R 694

Technical Report

PLATE BEARING TESTS ON SEAFLOOR SEDIMENTS

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PLATE BEARING TESTS ON SEAFLOOR SEDIMENTS

Technical Report R-694

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by

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ABSTRACT

A device was developed by the Naval Civil Engineering Laboratory to determine the short-term, in-situ bearing pressure and settlement response of marine sediments at any ocean depth. Tests were performed in cohesive sediments with both round and square bearing plates at ocean depths of 1,200 and 6,000 feet. During a typical test, measurement of load, settlement, and attitude of the device were transmitted acoustically to a surface vessel where they were monitored and recorded. The results of these plate bearing tests were found to be amenable to analysis by modified elastic and bearing capacity theory. A tentative procedure for predicting the short-term settlement of seafloor footings using the results of laboratory tests on core samples was developed on the basis of these two approaches.

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INTRODUCTION

Subject and Purpose of Report

This report presents the results of in-situ plate bearing tests performed on cohesive seafloor sediments located at sites ranging in water depth from 100 feet to 6,000 feet in the vicinity of the Channel Islands off the coast of Southern California. The work was sponsored by the Naval Facilities Engineering Command. The objectives of this report are: (1) to present an analysis of the results of the two most recently performed series of in-situ plate bearing tests, (2) to present a scheme for correlating the results of in-situ plate bearing tests with those of laboratory tests on core samples, (3) to report on a general procedure for predicting short-term foundation settlement from data on cores, and (4) to present updated information on NCEL's plate bearing test equipment and data processing procedures.

Analysis of Problem

The exploration and utilization of the ocean is progressing at an ever increasing rate. Frequently this endeavor involves the use of the seafloor to support foundations for such diverse structures as equipment test stands, acoustic arrays, and bottom-sitting submersibles. Some items are emplaced at one location for long periods of time while others are moved from site to site in the course of their use. Some structures are very large and apply significant stresses to great depths in the sediment while others are small, lightweight, and are supported primarily by the upper several feet of sediment. At present the weight of many underwater structures is reduced or these structures are even made positively buoyant by the use of buoyant elements. In these cases the foundation may be provided primarily to resist loads due to overturning moments on the structure or simply to keep the structure at one location on the seafloor. In most of the above-mentioned situations the possibility of a bearing capacity failure and the resulting excessive settlement or tilting of the structure needs to be investigated; failure to do so may render a structure useless for accomplishing its designated mission.

Quite often the only information on the engineering properties of the bottom sediment which is available or economically obtainable is from a few cores collected in the vicinity of the operations site. Thus, techniques for predicting the short-term and long-term settlements which can be expected when an object is emplaced, based on the results of conventional sediment core analyses, would be very useful in many situations. This report addresses itself primarily to the problem of predicting short-term settlement for small spread footings using the results of in-situ tests with NCEL's Plate Bearing Device and laboratory tests on cores recovered from the in-situ test sites.

Background

For several years NCEL has been developing test equipment, performing research, and accumulating data on the engineering properties of marine sediments and their response to foundation loads. Under this program a device for performing in-situ plate bearing tests on the seafloor was developed and tested. The basic characteristics of this equipment and the results of the first two series of tests have been previously reported.[1] At the time of this initial report the equipment was still in the developmental stages and had only been operated in a maximum water depth of 150 feet. Improvements have subsequently been made to both the mechanical and instrumentation systems, and tests have been performed in sediments located in water depths of over 6,000 feet. The reason for developing the plate bearing device was to provide a method for obtaining the bearing pressure—settlement response of the seafloor to loads imposed on small spread footings. Information from this test provides a basis for predicting the immediate settlement which occurs when a structure is placed on a spread foundation located at the sediment—water interface. Reliable information of this type is not presently obtainable for seafloor sediments from the analysis of laboratory tests on core specimens. It was anticipated that it would eventually be possible to relate the bearing pressure—settlement response of a foundation to a laboratory-measured property such as vane shearing strength if sufficient data were obtained both in situ and in the laboratory.

Approach and Scope

NCEL's approach to the problem of predicting the immediate settlement of spread footings on the seafloor has been to develop a test device capable of forcing various sizes and shapes of footings into the seafloor at a controlled rate and to measure the bearing pressure—settlement response resulting from tests using this device. In addition sediment cores were obtained at the test sites and analyzed in the laboratory. Schemes have been developed and are

presented for interpreting the in-situ test data in terms of the measured sediment properties. The resulting technique should be considered as a tentative method which needs to be substantiated by additional tests in a greater variety of sediments and by the actual performance of foundations.

TEST EQUIPMENT

The in-situ plate bearing device, Figures 1 and 2, provides a remote means for forcing a small spread footing into the seafloor at a controlled rate and measuring the resulting load on the footing versus displacement. Mechanically, the device consists of a moveable weight holder with a bearing plate attached to it. The weight holder is supported and its vertical displacement rate controlled by three closed-circuit, pressure-equalized hydraulic cylinders. A tripod framework, supported on three articulated bearing pads, guides the weight holder. The device is connected to its surface support vessel via a synthetic rope which attaches to the top of the weight holder. When the line is taut (during lowering or raising operation), the weight holder and bearing plate are in the "test ready" or retracted position; when slack (after the device is on the bottom), the weight holder moves downward forcing the bearing plate into the sediment. The equipment can accommodate a variety of bearing plates ranging in size up to 1.5 feet in diameter and can apply a maximum load of 6,000 pounds.

The instrumentation system provides sensors for measuring load and displacement of the bearing plate and vertical orientation of the device. The load transducer, located immediately above the bearing plate, consists of a strain-gaged element enclosed in an oil-filled pressure-equalized case.* The plate displacement is measured using a linear potentiometer which is mounted on the framework with the potentiometer's plunger connected to the moveable weight holder as shown in Figure 1. The vertical orientation of the device is indicated by a pendulum mounted on a rotary potentiometer. The techniques for measuring displacement and vertical orientation are essentially the same as described in the performance evaluation report.[1] The signal conditioning and telemetry system has been modified considerably since last reported on however. The variable voltage signals from the sensors are converted to variable frequencies and are transmitted acoustically to the surface as an FM signal on a carrier frequency of 40 kHz. A hydrophone aboard the surface vessel is used to sense the signal which is then discriminated to produce individual analog

* This unit replaces the spring and linear potentiometer method for load measuring which was described in the initial evaluation report on the device.[1]

readouts of load, displacement, and vertical orientation. These signals are recorded on both a direct-writing oscillograph to allow immediate monitoring of the progress of a test and on magnetic tape for later reduction by the process described in the Appendix.

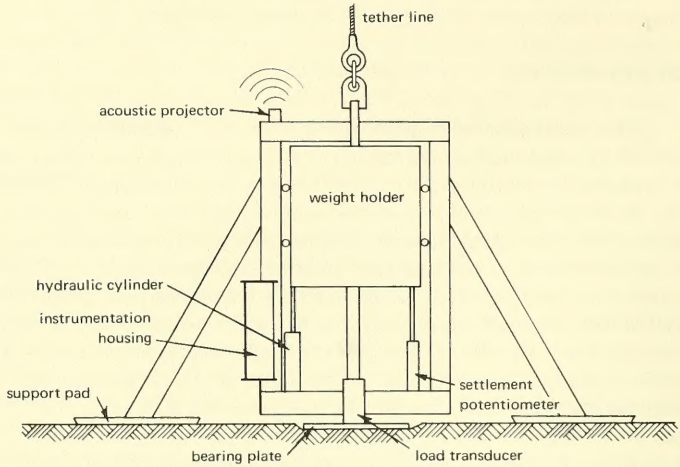

Figure 1. Schematic of in-situ plate bearing device.

TEST PROGRAM AND PROCEDURES

The tests described in this report were performed during four different sea cruises which were conducted during the development of the plate bearing device. Testing was concentrated at two sites located off the coast of Southern California in water depths of 1,175 and 6,000 feet. The tests at the shallower site are designated Series III and those at the deeper site are Series IV.* The geographic coordinates of the Series III site are 34°09.6'N, 119°45.3'W and the Series IV site are 33°52.1'N, 120°35.9'W. Figure 3 shows the location of these sites.

