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PENETRATION TESTS FOR SOIL MEASUREMENTS

**ARMY ENGINEER WATERWAYS EXPERIMENT STATION
VICKSBURG, MISSISSIPPI**

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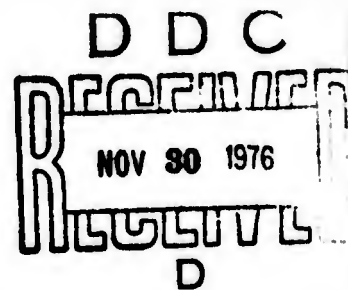
by

D. R. Freitag

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FOREWORD

This paper discusses results of tests conducted at the U. S. Army Engineer Waterways Experiment Station (WES) under the sponsorship and guidance of the Directorate of Research and Development, U. S. Army Materiel Command, as part of DA Project 1-V-J-21701-A-046, "Trafficability and Mobility Research." The tests were conducted by personnel of the Mobility and Environmental Division, WES, under the supervision of Messrs. W. J. Turnbull, W. G. Shockley, and S. J. Knight.

The paper was presented at the 1967 Winter Meeting of the American Society of Agricultural Engineers, at Detroit, Mich., 12-15 December 1967, as Paper 67-652.

PENETRATION TESTS FOR SOIL MEASUREMENTS

by

D. R. Freitag*

Trafficability studies have been conducted at the U. S. Army Engineer Waterways Experiment Station (WES) since 1945, when it was determined that a method was needed for assessing the ability of soil to withstand the traffic of military vehicles. Of primary concern in the earliest studies was the development of an instrument, or instruments, that could measure the strength of a soil over which military commanders would have to deploy their forces. The present WES cone penetrometer (fig. 1) was developed in 1948.¹ Since then, thousands of tests with the cone penetrometer have been made on various types of surface media around the world.

The principal objective of this paper will be to emphasize two things: (a) that penetrometers are extremely useful devices, and (b) that they do have limitations. When used in a knowledgeable way, the simple penetration test is a surprisingly accurate and efficient means of measuring the in-place strength of soils. Many measurements can be made rapidly at the surface and at some depths below the surface. The limitations of the test can readily be accepted for many applications, but, in others, the necessary restrictions may seriously curtail the use of penetrometers. An awareness of the factors that can affect the interpretation of the results of penetration tests should be useful in deciding whether such a device should be used in a particular research program.

Basically, a penetrometer is a very simple device--a sort of calibrated index finger. It is very easy to visualize a blunt stick or a finger being used to detect in a general, qualitative way the consistency of a mass of some material. By addition of some means of providing a quantitative determination, a penetrometer is devised. This quantitative determination is the unit force (usually in pounds per square inch of the base area) required to displace the test material beneath the probe.

Usually, a penetrometer is thought of as being used in relatively soft, yielding materials, but, in fact, penetrometers have been used on a variety of materials ranging from moderately viscous fluids to rather firm solids, such as soil, asphalt, snow, baker's dough, and cheese. The hardness test of metals, which measures an indentation caused by a standard pressure or impact, is also a type of penetration test. Penetrometers commonly are used when the mass whose consistency must be measured is so heterogeneous that many measurements must be taken to get a statistical average, or when materials are so complex rheologically that practical means of evaluating their stress-strain-time properties are not available.

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Penetrometer tests fall into two general classes according to the type of load applied. These are (a) the constant-rate-of-penetration test, and (b) the impact-loading test. For the constant-rate type, the force required to maintain a steady rate of penetration is considered to be the measure of the consistency of the soil. In these tests, the penetrometer has the very important ability to make measurements continuously with depth. In the impact-loading test, the energy stored in a spring or in a weight at a known higher elevation is used to drive the penetrometer into the soil. The depth of penetration achieved by the application of the fixed amount of energy is used as the measure of the soil consistency; however, to detect and measure variation in soil consistency with depth is difficult. This disadvantage has restricted the use of this test by WES to rather special applications, and tests of this type will not be discussed further in this paper.

Attempts to describe theoretically the penetration resistance of a cone in terms of soil stress-strain properties have not been particularly successful. Most theoretical studies have considered long, flat, loaded areas on the surface of the soil. None of the theories advanced appear to be particularly applicable to circular areas, to cone-shaped bases, or to areas at relatively great depths (i.e. width/depth ratios much greater than one). Also, these analyses have been oriented toward the static bearing capacity of footings, and have not considered dynamic effects. Thus, while the theories are of some assistance in understanding the nature of the penetration test, they do not provide any solutions that are directly applicable. Therefore, it is necessary to rely heavily on experimentation and accumulated practical experience to interpret the cone penetration test results.

The shear strength of soils commonly is considered to be composed of two components, cohesion and friction, with the function relation expressed by the Coulomb equation, $S = c + p \tan \phi$. If this is accepted as a basis and the cone penetrometer test examined on these terms, it is immediately apparent that the cone index does not differentiate between cohesion and friction. The results of tests made in two fine-grained soils are shown in fig. 2 to illustrate this fact.² These two soils derive most of their apparent strength from cohesion, but for some conditions, a significant frictional component is evident. The average cone penetration resistance, or cone index, for soil samples compacted in molds has been located relative to the cohesion and friction axes on the basis of unconsolidated-undrained triaxial shear test data obtained on samples similarly compacted. The numbers beside the points show the average cone index at that particular combination of cohesion and friction. It is apparent that a given cone index can be attained with many different combinations of cohesion and friction.

If it is imperative that both cohesion and friction be known, the indeterminacy of the simple penetrometer test appears to present an insurmountable obstacle. However, in many practical cases, either the parameters can be determined or estimated by some other means, or separation of the two parameters is not necessary. Where one of these cases is true, the penetrometer can be of direct usefulness.

The first case is well illustrated in the trafficability and mobility studies carried on at WES. In most of this work, fine-grained soils are very soft and nearly saturated. In this state, the effective friction angle is zero or nearly so, and the shear strength-cone index relation can be reduced to essentially a two-parameter one. The same data for which cone index contours were drawn in fig. 2 are shown in fig. 3 as a plot of cone index versus cohesion with the friction angle, when it was not zero, recorded beside the plotted point. A very strong correlation was obtained between cohesion and cone index when the friction angle was near zero (approximately 2 deg or less). The remainder of the test results are displaced from this basic relation generally in proportion to the magnitude of the friction angle. This relation shows that whenever a strength measurement is needed in a wet, fine-grained soil whose friction angle can be considered zero, the cone penetrometer can provide all the needed information with considerable accuracy.

