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This report presents results of uplift capacity tests on direct embedment fluke-type anchors in some cohesive ocean sediments. Most of the tests were short-term tests with a duration of one to four minutes between first load application and the completion of pull-out. Data on the optimum fluke design, on the travel distance required to effect fluke keying, and on the relationship of developed uplift capacities to those predicted are presented and discussed. A modification to the standing relationship for predicting uplift (continued)

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This report presents results of uplift capacity tests on direct embedment fluke-type anchors in some cohesive ocean sediments. Most of the tests were short-term tests with a duration of one to four minutes between first load application and the completion of pullout. Data on the optimum fluke design, on the travel distance required to effect fluke keying, and on the relationship of developed uplift capacities to those predicted are presented and discussed. A modification to the standing relationship for predicting uplift capacity is offered. Recommendations are made regarding optimum fluke design and uplift capacity prediction techniques.

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## INTRODUCTION

In simplest form, a direct embedment anchor is a flat plate which is driven edgewise vertically into the sediments by propellant, vibratory, or impact means after which the plate is rotated to a horizontal position (Figure 1). The operation of rotating the plate from the vertical to the horizontal position is referred to as "keying" of the fluke. Most load tests of the direct embedment anchors have been intended to verify only that the launcher would properly function or that the fluke could be properly embedded. These load tests did not serve as definitive tests of the empirical techniques being used to predict the ultimate holding capacity of such direct embedment anchors.

However, a few load tests have been performed where all the elements required for verification of holding capacity prediction techniques were present.* It is the purpose of this report to present those test results in a common format of load versus depth of embedment, to compare those results with the ultimate holding capacities predicted by present predictive techniques, to analyze the compared data, and to recommend appropriate changes in predictive techniques for direct embedment anchor holding capacity.

## PRESENT PREDICTIVE TECHNIQUES

### Idealized Plate Anchor Holding Capacity

The techniques employed by CEL in predicting the holding capacity of an embedment anchor are founded in theory but modified based on test data. Embedment anchors in pullout will deform a surrounding soil in either of two modes depending on the depth of the plate beneath the seafloor surface (see Figure 2). If the anchor is buricd quite deep, upward displacement of the anchor will cause soil to move in plastic flow from above the plate to beneath with no expression of the movement at the seafloor surface. If the anchor is buried shallow, then the seafloor surface will be thrust upward as a plug of soil is pushed out by the fluke. The transition from deep to shallow anchor behavior occurs in clays at a D/B of 2 to 5, and in sands at a D/B of 2 to 10 (after Vesic, 1969), where:

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*The elements required for sound comparison of measured and predicted short-term holding capacities are:

(1) a reliable profile of soil shear strength versus soil depth, and

(2) a reliable measure of load being applied to the anchor fluke versus depth, with depth also reliably measured.

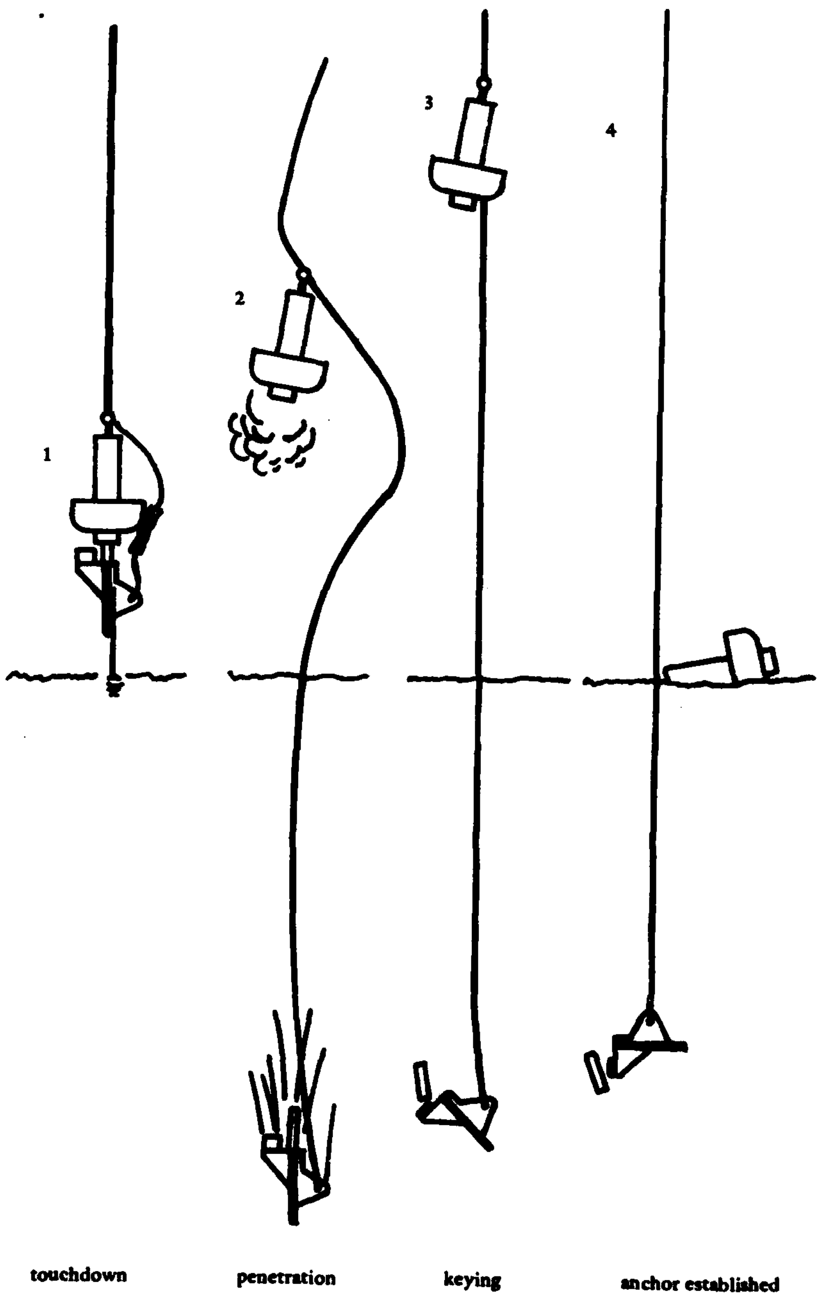


Figure 1. Propellant driven penetration and keying of a direct embedment anchor fluke.

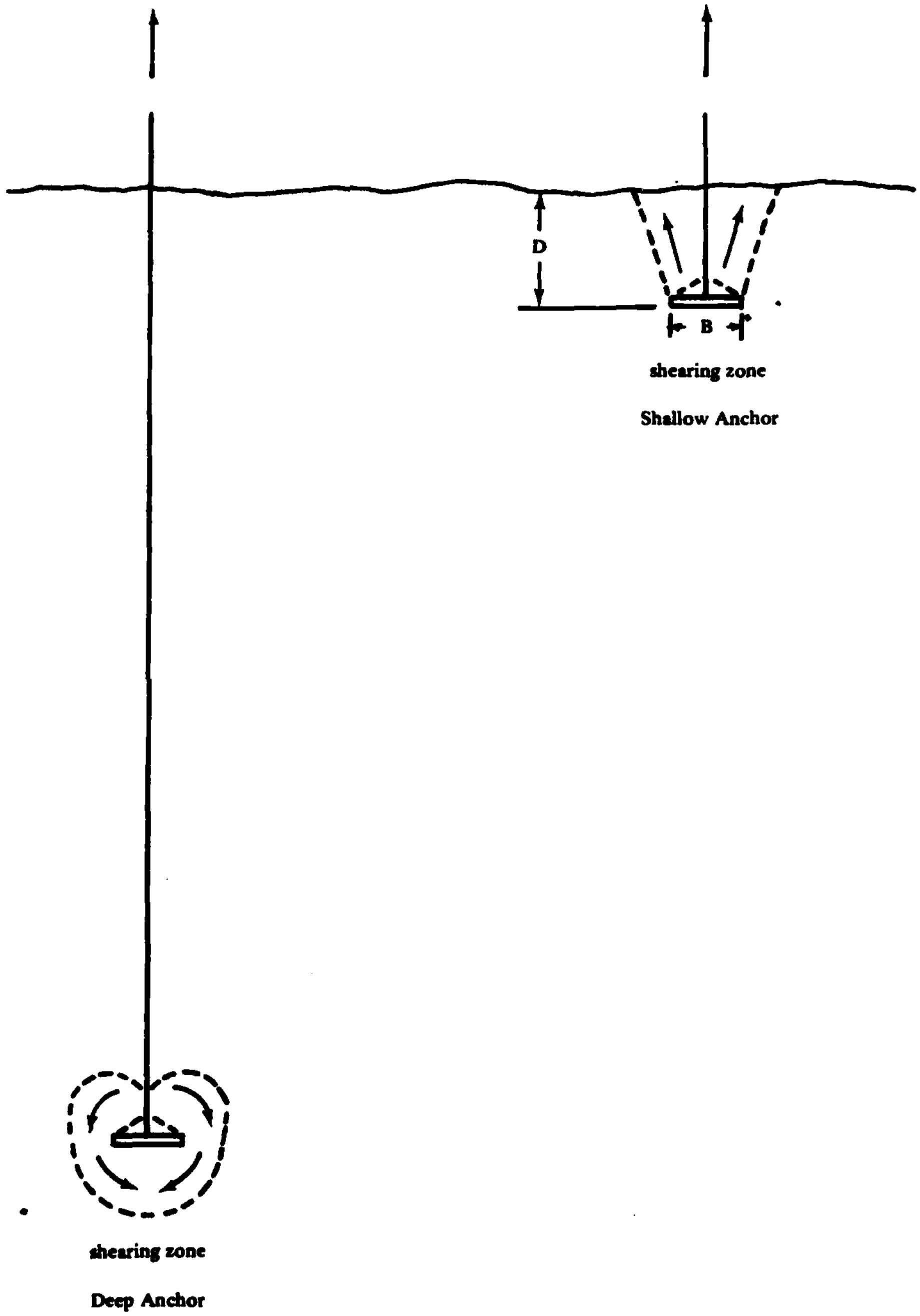


Figure 2. Failure modes for differing anchor burial depths.

D = depth of plate below the seafloor, m;* and
B = width or diameter of anchor plate, m.

The pullout resistance of a plate anchor, even if embedded in an isotropic, homogeneous medium, decreases when the failure mode changes from the deep to the shallow mode. Thus, an efficient design will usually emplace the anchor plate at a depth where deep anchor behavior begins.

The following relationship (after Vesic, 1969), patterned after the familiar relation for footing bearing capacity, is commonly used for representing the holding capacity of an embedded plate anchor:

$$Q = A\ (c\overline{N}_c + \gamma\ D\overline{N}_q)\ (0.84 + 0.16\ B/L)$$

where Q = ultimate holding capacity (horizontal sediment surface and fluke, and vertical pulling line), N**

A = projected area of the plate, $m^2$*

c = effective soil cohesion, Pa**

$\overline{N}_c$ = uplift capacity factor (no suction, use Figure 3; full suction, use Figure 4)

$\gamma$ = buoyant unit weight of the sediment, $N/m^3$

$\overline{N}_q$ = uplift capacity factor (see Taylor and Lee, 1972)

L = length of fluke, m.

The last factor in the equation accounts for plate shape (derived from Skempton, 1951).

The equation is general and can be used for shallow and deep embedment and also for long- and short-term loadings. The long-term holding capacity is the largest continuously-applied force that will not cause anchor breakout during the life of the facility. The short-term holding capacity is the largest rapidly-applied force that will not cause anchor breakout. In the equation, the cohesive term $c\overline{N}_c$ controls for short-term loadings in cohesive soils (clays) with the soil cohesion, c, being equal to the undrained soil shear strength. For short-term loadings, the frictional term, $\gamma\ D\overline{N}_q$, is equal to zero. For long-term loading conditions, the term $\gamma\ D\overline{N}_q$ controls, and the cohesive term becomes less significant. In cohesionless soils (sands), experience with flukes of conventional size shows that the frictional term controls for both short- and

*m = meter (unit of length).
**N = Newton (unit of force), and Pa = Pascal (unit of stress or pressure).

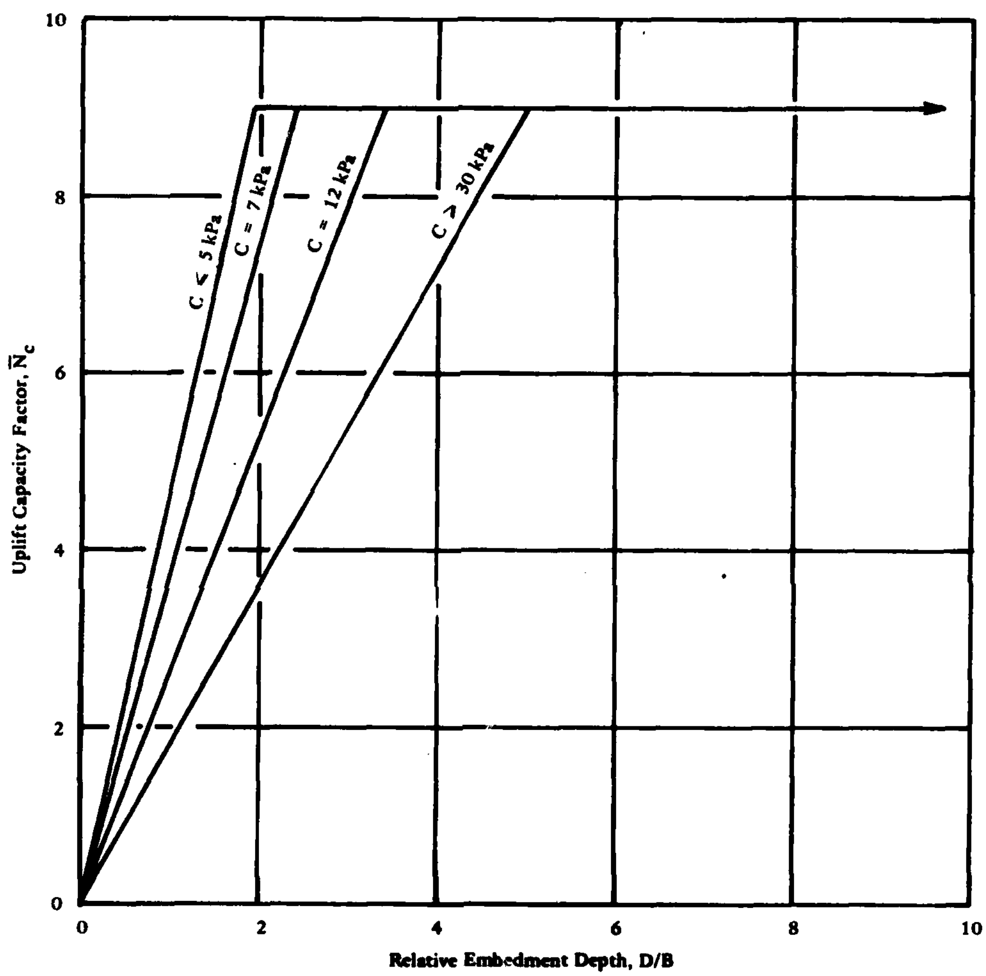


Figure 3. Uplift capacity factor, $\bar{N}_c$, for NO SUCTION condition (from Taylor and Lee, 1972).

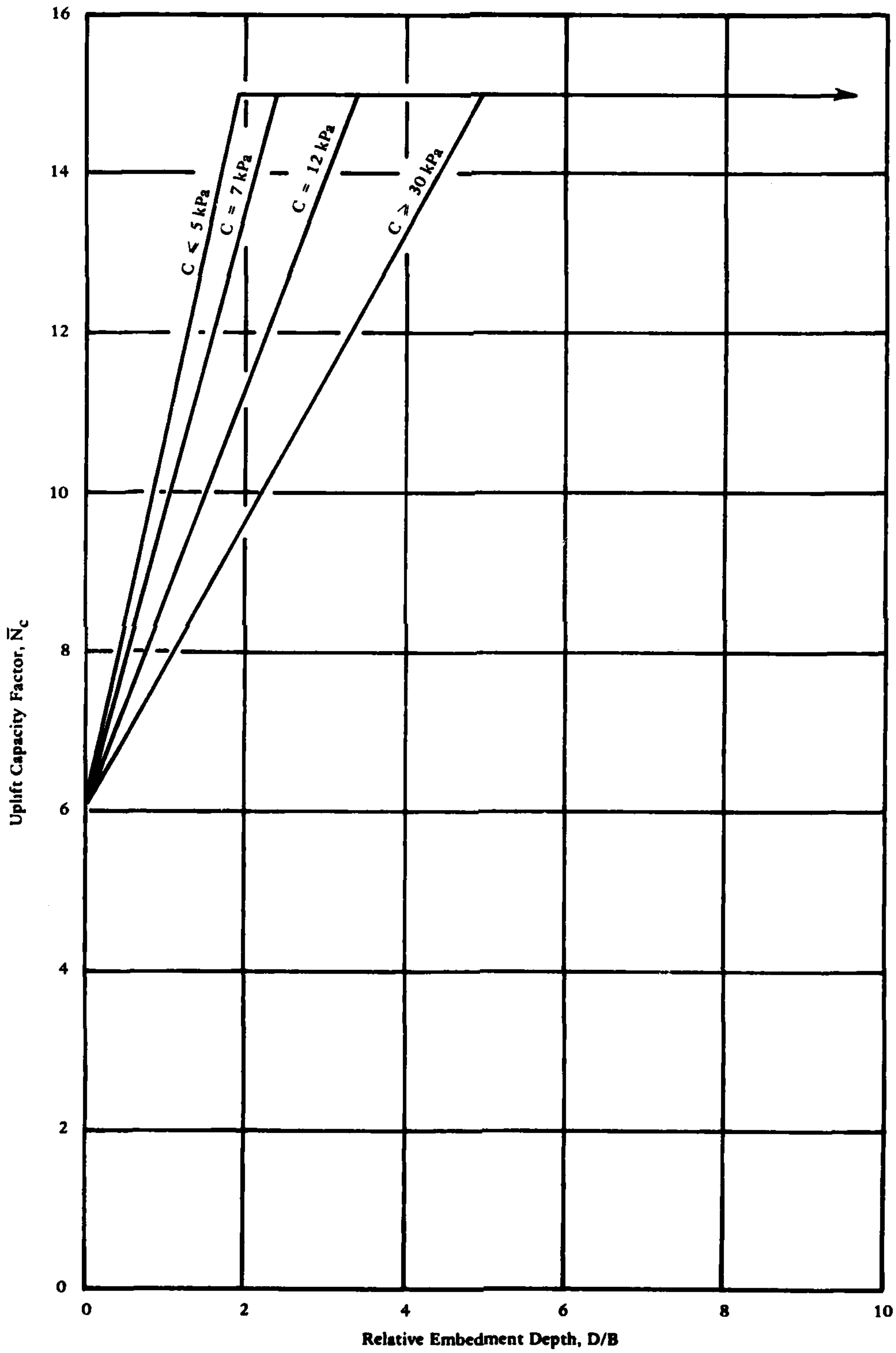


Figure 4. Uplift capacity factor, $\overline{N}_c$, for FULL SUCTION condition (from Beard, 1978).

long-term loading conditions.

In the load tests reported herein, the load applications were all made over increments of two to three minutes. In the subject sediments, including the calcareous ooze, dissipation of excess pore pressures did not have time to occur; thus, the holding capacity of the anchor flukes is best analyzed as an undrained failure. Thus, no further discussion of the long-term loading condition will be made here.

Initial development of the plate anchor uplift capacity theory was conducted to predict the performance of such anchors used as foundations for electric power transmission towers. In this use, the soil surrounding the anchor is often unsaturated. Also, when working on land, several factors are working together to establish a passage (vent) for air from the ground surface to the base of the plate. Thus under usual terrestrial conditions, the soil zone beneath the anchor plate is usually vented to the ambient air pressure and a suction condition does not develop. For this condition of no suction, and for a deep anchor plate, the uplift capacity factor, $\overline{N}_c$, has a value of 9. The value of $\overline{N}_c = 9$ has been established in several laboratory model tests (Ali, 1968; Bhatanger, 1968; Vesic, 1969; and Kupferman, 1971) and prototype field tests (Adams and Hayes, 1967; Adams and Klym, 1972). These tests all provided for plate (fluke) installation with minimal disturbance of the overlying soil, and all limited development of a suction force beneath the plate anchor. This uplift capacity factor, $\overline{N}_c$, of 9 for deep anchor behavior is represented in Figure 3 along with curves providing values of $\overline{N}_c$ for shallow anchor behavior.

With direct embedment anchors, in practice, the degree of disturbance of the soil (due to fluke penetration), the suction developed, and the loading applied to the fluke are all quite different from the conditions imposed with the above terrestrial prototype and laboratory model tests. In particular, suction is known to develop beneath keyed direct embedment anchor flukes based on the measured ultimate uplift capacities of pushed and propellant-driven flukes under very well-known conditions (Rocker, 1977). The holding capacities developed in those tests were of such magnitude that the suction force had to be a contributing factor, and, secondly, the hole formed by the penetrating fluke was noted to be squeezed tightly shut immediately behind the fluke shutting off any possible vent to the seafloor surface. The proportion of the undisturbed soil shearing strength mobilized and the shape of the soil failure zone (described by the $\overline{N}_c$ factor) should be expected to vary from those of the terrestrial tests above. The analysis of direct embedment anchor-holding capacity is complicated by the following factors, each of which will be discussed in turn:

(1) the magnitude and duration of the suction force,
(2) the influence of impact loads on soil shear strength,
(3) the influence of dynamic (oscillatory) loads,

(4) the influence of fluke penetration and keying on soil shear strength, i.e., the degree of soil disturbance,

(5) the fluke travel required (pullout) in order to key the fluke,

(6) the degree and influence of creep of the fluke through the soil under load.

## Influence of Suction Force

The suction force is that component of the short-term holding capacity carried by negative gage pressures (suction) in the pore water of the soil beneath the anchor. In time, these negative gage pressures will dissipate and thereby decrease the holding capacity. Suction is a problem associated with short-term capacities in cohesive soil since suction pressures dissipate almost immediately in sand. The earlier, and conservative, approach to estimating short-term anchor holding capacity in clays has been to ignore the suction force effect on holding capacity (i.e., Figure 3) (Taylor and Lee, 1972). However, recent idealized model test data have shown that for near normally consolidated clays, of low sensitivity, two mechanisms are working nearly simultaneously to maintain holding capacities at nearly double the magnitude calculated using Figure 3. Apparently the soil mass in shear above the anchor strengthens (through consolidation) at nearly the same rate that the holding capacity reduction due to suction dissipation beneath the anchor is proceeding, resulting in no net reduction in holding capacity. Altered holding capacity factors accounting for the effect for clays have been suggested (Beard and Lee, 1975). For the plate anchor acting in a deep failure mode, the $\overline{N}_c$ factor for full suction was suggested to be 16. The experimental data were later supported by the results of a finite element analysis. More recently, Beard (1978) has reported the results of a new series of laboratory tests, plus re-examined Rocker's (1977) field test data; Beard concluded that an $\overline{N}_c$ factor of 15 is more appropriate to the full suction condition.

## Influence of Impact Load

Impact loads are high live loads of very short duration such that the viscous and mass effects of the soil mass become significant. Loadings of this kind are applied to the anchor plate in very taut moors (steel wire rope) in shallow water. In general, taut moors generating high impact loads are not desirable because, to accommodate such loads, the various components of the mooring system must be sized to say three or four times larger than those of a comparable slack moor. Thus, significant impact loads are not normally applied to mooring systems, even those using direct embedment anchors. However, occasionally in the pullout testing of direct embedment anchors, using near-vertical steel load lines in shallow water without a spring line, impact loads are applied as the ship responds to the sea swell. Under such impact load conditions, the peak load that can be applied to the anchor fluke without causing initial pullout may be two to three times the sustained or static uplift capacity.

The response of terrestrial soils to impact loads, for footings supporting missile-launching or blast resistant structures, has been studied extensively, mostly by way of load tests on model footings. Footings on cohesive soils, when subjected to impact loads, generally show an increased bearing capacity as compared to the static load response. The results of undrained shear strength tests on clay samples at variable loading rates (Figure 5) suggest that this increase in bearing capacity will be continuous from the static to the impact condition (Vesic, 1975).

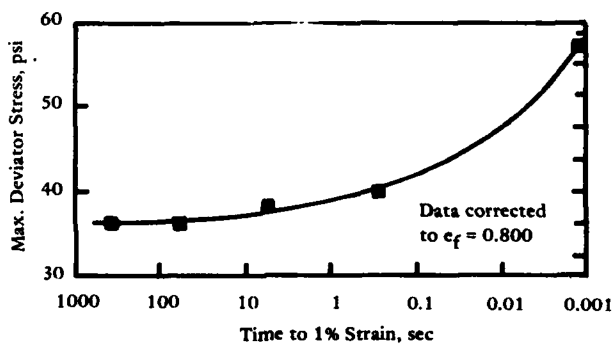


Figure 5. Effect of strain rate on undrained strength of a saturated, normally consolidated, fat clay (from Whitman, 1970).

