width of the arch increased much more rapidly than the width of the plunger. Apparently the cross sectional area of the arch increases with some power of the width of plunger. The parabola changed in depth with the increased width of plunger and the area of soil in which movement was consequently considerably increased.

With a uniform soil such as was used in these studies where the arch moves ahead of the plunger at a definite distance and with uniform width, the total penetration was found to be almost directly proportional to the pressure; i. e., if 5 lbs. gives .5 inch, 10 lbs. will give 1 inch penetration. This was only true, however, after the plunger had moved through enough soil to form the arch typical for that soil. It was found with all soils that an arch of the same form and dimensions would move ahead of the plunger through the entire mass of the soil in the container until the bottom or side of the container was reached. This, of course, means that the arch formation is a constant characteristic of a soil.

Different compactions (5 lbs., 7.5 lbs., 10 lbs., 15 lbs., per sq. in.) were given soils and arch studies made. With all different compactions the width of arch for any particular soil was practically constant. It was therefore tentatively concluded that structure, at least within the limits ordinarily found in field soils (in what is generally considered a state of good tilth) was not an important factor in arch width but that this would be closely correlated with the cohesive properties of the soil and the interlocking properties of the particles. Studies of the cohesive properties of the soil showed that cohesion varied with pressure up to a point where full contact of the particles was made and then became constant. Cohesion was also found to vary with moisture content. Tests of sandy loam of a wide range of moisture, (2.7, 4.2, 6.7, 10.0, and 11.1 per cent) however, gave practically the same width of arch. Evidently the cohesion is of minor, and the interlocking of particles of greater, importance in this connection. This is logical, as the force of cohesion should be uniform throughout the mass when full contact is established.

Although the width of arch was a constant property the sinking of the plunger varied with compression. A fifteen pound weight on the plunger sank 1.7 inches when a sandy loam soil containing 6.6 per cent moisture was compressed by a force of 10 lbs. per square inch; 2.2 inches when it was compressed by a force 7.5 lbs. per square inch and 3.7 inches when compressed by a force of 5 lbs. per square inch.

If the thickness of different soil layers beneath a plunger be measured and plotted it will be found that the compression varies inversely with the depth of the layer. This is plotted for four different pressures in Figure 11. If slight variation for original compaction be allowed, the curves may be considered as practically straight lines. When these values are, however, compared with the curve (Figure 7) giving the relation of compression to pressure it will be seen that the amount of compression would indicate pressures far beyond those possible with the apparatus used. This may be explained, however, by the movement of the soil from in front of the arch, and in fact this high resistance to compression apparently accounts in large measure for the soil movements which cause arch action.

It has been shown that the arch action is largely due to soil movement in front of the advancing surface. If this is true the arch could be vectored or thrown in any direction desired by slanting or curving the surface so that the soil movement is affected in a desired direction. It was observed that when a plunger, 1.2 inches wide, had a slope of 23° the arch, which was 2.8 inches wide, extended from 1.0 inch to the left and .6 inch to the right of the plunger. At this angle soil was moved to both sides of the plunger in about the percentages indicated. With the plunger set at an angle of 33° the ratio of 1.0 to .3 was obtained and it was observed that the arch itself was carried on one side of the plunger.

Cohesion

It is apparent that the sticking together of particles of soil is an important physical property affecting every tillage operation. That this property is largely dependent upon the moisture content of a soil is also evident. Theories of the forces exerted by film moisture are so satisfactory in explaining this phenomenon that they may be accepted as a basis for a practical understanding of this property. The force of cohesion undoubtedly is closely correlated with the size of particles, and the size of particle logically would govern the number and curvature of the moisture films. While this simple theory may not be all that is needed to explain the physical effect of colloidal material, it still is sufficiently accurate to be of the greatest assistance in enabling one to judge the properties of a soil by a physical analysis.

