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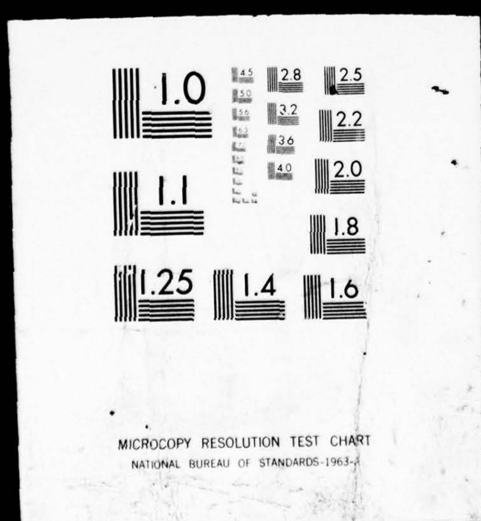

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The results of field testing propellant-actuated embedment anchors are presented. A large number of field tests were run in which 9 x 18-inch anchors were fired or pushed into a very soft, moderately sensitive clayey silt. A comparison is made between the predicted and observed holding capacities. The measured short-term holding capacities of these anchors were 75 to 85% of those predicted. This reduction in capacity could not be attributed to sediment disturbance during anchor penetration, but is thought to result

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primarily from sediment disturbance during anchor keying. Sediment disturbance during penetration does have a significant effect on anchor keying distance and, depending on the sediment strength profile and penetration, has an indirect effect on anchor holding capacity. A recommendation is made to reduce the computed holding capacity by 20% for anchors in the field.

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1. Embedment anchors 2. Sediment disturbance I. YF52.556.999.01.103

The results of field testing propellant-actuated embedment anchors are presented. A large number of field tests were run in which 9 x 18-inch anchors were fired or pushed into a very soft, moderately sensitive clayey silt. A comparison is made between the predicted and observed holding capacities. The measured short-term holding capacities of these anchors were 75 to 85% of those predicted. This reduction in capacity could not be attributed to sediment disturbance during anchor penetration, but is thought to result primarily from sediment disturbance during anchor keying. Sediment disturbance during penetration does have a significant effect on anchor keying distance and, depending on the sediment strength profile and penetration, has an indirect effect on anchor holding capacity. A recommendation is made to reduce the computed holding capacity by 20% for anchors in the field.

CONTENTS

INTRODUCTION

Objective

The objective of this study was to improve the accuracy of predictions for embedment anchor holding capacity in soft, cohesive deep-ocean sediments. The specific objectives were to evaluate the reduction in sediment strength produced by penetration of a propellant-actuated anchor fluke, the subsequent recovery of this strength, and the effect of these sediment strength changes on anchor holding capacity. Any improvement in the reliability of embedment anchor holding capacity predictions should enable one to design more accurate and less costly ocean facilities employing embedment anchors.

Background

Propellant-driven anchors have recently been developed for resisting high-capacity uplift forces in a deep-water environment (Taylor et al., 1975). This type of anchor is highly attractive for many special applications where large uplift forces are to be resisted and movement of the anchor from its position of implant is not desired. In many of these applications it is not cost effective nor is it practical to trade off the uncertainty of anchor holding capacity with additional or larger anchors. Therefore, it is necessary to be able to accurately forecast anchor holding capacity.

A theory for predicting the holding capacity of embedded anchor flukes has been developed by Beard and Lee (1976). The validity of this theory has been established primarily by laboratory testing of model anchor flukes embedded in soft cohesive sediments similar to those found in deep-water environments. In these tests, where the soil characteristics in the vicinity of the anchor fluke were accurately known, the holding capacity prediction has a lower confidence limit of 19% with a reliability of 95%. This means that there is a 97.5% chance that the measured capacity will be above the lower limit (Beard, 1976). In a real field situation this high level of accuracy will not apply. Both the embedment depth and soil characteristics at that depth will have to be estimated or calculated. Furthermore, the rapid penetration of the anchor fluke disturbs the soil and has been suspected of reducing anchor holding capacity through a reduction of sediment strength. This alteration of undisturbed sediment characteristics is known to exist, but it has not been studied and is the subject of this investigation.

TEST PROGRAM

It was possible to study the phenomenon in a number of ways. The method chosen was to test an anchor with a scaled-down fluke and smaller firing mechanism on land or in a tidal area in soft sediments. This approach was desirable and cost-effective because the site was acessible and anchor pullout could be easily controlled. This permitted a high accuracy of measurements during the tests and a significantly higher quantity of tests could be run.

Previous testing (True, 1975) in the San Pablo Bay mud flats along the Mare Island Naval Shipyard in Vallejo, California, indicated that the characteristics and depth of sediments in this area were desirable for the proposed testing.

A preliminary site investigation was made in May 1975 to confirm which site at this test area was most suitable. Coring and strength testing determined that the original (most accessible) site chosen for the tests was not suitable, and that the testing would have to be held on the mud flat itself. This testing was carried out in August and September 1975. Aircraft matting was laid over the mud flat to provide a working surface from which to operate. Vane shear tests were made at each embedment anchor location to establish a shear strength profile. Continuous cores were taken at several locations to provide high quality samples for subsequent laboratory testing.

Following these preliminary tests, 9 x 18-inch CEL-style flukes were fired into the sediment using modified Magnavox "Self-Embedment Anchor" equipment (Magnavox, undated) and an 800-pound frame to contain the gun-barrel reaction. After the anchor flukes were fired in, additional vane shear strength tests were made at 1-hour, 24-hour, and 7-day intervals to determine the post-firing strength profile.

The anchors were then pulled out in one of several ways, with force versus vertical movement measured for each anchor. Two other variables studied during the testing were the time the anchor was left in place before being retrieved, and the rate at which the anchor was retrieved (i.e., retrieval at a relatively constant rate or application of a constant vertical force and measurement of anchor displacement with time). In several cases, horizontal anchor displacements were measured.

The original testing program was modified considerably as the tests progressed. A large number of pushed-in anchor tests were made at the start to correct a keying problem inherent in the original fluke design.*

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*This keying problem was also identified as the major cause of low holding capacities found in previous deep-water embedment anchor tests in cohesive sediments; these tests provided the data for the redesign of the flukes.

Critical keying parameters were varied over a wide range of values to provide data for future fluke design and to produce an anchor that would work properly for these tests.

FIELD TESTS

Strength Tests

Vane shear strength profiles were established for 43 locations at Mare Island. The profiles extended to a depth of about 5 feet below the level at which the fired-in anchor flukes came to rest. The tests were taken at 0.5-meter intervals with an 18-cm-long by 8-cm-diameter vane. The standardized procedure followed was to penetrate the vane to the desired depth, and then rotate it at approximately 5 degrees per minute until a strength peak occurred. The vane was subsequently rotated 720 degrees to remold the sediment along the shearing plane, and then a second vane shear strength reading was immediately made at 5 degrees per minute. (The field equipment used allows the torque due to shear along the vane rod to be subtracted from the total torque measurement.)

In a significant number of these tests the vane was left in place, and additional tests were made at times which varied up to 3.7 days following the initial tests. This allowed the soil in the immediate vicinity of the vane to regain strength and adjust to the presence of the vane. After some of these tests the sediment was again remolded, and another shear test was made. These time variations were designed to separate the regain of vane shear strength with time from the effect of the presence of the vane on the strength regain process. An increase in shear strength after the second remolding is considered primarily as an indication of the latter.

The purpose of the majority of the vane shear tests, however, was to establish vane shear strength profiles before and after the anchors were fired. These were used to determine strength loss and subsequent recovery in the vicinity of the anchor flukes due to the penetration of the fluke. Such a profile was taken at the immediate site prior to firing. A second vane shear profile was taken after the firing, some 14 to 24 inches from the place of penetration. These measurements were normally made between 30 and 60 minutes after the firing due to the necessity of moving major pieces of equipment and the length of time it takes to run the test. At most sites a third profile was made approximately 24 hours after the firing in a new location but at the same radial distance from the point of firing. At some sites a fourth profile was made 4 to 7 days after the firings, again at a new location the same radial distance from the point of firing as the previous post-firing tests. A few vane profiles were taken at 5- or 10-foot horizontal distances from the point of fluke penetration to examine the lateral extent of sediment strength loss and subsequent gain with time.

Strength measurements were also made on the sediment from cores taken at several sites. A hand-held vane shear device was used to make measurements on the exposed end of the cores. Although these tests were consistent with trends shown by other data, they were discontinued after it became apparent that both the initial and remolded measurements were considerably below the comparable in-situ vane measurements. In most cases they were less than 50% of the in-situ measured values.*

Sediment Cores

Piston cores were taken at seven locations adjacent to sites where anchors were scheduled to be loaded on a long-term basis. These sediments would be the most appropriate for laboratory determination of strength parameters necessary for long-term holding capacity predictions. The sediment core size was approximately 2 inches in diameter by 2.5 feet in length. Coring was done prior to any anchor firings and was continuous over the depth range in which the anchor flukes were expected to come to rest.