Increases in the strain rate from zero to 1,000 percent per second have been shown to increase the ultimate strength of a range of cohesive materials by a factor of 1.5 to 3 (reported by Richart, 1965). The holding capacities of plate embedment anchors in cohesive soils might then be expected to show similar increases under impact load as compared to static load holding capacities. (In fact, the ocean test data to be presented here show these increases to exist under certain loading conditions and with some soils.) Given a measure of the response of the individual soil specimen to a loading pulse of comparable duration and magnitude as that in the design condition, it then appears possible to predict the response of a plate anchor to a given loading pulse (assuming that Richart's conclusions regarding footings are applicable also to plate anchors) (see Richart, 1965).

These impact load capacity prediction procedures are not a matter of general concern because usually even the designs for anchor tests avoid the condition-it is difficult enough to evaluate the influence of other pertinent test parameters without adding in the influence of impact loading. Thus, this text seeks only to inform the reader of the condition, and to explain the high load capacities measured for two of the anchor tests reported herein.

Influence of Dynamic (Oscillatory) Loads

Dynamic oscillatory loadings, or repeated loadings, can result from surface wave effects, cable strumming, load handling technique, and earthquakes. Preliminary results indicate holding capacity reductions as high as 40 percent in cohesive sediments (Bemben and Kupferman, 1974). Some ooze-type sediments, including those calcareous sediments to be described later, experience complete liquefaction when the load oscillations result in stress reversals in the sample (Herrmann and Houston, 1978). A complementary effort (to that reported herein) is now being sponsored by the Civil Engineering Laboratory measuring the shear strengths of typical deep ocean sediments subjected to dynamic (oscillatory) loads. This project seeks to formulate a mathematical model of the dynamic load holding capacity problem. In the meantime, for those sediments that do not undergo a substantial strength reduction (partial liquefaction) subject to the dynamic load applied, the techniques described by Richart (1965) for footings appear suitable for use in describing plate anchor displacements and, thereby, ultimate holding capacities.

Influence of Fluke Penetration and Keying on Soil Shear Strength

Earlier, in the discussion of uplift capacity factor, $\overline{N}_c$, and the influence of suction, $\overline{N}_c$ with suction acting was noted ideally to be 15 (and without suction acting to be 9). These values for $\overline{N}_c$ assume a non-sensitive to slightly sensitive cohesive soil.

Installation of the direct embedment anchor fluke in typical deep ocean sediments may result in significant differences from the idealized situation. The typical sediments have sensitivities ranging up to ten (Valent, 1974; Lee, 1976). Penetration of the fluke into the sediment causes disturbance of a small diameter shaft of sediment immediately surrounding the fluke's path. Then keying of the fluke causes still more disturbance and strength reduction, with the larger part of this disturbed soil being beneath the plane of the fluke. A comprehensive program measuring the short-term holding capacities of small embedment anchors, some pushed and the rest fired into a moderately sensitive bay mud deposit, showed that field measured holding capacities ranged from 70 to 80 percent of those holding capacities predicted from theory (Rocker, 1977) (percentages based on an $\overline{N}_c$ of 15). These realized holding capacity limits correspond to uplift holding capacity factors, $\overline{N}_c$, of 12 and 13.6 respectively. These holding capacity factors include the effects of soil disturbance due to fluke penetration and keying and also the effect of suction on the underside of the fluke.

A series of very well controlled laboratory plate anchor model tests, including extensive strength testing of the soil about the fluke along with pore pressure measurements in the fluke area, have led to a recommendation of $\overline{N}_c = 15$ for undrained pullout in a slightly sensitive cohesive soil (Beard, 1978). Note, in this latter series the anchor plates were placed into the soil specimen during forming, thus penetration and keying disturbance was not a factor. The $\overline{N}_c = 15$ value reflects the influence of suction on an idealized plate anchor.

The reader should note that this approach of accounting for all influences in anchor holding capacity in one factor, the vertical holding capacity factor, $\overline{N}_c$, leaves much to be desired. Probably the biggest discrepancy arises over the use of the $\overline{N}_c$ factor to account for soil disturbance. Soil disturbance should be treated as a reduction to be applied to the soil strength entered into the holding capacity equation--then the percentage reduction could be varied as a function of the soil sensitivity in shear. Such a rational approach has not been implemented because the field test data required to verify the approach are not available and would be very expensive to obtain in the required quantity and quality.

## Influence of Travel Required to Effect Keying

Keying distance is the vertical travel (upward) required to effect rotation of the penetrated anchor fluke from the vertical to an approximately horizontal orientation (Figure 6). Keying distance had for some time been assumed to be one fluke length in sands and two fluke lengths in clays. Recent field tests of small and prototype anchor flukes, some reported herein, have shown keying distance to be highly sensitive to fluke design--in cohesive soils, some fluke designs will not key at all, but rather will slide right back up in the column of remolded soil (remolded during penetration) without ever keying (Rocker, 1977). This reluctance to key rapidly is in large part due to the remolding of the sediment column during penetration. Rocker concludes from his work with small test anchor flukes that keying distance can be reduced by 30 to 50 percent by allowing the penetrated anchor fluke to remain undisturbed for 24 hours after firing before applying the keying load. Most of this benefit of reduced keying distance is attained within the first hour or two after penetration.

Anchor fluke configuration also has a large influence on the distance required to key a fluke. Fluke designs have now been shortened so the lengths are now no longer than the widths, and the keying

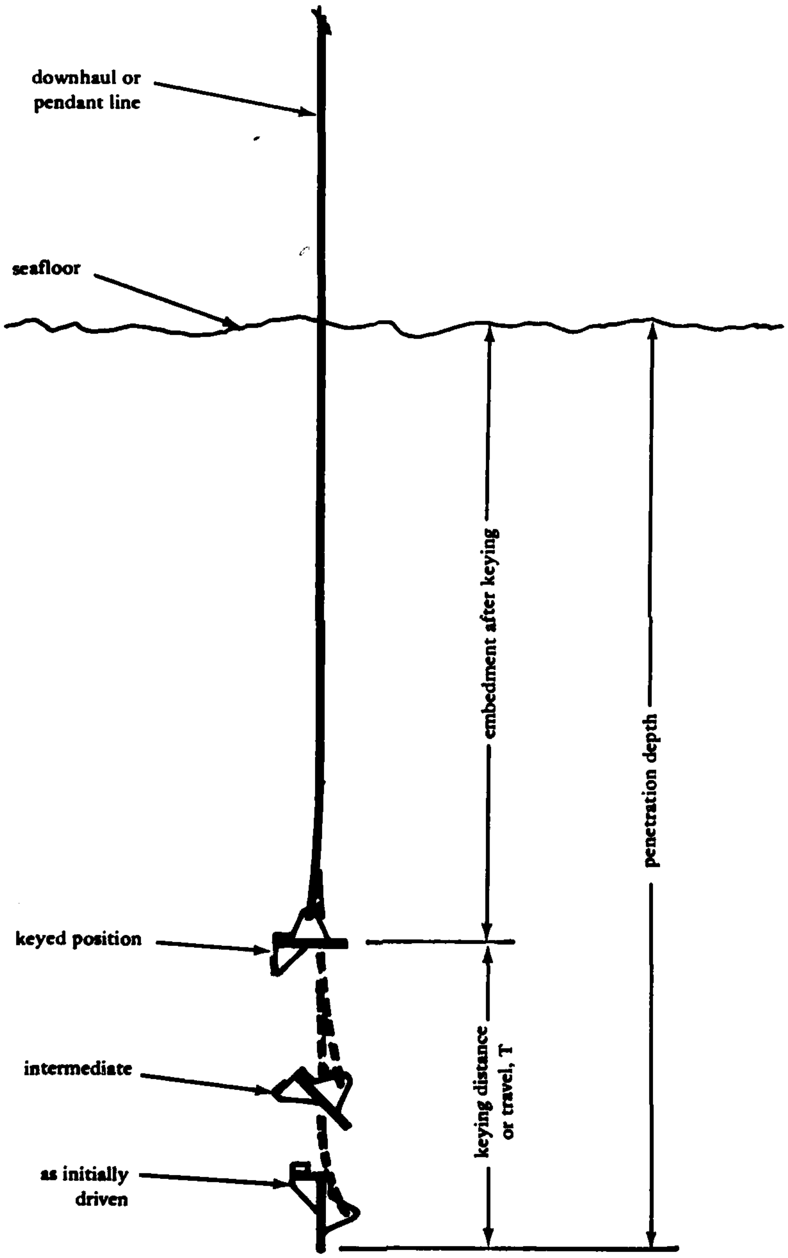


Figure 6. Illustration of keying distance.

arms (Figure 7) are now increased to 0.35 - 0.40 of the fluke length. Both changes in fluke geometry increase the potential for rapid keying of the fluke. In addition to geometry optimization, a "keying flap" has been added to clay fluke designs to enhance their potential for keying (Figure 7). The keying flap acts much like a very small embedment anchor, moving into the keyed position as the fluke is extracted, and increasing the drag force on the "bottom side" of the fluke, thus increasing the force couple acting to promote keying of the fluke. Thus the keying flap on the fluke performs the same function as a pilot chute on a parachute.

Influence of Creep of Fluke Under Load

Shear creep describes that situation whereby long-term shear straining of the soil occurs under the influence of a constant applied pullout load at the fluke. With terrestrial soils situations are known where the rate of such long-term shear straining increases with time until ultimately a complete failure occurs; such a failure is termed a creep rupture.

With some soils creep rupture of triaxial specimens has occurred at stresses as low as 60 percent of the measured strength (Singh and Mitchell, 1968). Some information is available on the creep response of seafloor soils from triaxial tests (Valent, 1978; Beard, 1978). For the soils tested, i.e., a pelagic clay and a calcareous ooze, creep under expected load safety factors will not be so great as to lead to pullout of a fluke (Beard 1978, Valent, 1978).

## FIELD TEST OBSERVATIONS

Summary

A total of fourteen ocean pullout tests of direct embedment anchor flukes are reported here (Table 1). Each of these fourteen possess the qualifications of:

1. known profile of soil shear strength versus soil depth, and
2. reliable measures of pullout load versus embedment depth.

The pullout tests will be treated in four groups, as they were conducted, with the procedures, observations, and results also treated with the test group.

March 1970 Tests - Circular Flukes - Vibratory Driven

Background: Two well-controlled, usable tests of the vibratory embedment anchor were conducted from the fleet tug USS Molala (ATF 106), with the tug maintained in position by a two-point moor. Details

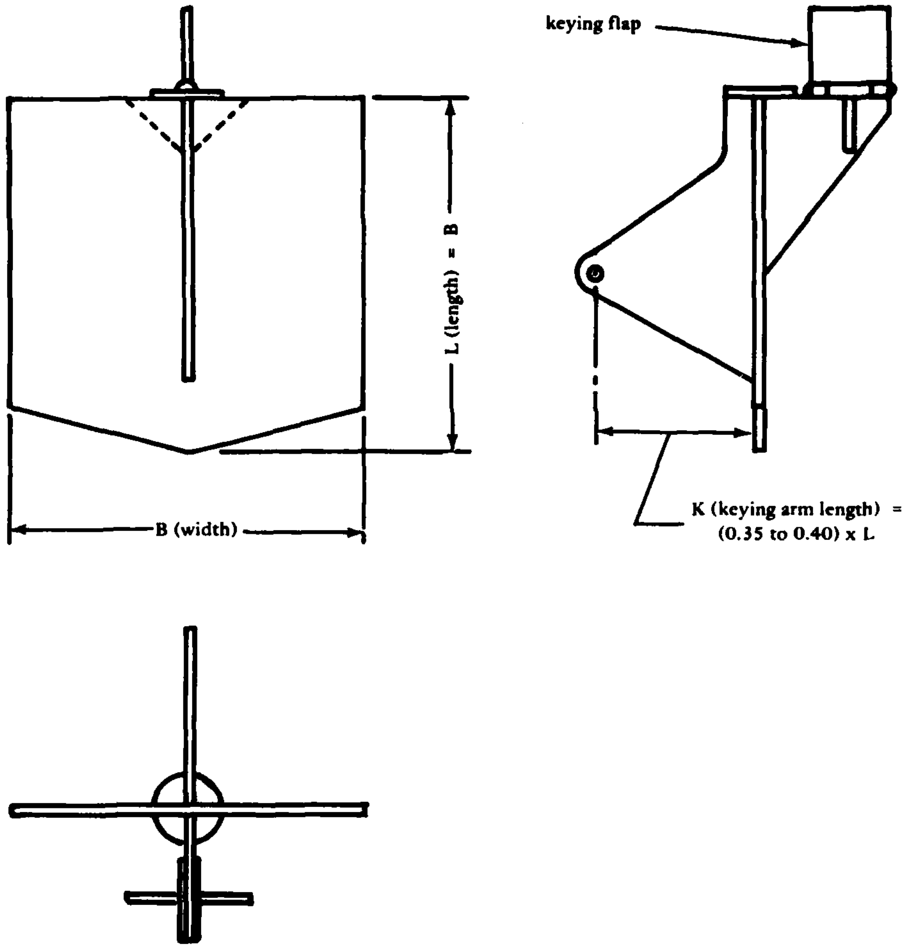


Figure 7. Recommended propellant anchor fluke design to promote rapid keying in soft sediments.

Table 1. Summary of Holding Capacity Tests

| Test No. | Date | Location | Water Depth(m) | Soil Type | Fluke Type | Keyed | Projected Fluke Area, ft² | (center of fluke) Keying Travel | Ratio, Keying Travel to Fluke Length | Keying Arm Ratio |
|---|---|---|---|---|---|---|---|---|---|---|
| VIBRATORY DRIVEN | | | | | | | | | | |
| V1 | 11-12 Mar 70 | Santa Barbara Channel | 29 | Clay-silt | 3' diameter | Yes | 6.12 | 0.2 m (0.5 ft) | 0.2 | 0.5 |
| V2 | 12 Mar 70 | " | 29 | Clay-silt | 3' diameter | Yes | 6.12 | 0.4 m (1.2 ft) | 0.3 | 0.5 |
| EXPLOSIVELY DRIVEN | | | | | | | | | | |
| 1 | 9 Jun 75 | Santa Barbara Channel | 400 | Soft silty clay | 2' x 4' Wye | Yes | 7.65 | 6 m (20 ft) | 5 | 0.24 |
| 2 | " | " | " | " | 2½' x 5' Flat | No | 12.57 | - | - | 0.24 |
| 3 | " | " | " | " | 2½' x 5' Wye | No | 11.81 | - | - | 0.24 |
| 4 | " | " | " | " | 2' x 4' Wye | No | 7.65 | - | - | 0.24 |
| 5 | " | " | " | " | 2½' x 5' Flat | No | 12.57 | - | - | 0.24 |
| 6 | " | " | " | " | 2½' x 5' Wye | No | 11.81 | - | - | 0.24 |
| 7 | 7 Jan 76 | " | " | " | 3' x 3'* Flat | Yes | 8.625 | 6 m (20 ft) | 7 | 0.3 |
| 8 | " | " | " | " | 2½' x 5'* Wye | No | 10.63 | - | - | 0.24 |
| 9 | 10 Sep 77 | Blake Plateau | 1,130 | Calcareous ooze | 2' x 2' Flat | Yes(?) | 3.66 | 9 m (31 ft) | 15 | 0.4 |
| 10 | " | " | " | " | 2' x 2'*Flat | Yes(?) | 3.66 | ? | ? | 0.4 |
| 11 | 11 Sep 77 | " | " | " | 2' x 2' Flat | Yes | 3.66 | 7 m (22 ft) | 11 | 0.4 |
| 12 | 17 Sep 77 | North of Puerto Rico Trench | 5,500 | Pelagic clay | 1½' x 2' Flat | Yes | 2.80 | 5 m (18 ft) | 9 | 0.4 |

*with keying flap

of the equipment and tests are present in Smith et al., 1970. The vibratory anchor apparatus (Figure 8) was used to embed the 3-ft diameter fluke a distance of 3.3 m (11.0 ft) into the clay-silt seafloor (measured to the tip of the fluke). Further penetration was believed impeded by a hard soil strata. Keying of the circular fluke (Figure 9) required 0.2 m (0.5 ft) upward travel of the fluke centroid in test V1 and 0.4 m (1.2 ft) in the second test. Line loads were measured inboard from a large roller at the stern; no corrections were made for the significant friction in that roller because it was known to be highly variable. Friction in that roller is believed to be no more than 10 percent of the measured line load. Vertical displacement of the anchor fluke was measured directly to within about 50 mm (2 in.) by a remote operating device consisting of a spring-loaded wire take-up mechanism, a rotating potentiometer, and a pinger (see Smith et al., 1970, for detailed description). The displacement measuring system transmitted data real time to the ship by varying the ping rate.

The Pitas Point test site (in the Santa Barbara Channel) has been used as a test-bed for CEL geotechnical investigation equipment and techniques; thus, a very good picture of the soil type and shear strength profile was available. Figure 10 presents the results of three in-situ vane shear tests at this site; these data are supported by in-situ cone penetrometer data and by laboratory vane and triaxial data on push piston cores obtained from the CEL DOTIPOS (Deep Ocean Test-In-Place and Observation System) (Demars and Taylor, 1971).

Anchor Test V1: 29 m water, 4 min duration: Vibratory anchor V1 was installed on the afternoon of 11 March and then load applied for a short-term pullout test. A peak load of about 190 kN (42,000 lbf) had been applied when the 5-in. circumference nylon spring line being used to dampen out some of the effect of wave action on load at the anchor parted at an eye splice. As darkness was approaching, it was decided to break for the day and to remake the load hookup and resume testing the next day, 12 March. Testing was resumed the following day with the fluke being pulled out over a 4-min period (Figure 11, (Beard, 1970). During those 4 minutes, one of the load peaks (occurring at 0815 local time, Figure 11) did exceed the scale of the load recording device; thus, the maximum peak load did exceed 260 kN (60,000 lbf).

The loading applied to anchor fluke V1 might be best described as a series of impact loads (Figure 11). This loading form is caused by the response of the ship, the loading platform, to the 0.9 to 1.2 m swell on the test days. In only 29 m of water and with a stiff wire line running vertically down to the anchor, the heave of the ship results in a series of impact loads on the fluke, with the load line going slack in between heaves.

Figure 12 illustrates the comparison between the predicted

**Figure 8. Prototype vibratory anchor.**

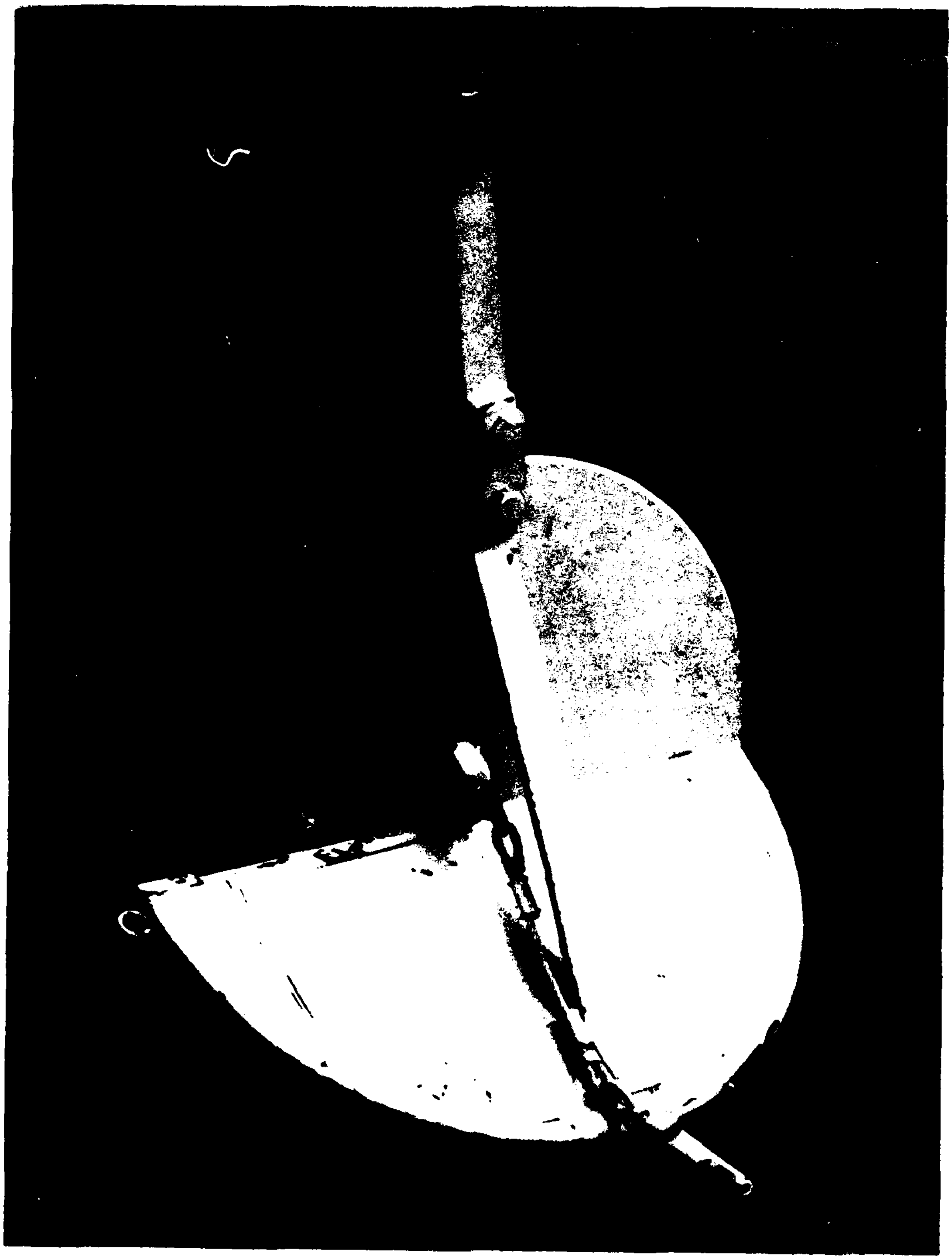

Figure 9. Navy vibratory anchor quick-keying fluke shown in position assumed after keying.

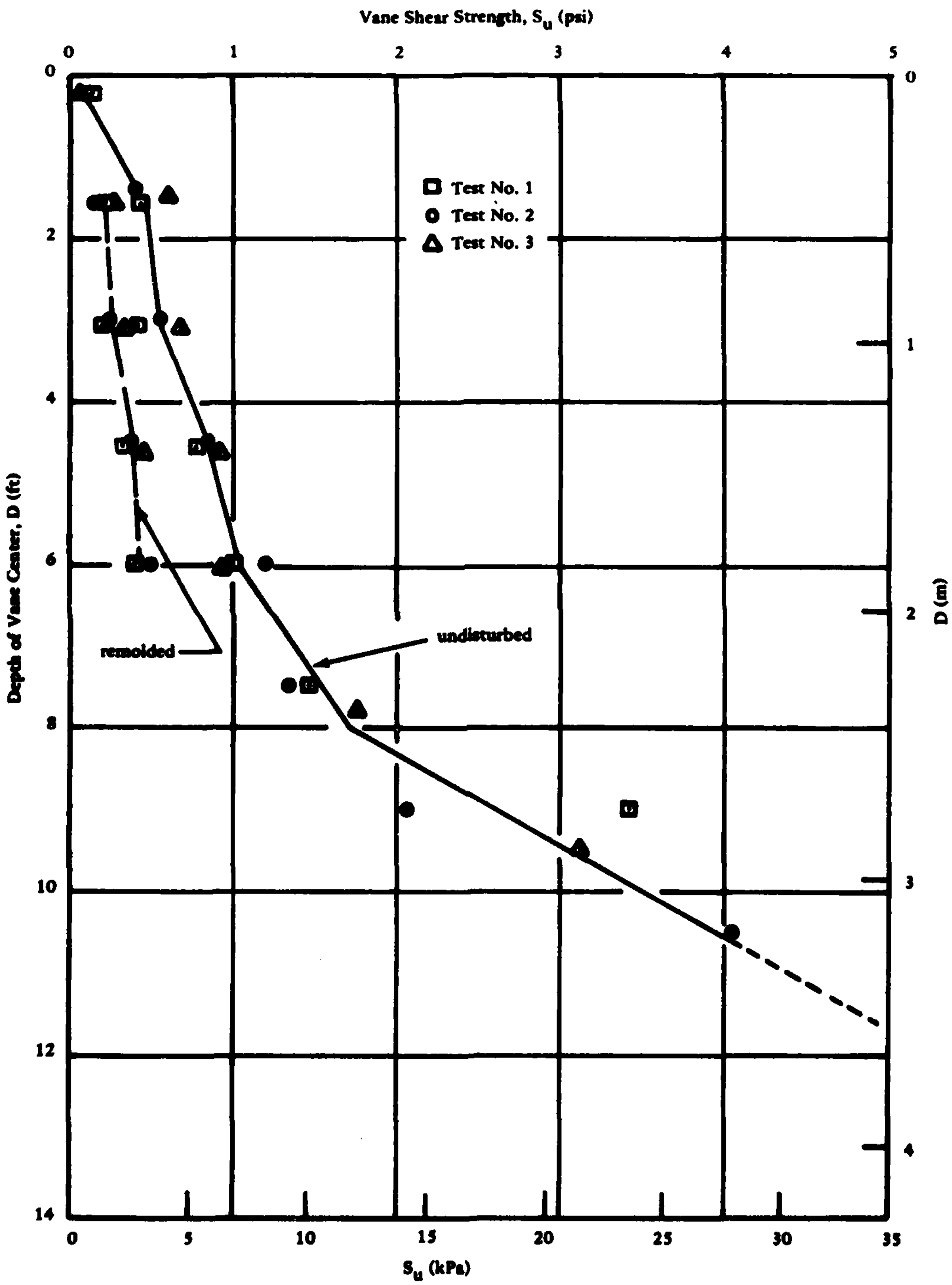


Figure 10. In-situ vane shear strength versus depth for CEL 29-m site in Santa Barbara Channel.