Relations, similar to those for fine-grained soils, probably could be developed among cohesion, friction angle, and cone index for sand at various moisture contents and densities. This has not been done to date, partly because there is a lesser interest in a broad variety of moisture conditions in sand, but also because preparation of closely similar samples of sand for penetrometer and triaxial tests is difficult. Those relations that have been developed are for air-dry sand for which the cohesion parameter was small enough to be ignored. In this case, the cone penetrometer data were interpretable in terms of the friction angle. The relation between cone index and friction angle could not be developed directly, because triaxial test samples could not be obtained from a mass of dry sand. Two intermediate steps were required: (a) relating cone index and bulk density of a mass of soil, and (b) relating friction angle and bulk density for the specially prepared triaxial samples. These relations are shown in figs. 4 and 5, respectively.³ It is apparent that the penetrometer can be used to make meaningful measurements of the pertinent strength parameters of air-dry sand.

An example of the second case might be the use of the penetrometer readings to detect changes in an unsaturated soil due to the compaction of traffic. The principal need here is to obtain relative evaluations, which can be done conveniently with the penetrometer. A good example of the use of relative measurements is given in a paper by McLeod et al,⁴ in which the width and depth of zones of compacted soil were determined for various intensities of load application. In this case, the penetrometer measurements also reflected the relative intensity of the applied compaction pressure.

Another case involving the use of a penetrometer for nonquantitative evaluation of soil compaction is shown in fig. 6. It is well known that the mechanical properties of a soil mass can change drastically, because of structural reorientation, if the soil is "overcompacted." In fig. 6, the cone penetrometer was used as a means of detecting this change. The compaction energy was applied in increments, and the penetration resistance of the soil was measured after each increment. The onset of the reorientation is readily apparent in the penetration test results.

Since the penetrometer test data presented to this point were obtained with a standard WES cone penetrometer, it is appropriate that inquiry be made as to the extent to which the results are dependent upon the configuration of this particular penetrometer and the manner in which the test is run. If variations in these factors can cause large variations in the test results, it becomes very important that a set of carefully prescribed standards be established, so that data from various sources can be used interchangeably. Some of the features that could influence the test data are: the size of penetrometer shaft relative to the cone size, the surface finish of the cone, the size and shape of the cone, and the rate of penetration. Each of these factors is examined in the following discussion to the extent of the data available.

The size of the penetrometer shaft relative to the diameter of the cone can influence the results of the test in two ways. The soil displaced by the passage of the cone tends to move outward and upward and to press into the opening in the soil left by the cone. If the shaft is relatively small, the pressure relief will tend to reduce the penetration resistance. On the other hand, if the shaft has nearly the same diameter as the cone, the drag of the soil on the shaft could cause an apparent increase in penetration resistance. Very few data exist on the influence of shaft size purely from the standpoint of pressure relief, but the evidence does support the statement made. The effects of shaft drag have been examined in more detail. It has been found that, except for soft, sticky clays, the friction of soil on the shaft is insignificant. The results of two penetration tests made with the WES cone penetrometer in soft clay are shown in fig. 7.² In the case of the 5/8-in. shaft, the increase in penetration resistance at a depth of about 6 in. is believed due to the adhesion of the soil to the shaft. The use of the 3/8-in. shaft avoids the shaft drag problem for penetration depths of at least 1 ft. Placing the force-measuring device at the base of the cone theoretically would be an even better solution, but the instrumentation problems would be significant.

Some critics have expressed the opinion that the WES cone penetrometer with its smooth finish and narrow, pointed apex angle was more apt to measure soil-metal friction than the strength parameters of the soil. To study the effect of surface roughness, a few tests were performed with a standard cone and a standard cone to which a thin sprinkling of sand had been glued. In fine-grained soils, the rough-surfaced cone consistently experienced 5 to 10 percent higher penetration resistance and, when removed, had a layer of soil adhering to its surface. This would seem to indicate that the rough surface indeed had some effect. However, the thickness of the glued sand layer plus the adhering clay was approximately great enough to account for the increased resistance in terms of the slightly larger projected base area. In sand, the rough-cone penetration resistance was 15 to 20 percent higher than for the smooth cone. This increase seems to be too large to be the result of a simple increase in base area caused by adhering sand.

To examine this problem further, tests were conducted with cones of equal base area and same surface finish, but with several different apex angles. The data obtained with cones having 90- and 30-deg apex angles

appear to represent the test results reasonably well. The 30-deg angle cone has almost three times the surface area of the 90-deg cone, so there should have been a large difference in the penetration resistance if soil adhered along the cone surface. In clay, the difference was again found to be about 10 percent or less, so the surface area could not be considered a major factor in the cone index results.

In sand, the penetration resistance, per unit base area, of a 90-deg smooth cone was slightly greater than that of a 30-deg smooth cone. However, when rough-surfaced cones were used, the 30-deg cone had 1-1/2 to 2 times the penetration resistance (per unit base area) of the 90-deg cone. The relatively large difference, although less than proportional to the surface areas, and the reversal in the relative magnitude of the pressures suggest that surface friction and cone apex angle do indeed influence the results of the cone penetration tests in sand. Further study of these factors needs to be done.

The actual size of the cone can influence the magnitude of the penetration resistance, even when the resistance is expressed in terms of the force per unit area. The penetration resistances in pounds per square inch, measured in a wet, fine-grained soil with a number of cones of similar shape but of various base diameters, are shown in fig. 8. The resistance per unit area was greatest for the smallest cone and smallest for the largest cone. While the differences are not great for cones of the sizes generally used for soil tests, it is apparent that if the test results from a small bearing area are used to estimate the pressures that could be expected under a much larger area, size must be taken into account.

Tests have shown that the rate at which the cone penetrates the soil can affect the pressure required to cause the penetration. The general relation obtained in a wet, fine-grained soil is shown in fig. 9. (The ordinate, indicating the strength of the soil, has been expressed in terms of the ratio of the penetration resistance of the standard 0.5-sq-in. cone penetrating at 72 in./min to the penetration resistance of the same cone at a different rate as indicated.) The penetration resistance is relatively low at slow speeds, but appears to increase rapidly as the speed of penetration increases. At the upper end of the curve the trend appears to level off again. Similar tests in sand showed little or no speed effects other than those that could be accounted for in terms of pure inertia effects.

The generally opposite trends in the relation between penetration resistance and size and between penetration resistance and speed suggested a common basis. It was found that when the ratio of speed to cone diameter was used as a basis, a single relation developed for all speed and cone-size combinations. A relation of this type is shown in fig. 10. (The strength ratio in this figure includes diameter as a variable, but all the cones used to develop this relation were 30-deg cones.) This analysis is now being used as the beginning point of a more thorough study of the rheological behavior of wet, fine-grained soil. Thus, it appears that in addition to

being a very useful field instrument and a test device for some of the more simple soil conditions, the cone penetrometer may provide the basis for a basic in-depth study of a very complex material.

