OTC 6033

Deep Embedment Plate Anchors

by W.P. Stewart, VSE Corporation, Houston Office; D. True, Naval Civil Engineering Laboratory; and T. Jones, Chesapeak Division, Naval Facilities Engineering Command

This paper was presented at the 21st Annual OTC in Houston, Texas, May 1–4, 1989.

ABSTRACT

In this paper a unique solution is presented for anchoring large Naval vessels in a difficult soil condition. Deep embedment steel plate anchors, originally designed by the Navy Civil Engineering Laboratory for explosive embedment, were installed using a long pipe pile follower. Anchor holding capacities in excess of 200 kips were obtained in 25 feet of water where 20 to 90 feet of very soft lagoonal sediments overlie a stiff clay. Design, installation, and field testing are described. Experience and retrospective analysis are combined to offer guidelines for future deeply embedded anchor designs.

INTRODUCTION

The Naval Inactive Ship Maintenance Facility exists in Middle Loch, Pearl Harbor, Hawaii, to preserve decommissioned naval vessels until such time as they are called up for service or scrapped. Since the vessels are unmanned and unpowered, they must remain moored in the hurricane force winds common to the site. A location map is shown in Figure 1

The Inactive Ship Facility has long relied on large concrete deadweight anchors. A typically spread mooring system uses four or more mooring buoys around the moored vessel(s). The buoys are connected via riser chains to 30 ton octagonal central clumps weights. Ground leg chains connect each clump to between three and five satellite anchors. The satellite anchors, commonly known as Pearl Harbor Anchors, are generally rectangular, with a wedge-shaped leading edge to help them dig into the mud as they are dragged along the bottom. They weigh either 30 or 60 tons and have been used in Middle Loch for over 40 years. A Pearl Harbor Anchor is shown in Figure 2.

References and figures at end of paper

In 1982 Hurricane Iwa caused many of the moorings in Middle Loch to be displaced. An anchor test program was conducted jointly by the Naval Civil Engineering Laboratory (NCEL), Port Hueneme, California, and the Ocean Engineering and Construction Project Office, Chesapeake Division, Naval Facilities Engineering Command, to determine the real capacity of the concrete anchors. By test pulling one mooring against another, the concrete anchor systems in use were demonstrated to have only 20 to 30 percent of the previously predicted holding capacity. Chesapeake Division was then asked to design 63 safe and cost effective buoy mooring systems for ships up to 25,000 long tons displacement. These would be installed over a five-year cycle starting in 1988. The first two mooring spreads were planned to be for two Material Support (AR's) vessels and four Destroyers (DD's). These moorings are the subject of this paper.

SITE CONDITIONS

In the northern end of Middle Loch, where these moorings are located, the water depth is consistently around 25 feet. The visible bottom is featureless and flat. The uppermost sediments are recent harbor deposits with undrained shear strength increasing uniformly with depth from around 5 pounds per square foot (psf) at the mud line, at a rate of about 6 psf per foot of depth.

Beneath the silt is a firm sandy clay. The anchor design has to accommodate silt depths in the range 10 to 90 feet.

Geotechnical investigation of the site prior to construction operations included a shallow seismic (sub-bottom profile) survey of the site and several soil borings.

The soil parameters shown in Table 1, where clay undrained shear strength is shown as 1800 pounds per square foot (psf) were used as the basis for anchor design. Full details of available soils information is given in References 1, 2, and 3.

For pile driveability analysis a clay undrained shear strength of up to 4000 psf was considered. This value had been found in the one triaxial test on a recovered borehole sample of the clay.

ANCHOR DESIGN CRITERIA

A comprehensive mooring system design study was performed and evolved the following criteria for the anchor systems for the site:

1) Maximum anchor chain load capacity of 240 kips required, based upon 50-year return period environmental conditions. (30-second wind velocity of 68 knots, co-linear current velocity 0.6 knots)
2) Close spacing of multiple mooring systems necessary. Hence drag distances and ground chain lengths must be as short as possible. Lateral vessel displacements under design loads must also be small.
3) Anchor size and installation method must be such as to make efficient use of local plant and equipment.
4) Lifetime cost economy based upon a 15-year design life.

SELECTION OF PLATE ANCHORS AT PEARL HARBOR

Reference 4 includes a full discussion of the anchor selection process. Concrete clump anchors, various drag anchors, pile anchors and Navy-designed plate embedment anchors (PEAs) were evaluated. Initial consideration was given to using the existing (Pearl Harbor) anchoring method. This system had two advantages:

1) Many concrete clumps were available at the facility
2) Local contractors were already experienced with installation of concrete clumps.

