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CONCERNING THE PHYSICAL PROPERTIES OF CLAYS

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It is the writer's purpose to present data that will indicate the effects of sample disturbance on the stress-strain and consolidation characteristics of inorganic clays and to present data that will show how the natural water content of an apparently homogeneous deposit of soil may be expected to vary with depth. To these ends, the results of field loading tests are compared with the results of unconfined compression tests of specimens prepared from test pit and bore-hole samples of soil similar to that subjected to the field loading tests. The data obtained from consolidation tests of specimens, that were prepared from samples obtained by three different sampling techniques, are compared, and data obtained from detailed investigations of the variations in natural water content are presented.

The data reported herein were obtained during the period from 1936 to 1941 in connection with subsoil investigations that were made during the planning and construction of several large buildings in Boston. All of the laboratory data presented in this paper were obtained from tests performed in the Soil Mechanics Laboratories of the Graduate School of Engineering of Harvard University under the direction of Professor Arthur Casagrande and in cooperation with Mr. L.S. Homer of the Turner Construction Company and Mr. H.A. Mohr of the Raymond Concrete Pile Company.

I. COMPARISON OF DATA OBTAINED FROM FIELD LOADING TESTS AND UNCONFINED COMPRESSION TESTS OF TEST PIT AND BORE-HOLE SAMPLES.

A. Description of Tests.

During the construction of the New England Mutual Life Insurance Company Building in Boston, extensive tests were made of the load bearing characteristics of a hard yellow clay stratum, 5 to 10 feet in thickness, which existed 40 feet below the ground surface and upon which the wall footings of this building were to be supported. These tests consisted of field loading tests as well as unconfined compression tests of specimens prepared from hand-cut, test pit samples and from bore-hole samples.

The field loading tests were conducted in a test pit 4.5 feet square at the bottom that extended from the ground surface to the top of the hard clay stratum. Load was applied to a platform erected at the top of the pit and supported by timber columns resting directly on a loading plate 18 inches square which was placed level on the surface of the hard clay. The settlement of the plate was measured by a precision dial gage that was supported by a rigid timber, which spanned the center of the pit at the level of the ground surface, and that was in direct contact with the top of a ½ inch pipe, which extended downward to the top of the center of the pad where it was screwed into a flanged fitting.

Two load tests were performed. The first of these was conducted by placing pig iron on the platform in increments of 2.25 tons at intervals of 15 minutes until a total load of 19.9 tons was obtained on the platform. The settlement of the pad was recorded 15 minutes after the application of each increment of load. Load was then removed from the platform in increments of 2.25 tons per 15 minutes until the platform was completely unloaded. The second test, which was conducted in essentially the same manner as the first test, was performed at a depth of 3 feet below that at which the first test was made.

After the completion of each test, samples were obtained by carefully cutting one-foot cubes of undisturbed soil from the region adjacent to the loaded areas. Unconfined compression tests were performed on specimens, prepared from these samples, having a length-diameter ratio of 2 to 2-1/2.

When exploratory borings were made at this site, samples of this stratum of hard clay were also obtained. These samples were secured by ramming a sampling tube 2 feet in length, 5 inches in internal diameter, and 1/4 inch in wall thickness into a cased hole by means of a 185 lb. weight dropping 30 inches. Three tests were performed on specimens prepared from samples obtained in this manner.

B. Interpretation of data.

The average settlement of a uniformly loaded, square area on the surface of a semi-infinite, elastic and isotropic mass due to the elastic deformation of the mass is expressed by the following equation: 1)

$$S = 0.95\,(1-\mu^2)\cdot\frac{p}{E}\cdot b \qquad (1)$$

wherein

μ = Poisson's ratio
p = intensity of pressure
E = modulus of elasticity
b = width of loaded area

The axial deformation, S, of an unconfined compression test specimen of elastic material is expressed by the following equation:

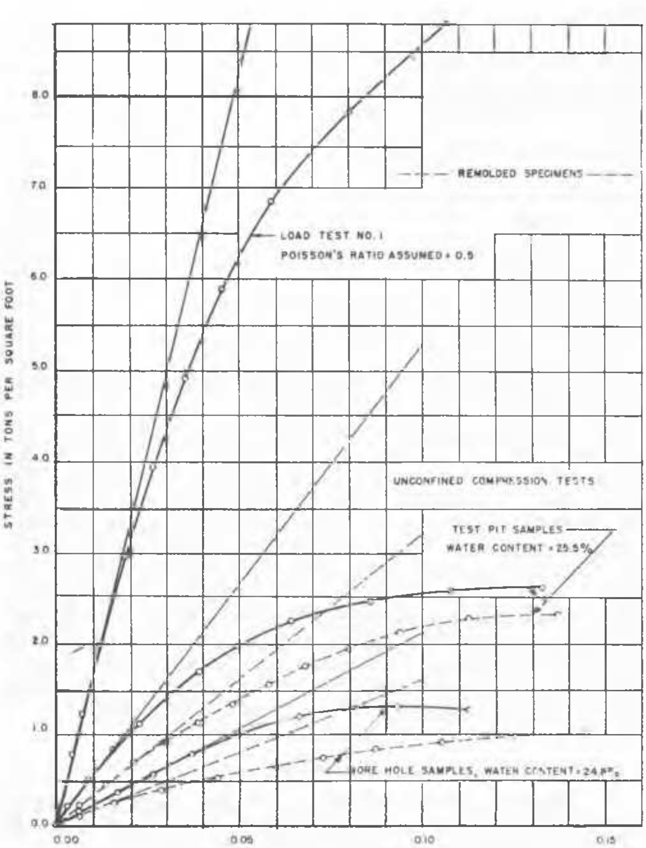
$$S = L\cdot\frac{p}{E} \qquad (2)$$

wherein

L = the length of the specimen.

Comparing equations (1) and (2), it is seen that the settlement obtained by applying a load of uniform intensity to a square area on the surface of a semi-infinite elastic mass is equal to axial deformation of a prismatic specimen of the same material subjected to the same intensity of load having a height equivalent to $0.95\,(1-\mu^2)b$. For Poisson's ratio equivalent to 0 this equivalent height is equal to 0.95 b, and for Poisson's ratio equal to 0.5, the equivalent height is equal to 0.71 b. If it can be assumed that the mass, which is loaded, is elastic and homogeneous to a depth equal to at least 1-1/2 times the width of the loaded area, it is possible to obtain a reasonable estimate of the equivalent strain from surface load test data by utilizing equation (2) and substituting for h its equivalent value, i.e., 0.95 b to 0.71 b, depending upon the value assigned to Poisson's ratio.

The procedure as outlined above was followed in evaluating the load test data. The stress-strain curve for load test No. 1, for an assumed value of Poisson's ratio equal to 0.5, is shown in Fig. 1 by the curve desig-



Stress- strain curves

FIG. 1

nated "Load Test No. 1". The modulus of elasticity x) for the limiting values of Poisson's ratio and corresponding to the slope of the initial position of the stress-strain curves for both tests are shown in Table I.

The moduli of elasticity as determined from the unconfined compression tests prepared from the hand-cut test pit samples are summarized in Table 2 and the stress-strain curve obtained from test No. 3, which is typical, is shown in Figure 1.

The data obtained from the specimens prepared from the bore-hole samples are tabulated in Table 3 and the stress-strain curve obtained from test No. 2, which is typical, is also shown in Fig. 1.

The data tabulated in Tables 1, 2, and 3 and the typical curves shown in Fig. 1 indicate the effects on the stress-strain characteristics of a soil that are due to sample disturbance. By comparing the moduli of elasticity obtained from the so-called "undisturbed" bore-hole samples with those obtained from the remolded specimens of the test pit samp-

x) The term "modulus of elasticity" is used herein to describe the resistance that a material offers to deformation. It is specifically defined as the slope of the linear portion of the stress-strain curve. The term "modulus of deformation" would be more appropriate to describe this property of a material but the term "modulus of elasticity" is retained because of its general acceptance in other fields of civil engineering.