Pushed-In Anchors

A short test series was planned for deploying anchors by pushing them through the sediment column to provide holding capacities for comparison with fired-in anchors. However, the number of tests was expanded when it was discovered the anchors as originally designed and constructed would not key in a reasonable distance. As a result, some 20 anchors of the 9 x 18-inch size were pushed into the sediment and subsequently loaded before a satisfactory design was verified. Several minor parameters that influence anchor keying were investigated before it was realized major changes had to be made to the flukes. The final fluke design (shown in Figure 1) incorporated the following three major changes: (1) A hinge was attached perpendicular to the fluke plate on the side opposite the flange to which the anchor cable is attached. The hinge has a small frontal area that resists penetration, but will flop over on its side during anchor pullout to present a large area for resisting pullout. This area assists the keying process by allowing it to take place over a much shorter distance. (2) The distance from the anchor plate surface to the cable attachment point was increased from 4.5 to 7.5 inches. This change increased the keying moment, allowing the fluke to key in a reasonably short distance. (3) The point at which the downhaul cable is attached

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*Laboratory vane measurements on cored sediments were also considerably higher than the hand-held vane values at equivalent depths.

to the anchor was advanced slightly toward the front of the fluke. Previously, it was located in the center of the fluke.

The pushed-in 9 x 18-inch fluke tests are summarized in Table 1. Three of these tests (13, 14, and 17) were made with flukes of the same design as those which were subsequently fired into the sediment. Smaller scale flukes of 3 x 6-inch and 4.5-inch-square sizes were pushed into sediments in the tidal zone adjacent to the major test site previously described. The three flukes shown in Figure 2 were used. Hinge size and location of the attachment point for the anchor cable were varied over a large range of significant values. These flukes were pushed 60 to 67 inches into the softer sediment, and most were immediately pulled out. Some of the 3 x 6-inch flukes were left in the sediment for up to several months duration to evaluate the effect of time on keying and to expand the knowledge gained from similar tests with the 9 x 18-inch anchors. These tests are summarized in Table 2.

A laboratory test series was performed during the same time period as the Mare Island tests. Flukes, 3 x 6 inches, were pushed into soft cohesive sediments prepared in the soil laboratory at CEL (Minardi, 1975). These tests served as an initial guide for determining what parameters should be varied in the testing at Mare Island. However, direct comparison of these data with the field tests is inadvisable due to major differences in the sediments. The comparatively rapid preparation of the laboratory sediment (Seal Beach slit) resulted in a test sediment of low sensitivity. It is suspected that sediment sensitivity is a significant characteristic with respect to embedment anchor fluke keying.

Fired-In Anchors

Embedment anchors were fired into the mud flat sediments at 13 locations using leased Magnavox Self-Embedment Anchor equipment. This equipment is designed to fire a different style fluke while submerged in a body of water (Magnavox, undated). Magnavox modified its equipment under a government contract, and CEL-styled flukes were manufactured to be compatible with this equipment. Initial penetration velocities, which were back-figured from recorded gun barrel pressure-time measurements, are estimated to be 150 to 200 fps, The gun barrel pistons remained attached to the anchor cable in line with, and about 7.5 inches from, the point of attachment to the fluke. The time between anchor firing and fluke loading varied from 20 minutes to 8 days. These tests are summarized in Table 3.

Short-Term Anchor Pullout

Anchor cables were loaded against a tripod reaction stand braced to distribute the reaction over a considerable surface area. Vertical movement and horizontal cable motion at the sediment surface were recorded versus cable tension. The speed of cable pullout, while not continuous due to characteristics of the test equipment, was approximately 10 to 20 ipm. Seven of the 13 fired-in anchors were pulled at this rate until they were within several feet of the sediment surface. The tests were terminated when the anchor resistance was considerably below the peak value that occurred immediately following keying. Five of the remaining anchors were withdrawn until keying occurred. At that point the cable tension was removed. Long-term tests were subsequently performed with these anchors. The remaining anchor was not keyed prior to beginning a long-term test.

Long-Term Anchor Pullout

The anchors for the long-term tests were loaded imcrementally until failure occurred. Cable tension was maintained by a weight stand and a series of pulleys suspended from a tripod reaction stand. Tension was increased by adding weights or changing the mechanical advantage of the pulley system. Several months were allowed for the rate of anchor movement to stabilize during each loading increment. Most of these tests have not been completed; the results will be reported at a future date.

LABORATORY TESTING

A number of tests were performed on the sediment cores. The physical properties measured were bulk wet density, specific gravity, natural water content, Atterberg Limits, and grain size distribution. The mud flat sediment was classified as clayey slit with 2 to 5% sand. Laboratory vane shear tests, residual pore pressure measurements, and undrained triaxial shear tests on consolidated sediment samples were also run. These data were used for predicting holding capacities and for comparing in-situ test results. Even though the sediment state varies with depth, for practical purposes the sediment type does not change over the depth range significant to anchor behavior. Laboratory-determined physical properties and field vane shear strength data are summarized in Figure 3.

PREDICTED AND MEASURED ANCHOR PENETRATION

Although prediction of anchor penetration was not an objective of the tests, the controlled firing of the propellant-actuated anchors provided an opportunity to test the accuracy of a recently developed predictive method (True 1975).*

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*The recommended procedure was altered to allow for a nonlinear shear strength profile. This modification is expected to be published in a update of the CEL-recommended calculation procedure.

This method requires one to know initial penetration velocity of the anchor fluke, geometric fluke characteristics, and soil physical properties. The latter two are accurately known for these tests. The initial penetration velocity of the anchor fluke was back-calculated from measured time-pressure characteristics of the gun barrel and dynamics laws. The computed and measured penetration values are shown in Figure 8a. A comparison of the two revealed the calculation procedure to be very accurate, slightly underpredicting the actual penetration.

SEDIMENT STRENGTH REDUCTION AND RECOVERY

The natural condition of a sediment is disturbed where a fluke passes through it and in the immediately adjacent areas. Figure 4 shows the soil profile in plan and section views immediately after a fired-in anchor has come to rest in a sediment mass. The affects of this firing will be discussed in terms of the three soil zones identified in the figure. Zone A is a narrow strip of soil through which the fluke has passed. The soil is physically distorted and momentarily displaced, resulting in a major strength reduction from the undisturbed state. However, after passage of the anchor fluke, the distorted soil occupies basically the same volume as it had previously. Zone C is that small area of soil adjacent to the fluke after it stops moving. Like the soil in Zone A it undergoes major strength reduction due to physical distortion, but this soil remains displaced from its original position. Zone B is the large mass of soil adjacent to Zones A and C that has not been physically distorted, but has been disturbed enough to cause a strength reduction. Note that these "zones" have no distinct boundary between them, but each blends more or less gradually into the next. Zone B, in fact, gradually becomes indistinguishable from the large mass of adjacent sediment that for practical discussion has been unaffected by the firings.

Time-dependent strength regain occurs for saturated cohesive soils (like these mud flat sediments) in each of these zones. In Zones A and C, which have been physically distorted, the strength regain is significant. It results from consolidation accompanying dissipation of excess pore pressures (generated by reorientation of the individual soil particles into a more compact state), and from thixotropic effects (strength increase with time at constant composition). Lambe and Whitman (1969) further describe these effects. Strength regain in Zone C should be more prominent because more consolidation must occur since the soil must occupy a smaller volume. A strength regain with time in Zone B could also be expected, although the magnitude of the increase would be small in comparison to the other zones since the strength decrease was small.

Embedment anchor holding capacity results from the resistance to shearing of soil from a relatively large volume above and below the fluke as illustrated in Beard and Lee (1976). Practically all of this is Zone B soil due to the relatively large size of this zone. While some of this resistance occurs in Zone A soil, Zone C soil is not a factor as the keying process would likely carry the fluke beyond the influence of this zone. Therefore, the slight reduction of strength in Zone B is the most significant factor in any strength-caused reduction of holding capacity. However, while Zone A and Zone C sediments may not contribute much to holding capacity, they do heavily influence the anchor fluke keying behavior. In this sense, they influence holding capacity because an anchor which keys quickly will be in a significantly stronger soil and will develop a higher capacity in soils where strength increases with depth.

A profile of vane shear strength measurements was established before and after the anchor firings. These profiles are shown in Figure 5a with tests from all locations averaged at each depth. Shear strength was consistently reduced over the 2-to-6-meter depth range, displaying post-firing strengths between 91.4 and 98.9% of the pre-firing strength. Further strength recovery after about one day and one week is shown in Figure 5b. Although there is some data scatter, the strength recovery with time is evident.