Tests SC-1 through SC-12 were performed at the Series III site during operations aboard the *USNS Gear*, ARS-34. These tests were conducted using the rather primitive mechanical spring-linear potentiometer combination for load measurement and a telemetry system which provided data from only one sensor at a time. The result was inaccurate load data in the very soft sediment

* Test Series I and II were previously reported.

at this site and quite often lack of sufficient data to define the initial part of the load—displacement curve. These problems prompted the development of the strain gage type load transducer and the FM telemetry system.

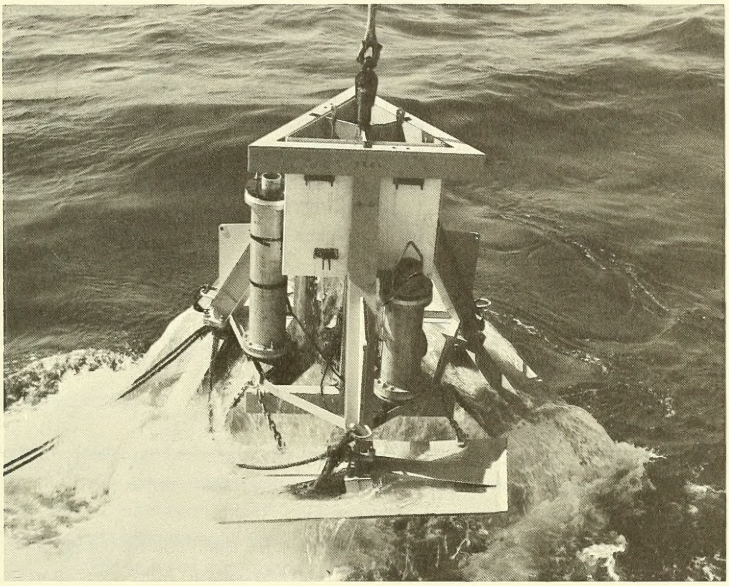

Figure 2. In-situ plate bearing device.

The second cruise to the Series III site was conducted aboard a Navy YFU primarily for the purpose of proof-testing the new load transducer and telemetry system. During this cruise tests SC-13 through SC-16 were performed resulting in the conclusion that the acoustic projector and receiving hydrophone were too directional to meet operational constraints. It is necessary at times to operate with the support vessel in a drifting mode. For practical purposes this requires the ability to receive the acoustic data signal when the receiving hydrophone, and therefore the ship, is laterally displaced from the device a distance not exceeding the water depth at the test site. At this distance the wire angle would be 45 degrees, the maximum allowed in order to avoid overturning the device upon retrieval. It was found during these tests that the signal was lost after the vessel drifted a distance of only about one-half of the water depth. To solve this problem a revised acoustic projector and hydrophone set were procured.

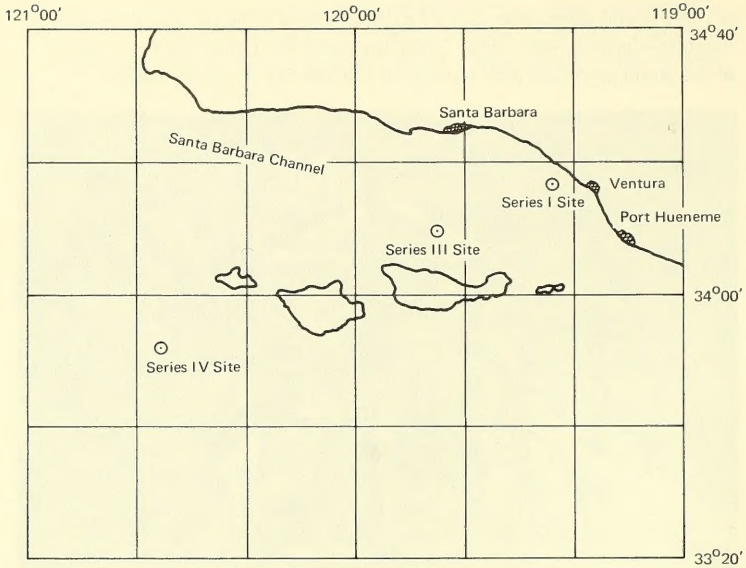

Figure 3. Chart of operating area off Southern California.

The third visit to the Series III site was once again conducted aboard the *USNS Gear*. This time a single-point moor was used to hold the ship in the vicinity of the desired test site. Tests SC-17 through SC-29 were successfully completed, and the device was found to perform very satisfactorily.

All of the tests were performed and the sediment cores recovered at the Series III site within a one-half-mile-diameter circle. Tests SC-17 through SC-29, performed while the ship was at anchor, are located within a circle 100 to 200 feet in diameter.

During a fourth cruise conducted aboard the Marine Mineral Technology Center ship *Virginia City*, a converted ATF, tests SM-1 through SM-5 were performed at the Series IV site in 6,000 feet of water. The ship was operated in a drifting mode during testing. All of the tests except SM-5 and the two sediment cores taken at the site fall within 1,000 feet of the previously given location of the test site. Test SM-5 falls within 2,000 feet of the center of the site.

Navigation control during all the tests was provided by the LORAC-B precise navigation system. The repeatability of this system in the two test areas is estimated to be from 50 to 100 feet, which exceeds the accuracy with which the position of the device was able to be determined with respect to the location of the support vessel.

During the test program, nine different bearing plates (0.5, 0.75, 1.0, 1.25, and 1.5 feet in diameter and 0.5, 0.75, 1.0 and 1.25 feet square) were used to investigate the effect of plate size and shape on the resulting bearing pressure—settlement response. The plates are made of one-half-inch steel plate, having a smooth painted surface, and are stiffened with steel webs to provide rigidity. The connection between the plates and the device is also rigid in order to keep the plate in the horizontal plane.

The displacement rate at which most of the tests were performed did not vary a large amount. The slowest test had a displacement rate of 0.0142 in./sec, and the fastest test was run at 0.0663 in./sec, which is about 5 times as fast as the slowest test. For the tests actually analyzed in this report, the displacement rate varied by a factor of about 2.5. Most of the tests were run at about 0.03 to 0.04 in./sec resulting in a test time of about 5 minutes for 11 inches of displacement.

RESULTS OF TESTS

Soil Properties

Three sediment cores at the Series III test site and two cores at the Series IV site were obtained using an Ewing-type gravity corer with a plastic liner and a "modified hinged" core retainer. The lateral distances between the cores at each site were less than a few hundred feet.

The results of laboratory analyses of the cores, including grain size, original water content, bulk wet density, Atterburg limits, and original and remolded vane shear strengths, are presented in Figures 4 through 8. According to the Trilineal Oceanic Soil Classification Chart,[2] the sediment throughout the lengths of the cores from Site III is classified as a clayey silt. The sediment at Site IV is a silty clay. The results of laboratory tests performed on cores from the same site do not vary greatly, evidently indicating that the soils at both sites have fairly good areal uniformity for the small areas represented by the cores.

All of the vane shearing strength data for the Series III and Series IV sites is presented in Figures 9 and 10. Both sets of data indicate an essentially linear increase in shear strength with depth. The strength at the surface for the Series III data is practically zero while the surface strength for the Series IV data is somewhat greater than zero.

The linearly increasing strength profiles may be attributable to either consolidation under the weight of overlying sediment or the effects of increasing age with depth or a combination of the two effects. The finite surface strength at Site IV may be due to either the removal of several inches of sediment by scour, the effect of age, or the existence of an intrinsic strength which is produced as soil particles come together in a flocculating environment.