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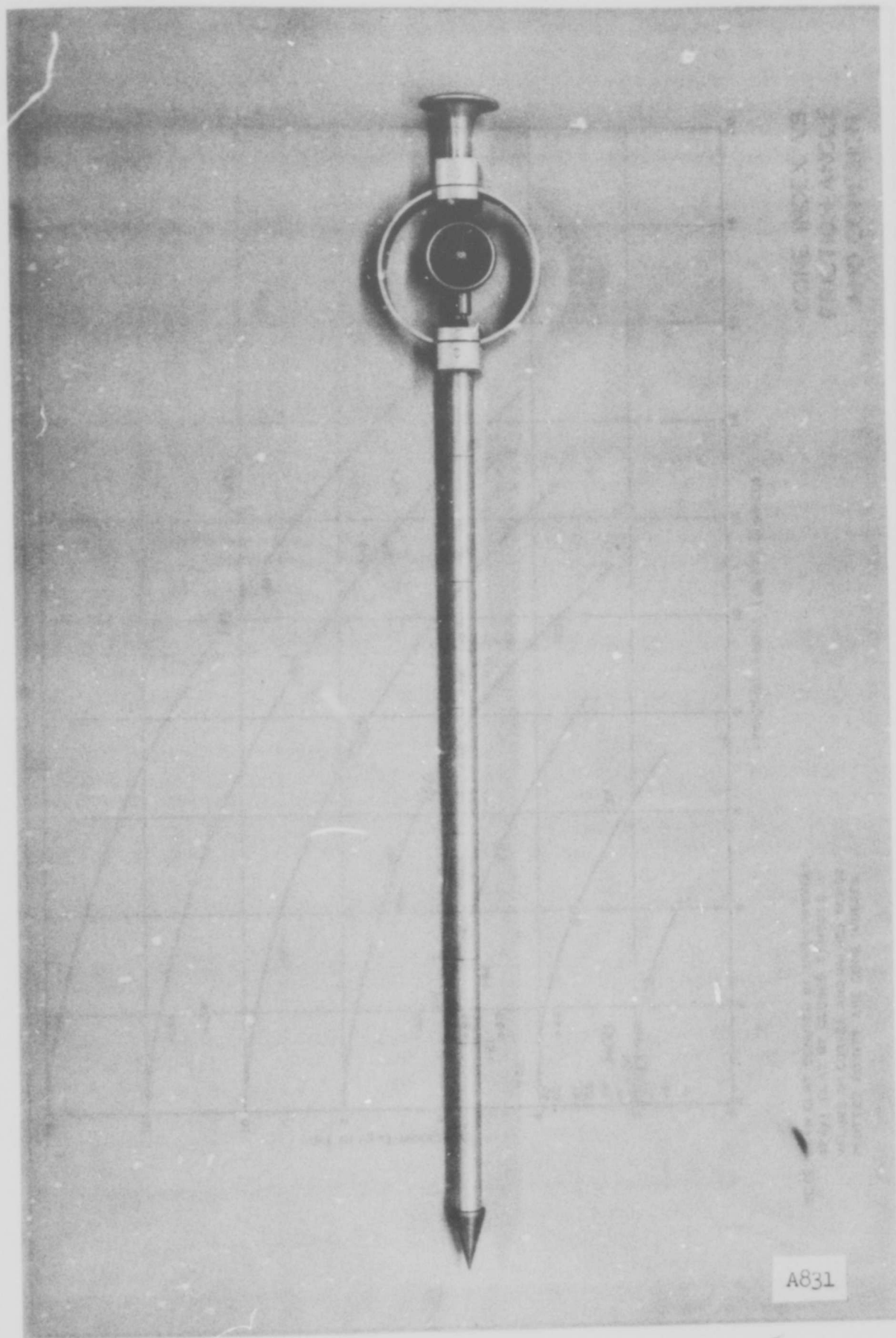
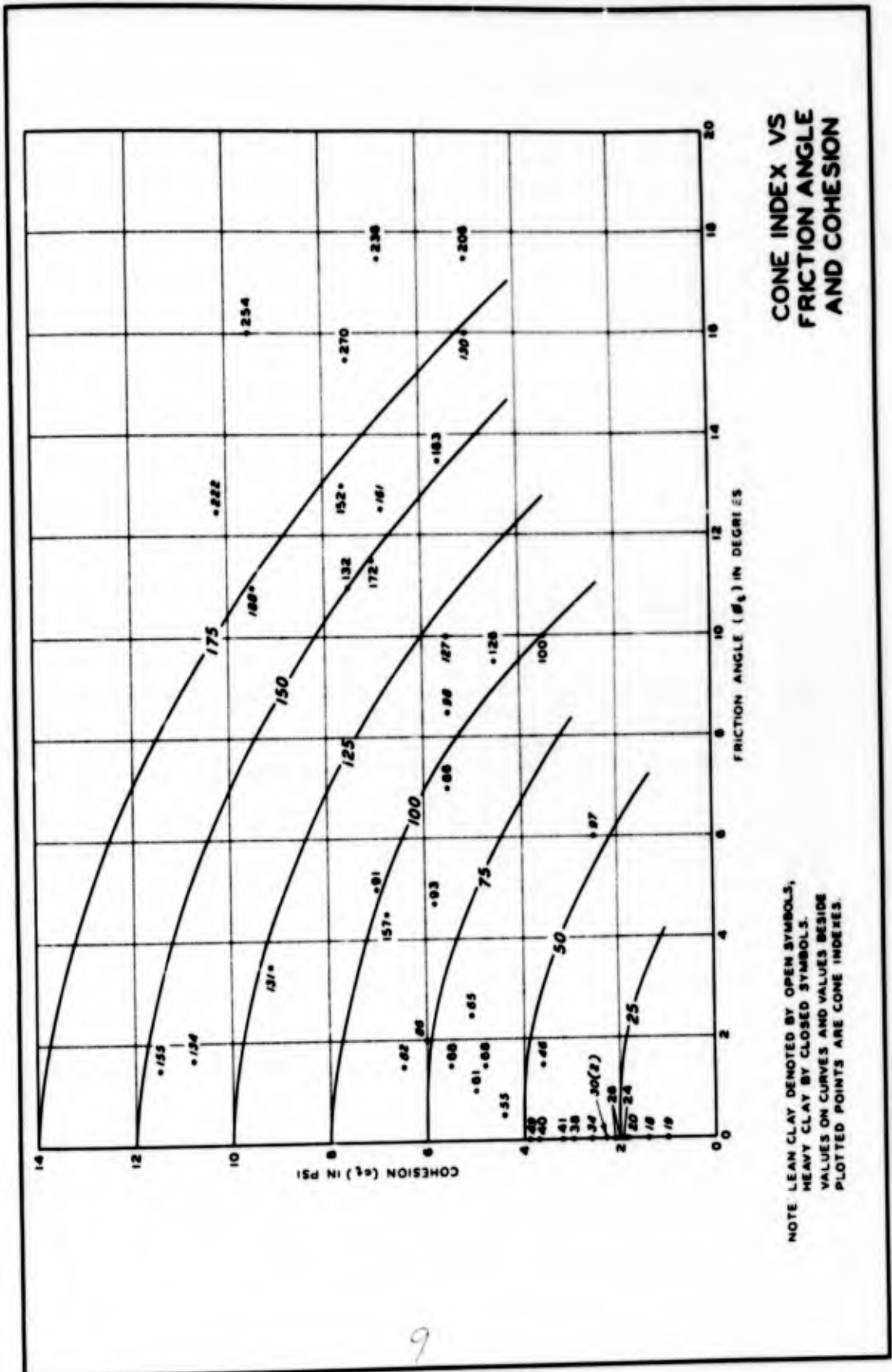