Although no strength measurements were made in Zone A or could be made in Zone C soil, the strength in these zones was likely to have undergone a major reduction. The immediate reduction may have been on the same order of magnitude as the strengths recorded after purposeful vane remolding (Figure 5a). After the normal sequence of initial shear tests, sediment remolding, and then "remolded" shear tests, time was allowed to elapse before a second "remolded" test was run. A significant time-dependent shear strength increase was noted on all tests. This is illustrated in Figure 6a. After 16 hours an average of over 60% of the strength loss (measured following remolding) was recovered. After 2 days most tests showed a strength of recovery of around 80%. Following a number of these tests, the sediment was again remolded, and a vane shear test taken immediately. These tests, also shown on Figure 6a, showed a remolded strength higher than that value determined immediately after the vane had been inserted and the initial tests run. This recovery averaged 28% of the total recovery noted above. This part of the strength increase is ascribed to consolidation of sediments around the inserted vane due to the presence of the vane blades in a volume previously occupied by sediment.

Strength recovery of soil in the vicinity of the anchor fluke following embedment (Zone C) can be estimated from the recovery of vane shear strength following remolding shown in Figure 6a. In both instances the sediment has undergone a remolding distortion and displacement due to the introduction of a foreign body (the anchor or vane). Strength increase in Zone A will not be as rapid. It can be estimated from the difference between the total recovery and the recovery ascribed to consolidation of sediment around the vane (28% of the total). However, specifying percentage of recovery is speculative because of significant differences in the manner of remolding.

Strength recovery in Zone B, which was directly measured, also occurs with time and is shown in Figure 5. The magnitude of the recovery is small in comparison to Zones A and C because strength loss was slight.

EFFECT OF SEDIMENT STRENGTH RECOVERY ON ANCHOR KEYING

The time an embedment anchor is left in place following deployment and prior to its being keyed has a significant effect on the distance required for keying. Keying occurs over a much shorter distance as this time increases. At Mare Island, identical anchors left in the sediment for 4 to 8 days keyed in approximately one half the distance required for anchors pulled within a half hour of their placement. This is shown in Figure 6b, where all data for similar 9 x 18-inch flukes are plotted. The data show no difference between the pushed-in and fired-in anchors. As an extension of these tests, two 3 x 6-inch flukes (one with and one without a hinge) were pushed into a lower strength Mare Island sediment and were keyed after 5-minute and 68-day time periods. The results were similar; after 68 days both hinged and hingeless anchors keyed in a shorter distance.

These changes in keying distance are evidence that sediment strength regain, which occurs in Zones A and C within the first day, has affected the keying process. The importance of the keying distance is in proportion to the soil-strength profile and penetration depth of the anchor. For an anchor buried in a cohesive sediment more than 4 or 5 times its length, the holding capacity is proportionate to the sediment strength. Because normally consolidated sediments usually display an increase in strength with depth, an anchor which keys in a shorter distance will have a higher holding capacity. Using Figure 5a, for these tests, an anchor which keys in 1.5 times its length will provide a holding capacity approximatley 10% higher than an anchor which keys in 3.0 times its length, and more than 20% higher than an anchor which keys in 4.5 times its length. The magnitude of this holding capacity difference will vary with soil characteristics and embedment depth. Normally anchors whose embedment-depth-to-fluke-length ratios are higher will not shown as strong as effect on their holding capacities. This is because the decrease in shear strength over the keying distance makes up a lower percentage of strength at deeper depths.

The anchor keys because sediment resistance along the fluke creates an overturning (keying) moment at the eccentric point of cable attachment. When strength is reduced due to sediment remolding, this turning movement is also reduced, and the fluke tends to back out in a vertical position within a channel of lower strength sediment (Zone A). As the sediment regains its strength with time, this lower strength channel becomes less distinguishable from the surrounding soil (Zone B).

Anchor behavior during keying can be seen through the plots of vertical and horizontal movement in Figures 7a and 7b. Cable tension initially increases rapidly and then remains constant for a significant distance of vertical movement, as shown in Figure 7a. A second steep tension rise occurs until a peak capacity is reached, roughly corresponding to final anchor rotation into the keyed position. Capacity then decreases but remains constant when the influence of the somewhat stiffer sediment surface is felt. In some cases there is a "double peak" in capacity before the significant decrease occurs. This is believed to be a result of anchor adjustment to overkeying or some eccentricity in its orientation. Where anchors have been left in place for some time prior to keying, there is often an initial tension peak prior to a constant prekeying value.

Figure 7b plots horizontal movement of the anchor versus vertical movement. The measured movements are not consistent from anchor to anchor. One would think that an anchor would move slightly in the direction it keys, and then move more rapidly in that direction when the steep tension climb occurs. This was not the case for most of these anchors. In fact, more show just the opposite. This may be the result of an "other than vertical" fluke orientation when the anchor comes to rest, or it may reflect variable influence of the piston. (The piston, shown on a larger scale in Figure 1, rests on but is not attached to the back of the fluke. It is attached to the anchor downhaul cable.)

EFFECT OF SEDIMENT STRENGTH CHANGES ON ANCHOR HOLDING CAPACITY

Several significant results concerning field holding capacity are apparent from these tests; they are:

(1) The embedment anchor holding capacity in the field is lower than that predicted on the basis of laboratory tests.

(2) The field holding capacity is the same for pushed-in and fired-in anchors.

(3) Holding capacity does not increase with an increase in the time the anchor is left in the sediment prior to pullout. This should not be confused with the effect of time on keying; a higher holding capacity does occur in this situation because the anchor keys in deeper (stronger) sediment.

Figure 8b compares anchor holding capacities predicted by the best available method (Beard and Lee, 1976) using measured sediment properties. The predictions were made on the basis of the formula

$$F_T = N_c A c$$

where F_T = holding capacity

A = fluke area

c = cohesion of soil

N_c = holding capacity factor (A value of 16 was used, which is recommended for deep anchors with suction.)

Holding capacities of pushed-in and fired-in 9 x 18-inch anchors were virtually the same - an average of 78.6 and 80.7%, respectively, of the predicted values. It had been expected that the anchors left in the ground a longer time would show slightly higher holding capacities due to sediment strength regain. This did not happen. The large anchors that were pulled out within a few hours of deployment averaged 81.8% of the predicted value, while those pulled out between 4 and 8 days after deployment averaged 77.4%. The difference is likely the result of the small statistical sample rather than a true reflection of behavior.

The prediction method is semi-empirical and is partially based on laboratory short-term pullout tests. Therefore, the comparison of field to predicted capacities is basically a comparison of field with laboratory short-term pullout tests. There are differences in these tests with regard to fluke size and method of pullout. The laboratory tests on which the predictive theory is based used 3-inch-diameter flukes which were loaded incrementally in a stress-controlled manner. That is, loading was increased and the fluke was allowed to adjust to this increase (for about 5 minutes) before additional load was applied. The tests lasted about 30 minutes apiece. The larger field anchors were pulled out at a rate of 10 to 20 ipm. Although the comparison is not straightforward, in effect this is a considerably higher pullout rate than both the laboratory tests and the field vane shear tests. This higher rate might result in a higher holding capacity if the sediment is sensitive to rate of strain.

The initial data obtained during the long-term tests suggest that an anchor would give a higher capacity by the field short-term method than with a short-term pullout rate similar to the laboratory tests. If this were the case, to neutralize the effect of strain rate sensitivity anchor loading would have to take place at approximately the same rate as the vane shear testing. This was impractical for the field tests. However, results consistent with the laboratory tests being discussed have also been established by other researchers at more rapid or varying pullout rates (Adams and Hayes, 1967; Bemben and Kupfermen, 1971).

There are reasons which may account, at least in part, for the lower-than-predicted capacities. While reduction of strength due to disturbance during penetration was anticipated to be the reason for this behavior, it did not appear to account for the measured decrease. If it were a factor, there should have been a significant increase in holding capacity with sediment strength regain. This did not occur.

However, sediment disturbance during keying is suspected to cause a significant decrease in holding capacity. During keying, the influence of the anchor on the sediment mass expands as the anchor rotates into the keyed position — as the cable tension rises to a peak level. Because sensitive cohesive sediments display a strength peak followed by a significant dropoff during shear much of the sediment contributing to the holding capacity peak value has already been sheared beyond its peak. This is a form of disturbance. Although this type of "progressive failure" also occurred prior to the peak holding capacity for the laboratory anchors (which were placed in the sediment in a keyed position), the disturbance level should have been considerably higher in the field anchors. This could cause part or all of the apparent difference.*

The smaller (3 x 6-inch) anchors, which were all pushed-in, averaged 93.7% of the predicted holding capacity values (Figure 8b). This may or may not reflect a real difference in results from the large anchors. The method used to measure shear strength in that area was relatively crude. The strength profile also showed an anomalous peak in the area where most of these anchors keyed. If it is a true reflection of behavior, it might be ascribed to a scaling factor or to differences in anchor shape.