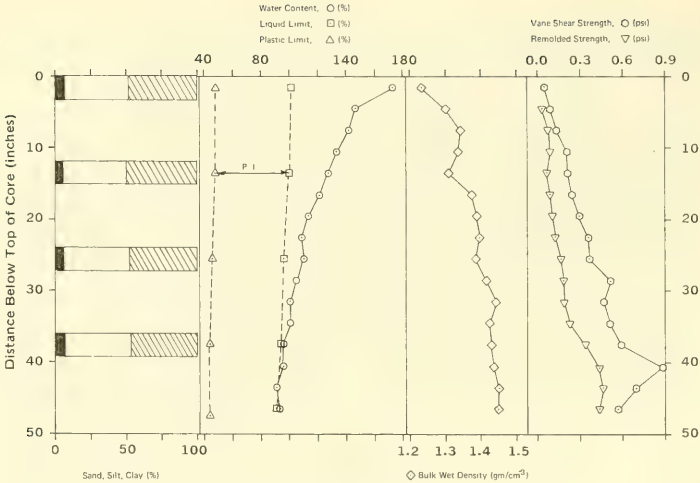

Figure 4. Sediment properties for Core PB-3, Series III.

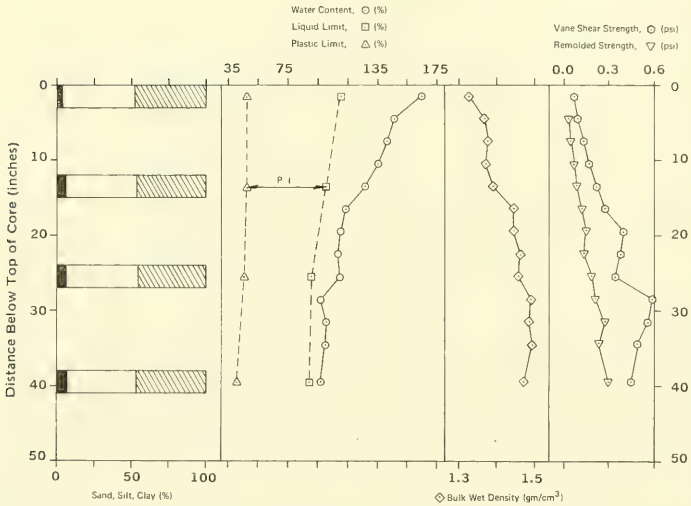

Figure 5. Sediment properties for Core PB-4, Series III.

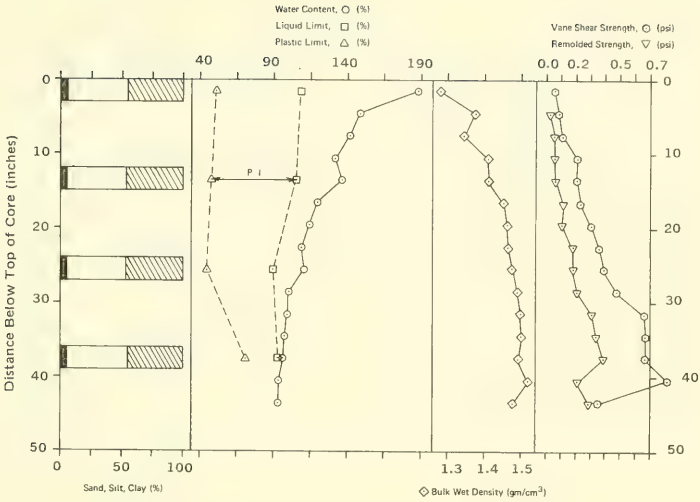

Figure 6. Sediment properties for Core PB-5, Series III.

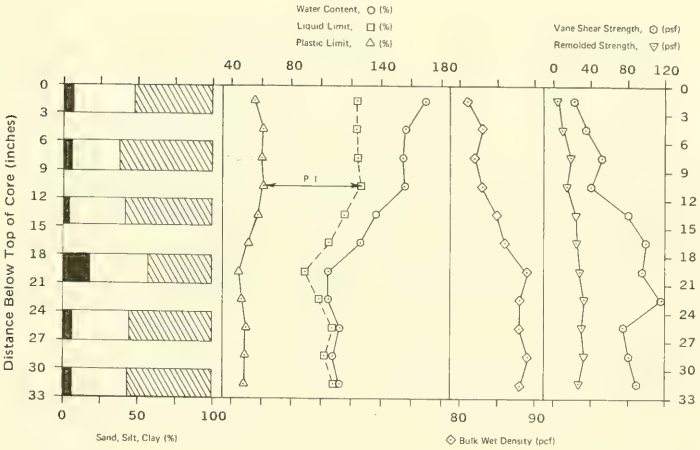

Figure 7. Sediment properties for Core SM-1, Series IV.

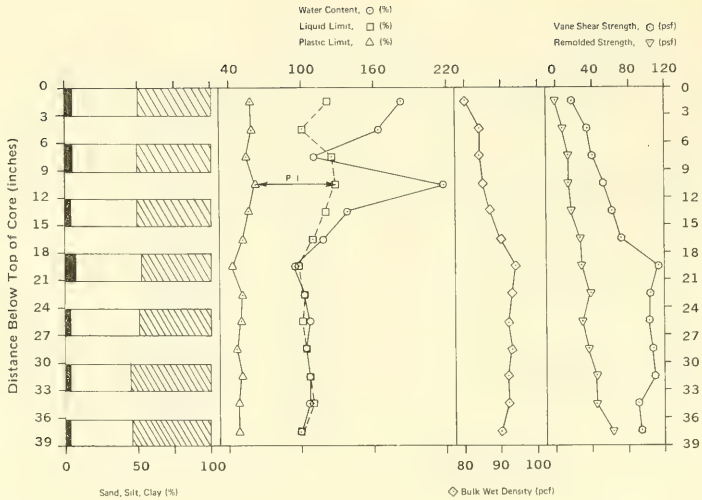

Figure 8. Sediment properties for Core SM-2, Series IV.

Test Data

The testing schedules for Series III and Series IV are presented in Tables 1 and 2, respectively. The plate size, area, and average vertical settlement rate are indicated for each test.

Figure 11 illustrates the general nature of the bearing pressure—time and displacement—time curves for a typical test. One characteristic apparent from these curves is the amount of displacement which occurs before the pressure begins to increase. Since the device is designed with the bearing plate initially located 3 inches above the elevation of the support pads, this initial displacement, subtracted from 3 inches, yields an estimate of the immediate settlement of the pads due to the placing of the device on the seafloor.

Another feature of Figure 11 is the marked reduction in pressure immediately following the attainment of full deflection. This might indicate that a portion of the peak pressure is velocity dependent or viscous and is subsequently eliminated when motion ceases. By extending this hypothesis it would be concluded that the testing rate is an important experimental parameter, however, it will be seen later that this is not the case.

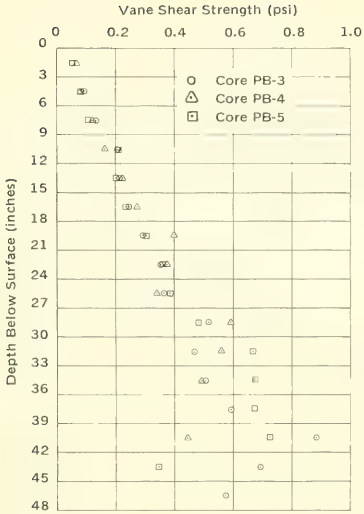

Figure 9. Vane shear strength versus depth, Series III.

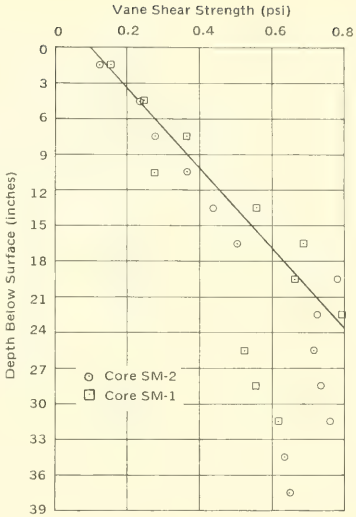

Figure 10. Vane shear strength versus depth, Series IV.