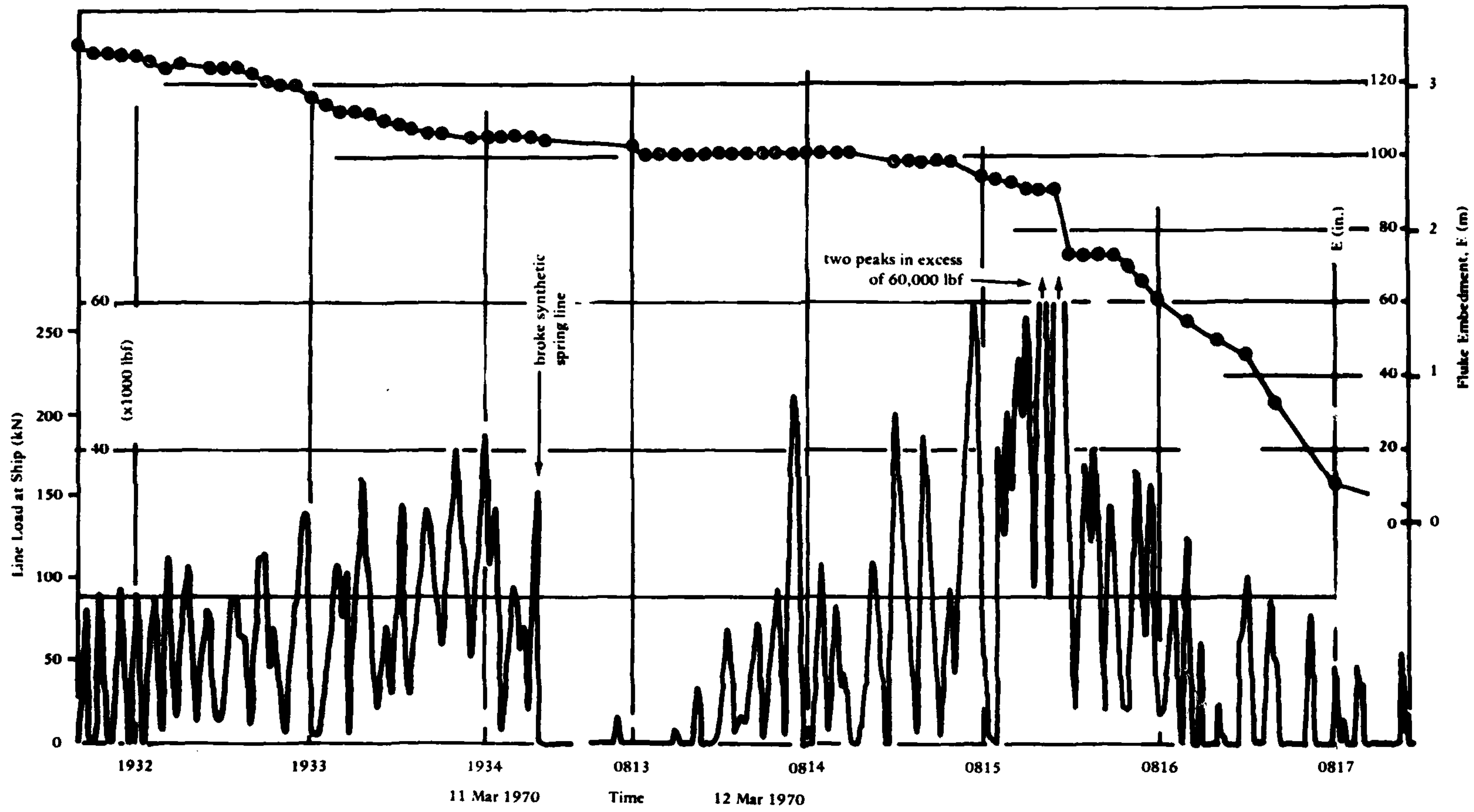


Figure 11. Load and displacement history, fluke V1.

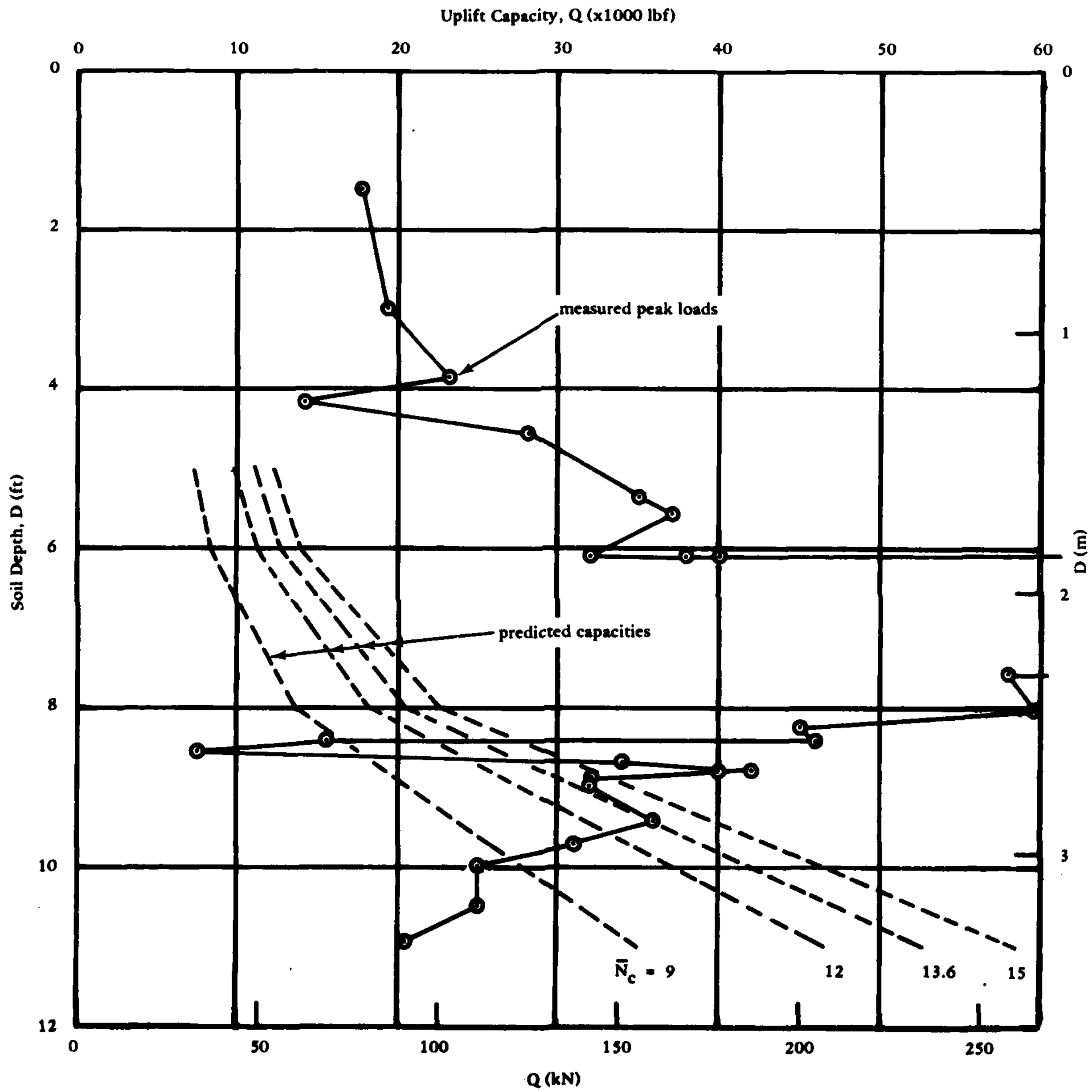


Figure 12. Anchor Test V1, vibratory driven 3-ft diameter fluke, 29 m water depth, clay-silt soil.

static uplift capacity of anchor V1 and the measured load required to cause displacement. Predicted static uplift capacity curves have been drawn for $\overline{N}_c$ factors of 9 (no suction), 15 (full suction), and 12 and 13.6 (intermediate values as recommended by Rocker, 1977), all as a function of depth in the soil profile. For these calculations, the shear strength selected for the analysis was that at the same depth, i.e., the shear strength taken to best represent the average shear strength mobilized in displacing the anchor fluke upward was that acting at the level of the plate centroid. The area of the plate acting for the uplift capacity relationship was taken to be the projected fluke area on the horizontal plane after fluke keying. Projected fluke areas for each of the tests are tabulated in Table 1.

The measured load required to cause displacement has been superimposed on the pullout predictions. The influence of the repeated impact loading on load capacity is readily apparent with the peak load attained being about three times greater than the predicted static capacity at that soil depth. This increased load capacity develops apparently due to an increase in the soil shear strength at higher strain rates. After fluke V1 had been extracted to about 2 m of embedment, the measured load capacity continued to stay high (almost 3 x ) relative to the predicted capacity until eventual pullout from 0.5 m embedment.

Anchor Test V2: 29 m water, 120 min duration: Vibratory embedment anchor V2 was installed on the afternoon of 12 March 1970. For this test, the plan was to keep the peak loads in the neighborhood of 90 kN (20,000 lbf). Loads were maintained on this anchor for a total of two hours. Approximately 25 load peaks ranging from 54 to 140 kN (12,000 to 32,000 lbf) displaced the fluke 1.1 m upward. Then two peaks to 140 kN (32,000 lbf) and one to 210 kN (47,000 lbf) displaced the fluke another 0.5 m. Twenty more peaks ranging from 40 to 150 kN (10,000 to 33,000 lbf) pulled the fluke free.

This load-displacement history is shown in Figure 13 along with the predicted uplift capacity curves. Anchor fluke V2 is seen to have pulled out at lower loads than V1. Pullout at this lower load could be attributed to the increased number of load impacts/cycles of test V2 (as compared to V1) causing some degradation in soil shear strength. However, the magnitudes of the impact loads attained in test V2 were deliberately maintained at lower levels than in test V1. The anchor fluke, V2, appears to have crept out little by little under each successive load impact/cycle: this behavior is little different from that of anchor fluke V1 except that V1 moved greater distances with each load impact (the magnitudes of some of the load impacts were, of course, greater in test V1). For depths of embedment less than 2 m (6 ft), however, performance of the flukes in the two tests was very much the same.

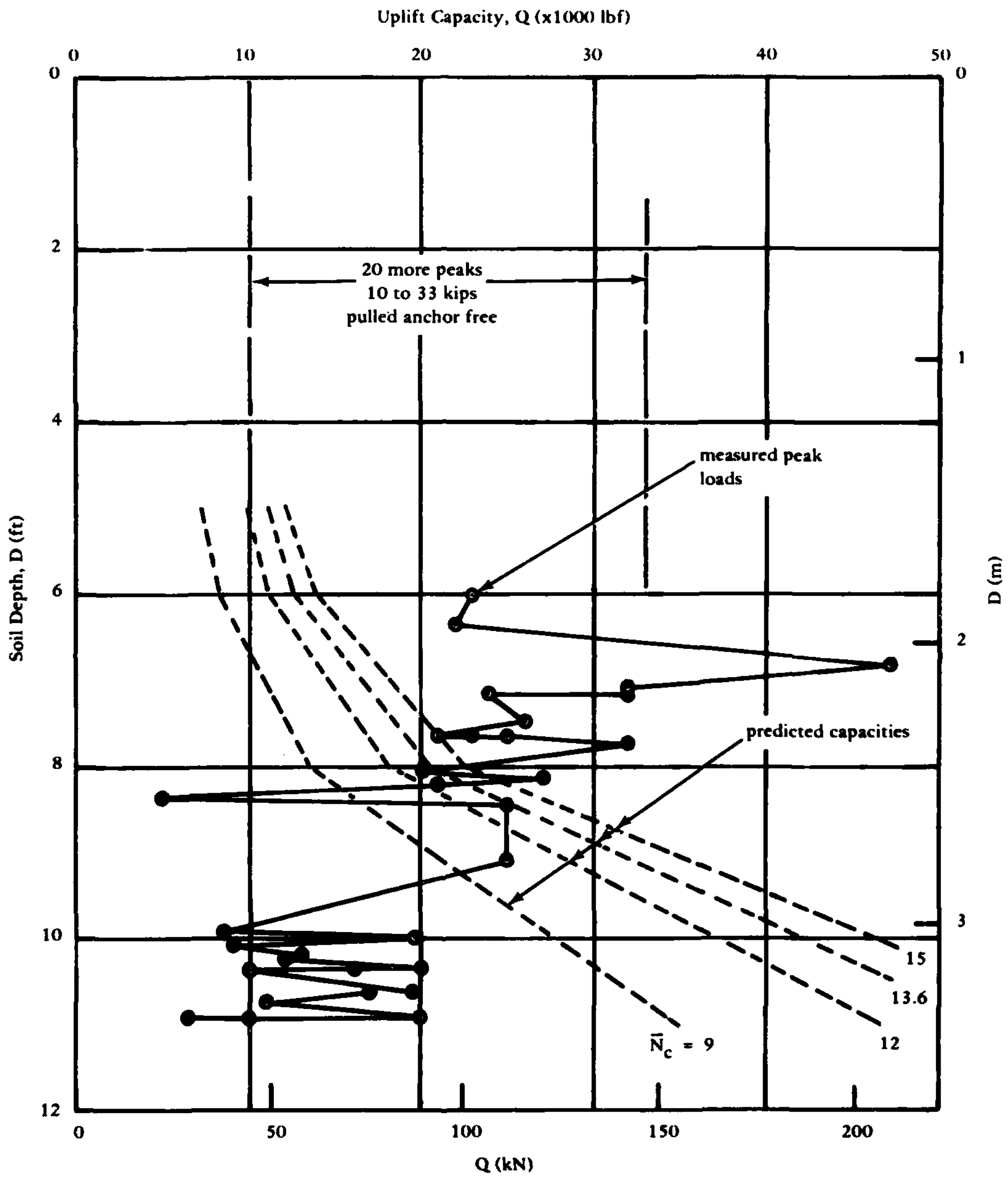


Figure 13. Anchor Test V2, vibratory driven 3-ft diameter fluke, 29 m water depth, clay-silt soil.

Thus it does appear that the 1 m (3 ft) diameter vibratory anchor flukes in the clay-silt seafloor are capable of sustaining impact loads at least two and possibly three times the predicted static uplift capacity. However, the fluke does move progressively upwards under these impact loadings. Further, it appears that similar progressive upward travel (and eventual pullout) would occur even if the impact loadings were maintained at magnitudes equal to the static capacity (see Figure 13 in the 9 to 7 ft depth interval). The impact loads are occurring with a period of about 8 sec, drainage of any excess pore pressures generated must not be complete in the clay-silt soil, and therefore some progressive strength degradation is probably taking place under all impact loads, even those considerably less than the static uplift capacity.

June 1975 Tests - Rectangular Flukes - Propellant Driven

Background. Several tests of the various CEL propellant-driven, direct-embedment anchors have been run to test and verify the functioning of the safe-and-arm devices, the launcher, and the fluke assembly (Smith et al., 1970; Taylor, 1976). In most of these tests an accurate profile of soil strength and/or accurate records of fluke displacement with load were not obtained.

The first attempt to gather complete sets of load test data was made in June 1975. Six load tests were conducted from the M/V Caldwell, an oil-field work boat. Weather conditions were ideal with the sea near flat. The Caldwell was not moored, but rather maintained herself on station using LORAC navigation. Pullout loads were applied to the anchors immediately after firing, thus drift of the ship and angular deviation of the load line from vertical were negligible.

The tests were performed using the CEL 20K Propellant Driven Anchor (Figure 14). The anchor flukes used all had a length to width ratio, L/B, of 2 (Table 1), four were of the Wye fluke design (Figure 15) while the remaining two were flat. Loads during anchor pullout were measured inboard of the stern roller by an electrical load cell. Roller friction was measured in several tests to be as high as 13 kN (3,000 lbf). Roller friction has not been accounted for in the anchor pullout loads listed because reliable measures of roller friction were not obtained for each test. Embedment of the fluke for tests at the 370-m site was measured using a 12 kHz pinger attached to the load line 15 m (50 ft) above the launcher. The embedment depth measurement is obtained from the time difference in arrival at the ship hydrophone between the direct signal from the pinger and the indirect signal reflected from the seafloor (see Figure 16). A good quality pinger height record using a 3.5 kHz pinger and recording on the host ship's 3.5 kHz Precision Depth Recorder is presented in Figure 17 (this record is actually that for anchor test 10 of this report). (For further information on the

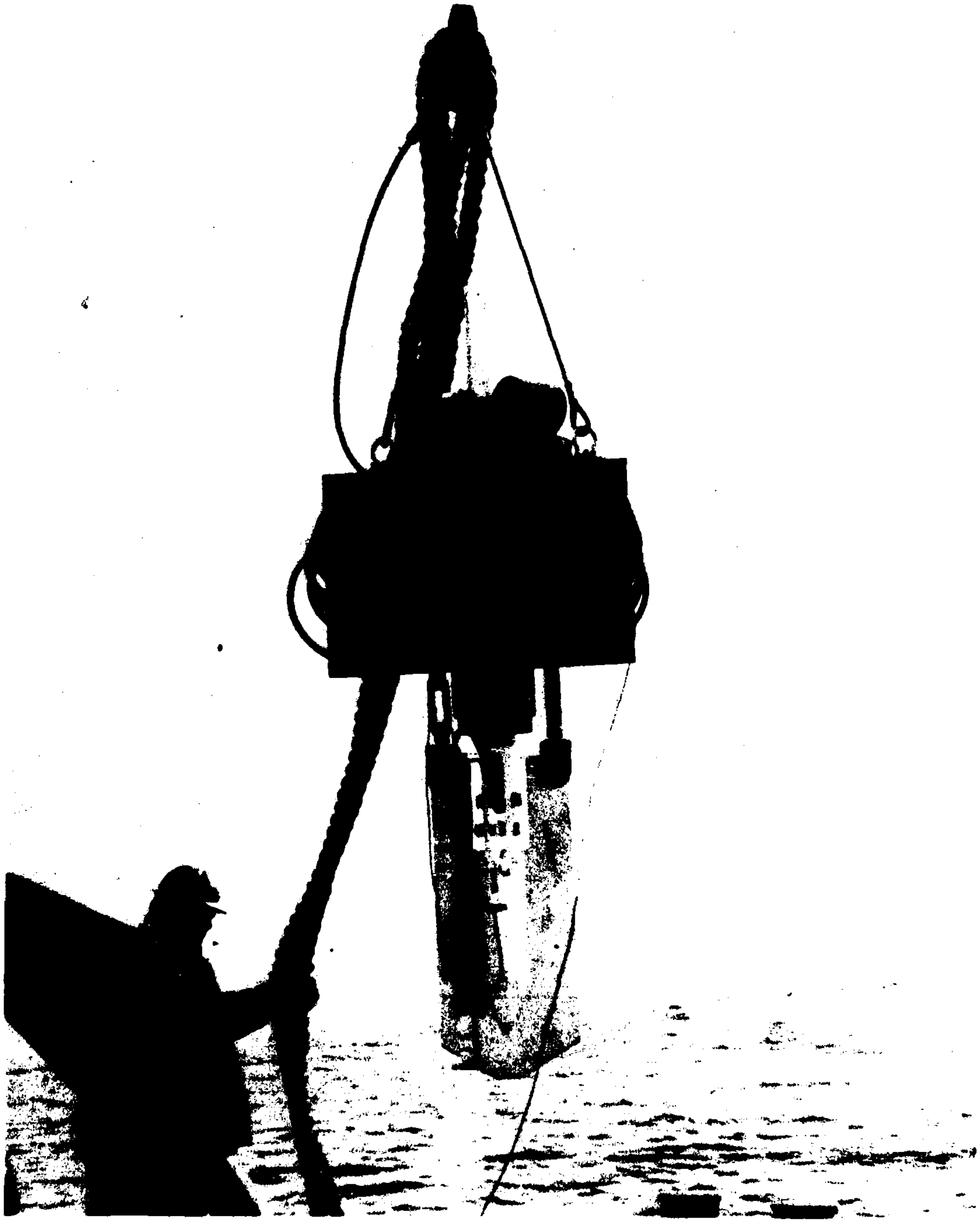

Figure 14. CEL 20K Propellant Anchor.

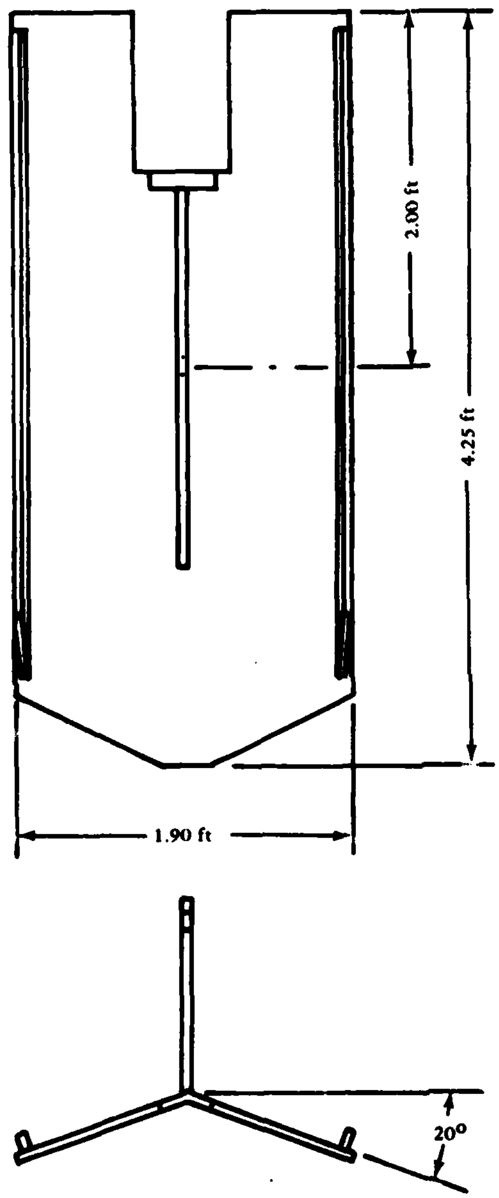


Figure 15. 2x4-ft wye fluke, detail omitted for clarity. 2x4-ft flat fluke similar except plate not bent, width of flat fluke is 2.00 ft instead of 1.90 ft with the wye. 2-1/2 x 5-ft flukes are geometrically similar.