PREDICTION OF FIELD EMBEDMENT ANCHOR HOLDING CAPACITY

In order to accurately predict embedment anchor holding capacity in the deep ocean, predictions must be made for penetration of the anchor fluke, keying distance of the fluke, and holding capacity of the fluke at its keyed depth. While each of these predictions can be treated independently, to be practical they all must be determined from the firing characteristics of the embedment anchor (to determine the penetration velocity of the anchor fluke), characteristics of the anchor fluke and some knowledge of the properties of the sediment through which the anchor would penetrate and into which it would key. Calculation procedures have been published for the penetration of projectiles into seafloor soils (True, 1975) and for predicting the holding capacity of direct embedment anchors under short-term and long-term loading conditions (Beard and Lee, 1976). Fluke keying has been considered a less significant parameter in the calculations. However, since it has presented some problems in soft cohesive sediments it does require prediction as a link between penetration depth and the depth of the fully keyed anchor fluke.

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*Mare Island sediments are considered to be moderately sensitive. Cohesive sediments in existence on the seafloor are likely to be at least as sensitive.

These field tests have identified problems with the prediction of holding capacity and keying. The short-term holding capacities of these large field anchors were about 20% below the predicted values. In addition, immediate keying of the anchor after placement resulted in holding capacities 10 to 20% lower than those that would have been obtained if the anchors had not been keyed for 24 hours. Also, the manner (speed, load level) in which the anchor is loaded can result in further reductions in the short-term holding capacities.

The prediction procedure must take into account these factors, some of which will vary from one deployment to the next, in order to obtain the most accurate estimate of holding capacity. If the predictive methods are generalized to include a variety of conditions, then loss of accuracy will have to be compensated by conservatisim in the design of embedment anchors. In the interim, design procedures for embedment anchors sited in cohesive ocean sediments should use 80% of the capacity predicted by Beard and Lee (1976) as the expected holding capacity. This holding capacity prediction should be made at the depth where full keying is expected, taking into account the expected method for post-deployment loading. This procedure should be considered tentative until a determination can be made of the influence of any strain rate effect on the field capacities. This may result in lowering or raising the recommended level of 80%.

CONCLUSIONS

1. The measured short-term holding capacities of the large anchors at Mare Island were 75 to 85% of those values predicted on the basis of semi-empirical laboratory data. This reduction in capacity may occur in soft, moderately sensitive cohesive sediments found in deep ocean areas.
2. The lower-than-predicted capacities are not attributable to sediment disturbance which occurs during rapid penetration of fired-in anchors. Pushed-in and fired-in anchors displayed the same average reduction of predicted capacity.
3. The lower-than-predicted capacities can result from sediment strength reduction due to disturbance of the soil mass during the keying process. Scaling and shape factor differences may cause some of the capacity reduction.
4. The time an anchor is left in a moderately sensitive cohesive sediment before it is keyed significantly affects the ultimate holding capacity. The keying distance immediately after placement can be 2 to 3 times that for an anchor left undisturbed for 24 hours, thereby resulting in a 10 to 20% lower holding capacity. Most of the benefit of leaving an anchor undisturbed is attained within the first hour or two after deployment. Almost all is attained within the first day.
5. The lower-than-predicted capacities do not increase measurably with an increase in time the anchors are left in the sediment prior to keying.

6. Vane shear strength of the soil in the vicinity of fluke penetration is reduced by 5 to 10% during anchor firing, but is recovered within a week. These changes had no measurable impact on holding capacity.
7. Vane shear strength reduction in a soil that has been distorted by a penetrating anchor is significant. However, this "lost" strength is regained with time. These changes in strength, particualrly in the immediate vicinity of the fluke, greatly influence the keying distance discussed in conclusion 4.
8. Cable tension during anchor pullout follows a characteristic pattern: An initial sharp rise in tension, corresponding to the first vertical anchor movement; then a relatively constant tension, corresponding to vertical movement without major anchor rotation; next a sharp rise to the peak holding capacity, corresponding to major rotation into keyed position; then, possibly, a second holding capacity peak, corresponding to anchor adjustment for an eccentric orientation; then a moderate dropoff, corresponding to movement into less strong sediment. Horizontal anchor displacement during pullout follows no consistent pattern.
9. Field testing with large anchors in the soft mud flat sediment at Mare Island is an excellent compromise between laboratory and deep ocean tests. It enables accurate data to be obtained from many large-scale tests in a natural sensitive sediment.

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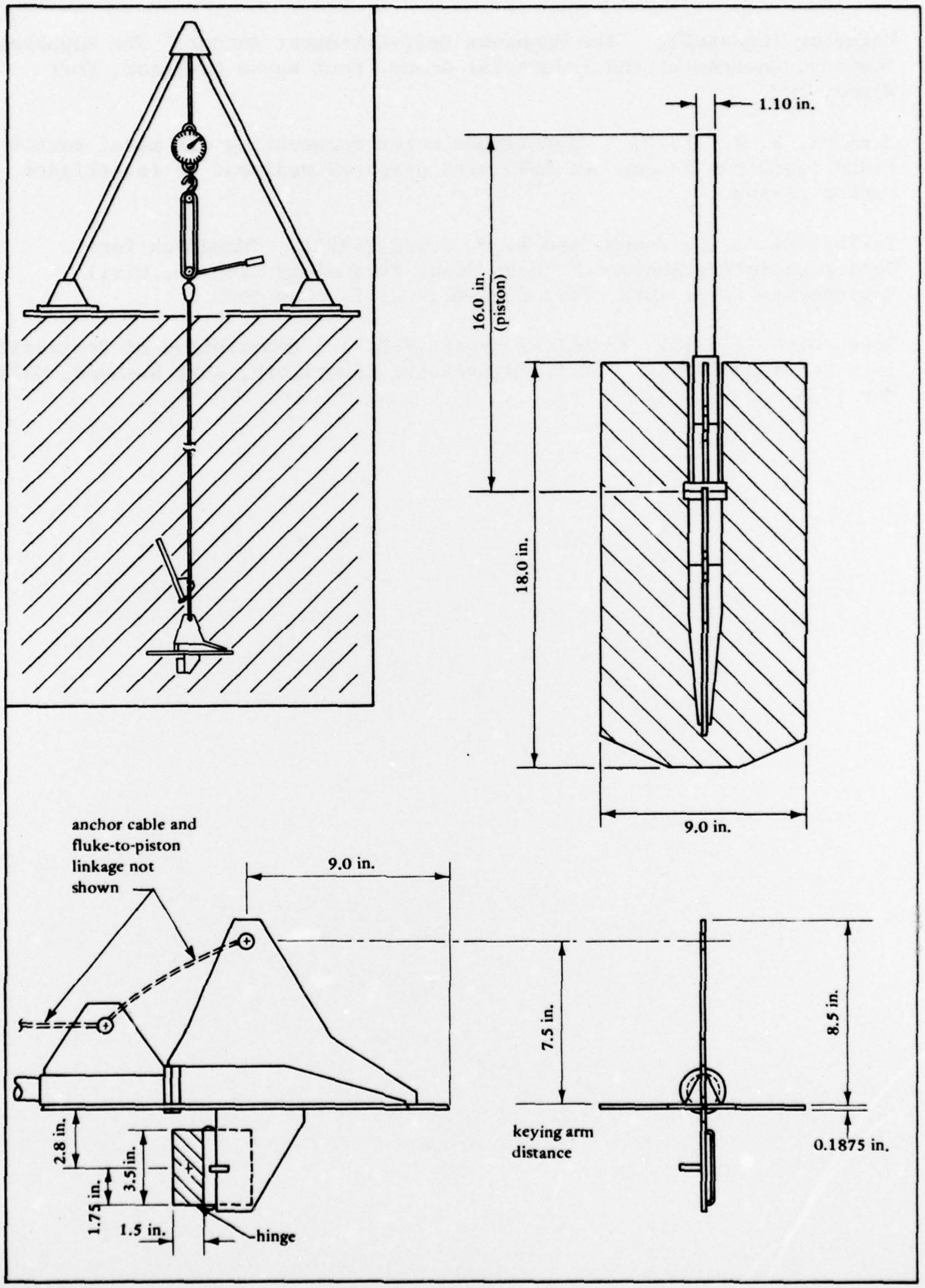


Figure 1. Details of large CEL-styled anchor fluke used for Mare Island tests.

