

A PROCEDURE FOR MEASURING SOIL
STRENGTH VALUES IN THE FIELD

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ABSTRACT

A PROCEDURE FOR MEASURING SOIL STRENGTH VALUES IN THE FIELD

by Xavier J. R. Avula

A procedure for measuring soil strength values in the field at an increased rate of measuring was developed. Such a procedure is valuable to statistical evaluation of a soil. Because the behaviour of natural soils under loading varies due to moisture content and other geological factors frequency distribution of soil strength values is the only practical basis for assessment of mobility in large areas and for correlating with soil classification maps. When a large number of tests have to be performed they ought to be performed in a short span of time because a long lapse of time usually results in changed weather conditions, which in turn fluctuate soil moisture. An increased rate of measuring soil strength values can be perfectly justified in this case.

A bevameter, an instrument used for measuring soil strength values was redesigned and constructed. This instrument was carried on the three-point hitch of the tractor for swifter movement along the test plots.

Load and torque in the load-sinkage and shear tests respectively were provided hydraulically using the tractor hydraulic system. Penetration forces up to 1900 lbs. (860 kiloponds) and shearing torques up to 820 in. lbs. (940 cm. kp.) were developed in the instrument. Strain gage transducers were used for measuring load and torque. A linear micropotentiometer was used for measuring sinkage.

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The results of load-sinkage and torque-time tests were recorded directly on an X-Y recorder. The torque-time relation was later converted to shear stress vs. soil displacement relationship using calibration information. Vertical movement of the bevameter frame during the test was considerably reduced by transferring tractor weight onto the frame by means of a hydraulic cylinder connected between the tractor drawbar and the bevameter frame.

The bevameter used in this work was operated by two men; one recorded the tests and drove the tractor, the other operated the shear head and penetrometer. Tests were performed at an average rate of 28 (12 shear tests and 16 penetration tests) per hour. This rate of testing is considerably higher than that obtained by earlier methods.

Shear and penetration tests were performed at different attenuations of the X-Y recorder. So, it was necessary to calculate the true values of load, sinkage, shear stress, normal stress, and soil displacement. This was done on data processing machines through transformation relations.

Preliminary data from the tests indicated that load-sinkage relationship could not be represented by a single expression as in Bekker's soil value system. More than one expression seemed to be necessary to represent the entire load-sinkage curve. Final results of the processed data are to be given in another dissertation.

Approved:


Major Professor

A PROCEDURE FOR MEASURING SOIL STRENGTH
VALUES IN THE FIELD

By

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INTRODUCTION

The military and the mechanized agriculture are the two major fields that are concerned with off-the-road locomotion. The theory of off-the-road locomotion is generally explained in terms of soil properties, loads, and the geometry of the wheels and tracks. When a vehicle moves on a soft soil thrust is developed by shearing the soil (Harrison, 1958). The shear stress "s" of soil was expressed by Coulomb as

$$s = c + p \tan \phi \dots \dots \dots (1)$$

where c is called cohesion, ϕ is called angle of internal friction, and p is normal stress. As a wheel or track shears the soil varying degree of slip occurs depending upon the shear strength of the soil. Slip causes reduction in speed of the vehicle.

It is also a common observation that when a vehicle moves on a soft soil it sinks into the soil due to weight and compaction of the soil below the tracks or wheels. This in turn increases rolling resistance causing increased power requirement (Czako and Hegedus, 1958). The basic equation used to express sinkage as a function of soil compaction is the Bernstein-Goriatchkin equation, namely

$$p = k z^n \dots \dots \dots (2)$$

where p is normal pressure (lb./sq. in.), k is called modulus of soil deformation (lb./in.ⁿ⁺²), z is sinkage (inches), and n is called exponent of sinkage. The value n refers to the physico-geometrical



structure of soil cross-section, and is practically constant for a given terrain. The value k is related both to soil physics and to the form and size of the loading area. Basing on a well-known fact that in purely frictional soils the sinkage is practically independent of the width of the loading area, and in purely cohesive soils the sinkage is dependent on the width of the footing, Bekker (1956) expressed the pressure-sinkage equation as

$$p = \left(\frac{k_c}{b} + k_\phi \right) z^n \dots \dots \dots (3)$$

where k_c is called cohesive modulus of sinkage, k_ϕ is called frictional modulus of sinkage, and b is width (smaller dimension) of loading area.

The constants c , ϕ , k_c , k_ϕ , and n in the above three equations are termed as soil strength values.

As we have seen above the two major aspects of the problem of land mobility are the reduction in speed and increase in power requirement. To find a solution to this problem it is necessary to understand the basic nature of top soils from their strength point of view. The difference in soil types all over the world strongly suggests an extensive study of soil strength properties, namely, c , ϕ , k_c , k_ϕ , and n in the laboratory and in the field.

A major portion of the soils of the world have been classified by giving the information about the type of top soil and sub-soil, how well the soil is drained, and the slope and degree of erosion. If it could be shown that the strength of the soil is related in some manner to the soil classification, a major contribution would be made not only to the land mobility problems, but also to some basic investigations in tillage (Payne, 1956).

Laboratory and field techniques to measure soil strength values for use under dynamic loading conditions were developed through the last decade, but the field techniques have been found unsuitable for covering large areas efficiently. Moreover, the data processing was too time-consuming. The project described here was undertaken to develop a procedure and instrumentation for collecting basic soil strength data in the field as efficiently as possible, and processing it on modern computers to produce the soil strength values which could be used in correlating with soil classification, and in the design of agricultural implements, earth moving machinery, and vehicles for off-the-road locomotion. Observation of the data obtained in this work made the validity of Bekker's equation doubtful, and therefore equations (1) and (2) have been considered in programming the data processing on computers to obtain c , ϕ , k , and n . However, consideration has been given to find correlations of k with k_c and k_ϕ during future investigations.



EARLIER EFFORTS IN MEASURING SOIL STRENGTH VALUES

(a) Penetrometers

Procter (1933) devised a hand-operated instrument known as Soil Plasticity Needle to measure soil plasticity in terms of the pressure required to force a rod (also called needle or penetrometer) with a slightly enlarged flat bearing surface. The force of penetration is measured with a calibrated spring. The penetrometer with a known bearing area of the tip is forced with a gradual, uniform push at a rate of about 1/2 inch per second to a depth of 3 inches into the soil, and the maximum resistance in pounds per square inch is read off the calibrated shaft of the penetrometer. The interchangeable tips of the penetrometer have bearing areas of 0.05, 0.1, 0.25, 0.5 and 1.0 sq. in.

Procter's plasticity needle has been used in the laboratory to prepare moisture-plasticity curves for various soils, and to obtain moisture content in the field soil by referring to these curves. As the force of penetration depends upon the state of compaction of the soil besides other factors the penetration force read from the instrument has been used as an index for attaining the desired compaction in the construction of earth dams.

McKibben and Hull (1940) used soil penetrometer tests as a means of predicting rolling resistance of steel wheels and pneumatic implement tires. They used two kinds of penetrometers--Iowa penetrometer and the Soil Hardness Gage (also called Roto-tiller penetrometer) along with rolling resistance measurements, and plotted the relationships between penetration and coefficient of rolling

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resistance. This is a good example where sinkage, being used as an index of soil strength, is correlated to a dynamic problem, the rolling resistance of a wheel.

Iowa penetrometer (McKibben, 1938) is shown in Fig. 1. The design is arbitrary. The penetrometer weighs 15 lbs., 5 lbs. each for the hammer A, the guide tube and penetrometer B, and the surface gage C. Its use consists of placing the instrument on the surface to be tested with the guide tube vertical, of lifting the hammer 3 feet and allowing it to drop, and, of reading the penetration at the top of the surface gage.

The Soil Hardness Gage (Stone and Williams, 1939) is shown in Fig. 2. It consists of a cylindrical tube or barrel mounted on a square plate of $3/16$ in. steel. The penetrometer is a piece of round steel 24 in. long, $1-1/8$ in. diameter at the top, and tapered to $1/4$ in. graduations. At the lower end of the barrel narrow slots are extended upward from the base on opposite sides. A retainer is mounted at the upper end of the barrel with a pin for suspending the penetrometer at a fixed height of 36 inches above the ground level. The retaining pin is withdrawn manually by the operator when the penetrometer is to be dropped. The depth of penetration is read through the slots on the sides. Some of the uses of the Soil Hardness Gage, as stated by the authors, are determining the ideal degree of firmness of the seed bed, expressing the degree of soil aeration, expressing accurately the hardness factor in classifying soil types in soil survey work and in tillage operations, comparing various types of tractor wheels, tracks, lugs and tires, and determining the relation between soil hardness and resistance to plowing.

The values obtained in the case of both the penetrometers described above are only indicative of the soil condition, and they do



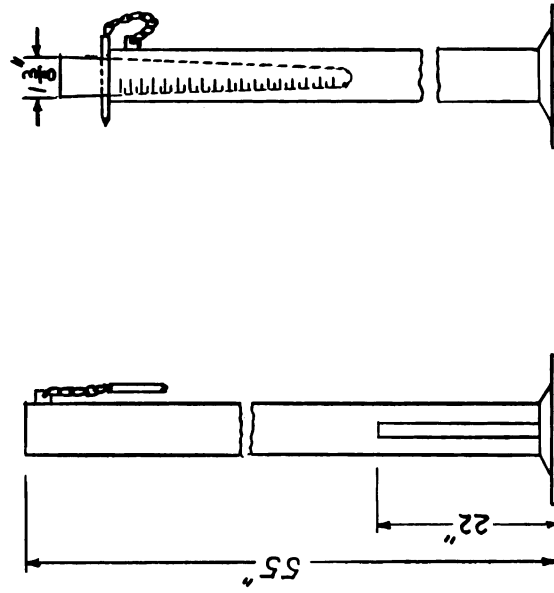


Fig. 2 - Soil Hardness Gage

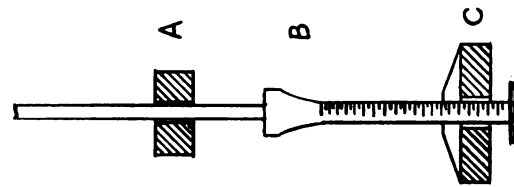


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Fig. 1 - Iowa Penetrometer

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not represent any definite strength value which can be used as a design parameter or in the correlations with soil classification.

Waterways Experiment Station of the Corps of Engineers used a cone penetrometer for field detection of critical soils. The test device consists of a 30 deg. cone with a base area of $1/2$ sq. in.; two 18 in. extension rods; a proving ring; a dial indicator, and a handle (Janosi, 1958). The cone index of the soil is defined by the force required to move the cone through a given plane against the resistance of the soil in that plane. This force is indicated on the dial indicator. An investigation by the Land Locomotion Research Branch of the Ordnance Tank Automotive Command (OTAC) indicated that the cone index can be predicted by the physical soil strength values for the given soil, and that the reverse procedure of predicting the soil strength values from the cone index alone is not possible. The disadvantage of the cone index is that it does not provide an engineering basis for predicting the performance of any vehicle or its design parameters, whereas the soil value system does. In the light of this disadvantage the measurement of soil strength values becomes inevitable.

Caterpillar Tractor Corporation (Cohron, 1958) developed a soil test machine to determine the soil strength values. It is a two-wheeled towed unit weighing 3300 lbs. It has a 3500 watt generator which supplies power for electronic recording equipment and a 1 hp motor. The motor drives a hydraulic pump which supplies a flow of 1.7 gpm at 600 psi. There are two penetrometers mounted on the machine besides a shear test device. Each penetrometer consists of a 2 in. diameter hydraulic cylinder. The penetrometer plate sizes range from 2 to 38 sq. in. SR-4 strain gages are used in the vertical force transducers. The sinkage is obtained from a 10-turn potentiometer driven by a dial cord attached to the penetrometer plate

and wound over a pulley on the potentiometer shaft. The electrical output from the potentiometer and the strain gage transducer are fed into the two axes of a Moseley X-Y recorder to obtain the pressure-sinkage curve. The shear test device is described on page 13.

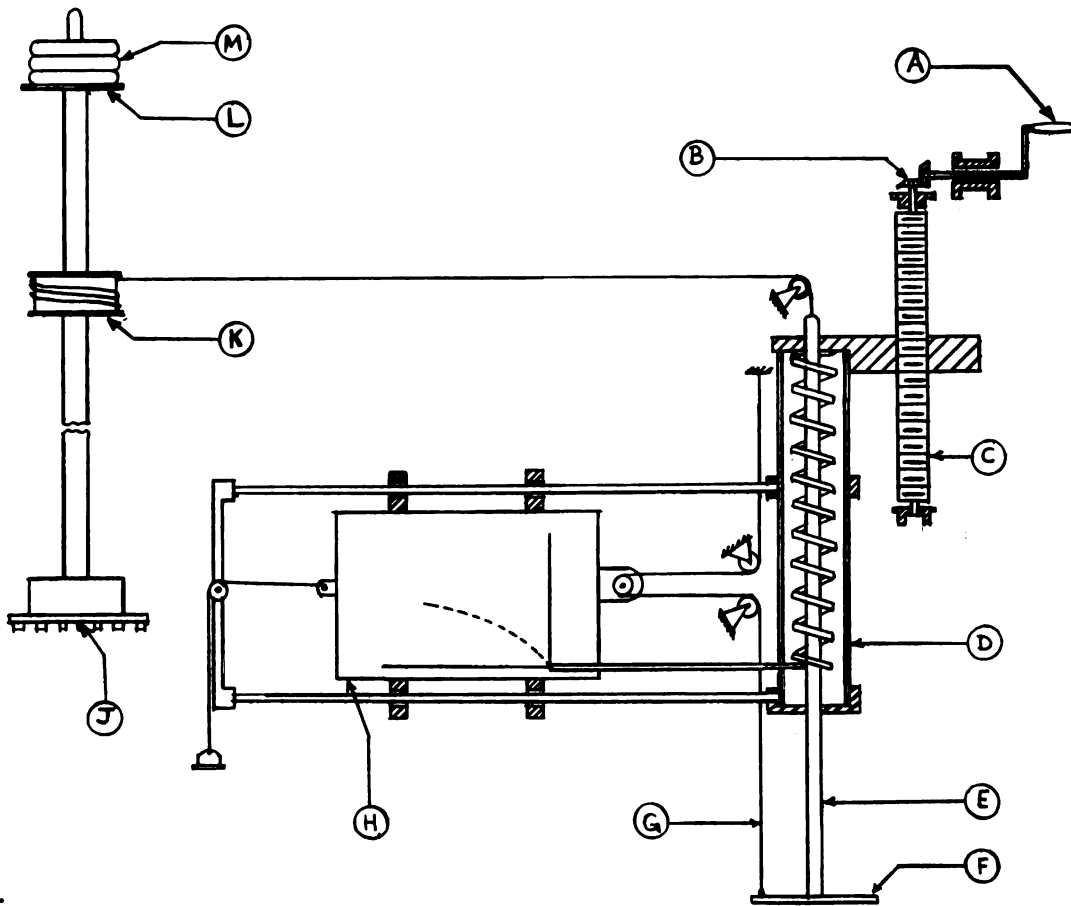
The advantages of the Caterpillar Tractor Corporation's soil test machine are that two pressure-sinkage tests can be done without moving the entire machine, and the data can be processed with minimum effort. But, the disadvantages seem to be many. As the machine is a towed unit movement up and down the plot takes relatively more time. If the shear and sinkage data is taken without moving the machine switching the X-Y recorder from one test to the other and adjusting it appropriately takes more time too. The machine is heavy and expensive. The machine, in spite of its weight, does not guarantee against lifting of the frame during sinkage test. There is no arrangement to get rid of vegetative cover on the soil during the test, and the penetrometers are not located in easily accessible positions.