Fig. 1. Cone penetrometer



**CONE INDEX VS
FRICTION ANGLE
AND COHESION**

NOTE LEAN CLAY DENOTED BY OPEN SYMBOLS,
HEAVY CLAY BY CLOSED SYMBOLS.
VALUES ON CURVES AND VALUES BESIDE
PLOTTED POINTS ARE CONE INDICES.

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FIG. 2

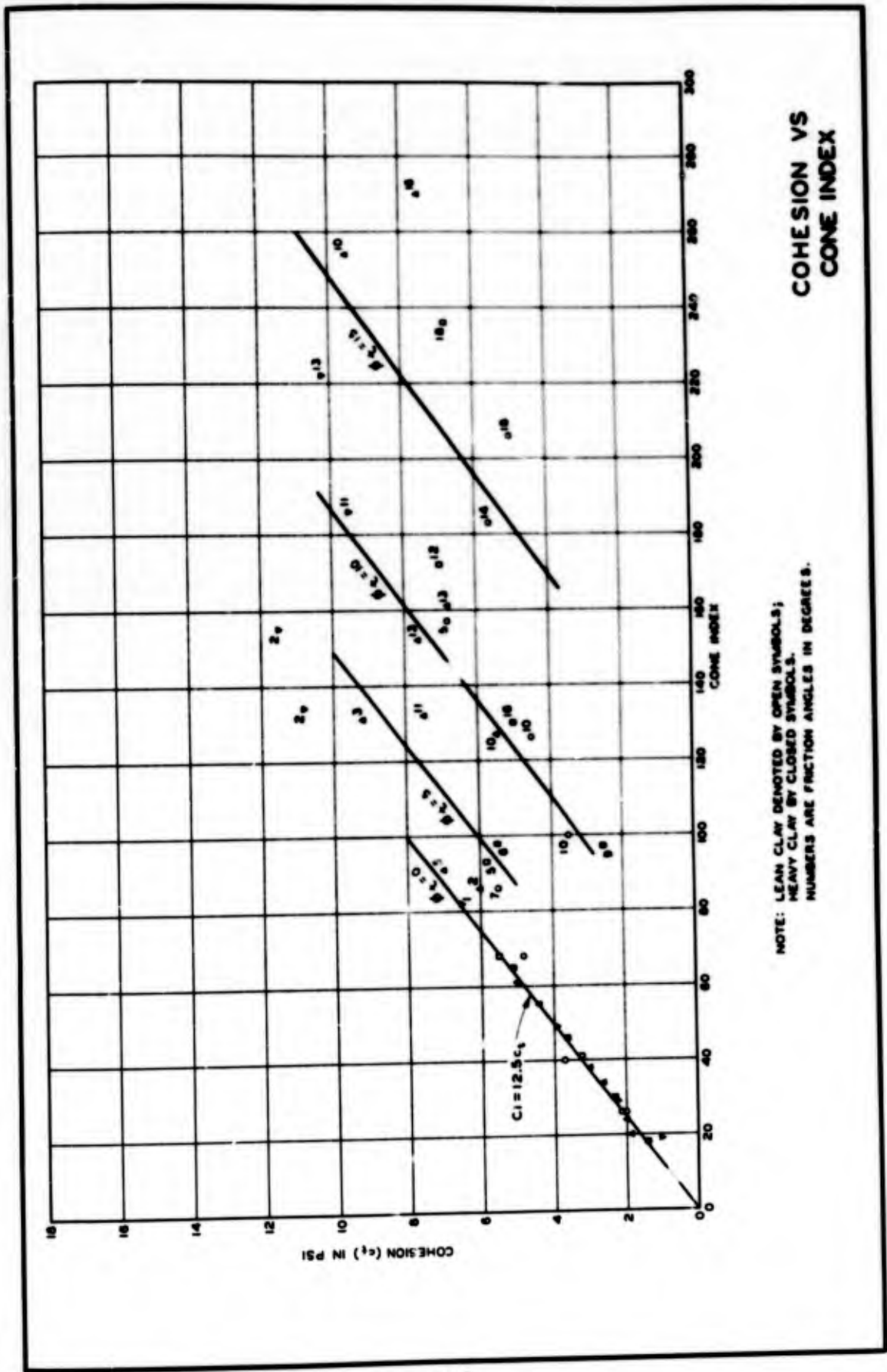
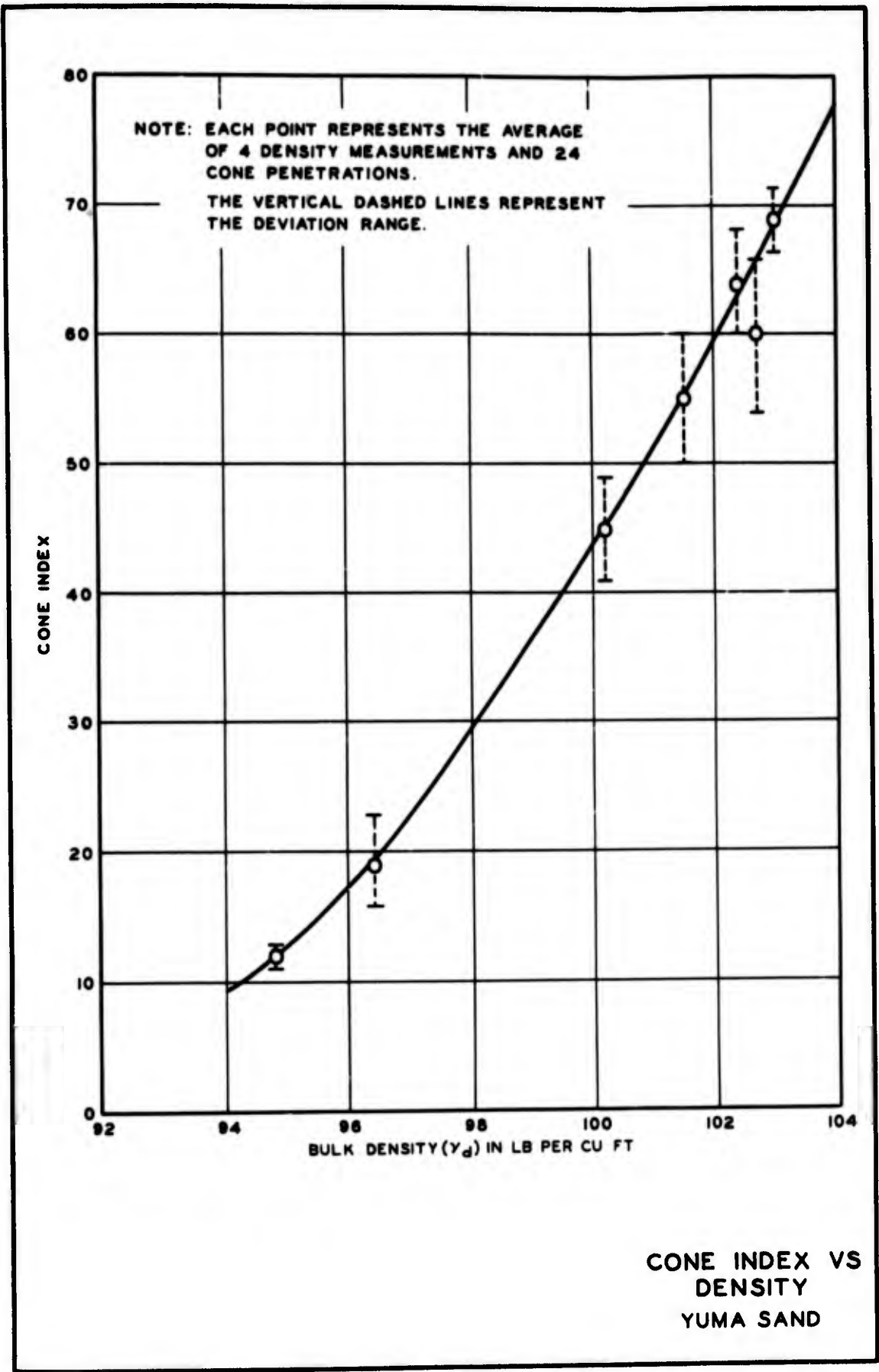