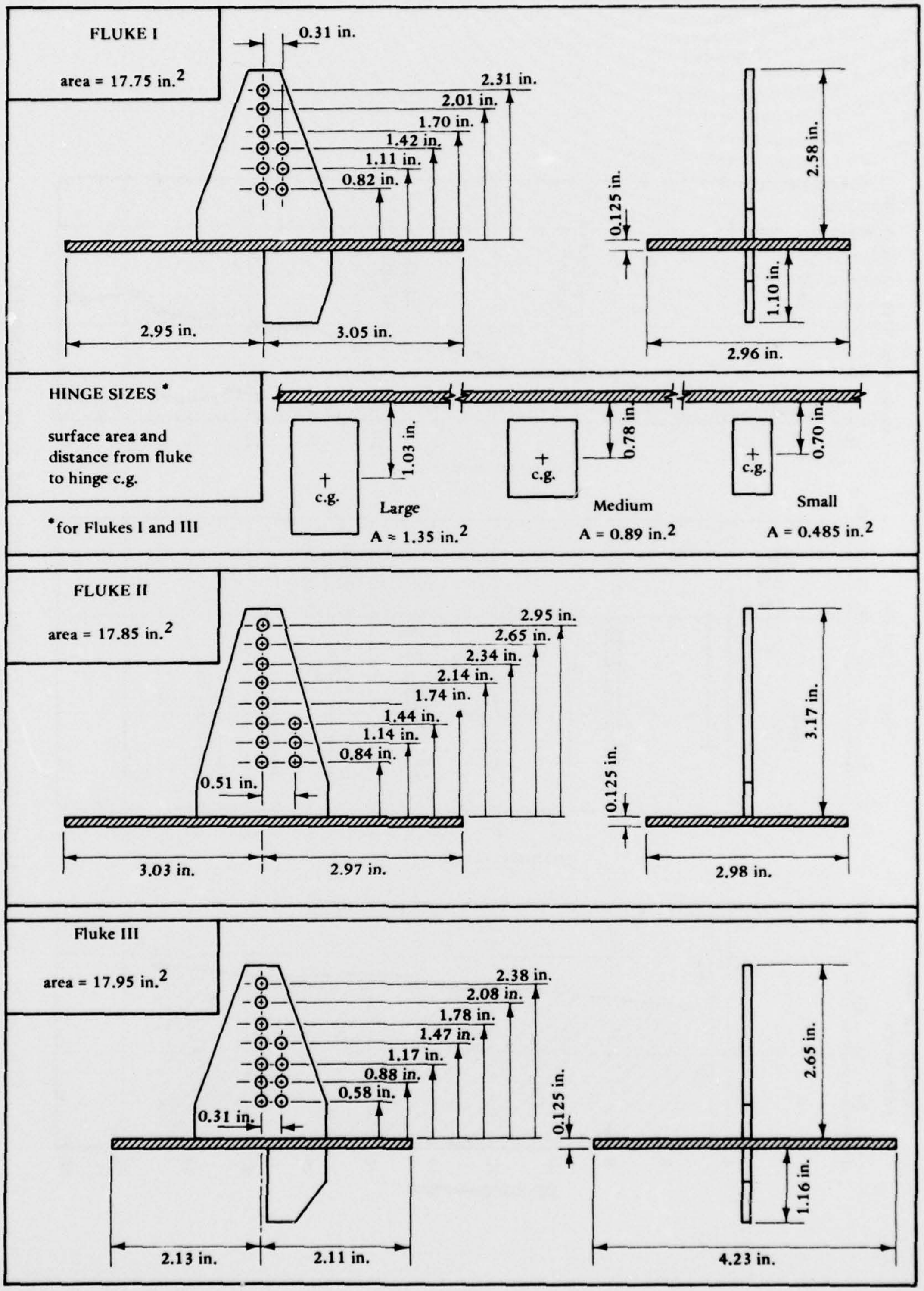


Figure 2. Details of small anchor flukes used in pushed-in tests at the mud flats tidal zone.

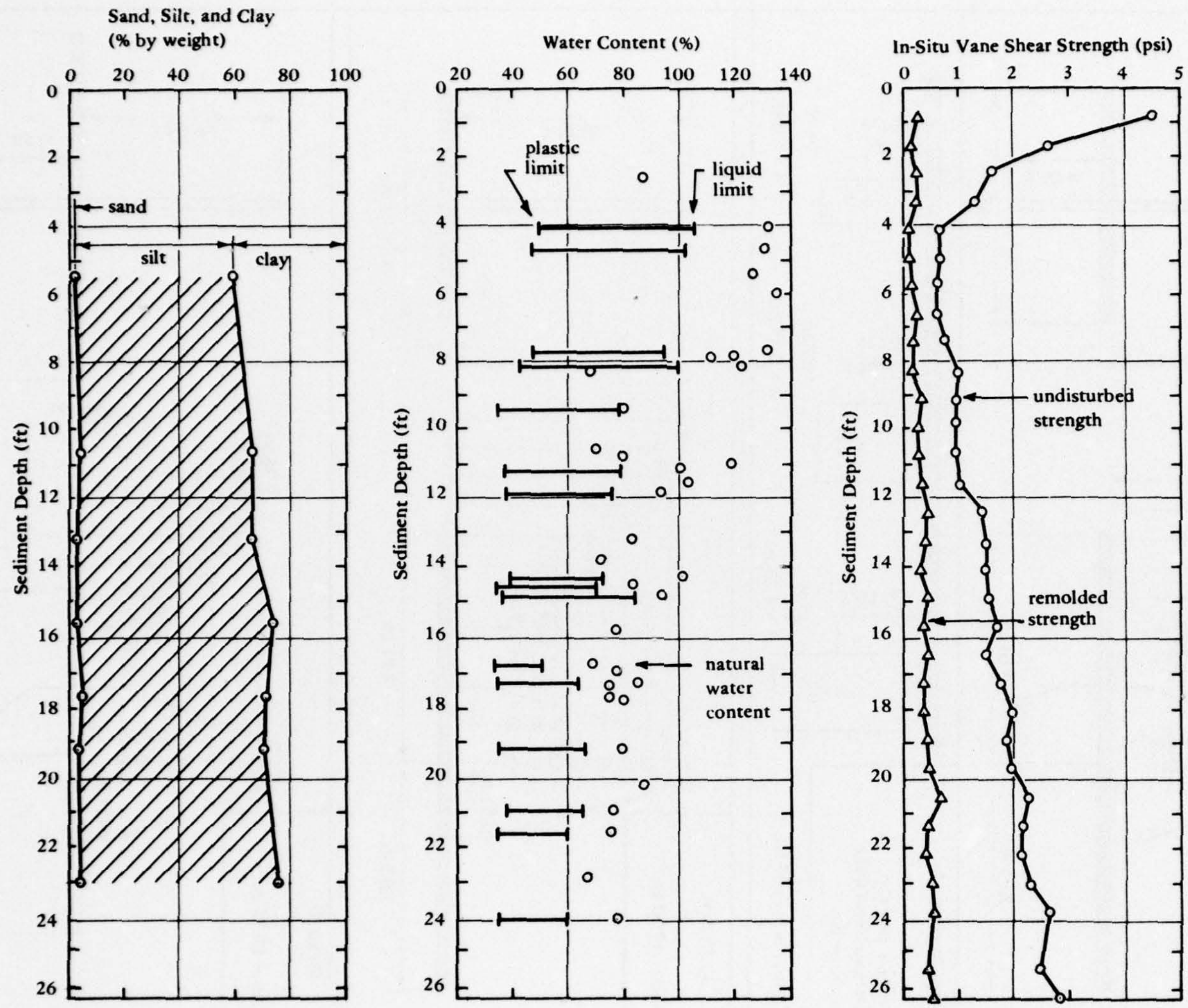


Figure 3. Physical properties of Mare Island mud flat sediments.