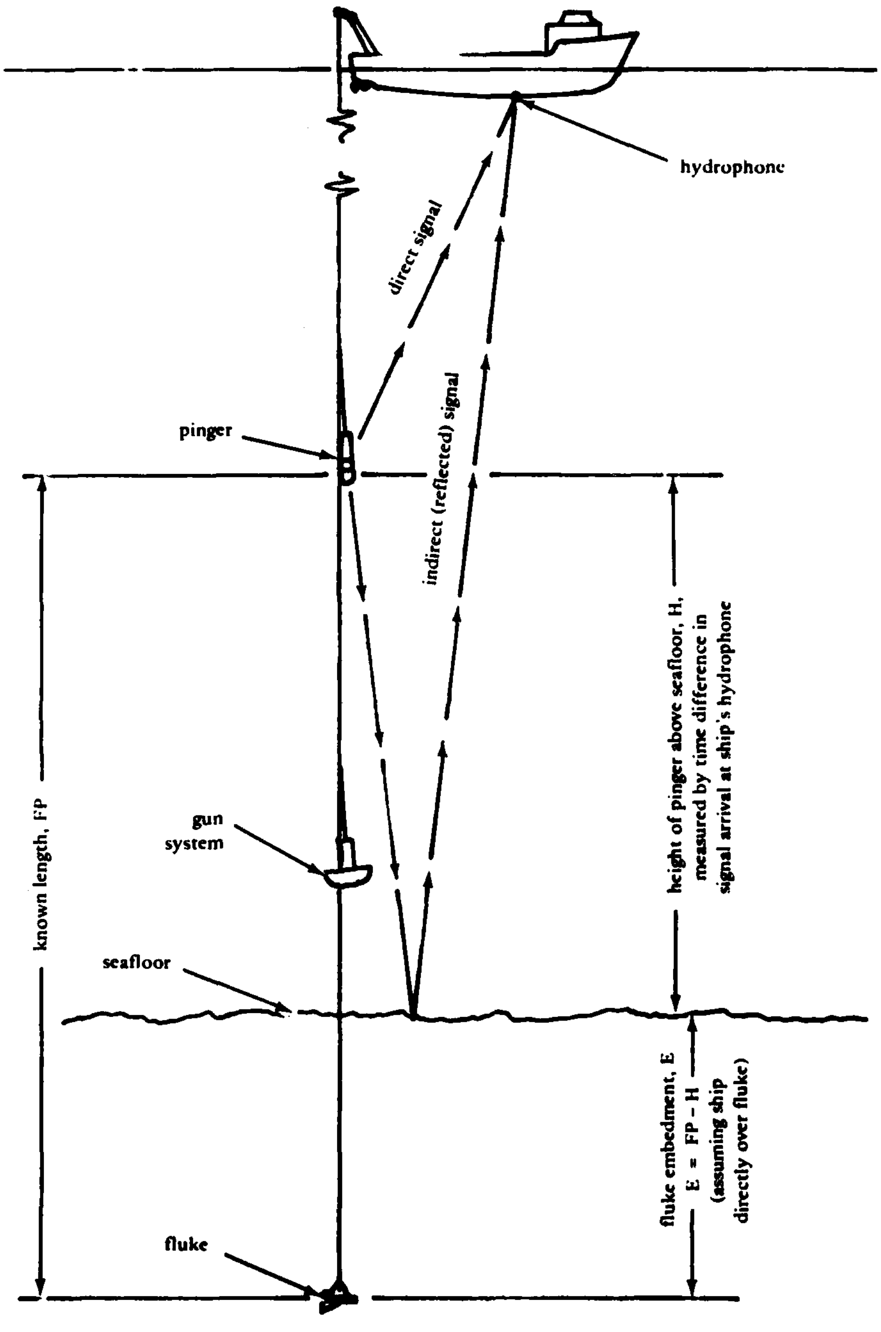


Figure 16. Illustration of acoustic technique used to measure fluke embedment.

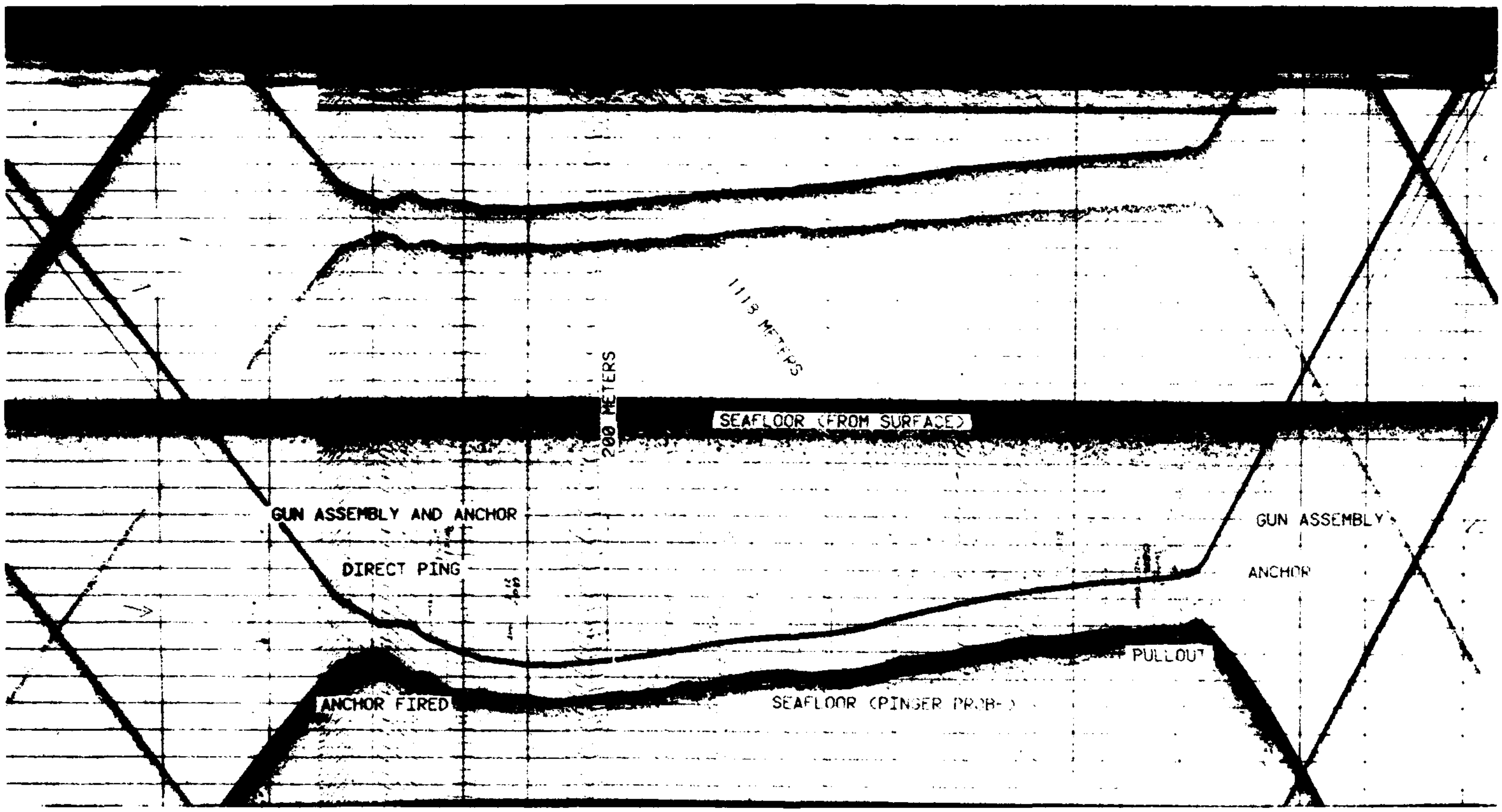


Figure 17. Acoustic record from 3.5 kHz Pinger Probe system which provides an indirect measurement of fluke embedment.

Pinger Probe system see Malloy and Valent, 1978.)

These six tests were conducted at the CEL 1200-foot site (370 m water depth) in the Santa Barbara Channel. The seafloor engineering properties of this site are well known from in-situ measurements and from laboratory tests on cores (Demars and Taylor, 1971). The soil is classified as a soft, normally consolidated silty clay, designated CL by the Unified Soil Classification System. Figure 18 presents in-situ and laboratory vane shear strength data and a projected curve of undrained shear strength versus depth based on laboratory triaxial tests on core samples (consolidated isotropically and sheared undrained). The areal variability of the seafloor properties is slight at this location and the anchor test locations were all held within about 0.4 km (0.2 naut. mi) (Figure 19); therefore, the strength data of Figure 18 are expected to be representative of each test location.

Anchor tests 1 through 6: 370 m water, 2 min duration: The short-term pullout test results for these six anchors are presented in Figures 20 through 25. The anchors were loaded and extracted from the seafloor immediately after embedment with the total duration for fluke pullout ranging from 1.4 to 2.1 min. The loads measured on deck are typified by Figure 26. The load displacement data presented in Figures 20 through 25 are of two forms: one set (solid line) are the average loads in the downhaul, i.e., average of adjacent maximum and minimum in the recorded cyclical load curve; the other set (dashed line) are the maximum loads in the load curve. Both sets of data are presented for these tests; however, the maximum loads or load curve peaks (dashed line) are thought to govern anchor fluke short-term displacement more than the average loads.

All six anchors deployed in this test series performed poorly, with only anchor 1 attaining anywhere near the rated uplift capacity. At the time of testing, this poor performance was attributed to one or more of the following three factors:

1. Improper or a lack of fluke keying,
2. A crooked penetration trajectory of the fluke in the soil resulting in less net penetration than indicated by the pinger measurement, and/or
3. Severe soil disturbance caused by fluke penetration resulting in lower soil strengths than expected.

The probable contribution of each of these factors was the subject of a controlled field test on the San Pablo Bay mud flats during August and September 1975. This study used small 0.46 m long by 0.23 m wide flukes (18.0 in. by 9.0 in.) embedded in a sediment of similar sensitivity (about 3) (Rocker, 1977).

Rocker (1977) found in his mud flat tests that the second factor, crooked trajectory, was not a significant contributor to the low

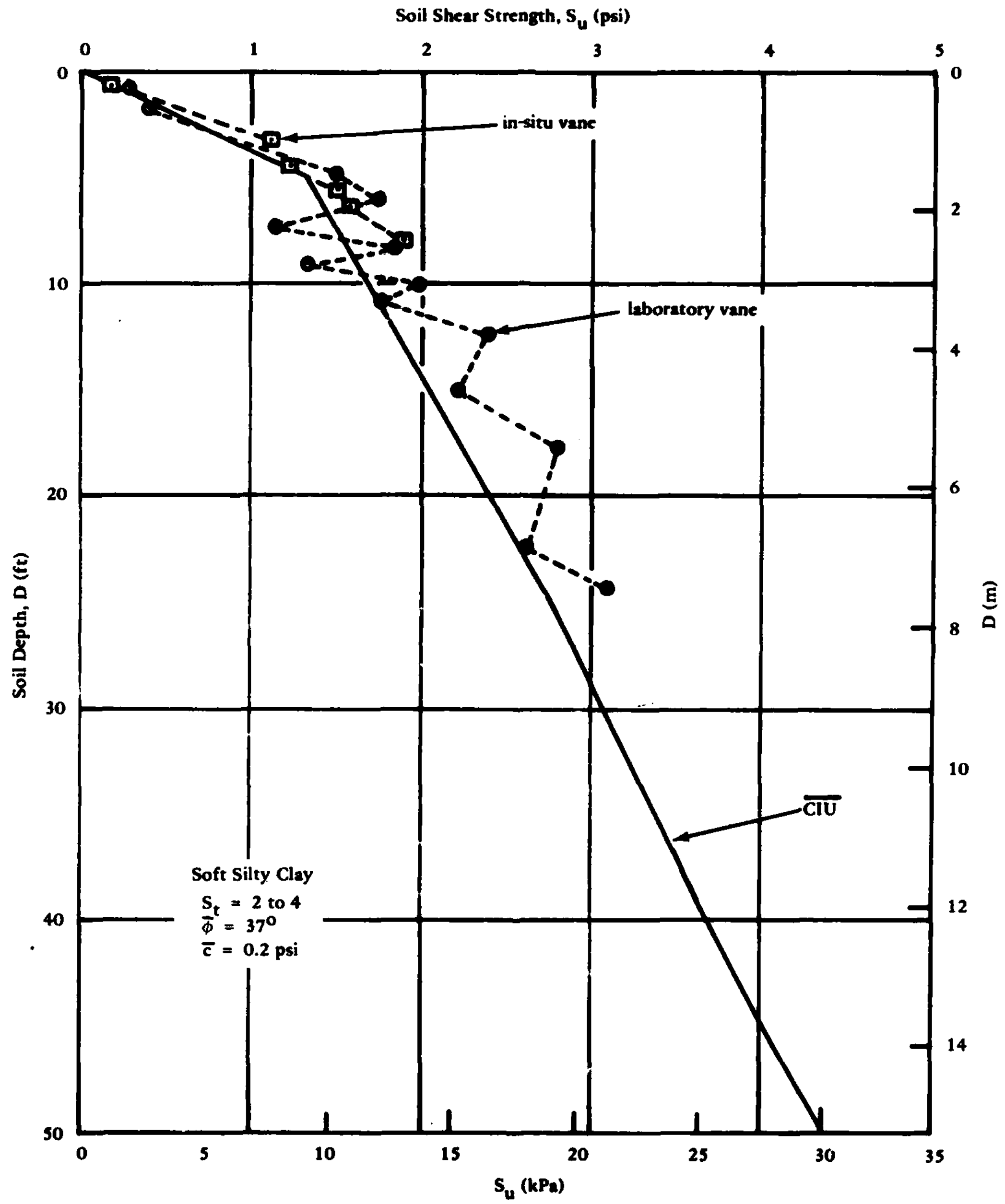


Figure 18. Shear strength data versus soil depth for CEL 370 m site.

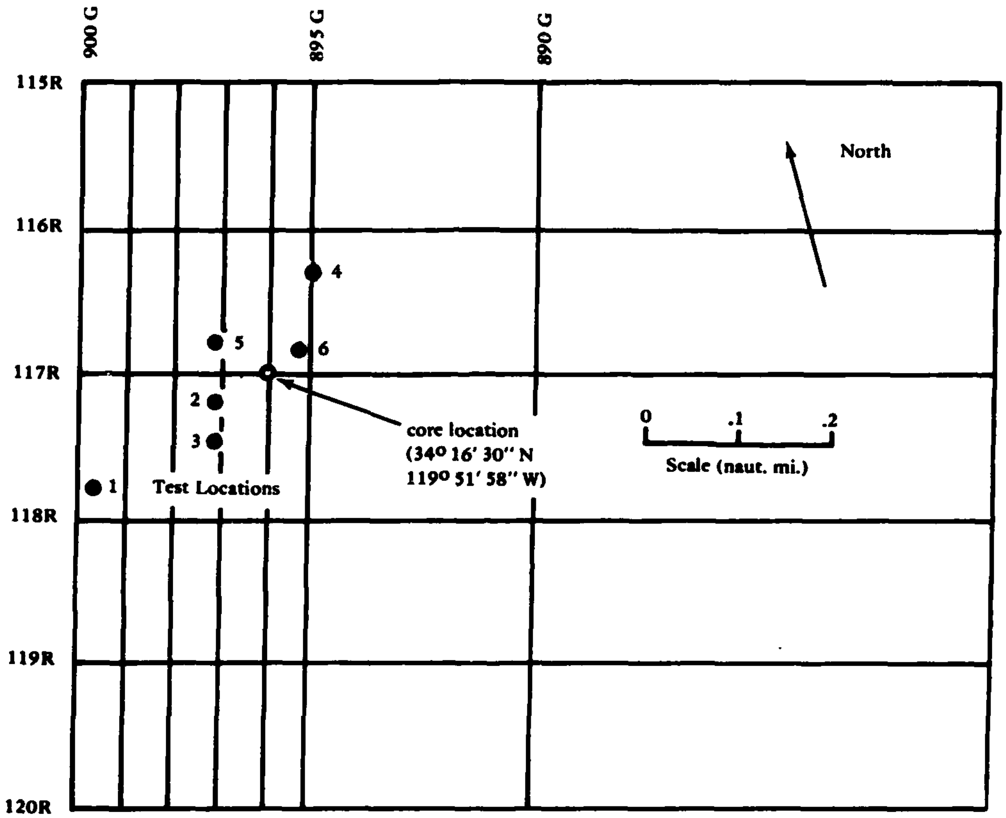


Figure 19. Location (LORAC coordinates) of anchor tests at 370 m site in relation to core location.

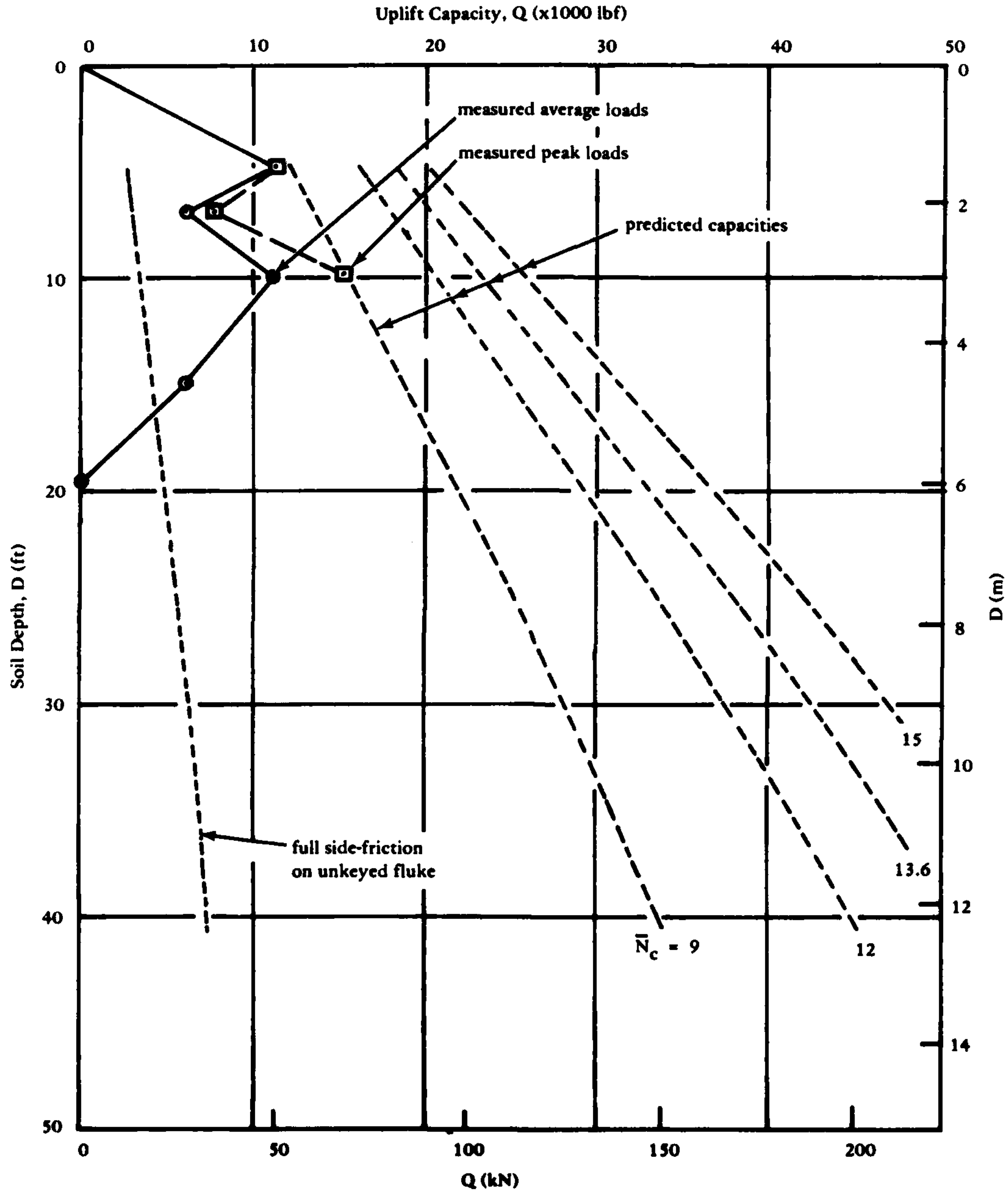


Figure 20. Anchor Test 1, propellant driven 2x4-ft wye fluke, 370 m water depth, soft silty clay.

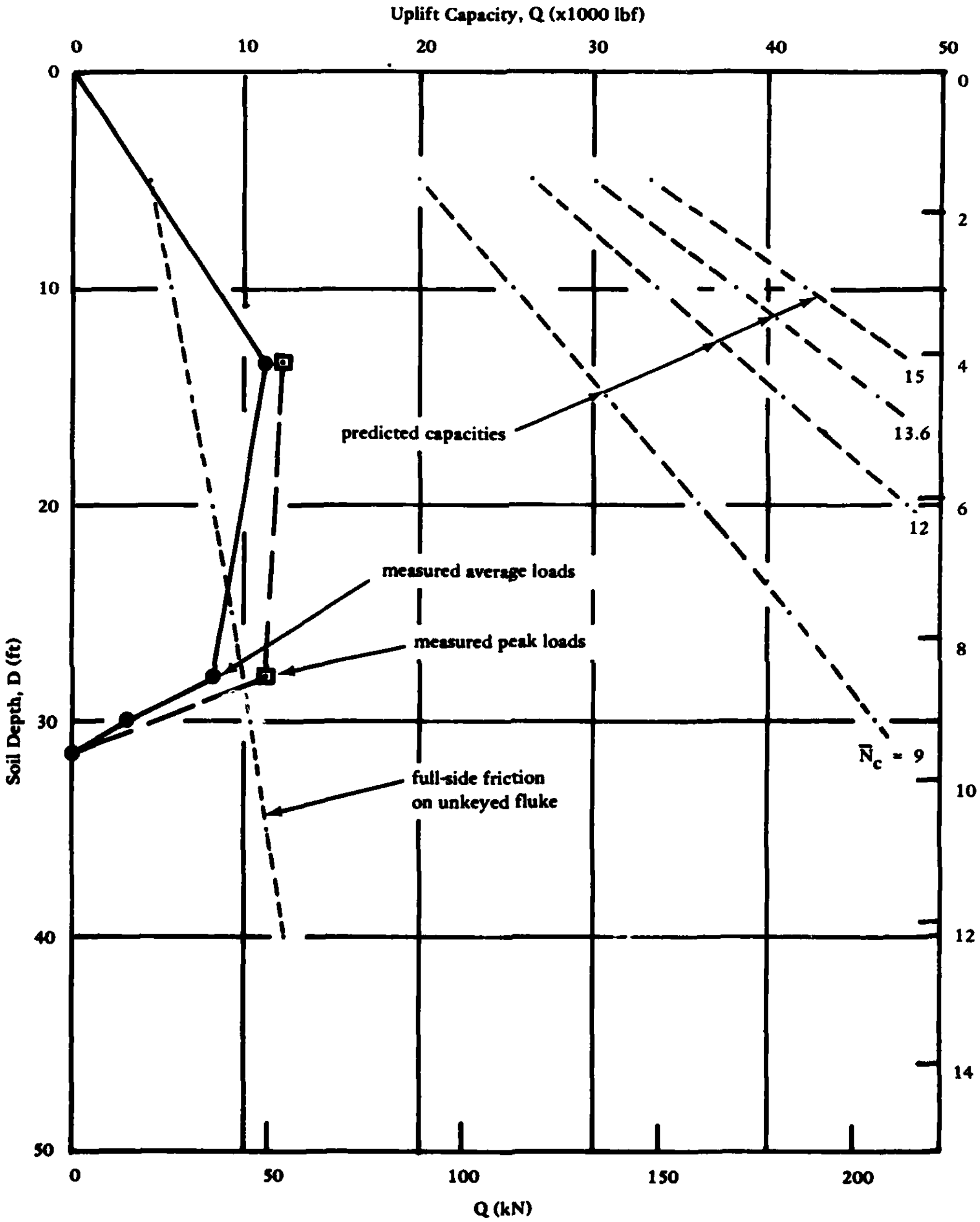


Figure 21. Anchor Test 2, propellant driven 2-1/2 x 5-ft flat fluke, 370 m water depth, soft silty clay.