In the earlier test pulls it had been shown that the holding capacity of the concrete clumps could be made sufficient if the clumps were buried in the clay below the silt. Despite other economic advantages, the cost of this burial operation in the silt depths for these moorings made this solution relatively expensive.

Various drag anchors were considered, including combinations of:

i) NAVMOOR 10 (the Navy's new anchor)
ii) Navy 18 kip Stockless
iii) Bruce
iv) Stato
v) Boss

All reasonable combinations of these anchors require lengthy ground chains and large anchor drag distances. This posed serious difficulty in the confines of Middle Loch with the targeted proximity and number of moorings.

Conventional pile anchors such as NAVFAC's standard stake piles (Reference 5) or pipe piles were evaluated. They were another feasible but relatively expensive solution.

The selected solution was the 300-kip (nominal) PEA under development by NCEL. However, the fluke would have to be embedded in the clay in order to have sufficient capacity. The combination of large silt depth and shallow water depth dictated that ballistic penetration should be replaced with penetration forced by a pile driving technique. An economic advantage of this solution was the free availability of a number of 300K flukes. The Navy was confident that a satisfactory method to drive these plate anchors deep into the clay could be developed within the given time limitation.

BACKGROUND TO PLATE ANCHOR DEVELOPMENT

The design of the plate anchor used in this project evolved over the last two decades as part of a Navy PEA. The anchor plate has come to be called a fluke, after the moveable flukes of drag embedment anchors. Anchor flukes project a large area to mobilize soil resistance so as to create pull-out resistance. The original PEA fluke design was developed by Taylor circa 1970 (Taylor and True, 1976, Reference 6) for a 20K PEA (20 kips nominal peak working load in the weakest normally consolidated sediments). Subsequently, PEAs have been developed by NCEL in 10K to 300K sizes (References 6 and 7). They are generally made of hard, high-strength steel.

The fluke is embedded edgewise, presenting a minimum frontal area, and is then rotated toward the direction of line pull to maximize its projected area to the soil. This rotation, or "keying," is designed to occur by application of a vertical line pull to a connection point on the spine plate. The eccentricity of the connection point, together with the additional eccentric vertical pull-out resistance that comes from the keying flaps (which are designed to open during keying) are a careful design balance for the fluke size and soil type.

In cohesive soils the keying operation can be thwarted by the fluke's tendency to slide back up the path of embedment. This is because these soils normally are "sensitive," that is, they exhibit a ratio of undisturbed to remolded strength greater than 3. To reduce the probability of this problem occurring additional area was added to the normal keying flaps for the 300K fluke. The design provides for full keying (90 degrees rotation) within a pull-back distance of two fluke lengths. The general arrangement of the installed flukes is shown in Figure 3.

PLATE ANCHOR CAPACITY

When correctly installed, a plate anchor is calculated to have a capacity, F, which is given by the product of the plate's projected area, A (with a geometry correction for aspect ratio, B/L) a bearing capacity factor, N_c, the undrained shear strength of the soil, s_u (at the installed depth) and a soil strength disturbance factor, h:

$$F = A.s_u.h.N_c.[0.84 + 0.16(B/L)]$$

Using the above formula and the available 300K flukes, it was clear that even in the deepest silt the pullout resistance of the anchors would not be sufficient. The flukes would have to be embedded in the clay.

For this installation, N_c is taken from figure 6.5-3 in Reference 8, without allowance for the silt overburden, resulting in N_c values of around 6.7, depending upon the embedment depth of the fluke in the clay. Also from Reference 8, h is taken conservatively as 0.8. The 300K fluke has an area of 56 square feet.

In the clay with s_u = 1800 psf, anchor resistance at installed depth 24 feet (into the clay, beneath the silt, after keying) is calculated to be 530 kips at pull-out. This gives a design maximum capacity of 265 kips, with a factor of safety of 2.

PILE FOLLOWER DESIGN AND ANALYSIS

No other attempts to drive plate anchors into soil of this depth are known. The design concept for this installation was as follows:

1) use the existing 300K flukes with the minimum of modification.
2) hold the plate anchor in the end of a slender pile follower and attach the mooring chain
3) upend the plate/pile/chain assembly and lower into water at target location
4) prevent plate anchor from slipping out of follower by a weak link that will be broken during installation or follower removal
5) drive the plate, via the pile follower, to target depth with mooring chain attached, keeping chain close to follower
6) remove the follower, leaving plate anchor and chain in place
7) key the plate by applying vertical keying load to the chain
8) cut chain laterally through the silt by applying design maximum mooring load to the chain in target direction

To minimize installation and removal resistance of the follower a tapered pipe pile was developed. The upper 100 feet was 24-inch diameter, 1-inch wall thickness and the lower 40 feet was 18-inch diameter, 1-inch wall thickness pipe (nominally ASTM A36 grade steel). Only the 18-inch section, with the fluke at the bottom, was intended to be driven into the clay. Bending stresses during handling were a major concern.