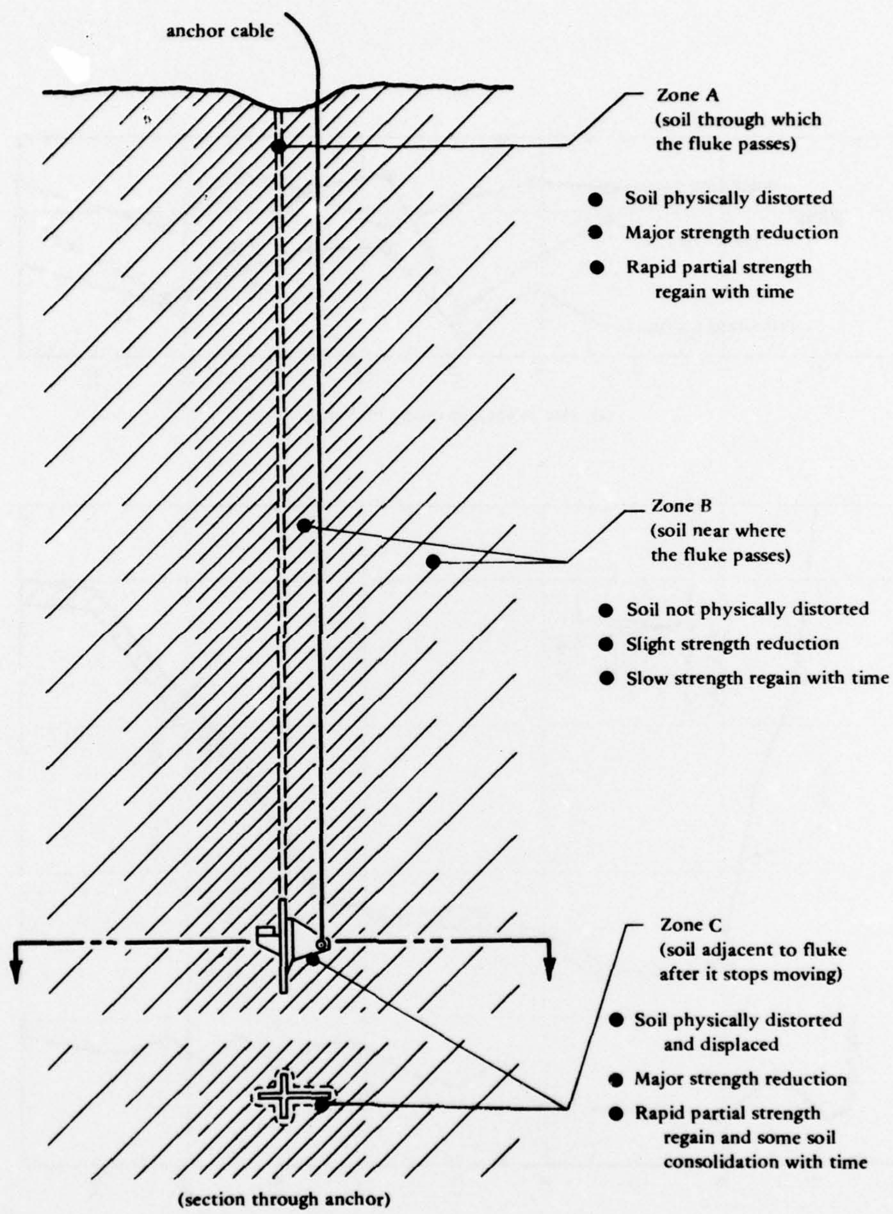
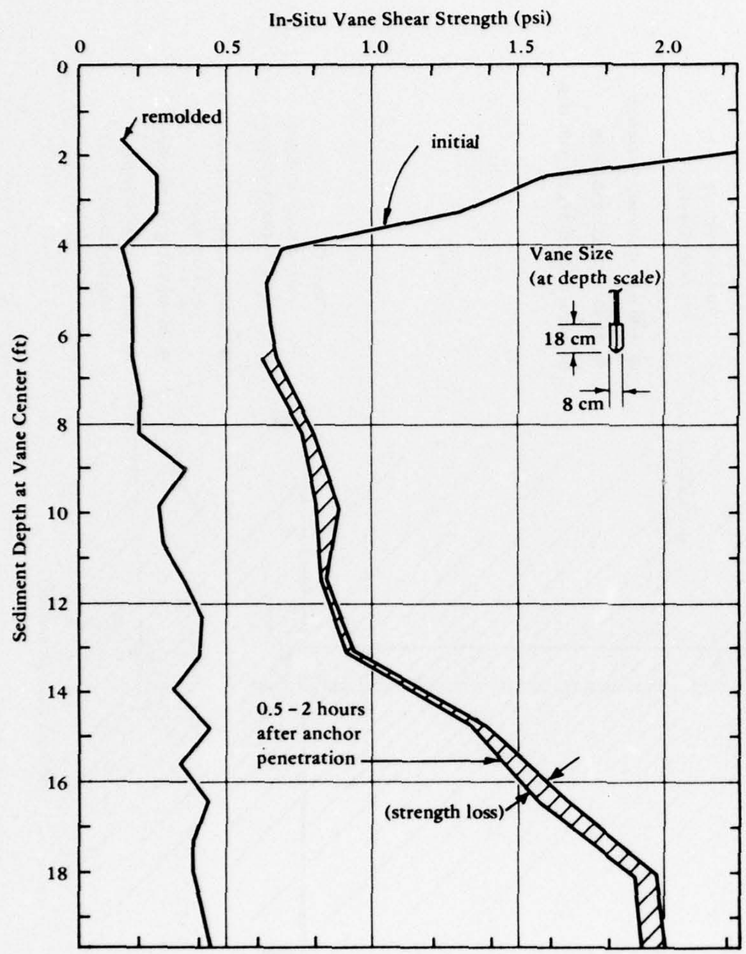
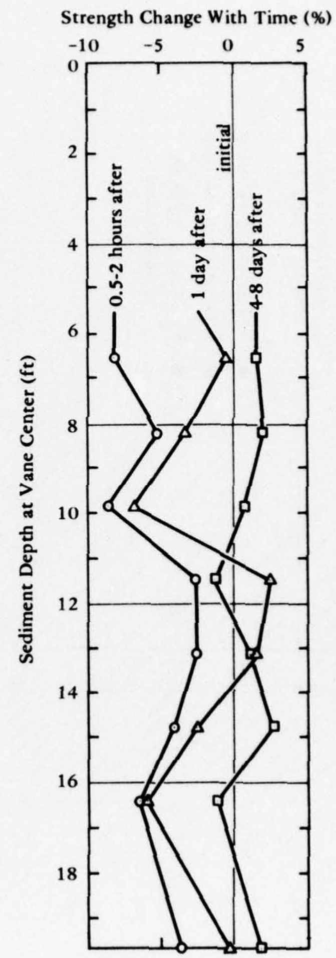


Figure 4. Soil profile schematic showing anchor location following firing.

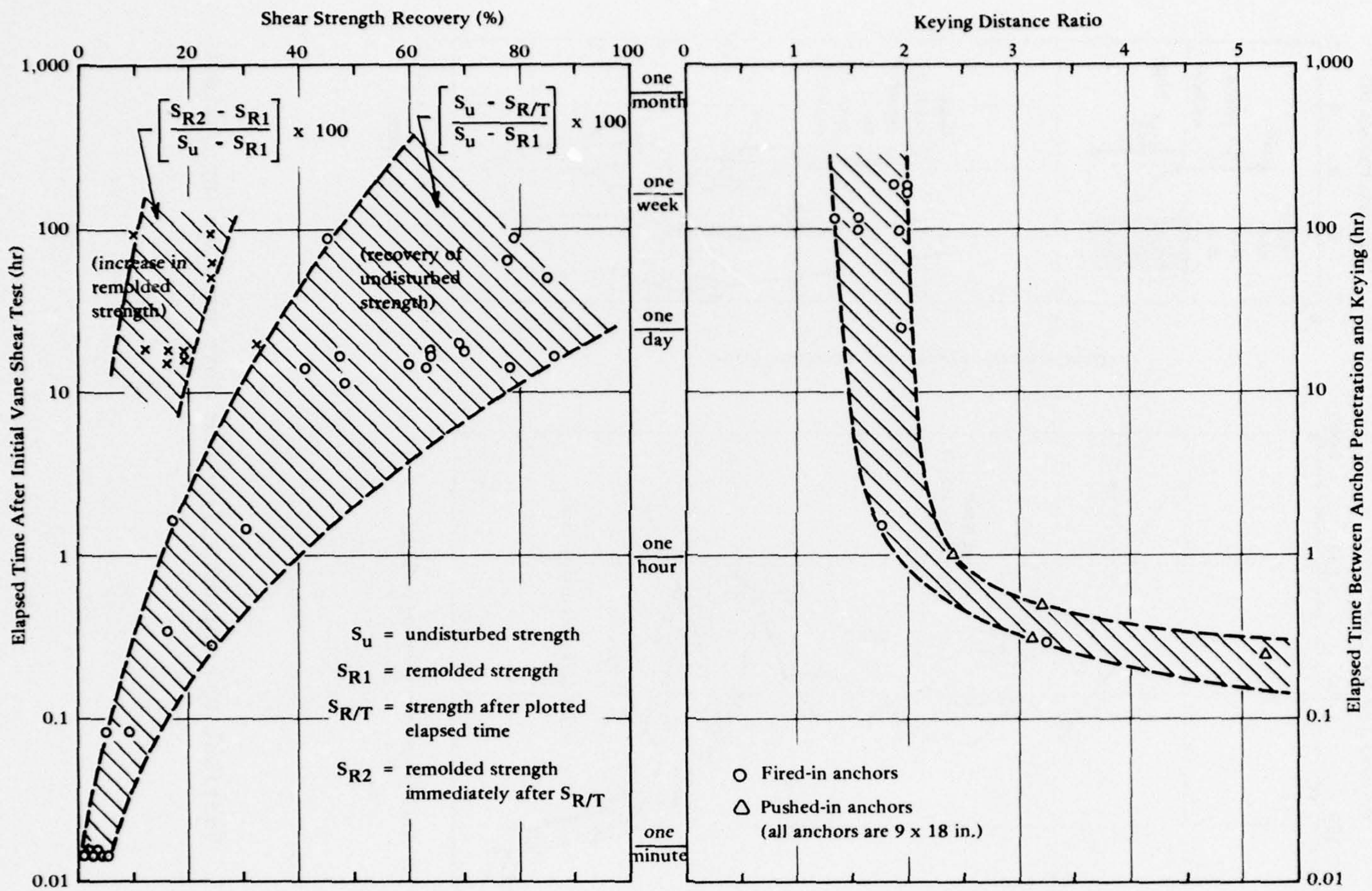


(a) Strength before and after firing.



(b) Strength regain with time.