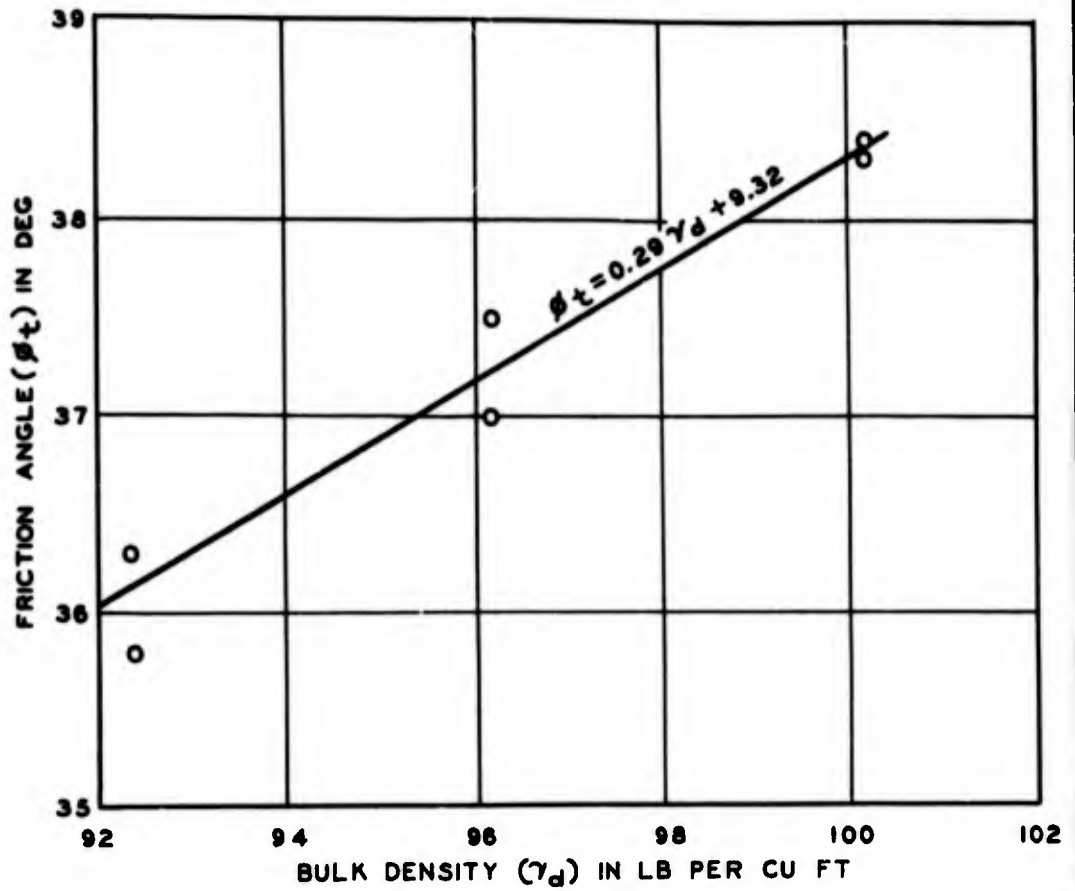
FIG. 3

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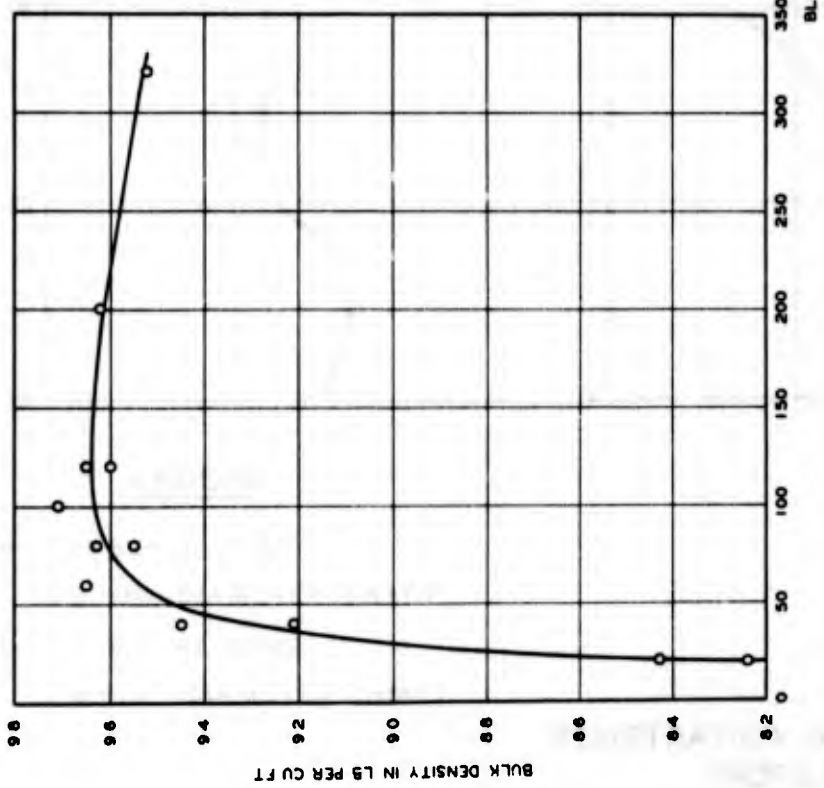
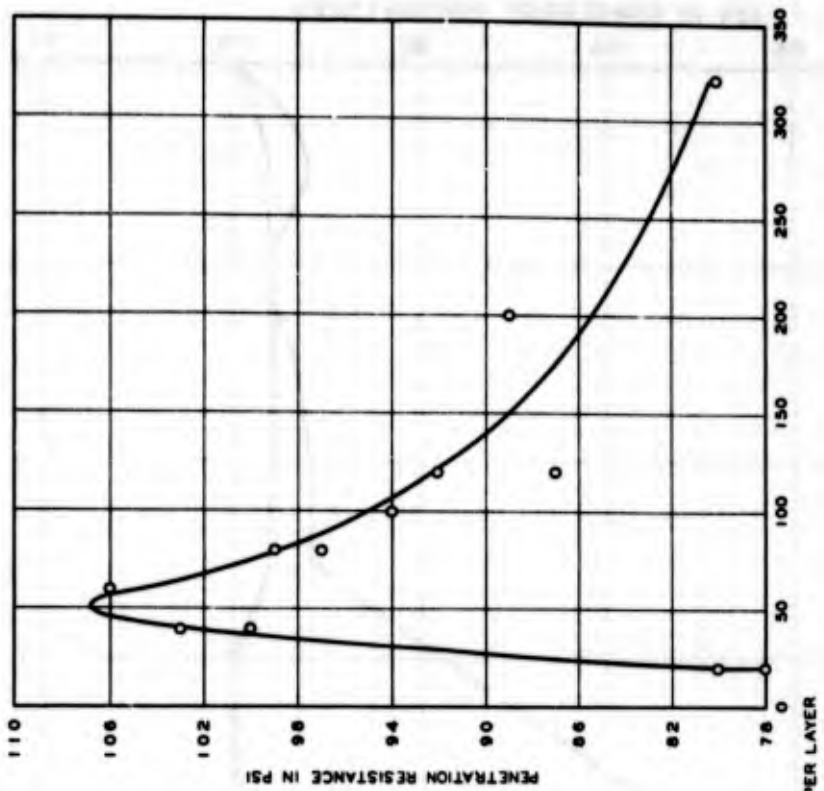
FIG. 4