An expendable ring was added to the bottom of the follower a short distance above the anchor. Its purpose was to increase the effective diameter of hole made by the 18-inch pipe to 20 inches during driving, . The the ring would be left in the hole during follower extraction, and reduced frictional resistance between pile and clay would result.

Upper "jaws" on the follower were designed to support the chain weight and hold the chain close to the pipe during installation, while lower jaws pulled the chain with the follower down into the soil, minimizing the eccentric load tending to deflect the plate.

For installation conditions, pile, chain, and fluke resistances were predicted in a range of silt and clay strengths. Pile driveability analysis was performed using a modern wave equation program (Reference 9). Blow count per foot of penetration and pile follower stresses were examined with different hammer types with the maximum and minimum predicted resistances and resistance distributions. From this information, acceptable pile hammer capabilities were determined.

Since the anchors were unusually deep, effort was made to predict the mooring chain profile from the sea bed back to the fluke padeye under design loads. This information led to knowledge of the probable chain tensions *and direction of load* at the fluke, as well as increased confidence in the anchor capacities. The method used was first described by Vivatrat et al (Reference 10) in 1982. Normal and tangential forces on elemental chain lengths are calculated, together with chain tension, tension change and direction change over the length of the element. The method was embodied in a computer program which tabulates the tension and position of the chain from the sea bed down through the silt and clay, back to the fluke. Any silt/clay strength profile may be specified by the user. Chain profiles are automatically produced. Chain lengths to be pulled in during installation test loading of the anchors were predicted with this buried anchor chain program.

A typical chain profile is shown in Figure 4. Tension has been reduced through soil contact from 240 kips at the mudline to 202 kips at the fluke. Chain angle has changed from 20 degrees at the mudline to 90 degrees at the fluke.

FIELD INSTALLATION

During the first fluke installation (silt depth 76 feet) the fluke deviated from vertical, bending the 18-inch section of follower, although the fluke was installed close to target depth in the clay.

The follower and method of fluke attachment were redesigned. The new follower was stiffer, being a uniform 24-inch diameter, 1-inch wall thickness pipe, approximately 140 feet long. In the end of this pipe a smaller diameter mandrel was welded (a section of 18-inch, with ribs, using available materials on site). Each fluke had a 7-foot length of the 24-inch pipe welded to it with a 27-inch diameter hole expanding, or clearance, ring at the upper end. The mandrel fitted into this pipe and a shear bolt held it in place. The shear bolt was designed to be broken with the first hammer blow. This fluke connection was stronger than the original design and more expensive. The arrangement is shown in Figure 5. The field modified follower was successfully used for driving the remaining 13 modified anchors.

A KOBE KB60 diesel hammer (rated capacity 120,000 ft-lbs) was used with a 10-ton drop hammer as back-up. As it occurred, the drop hammer was used as the principle tool since the crane boom height was frequently too short to lift the longer diesel hammer and leads into position.

All 14 flukes were driven and a vertical (upwards) keying load of 200 kips was applied to each. After applying the keying loads, all chains were pulled with a force of 240 kips almost horizontally (design maximum mooring tension) in the target load direction for the mooring legs. This latter loading had the effect of cutting the chains through the silt, thereby preventing large excursions of the system when in operation as the chains gradually dug in. This was also a proof of each anchor system's holding capacity. Measurement of loads was performed with a three-wheel type tensiometer mounted on a cable link in the hydraulic tensioning system on the contractor's barge. Anchors chains were pulled against each other in pairs to obviate the need for strong moorings for the barge.