TABLE I

Moduli of Elasticity Obtained from Loading Tests

Test Number	Poisson's Ratio = 0	Poisson's Ratio = 0.5
1	220 tons per square foot	165 tons per square foot
2	240 tons per square foot	180 tons per square foot
Average	230 tons per square foot	173 tons per square foot

TABLE II

Moduli of Elasticity Obtained from Unconfined Compression Tests of Specimens Prepared from Test Pit Samples

Test Number	Area of Specimen sq. in.	"Undisturbed" Specimen tons per sq. ft.	Remoulded Specimen tons per sq. ft.
1	1.64	58	----
2	1.67	58	23
3	6.20	53	25
4	6.16	84	17
5	1.73	51	----
6	2.34	58	30
7	1.27	85	----
8	1.35	53	----
Average		63	26

TABLE III

Moduli of Elasticity Obtained from Unconfined Compression Tests of Specimens Prepared from Bore-Hole Samples

Test Number	Area of Specimen sq. in.	"Undisturbed" Specimen tons per sq. ft.
1	6.00	12
2	2.62	21
3	2.82	18
Average		17

les it is evident that the bore-hole method of sampling completely disturbed the samples. It is to be noted that the limiting values of the moduli of elasticity obtained from the field loading tests are equal to 3 to 4 times the average of the modulus of elasticity obtained from the test pit samples and 10 to 14 times that obtained from the bore-hole samples. Thus, the elastic deformations of such a mass as computed from the modulus of elasticity obtained from unconfined compression tests would not be even approximately correct.

II. COMPARISON OF CONSOLIDATION DATA FROM SAMPLES OBTAINED BY THREE DIFFERENT SAMPLING TECHNIQUES.

A. Description of Methods of Obtaining Samples.

In 1936, 1938, and 1941, samples of Boston Blue Clay were obtained by "undisturbed" sampling methods at three different locations within the Boston Basin. The geologic profile is essentially the same at all locations. The methods of sampling, however, were in each case different due to improvements that were made in sampling techniques during this period.

In 1936, the samples were obtained by a soil sampler designed by Casagrande, Mohr, and Rutledge 2). This sampler had a core barrel 2 feet in length, an internal diameter of 4.76 inches, and an area ratio ratio xa) of 44 percent. A sample was obtained by ramming this sampler a distance of 2 feet into a cased bore-hole. Due to the large area ratio of this sampler and the method of advancing it, the samples suffered considerable disturbance.

In 1938, a new type of sampler developed by H.A. Mohr xb) was used. This sampler had an over-all length of 9 ft. 2 in. that provided space for five one-foot removable liner sections approximately 4 inches in diameter and a two-foot section on top of the liner sections to serve as a reservoir for cuttings and shavings. The cutting edge section of this sampler was provided with four flap valves that prevented loss of the sample during the withdrawal operation. The area ratio of this sampler was the same as that used in 1936. To minimize disturbance, this sampler was advanced slowly in a cased bore-hole by jacking with levers.

In the latest sampling operations, a Shelby Tube of sampler xc) developed by H.A. Mohr was used. Tubes 3 inches in diameter, 18 gage wall thickness and from 3-1/4 to 5 feet in length were used. The ends of these tubes were sharpened and turned in slightly so as to provide a small inside clearance. The area ratio was equal to 8 to 9 percent. A sample was obtained by advancing the tube in a quick, continuous motion by a block and tackle system reacting against the casing. Laboratory inspection of these samples indicated that they were less disturbed than those obtained by the two methods described previously.

B. Interpretation of Data.

Eleven consolidation tests were performed on specimens prepared from the 1936 samples, 33 from those obtained in 1930 and 24 from those obtained in 1941. The original water content, the original void ratio, e_o, and the compression index, C_c, xd) of each sample was determined from these tests.