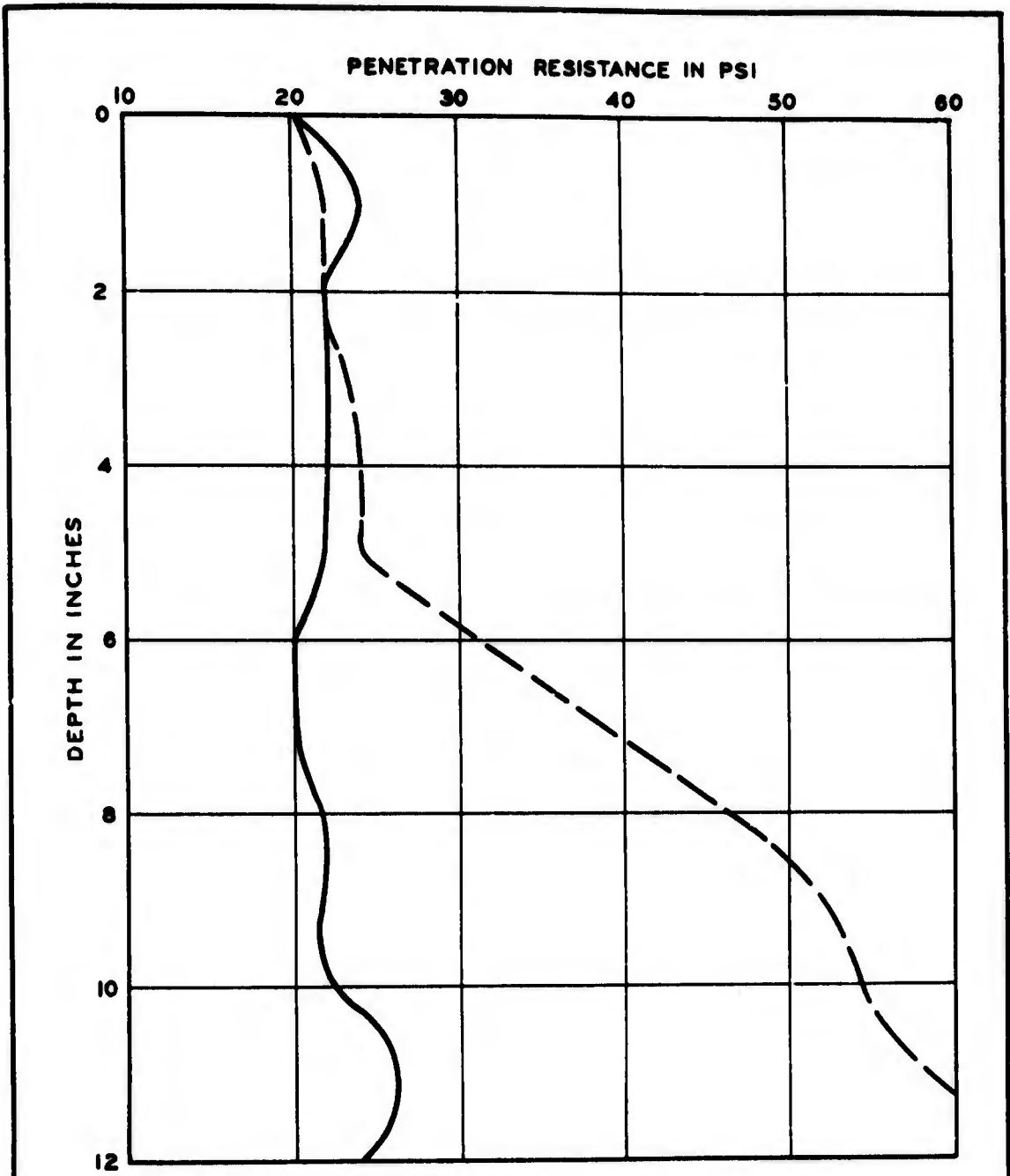


FRICTION ANGLE VS
BULK DENSITY
YUMA SAND

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**RELATION OF SOIL PROPERTIES
AND COMPACTION
LEAN CLAY**