RESULTS OF KEYING LOADS

None of the flukes moved more than two inches when the 200 kip keying loads were applied. This indicates that the combination of soil friction on the chain, soil friction on the fluke, and any end bearing on the fluke (possibly as a result of being out of vertical) was always greater than 200 kips. The surface area of the anchors (as modified with the driving tube and larger flaps) is 191 square feet. Chain and plate end bearing resistance to pull-out are both small in comparison to plate friction. Neglecting other resistances, a soil/plate shear stress of 1053 psf would be required to give 200 kips resistance. This may be commensurate with a clay having 1800 psf undisturbed shear strength that does not become significantly reduced as a result of remolding. Alternatively, it may be that sufficient time for major strength recovery was allowed before applying the keying load (24 hours). The sensitivity factor for the sandy clay was expected to be in the range 2-4 (ratio of undisturbed to remolded shear strength) and a full recovery time was expected to be as long as several months (Vesic, 1975, Reference 11). A more probable explanation is that the clay had a higher than 1800 psf undisturbed shear strength.

The fact that the flukes did not key under the 200 kip load would have been of concern if the later 240 kip mooring load tests had resulted in anchor movement, or if the normal load direction on the chains attached to the flukes would have been vertical.

RESULTS OF CHAIN PULL TESTS

The field results from the chain pull tests were found to be closely predicted using the buried anchor chain program described above. Typical results for applied load versus accumulated chain length pulled in (i.e. deflection from both chains cutting through the sea bed) are shown in Figures 6 and 7. Average silt depth for results in Figure 6 is 6 feet. For results in Figure 7 the average silt depth is 67 feet. Because it is not possible to know how much slack chain has been laid along the sea bed prior to the pull test starting, a balance point at 100 kips tension is used to compare the measured field values of chain length changes with the theoretical values. Chain was 2.75-inch stud link, with anodes on each link.

All chains reached a tension of 240 kips in the manner anticipated (meaning that the load deflection curves had no unexpected characteristics) indicating that the anchors were set satisfactorily. The 240 kip load was held for 5 minutes in each test.

RETROSPECTIVE ANALYSIS

Reference 12 provides a detailed description of the installation part of this project. As part of this work, a retrospective analysis, using the field blow count records, was performed to investigate the probable clay and silt strengths. Information gained from this analysis is being used to improve the reliability and cost effectiveness of the next anchors to be installed in Middle Loch.

The average silt undrained shear strength was originally predicted to be equivalent to silt overburden pressure multiplied by a factor, k, of between 2 and 3. From Figure 7 it is seen that two curves for the theoretical chain load-deflection relationship are shown. These curves were generated with the buried anchor chain program for $k = 0.2$, and for $k = 0.4$. The curve for $k = 0.2$ closely matches the measured results, indicating that the silt strength is on the low side of the predicted range.

Given a value for the silt strength, the pile driving blow count records can be used to predict average values for the strength of the clay. Quite large variations in the silt strength have little influence on the overall pile-chain-fluke resistance, as the friction in the silt is generally a relatively small contribution to total driving resistance. The retrospective analysis proceeds as follows:

1) Blow count records are examined for each fluke and one (or sometimes two) maximum value is selected.
2) The fluke depth at the selected blow count(s) is noted.
3) The static resistance corresponding to the selected blow count(s) is found from the driveability graphs.
4) The clay shear strength is calculated that will give this resistance in conjunction with the resistance from the silt.

Because the silt depths and depth of embedment in the clay are different for each selected blow count record, a series of resistance curves were produced for various silt depths and depths of embedment in the clay. For a given silt depth each set of curves shows the theoretical relationship between driving resistance, depth of embedment in the clay, and average clay shear strength. One line in each set shows the resistance-strength relationship for a given depth of embedment. Interpolation between the curves allows the analyst to match all variables and to find an average clay shear strength that corresponds to the driving record blow count conditions. The procedure is illustrated in Figure 8. Figures 9 and 10 show the predicted driveability curves for the two hammers used. Table 2 shows the relative resistance contributions of the various components in the driven system.

Table 3 shows the results of the retrospective analysis. In many cases the clay shear strength value is found to be in excess of 3600 psf. However, in two cases the shear strength is found to be lower than the "design" value of 1800 psf.

REDESIGN OF DEEPLY EMBEDDED ANCHORS

The experience from this installation demonstrates that the embedment of keying plate anchors by pile driving is operationally suited to available support and site conditions at Middle Loch and similar locations. For the next moorings, however, previously fabricated plate anchors are not available. The following rationale has been used to design a new anchor type:

1. Existing follower should be used, if possible.
2. Requirement for keying should be avoided, if possible.
3. 36 ksi steel should be used, if cost effective.
4. Anchor shape should be simple, minimizing fabrication costs.
5. Full benefit of the clay strength should be taken without requiring a minimum embedment depth (as necessary for keying)

An anchor that meets these requirements is a deeply embedded pipe pile, with a padeye located some distance from the top. A preliminary version, 28 feet long, has been designed for Middle Loch. Using the buried anchor chain program, it can be shown that the top of the anchor needs only to be driven to the top of the clay. The follower can be 40 feet shorter than that previously required. The connection of the pile to the follower is the same as was developed for the plate anchors. The pile is simple with welding costs associated only with the padeye.