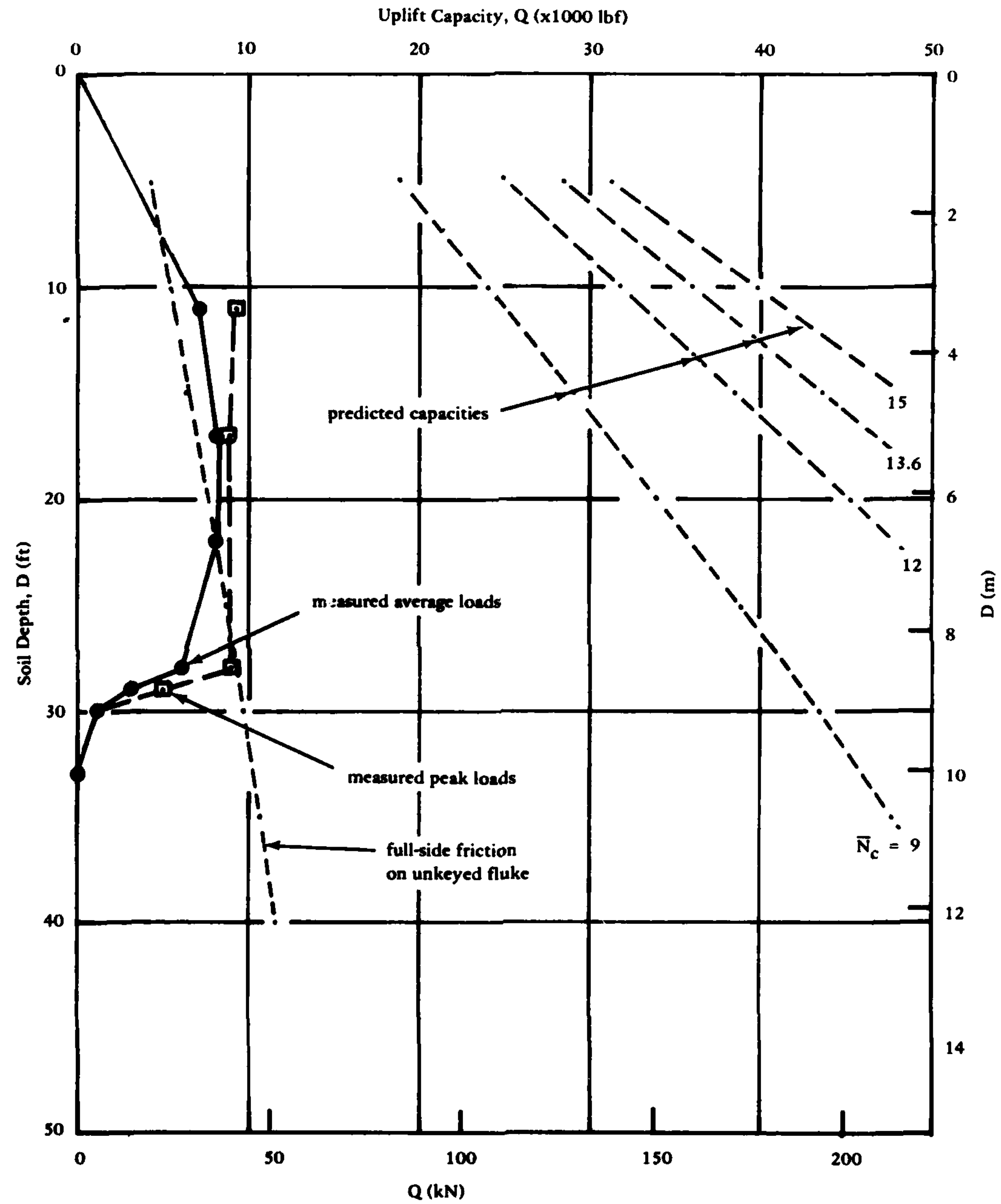


Figure 22. Anchor Test 3, propellant driven 2-1/2 x 5-ft wye fluke, 370 m water depth, soft silty clay.

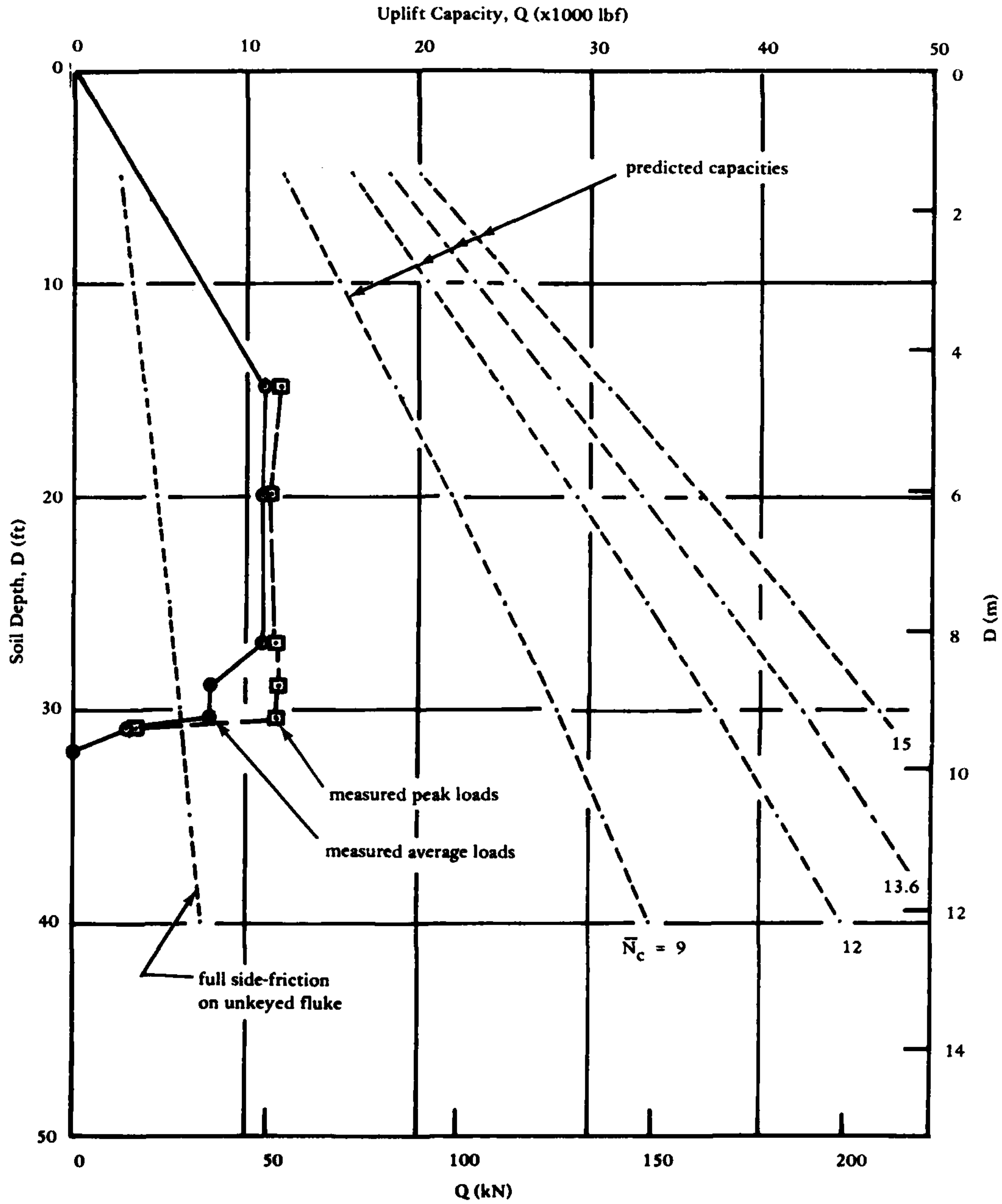


Figure 23. Anchor Test 4, propellant driven 2x4-ft wye fluke, 370 m water depth, soft silty clay.

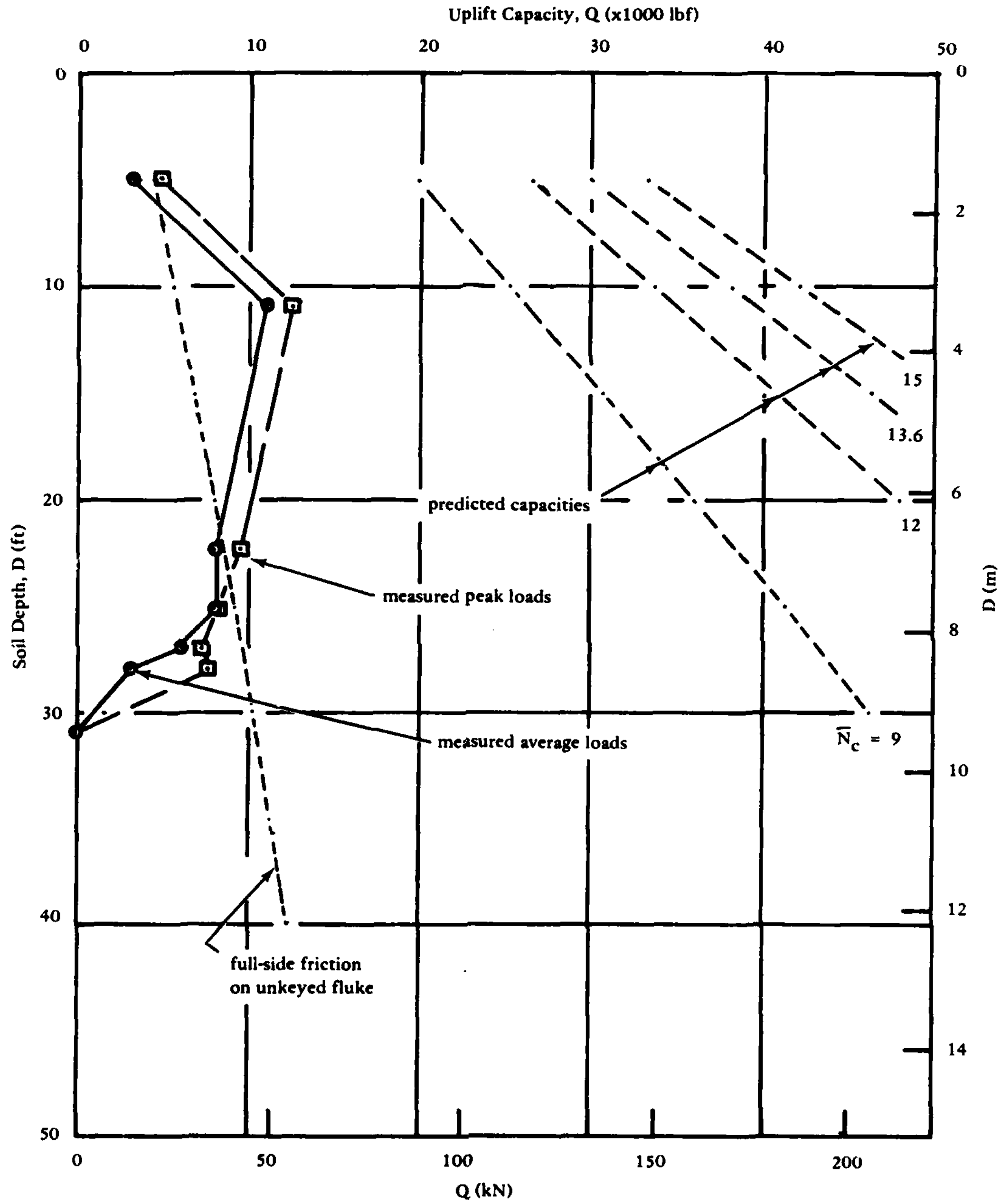


Figure 24. Anchor Test 5, propellant driven 2-1/2 x 5-ft flat fluke, 370 m water depth, soft silty clay.

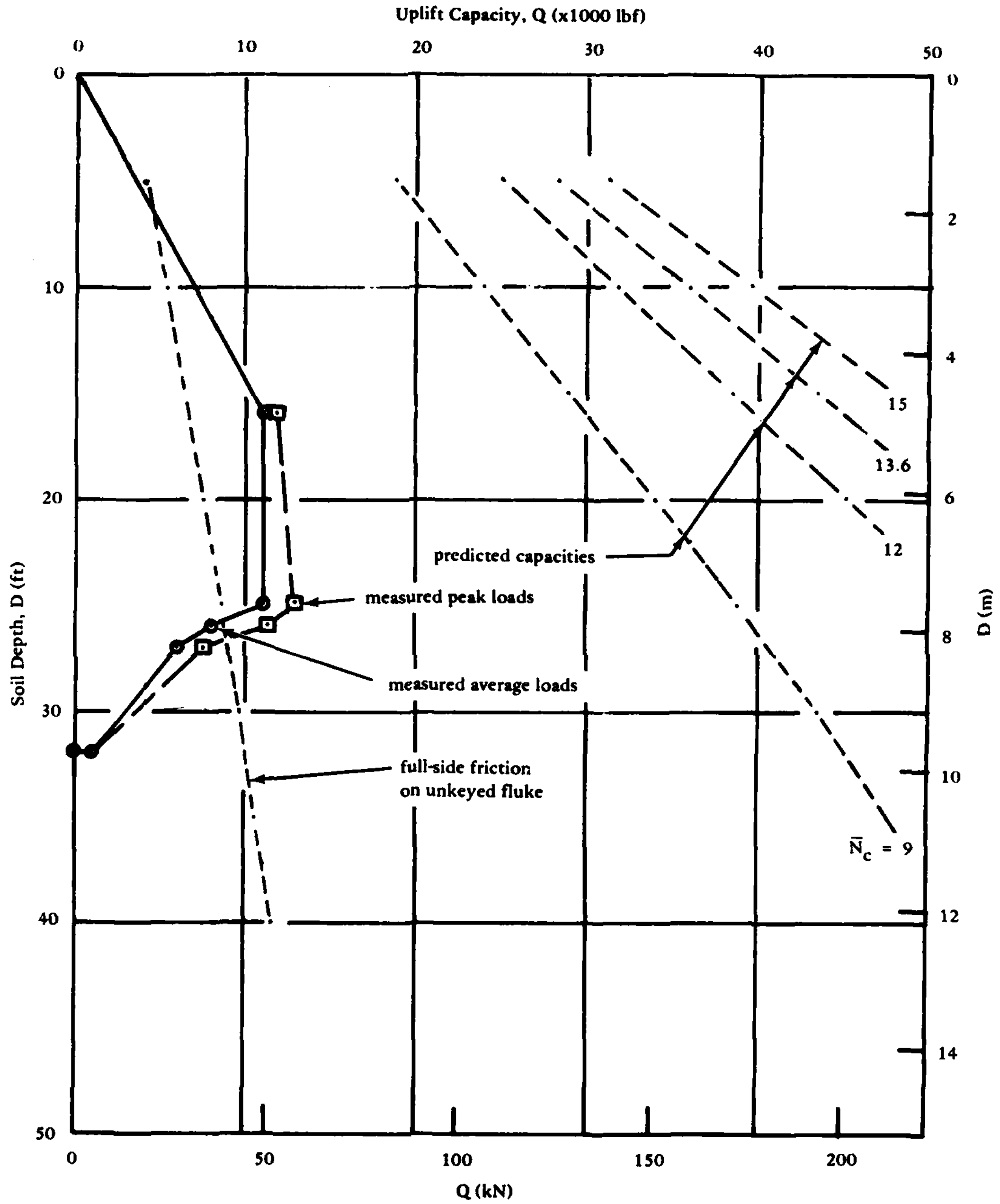


Figure 25. Anchor Test 6, propellant driven 2-1/2 x 5-ft wye fluke, 370 m water depth, soft silty clay.

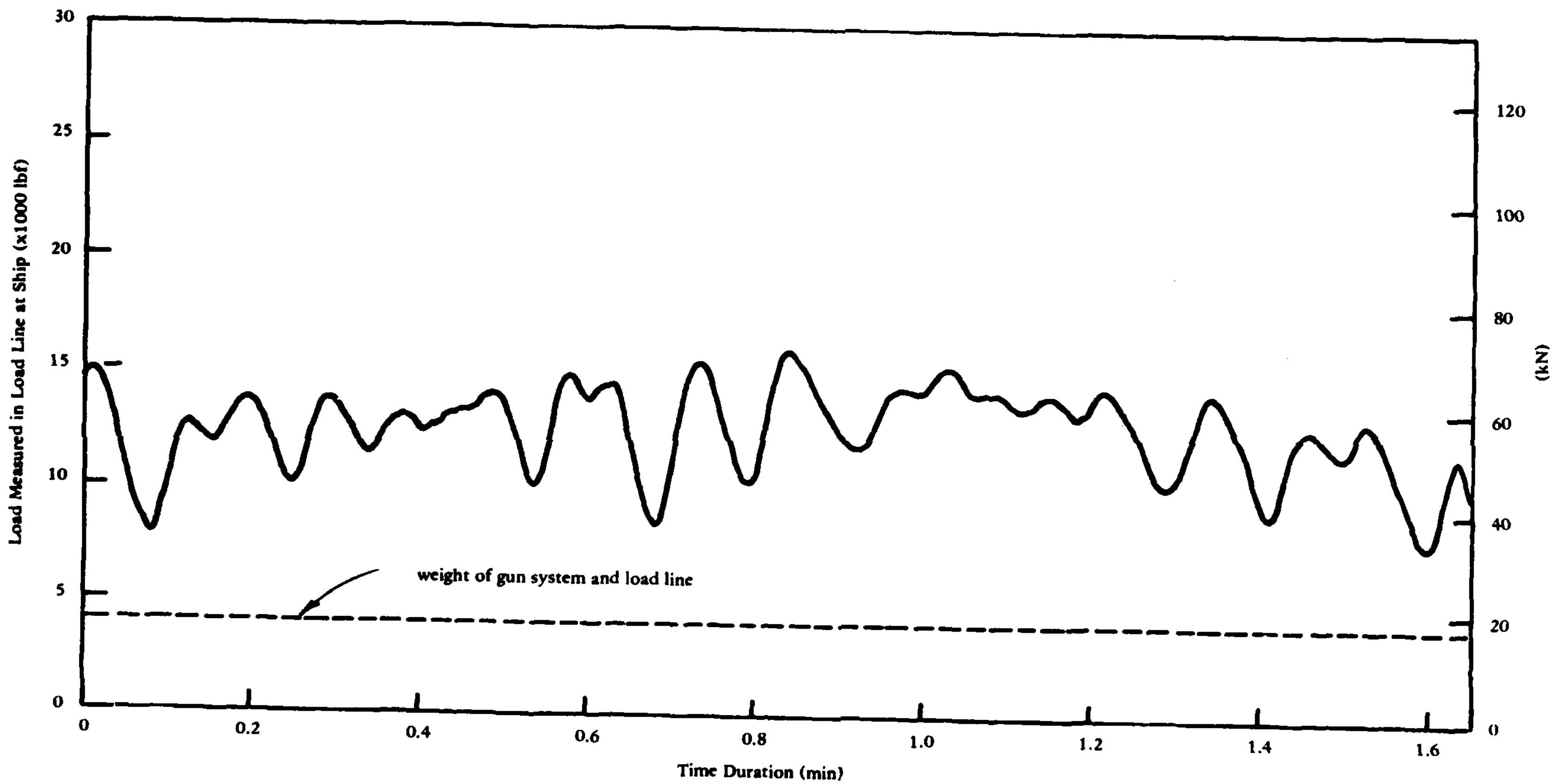


Figure 26. Representative segment of load history curve for anchor tests 1 through 6, this particular segment from Anchor Test 2 pulled out over 2.1 min.

measured uplift capacities. Anchor fluke trajectories were found to be quite straight. Also, Rocker determined that soil disturbance, as it influences soil strength and thereby the uplift capacity developed by a keyed fluke, is not a major factor in and of itself. The vane shear strength of the soil in the vicinity of the fluke penetration path was reduced by only 5 to 10 percent due to penetration. This strength reduction is apparently partly responsible for Rocker's recommendation of uplift capacity factors, $N_c$, between 12 and 13.6, rather than 15 or 16 for design of uplift resisting anchors in short-term conditions.

However, Rocker's tests did show that soil disturbance has a strong indirect influence on soil holding capacity because soil disturbance influences the travel distance required to key the fluke.

Rocker's mud flat tests indicated that the largest contributor to the poor uplift capacities of anchors 1 through 6 was a lack of fluke keying. It was shown that these test anchor flukes probably slid right back out of the shaft of disturbed soil without the fluke ever keying. This behavior is probably true for all tests of the rectangular fluke in soft clays, except for test 1, where the fluke seems to have keyed at about 3 m (10 ft) of embedment.

As a result of Rocker's mud flat tests, a new configuration for propellant-driven embedment flukes was adopted at CEL in order to increase the probability of fluke keying, as follows:

1. Change of the fluke L/B ratios from 2 to 1; i.e., making the flukes square rather than rectangular;
2. Change of the fluke keying arm length, K, from 0.3L and less to 0.35L and greater; i.e., to increase the eccentricity of the line load on the unkeyed fluke, thereby increasing the keying moment;
3. Addition of a keying flap on the bottom side of the fluke to act much like a drogue chute in properly deploying a parachute; the keying flap acts to increase the keying moment, in this case by increasing the magnitude of the force couple causing keying (Figure 27).

Despite the fact that the flukes performed poorly, these six tests did provide some data regarding the pullout forces that should be expected in such situations. A detailed evaluation of these data is not merited in this report on keyed fluke uplift capacity; however, some observations are pertinent. The loads measured at the load cell inboard of the roller reach magnitudes of about 20 to 40 kN (4,000 to 8,000 lbf) over that predicted for simple side friction (full undrained soil strength) on the unkeyed fluke. If the largest measured value for stern roller friction (13 kN or 3,000 lbf) is accounted for by subtracting it from the measured line load, then the pullout load at the fluke exceeds the full-side friction predictions by 7 to 27 kN (1,000 to 5,000 lbf). This additional force

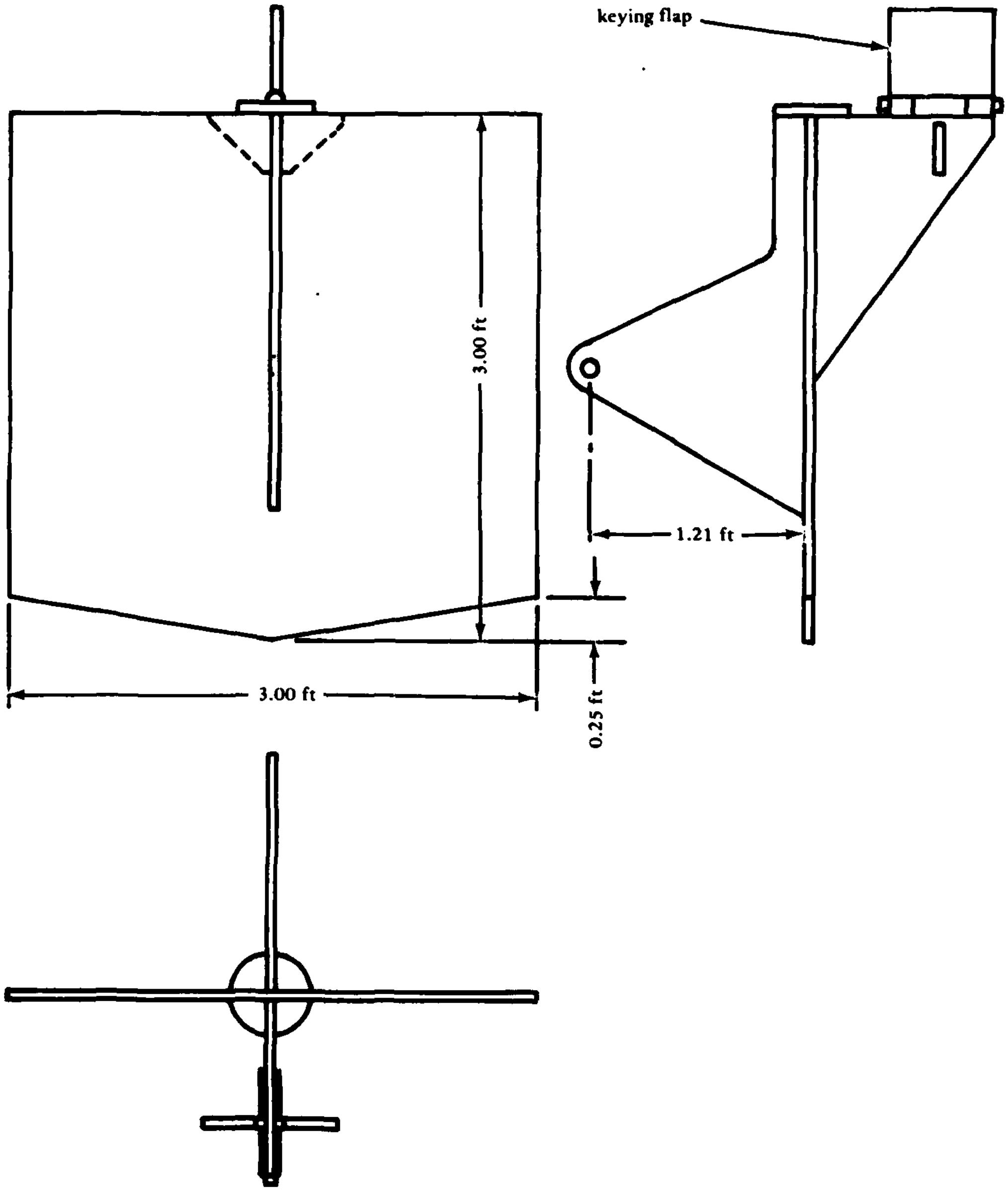


Figure 27. 3x3-ft fluke with keying flap, for 20K propellant driven anchor system, for soft sediment.

required for unkeyed pullout is easily accounted for by other anchor items adding side area to the friction force calculations, e.g., keying arm on the fluke, linkage to the downhaul cable, the length of 5/8-in. diameter wire rope downhaul embedded in the seafloor, and the anchor system piston. However, the sum of friction forces on these items certainly does not amount to much more than the 7 to 27 kN. Thus, if the assumption of no keying is correct, then the anchor flukes in being extracted are mobilizing nearly 100 percent of the undisturbed undrained shear strength in side friction. This information, for the particular soils involved, is in agreement with Rocker's (1977) findings on the mud flats.