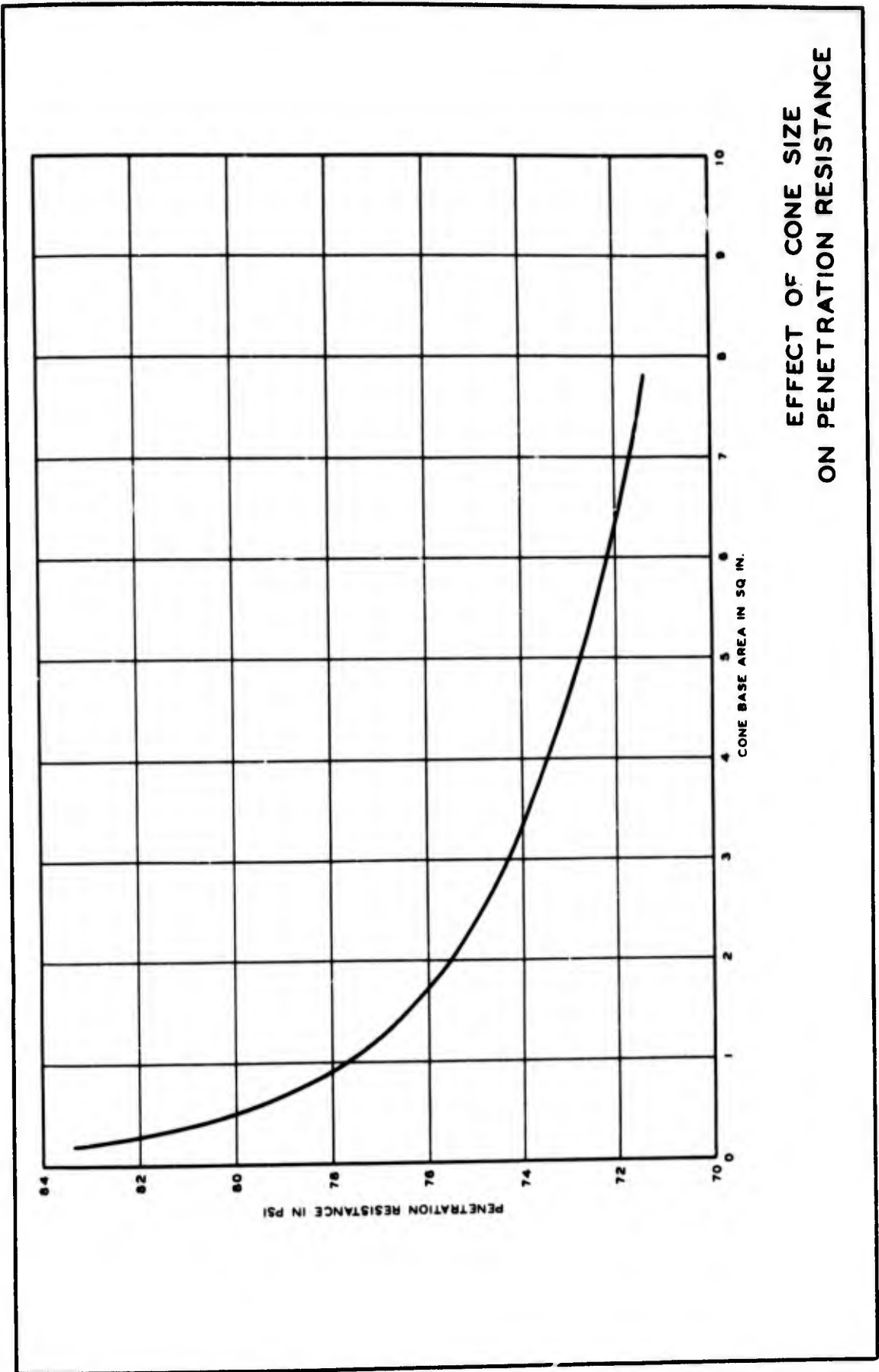
LEGEND

- 0.5-SQ-IN. CONE,
3/8-IN.-DIAMETER SHAFT
- - 0.5-SQ-IN. CONE,
5/8-IN.-DIAMETER SHAFT

**PENETRATION RESISTANCE
PROFILES**
0.5-SQ-IN. CONE, CLAY

14

FIG. 7