CONCLUSIONS

1) Plate embedment anchors can be economically installed by pile driving.

2) The capability to embed keying plate anchors deeper by pile driving than by ballistic means extends their applicability to sites not otherwise suited to PEAs (where a weak but deep surface layer wastes ballistic energy so deeper layers cannot be properly penetrated.)

3) Lessons learned in pile follower design will lead to greater efficiency in similar anchor installation projects in the future.

4) Deeply embedded *piles*, instead of *plates*, installed by the same type technique, offer a potentially more economic anchoring solution in site conditions typified by Middle Loch.

5) Buried anchor chain profiles and chain tension reduction in the soil can be reliably predicted.

6) Optimized deeply embedded anchor designs take benefit from the reduction in anchor tensions as a result of chain/soil interaction.

7) Retrospective analysis has shown clay strengths in Middle Loch to be variable in the range 1000 to >3600 psf.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the contributions to this paper made by Gene Mitchell and Thomas Hudon of VSE Corporation, and by Bill Seelig of Chesapeake Division, Naval Facilities Engineering Command, whose encouragement was of great benefit throughout the project.

REFERENCES

1. Pelagos Corporation: "A Seabed Survey of Middle Loch (Pearl Harbor), Oahu, State of Hawaii," June 1987.
2. Pelagos Corporation: "A Seabed Survey of Middle Loch (Pearl Harbor), Oahu, State of Hawaii (Supplement)," December 1987.
3. Geolabs - Hawaii: "Geotechnical Exploration: Mooring Designs, Navy Inactive Ship Maintenance Facility, Middle Loch, Pearl Harbor, Hawaii," November 1987.
4. Ocean Engineering and Construction Project Office, Chesapeake Division, Naval Facilities Engineering Command: "Design of Hurricane Moorings at NISMF Pearl Harbor HI," report FPO-1-87(26), January 1988.
5. Naval Facilities Engineering Command: "Fleet Moorings," Design Manual DM-26.5, June 1985.
6. Taylor, R. J. and True, D. G.: "Use of Propellant-Actuated Anchors in Underwater Construction," OTC2465, Proceedings, 1976 Offshore Technology Conference, Houston, Texas.
7. True, D. G. and Link, H. F.: "A Large Propellant Embedment Anchor for Offshore Moorings," OTC3668, Proceedings, 1979 Offshore Technology Conference, Houston, Texas, 2731-2736.
8. Naval Civil Engineering Laboratory: *Handbook for Marine Geotechnical Engineering* (March 1985).
9. WEAP 86 Wave Equation Analysis of Piled Foundations, FHWA-IP-86-18, July 1986.
10. Vivatrat, V., Valent, P.J. and Ponterio, A.A.: "The Influence of Chain Friction on Anchor Pile Design," OTC4178, Proceedings, 1982 Offshore Technology Conference, Houston, Texas, 153-163.
11. Vesic, A.S.: *Principles of Pile Foundation Design*, Soil Mechanics Series No. 38. Durham, NC: School of Engineering, Duke University, 1975
12. Ocean Engineering and Construction Project Office, Chesapeake Division, Naval Facilities Engineering Command: "Project Documentation Report for the Installation of Moorings 16 and 17, Naval Inactive Ship Maintenance Facility, Pearl Harbor, Hawaii," Report FPO-1-88(45) (January 1989)

TABLE 1			
SOIL PARAMETERS USED FOR DESIGN			
PARAMETER	SILT	CLAY	UNITS
BUOYANT UNIT WEIGHT	23	44	PCF
DRAINED SOIL COHESION	0	420	PCF
DRAINED FRICTION ANGLE	22	25	DEGREES
LIQUID LIMIT	100	80	
PLASTIC LIMIT	50	80	
SENSITIVITY	2.3	2	
UNDRAINED SHEAR STRENGTH	0 TO 700	1800	PSF