The Land Locomotion Research Branch, OTAC (Pavlics, 1958), developed various devices to measure physical soil values. One of such devices is the hand-operated load-sinkage and shear test apparatus (Fig. 3). In this apparatus a hand crank coupled with a bevel gear system turns a drive screw, which, in turn operates the penetrometer up and down depending upon the direction of rotation of the crank. A chart carriage is attached to the penetrometer by means of a system of wires and pulleys so that the chart is carried horizontally to indicate sinkage while the penetrometer moves vertically. A spring is attached to the penetrometer shaft such that it is compressed while the plate is being pushed into the soil. A pen attached at the end of the spring records the pressure-sinkage curve. This device is useful for laboratory work when soil compaction is low, and higher loads are not



Legend:

- A. Crank
- B. Bevel gear
- C. Drive Screw
- D. Spring scale
- E. Shaft
- F. Penetrometer
- G. Cable and pulley
- H. Chart
- I. Shear ring
- J. Drum and cable
- K. Weight retaining ring
- L. Weight



Legend:

- A - Crank
- B - Bevel gears
- C - Drive Screw
- D - Spring scale
- E - Shaft
- F - Penetrometer plate
- G - Cable and pulley system
- H - Chart
- J - Shear ring
- K - Drum and cable
- L - Weight retainer
- M - Weight

Fig. 3. Schematic of Hand Operated Load-Sinkage and Shear Test Apparatus

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necessary. The maximum load one can attain on this hand-operated device is 250 lbs., and maximum sinkage is 15 inches.

The Land Locomotion Research Branch has also devised a load-sinkage apparatus in which the drive is performed by a hydraulic power unit, and both sinkage and load are measured by electrical resistance transducers. The load-sinkage curve is recorded on X-Y plotter. This apparatus is more suitable for field work than its predecessor since the maximum load is 1000 lbs. and maximum sinkage is 24 inches.

The above devices developed by the Land Locomotion Research Branch have with them the shear test apparatus also on the same frame. This makes easier to run both the load-sinkage and shear tests with the same unit. Shear test apparatuses are discussed in section (b) of this chapter.

Stong (1960) used a bevameter developed and loaned by the Land Locomotion Laboratory, Detroit Arsenal. It consists of the hand-operated load-sinkage and shear test apparatus. Stong mounted a hydraulic motor on the bevameter frame to provide drive to the spring housing, and attached a three point hitch to facilitate moving of the bevameter by a tractor. Stong's procedure for field tests is similar to that recommended by Hanamoto and Hegedus (1958). A 48' x 50' test site is divided into fifteen 16' x 10' plots. In each plot a complete series of soil value tests are conducted, and at least two 18" x 3" core soil samples are obtained. Circular plates having diameters 1 in. to 6 in. and varying sizes of rectangular plates are used in load-sinkage tests. The apparatus is likely to get lifted during sinkage tests. This is undesirable as it will result in inaccurate sinkage measurement.

Trask and Skjei (1958) designed a soil testing apparatus to measure bearing stress on soil samples subjected to a constant rate

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of strain. The measurements are made by driving into the soil a plunger geared to a constant-speed motor. The center section of the plunger consists of a calibrated, machined aluminum test ring which is bonded with four SR-4 strain gages. The signal from the strain gages is recorded on a moving roll graph of a Brush magnetic oscillograph. Since the roll graph is driven by the constant-speed motor, which is also driving the plunger, sinkage is proportional to the displacement of roll graph. It has been reported that inaccuracies of measurement may result from bearing friction at extremely light loads, and from inadequate compensation for test ring deflection at extremely heavy loads.

(b) Shear Test Devices

Hvorslev (1939), in his review of various apparatuses which have been developed for soil shear tests, discussed the practical advantages and disadvantages of torsion shear tests compared to other available methods. Most of these tests are for civil engineering purposes, and the shear resistance after the soil failure is of no concern to civil engineers.

Terzaghi (1948) developed a translatory shearing apparatus which, in spite of its simplicity, has the disadvantage of decreasing the effective cross-section of the sample during the test, and resulting in a rather complicated stress condition that causes progressive failure to start during the early stages of the test.

One of the early torsion shear apparatus for soils was developed by the A.S.C.E. Special Committee to Codify Present Practice on the Bearing Value of Soils for Foundations (1917). It consists of a cylindrical container and a piston through which a vertical normal load is applied to the sample. In a recess in the bottom of the cylinder is

a disc which can be rotated by means of a lever under the cylinder. The soil sample is placed between the piston and the disc. The principal advantage of this type of apparatus is that the cross-section of the sample does not change during the test. The disadvantage is that the sample undergoes a considerable volume change from the center radially to the surface, and, since the piston does not yield to accommodate for the volume change, causes a non-uniform and unknown distribution of the normal stresses on the plane of failure.

The above mentioned disadvantages were eliminated by the so-called ring shearing apparatus developed independently in 1934 by Gruner and Haefeli, Cooling and Smith (1936), and Hvorslev (1936). The apparatus consists of two rings, one over the other, with arrangement for relative motion. The soil sample is held between the rings in the ring shaped groove carved in them. The walls of the shearing ring grooves are equipped with radial teeth which prevent slipping between ring wall and soil sample during torsion. Hvorslev measured the torque by strain gage instrumentation.

None of the above methods of measuring shear strength are suitable for using on the field soil in its state of continuity because the design of the apparatus is such that only soil samples are required for the tests.

Payne and Fountaine (1952) have developed a method of measuring the shear strength of soils in the field, in which a cylinder of soil is sheared in torsion, and a moment against angle-of-twist (proportional to strain) curve obtained. The apparatus (Fig. 4) consists of a cylindrical torsion box (A) 5 in. diameter and 2 in. deep with a removable lid (B), a torque meter (C), a removable wire pointer (D) 36 in. long, and a series of slotted lead weights (E). On the inside of the walls of the torsion box there are six equally spaced small fins 2 in. long, $3/16$ in. wide, and $1/32$ in. thick which prevent the soil from slipping

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relative to the box. In use the torsion box is forced into the soil in the field to 2 in. depth, the required number of weights added, and the surrounding soil is removed to a depth of about 1/8 in. below the bottom of the box to prevent its edges from carrying any of the normal load. A twist is applied to the handles (F) of the torque meter at as near a constant speed as possible. The average deflection of the two ends of the pointer on scales (G) is recorded for as many values of the torque as possible. Shear stress is then given by:

$$S = \frac{3}{2\pi r^3} \left(M + \frac{\theta}{3} \frac{dM}{d\theta} \right) \dots \dots \dots (4)$$

where S is shear strength in p. s. i.

r is radius of torsion box in inches

M is applied twisting moment in lb-in.

θ is angle of twist corresponding to appropriate twisting moment in any units.

For moist soils $S = \frac{3M}{2\pi r^3} \dots \dots \dots (5)$

gives an answer close to the one obtained by equation (4)

Payne and Fountaine concluded that the torsional shear box test gives readings in satisfactory agreement with the results obtainable by vane and triaxial testing machine. However, it seems there is greater chance for human error in shear box test as there is no arrangement for recording torque and angle of twist continuously.

Soehne (1953) developed a shear ring apparatus for measuring cohesion and friction of soils. He used the same apparatus with friction rings to measure soil-rubber and soil-metal friction coefficients. The torque recording unit is a spring mounted mechanical device with a pen marking on a wax paper.

The shear test device used by the Caterpillar Tractor Corporation (see page 8) consists of a shear head, a hydraulic pressure unit,

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a strain gage transducer and a potentiometer. The shear head has an outside diameter of 11 in., and an inside diameter of 9.25 in. The 1/4 in. high grousers are mounted radially at 15 deg. intervals. The shear head loading is provided hydraulically and varied by adjusting a pressure control valve. The normal load on the shear head is read on a calibrated pressure gage directly in p.s.i. The shear head is rotated by turning a hand-operated wheel. Shearing force is measured with SR-4 strain gages bonded to the shear head driving arms. The shear head displacement is measured by a battery powered potentiometer mounted between fixed and rotating parts of the shear head drive mechanism. The electrical output from the strain gages and potentiometer are fed into the two axes of a Moseley X-Y recorder to obtain the shear force vs. soil displacement curve. A favourable feature of the machine is that the shear head is mounted on a movable "buggy" so that a complete set of data may be run without moving the machine. Separate shear tests at three different normal loads can be run with one setting of the machine. Other features of the machine are discussed in section (a) of this chapter.

United States Bureau of Reclamation (Gibbs et al., 1960) used a vane shear test apparatus for determining the in-place shearing resistance of soil foundations consisting of soft, saturated clays, and silty clays. The apparatus consists of a rod having four vanes on its lower end, a rotation indicator and a torque measuring device. The torsional force is measured by very small strain of a resilient ring, and is indicated by a mechanical strain gage. The instrument can operate at variable depths depending upon the shaft extensions used. The test gives a shearing strength value of the soil as it exists in place with natural overburden pressures acting. There is no provision for normal loading of the soil to draw a relationship between normal stress and shear stress, which enables evaluating c and ϕ .

The shear test device designed by the Land Locomotion Research Branch functions similar to their load-sinkage device (see Fig. 3). To the shear head shaft is attached a drum with a cable coiled around it. The other end of the cable is attached to the spring scale. Turning of the crank moves the spring housing vertically causing the chart carriage to move horizontally. The horizontal displacement of the chart represents the shear head displacement. The torque on the shear head causes the spring to compress proportionally. The pen records the torque-displacement curve. This device has been further developed by providing hydraulic power to turn the shear head, and measuring torque and displacement by electrical resistance transducers. This has been designed for both laboratory and field work. This device is not so efficient from the mobility point of view.

Stong (1960) improved the above device loaned by the Land Locomotion Research Branch, on the mobility aspect by attaching a three point hitch. He used hydraulic power from the tractor hydraulic system to turn the drive screw that operates the shear head. The recording device is a mechanical X-Y plotter as shown in Fig. 3. The shear test had been conducted under four normal pressures of 1.01, 2.02, 3.03 and 4.04 p. s. i.

Fountaine and Brown (1959) measured shear strength of top soils in the field under small normal loads in the range 0-10 p. s. i. by using the torsional shear box developed by Payne and Fountaine in 1952, and concluded that the torsional shear box gives readings in satisfactory agreement with other methods of shear testing, and that the rate of straining has a negligible effect on the maximum shear strength of top soils within the range they tested.

Wilson, Nuttal, Raimond Engineers Inc. have designed a soil shear graph for rapid measurement of soil shear strength in-situ

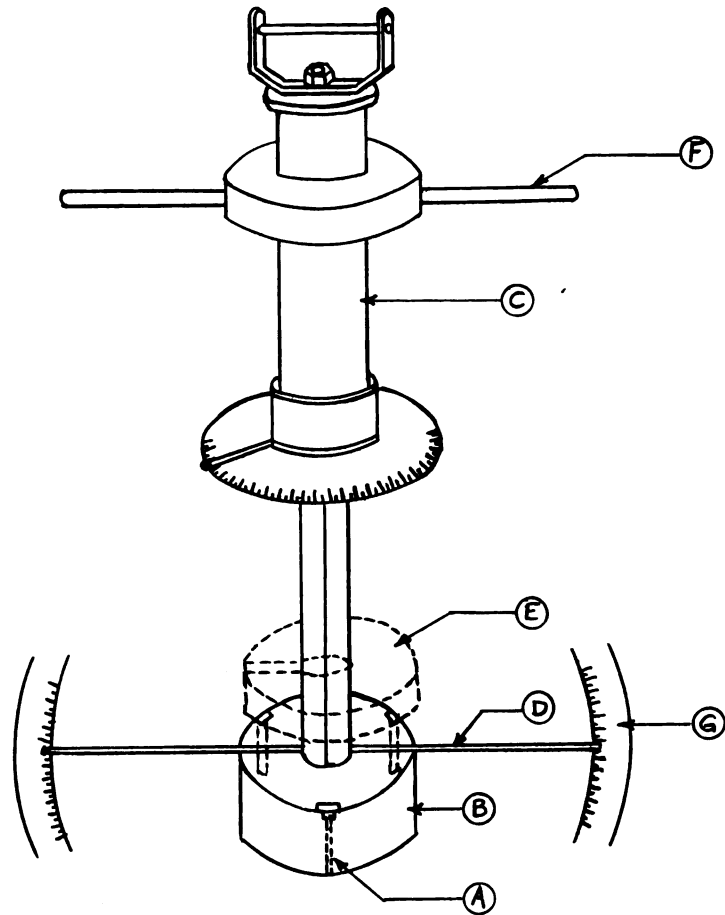


Fig. 4. Torsional Shear Box

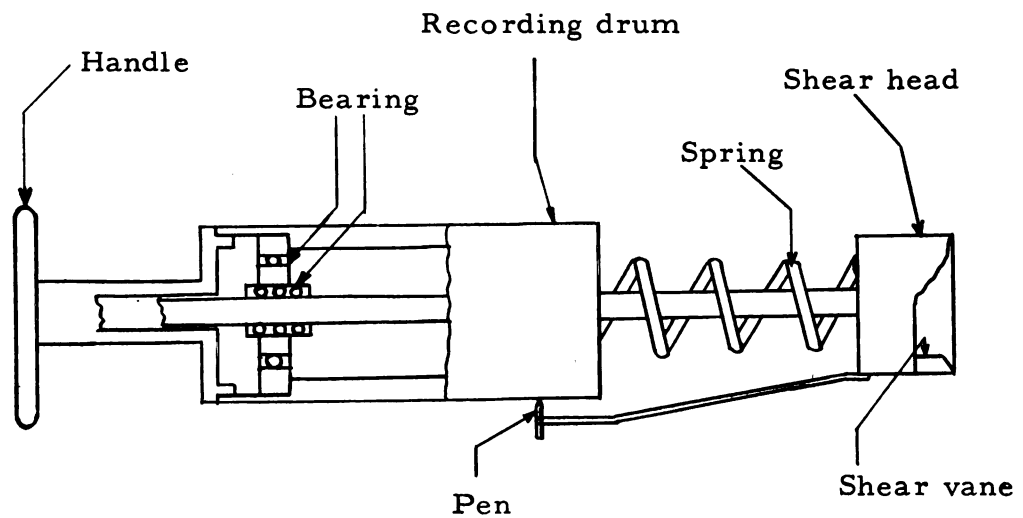


Fig. 5. Soil Shear Graph

(Cohron, 1964)

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(Cohron, 1962). They used the torsional shear head principle as put forth by Payne and Fountaine (Fig. 5). In operation, the shear head is completely inserted into the soil, normal stress is applied to the shear surface through axial deflection of the spring, and shearing stress is applied by twisting the recording drum until the soil fails. The pen will record the shear stress vs. normal stress curve.