EFFECT OF CONE SIZE
ON PENETRATION RESISTANCE

15

FIG. 8

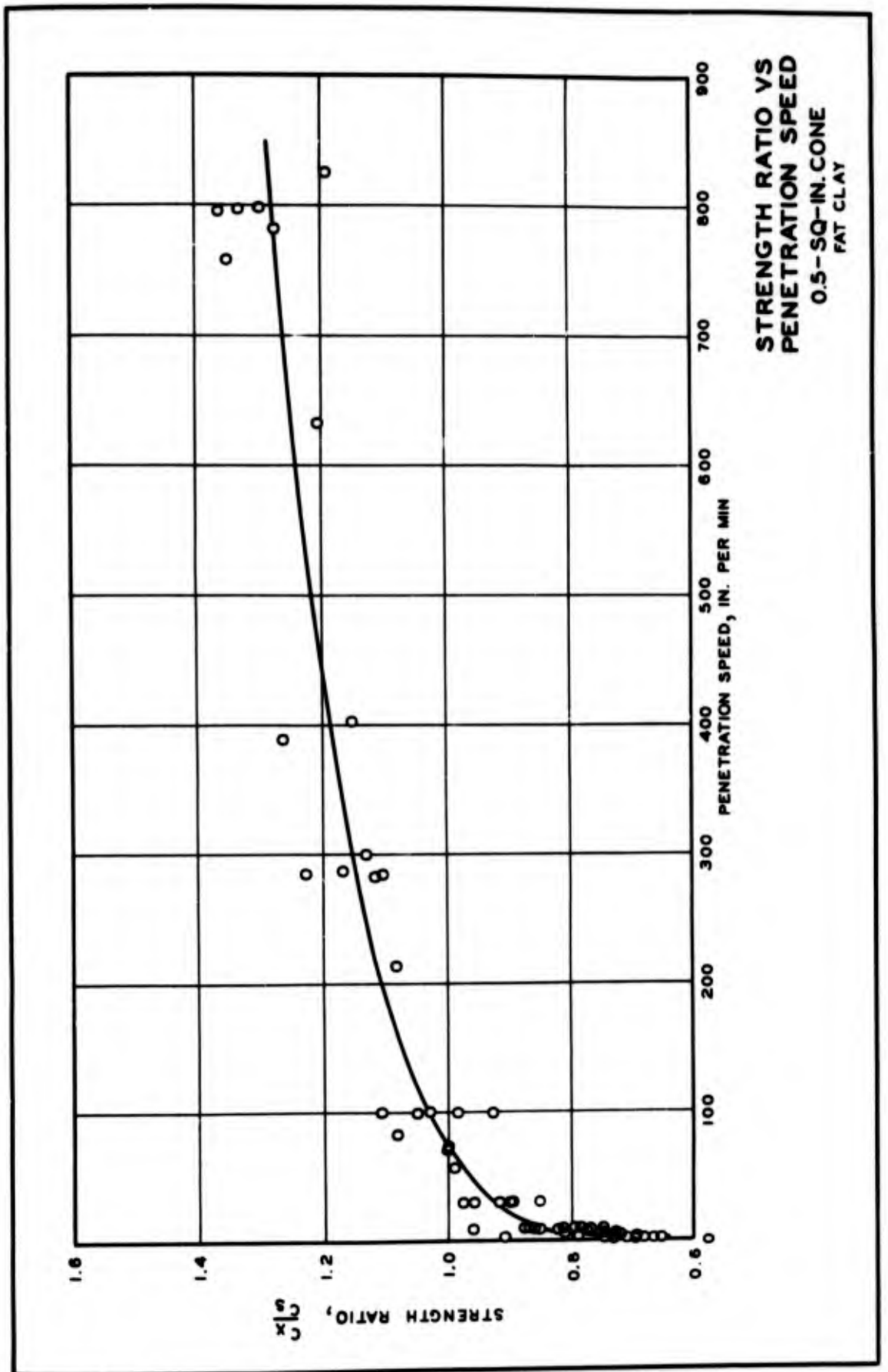
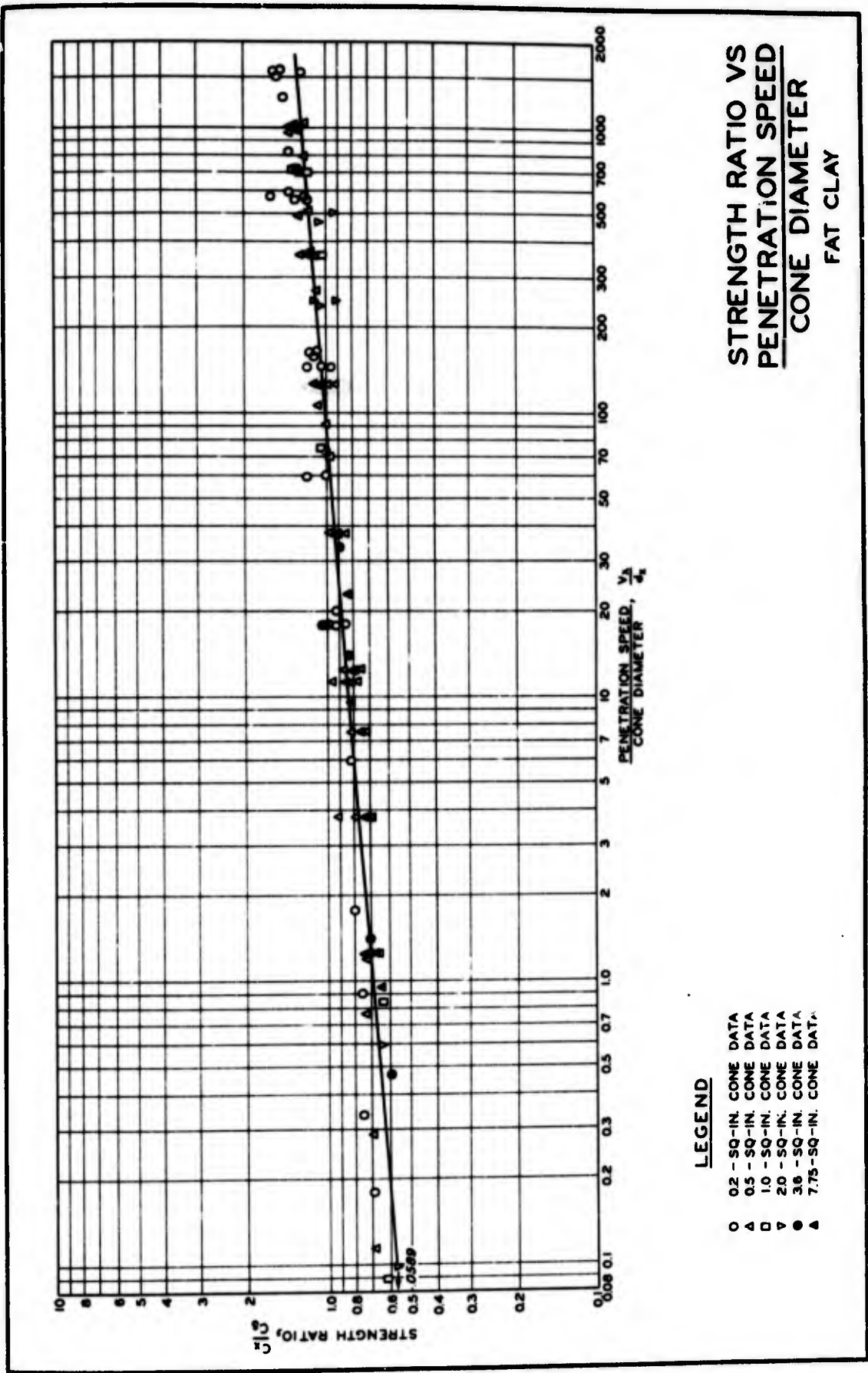


FIG. 9



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