Alternately, the soil shear strength mobilized may be equal to 100 percent of the undisturbed undrained shear strength, but may actually be composed of some partially remolded soil shear strength with a strain rate effect added on top; that is, the soil may actually be partially remolded, resulting in a decrease in the undrained shear strength, but that decrease may be compensated for by an increase in strength due to a strain rate effect.

January 1976 Tests - Square Fluke - Propellant Driven

Background. After the San Pablo Bay mud flat tests (Rocker, 1977) and their impact on the anchor fluke design, two additional tests were run, Nos. 7 and 8, at the CEL 1,200-foot site, this time from the CEL warping tug. The tug was dynamically positioned using LORAC navigation as reference. Loads were measured in board of a small, specially-built, low friction bow roller. Again the 20K gun assembly was used for these tests (Taylor, 1976).

Anchor Test 7: 370 m water, 4 min duration: Test 7 used a 3 ft x 3 ft fluke (0.92 x 0.92 m) with a 0.9 ft keying arm (0.27 m), for a keying arm length, K, of 0.3L (Figure 27).* A hinge flap was also attached on the "bottom" side of the fluke to increase the keying force couple. Again, embedment during pullout was measured using a 12 kHz pinger system with the pinger attached to the load line about 15 m (50 ft) above the gun system. Figure 28 presents the measured peak loads applied to this square fluke versus the fluke depth and compares this data to the predicted uplift holding capacities for a 3 ft x 3 ft fluke. The performance of this fluke is radically different from that of the rectangular flukes, reaching a marked peak load at about 4.3 m (14 ft) embedment. This fluke quite obviously did key. However, it must be noted that the fluke

*The keying arm length, K, for this anchor fluke was 0.30L, less than the recommended lower limit for K, 0.35L, because it was to serve as a control test in verifying the arm length criteria. Testing of a second 3 x 3 ft fluke with a keying arm of 0.35L was planned, however, this fluke was prematurely launched and lost due to improper gun system lowering procedure.

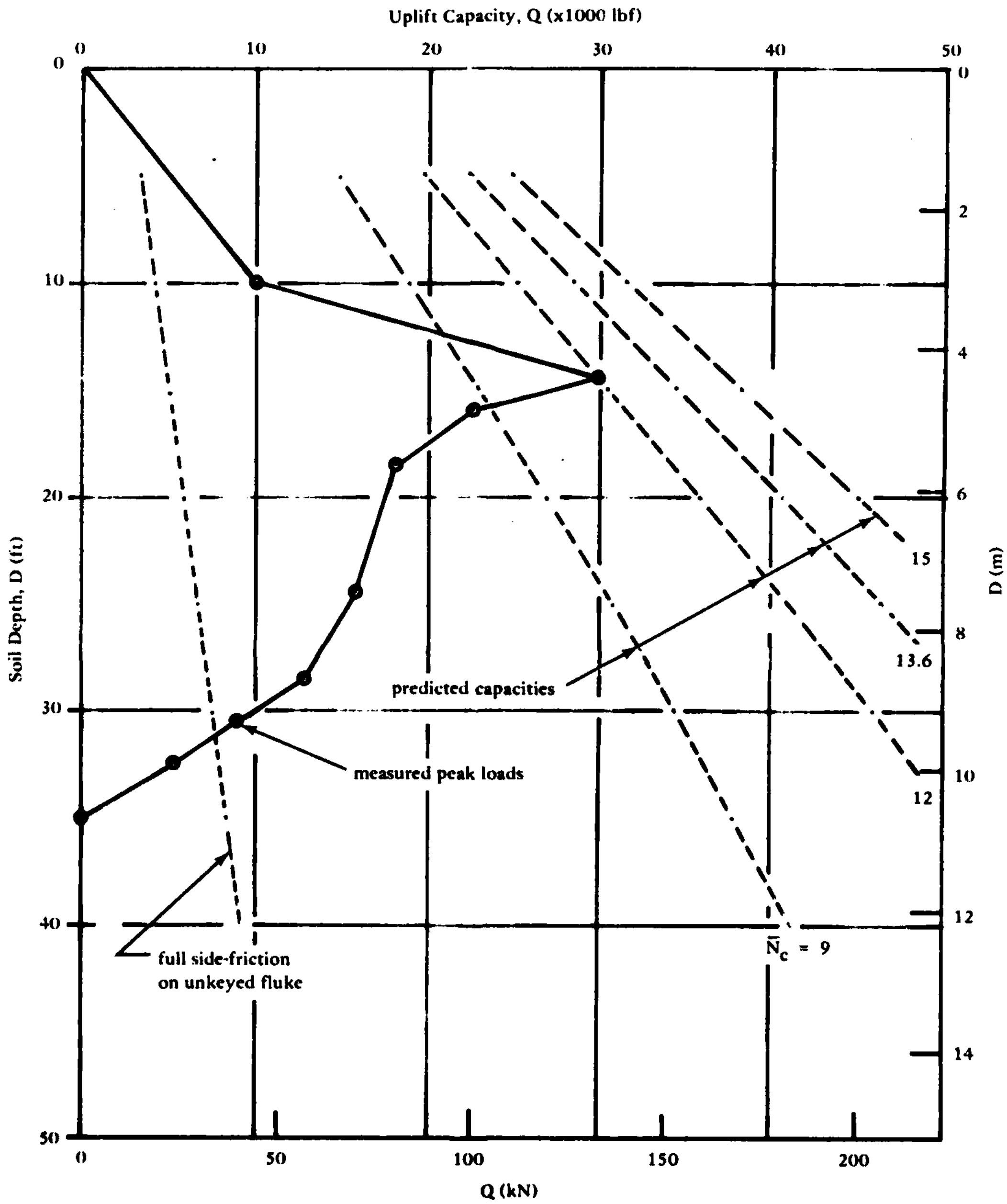


Figure 28. Anchor Test 7, propellant driven 3x3-ft flat fluke with keying flap, 370 m water depth, soft silty clay.

apparently traveled 6 m (20 ft) upward before completing keying. This ratio of fluke travel during keying to fluke length, of 20/3 = 7 is so inefficient that it is not acceptable. Quite likely the use of larger keying arm ratios, say K/L of 0.4, or more effective keying flaps, would improve performance.

When the fluke did finally key, it mobilized an uplift capacity equivalent to that predicted using an $\bar{N}_c$ factor of 12, assuming full mobilization of the undisturbed undrained shear strength (Rocker's 1977 75 percent recommendation). It should be noted here that the fluke had already been extracted to about 4.3 m depth at this point of maximum load. At this shallow depth, the soil failure mode may already have started to shift from that of a deep fluke to that of a shallow one (Figure 2), with a corresponding decrease in the expected value of the holding capacity factor, $\bar{N}_c$.

The load versus embedment curve also suggests that the uplift capacity drops off markedly at the 3 m (10 ft) embedment level. This drop off may largely be due to a change in the failure mode from that of a deep anchor to that of a shallow embedded anchor (see Figure 2). The curves of predicted uplift capacity do not treat the shift from deep to shallow anchor behavior.

Anchor Test 8: 370 m water, 2 min duration: Test 8 was a test of simple modifications to the original 2½ ft x 5 ft clay fluke to see if the large number of clay flukes of that type in existence at that time could be simply modified to function in soft sediments. Six inches (0.15 m) were cut off the tip of the fluke to reduce the L/B ratio, and a hinge flap was placed on the bottom side of the fluke. Unfortunately, the depth of embedment of the fluke could not be measured during this test because of a problem with the 12 kHz pinger; only the line loads during pullout could be measured. However, these load data have proven quite valuable in that the measured peak load of about 70 kN (16,000 lbf) is considerably short of that load capacity expected from a properly keyed fluke (Figure 29). Thus, the load data indicate that the modified 2½ ft x 5 ft clay fluke, even with the keying flap, did not key (Taylor, 1976).

## September 1977 Tests - Square Flukes - Propellant Driven

Background. The previous anchor tests described were all conducted in terrigenous soils. This last test series was conducted in two typical deep ocean soils, a calcareous ooze and a pelagic clay. Both test sites were visited earlier on the USNS Lynch (T-AGOR-7) at which time in-situ vane shear strength measurements were made and cores were obtained with a long piston corer and a spade box corer (Lee, 1976), thus an adequate picture of the soil profile was already available. The September 1977 cruise, also on the Lynch, was intended as a test of penetration and holding capacity predictions for the propellant-driven embedment anchor

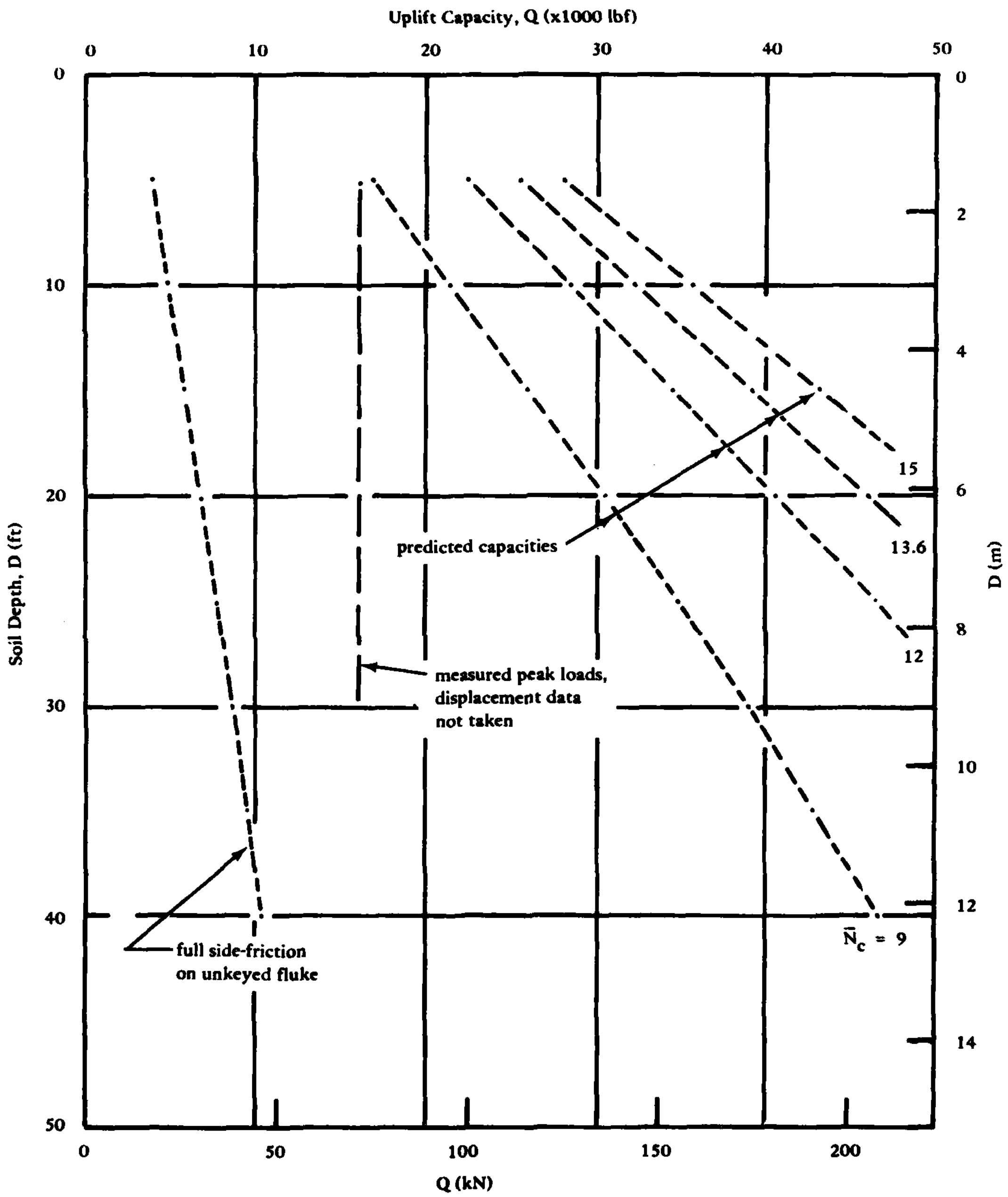


Figure 29. Anchor Test 8, propellant driven MODIFIED 2-1/2 x 5-ft fluke, 370 m water depth, soft silty clay.

and of the Free-Fall Doppler Penetrometer (Beard, 1977) with some additional cores and in-situ measurements being taken in support of the penetration and holding capacity work. The 9/16-in. diameter steel wire rope available on the Lynch was used as the load line. The limited breaking strength of this rope dictated that the anchor fluke sizes be held to 2 ft x 2 ft at the calcareous ooze site and held to 1.5 ft x 2 ft at the deeper water pelagic clay site. The CEL 10K Propellant Driven Anchor gun assembly was used for these tests as it was more than adequate for the task (Figure 30), (Wadsworth and Taylor, 1976).

The load line was passed through a sheave at the top of the ship's U-frame. Loads were measured by a load cell in the linkage between the sheave and the U-frame; the influence of friction in the sheave on the measured loads is negligible. The Lynch was maintained on station by dynamic positioning using the angle of the load line as a reference; i.e., the load line was maintained near vertical. Embedment of the anchor fluke was measured using a new CEL assembled 3.5 kHz pinger probe (Malloy and Valent, 1978) attached to the load line 30 m (100 ft) above the gun assembly. Figure 17 presents one of the fluke pullout records, this one for anchor test 10, a long-term test maintained over a duration of 49 min. (The results of this one "long-term" test are included in this report on short-term uplift capacities for purposes of comparison of behaviors in calcareous ooze.)

<u>Anchor Test 9: 1,130-m water, 2 min duration</u>: Anchor tests 9, 10, and 11 were conducted north of Grand Bahama Island on the Blake Plateau in 1,130 m (3,700 ft) water depth. This site was selected because of its calcareous ooze sediments with high calcium carbonate content, i.e., 77 - 86 percent carbonate by weight. Figure 31, prepared by Lee, 1976, presents a band of possible undrained shear strengths versus depth for this site (referred to as Site III in Lee's report). For this uplift capacity evaluation the strength profile representing the lower limit of possible strengths, profile A, was assumed to be the correct profile.

Anchor test 9 at the calcareous ooze site in 1,130 m of water used a 2 ft x 2 ft fluke. This fluke was essentially geometrically similar to the 3 ft x 3 ft fluke shown in Figure 27, except the 2 ft x 2 ft fluke did not have a keying flap when tested.* The load cell record (Figure 32) shows that the anchor was extracted from the seafloor over a period of 2 min. The dynamic load resulting from the heave of the ship amounted to about 20 percent of the anchor pullout load, trough to peak. Apparent fluke embedment depths from

*The keying flaps in anchor tests 9 and 12, and probably in test 11, were torn off the flukes during launch from the gun.

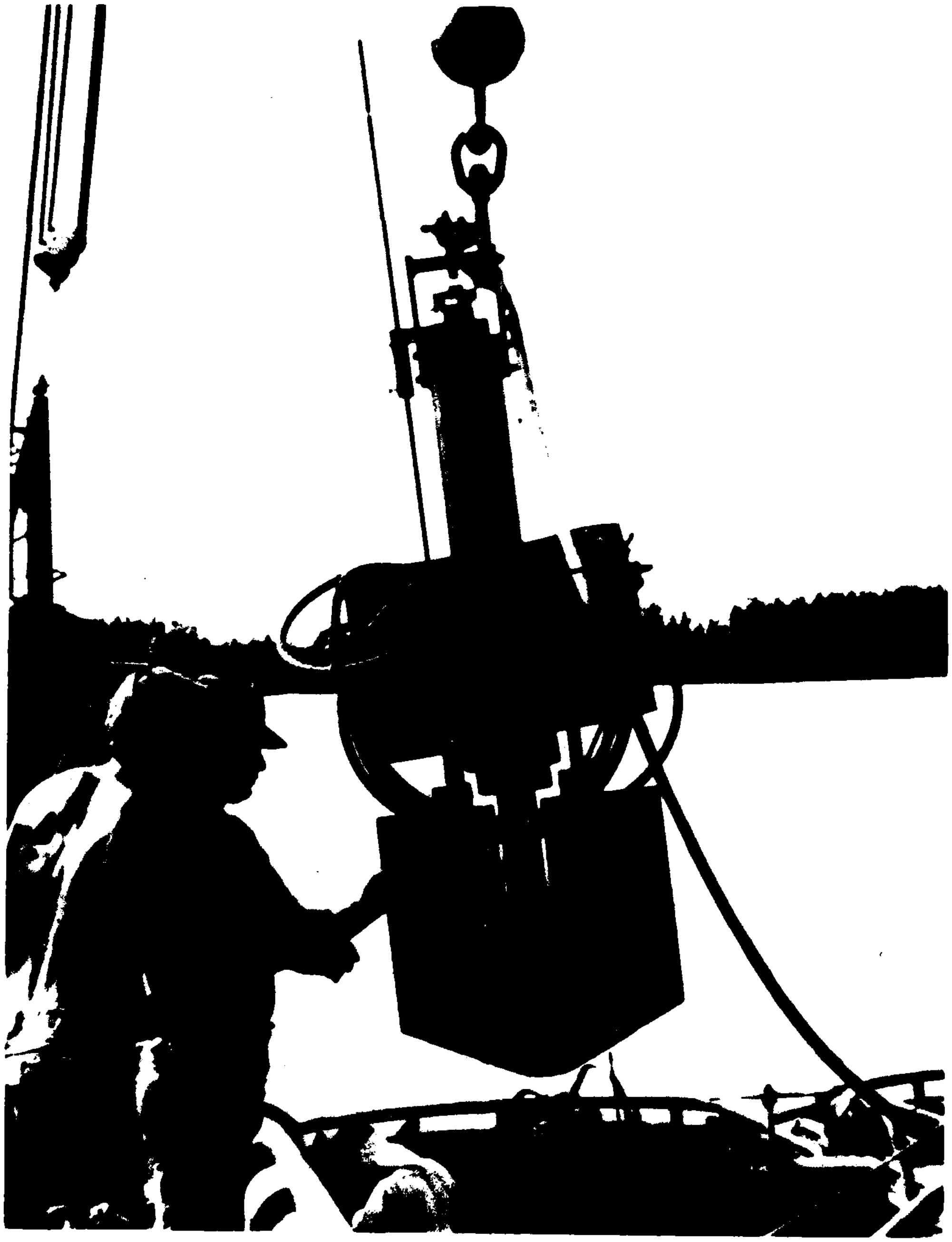

Figure 30. CEL 10K Propellant Anchor.

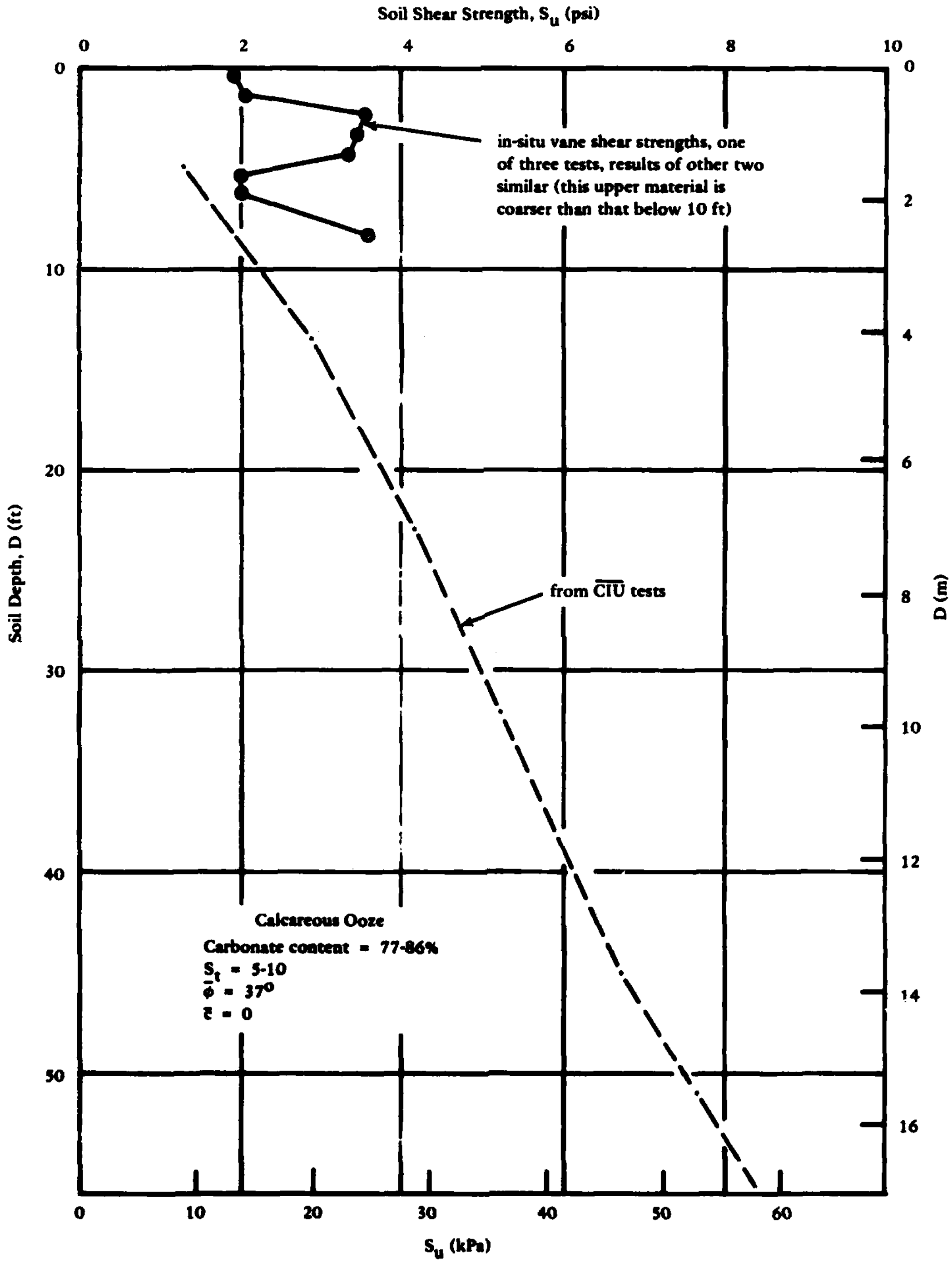


Figure 31. Shear strength data versus soil depth for 1130-m site on Blake Plateau.