The relation between the original (natural) water content and the physical constants, which describe the consolidation characteristics of a soil, as expressed by the ratio $C_c/(1 + e_o)$, is shown in Fig. 2. Each point in this figure represents the data obtained from one consolidation test. Three different symbols are used to distinguish the data obtained from the three different series of samples. The symbols in each case are connected by straight lines to differentiate the data more clearly.

The broken line representing the data obtained from the 1936 samples, which were considerably more disturbed than those obtained in 1938 and 1941, shows the smallest change in the ratio $C_c/(1 + e_o)$ with respect to the natural water content. Rutledge 3) found that the compression index obtained from remolded specimens (completely disturbed) is smaller than that obtained from an undisturbed specimen of the same soil. It is also known that, in general, the higher the natural water content of a clay, the greater will be the difference between the consistency when undisturbed as compared to the consistency when remolded. It is not surprising therefore, that the effects of disturbance to the samples, suggested by the difference in the values of $C_c/(1 + e_o)$ for a

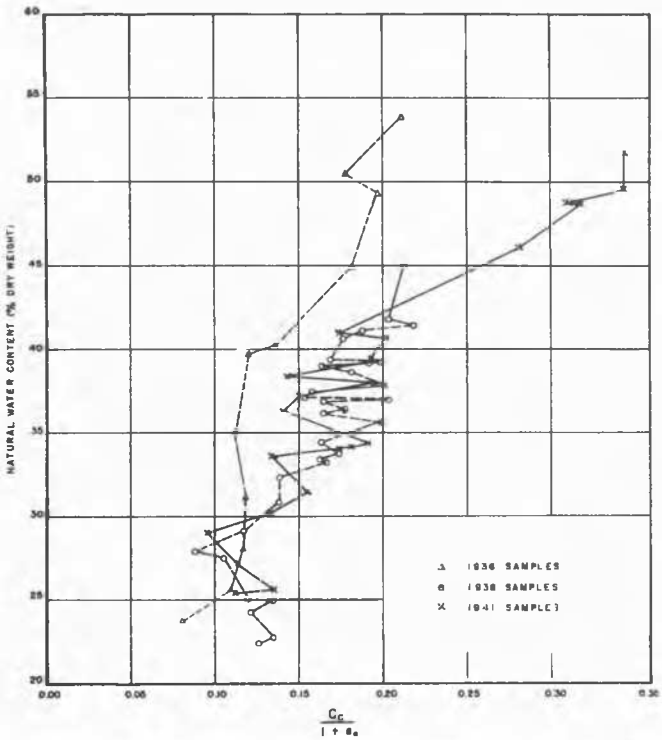
xa) The area ratio is defined as the ratio of the cross-sectional area of a sampler at its largest section minus the area of the opening through which the sample enters to the area of the opening through which the sample enters. It is thus a measure of the amount of soil that must be displaced by the walls of the sampler. Thus the smaller the area ratio the less is the disturbance to the sample.

xb) loc. cit. Ref. 2, p.56.

xc) loc. cit. Ref. 2, p.44.

xd) The compression index is defined as the slope of the linear portion of the void ratio vs. log of pressure curve:

$$C_c = \frac{e_1 - e_2}{\log P_2 - \log P_1}$$



Relation between natural water content and $\frac{C_c}{1+e_o}$.

FIG. 2

given water content increases as the natural water content increases.