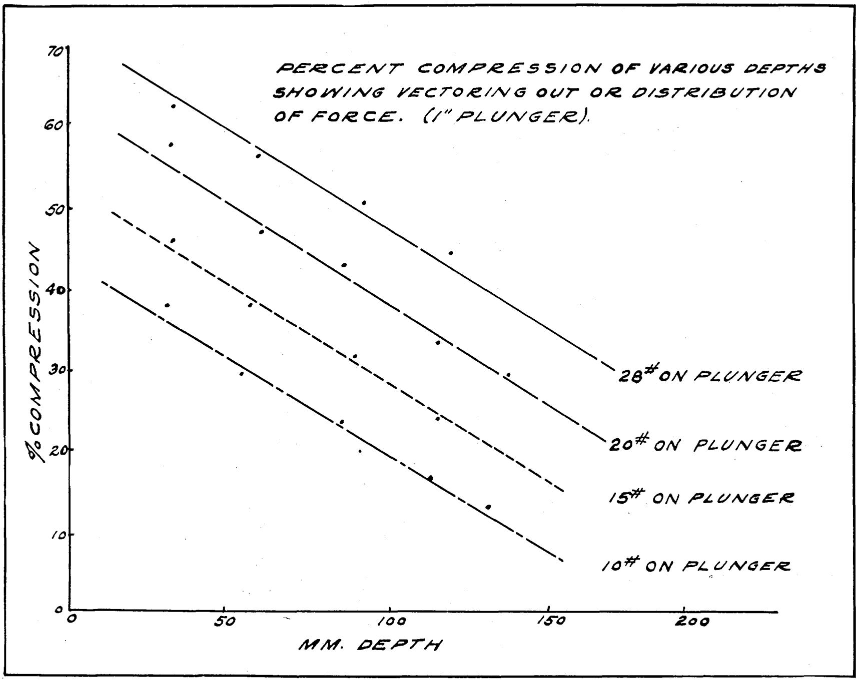

FIGURE 11

The apparatus used at this station for measuring cohesion (Figure 12) consists of a modification of the "Tenacity of Soil Apparatus" developed at the University of Illinois (manufactured by Central Scientific Company). The modification which enables the measurement of cohesion or tenacity of such soils as sand consists primarily of substituting a sensitive Jolly balance (A) for the sand weight bag, and filling the soil containers (B) with blocks of wood so that the soil chamber is one inch in all three dimensions. It was found necessary to give the soil a uniform compression so that the square inch of soil being pulled apart would always contain approximately the same number of films. This was done by means of a calibrated spring compressor (C). To avoid jerking the mechanism the Jolly balance was driven by a worm reduction gear (D) which applied the pull to the spring very slowly and uniformly. By careful manipulation the results obtained with this apparatus could be made to check within 5 per cent, which was considered a sufficient degree of accuracy for such a varying material as soil. In each case twenty or more measurements were made and the averages taken as the cohesion.

In general, cohesion was found to increase with moisture, the curve rising rapidly at first and gradually decreasing in slope until a certain maximum was reached when the curve fell off quite abruptly. Since the falling off in the high moisture ranges was evidently due to free moisture, a soil condition of little interest in tillage, the tests were not generally carried much beyond the range of plowing conditions.

The number of particles in contact, as indicated by the apparent specific gravity, is of the greatest importance with a soil of sufficiently low moisture content to stand packing without rupture of the films. It was found that the cohesion varied with pressure up to a certain point and then became fairly uniform. Up to this point the results were more or less erratic as checks were difficult to obtain with the most painstaking manipulation of the apparatus. Undoubtedly this was due to differences in structure which determine the amount of contact between particles, because until sufficient pressure was applied to insure full contact, the measurement depended as much on the amount of soil or number of films being broken as on the tenacity of the films themselves.

The effect of soil structure is of considerable importance not only in cohesion but in the study of other dynamic properties of soil. Obviously the structure of soil is a thing of infinite variability and it is illogical to expect even such small quantities as gram samples to be exactly alike in structure and consequently exactly alike in such physical properties as cohesion, shear, resistance to compression, etc. On the other hand every plowman knows that by proper tillage a satisfactory and practically uniform condition of tilth can