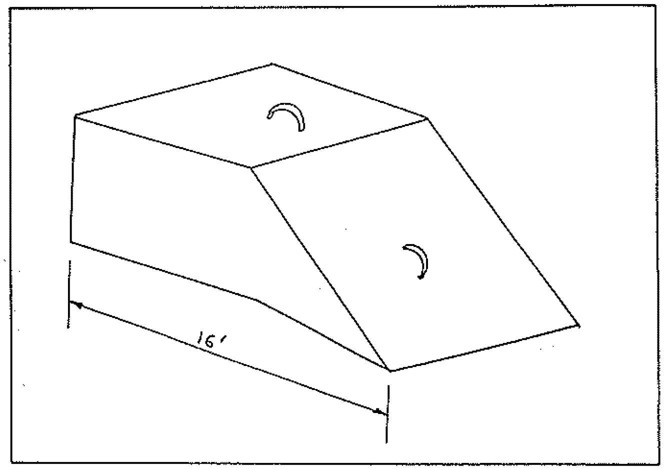

Figure 2 60 ton Pearl Harbor Anchor

TABLE 2		
DRIVING RESISTANCES FOR FLUKE INSTALLATION		
DEPTH INTO CLAY = 30 FT		
SILT DEPTH OVER CLAY	90 FT	50 FT
RESISTANCE CONTRIBUTION	KIPS	KIPS
FRICTION IN SILT	230	83
PILE FRICTION IN CLAY	255	219
PLATE FRICTION IN CLAY	232	199
END BEARING IN CLAY	113	113
TOTAL RESISTANCE TO DRIVING	830	614

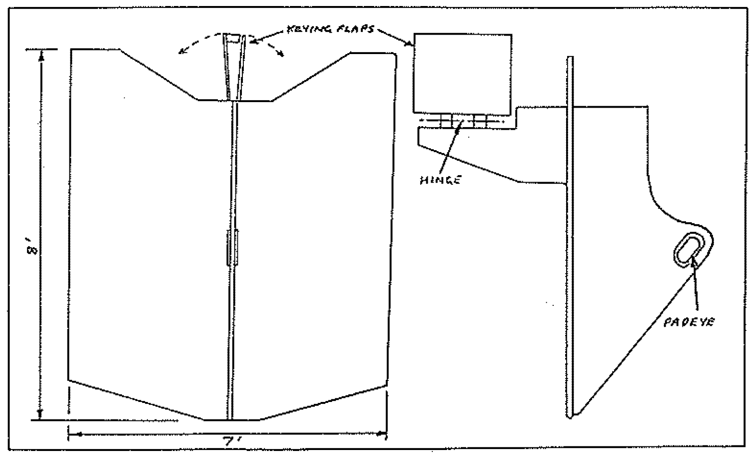

Figure 3 300K Fluke

TABLE 3		
RETROSPECTIVE ANALYSIS SUMMARY		
FLUKE NUMBER	1st Su value (PSF)	2nd Su value (PSF)
16B	3100	none calculated
16C	3600	none calculated
16D	>3600	3550
16E	>3600	none calculated
16F	>3600	2700
16G	1300	none calculated
16H	3600	none calculated
17A	3200	2200
17B	3000	3400
17C	>3600	none calculated
17D	1050	2060
17E	2600	900
17F	3250	1600

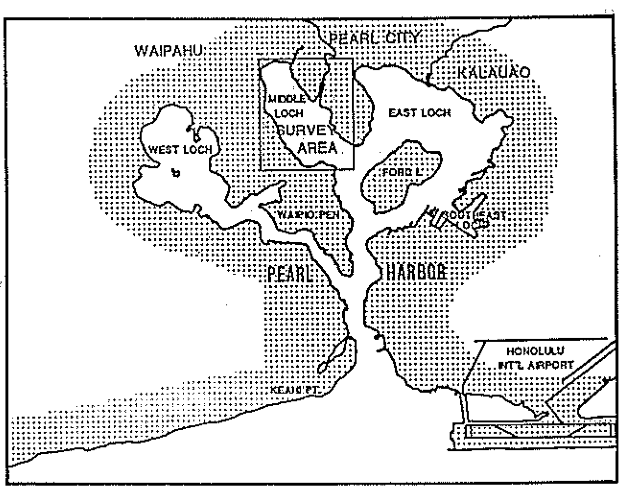

Figure 1. Location Map.