Wills (1963) built an annular torsional shear test apparatus and a translational rigid track shear test apparatus powered by a hydraulic ram. He observed significant difference in the results obtained, and concluded that the annular torsional shear test apparatus was preferable.

(c) Data Analysis

Pressure-sinkage test data:

Pressure-sinkage curve is used for evaluating k and n in the Bernstein-Goriatchkin equation,

$$p = k z^n \dots \dots \dots (2)$$

Taking logarithms on both sides yields

$$\log p = \log k + n \log z$$

It can be seen that this equation represents a straight line if k and n are constants. When the relationship between p and z is illustrated on a log-log paper the values of k and n are readily obtained as intercept on load axis and slope of the straight line respectively (Fig. 7-a).

Bekker (1960) obtained the values of k_c , k_ϕ , and n by the following procedure from his load-sinkage equation,

$$p = \left(\frac{k_c}{b} + k_\phi \right) z^n \dots \dots \dots (3)$$

Let

$$a_1 = \frac{k_c}{b_1} + k_\phi$$

$$a_2 = \frac{k_c}{b_2} + k_\phi$$

Solving for k_c and k_ϕ ,

$$k_c = \frac{(a_1 - a_2)b_1b_2}{b_2 - b_1}$$

$$k_\phi = \frac{a_2b_2 - a_1b_1}{b_2 - b_1}$$

To obtain a_1 and a_2 the values of p vs. z are plotted on log-log paper. If sinkage follows the equation proposed by Bekker then two straight parallel lines should be obtained for two sizes of loading area, b_1 and b_2 . The values of a_1 and a_2 are the pressures corresponding to b_1 and b_2 at 1 in. sinkage. The value of n is the slope of the parallel lines (Fig. 7-b).

The procedure described above is good when pressure-sinkage relationship follows either Bernstein-Goriatchkin equation or Bekker's modified equation. For the unknown conditions occurring in nature deviations are inevitable. In a number of cases data obtained in the field did not show exponential relation between pressure and sinkage. Moreover, this procedure is tedious when there is a large amount of data available for the evaluation of soil strength values.

Shear Test Data:

Torque-displacement curve obtained from torsional shear test is used to evaluate c and ϕ (Hvorslev, 1939). The maximum torque reading M , is converted to shear stress S , as shown below (see Fig. 6).

The moment resisted by the soil can be written as

$$dM = 2 \pi r dr S$$

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

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

Therefore,

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

$$S = K M \text{ where } K = \frac{3}{2 \pi (r_2^3 - r_1^3)}$$

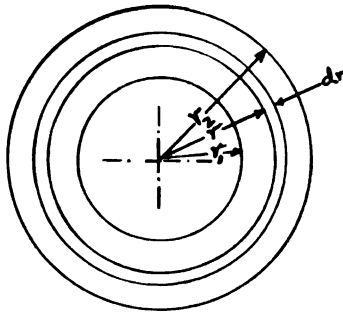


Fig. 6. Shear Ring

In the formulation of the above relation it has been assumed that the shear stress is uniformly distributed over the plane of failure.

The normal stress p is calculated by dividing the load W on shear head with shear ring area A .

The variation of maximum shear stress is then plotted against normal stress. The resulting relationship approaches a straight line described by Coulomb's equation

$$s = c + p \tan \phi \dots \dots \dots (1)$$

The slope of this straight line gives the "angle of internal friction ϕ ", and the intercept on shear stress axis at zero normal stress is the "cohesion c " (Fig. 8-a, b). This procedure is almost universally used for the evaluation of c and ϕ .

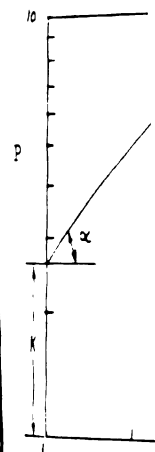


Fig. 7-a. Eva



Fig. 8-a. Torque
Curve

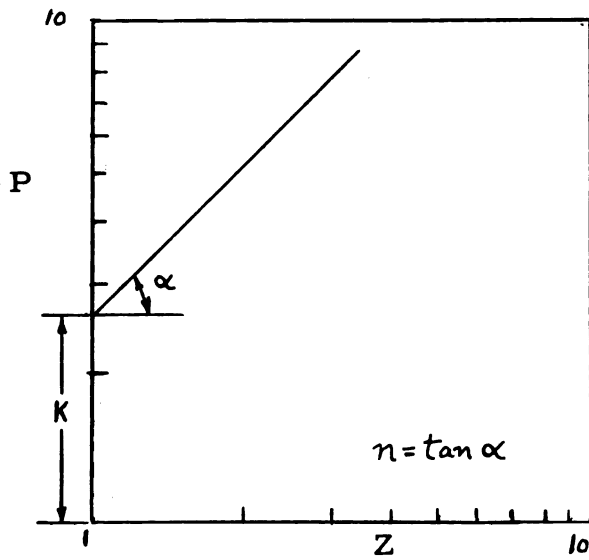
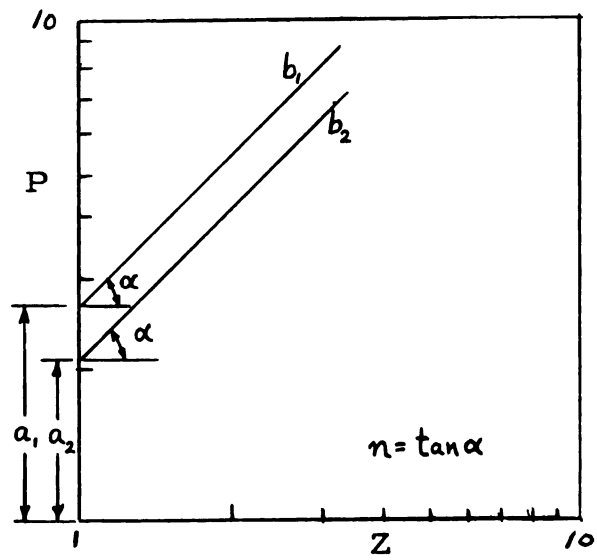
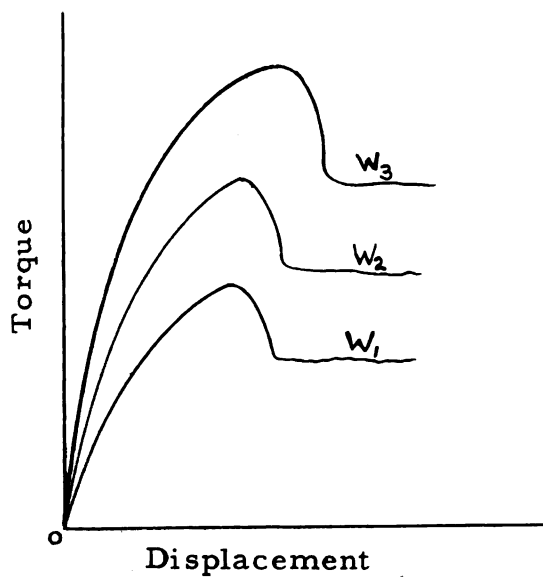
Fig. 7-a. Evaluation of k and n Fig. 7-b. Evaluation of a_1 , a_2 and n 

Fig. 8-a. Torque-Displacement Curves

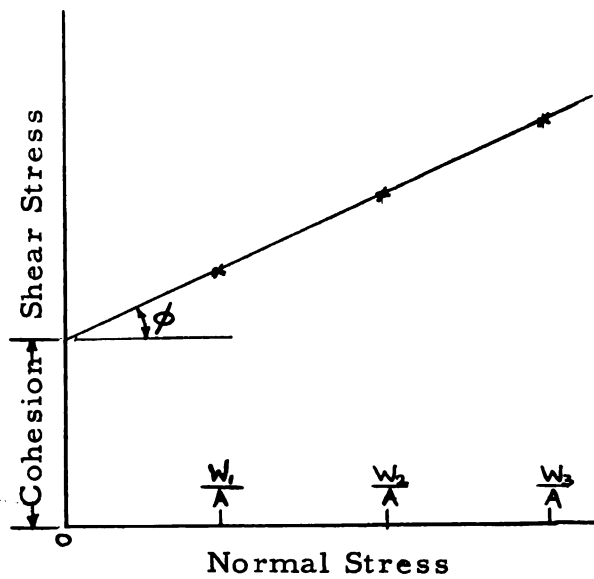


Fig. 8-b. Shear Stress vs. Normal Stress Curve

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INSTRUMENTATION

The instrument used to measure soil strength values is ordinarily called bevameter (Bekker Value meter). The bevameter consists of a penetrometer, a shear head, and a recording device.

Hydraulic components, strain gage transducers, a shear head, and a Moseley X-Y recorder have been supplied for the construction of the bevameter by the Land Locomotion Laboratory, Detroit Arsenal, the sponsors of the project.

A Massey-Ferguson tractor has been provided for the project. The tractor tread is widened such that the pressure distribution under the wheels does not disturb an approximately 30 in. wide and 18 in. deep soil strip between the wheels (Fig. 9). Thirty inches is the distance between the two extreme points of the largest penetrometer plate and the shear ring. A depth of 8 in. is allowed for penetration from the surface of a 10 in. deep plot. Thus a 30 in. wide 18 in. deep undisturbed soil strip is required for testing.

A special frame with three point hitch and two adjustable feet is constructed. The shear head assembly, gear reduction unit, hydraulic motor, penetrometer cylinder, and the control panel are mounted on this frame as shown in Fig. 10. The penetrometer cylinder and the shear head assembly are so located that they can be operated within the undisturbed soil strip.

The tractor hydraulic system is used to provide the necessary pressure for operating the bevameter. Penetration force is provided by a 2 in. inside diameter double acting hydraulic cylinder. The turning of the shear head is caused by a hydraulic motor with a displacement of 18.2 gpm at 1800 rpm, connected to a 80:1 wormgear reduction unit. The relief valve in the hydraulic circuit is set to

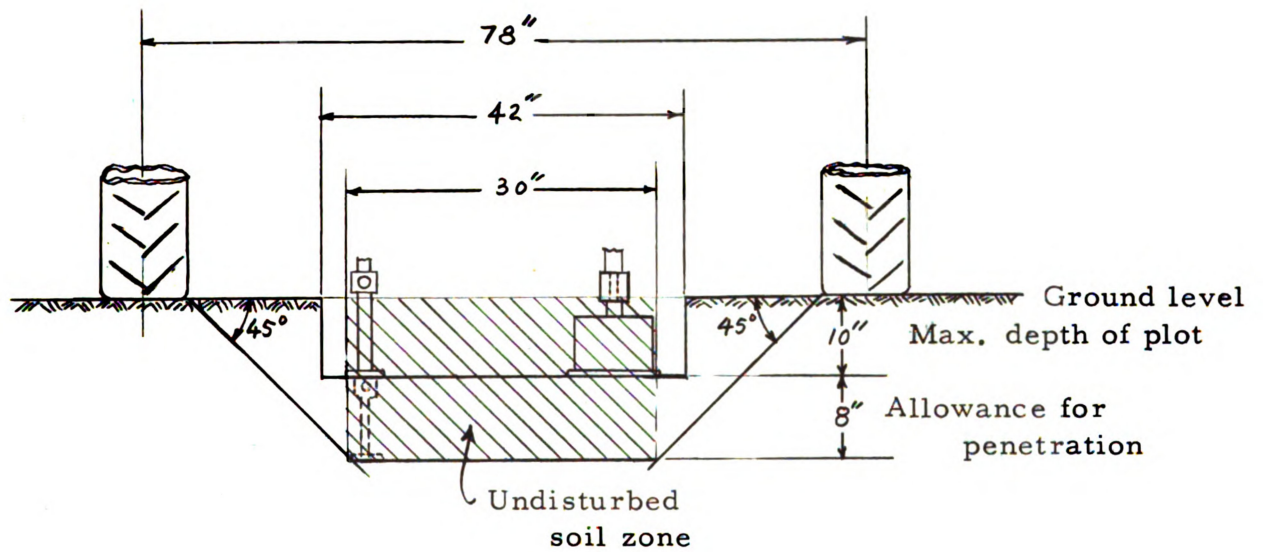


Fig. 9. Determining the Tractor Tread to Obtain 30" x 18" Undisturbed Soil Zone

allow a maximum penetration force of 1900 lbs. and torque of 600 in.-lbs.

For pressure-sinkage test series six sizes namely, 1-1/2 in., 2 in., 3 in., 4 in., 5 in., and 6 in. diameter penetrometer plates, and a 30 degree cone with 1/2 sq. in. base area are made available. Sinkage tests are normally conducted with at least three different sizes of penetrometer plates and the cone penetrometer. One and one-half, 2 and 3 in. diameter plates are used in heavy soil, 2, 3, and 4 in. diameter plates in medium and light soils. Four, 5 and 6 in. diameter plates are used on all the soils in plowed condition.

A shear ring of 5.25 in. inside diameter and 7.25 in. outside diameter is used for shear tests. On the shear head 18 grouser plates, each 1 in. long, 1/4 in. high and 1/32 in. thick, are soldered to the bottom side of the ring at equal intervals (see Fig. 11). Shear tests are conducted under three different normal stresses, namely, 0.81 psi, 2.84 psi and 8.93 psi. These stresses are obtained by placing 0, 2 and 8 weights (each weighing 20 lbs.) respectively on a platform on the shear head shaft. The shear head assembly weighs 16 lbs., and the annular area of the shear ring is 19.72 sq. in.

Lifting and lowering of the shear head is done hydraulically by a double acting cylinder situated on the left of the shear head assembly. A fork is attached to the plunger of the cylinder for this purpose.

A simple attachment to the shear head bottom is made to plane the soil surface in order to obtain a uniform contact between the soil and the shear ring. This device is easily detachable (Fig. 11). The planing operation is done with no load on the shear head. This operation is also useful to get rid of the top soil layer that is subjected to changing moisture conditions.

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Fig. 10. Bevameter in operation. Operation of powered soil sampler can be seen in the background.