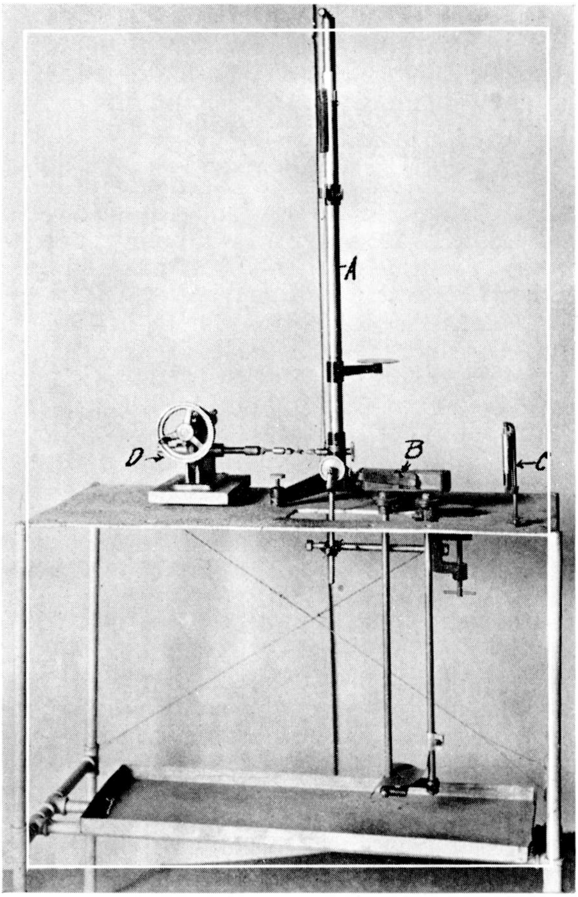

FIGURE 12.—Apparatus for Measuring Cohesion.
A. Jolly Balance
B. Soil container
C. Spring compressor
D. Worm gear driving apparatus.

be obtained over large acreages. It is evident, therefore, that there are certain general conditions which must be obtained by the tiller and that these conditions prevail between rather wide limits. There is little doubt that the reactive forces of field soil vary. This suggests the important question: What is a reasonable degree of accuracy in experiments of this kind? The only answer that can be offered to this question is that studies of this nature must be, at least for the present, qualitative rather than accurately quantitative, and that the most accurate measurements are of importance simply as they indicate the order of magnitude of the reactive forces being studied.

Shear

From an engineering viewpoint the shear value of soil is generally accepted as being of the greatest importance. Unfortunately, however, there appears to be little or no information concerning this property of soil or even any generally accepted method of making a determination of the shear value of a soil. It was found necessary to define soil shear and devise a method of measuring it.

Observation showed that, except in soils which had dried so that the colloid formed a cementing material, the separation of particles in a definite manner, such as is found in shear of solids, did not commonly take place in soil. The dynamic properties of the soil are such that when one layer is forced by pressure to slip over another layer, the bondage of the particles may be increased instead of decreased due to the increased amount of surface contact, or with high moisture contents, to a rupture of the films and a puddling effect. Moreover, due to the interlocking of particles, there is a rolling effect and the area of shear is indefinite, sometimes extending more or less through a large mass of the soil. This effect would be nearly as accurately described by the term viscosity as by the term shear. The term shear, therefore, was defined as the slipping of soil over soil and its value is that of the internal resistance of a soil to any movement of its particles.

To obtain a quantitative value of shear the following apparatus (See Figure 13) was devised. A soil cylinder (A) 5 inches high and 6 inches in diameter was mounted in a press in such a manner that the soil could be confined at any desired pressure; the pressure being applied by means of a screw and plunger (B) fitting the top of the cylinder. The pressure on the soil was measured by means of a Goldbeck gauge (C) which closed the entire base of the cylinder. The cylinder was cut so as to form three rings, the lower being one inch thick and the two upper rings two inches thick, respectively. The lower and upper rings were fastened securely in place and the center section hinged so that it would swing out by means of a lever (D). When the center section was swung out, the confined soil was "sheared" at the upper and lower surfaces of the hinged ring. The lever was pulled by means of a crank and windlass (E) to avoid jerking and