It is felt that this phenomenon is actually attributable to the development of a small amount of drained compression beneath the plate. This effect would be negligible during the penetration process but rather significant after the cessation of motion. Any slight settlement of the plate would result in an expansion of the load transducer leading to a marked decrease in the measured load. Fortunately, this sort of behavior would not affect the validity of the loading curves and might, in fact, be of some use in analyzing the consolidation behavior of seafloor sediments.

A final important characteristic of this data is the relatively large negative pressure attained at the end of a test as the plate is being withdrawn. This data has been analyzed elsewhere in a study directed toward the prediction of breakout forces.[3]

Table 1. Plate Bearing Test Data for Series III Site

NCEL Test No.	Plate Size (ft)	Plate Area (ft^2)	Average Displacement Rate (in./sec)	Remarks
SC-1	1.0	0.785		Instrumentation problem; no data
SC-1A	1.0	0.785		Instrumentation problem; no data
SC-2	1.0	0.785	0.0298	
SC-3	1.5	1.77	0.0142	
SC-4	1.25	1.23	0.0167	
SC-5	1.25 x 1.25	1.56	0.0146	
SC-6	0.75 x 0.75	0.562	0.0163	
SC-7	1.0 x 1.0	1.00	0.0133	
SC-8	0.5 x 0.5	0.250	0.0208	
SC-9	0.75	0.442	0.0174	
SC-10	0.5	0.196	0.0230	
SC-11	1.0	0.785	0.0145	
SC-12	1.25	1.23	0.0166	
SC-13	1.25 x 1.25	1.56		Instrumentation and station keeping problems; no data
SC-14	0.5 x 0.5	0.250		Instrumentation and station keeping problems; no data
SC-15	0.75	0.442		Instrumentation and station keeping problems; no data
SC-16	1.5	1.77		Instrumentation and station keeping problems; no data
SC-17	1.0 x 1.0	1.00	0.0309	
SC-18	1.5	1.77	0.0663	
SC-19	1.5	1.77	0.0252	

continued

Table 1. Continued

NCEL Test No.	Plate Size (ft)	Plate Area (ft^2)	Average Displacement Rate (in./sec)	Remarks
SC-20	1.0	0.785	0.0460	
SC-21	0.5	0.196	0.0389	
SC-22	0.75 x 0.75	0.562	0.0351	
SC-23	1.25 x 1.25	1.56	0.0445	
SC-24	0.5 x 0.5	0.250	0.0412	
SC-25	0.75	0.442	0.0388	
SC-26	1.25	1.23	0.0468	
SC-27	1.25	1.23	0.0326	
SC-28	0.5	0.196	0.0371	
SC-29	1.0	0.785	0.0348	

Table 2. Plate Bearing Test Data for Series IV Site

NCEL Test No.	Plate Size (ft)	Plate Area (ft^2)	Average Displacement Rate (in./sec)	Remarks
SM-1	1.0	0.785	0.0375	
SM-2	1.5	1.77	0.0366	
SM-3	0.75	0.442		Instrumentation problem; no data
SM-4	0.75	0.442	0.0446	
SM-5	1.25	1.23	0.0250	

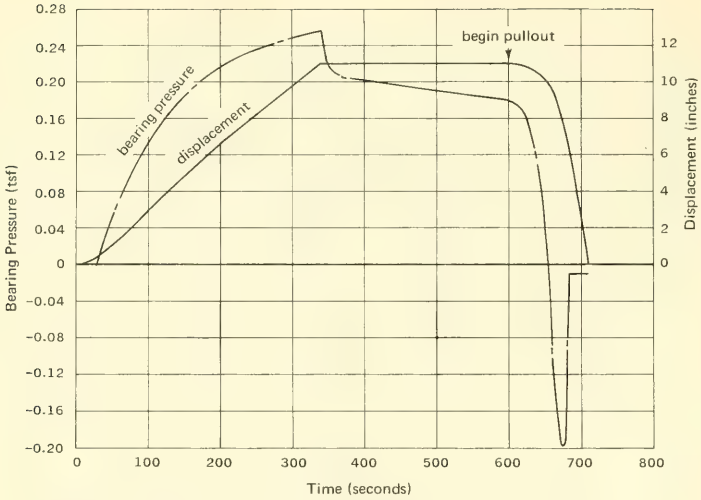

Figure 11. Typical curves for bearing pressure and development versus time.

Data Analysis

Of interest in the analysis of the plate bearing test data is the relationship between bearing pressure and plate settlement. Parameters which may be significant in affecting this relationship are the plate settlement rate, the shape of the plate, and the plate width or diameter. In order to determine the effect of each parameter on the test results, various tests in which only one parameter was varied were compared.

Figures 12 and 13 present representative comparisons of pressure—settlement curves on the basis of settlement rate (SC-18 and SC-19) and plate shape (SC-17 and SC-29). Figure 13 also presents curves for two tests (SC-20 and SC-29) with essentially identical parameters. The variation between the last two curves may be taken as typical of the data scatter inherent in the test program. As may be seen from these figures, the variation among test results in which the testing rate differs by a factor of 2.5 or in which the plate shape varies from round to square is of the same order as the variation between the results of two tests with the same parameters. On the basis of these and other results from this test series, it was concluded that the plate shape and testing rate do not have an important effect on the pressure—settlement curves for tests run with the range of parameter values considered here on cohesive marine sediments. This is in line with the conclusion of Reference 1.

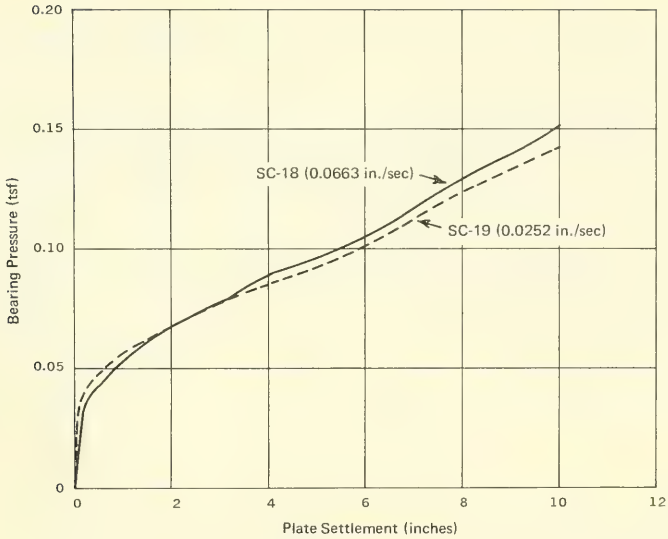

Figure 12. Bearing pressure versus plate settlement, indicating lack of testing rate effect, Series III.

Figure 14 presents a comparison of the Series III test results on the basis of plate size. Each pressure—settlement curve shown represents an average of the curves for a particular plate diameter or width for tests SC-17 through SC-29. The results of tests SC-1 thorugh SC-16, which were considered to be less accurate because of instrumentation difficulties, are not included although their trend does not differ from that of the later test results.

A significant feature evident from Figure 14 is that the plate size does not seem to be an important parameter in determining the pressure—settlement curves at this test site. The variation among these curves is not any greater than the variation among curves for tests with identical parameters. This trend is considerably different from the observed behavior at the Series I site where settlements consistently increased with plate size for the same bearing pressure.

Figure 15 presents the four usable pressure—settlement curves for the Series IV tests. If, as suggested by earlier results, the effect of settlement rate is neglected, then the results of these tests performed with four different plate sizes present another opportunity to compare curves on the basis of

size. As may be seen in the figure, the results are inconsistent although there may be a slight trend toward greater settlement at a particular pressure for larger plates.

In summary, test Series I indicated a definite increase in settlement with plate size at constant pressure, test Series III indicated no size effects, and test Series IV was inconclusive. It is felt that these relations may be attributed to the variation of soil parameter depth distributions from site to site.