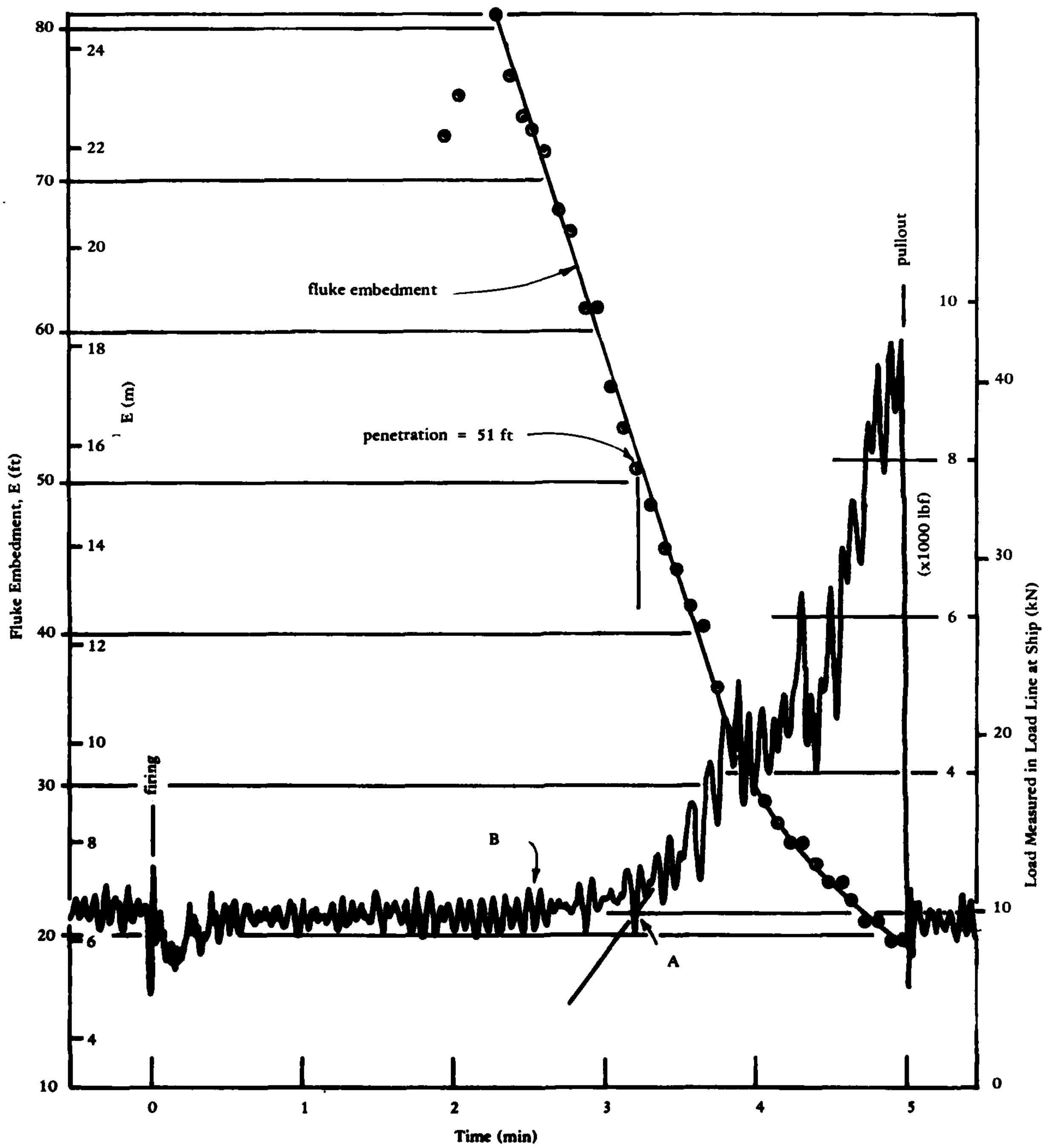


Figure 32. Load and displacement history, fluke 9.

the 3.5 kHz pinger record are plotted on the same figure. The embedment data indicate that the fluke pullout was quite smooth.

The depth of fluke penetration (maximum embedment) was arbitrarily identified by first finding point A, the intercept of the straight line approximation to the loading curve and the horizontal straight line approximation to the no-load condition. The time at which this load intercept occurred was taken as the time at which the first load was applied to the fluke and the keying process begun. From the apparent embedment plot the depth of fluke embedment at this time (maximum penetration) is 51 ft (15 m). The "apparent" embedment plot shows embedments to 81 ft, this additional 30 ft of embedment is not real. This 30 ft represents slack cable between the pinger and the seafloor (and the fluke).

A more perplexing question concerns the slight rise in measured load before the fluke is believed to be loaded. Specifically the load seems to rise between points B and A on the load curve, but this load rise is thought to be occurring while slack cable is being picked up off the seafloor. The recorded load increase is too large to be accounted for by the weight of 30 ft of 9/16-in. wire rope. However, it could be that much of the slack wire rope follows the anchor fluke into the seafloor; and that this early load measurement represents a frictional load on the wire rope itself.

The measured uplift capacities and the predicted uplift capacities versus soil depth are presented in Figure 33. Judging from the shape of the load versus displacement curve, it does appear that the fluke probably did key at about 20 ft (6 m). However, the anchor, even though keyed, held only 1/3 to 1/4 of its expected uplift capacity, based on the undrained shear strength of the calcareous soil (Figure 31). This very low measured uplift capacity is believed to be due to two complementary causes: first a large decrease in the undrained shear strength of the soil due to disturbance during fluke penetration and during the fluke keying process, and second, a decrease in the undrained shear strength of the calcareous ooze when subjected to the dynamic load from the ship's heave. Strength decreases due to disturbance in this calcareous material are very easy to understand considering the fragile, hollow shell structures comprising the greater part of the sediment volume. Lee, (1976), reports measured in-place sensitivities of 5 to 10 at this site; Valent, (1974), measured laboratory vane sensitivities of 3 to 6 on a slightly more cohesive calcareous ooze. Examination of dynamic behavior data presented by Herrmann and Houston, (1978), with some extrapolation, indicates that the dynamic loading alone is not likely to be responsible for the pullout of anchor fluke 9 at the bias and cyclic load levels applied. (Note: Wave equation analysis of the load line indicates that the load history felt by the anchor fluke is essentially the same as that history measured at the U-frame sheave.) Therefore, it would appear that the pullout of anchor fluke 9 is

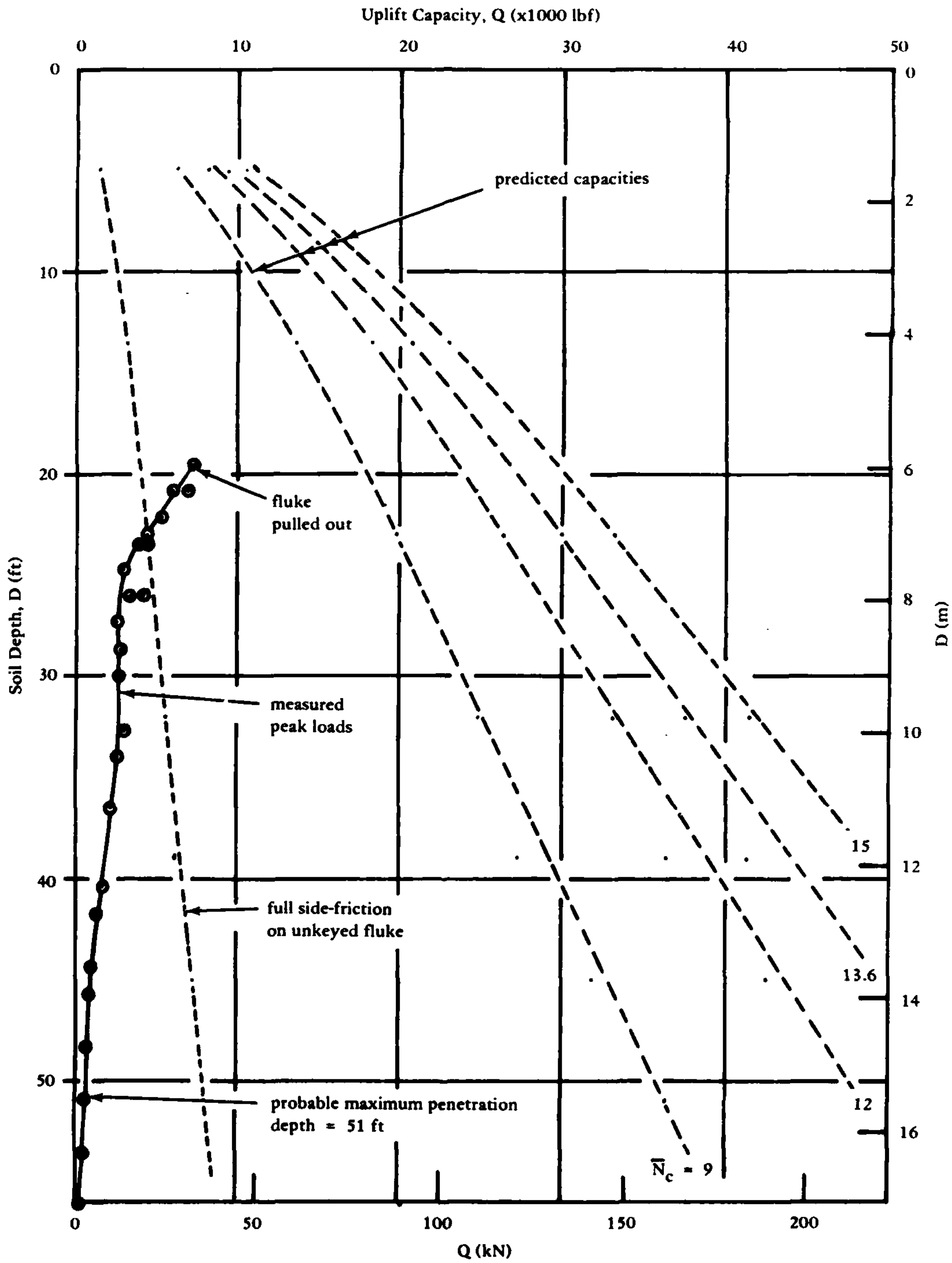


Figure 33. Anchor Test 9, propellant driven 2x2-ft flat fluke, 1130 m water depth, calcareous ooze.

likely due to reduced soil shear strengths due to disturbance during fluke penetration and due to progressive disturbance during keying of the fluke. The degree of the contribution of the dynamic load to the sediment strength loss is unknown, but may be substantial. Note that at higher cyclic stress levels, the response of the soil to this cyclic load condition would probably overshadow that response due to disturbance during penetration.

Anchor Test 10: 1,130 m water, 49 min duration: Anchor test 10, at the calcareous ooze site, was loaded over a period of 49 min to achieve a semblance of a long-term dynamic load. This fluke was also 2 ft x 2 ft; in addition, this particular fluke did include a keying flap. The load cell record for this fluke test is not included here because of its physical length; however, the 3.5 kHz pinger record has already been presented (Figure 17).

The pullout load versus adjusted fluke embedment curve is compared to the predicted static uplift capacities in Figure 34. Again, as with anchor test 9, the measured uplift capacity is significantly lower than the predicted values. However, the added 45 min of dynamic load did not reduce the uplift capacity of fluke 10 compared to that of fluke 9, but rather, resulted in the uplift capacity being somewhat larger.

This test is primarily presented to illustrate two other problem areas. The first is that of obtaining believable estimates of fluke embedment from long-term pinger records while the receiving ship is maintained on station using the wire load-line angle as a reference. At the ship, the "bias" loading was cycled over a period of about 3 min; however, when the load was picked up or increased by the ship's winch it appeared that the measured "apparent" fluke embedment was not recovered. Most certainly the fluke had not embedded itself deeper into the sediment with the slackening of line load. Therefore, the plausible explanation for the phenomenon is that the wire angle at the seafloor had increased markedly due to a slight drift of the ship and to the influence of the mass of the gun system and the pinger on that now slightly inclined load line. The net effect of this increased line angle is that the pinger is brought closer to the seafloor and the resulting pinger record at the ship shows the fluke to be apparently embedded deeper in the seafloor than it really is. No sure-fire, inexpensive solutions to this dilemma are available.

The second problem evident from Figure 34 is the difficulty of ascertaining that the fluke has been keyed. Indeed, the shape of the load versus displacement curve from test 10 would ordinarily suggest that the anchor fluke was not keyed during pullout because no sharp break, indicative of keying, occurs. However, the maximum uplift capacity mobilized by anchor fluke 10, 40 kN (9,000 lbf), is about 6.6 kN (1,500 lbf) greater than that mobilized by anchor fluke 9. Further, the uplift capacity mobilized is about 20 kN (4,500 lbf) greater than that predicted for an unkeyed fluke developing the full

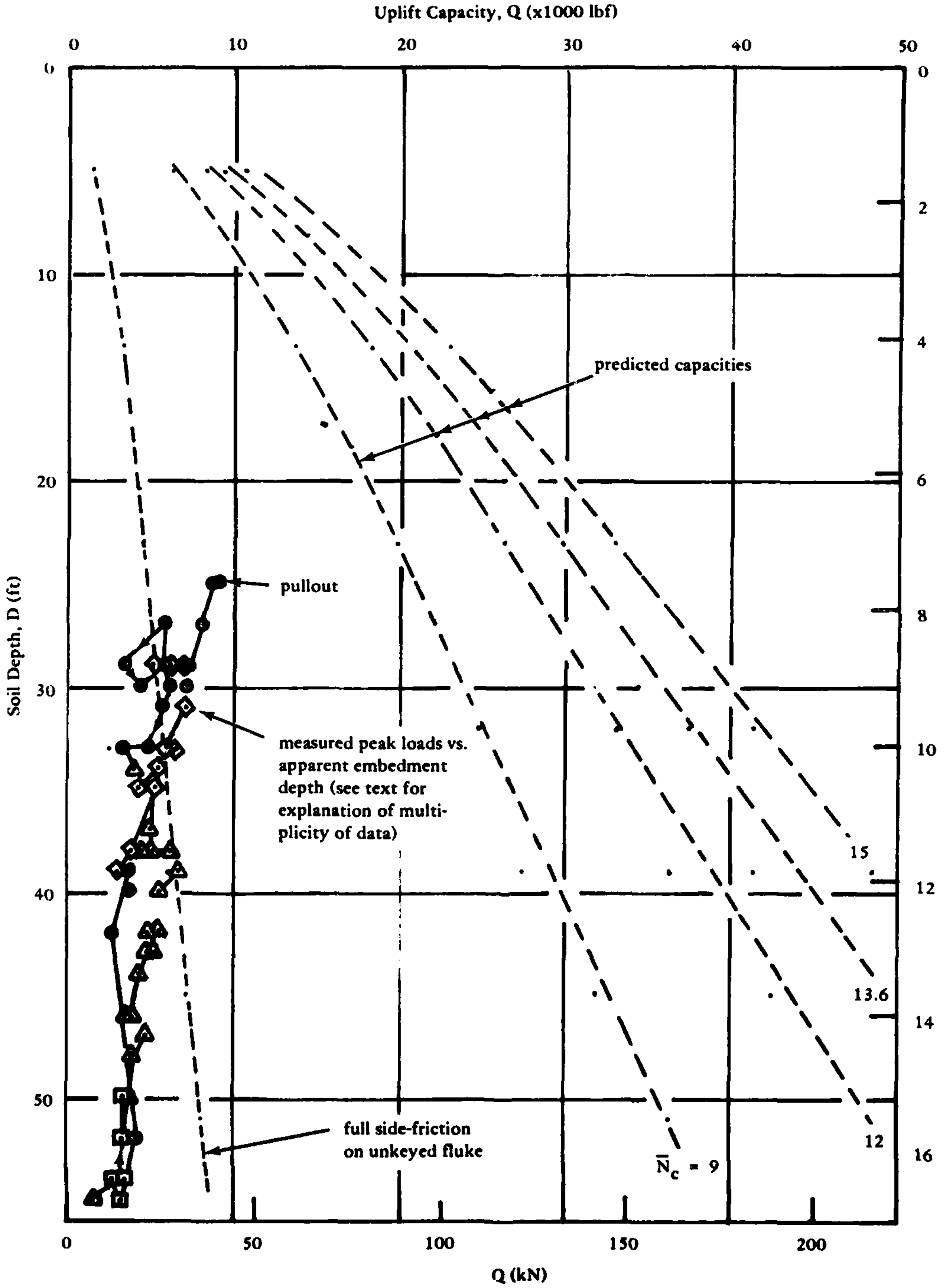


Figure 34. Anchor Test 10, propellant driven 2x2-ft flat fluke with keying flap, 1130 m water depth, calcareous ooze, slow test.

undisturbed shear strength of the ooze. Thus, it appears likely that fluke 10 did key. However, the occurrence of fluke keying is indicated as probable by indirect evidence, not by direct interpretation of the shape of the load-displacement plot.

Anchor Test 11: 1,130 m water, 2 min duration: Anchor test 11, at the calcareous ooze site, was loaded over a period of 1 min. This fluke was a 2 ft x 2 ft fluke without keying flap. The load cell record shows again that the ship's heave was causing a cyclic load component of about 20 percent of the ultimate load, trough to peak. An examination of the load curve and the plot of apparent fluke penetration suggests that the maximum penetration reached by the fluke was about 17 - 18 m (56 - 60 ft), (Figure 35).

Anchor fluke 11 did not pull out of the seafloor, rather a weak link inserted in the downhaul below the gun system parted. This weak link was necessary to ensure that the ship's load line would not part and be lost.* The load versus embedment curve (Figure 36) suggests very strongly that this fluke had keyed; however, the keying distance approached 7 m (22 ft) for a keying length of 11 x L. Such long travel distances in order to achieve keying represent a substantial loss in fluke uplift capacity--this fact of fluke behavior will be discussed later.

Anchor Test 12: 5,500 m water, 1 min duration: Anchor test 12 was conducted north of the Puerto Rico trench in 5,500 m (18,000 ft) in a pelagic clay or "red clay" deposit. Water contents in the upper 1.2 m (4 ft) run about 98 percent; sensitivities in the laboratory vane shear test are about 3. The estimated undrained shear strength profile from triaxial tests on core samples is presented in Figure 37 (Lee, 1976).

Anchor test 12 used a 1½ ft x 2 ft fluke, cut from a 2 ft x 2 ft fluke by burning off 75 mm (3 in) from each side. This fluke did not have a keying flap when tested. The fluke was extracted from the seafloor over a period of 1 min (Figure 38).

The dynamic loads depicted in Figure 38 are interesting in themselves. Specifically, the measured load pattern changes significantly while the fluke is under load as compared to when the system is free of the seafloor: the dynamic loads are about four times higher when the system is free of the bottom. This is so because the response of the ship to the sea changes when the stern of the

*The first objective of tests 9 through 11 was to verify that the 10K anchor system would develop its rated capacity of 10,000 lbf (44kN). Pullout of the anchor flukes to obtain the ultimate holding capacity was a secondary objective to be accomplished only within the safe load limit of the load line. The weak links were designed to break at a load of 14,000 lbf (62 kN) providing a factor of safety of 2 against breaking of the load line at the ship.

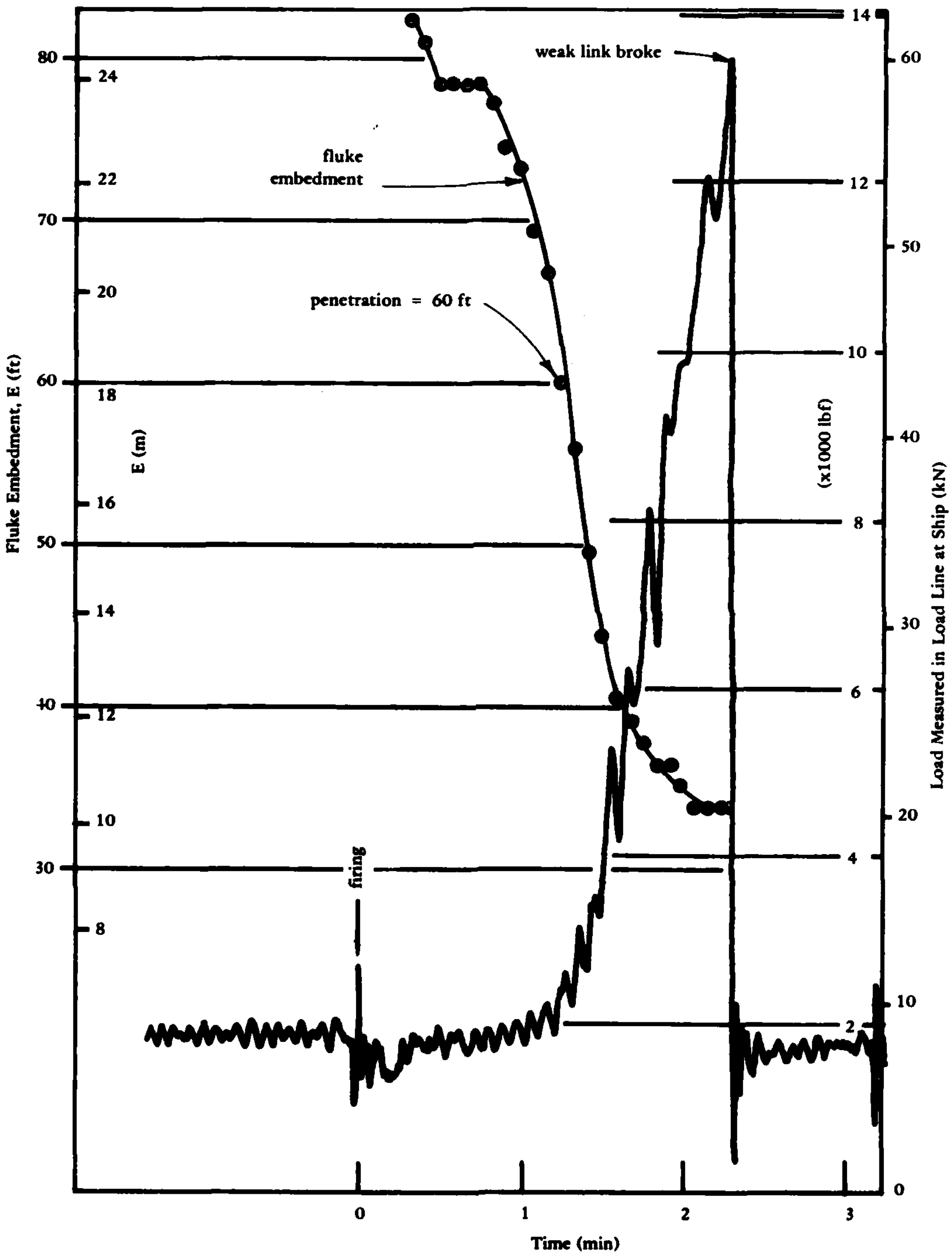


Figure 35. Load and displacement history, fluke 11.

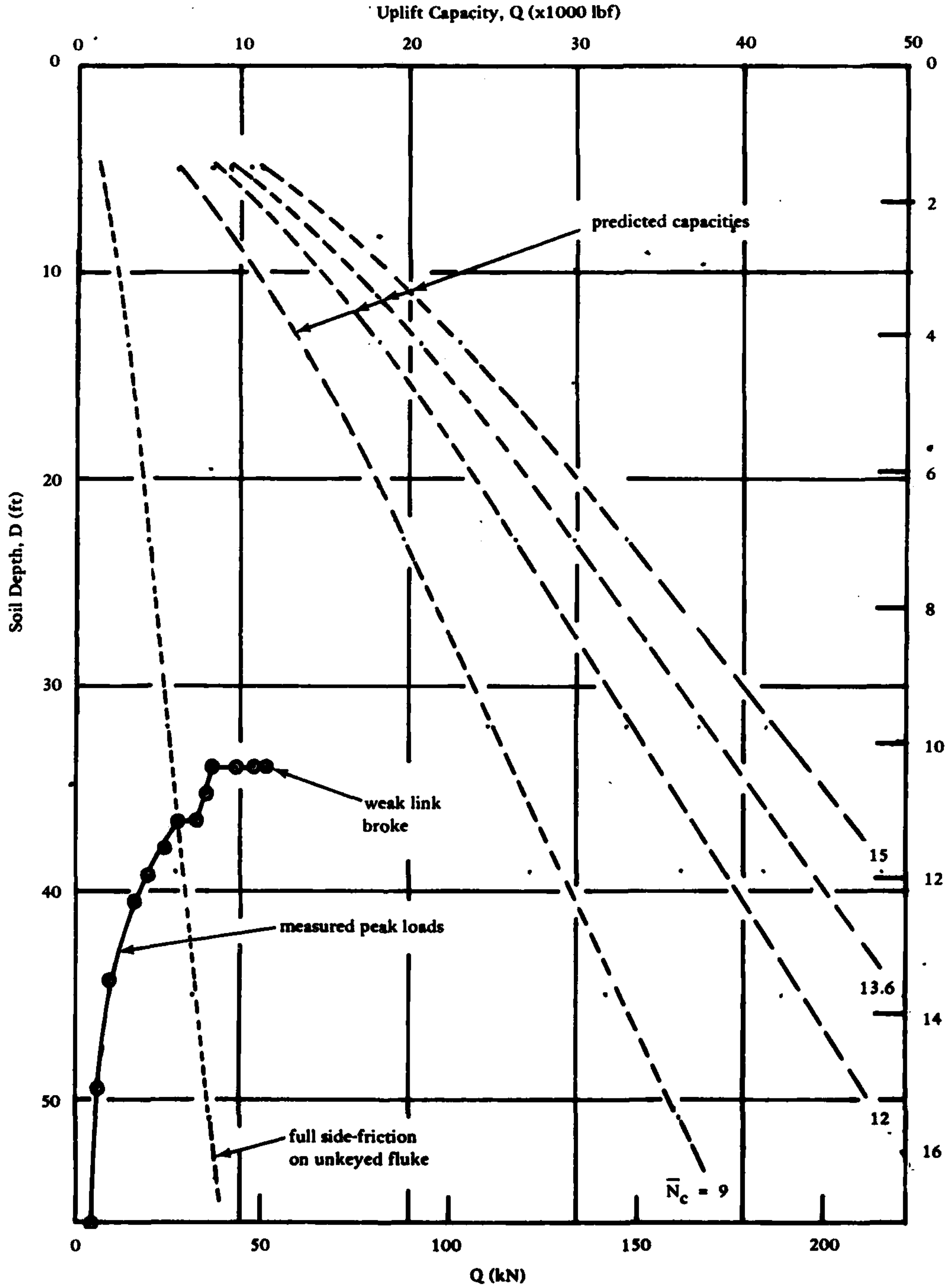


Figure 36. Anchor Test 11, propellant driven 2x2-ft flat fluke (with keying flap), 1130 m water depth, calcareous ooze (probable maximum penetration depth = 60 ft).