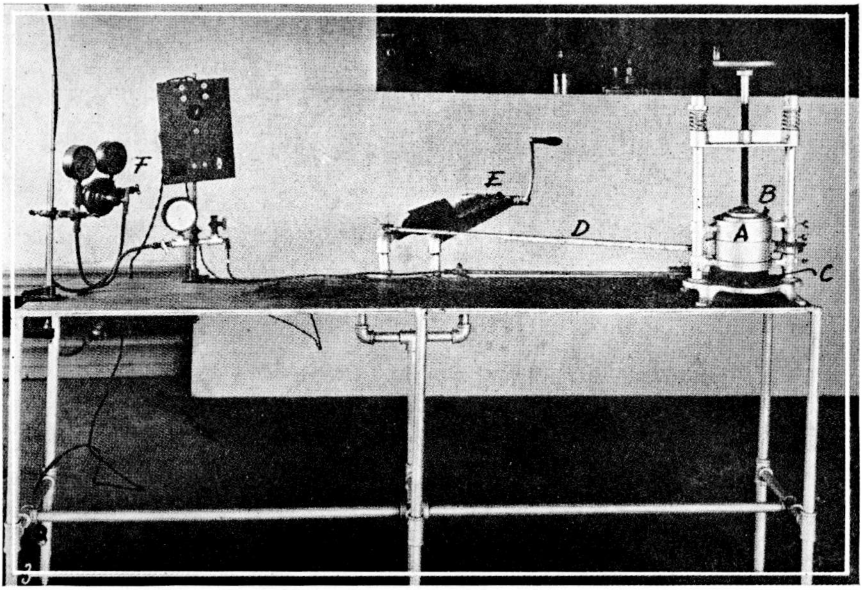

FIGURE 13.—Shear Apparatus.
A. Soil cylinder
B. Compression plunger
C. Goldbeck gauge
D. Lever
E. Windlass and spring
F. Air and electrical apparatus for measuring pressure on Goldbeck gauge.

the pull measured by a calibrated spring. The shear in pounds per square inch could be determined since the leaverage, as well as the number of square inches of shear area, was known.

Even with this simple apparatus, difficulty was encountered in getting exact values since the soil would compress in front of the moving section before it would shear, that is at least under pressures of the magnitude to be expected in field soils. This means that the area of actual shear was varying and the value obtained was too low when calculated on the square-inch basis. It was possible, however, to measure quite accurately the exact area over which shear was taking place as the center ring swinging out exposed the edge of the soil column and the distance between it and the edge of the ring was the amount of compression. The pressure exerted in this compaction was also measured by the Goldbeck gauge. While a few exact quantitative measurements of this kind were made in the studies to date, this degree of exactness has not been generally attempted for the reason that the first objective has been to determine what properties are of importance and by an approximate evaluation determine something of their relative importance to design. Considering the extreme variability of field soils and the number of factors affecting the shear of soil the value of a high degree of accuracy in quantitative measurements of this kind is questionable. Tests of shear value have been run with a large number of soils ranging from pure sand to heavy colloidal clays. From these tests certain definite general facts have been determined. In all cases shear was found to vary directly with pressure. The ratio of shear to pressure, however, varied with the moisture percentage. With increasing moisture the shear increased up to a certain point and then fell off as the moisture increased. The connection between force required for shear, pressure and the other variables, and the design of tillage implements is obvious.

EXPERIMENTAL METHODS FOR STUDY OF SOIL METAL RELATIONSHIPS

Friction

Methods of studying friction between soil and metal, and some conclusions drawn from these studies have already been published (5). The importance of this in relation to soil dynamic studies is sufficient however to warrant a repetition of the discussion of the methods used and a summary of conclusions with applications to show their justification.

In these studies the primary equipment consists of a piece of flat metal pulled by hand with a calibrated spring balance. The scale reading divided by the weight of the slider gives the coefficient of kinetic friction (U^1). For studies of the effect of speed on friction the slider is drawn by a constant speed motor through suitable reducing gears.

It was found that there were four different sets of conditions depending largely upon the film moisture and the weight and material of the slider, and that the laws governing friction varied with these conditions.

The adhesions of the soil moisture to the metal was found to be a most important factor in the so-called "friction" between soil and metal. When the pressure of the slider or the attraction of its metal for the soil moisture was sufficient to cause the wetting of its surface, the soil would stick or adhere to the metal and the "friction" would greatly increase. This necessitates the determination of the value of the wetting or spreading coefficient of the metal before the general laws of friction can be applied to any surface. The law governing this property was stated by Harkins as $S = Wa - Wc$, (6). This expression exhibits the extremely simple relation that spreading occurs if the adhesion between the liquid of the films and the metal surface (Wa = Work of adhesion) is greater than the cohesion of the liquid (Wc = Work of cohesion). It is obvious that a positive value of the spreading coefficient corresponds to spreading or wetting and a negative value to non-wetting.

From the studies made it seemed possible to lay down tentatively certain fundamental laws for sliding friction between a metal surface and the soil, remembering that these hold only between certain limits (a fact common to all laws of friction).