In the following sections a scheme for correlating the results of in-situ plate bearing tests with those of laboratory tests on core samples will be presented, and an empirical procedure for predicting settlements will be developed.

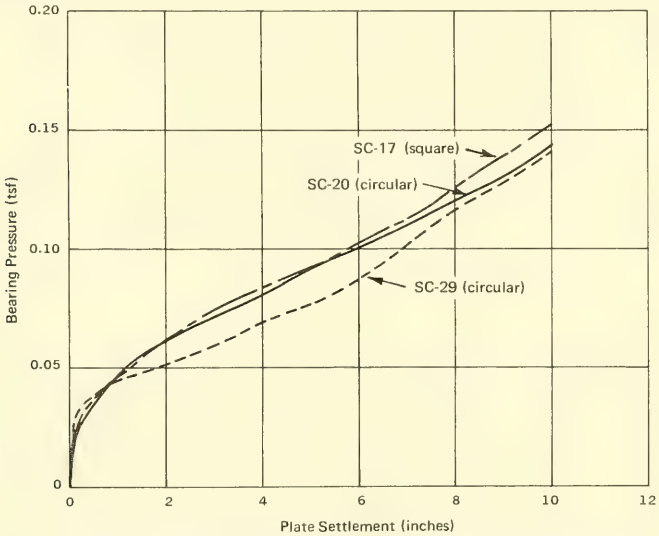

Figure 13. Bearing pressure versus plate settlement, indicating lack of plate shape effect, Series III.

CORRELATION OF TEST DATA

Theory

In order to gain a better understanding of the physical processes governing the results of these tests and to develop general techniques for predicting immediate settlements of actual foundations, an attempt was

made to interpret the in-situ test data in terms of measured sediment properties. A purely statistical approach was considered initially but was dismissed in favor of the two approaches presented below. They are highly approximate and include statistical concepts but retain a few of the solid mechanics characteristics thought to be involved in the plate penetration process. These two approaches utilize respectively small and large displacement theory. For small displacements and loads the behavior of saturated soil has been found to be essentially elastic; that is, its stress—strain behavior is approximately described by a unique, reversible relation. For sufficiently small strains this relation is almost linear, and the theory of linear elasticity is applicable. For large loads a situation of steadily increasing strain at constant stress develops. The stress necessary to produce this behavior is known as the failure stress or strength, and a soil media which has been stressed to this point is analyzed according to limiting equilibrium or plastic theory. In soil engineering the foundation load which will cause failure to occur along continuous surfaces in the subsoil is defined as the bearing capacity.

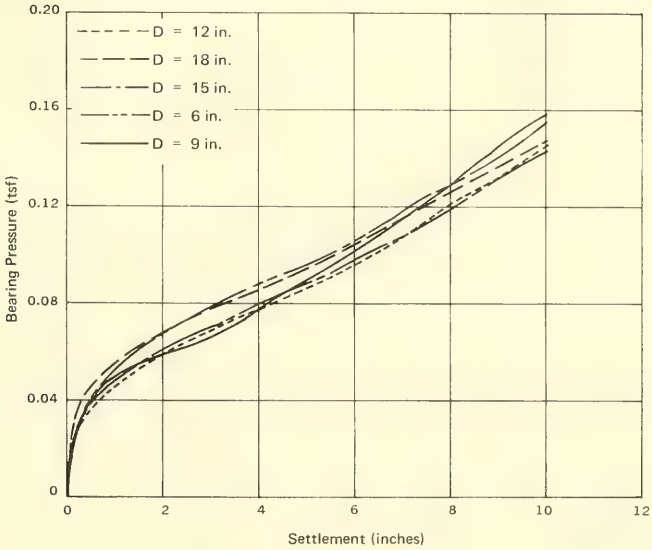

Figure 14. Bearing pressure versus plate settlement for tests at Series III site.

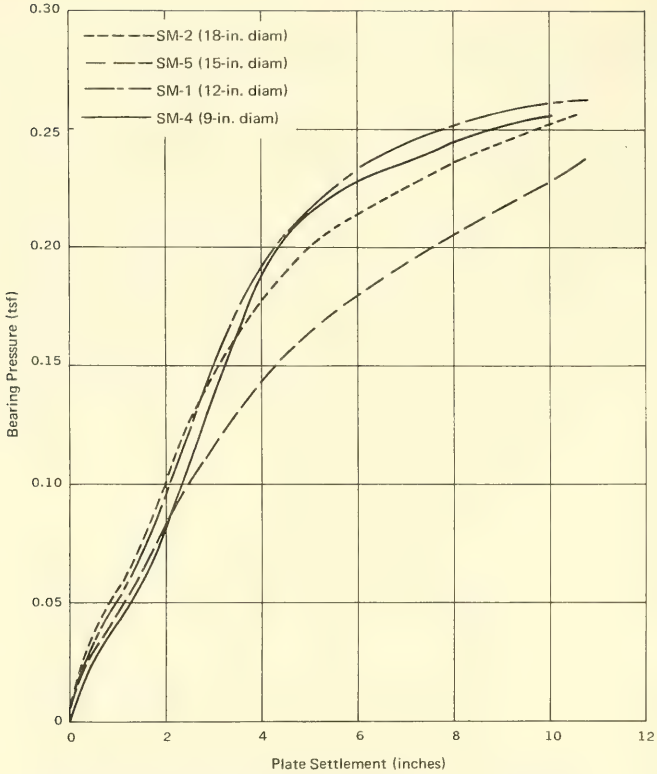

Figure 15. Bearing pressure versus plate settlement for tests at Series IV site.

It was originally felt that the plate bearing data would lend itself to analysis by elastic theory for relatively small stresses and by bearing capacity theory for relatively large stresses. For intermediate stresses it was anticipated that some sort of empirical relation would be required. The following sections present the development of these two approaches to the point at which their predictions may be checked with the in-situ test data.

Elastic Theory

An elastic theory solution often applied to soil mechanics is the Boussinesq Equation for the stresses and displacements beneath a point load applied at the surface of a semi-infinite, homogeneous, linearly elastic solid.

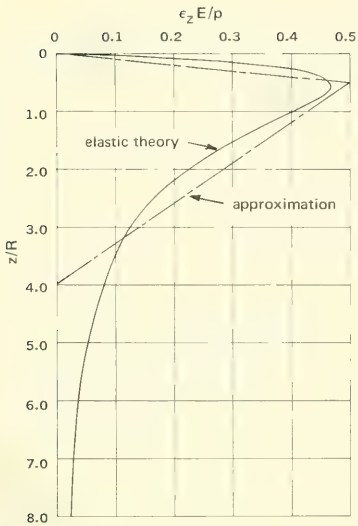

Figure 16. Normalized vertical strain versus dimensionless depth.

By expressing this equation in terms of differentials, it is possible to integrate it over a section of the surface and determine the stresses and strains beneath a loaded area. This has been done for a circular area, and the results are presented in the literature.[4] One representation of these results is given by Figure 16 in the form of an average normalized vertical strain plotted versus a dimensionless depth. The normalized strain is expressed by the quantity

$$\frac{\epsilon_z E}{p}$$

where ϵ_z = vertical strain at depth z (averaged over the range of radial offset distance 0 to R)

E = modulus of elasticity

p = plate bearing pressure

R = radius of loaded area

In obtaining this quantity, an incompressible material, that is, a material with Poisson's ratio equal to 0.5, was assumed.

Two general characteristics of this relationship are of interest. First, the normalized strain is predicted to be identically equal to zero at the surface. This effect is primarily a result of the incompressibility assumption and will be rapidly altered as drained compression or consolidation begins to occur. For the small time span involved in the plate bearing test, however, this effect will probably persist, at least with fine-grained soils. The second feature of interest indicated by Figure 16 is the occurrence of a maximum strain at a depth which varies linearly with the radius of the loaded area. Combining this feature with the first implies that the plate penetration process involves pressing a slightly strained soil volume, the thickness of which varies with the size of the loaded area, into a heavily strained zone. The significance of this will be discussed below.