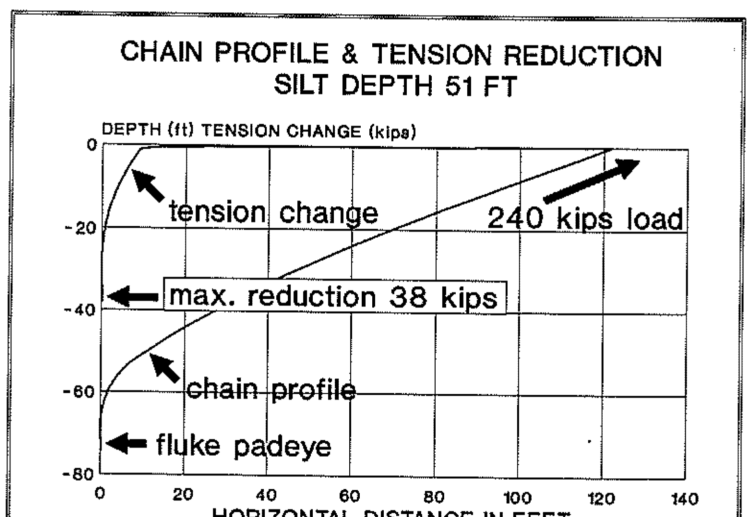

FIGURE 4

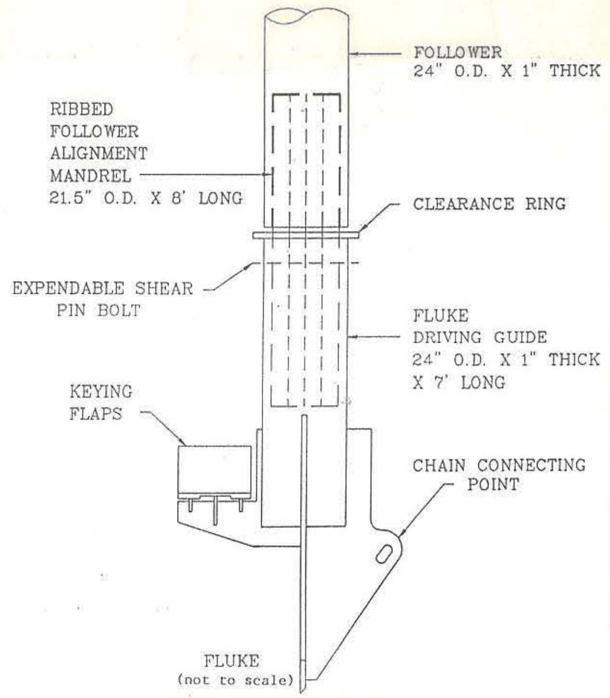

Figure 5

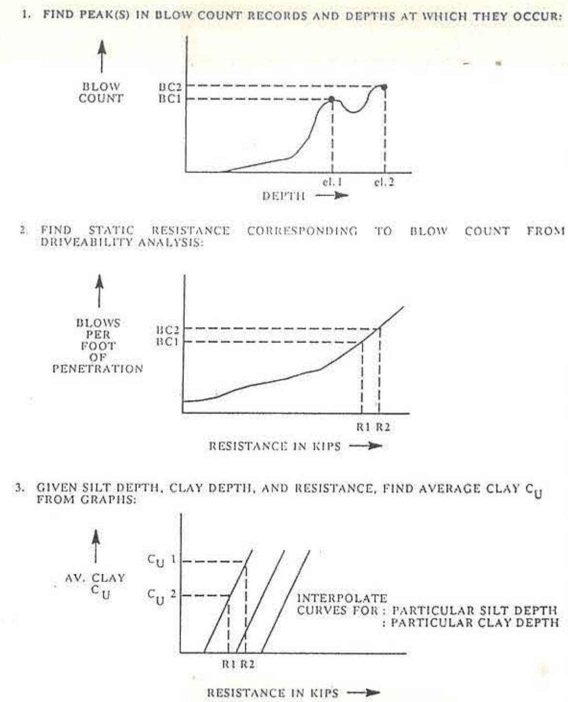

Figure 8 Method for Estimating Average Clay Strength from Installation Data