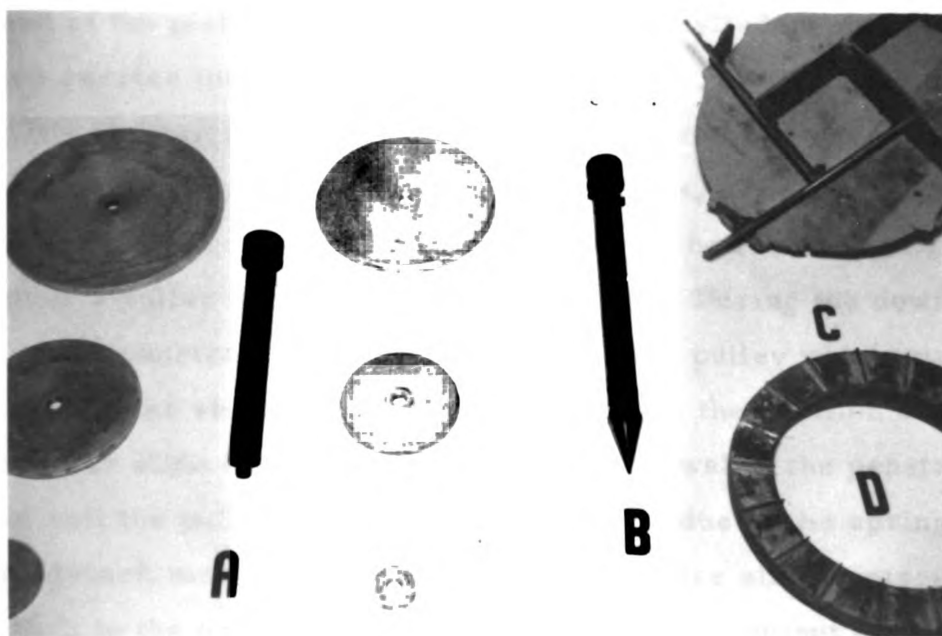


Fig. 11. Plate penetrometers (A), Cone penetrometer (B), Surface planing attachment (C), and Shear Ring (D).

A double acting hydraulic cylinder is mounted between the bevameter frame and the tractor drawbar to transfer a part of the tractor weight onto the bevameter. This prevents lifting of the bevameter frame during sinkage test (Fig. 14). During the tests lifting is found to be less than $1/2$ in. at the highest penetration force of approximately 1900 lbs. Pressure to the hydraulic cylinder is directly taken from the tractor hydraulic system.

The hydraulic circuit details for the operation of bevameter are shown in Fig. 12. Load-sinkage and shear stress-deformation tests are performed separately one after the other.

Electrical resistance strain gages are used in the measurement of load and torque in the load-sinkage and torque-deformation tests respectively. The load cell consists of a machined aluminum ring which is bonded inside and outside with four SR-4 strain gages and coated with moisture proofing material. The transducer circuit is shown in Fig. 13-a. One end of the load cell is screwed into the lower end of the piston rod of the penetrometer cylinder, and the other end carries the penetrometer shank.

The sinkage measuring device is a 10-turn micropotentiometer with a spring attachment for automatic reel-back. The potentiometer is driven by a dial cord hooked at the bottom of the load cell and wound over a pulley on the potentiometer shaft. During the downward motion of the penetrometer the cord unwinds the pulley which turns the potentiometer shaft and along with it changes the position of the potentiometer slide contact. During the withdrawal of the penetrometer from the soil the pulley winds the cord on itself due to the spring action of the reel-back mechanism, and the potentiometer slide contact comes back to the original position. The electrical output of the potentiometer varies linearly with the length of the cord wound or unwound from the pulley. The potentiometer circuit is shown in Fig. 13-b.

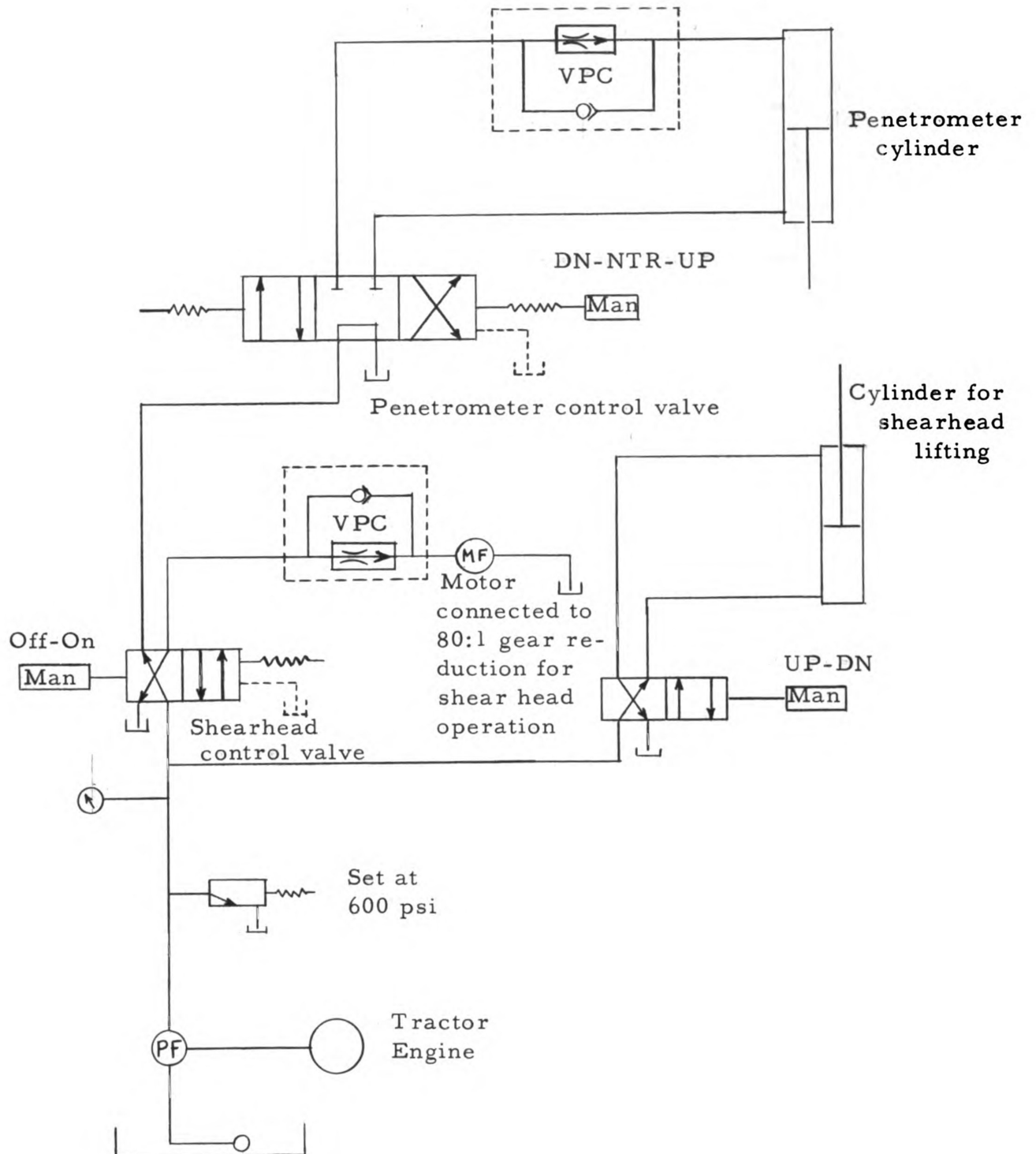


Fig. 12. Hydraulic Circuit of Bevameter Operation

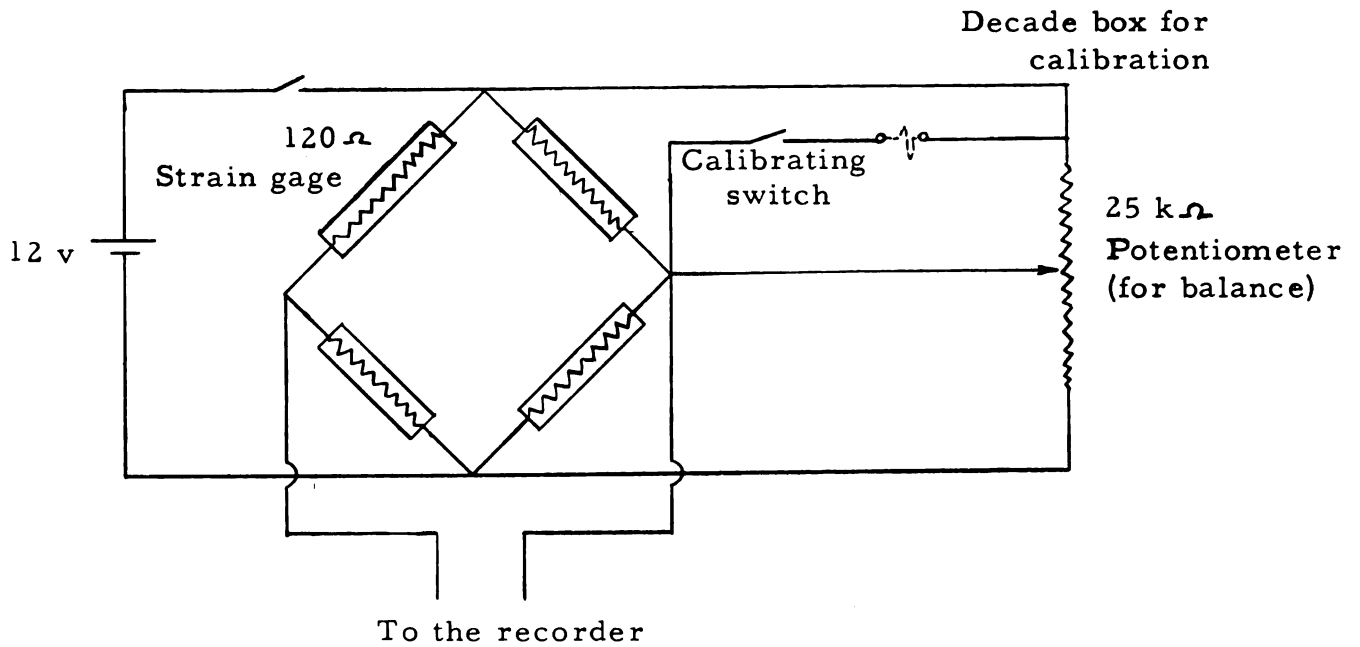


Fig. 13-a. Transducer circuit--Load and Torque Cells

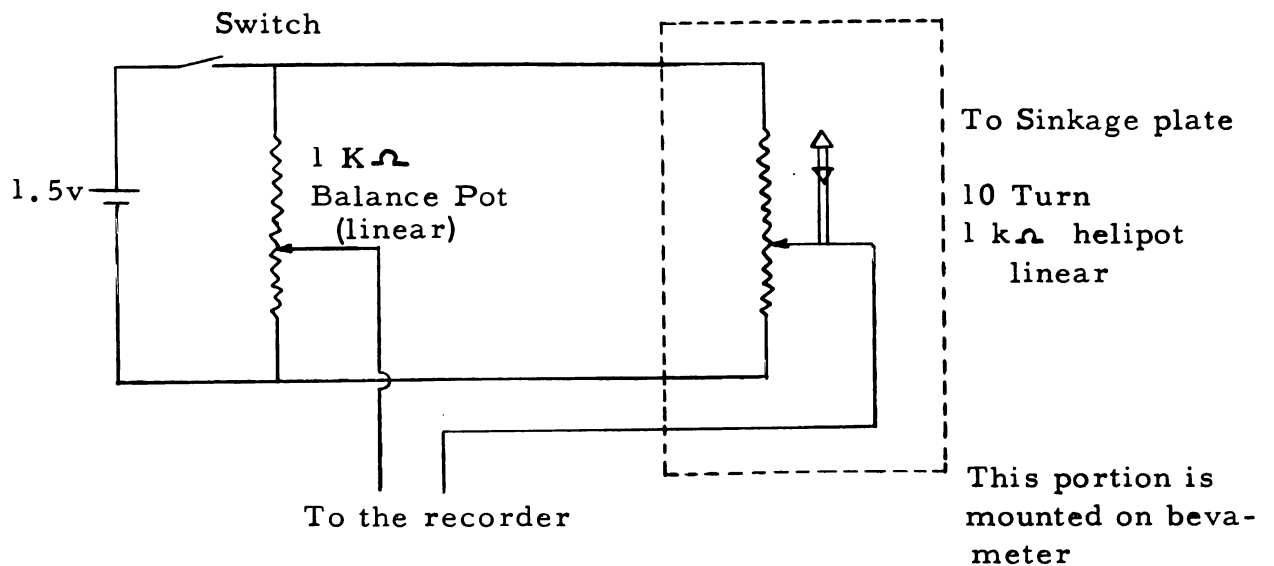


Fig. 13-b. Sinkage Measuring Device

The torque cell consists of a short aluminum shaft with four SR-4 strain gages mounted at 45 degrees to the neutral axis. The electrical circuit is the same as shown in Fig. 13-a.

The recording device is a Moseley X-Y recorder, model 135. This is placed on the tractor to the right of the driver's seat (Fig. 15). Power to the recorder is supplied by a 110 V, 500 W, 60 cps Blue Diamond Gas-O-Lectric generator which is mounted on the front end of the tractor (Fig. 16).

The electrical output from the load cell and from the potentiometer are fed into the X and Y axes of the recorder respectively, and the resulting load-sinkage curve obtained.

The shearstress-deformation curve is actually recorded as torque-time curve. To obtain soil deformation rate the shear head displacement has to be calibrated with respect to time. There is provision on the X-Y recorder to have time base on X-range. A micro-switch is mounted on the control panel in a position such that when the lever of the shear head control valve is put in "ON" position the time-base circuit of the X-Y recorder is closed. A cam mechanism is used for this purpose. The torque recorded is later converted into shear stress by multiplying with $\frac{3}{2 \pi (r_2^3 - r_1^3)}$, where r_1 and r_2 are the inner and outer radii of the shear ring. The details of converting torque into shear stress, and time into soil displacement are given in Chapter V.

The load and torque cells are precalibrated in the laboratory with known loads and torques. A balance box is built and attached to the X-Y recorder in the Land Locomotion Laboratory, Detroit Arsenal, to aid zero setting of the instrument. When the recorder pen is set at a convenient zero position on the chart and then the transducer bridge is connected to the input terminals of the recorder the pen will deflect away from the set zero position due to unbalance in the transducer

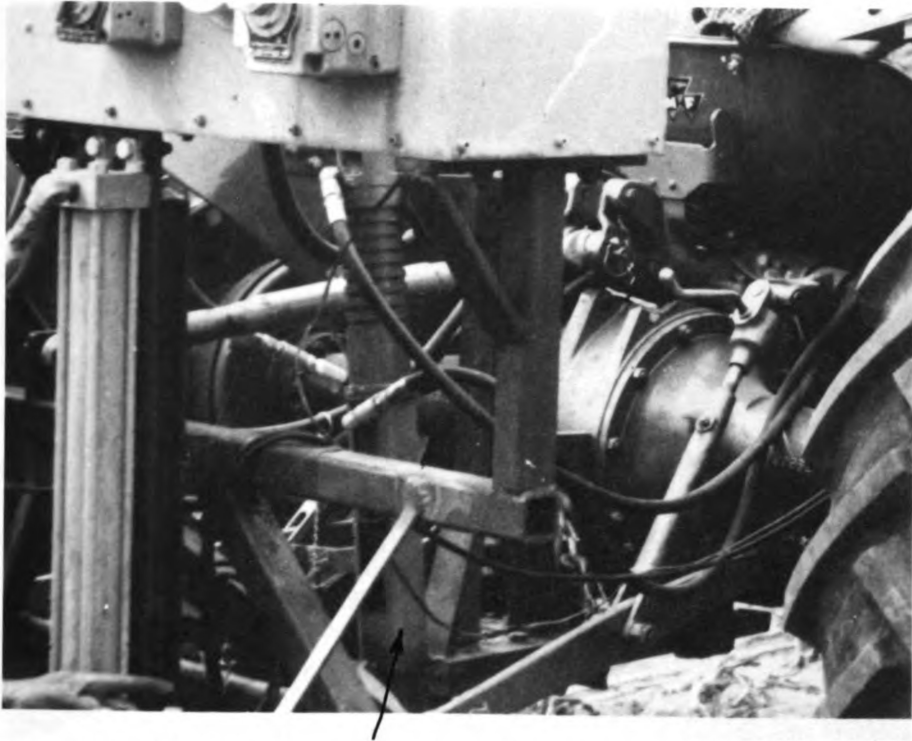


Fig. 14. Hydraulic cylinder to prevent vertical movement of Bevameter frame during test.