If the soil tested with the plate bearing device were indeed linearly elastic and homogeneous, and if the elastic parameters could be determined, it would be a simple matter to determine settlement, S, in terms of surface load. This would be done by means of a numerical integration of the Figure 16 data according to Equation 1.

$$S = \int_0^\infty \epsilon_z \, dz \tag{1}$$

It may readily be seen that this would lead to a linear relationship between settlement and plate width, a well-known result which has been presented in the literature[5] and which was discussed in an earlier report on the plate bearing device.[1] Unfortunately, this relationship apparently does not apply to any of the plate bearing test data. This is best exemplified by the Series III data in which settlement was found to be independent of the plate width.

It is felt that these deviations are produced by variations in soil stiffness with depth. According to the data presented in Figure 16, as the plate radius, R, is increased, the thickness of the zone of high normalized strain increases linearly. With a constant modulus this results in a linear increase in settlement. However, the depth below the surface of the zone of high normalized strain also increases, as noted above. If the modulus should increase with depth, then, by the definition of normalized strain, the actual magnitude of strain would decrease. It may be seen that if the modulus increases linearly from a value of zero at the surface, the magnitude of the strain produced will decrease with plate size at exactly the same rate as the thickness of the strained zone increases. The net effect is an amount of settlement which is independent of plate width. If the modulus has a non-zero value at the surface and also increases with depth, an intermediate settlement—plate width relationship results. Qualitatively, these results compare well with the plate bearing data, assuming vane shear strength to be an indicator of soil stiffness.

Analytically this sort of behavior may be predicted by allowing the soil stiffness, as reflected by the elastic modulus, to vary linearly with depth.

$$E = K(H + z) \tag{2}$$

where K and H are constants which relate E to z.

For the sake of simplicity the exact elastic theory solution may be replaced by an approximate relationship which is plotted in Figure 16 and expressed analytically as follows:

$$\left.\begin{aligned} \epsilon_z \frac{E}{p} &= 2\,\frac{z}{D} && 0 \leqslant z \leqslant \frac{D}{4} \\ &= \frac{4}{7}\left(1 - \frac{z}{2D}\right) && \frac{D}{4} \leqslant z \leqslant 2D \\ &= 0 && 2D \leqslant z < \infty \end{aligned}\right\} \qquad (3)$$

where D is the plate diameter.

Substituting Equation 2 into Equation 3 and integrating according to Equation 1 yields the solution:

$$\frac{SK}{p} = 2\left(\frac{H}{D}\right)\ln\left[\frac{H/D}{(H/D) + (1/4)}\right] + \frac{2}{7}\left(2 + \frac{H}{D}\right)\ln\left[\frac{(H/D) + 2}{(H/D) + (1/4)}\right] \qquad (4)$$

This relation is plotted in Figure 17. It should be noted that this is not an exact theoretical solution because of the approximations involved in Equation 3 and the violation of the Boussinesq homogeneity assumption. The trends displayed by this solution and summarized below should be correct, however.

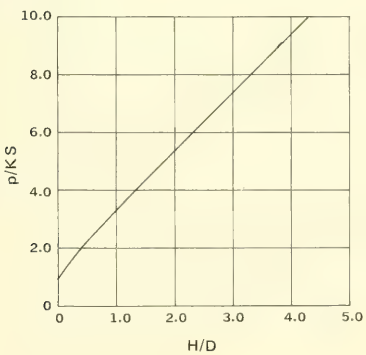

Figure 17. Plot of Equation 4 relation.

1. The settlement, S, varies linearly with the surface pressure, p, and the inverse of rate of stiffness increase, 1/K.

2. S is a nonlinear function of the quantity H/D. If H, which is an indicator of the stiffness at the surface, is equal to zero, then S is independent of D. As H increases, S becomes more and more dependent on D.

These results also seem to be qualitatively correct. However, since it is not possible to determine directly elastic parameters for the soils under consideration using available data, an

exact quantitative evaluation cannot be made. It will, therefore, be necessary to resort to empirical correlations in order to obtain practical results for engineering analysis.

Empirical Derivation of Elastic Coefficients

It has been suggested that the modulus of elasticity of soil varies approximately linearly with the undrained shear strength.[6, 7]

$$E = Ac \tag{5}$$

where A = constant of proportionality

c = undrained shear strength of soil

For the nonlinear stress—strain curves of typical soils, secant moduli, which are functions of the stress state, are often substituted for E. Using the bearing pressure p as a measure of the stress state, Equation 5 may be rewritten as

$$E(p) = A(p)\,c \tag{6}$$

where $E(p)$ = secant modulus as a function of p

$A(p)$ = coefficient of proportionality, also a function of p

If the shear strength is assumed to vary linearly with depth, then

$$c = K'(z + H') \tag{7}$$

where K' and H' are soil profile parameters.

Combining Equations 2, 6, and 7 yields

$$A(p) = \frac{K}{K'}\left(\frac{H + z}{H' + z}\right)$$

$A(p)$ should be independent of z. Therefore,

$$H = H' \tag{8}$$

and

$$K = A(p)\,K' \tag{9}$$

The function A(p) may be evaluated empirically from the test data as follows: K′ and H′ may be estimated using a linear least squares fit of the vane shear strength versus depth data. Since K′ and H′ may vary depending upon the range of depths considered, a reasonable rule is to consider only the data between z = 0 and z = 2 D, the assumed region of stressing. With H′ = H known, any set of D, p, and S values obtained using the plate bearing device will determine a quantity K according to Equation 4 (Figure 17). This K divided by K′ will yield a quantity A(p).

Values of A(p) were calculated for each plate diameter or width tested at each site using the average pressure—displacement curves. For any given value of p, it was found that the experimentally determined values of A(p) were distributed approximately normally. Assuming that these values were indeed random samples from a population with a normal distribution, the statistical characteristics of future tests were estimated. The expected value of A(p) for a particular pressure at a future test site was taken to be the average of the previously calculated values of A(p) for that pressure. This quantity, plotted versus p in Figure 18, is statistically the best possible prediction on the basis of these data. It may be incorrect, however, and the magnitude of error which may occur is indicated by the 95% confidence limits shown in Figure 18. The probability that a value of A(p) obtained in a future test will lie within these limits is 0.95. The limits were calculated on the basis of the scatter of the experimental data using statistics theory.

Figure 18 may be applied as follows: The expected value of A(p) is taken from the graph and used to calculate the expected settlement. Values of A(p) taken from the 95% confidence limits curves are used to estimate the range of settlement values which can be expected.

Two characteristics of Figure 18 should be noted.

1. Except at very low pressures, the range of data scatter is small considering the usual magnitude of error present in settlement prediction schemes.

2. The amount of data scatter varies inversely with pressure.

Therefore, it may be concluded that for relatively large pressures the errors introduced by the various assumptions which led to Equation 4, including the violation of the Boussinesq assumption, are small.

Bearing Capacity Solution

Skempton[8] has proposed the following equation for the bearing capacity of an embedded rectangular footing with width B and length L.

$$p = 5c\left(1 + 0.2\,\frac{D_f}{B}\right)\left(1 + 0.2\,\frac{B}{L}\right) + \gamma_s D_f \qquad (10)$$

where p = plate bearing pressure

c = average soil shear strength along failure zones

D_f = depth of embedment

γ_s = unit weight of soil (submerged unit weight if under water)

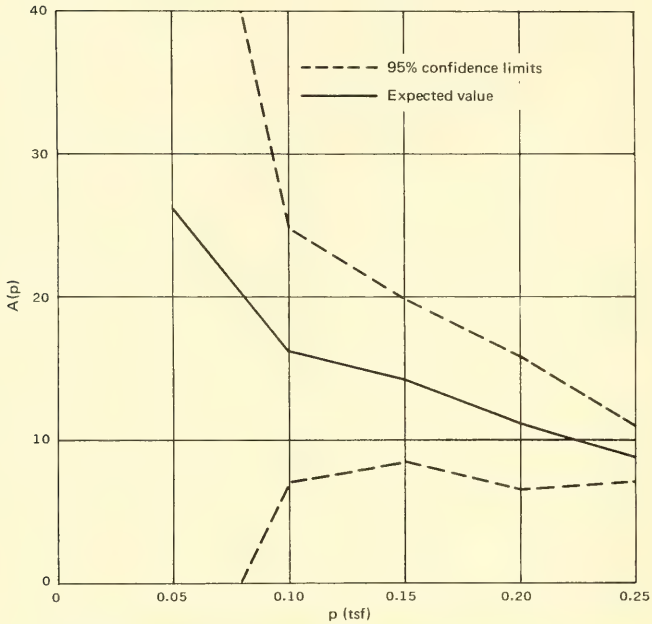

Figure 18. Statistical presentation of parameter A(p) as a function of bearing pressure, p.