A. Friction Phase.—In a dry soil when the value of S is negative and when the bearing power of a soil is less than the pressure, the coefficient of sliding friction (U′).

(a) Varies with the speed,
(b) Is proportional to the pressure per unit area, and
(c) Varies with the smoothness of the surface and the materials of the surface.

B. Friction Phase.—When the bearing power of a soil is greater than the pressure per unit area and the value of S is negative; i. e., the slider does not get wet.

(a) The magnitude of the friction is proportional to the total pressure between the two surfaces:
(b) The value of U′ depends upon the roughness of the surfaces and the materials of the surfaces;
(c) It is independent of the area of contact, and
(d) It is independent of the speed of sliding.

C. Adhesion Phase.—When there is enough moisture present to cause the soil to adhere to the sliding surface (a positive value of S) but not enough to have moisture brought to the surface, then U′ varies

(a) With the speed,
(b) With area of contact,
(c) With the pressure per unit area,
(d) With the surface tension of the film moisture; i. e.,
  (1) It varies with the amount of colloidal matter present.
  (2) It varies with the amount of water present, and
  (3) It varies with the temperature and viscosity of soil solution.
(e) With the surface and kind of metal.

D. Lubrication Phase.—Where there is enough moisture present to give a lubricating effect, U′ varies

(a) With the pressure per unit area,
(b) With the speed,
(c) With the amount of moisture and viscosity of the solution, and
(d) With the nature of the surface and kind of material of which it is composed.

It will be seen that the coefficient of sliding friction is a constantly varying factor rather than a fixed quantity and that in any soil it is affected by moisture content and particle size. The relation of these factors to the elements of design of tillage equipment is quite important. To show this connection a few applications of the findings to plow design follow. In the A phase the shape that would give the lowest surface speed of soil over the metal surface and the lowest pressure per unit area of contact would give the least frictional resistance. Soils having these

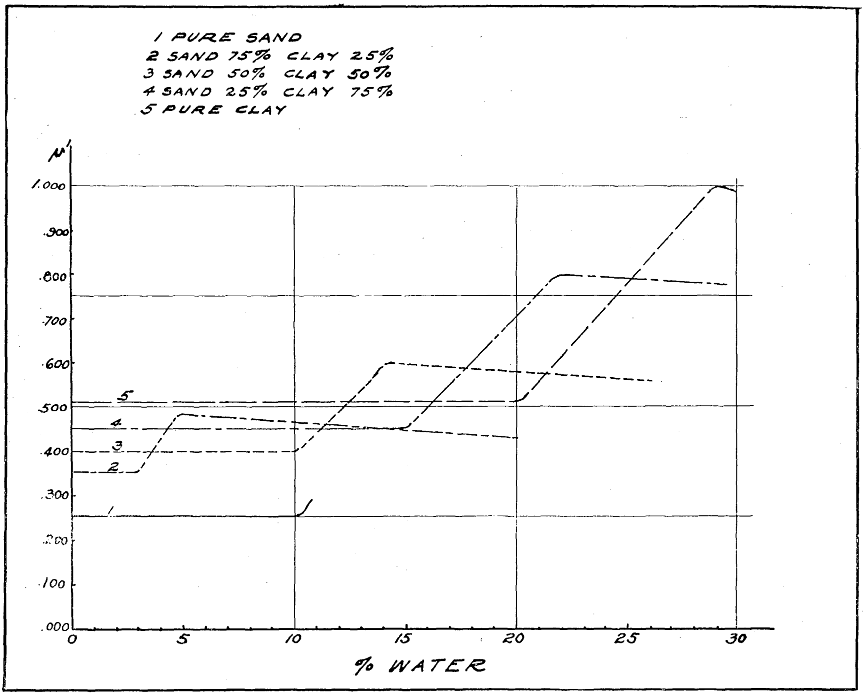

FIGURE 14.—Friction Curves: Soil and Chilled Plow Iron.
The five curves give the coefficient of kinetic friction for five soils of the composition shown. The curves show the effect of moisture quite distinctly. In each curve the lower moisture ranges have a constant coefficient of friction represented by a straight line which covers the A and B friction phases. The adhesion of C phase is represented by the sudden rise in the curve to a maximum. Following this the sloping portion of the curve covers the lubrication or D phase.

properties are usually worked with a steep moldboard plow which is exactly the opposite to what frictional laws would seem to indicate as advisable. The ordinary range of plowing is represented by the A and B phase. The B phase would also seem to indicate gentle slopes of the moldboard. In some soils (push soils) B completely disappears, the value of S being positive, due probably to a low value of Wc in the formula S equals Wa minus Wc. The possibilities of a practical solution of this problem would appear to depend largely upon the development of metals having a low Wa value. It should be noted however, that the importance of the equation S = Wa — Wc is not limited to push soils, the limits of the C and B phase being determined entirely by the sign of S.