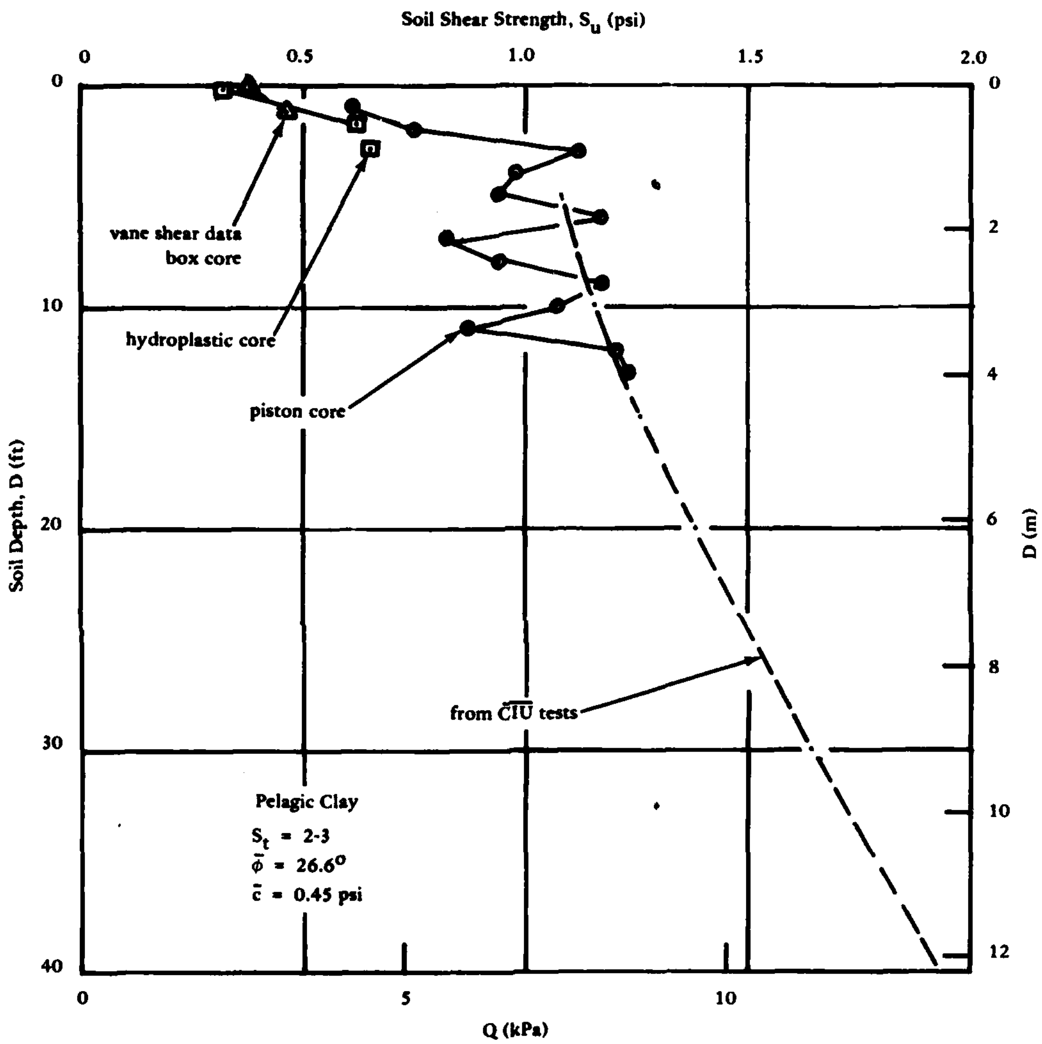


Figure 37. Shear strength data versus soil depth for 5,500-m site north of Puerto Rico Trench.

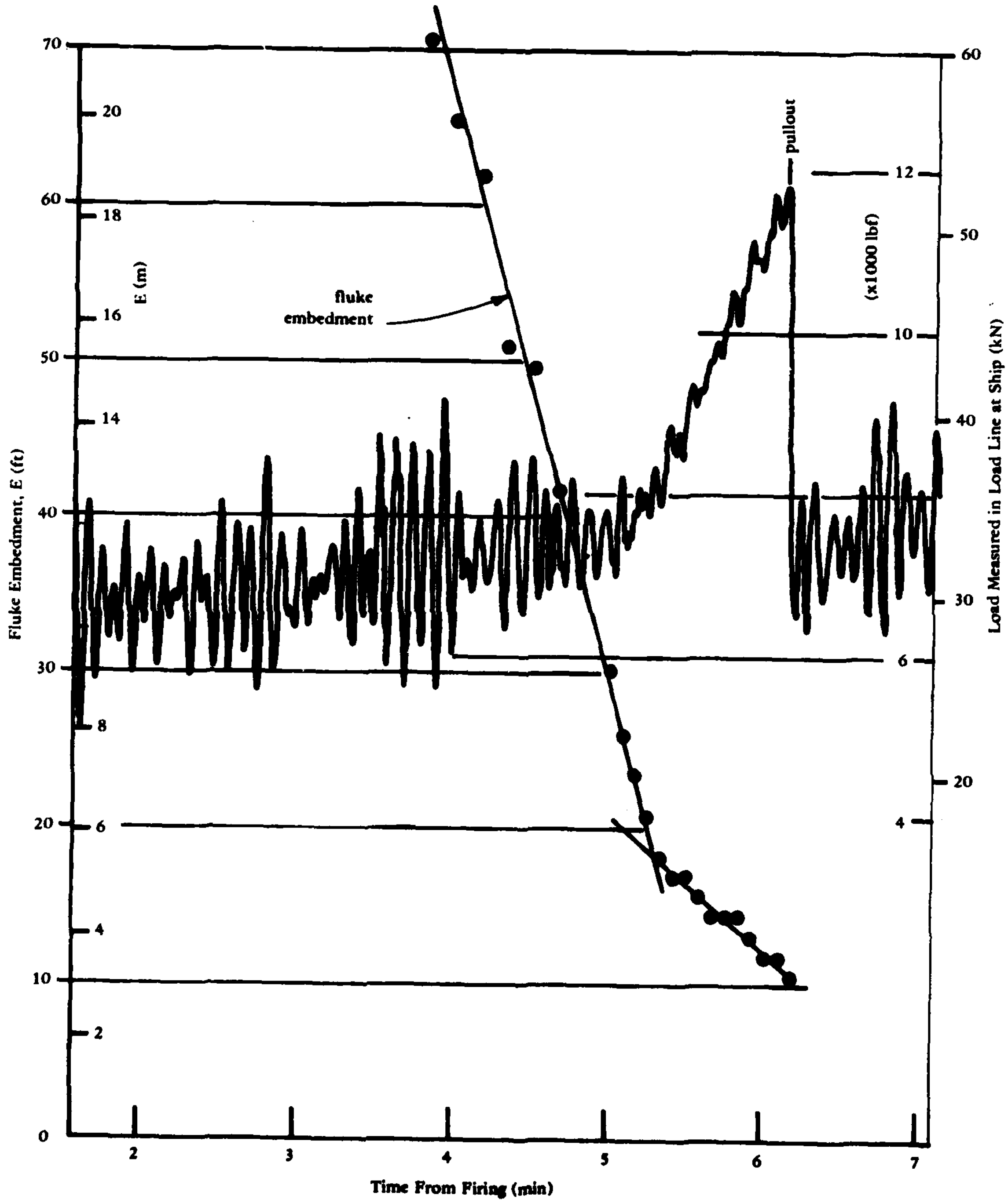


Figure 38. Load and displacement history, fluke 12.

ship is loaded against a fixed point, i.e., the embedded anchor fluke. Again, the velocity of the stress wave in the wire rope is fast enough that the fluke essentially feels the same load measured at the U-frame sheave. The dynamic or cyclic load magnitude, trough to peak, is seen to be somewhat less than 20 percent of the fluke pullout load.

Maximum fluke penetration estimated from both the load versus time curve (Figure 38) and the load versus apparent embedment curve (Figure 39) is about 9 m (30 ft). From the load versus embedment curve the fluke appears to have fully keyed with about 3.7 m to 4.6 m (12 ft to 15 ft) of embedment remaining; the travel required for keying then for this 1½ ft x 2 ft fluke in a pelagic clay is 6 to 7.5 x L. Again, this travel distance required to effect keying is too great.

The uplift capacity mobilized by this anchor fluke, if soil disturbance is assumed negligible and the uplift factor $\overline{N}_c$ is assumed to be the sole variable, is seen to be somewhat above the no suction value of $\overline{N}_c = 9$ and close to Rocker's measured lower bound for his mud flat tests, $\overline{N}_c = 12$. Deviation from Rocker's prediction is about 10 percent which should be well-within the range of expected deviations for such a test, and which would be adequately covered by usual safety factors, i.e., usually 3.

## SUMMARY AND CONSLUSIONS

### Fluke Design

The design of an efficient plate embedment soil fluke must include several operational considerations. The fluke must be streamlined to ensure deep penetration into the seafloor; all fluke elements must withstand the forces of firing, penetration, fluke keying, and mobilizing the soil uplift capacity; fabrication must be relatively simple; and lastly the fluke must key readily in a relatively short travel distance. This report has been limited to this last item, fluke keying distance.

Most seafloor soil strength profiles increase with depth, e.g., Figures 10, 18, 31, and 37, thus the greater the keying distance and thereby the shallower the fluke is when it does finally key, the lower the mobilized uplift capacity will be. Therefore, it is imperative to minimize fluke keying distances. Rocker's (1977) work indicates that keying distances of 2 x L (twice the fluke length, fluke tip to fluke base (Figure 6)) are quite reasonable to expect for the flat plate fluke. And, although they represent a special case, the keying distances of the circular, vibratory driven flukes V1 and V2 were measured to be 0.2 and 0.3 x L, respectively. Thus there is little doubt that proper fluke design can achieve fluke keying distances of 2 x L. However, this review of latest in-situ

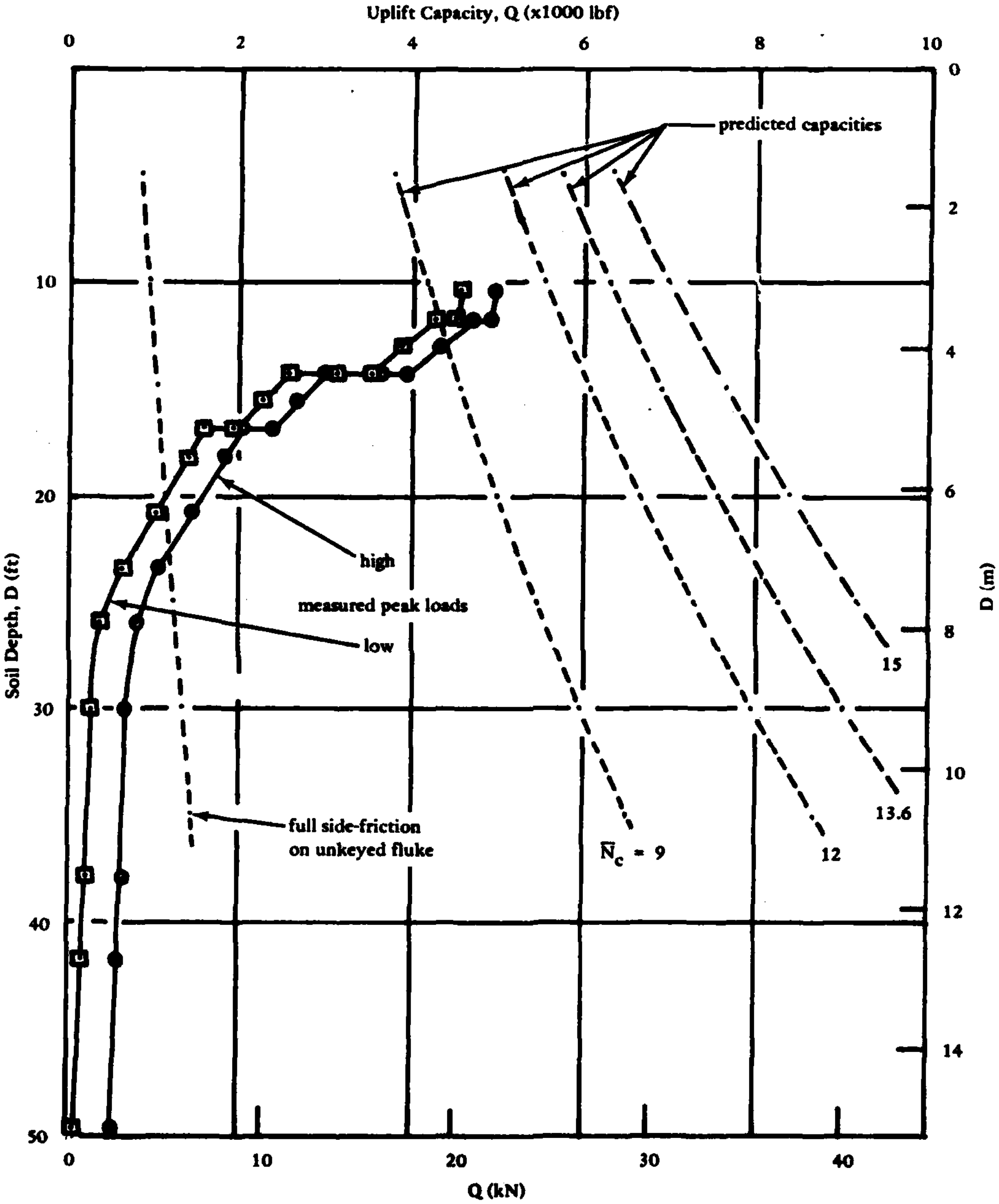


Figure 39. Anchor Test 12, propellant driven 1-1/2 x 2-ft flat fluke, 5,500 m water depth, pelagic clay.

tests has shown fluke keying distances of 7 to 15 x L to be the more common occurrence. Strict adherence to more stringent fluke configuration requirements is demanded. These requirements are as follows:

1. The fluke length to width ratio, L/B, should be 1,
2. The fluke keying arm ratio, K/L, should be 0.35 to 0.4 or, better yet, if possible without upsetting fluke dynamic stability, 0.5, and
3. Keying flaps of adequate area should be employed to increase the keying force couple. Sufficient field data are not available at this time to be specific in defining "adequate area" for keying flaps; however, 3 to 4 percent of the fluke area appears to be a minimum.

Each of these requirements acts to increase the end area of the fluke, decrease the fluke streamlining, and thus decrease achieved penetration into the seafloor. However, the expected decrease in total penetration will permit achieving a considerable reduction in fluke keying distance resulting in a net fluke embedment after keying that is considerably increased over present keyed embedments.

Rocker (1977) has also shown keying distance to be significantly affected by the time duration the fluke is left in place before a tension is applied to the load line to key the fluke. Apparently, the degree of soil disturbance around the fluke influences the keying distance: allowing an hour or two between anchor deployment and fluke keying may decrease the keying distance by two to three times (Rocker, 1977). Whenever operationally practical, consideration should be given to incorporating such a time delay into the operating schedule.

Uplift Capacity Prediction

Uplift capacity predictions for plate embedment anchors have been treated by most as a function of the undrained shear strength on undisturbed samples. Thus, penetration and keying of the fluke were assumed, for purpose of analysis, to have a negligible effect on the shear strength of the adjacent soil. This approach was taken because the investigators felt that sufficient data were not available to separate and identify the individual contributions of the soil failure model, accounted for by the $\overline{N}_c$ factor, and the shear strength mobilized, $s_u$ (e.g., Rocker, 1977). For the time being, until more data of a controlled nature are obtained, this approach, lumping all variations in the $\overline{N}_c$ factor, is probably the best that can be hoped for. However, it should be apparent from just the few pieces of good data presented here that it is the mobilized shear strength of the soil which is the greatest variable in the uplift capacity prediction. For example, in a pelagic clay soil with a lab vane sensitivity of 3, the uplift capacity was reduced by about 30 percent from the value predicted using an $\overline{N}_c$ of 15; whereas in a calcareous ooze with a lab vane sensitivity of 10, the uplift capacity was reduced by over 75 percent from that predicted using an $\overline{N}_c$ of 15.

The suggestion that the soil strength in the uplift capacity equation be corrected for disturbance is not new. Taylor (1973) suggested a correction be made for disturbance of that soil beneath the keyed fluke, i.e., (for cohesive soils, short-term loading only):

$$Q = (As_u\overline{N}_{ct} + A \frac{s_u}{S_t} \overline{N}_{cs}) \; (0.84 + 0.16 \frac{B}{L}) \quad \text{(after Taylor, 1973)}$$

where Q, A, B, and L are as defined earlier,

$s_u$ = undrained shear strength on undisturbed soil,

$S_t$ = sensitivity or ratio of undrained shear strength on undisturbed soil to undrained shear strength on completely remolded soil,

$\overline{N}_{ct}$ = uplift capacity factor dependent upon fluke embedment depth and soil shear strength, assumes no suction beneath fluke, magnitude of factor for deep anchor is 9.

$\overline{N}_{cs}$ = suction uplift capacity factor: for fluke vented to seafloor surface $\overline{N}_{cs}$ is 0; for full suction acting $\overline{N}_{cs}$ has been suggested to be 7 (Taylor, 1973).

This approach breaks the uplift capacity equation into two parts: the first treating the soil mass above the fluke supposedly not influenced by suction nor by soil disturbance; the second part treating the soil mass below the fluke supposedly so disturbed by the keying process that it approaches the state of completely remolded soil (i.e., remolded strength = $s_u/S_t$). The assumption of no soil disturbance above the fluke and complete soil disturbance below marks a step in the right direction in that it recognizes soil disturbance as an important variable in the uplift capacity of embedment anchors; however, intuition and Rocker's (1977) mud flat tests show the details of the strength correction applied are questionable. Rocker's work indicates that some soil disturbance occurs above the fluke as a result of fluke penetration; further, the assumption that the uplift capacity factor, $\overline{N}_c$, can be broken into two components with different strength values acting on each is somewhat premature and may not be true.

However, the average soil shear strength mobilized over the "plane" of failure about a keyed anchor fluke must be considered as different from the undisturbed shear strength. Further, this mobilized strength, even for an anchor loaded to failure and slowly being pulled out of the seafloor, would not on the average be as low as the remolded strength. It is also obvious from the test data presented herein that the degree of strength reduction can vary widely depending on the soil type, i.e., pelagic clay versus calcareous ooze, and possibly other factors. Because of this expected variation in degree of strength reduction with soil type, the author suggests that the strength correction be handled by a reduction factor applied to $s_u$, the undrained strength on undisturbed material. Then the equation for uplift capacity would take on the form:

$$Q = Afs_u\overline{N}_c \left(0.84 + 0.16 \frac{B}{L}\right)$$

where f = correction factor to account for the degree of soil disturbance, with "f" being a function of soil type and sensitivity, $S_t$.

The uplift capacity factor, $\overline{N}_c$, for deep anchor behavior, would be treated as a constant having a value of 9 for those flukes believed vented to the seafloor surface and a value of 15 for those flukes with full suction acting (Beard, 1978). For shallow anchor behavior the $\overline{N}_c$ factor would be adjusted as before for relative depth of embedment, as shown in Figure 4.

The undrained shear strength correction factor, f, is intended to account for disturbance effects on the soil due to fluke penetration and fluke keying. Unfortunately very few complete data sets are available from which to develop an adequate data bank of "f" values. These data, from tests reported herein and from Rocker (1977), are presented in Table 2. It remains for the tendency noted between $S_t$ and f to be built into a viable and dependable relationship by the addition of data from (1) future well-controlled uplift capacity tests and (2) possibly other similar soil-structure interaction correlations.

The reader should note that the "f" value quoted for the one calcareous ooze, f = 0.25, is subject to considerable question. It is possible that the flukes in the calcareous ooze did not key, or in some way remained only partially keyed. If this is true, then the full potential holding capacity of the fluke was not developed, and the calculated correction factor, f, of 0.25 is lower than the real f factor for a fully keyed fluke in this calcareous ooze.

The f factor of 0.25 is also subject to question because the loading applied to the test anchor flukes included a significant dynamic component which <u>may</u> have had a strong influence on the measured uplift capacity in these calcareous ooze tests. The data available are not sufficient to prove that the dynamic loading was not

Table 2. Values for Strength Reduction Factor, f.

| Soil Type | $s_u$ | $S_t$ | f |
|---|---|---|---|
| (1) Very soft, moderately sensitive, clayey silt (from Rocker, 1977) | ~1 psi | 3 | 0.8 - 0.9 |
| (2) Soft, normally consolidated, silty clay, CL (anchor test 1) | 1.7 psi | 3 | 0.6[a] |
| (3) Soft, normally consolidated, silty clay, CL (anchor test 7) | 2.0 psi | 3 | 0.8 |
| (4) Calcareous ooze, 77-86% carbonate (anchor test 9, supported by 10 & 11). | 2.2 psi | 10 | 0.25[b] |
| (5) Pelagic clay (anchor test 12) | 1.2 psi | 3 | 0.7 |

[a]data point questionable because fluke may not have been fully keyed.

[b]assumes that measured low uplift capacities are due entirely to strength reductions due to penetration and keying.

significantly responsible for the low uplift capacities; the dynamic loading may have caused a "softening" of the calcareous ooze (partial liquefacion) without significant remolding taking place. On the other hand, the dynamic loading of fluke 9 for 2 min duration and of fluke 10 for 49 min duration produced the same percentage reduction in uplift capacity compared to the predicted capacities at those fluke levels; thus the duration of dynamic loading did not have a strong influence. Since the duration did not have a strong influence, then, at these load levels, it is likely that the dynamic loading did not strongly influence the uplift capacities in these calcareous ooze tests. (Note, however, that at higher load intensities the dynamic loading is expected to cause significant soil shear strength reduction.) Thus there are three possible explanations for the very low magnitude of the correction factor, $f = 0.25$, measured for the calcareous ooze:

1. the f factor represents the residual soil shear strength resulting from penetration and keying,

2. the low f factor is the result of low mobilized holding capacity resulting from an unkeyed or only partially keyed fluke, and/or

3. the low f factor is the result of partial liquefaction of the ooze under the influence of the dynamic loads due to the ship's heave, and as such may not be representative of the ooze/anchor interaction subject to a continuously increasing pullout load.

The available data are not sufficient to justify elimination of any one of these explanations for the low f value. It appears appropriate, until demonstrated otherwise, to assume that remolding due to penetration and keying is a likely explanation and to adopt an f factor value of 0.25 for near-cohesionless calcareous oozes.

## RECOMMENDATIONS

1. Plate-type direct embedment anchor flukes are to be designed according to the following guidelines in order to ensure rapid keying:

   a. fluke length to width ratio, L/B, of 1,
   b. fluke keying arm length to fluke length, K/L, of at least 0.35 to 0.4
   c. fluke keying flap with an area of at least 3 to 4 percent of the bearing area of the fluke.

2. If operationally possible, the fluke should be given a one-hour rest period after insertion/penetration of the fluke before applying load to the fluke; this hiatus has a beneficial effect in reducing the keying distance.

3. An enlarged data base on prototype direct embedment anchor fluke performance in typical ocean sediments is sorely needed. To help gather this data, pullout tests on anchors should be made a part of each service anchor installation where operationally feasible. These pullout test data would also serve to verify the uplift capacities of the service anchors. Pullout tests, to be useful, must include well correlated fluke embedment versus applied load data and must include a reliable profile of soil undrained shear strength and sensitivity.

4. Until the additional supporting data are generated, the following recommendations are advanced for the analysis and design of plate-type direct embedment anchors:

   a. For all seafloor soils, with unvented flukes, $\overline{N}_c = 15$,
   b. For short-term, undrained loadings:

      (1) with terrigeneous silty clays and clayey silts, $f = 0.8$,
      (2) with pelagic clays, $f = 0.7$,
      (3) with calcareous oozes, $f = 0.25$.

5. Based largely on the results of Rocker's (1977) work, keying distances for flukes conforming to recommendation 1 and used in cohesive soils (including most oozes) should be assumed to be:

   a. 4 x L for flukes keyed immediately after implant.
   b. 2 x L for flukes keyed 1 hour or longer after implant.

6. Dynamic load components reaching the anchor fluke must be minimized by modifying the mooring design. Dynamic load components, trough to peak, of magnitude 10 percent or greater than the design static load will require a special dynamic load response evaluation (in preparation by Herrmann).

7. The recommendations made above are based on obviously scant field data, some supporting laboratory data, and a lot of engineering judgment. Thus these recommendations must themselves be regarded as in a state of flux and development.

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