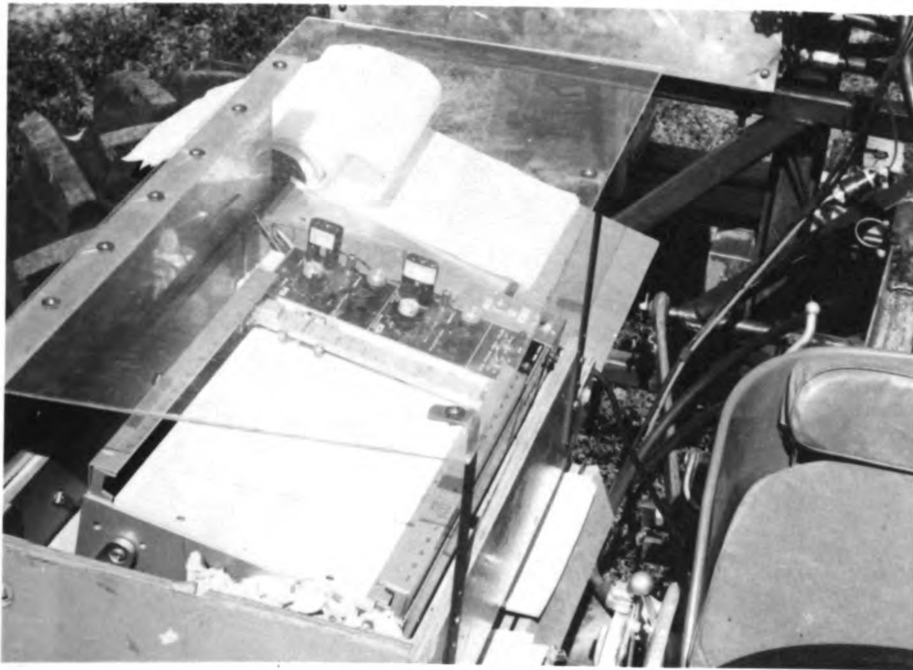


Fig. 15. X-Y recorder installed on the tractor.



Fig. 16. Electric generator on the tractor front end.

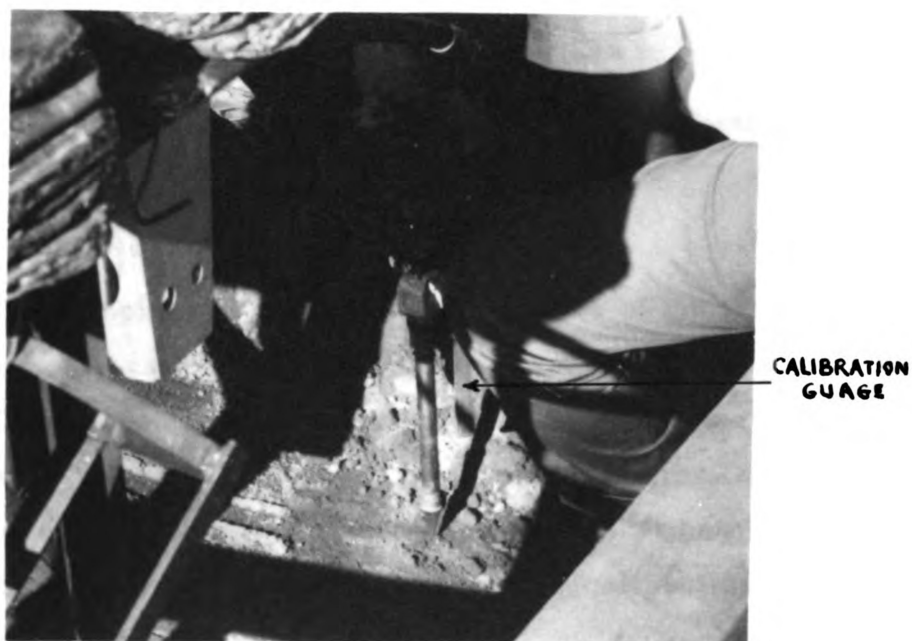


Fig. 17. 'In situ' calibration of sinkage measuring device.

resistance. This has to be properly counterbalanced by some external resistance. The external resistance is provided from the balance box by adjusting a linear potentiometer connected in the circuit as shown in Fig. 13-a, b. This helps in regaining the zero position on the chart. Then, a known load or torque is applied to the transducer, and the corresponding deflection is recorded. This implies that the distance marked on the chart is equivalent to the applied load or torque. The load cell is calibrated in steps of 100 lbs. for a maximum load of 1600 lbs. The torque cell is calibrated in steps of 120 in.-lbs. for a maximum torque of 600 in.-lbs.

The load cell used in the bevameter has the following characteristics at the load applied:

Load Applied	Calibrating Attenuation	Deflection on Chart
250 lbs.	.5	5 in.
250 lbs.	1	2.5 in.

The torque cell has the following characteristics:

Torque Applied	Calibrating Attenuation	Deflection on Chart
159 in.-lbs.	.5	5.3 in.
159 in.-lbs.	1	2.65 in.

The principle of null balance operation of the transducer bridge is used for calibration of the recorder chart during the field measurements. This consists of connecting an additional resistor electrically in parallel with one of the bridge legs, and adjusting the recorder output to give approximately the same deflection that has been obtained at a particular attenuation in the laboratory calibration (Perry and Lissner, 1955, p. 184).

The potentiometer for sinkage measurement is calibrated "in situ" by pulling the cord a known length, and adjusting the attenuation

of the recorder to get a reasonable deflection of pen in Y-range. Distance pieces, 6 in. and 2 in. long, are used to accomplish sinkage calibration (Fig. 17).

The calibration deflection in both the tests are recorded on the recording chart, and the tests are run as described in the following chapter.

PROCEDURE FOR MEASURING SOIL STRENGTH VALUES

(a) Plot Lay-out and Preparation

A procedure is developed to measure soil strength values for correlating with soil classification maps. Three sites in different areas of Michigan are selected. The soils in the three selected sites are: Conover in the Soil Science farm of the Michigan State University, East Lansing; Gray calm near Ballantine Road, 10 miles North of East Lansing; and Hoytville clay loam in Riga, Lenawee county. It is decided to take measurements at three different periods of the year with the intention of getting different soil moisture content. Each site is divided into a number of blocks according to latin square design with three replications. The plot treatments that are studied in three different periods are (i) undisturbed area in sod at surface level, 3 in. depth, and 10 in. depth, (ii) cultivated and planted area at surface level, 3 in. depth, and 10 in. depth, and (iii) area plowed to a normal depth of 7 to 8 inches.

Normally soil physical properties vary both laterally and vertically. The positioning of plots under treatments and sub-treatments, and the replications are so designed that they may fairly represent the lateral and vertical variation in soil which possibly occur. Four replications of each test are performed in four different divisions of the plot at random. The length of the plot is selected so that an adequate number of tests can be performed at a safe interval of distance, which is about 1-1/2 to 2 feet. Place for additional tests in case of obstacles, such as stones, is also provided. The dimensions of plots, the periods in which the measurements are to be taken, and the plot treatments are marked in the plot lay-out shown in Fig. 18.

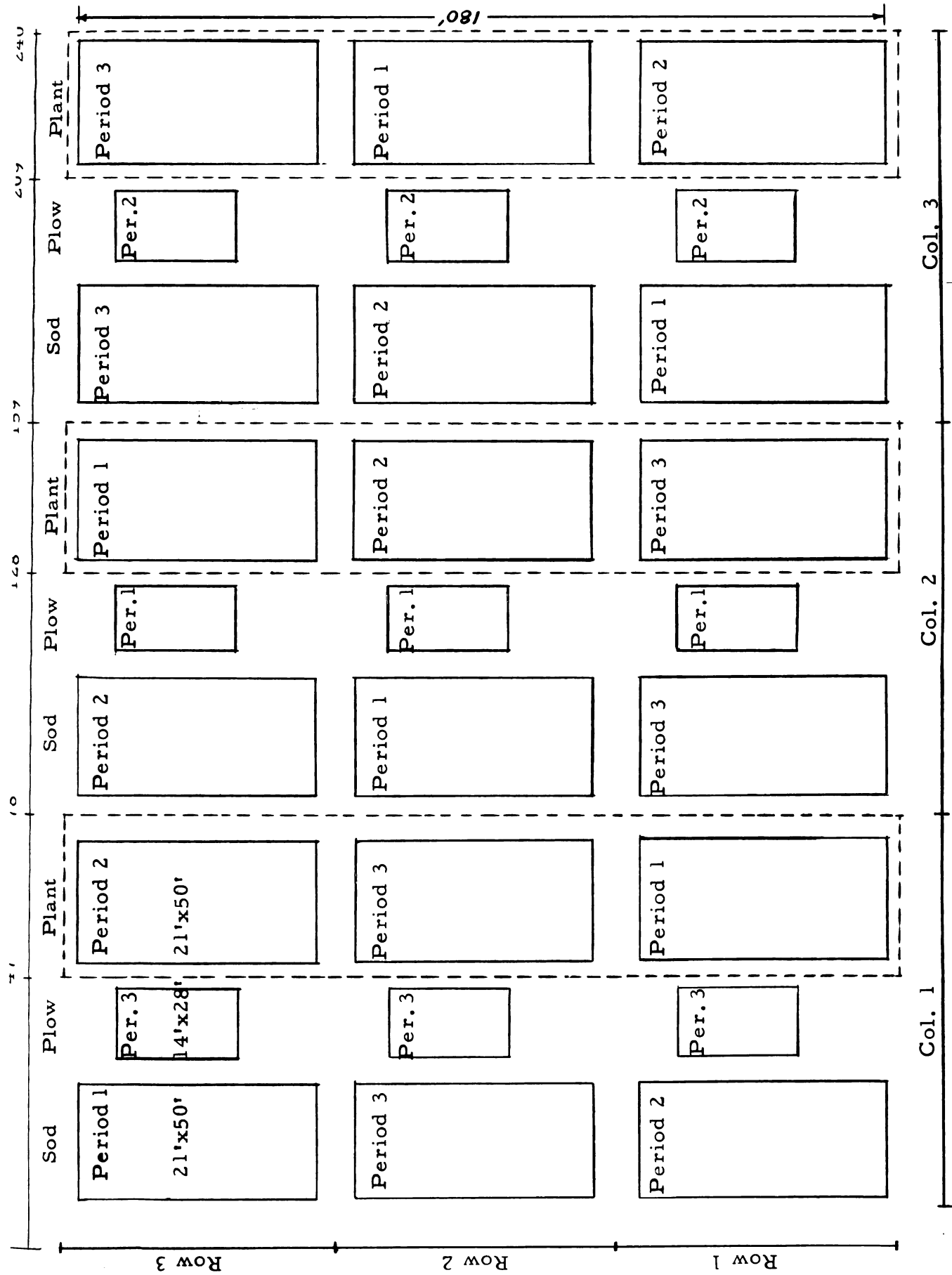


Fig. 18. Plot Layout

Plot preparation is an important aspect of testing as the uniformity in plot preparation influences the consistency in measurements. At surface the vegetation is first cut off by a rotary mower, and the test spots are scraped by the horizontal motion of a flat-bottom spade to minimize any compaction that could result otherwise. The 3 and 10 in. depths are obtained either by first plowing and then scraping or, by only scraping a number of times until a satisfactory surface is obtained at the desired depth. A scraper, carried on the three point hitch of a tractor, is made for this purpose.

(b) Performing of Tests

The series of tests that are performed is presented in Table I, and the procedure for performing each test is given below.

(i) Load-sinkage Test

The bevameter is carried along the length of the plot. The tractor is stopped when the penetrometer plate comes over a test spot, where the surface is prepared by taking off about 1/4 in. to minimize effects of changing moisture, and the bevameter is set on the ground and a part of the tractor weight is transferred onto the bevameter feet to minimize the lifting of the bevameter frame.

After preliminary adjustments on the X-Y recorder the load cell and sinkage potentiometer are calibrated as discussed in the preceding chapter, and the corresponding pen deflections are marked on the chart. One important aspect of calibrating the sinkage potentiometer "in situ" is that the penetrometer plate should be brought down so that it is 1/4 to 1/2 inch above the soil surface (Fig. 19). This will eliminate to a great extent errors due to change in diameter of the cord-reel while unwinding.

Table I. Details of the complete series of tests undertaken in the project.

Treatment	Sub-treatment	Load-sinkage Test		Shear Test	
		Plate Size	Replications	Normal Load	Replications
Sod	Surface	2 in. dia.	4	** 0 Loads	4
		3 in. dia.	"	2 Loads	"
		4 in. dia.	"	8 Loads	"
		30 deg. cone	"		
	3 in. depth		Same as above		
	10 in. depth		Same as above		
Planted with corn	Surface		Same as above		
	3 in. depth		Same as above		
	10 in. depth		Same as above		
Plowed	Before plowing	2 in. dia.	4	2 Loads	4
	Freshly plowed	4 in. dia.	4	0 Loads	4
		5 in. dia.	"	2 Loads	"
		6 in. dia.	"	8 Loads	"
		30 deg. cone			
	Treated by rototiller				
			Same as above		

**Each load weighs 20 lbs. 0 load includes self weight of the shear head assembly.

After calibration the pen is brought to a convenient zero position by adjusting "ZERO" knobs, and the pen switch is put in "DN-SWEEP" position. The X-Y recorder operator then signals the bevameter operator to begin the load-sinkage test. The penetrometer plate is then forced into the soil by pushing the corresponding control lever into "DOWN" position. Pressure to the penetrometer cylinder is stopped soon after the penetration ceases, or when the penetrometer shank is completely in the soil, or when the penetrometer tends to lift the bevameter frame (Fig. 20). When the X-Y recorder operator signals that the pen switch is brought to "STAND BY" position the penetrometer is taken out of the soil. Four replications of the test are performed in the above manner in approximately four divisions of the plot. The whole procedure is repeated with different sizes of penetrometer plates at approximately 2 feet intervals from the previous test spots.

All the load-sinkage tests are performed at an average penetration speed of 1.25 in./sec., which is obtained by properly adjusting the flow control valve directing the penetrometer cylinder. Normal loads up to 1900 lbs. are used in the field. For all the tests the tractor engine speed is maintained at 1000 rpm.