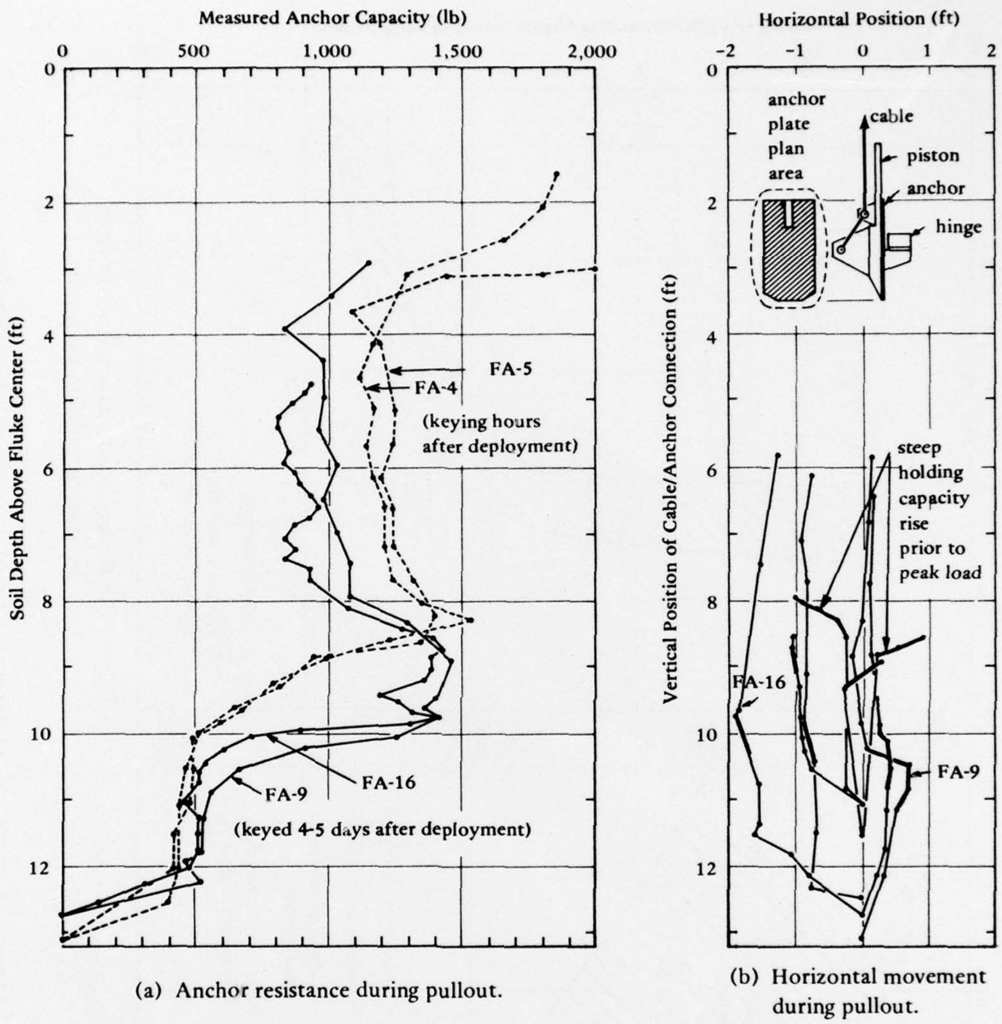
Figure 5. Effect of elapsed time after anchor firing on sediment shear strength.



(a) Sediment strength recovery.

(b) Keying distance as a function of time between penetration and keying.

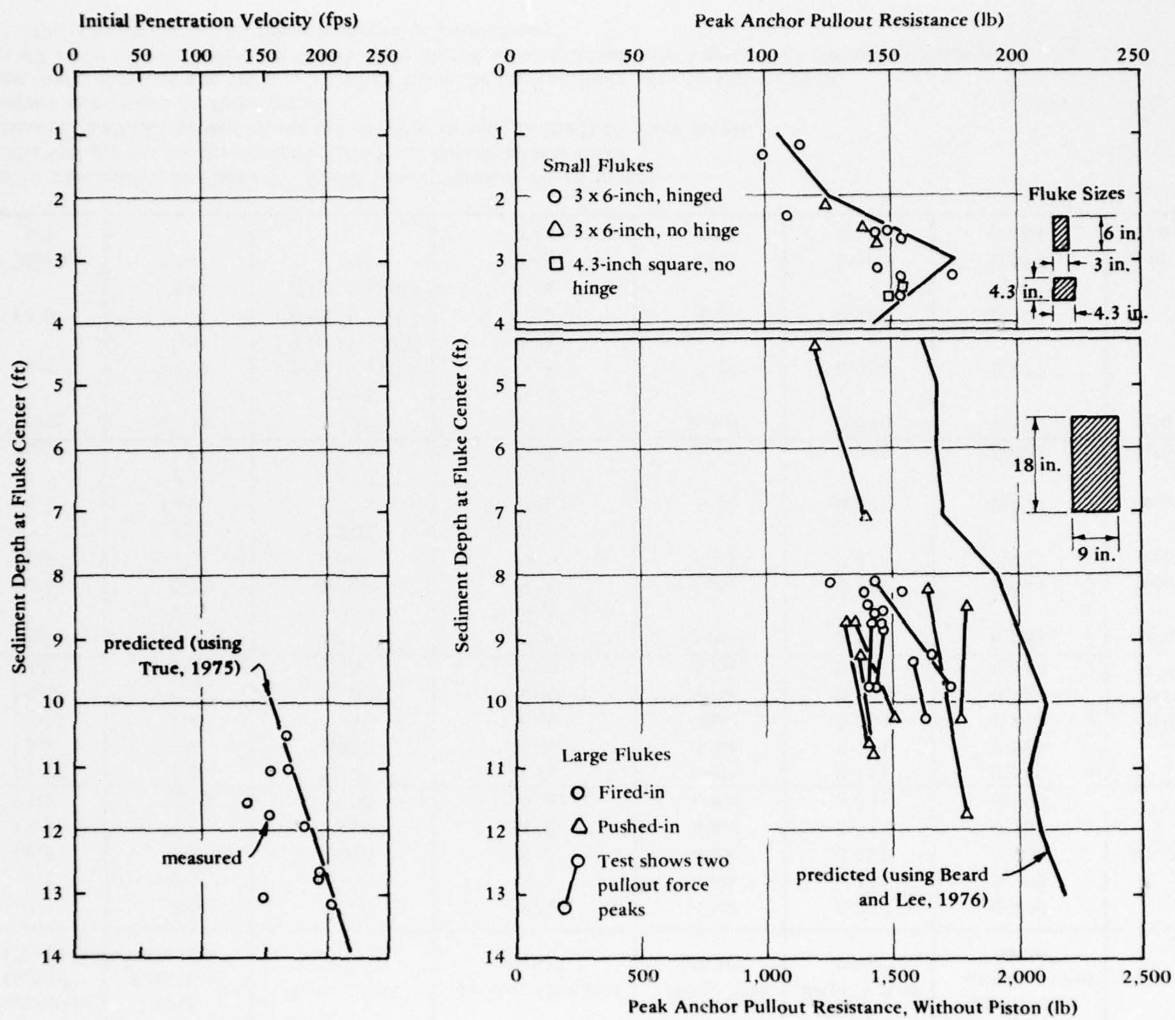
Figure 6. Effect of time on sediment strength and anchor keying.



(a) Anchor resistance during pullout.

(b) Horizontal movement during pullout.

Figure 7. Vertical and horizontal anchor movements during pullout.



(a) Anchor fluke penetration.

(b) Anchor holding capacity.

Figure 8. Comparison of predicted and measured anchor penetration and holding capacity.

Table 1. Summary of Large Pushed-In Anchor Tests[a]

Test Number	Penetration Depth[b] (ft–in)	Depth at Peak Load (ft–in)	Peak Load (lb)	Keying Distance Ratio[c]	Hinge Size (sq in)	Keying Arm Ratio[d]	Horizontal Advancement Ratio[e]	Comments
PA-1	13-0	3-0	2,300	N/A	none	0.251	0.509	
PA-2	8-7	2-2	2,300	N/A	none	0.251	0.509	
PA-3	18-5	2-3	1,050	N/A	none	0.251	0.509	w/o piston
PA-4	15-5	2-6	800	N/A	none	0.251	0.509	
PA-5	15-1	2-11	800	N/A	none	0.251	0.509	
PA-6	13-10	1-6	2,900	N/A	none	0.251	0.509	
PA-7	13-0	2-0	1,400	N/A	none	0.251	0.509	
PA-8	12-11	2-9	950	N/A	none	0.251	0.509	w/o piston
PA-9	15-0	1-1	1,400	N/A	none	0.300	0.484	w/o piston
PA-10	9-5	1-3	2,400	N/A	none	0.355	0.484	w/o piston
PA-11	20-5	11-8	1,800	5.9	none[f]	0.502	0.505	w/o piston
		8-3	1,650	N/A				
PA-12	22-4	0-10	1,800	N/A	none	0.300	0.484	w/o piston
PA-13	11-9	7-1	1,400	3.1	5.25	0.428	0.477	w/o piston
		4-4	1,200	N/A				
PA-14	18-1	10-3	1,775	5.2	5.25	0.428	0.477	w/o piston
		8-6	1,800	N/A				
PA-15	15-3	3-3	700	N/A	none	0.355	0.484	w/o piston
PA-16	14-11	10-10	1,425	2.7	none[f]	0.446	0.501	w/o piston
		9-3	1,375	N/A				
PA-17	14-3	10-7	1,550 (1,410)[g]	2.4	5.25	0.428	0.477	
		8-9	1,450 (1,325)[g]	N/A				
PA-18	15-0	10-3	1,650 (1,510)[g]	3.2	5.25	0.316	0.477	
		8-8	1,475 (1,350)[g]	N/A				
PA-19	20-10	13-4	500	N/A	10.5	0.300	0.484	w/o piston
PA-20	9-0	–	–	N/A	10.5	0.355	0.484	w/o piston