Adhesion

Figure 14 gives the relation between moisture and the coefficient of kinetic friction (U′) for four synthetic soils and chilled iron, and illustrates the importance of the adhesion phase. From these curves it is evident that adhesion can be determined roughly by the slider method. Various treatments of metal surfaces such as polishing and chilling against various substances were found to cause them to vary in their adhesion to soil. The slider method, however, does not show with sufficient accuracy the various adhesive values of metal, for when S is positive, the metal wets and the increased height of the curve depends upon the moisture films alone. In other words, if soil sticks to a metal, the method provides no means of telling how hard it is sticking so as to judge the various values which the metal surfaces or treatments thereof may have.

The difficulty of preparing samples of various metals with different treatments in pieces large enough to conduct slider tests also renders the above method impractical. For the above reasons an indirect method of rapidly measuring adhesion has been developed. This consists of running tests with a nickel surfaced slider on the various soils and comparing the attraction of this metal for water with the attraction of other metals to be tested. If desired, the soil solution may be used in place of the water. The attraction for water is determined by (Figure 15) suspending the edges of two pieces of metal in a constant tem-

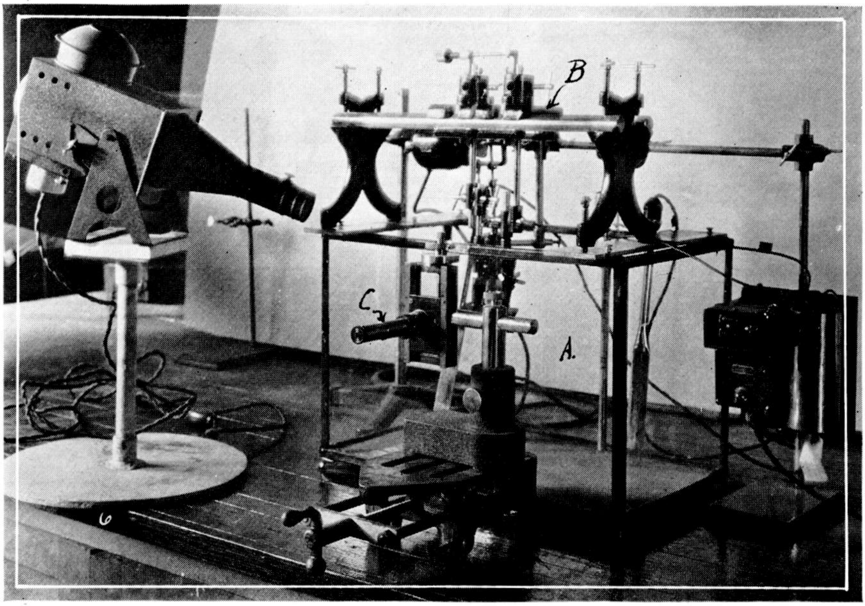

FIGURE 15.—Apparatus for Measuring Capillary Attraction of Various Surfaces.
A. Constant temperature bath
B. Apparatus for controlling distance apart of parallel surfaces of metal
C. Measuring microscope.

perature bath so that their faces are parallel and a known and controllable distance apart, and then measuring the height of the capillary column drawn up between them by means of a microscope equipped with an eyepiece micrometer. Only preliminary studies have as yet been made by this method but it is included in this discussion as the most promising avenue of attack.