(ii) Shear Test

The setting-up of the bevameter is the same as in the load-sinkage test. However, transfer of tractor weight onto the bevameter feet is not essential, nor is it disagreeable. Any vegetation on the test spot is removed by a flat-bottom spade. The planing device is attached to the bottom of the shear head, and then the shear head assembly is lowered (Fig. 21). The loads on the shear head, if there are any, are intercepted by a metallic frame to avoid normal load on the shear head during planing operation. Planing is done by turning



Fig. 19. Penetrometer before forcing into the soil.



Fig. 20. Penetrometer completely in the soil.

the shear head, and with the leads to the torque cell unhooked. After planing the soil surface the shear head is raised, and the loose soil particles are wiped from the test spot because loose soil particles mean a soil failure. The planing attachment is removed from the shear head, and the shear head is again lowered onto the soil surface, now with the weights on.

The recording is calibrated in the same manner as for the load cell, but this time the transducer bridge is connected in the Y-range. The calibration deflection is marked on the chart.

After calibration, with recorder pen position in "DN-SWEEP", the shear head control lever is made "ON" to rotate the shear ring under the given normal load (Fig. 22). After the test the shear head is raised and the grouser teeth are cleaned. Four replications are performed under each normal load adopting the same procedure as in the case of load-sinkage tests.

All the shear tests are performed at an average shear rate of 0.91 in./sec. The tractor engine speed is maintained at 1000 rpm during the tests.

When tests are to be made on a large scale the operations have to be fast. The bevameter nearly met the requirements needed for fast operation. Tests were performed at an average rate of 28 tests (12 shear tests and 16 penetrometer tests) per hour, which means one plot under a sub-treatment took one hour for complete series of tests.

The operation of the bevameter needs the services of two men. One operator is needed for driving the tractor as well as operating the X-Y recorder. The other operator is needed for operating the bevameter which includes preparing the soil surface and operating the shear head and penetrometer controls.



Fig. 21. Shear head with surface planing device attached.



Fig. 22. Shear head in operation.

Soil moisture and bulk density are known to have considerable influence on soil strength values. If soil strength measurements are not correlated with moisture content and bulk density the results will be meaningless. This aspect of measurements makes it necessary to collect soil samples at the time of testing. Soil samples are taken by Buchele's power operated soil sampler (Fig. 10, background), and by hand sampler. In every plot machine samples at three places and hand samples at three places are taken. From the machine sample six cores of 3" x 3" are obtained. Hand sampling is done for three 3"x3" cores at every spot. Comparison of results from both methods of sampling could lead to reliability of moisture and bulk density data.

Soil moisture fluctuates with changing atmospheric conditions. As it is not always possible to take soil samples immediately after the tests, places where soil samples are to be taken are covered by sheets of plastic to arrest evaporation, or to prevent precipitation from light drizzle. The soil core, when taken out of the sampler, is put into moisture-tight boxes, and further analysis made in the laboratory.

DATA PROCESSING PROCEDURE

In summer 1963 about 1700 tests have been performed in the three selected soil types. It has been decided to process the collected voluminous data on computers.

Attempts were made to change the attenuation of the recorder for different tests to obtain extended curves that can be evaluated more accurately. In the process calibration deflection on the chart was not consistent. To get the same deflection on the chart as in the laboratory calibration was too difficult and time consuming. As the calibration deflection is different from chart to chart load, sinkage and torque deflections have to be multiplied by some scale factor to obtain the corresponding true values. The scale factor depends upon the calibration deflection on the chart and the corresponding calibration load, sinkage, or torque. Calculation of the scale factor and true values is done by punched card technique through transformation relations.

Observation of the data collected showed four distinct types of load-sinkage curves, and two distinct types of torque-time curves. The typical shapes of these curves are shown in Fig. 23-a, b, c, d, and in Fig. 24-a, b. The data from the load-sinkage and shear tests is punched separately on IBM cards together with the corresponding identification code. The punched data includes calibration data as well as the coordinates of different points representing the curve. The treatment of load-sinkage data and torque-time data is described in the following.

(a) Load- sinkage Test Data

Coordinates of eight points on load-sinkage curve are considered. Considering the possible variation in soil properties in the vertical direction eight points seem to be reasonably close to represent the curve. However, at this stage no assumptions are made regarding the type of regression equation. The curves are merely classified into four types--type I, II, III and IV depending upon the shape (see 23-a, b, c, d). For types II and IV the load coordinates are taken at equal intervals, and the corresponding sinkage coordinates measured, both in millimeters. Types I and III require individual attention because of the peculiarities in their nature. Type I curve has a distinct change of slope about the middle. Different intervals for load coordinates are selected for the first four points and the next four points depending upon the steepness. In type III the end portion of the curve is too steep; in some cases there is no increase in load with corresponding increase in sinkage, and in some cases the steeper portion of the curve is irregular. Under these circumstances load coordinates of the last four points are selected to fairly represent the actual curve.

Two additional points are considered. The initial point of the load-sinkage curve is not consistent with the rest of the curve. So, the consistent portion of the curve is prolonged backwards to meet the vertical line through the point of zero load. The intersection point is assumed to be the theoretical zero point, and the coordinates of the rest of the points on the curve are measured with reference to this theoretical point. The initial point where the curve begins to deflect from the vertical is called special point 'one'. It may be noted that both the theoretical zero point and the special point 'one' are on the same vertical line. It has already been stated that a number of load-sinkage curves classified under type I (Fig. 23-a) show a distinct

change of slope in the curve. The point where the change of slope occurs is interesting to note, and this point is called special point 'two'.

Thus there are altogether ten points whose coordinates are measured in millimeters and the values punched on IBM cards together with calibration data. In other types of curves special point 'two' does not exist. In some cases the special point 'one' is absent. The IBM card is left blank in appropriate columns when these points do not exist. The arrangement of data on the card is described in Table II.

The values punched on the IBM card do not give the true values of load and corresponding sinkage. These values have to be transformed appropriately to obtain the true load-sinkage relationships. An example of calculating true load and sinkage are shown below.

True load and sinkage are calculated for point 1.

Load coordinate X(18) mm.

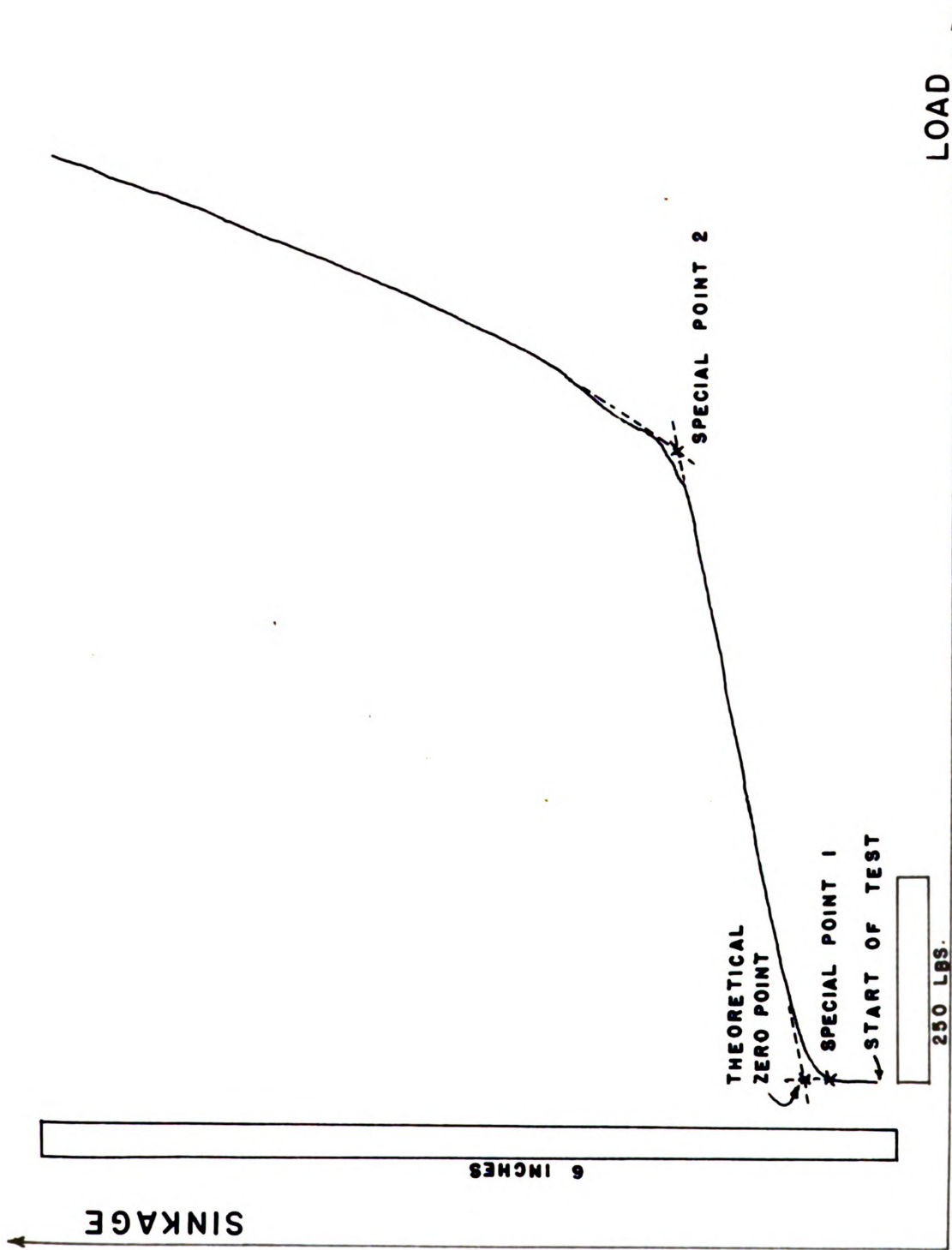
Calibration deflection against 250 lbs. X(13) mm.

$$\begin{aligned} \text{True load, } X(37) &= \frac{X(18) * 250}{X(13)} = \frac{X(18) * 250 * 453.6}{X(13) * 1000} \\ &= \frac{X(18) * 113.25}{X(13)} \quad \text{kiloponds} \end{aligned}$$

Sinkage coordinate X(17) mm.

Deflection against X(11) mm. of calibration sinkage . . . X(12) mm.

$$\text{True sinkage, } X(36) = \frac{X(17) * X(11)}{X(12)} \quad \text{mm.}$$

FIG 23- α LOAD-SINKAGE CURVE, TYPE I

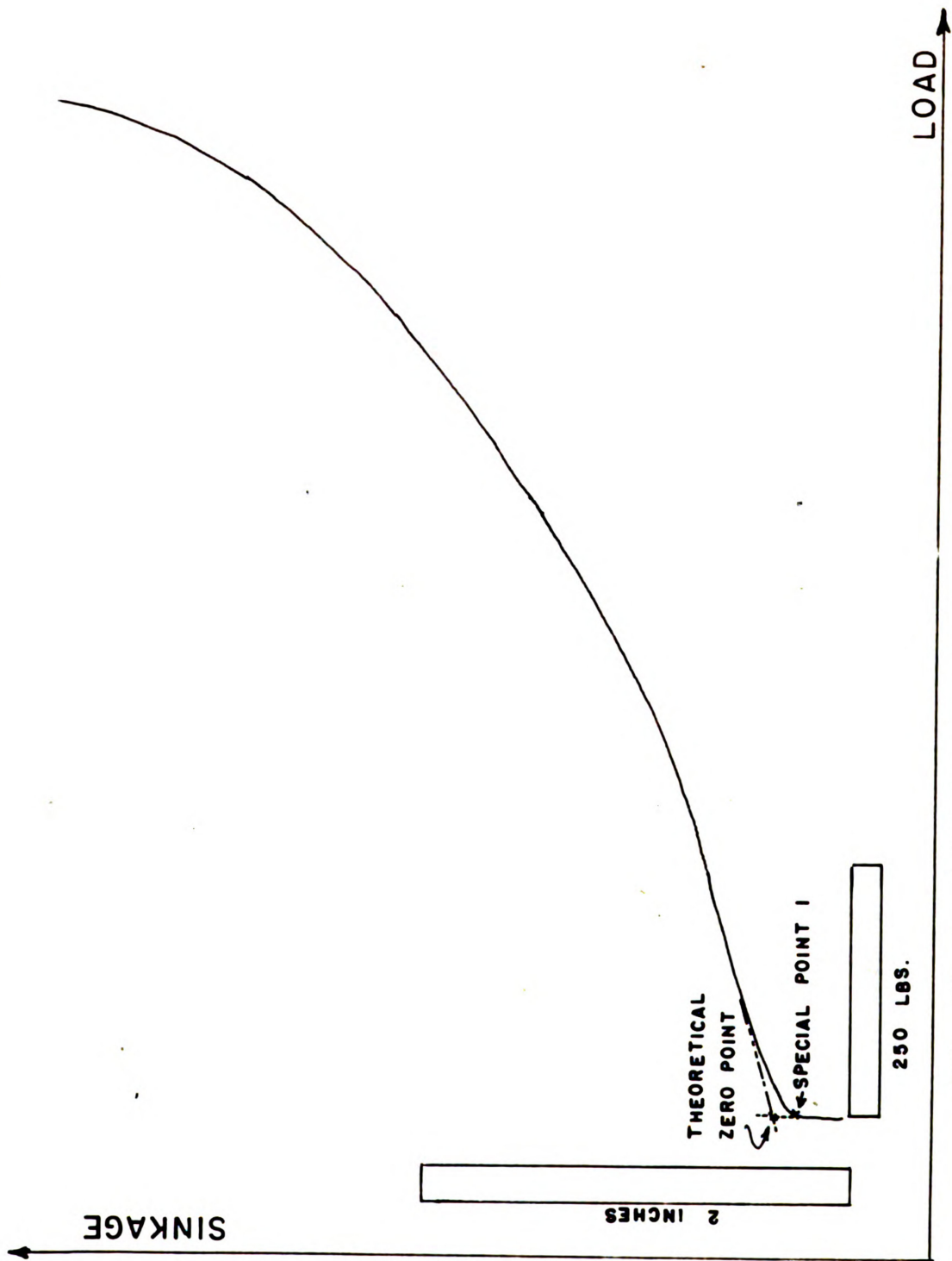
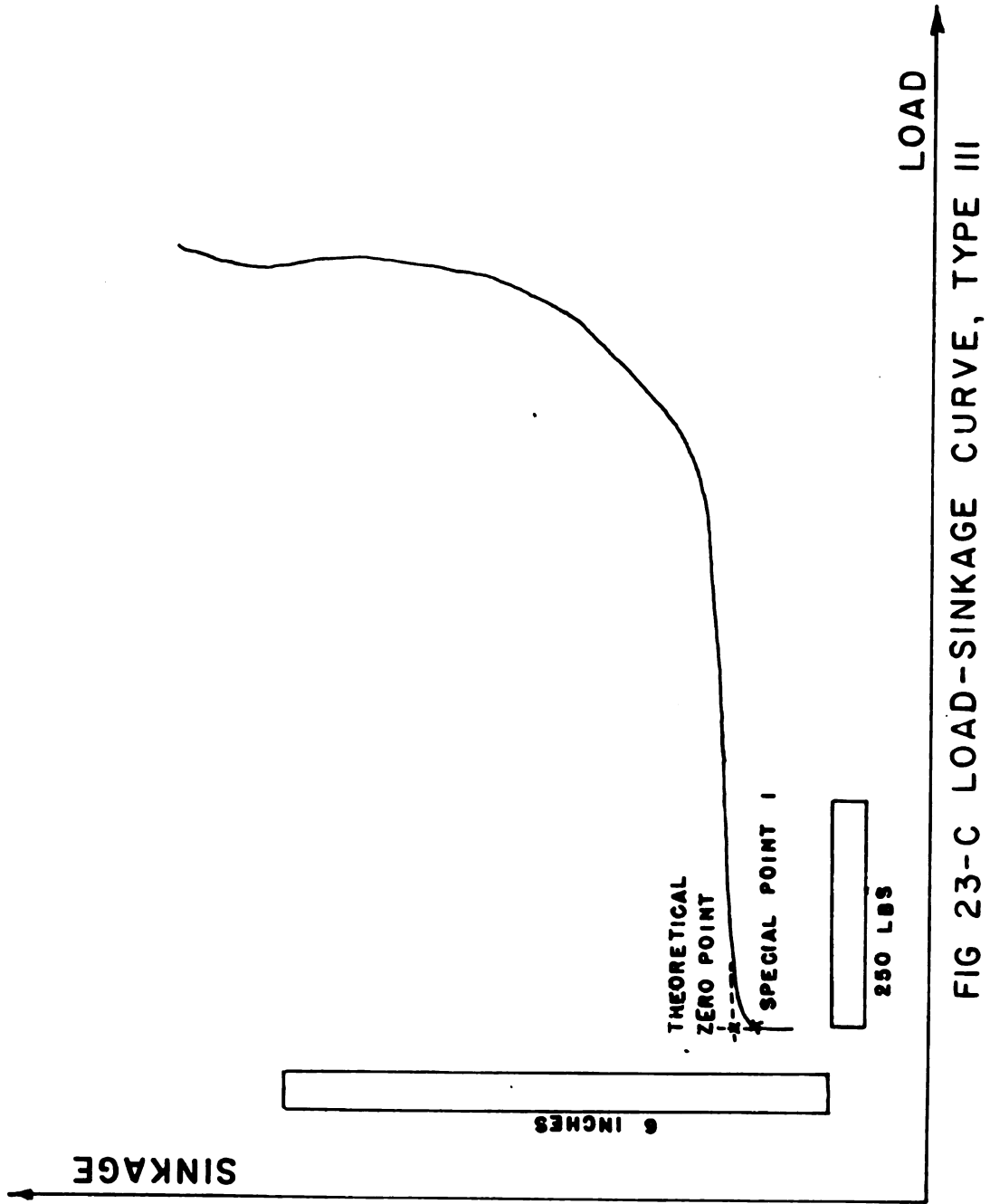