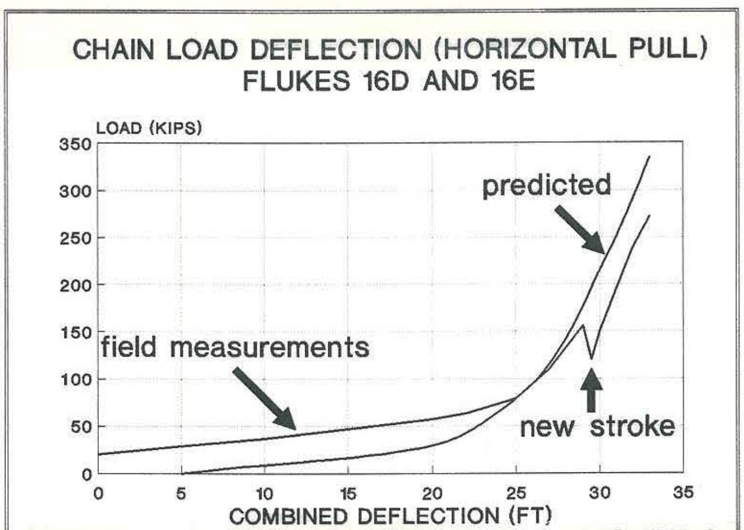

FIGURE 6

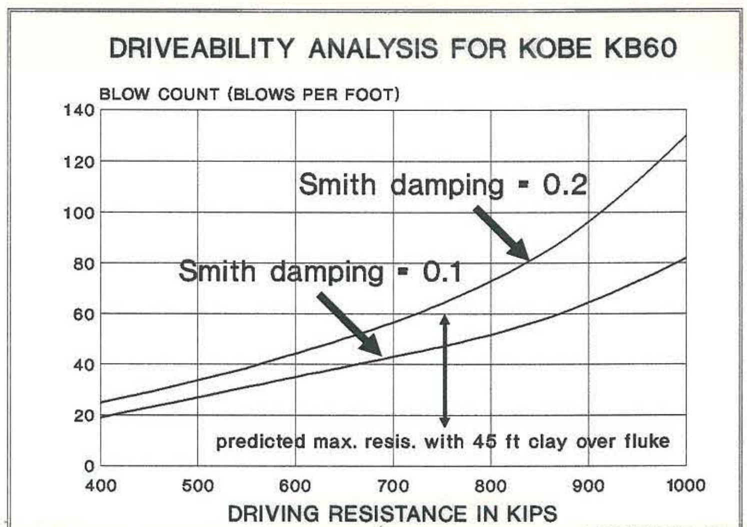

FIGURE 9

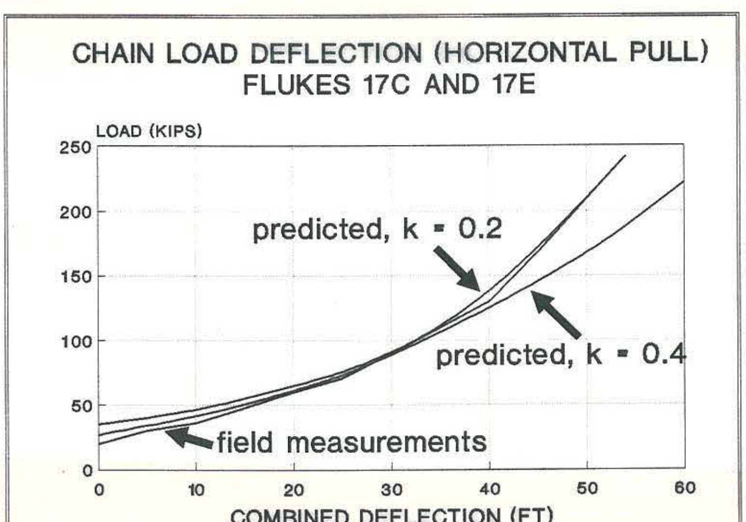

FIGURE 7

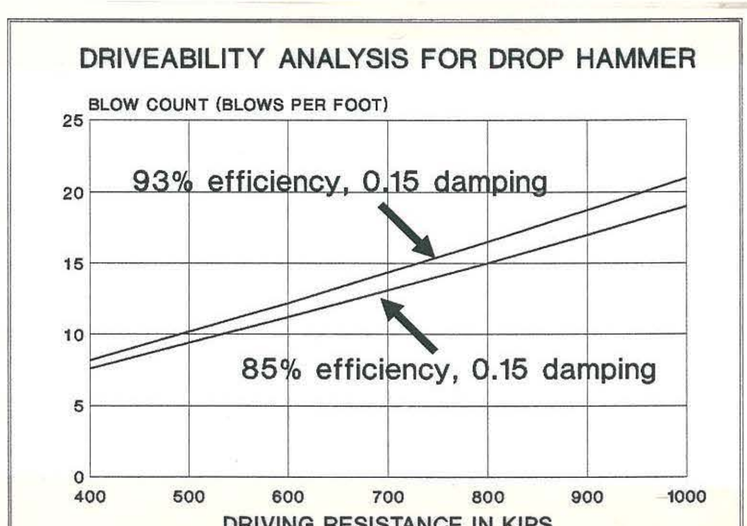

FIGURE 10