Effect of Shape of Surface Applying Pressure To Soil

The value of methods of measuring and studying the different soil variables affecting design depends upon establishing the relationship between these variables and the different elements of design. This calls for an analysis to determine what the possible elements of design are. It has already been pointed out that about the only way force can be applied to soil is by pressure. Even such application as that exerted in the cutting action of the rotary plow or harrow resolve themselves into this one essential. Design, therefore, being limited to devices for pressure application resolves itself into considerations of amount of pressure and character of surface applying the pressure. Character of surface depends upon the kind of metal, its physical state of hardness, and its polish. Methods of studying metals in this connection have been touched upon briefly under the heading of adhesion. Therefore, it only remains necessary to suggest methods of studying the effect of amount and direction of pressure,

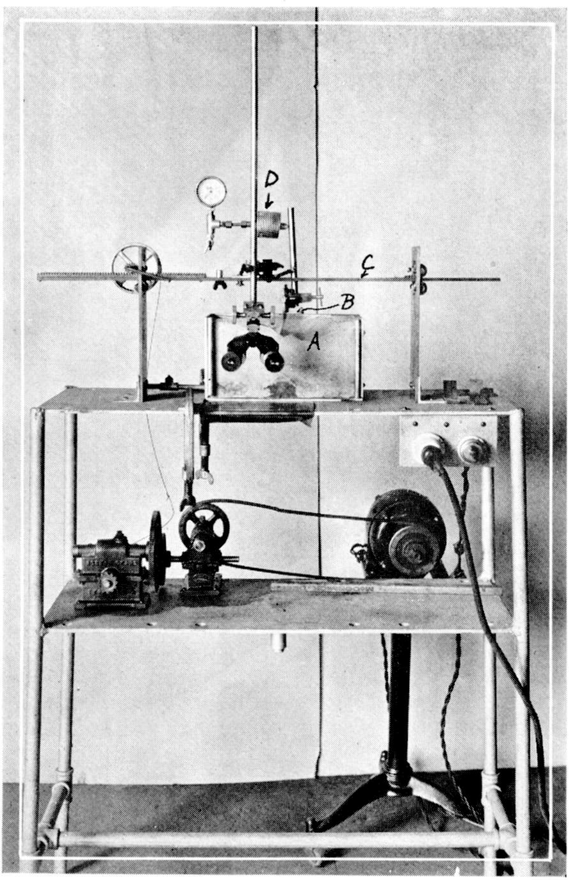

FIGURE 16.—Soil Chisel Apparatus.
A. Glass-sided soil container
B. Chisel
C. Movable metal bar supporting chisel
D. Sylphon bellows and gauge.

or from a practical design standpoint, area and curvature of the applying surface.

Apparatus for studying the effect of curvature has been devised (Figure 16) and studied. This consists essentially of a box (A) in which various soils having known physical qualities are confined and a device for pushing chisel-shaped pieces of metal through them. Observations and measurements of the reactions of the soil are made to determine how these reactions are affected by different depths, curvatures, etc., of the chisel. The chisel (B) is mounted on a bar of metal (C) moving parallel with the surface of the soil on ball bearings and driven by an electric motor through reducing gears so as to give any speed desired. The force exerted by the chisel in passing through the soil is measured by Sylphon bellows (D) filled with water and connected with pressure gauges. Soil distortion is measured directly by calipers through the plate glass side of the containers which permits continual observation of all soil movement in front of the chisel. It is possible to facilitate the study of soil reaction by means of small objects placed at regular intervals throughout the soil or by means of thin pieces of aluminum leaf placed in layers. To show the application of this apparatus and its value in connection with design, a brief review of a few experiments with the conclusions drawn from them follows:

For the purpose of studying the effect of angle of force application, a series of nickel plated copper chisels were made. These were one inch wide and arranged so as to run in the soil at any depth desired up to four inches. The nickel plating was done so as to give a constant low and known coefficient of friction in all cases. The series consisted of four chisels bent to give angles of 22.5°, 45°, 47.5°, and 90° with the horizontal surface of the soil. Various means of observing the soil were used but layers of thin aluminum foil placed beside the glass and small objects such as rivets equally spaced throughout the mass were most satisfactory. Observation of soil action was also made with a binocular prismatic microscope equipped with an eyepiece micrometer. With this latter equipment the details of the soils reaction could be observed closely through the plate glass side of the box while the large movements were followed by means of the movements of the marker indicated. At various time intervals graphs of the movements were made on coordinate paper for record and study.