FIG 23-b LOAD-SINKAGE CURVE, TYPE II



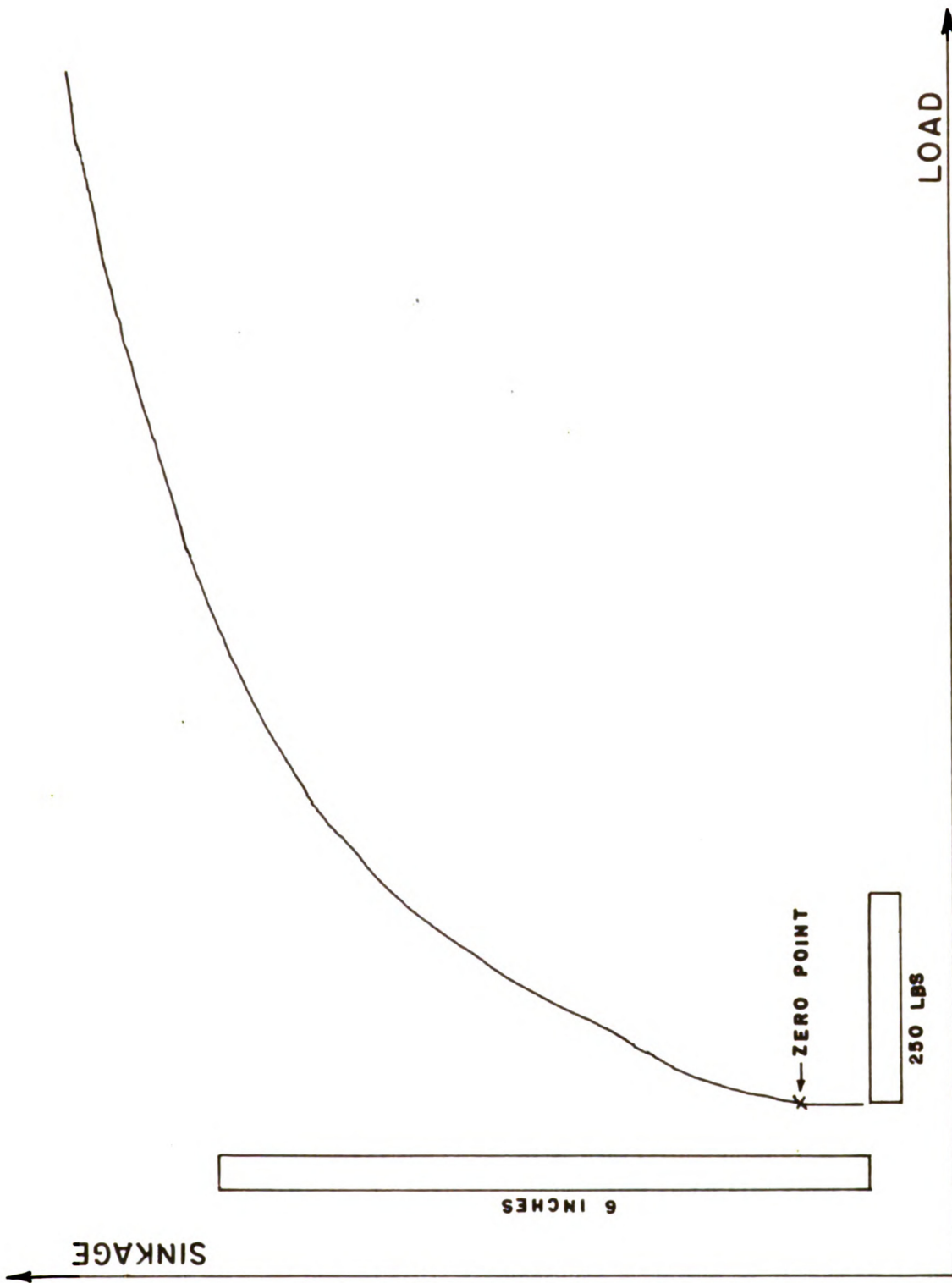


FIG 23-d LOAD-SINKAGE CURVE, TYPE IV

Table II. Arrangement of Primary Load-sinkage Data.
Card Deck No. 01

Column	Variable	Description of the Variable
1	X(1)	Site 1. Soil science farm, M.S.U., East Lansing. 2. Ballantine Road, 10 miles north of East Lansing. 3. Riga, Lenawee County, Michigan.
2	X(2)	Surface 1. Sod 2. Planted with corn 3. Plowed 4. Plowed plot before plowing
3	X(3)	Period 1. Summer, 1963 2. Fall, 1963
4	X(4)	Row in plot Three rows -- 1, 2, and 3
5	X(5)	Column in plot Three columns -- 1, 2, and 3
6, 7	X(6)	Depth 1. Surface (Sod, Planted, and Plowed) 2. Surface, plowed and treated by cultivator 3. 3 inches depth 10. 10 inches depth
8	X(7)	Test Code Number 1. Load-sinkage test 2. Shear test
9	X(8)	Penetrometer Dimension 1-6. 1"-6" dia. plates 9. Cone, 30 deg. and 1/2 in.² base area.

Continued

Table II - Continued

Column	Variable	Description of the Variable
10	X(9)	Replication Four replications--1, 2, 3, and 4
11	X(10)	Type of curve 1. As shown in Fig. 23-a 2. As shown in Fig. 23-b 3. As shown in Fig. 23-c 4. As shown in Fig. 23-d
12, 13, 14	X(11)	**Calibration sinkage
15, 16, 17	X(12)	Deflection for calibration sinkage
18, 19, 20	X(13)	Deflection for 250 lbs. calibration force
21, 22	X(14)	Deflection for Sinkage, special point 1
23, 24, 25	X(15)	Sinkage } special point 2
26, 27, 28	X(16)	Force } special point 2
29, 30	X(17)	Sinkage } point 1
31, 32	X(18)	Force } point 1
33, 34	X(19)	Sinkage } point 2
35, 36	X(20)	Force } point 2
37, 38, 39	X(21)	Sinkage } point 3
40, 41, 42	X(22)	Force } point 3
43, 44, 45	X(23)	Sinkage } point 4
46, 47, 48	X(24)	Force } point 4
49, 50, 51	X(25)	Sinkage } point 5
52, 53, 54	X(26)	Force } point 5

** Variables X(11) to X(32) are measured in millimeters.

Continued

Table II - Continued

Column	Variable	Description of the Variable
55, 56, 57	X(27)	Sinkage
58, 59, 60	X(28)	Force
61, 62, 63	X(29)	Sinkage
64, 65, 66	X(30)	Force
67, 68, 69	X(31)	Sinkage
70, 71, 72	X(32)	Force
79, 80	---	Card Deck No. 01

The transformation relations and the arrangement of calculated data are presented in Table III.

Table III. Arrangement of Transformed Data
Card Deck No. - 02

Column	Variable	Description of the Variable
1 to 11	Identification number	Repeated from card 01
12, 13, 14	$X(33) = \frac{X(14)*X(11)}{X(12)}$	† Sinkage, special pt. 1
15, 16, 17	$X(34) = \frac{X(15)*X(11)}{X(12)}$	Sinkage
18, 19, 20, 21	$X(35) = \frac{X(16)*113.5}{X(13)}$	Force
22, 23, 24	$X(36) = \frac{X(17)*X(11)}{X(12)}$	Sinkage
25, 26, 27, 28	$X(37) = \frac{X(18)*113.25}{X(13)}$	Force

† Sinkage in millimeters, and force in kiloponds.

Continued

Table III - Continued

Column	Variable	Description of the Variable	
29, 30, 31	$X(38) = \frac{X(19)*X(11)}{X(12)}$	Sinkage	} point 2
32, 33, 34, 35	$X(39) = \frac{X(20)*113.25}{X(13)}$	Force	
36, 37, 38	$X(40) = \frac{X(21)*X(11)}{X(12)}$	Sinkage	} point 3
39, 40, 41, 42	$X(41) = \frac{X(22)*113.25}{X(13)}$	Force	
43, 44, 45	$X(42) = \frac{X(23)*X(11)}{X(12)}$	Sinkage	} point 4
46, 47, 48, 49	$X(43) = \frac{X(24)*113.25}{X(13)}$	Force	
50, 51, 52	$X(44) = \frac{X(25)*X(11)}{X(12)}$	Sinkage	} point 5
53, 54, 55, 56	$X(45) = \frac{X(26)*113.25}{X(13)}$	Force	
57, 58, 59	$X(46) = \frac{X(27)*X(11)}{X(12)}$	Sinkage	} point 6
60, 61, 62, 63	$X(47) = \frac{X(28)*113.25}{X(13)}$	Force	
64, 65, 66	$X(48) = \frac{X(29)*X(11)}{X(12)}$	Sinkage	} point 7
67, 68, 69, 70	$X(49) = \frac{X(30)*113.25}{X(13)}$	Force	
71, 72, 73	$X(50) = \frac{X(31)*X(11)}{X(12)}$	Sinkage	} point 8
74, 75, 76, 77	$X(51) = \frac{X(32)*113.25}{X(13)}$	Force	
79, 80	-----	Card Deck No. 02	

The transformed data can be used to evaluate the soil strength parameters from the particular measurement, and in statistical programming for correlations with soil classification.

(b) Shear Test Data

Typical torque-time curves are shown in Fig. 24-a, b. The points of interest are noted thereon. The coordinates of these points are also measured in millimeters, and punched on data cards. Arriving at the transformation relations for calculating normal stress, shear stress, and soil deformation are shown below:

(i) Normal Stress

Normal load X(8)

True normal load = $\{X(8)*20 - 4\}$ lbs.

Annular shear ring area 131 cm.²

$$\begin{aligned}\text{Normal stress} &= \frac{\text{Normal load}}{\text{Shear ring area}} = \frac{\{X(8)*20 - 4\} \cdot 0.4536}{131} \\ &= \{X(8)*20 - 4\} \cdot 0.00358 \text{ Kp/cm.}^2\end{aligned}$$

(ii) Shear Stress

From Chapter II, section (c)

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

where S is shear stress

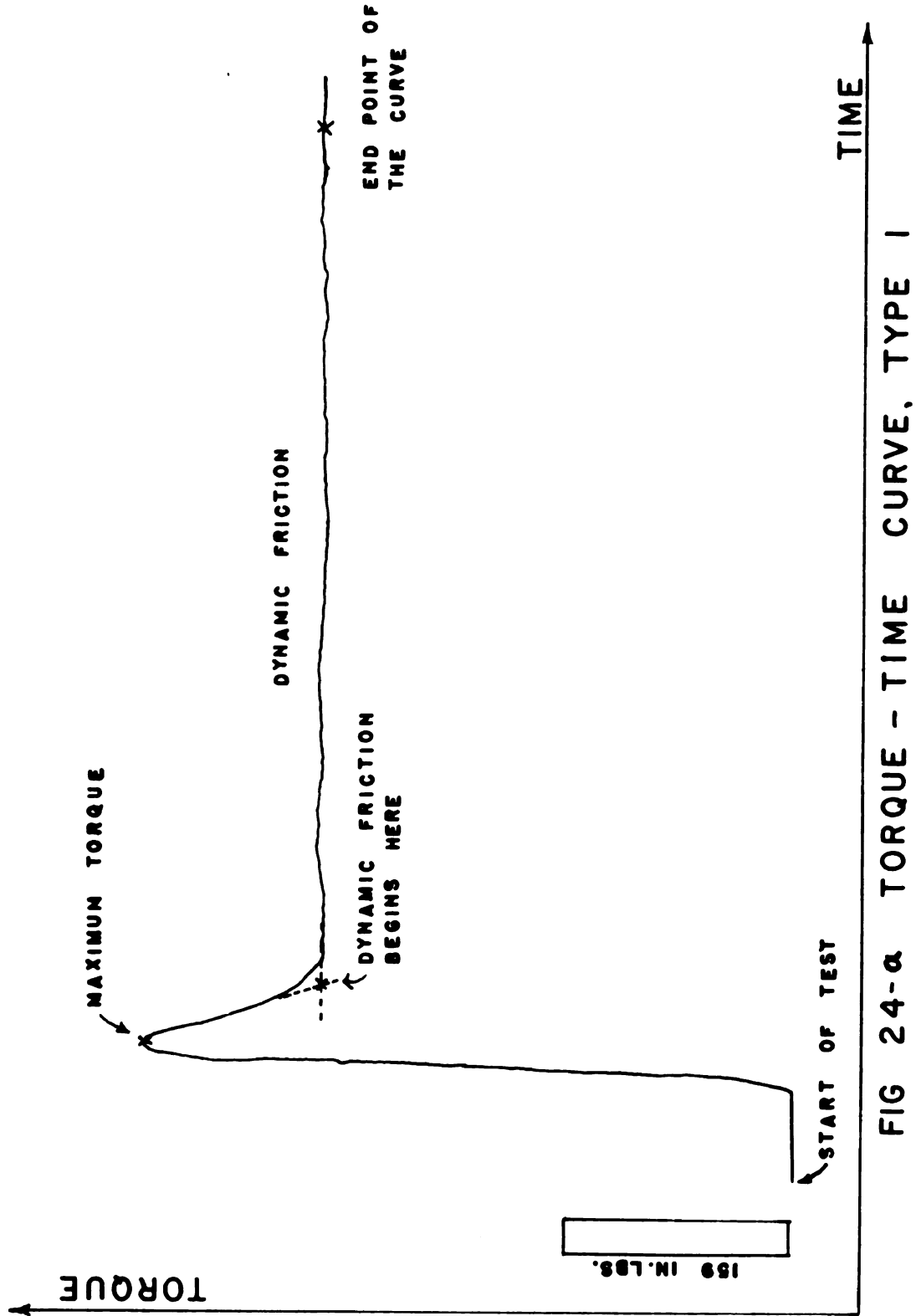
M is torque applied

r_1 is inside diameter of the ring, 6.6 cm.

r_2 is outside diameter of the ring, 9.2 cm.