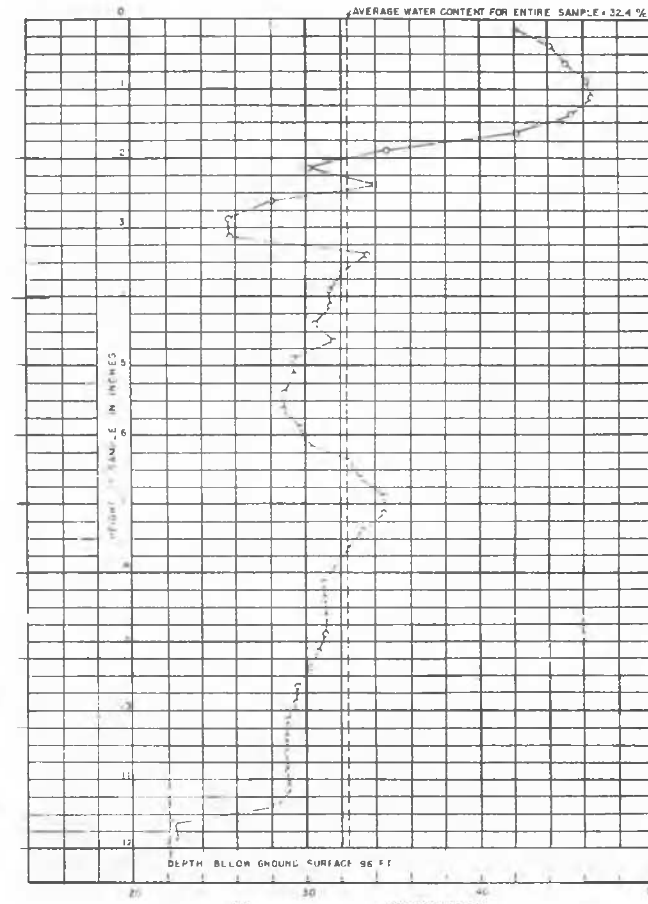
It can be seen from Fig. 2 that the range in values of $C_c/(1 + e_o)$ obtained from samples having approximately the same water content is such that the ratio of the value of $C_c/(1 + e_o)$ for the least disturbed sample to that of the most disturbed sample is in no case greater than 2 to 1.

It is to be noted, therefore, that the effects of disturbance on the consolidation characteristics of a clay, as expressed by the ratio $C_c/(1 + e_o)$, are small as compared with the effects of disturbance on the stress-strain properties. It is also to be noted that the extreme range in values of the ratio $C_c/(1 + e_o)$ obtained from these samples of inorganic clay subjected to varying degrees of disturbance and having natural water contents ranging from 22 percent to 54 percent is approximately 0.10 to 0.35.

III. VARIATIONS IN NATURAL WATER CONTENT IN A CLAY DEPOSIT.

A detailed examination of the variations in natural water content in a clay deposit was made from bore-hole samples obtained at the site of the New England Mutual Life Insurance Company Building. The samples were obtained by means of a Shelby Tube type of sampler, 3-1/2 inches in diameter and 4 to 5 feet in length. The sampler was driven by means of a 140 lb. weight falling 30 inches. Samples were taken as continuously as possible.

Water content determinations were made of each ¼ inch length of these samples as soon as they were received in the laboratory. Typical variations in water content within a 12-inch length of sample are shown in Fig. 3. A summary of all tests made in this manner, approximately



Variations in natural water contents

FIG. 3

1.400, is shown in Fig. 4. The maximum and minimum water contents found in each 12-inch length of sample are shown by the extremities of the horizontal lines in this figure. The average water content for each section is represented by a small circle.