[a] Anchors similar to that shown in Figure 1. Fluke size is 9 inches by 18 inches.
[b] Distance from the soil surface to the center of the 9 x 18-inch anchor fluke.
[c] Ratio of the distance the fluke center moves (to develop maximum load) to fluke length.
[d] Ratio of the keying arm length to fluke length.
[e] Ratio of the horizontal distance the cable is attached from the leading fluke edge to fluke length.
[f] No hinge, but a 42 sq in. counterbalancing flange plate placed to counteract large keying arm during penetration.
[g] Maximum load after subtracting piston force is shown in parentheses.

Table 2. Summary of Small Pushed-In Anchor Tests

Test Number	Fluke Number[a]	Penetration Depth[b] (in)	Depth at Maximum Load (in)	Maximum Load (lb)	Keying Distance Ratio[c]	Hinge Size (sq in)	Keying Arm Ratio[d]	Horizontal Advancement Ratio[e]
MA-1	II	60	18	55	N/A	none	0.241	0.495
MA-2	II	60	29	135	5.17	none	0.443	0.495
MA-3	II	60	12	100	8.00	none	0.291	0.495
MA-4	II	66	33	145	5.50	none	0.358	0.495
MA-5	II	66	26	125	6.67	none	0.291	0.495
MA-6	II	67	13	65	N/A	none	0.241	0.495
MA-7	I	66	40	48	N/A	0.89	0.137	0.508
MA-8	I	66	18	50	N/A	0.89	0.185	0.508
MA-9	I	64	14	115	8.34	0.89	0.237	0.508
MA-10	I	66	32	155	5.67	0.89	0.283	0.508
MA-11	I	66	16	100	8.34	0.89	0.237	0.508
MA-12	I	66	31	145	5.83	1.35	0.237	0.508
MA-13	I	66	39.	60	N/A	1.35	0.185	0.508
MA-14	I	66	38	145	4.67	1.35	0.283	0.508
MA-15	I	66	41	155	4.17	1.35	0.237	0.457
MA-16	I	66	28	110	6.33	1.35	0.185	0.457
MA-17	I	66	31	150	5.83	1.35	0.185	0.457
MA-18	III (square)	66	41	160	5.90	none	0.276	0.498
MA-19	III (square)	66	12	75	N/A	none	0.207	0.498
MA-20[f]	III (square)	66	40	125	6.13	none	0.207	0.425
MA-21[f]	III (square)	66	47	115	4.48	none	0.207	0.425
MA-22[f]	III (square)	66	52	90	3.30	0.485	0.207	0.425
MA-23	I	66	43	155	3.83	0.485	0.237	0.457
MA-24	I	66	21	80	N/A	0.485	0.237	0.508
MA-25[g]	II	67	30	140	5.00	none	0.291	0.495
MA-26[g]	I	67	39	175	4.67	0.89	0.237	0.508
MA-27[g]	III	67	43	150	5.33	none	0.207	not recorded
MA-28[h]	II	67	35	90	5.33	none	0.291	0.495
MA-29[h]	I	67	39	75	4.67	0.89	0.237	0.508

[a]Anchors I, II and III are shown in Figure 2. All flukes are 18 sq in. in area.
[b]Distance from the soil surface to the center of the anchor fluke.
[c]Ratio of the distance the fluke center moves (to develop maximum load) to fluke length.
[d]Ratio of the keying arm length to fluke length.
[e]Ratio of the horizontal distance the cable is attached from the leading fluke edge to fluke length.
[f]Interference with keying–cable not perpendicular to fluke plate and the fluke "skates."
[g]Special tests–repeat of previous tests but 68 days elapsed between penetration and keying.
[h]Special tests–repeat of previous tests but 154 days elapsed between penetration and keying. Disturbance of area was apparent.

Table 3. Summary of Large Fired-In Anchor Tests[a]

Test Number	Penetration Depth[b] (ft–in)	Depth at Peak Load (ft–in)	Peak Load (lb)		Keying Distance Ratio[c]	Elapsed Time Before Keying (day-hr)	Calculated Penetration Velocity[d] (fps)	Piston Linkage Length (in)
			With Piston	Without Piston				
FA-1	7-4	1-0	N/A	960	N/A	0-0.5	–	N/A
FA-2	30-7	27-8	N/A	1320	N/A	1-?	–	N/A
FA-3	12-9	10-5	450	310	N/A	1-0	193	6
FA-4	12-11	8-3	N/A	1550	3.11	0-?	–	no piston
FA-5	13-1	8-3	N/A	1400	3.22	0-0.3	149	no piston
FA-6	11-11	9-3	1775	1665	1.78	0-1.5	183	48
FA-7	12-9	9-10	1850	1740	1.95	0-2.0	193	48
		8-1	1550	1440	(3.11)			
FA-8	13-2	10-3	1750	1640	1.95	1-0	203	48
		9-4	1700	1590	(2.56)			
FA-9	12-8	9-10	1580	1445	1.56	5-0	193	6
		8-10	1600	1475	(2.56)			
FA-10[e]	10-7	8-7	1600	1475	1.33	5-0	168	6
FA-11[f]	11-9	9-2	–	–	1.72	5-17	155	6
		6-11	2450	2340	–			
FA-12[e]	11-1	8-1	1400	1260	2.00	8-0	170	6
FA-13[e]	11-9	8-11	1550	1410	1.89	8-0	–	6
FA-14[e]	11-7	8-7	1580	1440	2.00	8-0	137	6
FA-15[e]	11-1	8-9	1600	1475	1.56	4-2	157	6
FA-16[a]	12-8	9-9	1550	1420	1.94	4-2	138	6
		8-9	1560	1435	(2.61)			

[a]Anchors FA-4 through FA-15 are type shown in Figure 1. FA-3 is similar, but has no hinge and a keying arm ratio of 0.25. FA-16 is similar, but has no hinge and a keying arm ratio of 0.445. FA-1 and FA-2 are Magnavox flukes.

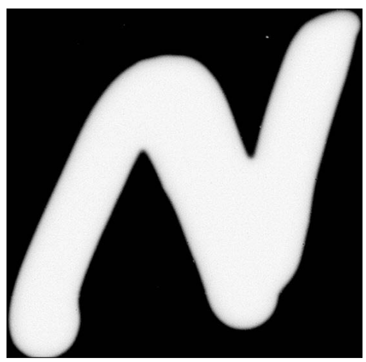
[b]Distance from the soil surface to the center of the 9 x 18-inch anchor fluke.

[c]Ratio of the distance the fluke center moves (to develop maximum load) to fluke length.

[d]Velocity calculated from gun pressure-time traces.

[e]Anchors keyed to peak load, then long-term load applied with incremental increases.

[f]Long-term loading without pre-keying. After sustained load of 1,810 pounds held for 165 days, a short-term load of 2,450 pounds was successfully resisted.



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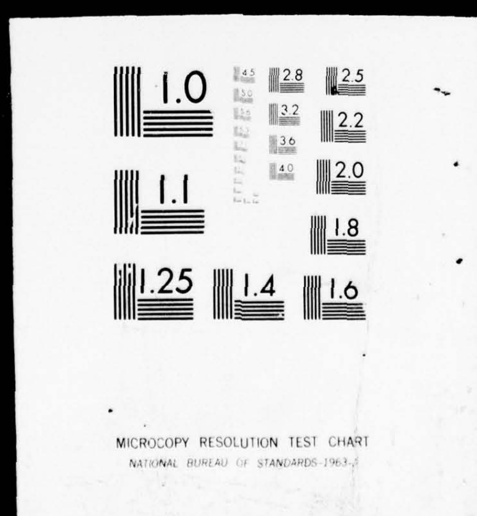

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From: Officer in Charge
To: Distribution

Subj: Errata Sheet for Technical Note N-1491, "Reduction of Embedment Anchor Capacity Due to Sediment Disturbance," by K. Rocker

1. Please make the following pen and ink corrections:

Page 13: delete conclusion 5.

Page 14: renumber the last four conclusions 5, 6, 7, and 8.

Peter D. Triem
PETER D. TRIEM
By direction