Substituting for r_1 and r_2 in the above equation yields

$$S = \frac{3M}{3042} \text{ Kp/cm.}^2$$



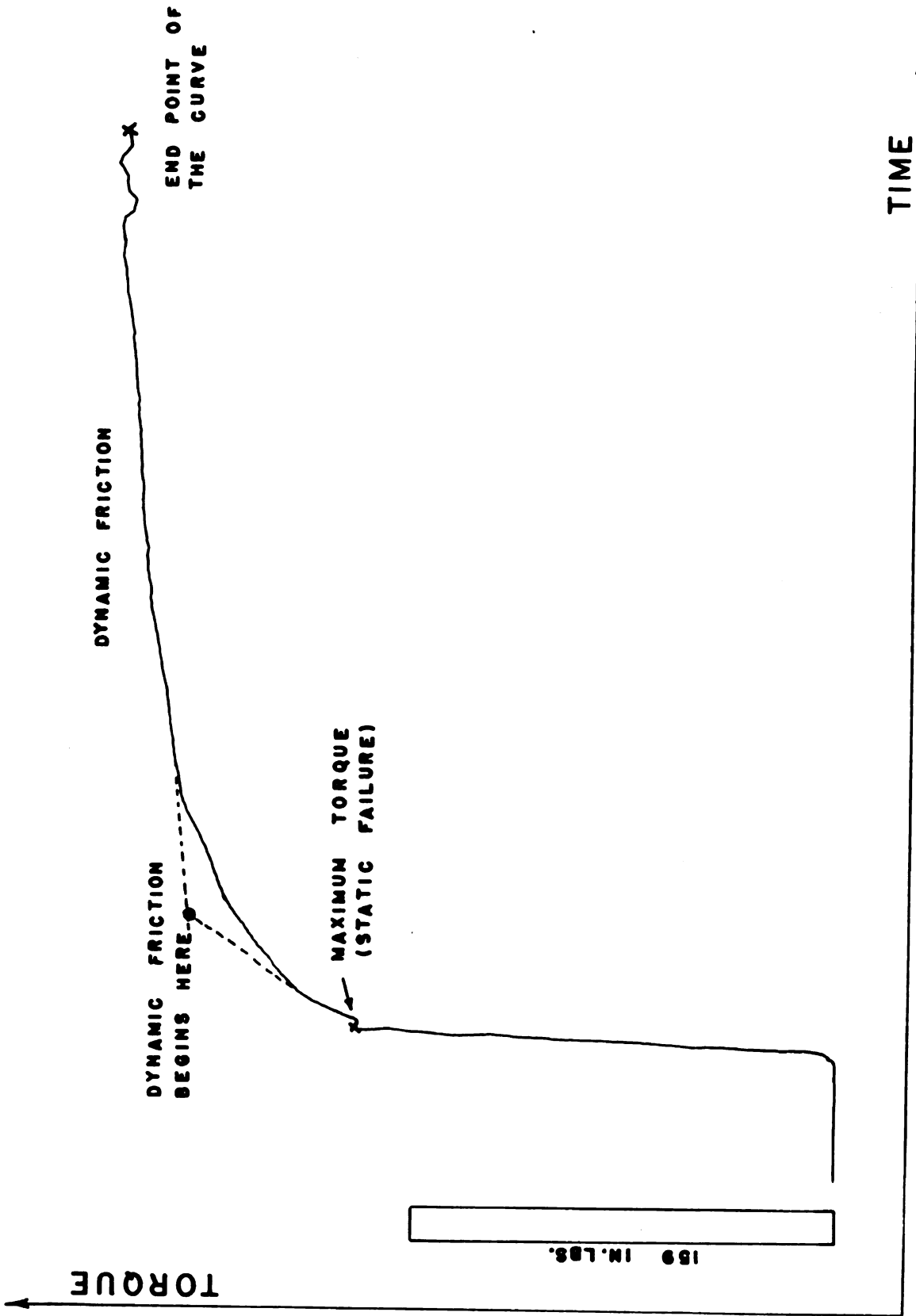


FIG 24-b TORQUE - TIME CURVE, TYPE II

X(11) mm. on chart represents 159 in. lb. calibration torque.

X(12) mm. is the deflection corresponding to maximum torque.

Therefore,

$$M = \frac{X(12)*159}{X(11)} \text{ in.lb.} = \frac{X(12)*159*2.54*0.4536}{X(11)} \text{ Kp.cm.}$$

Substituting for M in the expression for shear stress,

$$S = \frac{X(12)*0.181}{X(11)} \text{ Kp./cm.}^2$$

(iii) Soil Displacement

Average circular displacement of the shear ring, measured at the center of the annular width = 0.91 in./sec.

Pen displacement on the chart at recorder attenuation 2 is . . .

$$. = 0.475 \text{ in./sec.}$$

Time deflection on the chart at max. torque = X(13) mm.

$$\text{True displacement of the soil} = \frac{X(13)*0.91}{0.475} = X(13)*1.916 \text{ mm.}$$

In the case of shear test data both the basic data and the transformed data are punched on the same card. The arrangement of the data and the transformation relations are shown in Table IV.

Table IV. Arrangement of Primary and Transformed Shear Test Data
Card Deck No. 04

Column	Variable	Description of the Variable
		Identification:
1	X(1)	Site
2	X(2)	Surface
3	X(3)	Period
4	X(4)	Row in plot
5	X(5)	Column in plot
6, 7	X(6)	Depth

Continued

Table IV - Continued

Column	Variable	Description of the Variable
8	X(7)	Test code No.
9	X(8)	Normal load 1. Self weight of the shear head assembly, 16 lbs. 3. Two weights, each weighing 20 lbs. 9. Eight weights each weighing 20 lbs.
10	X(9)	Replication
11	X(10)	Type of curve 1. As shown in Fig. 24-a 2. As shown in Fig. 24-b
<u>Deflections on chart in mm.</u>		
12, 13, 14	X(11)	Deflection for 159 in. lb. torque
15, 16, 17	X(12)	Maximum torque deflection
18, 19, 20	X(13)	Deflection on time axis corresponding to X(12)
21, 22, 23	X(14)	Torque deflection at the beginning of dynamic failure
24, 25, 26	X(15)	Deflection on time axis corresponding to X(14)
27, 28, 29	X(16)	Torque deflection at the end of the dynamic portion of the curve
30, 31, 32	X(17)	Deflection on time axis corresponding to X(16)
33, 34, 35		Blank

Continued

Table IV - Continued

Column	Variable	Description of the Variable
		<u>True normal and shear stresses in kp./cm², and soil displacement in mm.</u>
36, 37, 38	$X(18) = [X(8)*20 - 4]$	0.00358 Normal stress
39, 40, 41, 42	$X(19) = \frac{X(12)*0.181}{X(11)}$	Max. shear stress
43, 44, 45	$X(20) = X(13)*1.916$	Soil displacement corresponding to X(19)
46, 47, 48, 49	$X(21) = \frac{X(14)*0.181}{X(11)}$	Shear stress at the beginning of dynamic failure
50, 51, 52	$X(22) = X(15)*1.916$	Soil displacement corresponding to X(21)
53, 54, 55, 56	$X(23) = \frac{X(16)*0.181}{X(11)}$	Shear stress at the end of the dynamic portion of the curve
57, 58, 59	$X(24) = X(17)*1.916$	Soil displacement corresponding to X(23)
60, 61, 62		Blank
		<u>Soil Constants</u>
63, 64, 65, 66	$X(25) = \frac{X(14)}{X(12)}$	Ratio of shear stresses at static and dynamic failures
67, 68, 69, 70	$X(26) = \frac{[X(16) - X(14)]*0.181}{[X(17) - X(15)]*0.1916*X(11)}$	Shear force per unit volume, kp./cm ³
79, 80		Card deck No. 04

Identification code is same as for load-sinkage test data except for X(8) and X(10). The code used for these variables are given against X(8) and X(10) in the table.

The transformed data from Table IV can be used to evaluate c and ϕ , and in statistical programming for correlations with soil classification maps.

DISCUSSION

(a) Instrumentation and Procedure

The procedure nearly met the requirements for fast collection of soil-value data on a large scale. The major difficulties faced during the tests in the field were vertical movement of the bevameter frame relative to the penetrometer plate, and failure of the recorder in cold and wet weather. When the soil under penetrometer plate did not yield after reaching a certain point the bevameter frame moved vertically causing an error in sinkage measurement. Humidity and cold affected the recorder components. The recording pen, in a number of instances, did not respond to the control knobs, and when responded the calibration deflection was erroneous. On time base the movement of carriage was sluggish and inconsistent.

Efforts were made to overcome the difficulties mentioned above. Vertical movement was reduced by adding a hydraulic cylinder between the tractor and bevameter frame. Complete elimination of this movement was not possible because of the position of the bevameter and limited tractor weight. A vertical movement of about $1/4$ to $1/2$ inch was found in most of the cases. The portion of the curve recorded during the vertical movement of the bevameter was eliminated in data processing. The recorder was made to work by insulating the recorder housing with cardboard and cotton rags. The air blown by the cooling fan of the recorder motor is kept circulated within the bottom of the recorder by properly closing the side gaps thus keeping the recorder surroundings warm.

Other difficulties encountered were in dusty conditions. Accumulation of dust in the recorder vacuum pump, and in the vertical bearing of the shear head shaft considerably delayed the normal work a couple of times during the test series (June-December, 1963). The vacuum pump which helps to hold the recording chart to the platten was put out of function, and adhesive tape was used for that purpose. Fastening and removing of recording chart from the platten time and again consumes additional time. Dust in the shear head shaft bearing causes holding of the shear head from completely contacting the soil surface, thus resulting in decreased torque.

(b) Load-sinkage Curves

The abrupt change in slope of the load-sinkage curve as shown in Fig. 20-a might be due to the existence of a soil layer with a higher bulk density below the region of special point 'two'.

Type II curve (Fig. 20-b) seems to be the most general type obtained in a homogeneous soil medium. However, there have been differences in end values in this type.

Type III curve (Fig. 20-c) suggests a high moisture content, and existence of voids in the sub-soil. Non-homogeneity of soil profile, in general, could be the cause of such character.

Type IV curve (Fig. 20-d) appears to be characteristic of plowed soil. If the load-sinkage curve at the same spot obtained before plowing is superposed on the curve obtained after plowing the difference in curvature can be clearly seen. It shows that at the same pressure higher sinkage occurs in loose soil than in compacted soil, as expected. It might be concluded from this that a particular soil compaction could exist in nature where sinkage varies nearly proportionally with

pressure. This casts doubt on the validity of Bekker's load-sinkage equation for soils in natural condition.

(c) Torque-displacement Curves

When shear tests were performed in plowed soil the shear head sank almost as much as 4 inches deep depending on the normal load. This could be one of the causes for increasing slope of the torque-displacement curves beyond the point of peak torque (Fig. 24-b). The curve shown in Fig. 24-a is very common in compact soils.

SUMMARY

A procedure for measuring soil strength values in the field at an increased rate of measuring was developed.

A bevameter, an instrument used for measuring soil strength values, was redesigned and constructed. This instrument rests on two adjustable feet, and is carried on the three-point hitch of the tractor. This feature is advantageous in that the instrument can be positioned to conform the shear head and penetrometer plate parallel to the soil surface by adjusting the top link of the three-point hitch. Vertical movement of the bevameter frame during the test was considerably reduced by transferring as much of the tractor weight as possible onto the frame by means of a hydraulic cylinder connected between the tractor drawbar and the bevameter frame.

Load and torque in the load-sinkage and shear tests respectively were provided hydraulically using the tractor hydraulic system. Penetration forces up to 1900 lbs. (860 kiloponds) and shearing torques up to 820 in. lbs. (942 cm-kp) were developed in the instrument. Strain gage transducers were used for measuring load and torque. A linear micropotentiometer was used for measuring sinkage. The results of load-sinkage and torque-time tests were recorded directly on an X-Y recorder. The torque-time relation was later converted to shear stress vs. displacement relationship using calibration information.

An important feature of the procedure was performing the tests at a considerable speed. Tests were performed at an average rate of 28 tests (12 shear tests and 16 penetration tests) per hour, which means one plot under a sub-treatment took one hour for running the complete series of tests. In the three selected sites about 1700 tests were run

during summer 1963. The operation of the bevameter needed the service of two men, one for recording the tests and driving the tractor, the other for operating the shear head and penetrometer.

As a scale factor was involved in the curves obtained from load-sinkage and shear tests, true values of load, sinkage, shear stress, normal stress, and soil displacement were calculated on data processing machines through transformation relations. The transformation relations were so programmed as to draw correlations between soil types and soil strength values in future.

Preliminary data from the tests indicated that load-sinkage relationship cannot be represented by a single expression as in Bekker's soil value system. More than one expression seems to be necessary to represent the entire load-sinkage curve. Final results of the processed data are to be given in another dissertation.

SUGGESTIONS FOR FUTURE CHANGES

The equipment should be changed so as to obtain greater penetration forces without lifting the tractor, because in some instances penetrometer plates larger than 3 in. diameter did not sink deep enough when the soil is in undisturbed condition. To reduce sinkage of shear head in loose soils a larger shear head should be used.

The instrumentation should be so modified as to facilitate alternate recording of penetration and shear tests. This will reduce the time lapse between the penetration and shear tests at any one spot.

Soil strength parameters should be evaluated in parallel with the recording of basic data. This could be done by using logarithmic transformers before the X-Y recorder.

Devices for easier and more uniform preparation of soil surface should be made.

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