Applying this to the plate bearing device with a plate settlement S yields

$$p = 6c\left(1 + 0.2\,\frac{S}{D}\right) + S\gamma_s \qquad (11)$$

where D is the plate width or diameter.

Considering that most of the soil bearing capacity resistance is derived from nearly circular failure surfaces extending below the base of the footing, the quantity c may be taken as the shear strength at the depth D/2 below the footing base. If the shear strength is assumed to vary linearly according to Equation 7, then Equation 11 may be rewritten as

$$p = 6K'\left(S + \frac{D}{2} + H'\right)\left(1 + 0.2\,\frac{S}{D}\right) + S\gamma_s \qquad (12)$$

In addition to being the bearing capacity equation for a plate which has settled an amount S, the above may also be interpreted as a pressure—settlement formula for pressures in excess of the surface bearing capacity (that is, the bearing capacity for S = 0). For example, if the soil and plate parameters γ_s, H′, K′, and D are known and if a settlement S greater than zero is assumed, then a value of p may be obtained from Equation 12. If this pressure is applied to the plate at the surface, the bearing capacity will be exceeded and the plate will begin to settle. When it has settled an amount S, the pressure will just equal the bearing capacity and equilibrium will be established. Equation 12, therefore, can be used to predict settlements for relatively large bearing pressures.

Comparison of Solutions

A specific example was chosen for the purpose of comparing the elastic and bearing capacity solutions. The settlements corresponding to the 0.125-tsf bearing pressure level were obtained from the Series III average results; and the quantity p/S, derived from these results, was plotted versus the plate size D in Figure 19.

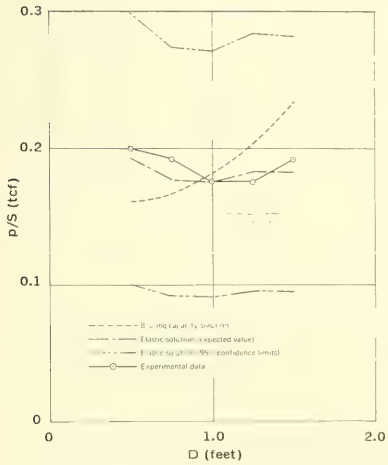

Figure 19. Comparison of experimental data with elastic and bearing capacity solutions (Series III, p = 0.125 tsf).

Predictions of p/S for this situation, obtained using both the elastic and bearing capacity solutions, are also presented in Figure 19. The bearing capacity values were calculated according to Equation 12 using the soil parameters derived from a least squares fit of the vane shear strength data of Figure 9. The elastic predictions including confidence limits were obtained from Equations 8 and 9 using Figure 18 for the expected value and 95% confidence limits of A(p).

As may be seen from Figure 19, both the expected settlements predicted by the elastic solution and the settlements predicted by the bearing capacity solution closely approximate the

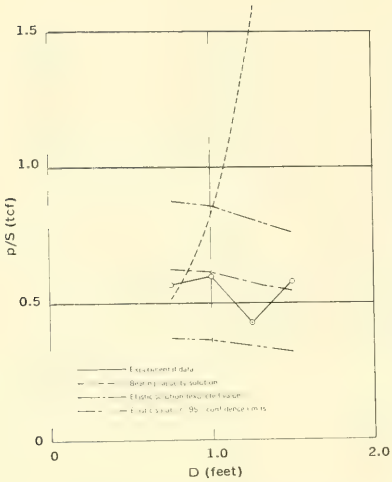

Figure 20. Comparison of experimental data with elastic and bearing capacity solutions (Series IV, p = 0.15 tsf).

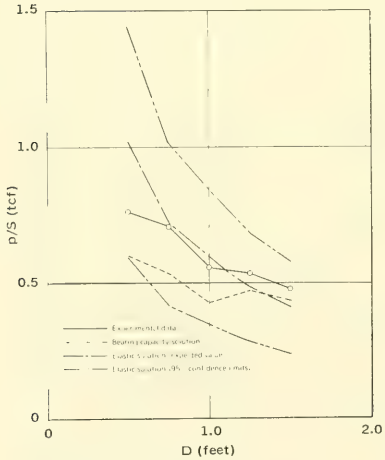

Figure 21. Comparison of experimental data with elastic and bearing capacity solutions (Series I, p = 0.20 tsf).

experimentally determined values. The largest error is only about 20%, a small value for a settlement estimating technique. The major difference between the two results lies in their trends. The elastic result follows the experimental data along a horizontal line whereas the bearing capacity curve diverges from the data for larger values of D. This is probably because the surface bearing capacity pressure–settlement equation is no longer valid.

Two additional examples are given in Figures 20 and 21. The first, for a particular pressure at the Series IV site, presents the same characteristics which were apparent in Figure 19. Both solutions give good predictions for small D; but as D increases, the bearing capacity curve diverges while the elastic curve follows the data. Here the bearing capacity curve diverges even more rapidly than for the last example.

The example of Figure 21 for a given pressure at the Series I site shows good correlation for both prediction schemes.

In general the following comments may be made about the two schemes presented here:

1. The bearing capacity equation is only valid for certain relatively high pressures. However, for these values no additional empirical coefficients are needed in order to obtain relatively good predictions. This solution would probably provide acceptable predictions at sites with considerably different soil profiles.

2. The elastic theory equation with empirical coefficients is valid for all of the data obtained so far. However, because it is empirical, it might not provide accurate predictions at sites with different soils. Also there is no theoretical justification for applying elastic theory to problems with pressures near the bearing capacity. The fact that it seems to function well for these three test sites may be due to compensating errors.

For field predictions settlements should be calculated using both procedures. If the trend followed by the data of these three test series is continued, the settlement predicted by the bearing capacity solution will either lie within or below the 95% confidence limits of the elastic solution prediction. In this situation the elastic solution will give the most conservative and probably the most nearly correct estimate. However, if the bearing capacity solution yields a larger settlement than the elastic solution upper confidence limit, it is possible that the empirical elastic coefficients are no longer applicable. The bearing capacity solution should then be used as the more conservative result.

APPLICATION

Summary of Settlement Prediction Scheme

The following scheme is suggested for predicting the immediate settlement of a round or square footing at a seafloor site where the distribution of vane shear strength with depth has been measured.

1. Fit a straight line through the vane shear strength data according to the principle of least square. The line will have a slope and intercept K' and H' defined by the equation

$$c = K'(H' + z)$$

where c = vane shear strength

z = depth below surface

Only the vane shear strength data for the depths $z = 0$ to $z = 2D$ should be considered. (D = plate width or diameter.)

2. Calculate the quantity H/D letting $H = H'$. Use this value to obtain p/KS from Figure 17.

3. For the design footing pressure p, determine the expected value and confidence limits of $A(p)$ from Figure 18.

4. Find the expected value and confidence limits of the parameter K according to the equation

$$K = A(p)\,K'$$

5. Multiply the quantity p/K S obtained in Step 2 by the values of K calculated in Step 4 to obtain values of p/S. Invert these and multiply by p to obtain the expected value and 95% confidence limits of the settlement S.