It has been previously noted that the normal shear angle of soil reaction to a plow was approximately forty-five degrees. In general this seemed to hold with the soil chisels regardless of the angle or curvature of the advancing chisel. When using a perpendicular chisel the soil would compress a certain amount and then a shear plane would develop running from a point near the top of the chisel upward and forward, following this at regular distances down the chisel other planes would develop until the point was reached, the last one starting from just beneath the point. With a perpendicular chisel one and one-half inches deep, in a Louisa clay containing 12.7 per cent water, four of the planes were developed before the soil shear plane developed from the bottom of the chisel. As the pressure varies uniformly with depth, and as shear value is in direct proportion to pressure, it is to be expected that the shear planes would develop at regular intervals. When a part of the soil shears off, the pressure of the advancing chisel forces the block of soil to slip up the shear plane; when the next lower plane develops the two blocks move as a solid block, the entire sheared area always slipping up the lowest or last shear plane. This means that there is a gradual movement upward and forward so that in front of a perpendicular chisel a row of rivets placed horizontally in the soil should by the soil movements be rearranged in a vertical row before the chisel. This was found to be the case.

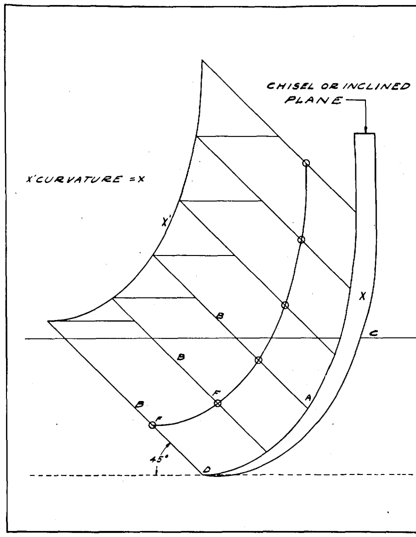

FIGURE 17.—Soil being forced upward and forward by a soil chisel (X) or inclined plane slips on the shear planes (B) until X and any point X′ have similar slopes throughout. A set of rivets (F) placed horizontally below the surface will arrange themselves so that they have the same curvature as the chisel and the movement on these planes. The new shear planes develop at the point (D) as it moves forward in the soil, and the movement on these planes over one another is at a rate dependent upon the curvature of X.

Similarly with other chisels at different angles the soil moves in such a manner that a horizontal set of rivets in the soil will arrange themselves in a plane parallel to the surface of the advancing chisel. (Figure 17). If the chisel has a varying curvature, the rivets will arrange themselves to conform with the curvature of the chisel. This gives us an insight into the effect of curvature of the surface of a plow or other implement. The amount that a soil slips over itself depends upon the steepness of the slope of the chisel. With a uniformly advancing curve the rate of slipping is proportionate to the slope. If the curvature is gradually and constantly increasing, the conditions are such that the soil must slip on all the shear planes at once in order to effect this arrangement. As this soil is being forced upward and forward the direction of its movement depends upon the weight of the soil above and the resistance offered in front of it. The resistance in front of the advancing soil gradually diminishes as it is lifted above the top surface.

APPLICATION TO DESIGN

While it is impossible to make an accurate evaluation of the methods which have been set forth until they have proved themselves by contributing definitely to development of improved design in practice, a few examples of their relation to some important problems of soil mechanics may be of interest. The amount a soil will compress and the relation of this compression to shear value gives a ready means of measuring the "permissible slip" of a tractor wheel. The arch action of a soil should govern the spacing of tractor lugs and their distance apart on the rim. It is possible to compare accurately the effect of different design elements by determining the amount of shear, compression, etc., caused by various surfaces by the variable methods outlined. By studying these effects and their correlation with certain soil qualities, known or controlled, it seems entirely possible to come to the definite conclusions necessary for intelligent design.

SUMMARY

The object of the study of the soil properties discussed in this bulletin is to obtain a basis for the design of tillage implements. For the purpose of determining the properties affecting design, a small, nickel plated plow was mounted to run beside a glass surface permitting observation of the soils reaction. From this and supplemental studies a chart of the variables entering into these reactions was prepared. The study then resolved itself into determining the interrelationship of the factors through their most probable range of variation. Standard methods of measuring and studying many of the variables were used. New methods were evolved for moistening soil and measuring resistance to compression, arch action, cohesion, shear, friction, adhesion, and the effect of shape of surface applying pressure to the soil. Sufficient result data are included to show the applications of the methods. The study of friction between metal and soil was carried sufficiently far to formulate definitely laws covering this phase of the study.

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