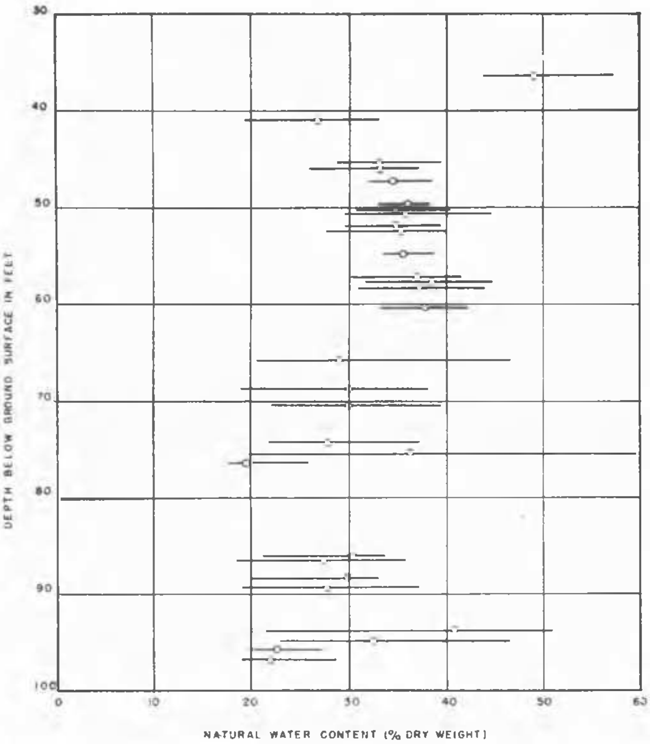
This detailed examination showed extreme variations in natural water contents of from 19.8 percent to 59.5 percent within a single 12-inch length of sample. The average water content obtained from each 12-inch length of sample ranged from 19.4 percent to 49.0 percent and the aggregate average of all samples tested was approximately 37 percent.

Many of the samples tested appeared homogeneous and uniform in their undisturbed condition. Yet, the variations in water content in some of these samples were found to be surprisingly great.

Since many of the physical properties of clays are related to the natural water content, it is evident that extreme care must be exercised in evaluating the overall performance characteristics of a given clay deposit.

IV. SUMMARY AND CONCLUSIONS.

1. From a comparative study of the results of field loading tests and unconfined compression tests of specimens prepared from test pit and bore-hole samples of a hard, yellow, inorganic clay stratum similar to that subjected to the field loading tests, it was found that the modulus of elasticity determined from the field loading tests was equal to from 3 to 4 times that obtained from the test pit



Variations in natural water content. Extremities of each horizontal line represent maximum and minimum water contents in a 12 inch length of sample.
O represents average of 48 water content determinations for each 12 inch length of sample.

FIG. 4

samples and 10 to 14 times that obtained from the bore-hole samples. It is evident, therefore, that the stress-strain characteristics of clay-like soils are extremely sensitive to disturbance. Since some disturbance is inevitable in the operations of sampling and in the preparation of test specimens for unconfined compression tests, the elastic deformation of a mass of such soil computed from the moduli of elasticity obtained from such tests will not be even approximately correct.

2. A comparison of the results of 68 consolidation tests performed on specimens prepared from samples of inorganic clay that were obtained by three different sampling techniques, in which the three series of samples were subjected to different degrees of disturbance, showed:

a. that the consolidation characteristics of clays of high natural water content are more sensitive to the effects of disturbance than are those of low natural water content.
b. that the range in values of the consolidation characteristics as expressed by the ratio $C_c/(1 + e_o)$ obtained from bore-hole samples having approximately the same water content is such that the ratio of the value of $C_c/(1 + e_o)$ for the least disturbed sample to that of the most disturbed sample is in no case greater than 2 to 1. Therefore, the effects of disturbance on the consolidation characteristics as expressed by the ratio $C_c/(1 + e_o)$, are small as compared with the effects of disturbance on the stress-strain properties, and
c. that the extreme range in values of the ratio $C_c/(1 + e_o)$ obtained from these samples, which were subjected to varying degrees of disturbance and which had natural water contents ranging from 22 percent to 54 percent, is approximately 0.10 to 0.35.

3. A detailed investigation of the variations in natural water content of a clay deposit, approximately 60 feet in thickness, showed:
a. extreme variations of from 19.8 percent to 59.5 percent within a single 12-inch length of sample.
b. variations in the average water content obtained from each 12-inch length of sample ranging from 19.4 percent to 49.0 percent, and
c. no consistent variation with depth.

It was observed, furthermore, that even those clay samples that appeared homogeneous had large variations in water content. Therefore, it is imperative that extreme care be exercised in evaluating the over-all performance characteristics of a given clay deposit by means of laboratory test data.

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