6. Recalculate S according to the bearing capacity equation (Equation 12).

7. Use either the upper confidence limit of S from Step 5 or S calculated from Step 6, whichever is larger, as a conservative design settlement. The expected value of S calculated from Step 5 will usually give the most nearly correct estimate of the settlement.

Example

Given: An 18-inch-diameter circular footing has a bearing pressure of 0.2 tsf. Least squares fit of vane shear strength data has yielded the parameters $K' = 0.02$ tcf and $H' = 0.45$ foot. Average submerged unit weight of soil is 0.01 tcf.

Calculate: Expected immediate settlement.

Solution: (Step numbers are the same as those used in the discussion above.)

1. $K' = 0.02$ tcf and $H' = 0.45$ foot

2. $H'/D = 0.45/1.50 = 0.30$

From Figure 17, $p/KS = 1.75$

3. From Figure 18, $A(p)_{expected} = 11.1$

$A(p)_{UCL} = 15.8$

$A(p)_{LCL} = 6.5$

where UCL = upper confidence limit

LCL = lower confidence limit

4. $K_{expected} = (11.1)(0.02) = 0.222$ tcf

$K_{UCL} = (15.8)(0.02) = 0.316$ tcf

$K_{LCL} = (6.5)(0.02) = 0.130$ tcf

5. $(p/S)_{expected} = (0.222)(1.75) = 0.389$ tcf

$(p/S)_{UCL} = (0.316)(1.75) = 0.553$ tcf

$(p/S)_{LCL} = (0.130)(1.75) = 0.228$ tcf

$S_{expected} = 0.514$ foot $= 6.2$ inches

$S_{LCL} = 0.360$ foot $= 4.32$ inches

$S_{UCL} = 0.876$ foot $= 10.50$ inches

6. Check result with bearing capacity solution. Insert the following values into Equation 12:

$K' = 0.02$ tcf	$D = 1.5$ feet
$p = 0.20$ tsf	$\gamma_s = 0.01$ tcf
$H' = 0.45$ foot	

Solve resulting quadratic equation to find S

$$S = \mathbf{0.362\ foot} = \mathbf{4.3\ inches}$$

This is smaller than S_{UCL} calculated using the elastic solution. Therefore, the elastic result is the more conservative value. The solution to the problem is:

$$S_{expected} = \mathbf{6.2\ inches}$$

expected range of S: 4.32 inches $< S <$ 10.50 inches.

FINDINGS

The Device

1. A useful tool, capable of determining, in situ, the short-term bearing pressure—settlement response of marine sediments loaded by a variety of plates, was developed and successfully tested in cohesive sediments to a water depth of 6,000 feet.

2. All major components of the in-situ plate bearing device operated satisfactorily.

Test Results

1. Neither the shape of the plates (whether round or square) nor the plate settlement rate, within the range imposed, appeared to have a significant effect on the bearing pressure—settlement relationship.

2. The plate size appeared to have no effect on the bearing pressure—settlement relationship at the Series III site and to have an inconsistent effect on the relationship at the Series IV site. This behavior, which conflicts with some generally accepted soil mechanics concepts, is thought to be partially attributable to the soil shear strength profiles existent at the two sites.

3. At the Series III site soil strength increased approximately linearly with depth from a value near zero at the surface. At the Series IV site strength also increased linearly with depth but from a distinctly non-zero surface value.

Data Analysis

1. The data obtained in the two test series reported here and in a cohesive soil test series reported earlier may be analyzed in terms of elastic theory and bearing capacity theory.

2. The elastic theory solution was utilized successfully in analyzing all of the plate bearing data considered. However, the use of empirical relations between elastic parameters and shear strength data based on the plate bearing test results was found to be necessary.

3. Bearing capacity theory was successfully applied to the test data for relatively high bearing pressures. No additional empirical correlations were needed for this application.

4. A suggested technique for predicting immediate settlements was developed and presented.

CONCLUSIONS

1. The equipment described in this report provides a means of obtaining information on the short-term response of marine sediments to surface-loaded footings.

2. The data obtained may be analyzed using modified versions of current theory for terrestrial soils. The most significant factor affecting the application of these theories is the distribution of soil shear strength with depth.

3. Procedures for predicting the short-term settlement of footings on the seafloor using the results of laboratory tests on sediment core samples may be developed on the basis of the program which has been presented here. Because of the limited extent of this program, however, these procedures should be considered as tentative.

RECOMMENDATIONS

1. A substantial number of plate bearing tests should be run on different cohesive soils. The deep sea pelagic oozes would be of particular interest. Additional experimental results would be used to check the settlement prediction procedures presented here and to provide a basis for any modified procedures.

2. Additional tests should be performed on noncohesive sediments.

3. Some test results should be obtained for footings larger than the maximum size which the plate bearing device accommodates in order to examine further the possibility of extrapolating the plate bearing test data from smaller to larger footings.

Appendix

REDUCTION OF TAPED DATA

The FM signals containing the deflection, load, and attitude transducer output for each test were multiplexed with a carrier frequency on one channel of a magnetic tape. This taped data was processed by the NCEL analog to digital conversion (ADC) system.[9] This facility is capable of sampling analog data such as this at a specified rate over a given time range and storing it as digital data on the disk of an IBM 1620 System. The sampling procedure was as follows:

1. The tape was played through a discriminator with a time scale of 32 times real time and all of the signals but one (for example, the load) were filtered out.

2. This signal was in turn modified by a low pass filter which was used to remove some of the noise present.

3. The point on the tape at which sampling was to be initiated was marked by a key on an unused channel. When this key was reached, the ADC System began sampling at a predetermined rate (usually 25 to 50 samples per 32 seconds real time) and continued until a given number of samples had been taken. This number was based on the estimated test length (usually 10 to 20 minutes).

This process was continued for all of the data on a channel with each element of data being stored on the disk. The data was then automatically punched on computer cards with a format directly acceptable to the IBM 1620 System. Each card had 24 three-digit samples. The first digit of each sample was always flagged (that is, had a minus sign superimposed on it), and the last digit was flagged if the sample were negative.

A general system of routines (with the acronym SUPER)[10] was devised for scaling and subsetting ADC data and plotting one set (for example, load) versus another (for example, displacement). However, because of noise and calibrate phases, the data obtained according to the procedure described above was not in the correct form for accurate plotting. It was necessary to edit out this extraneous information and substitute in its place more appropriate data. This was accomplished with a program written for this purpose with the acronym ADEDIT.[11] This routine is capable of changing any ADC data element value to any other value and producing a new computer card deck. It was modified so that a series of data elements could be removed at once and replaced by a series of linearly varying elements. In this way a calibrate signal or a region of noise could be replaced by a straight line.

To correctly plot this data, the SUPER routines required the submission of certain calibration and subsetting parameters. For calibration the voltage corresponding to some known situation (for example, full deflection or 80% full load) and the voltage for a zero reading were needed. These were taken directly from a listing of the ADC data. The required subset information included the sequence numbers of the first and last samples to be plotted. With these available for each test, the SUPER routines produced graphs of load or bearing pressure versus deflection using the on-line plotter associated with the NCEL IBM 1620 System.

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LIST OF SYMBOLS

A	Coefficient relating shear strength to elastic modulus (dimensionless)
A(p)	A as a function of the bearing pressure p
B	Rectangular footing width
c	Undrained shear strength of soil; average soil shear strength along failure zones
D	Plate diameter or width
D_f	Depth of embedment of footing on plate
E	Modulus of elasticity
E(p)	E as a function of the bearing pressure p (secant modulus)
H, K	Parameters which define a linear depth—modulus of elasticity distribution. (H has the dimensions of a length; K, the dimensions of a force per unit volume.)
H', K'	Parameters derived from a linear fit of a shear strength—depth distribution. (H' has the dimensions of a length; K', the dimensions of a force per unit volume.)
L	Rectangular footing length
p	Plate bearing pressure
R	Radius of loaded area
S	Plate settlement
z	Depth
γ_s	Soil buoyant unit weight
ϵ_z	Vertical strain

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