PROJECT THEMIS

THE VERTICAL PULLOUT CAPACITY OF MARINE ANCHORS IN SAND

By
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ABSTRACT

This investigation considers the vertical pullout capacity of marine anchors embedded in sand by vibration. Small size anchors having projected horizontal areas of about 15, 30, 55, and 110 square inches were inserted to various depths ranging between 2 feet and 6 feet in a flooded sand soil and load tested for vertical holding capacities. The anchors were tested in a large scale outdoor test bin. For insertion, the anchors were attached to the lower end of a rigid pipe and vibrated into place by means of a vibrator unit attached to the upper end.

Test data indicates that for small size anchors having a short length of loading time, there appear to be two mechanisms of failure within the soil mass in which the anchor is embedded. The mechanism which develops is a function of depth of embedment, size and shape of the anchor, and sand density; and it controls the shape of the curve of pullout load versus anchor depth. The length of the loading time affects the pullout capacity even though the permeability of the flooded sand is 0.1 feet per minute.

The data presented is applicable for the design of anchorages for ocean installations.

Key Words: Anchors, Embedment, Holding Power, Marine, Sand, Test Bin, Vertical Pullout Capacity, Vibratory Driving.

ACKNOWLEDGEMENT

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I. INTRODUCTION

A. Applicability of Work

The increase in man's desire to accomplish work in or on the ocean has imposed greater demands on the design of deep ocean anchorages. The installation of marker buoys and oceanographic and meteorologic instrument systems requires anchorages which can be placed at specified locations and can be expected to stay at that place. Structures and equipment such as pipelines which must be secured to the ocean floor will require sea floor anchors which can be placed rapidly and precisely, and will function with maximum reliability. The design of anchorages for use in the above applications requires anchors capable of resisting either horizontal or vertical tension loads or a combination thereof.

An anchor is a structural element which provides a resisting force when an attempt is made to move it after placement. The resisting force or holding power of the anchor is due to the anchor weight and to the resistance to movement offered by the confining medium. Crumpler and Hromadik (1964) have classified conventional anchors and systems into three groups: (1) dead weight anchors, (2) standard drag type anchors and component systems, and (3) drilled-in-piles and foundation anchors. A type of foundation anchor which has recently been developed is the embedment anchor which derives the majority of its holding power from being buried beneath the sea floor. The holding power of these anchors is related to both penetration depth and soil composition, however, little is known as to the manner in which the anchor and bottom soil interact.

B. Object

The purpose of this investigation was to determine the vertical pullout capacity of specific designs of marine anchors which have been embedded in a flooded sand by vibration. Specific objectives were:

a. The determination of the effects of the size and shape of the anchor on the vertical pullout capacity of marine anchors;

b. The examination of the effects of variable depth of burial and density of sand on the vertical pullout capacity of marine anchors; and

c. The evaluation of the feasibility of inserting marine anchors into a flooded sand soil using vibration as a source of energy for emplacement.

C. Scope

Small size anchors having projected areas of about 15, 30, 55, and 110 square inches were inserted to various depths ranging between 2 feet and 6 feet in a flooded sand soil and load tested for vertical holding capacities. The tests were conducted in a large scale outdoor test bin facility located near the Main Engineering Building of the University of Massachusetts.

The test bin facility was selected in lieu of in-situ tests for overall ease of testing and to keep the cost of field tests within reason. The pullout capacity of an anchor which will develop in a shallow water test facility is practically identical with that which would develop in an in-situ ocean test. This is so because the pullout capacity is related to the effective stresses which exist in the stressed soil mass rather than the total stresses within the soil mass. For a given anchor, the effective stresses which will develop in the test bin are identical to those that will develop in the in-situ test. The difference in the water pressure in the two situations affects the total stresses but does not affect the effective stresses and therefore does not affect the anchor pullout capacity.

For insertion, the anchors were attached to the lower end of a rigid 2-inch diameter pipe and vibrated into place by means of a vibrator unit attached to the upper end of the pipe. A horizontally canceling double eccentric vibrator and a single eccentric vibrator were employed; both units being driven by a controlled variable speed alternating current motor. The pulling loads of the various anchors were applied using a hydraulic jack assembly mounted on a movable reaction frame spanning the test bin. Pullout loads were measured using a load cell and recorded versus movement of the anchor. The density of the flooded sand soil was determined both before and after insertion of the anchor by means of a hand-operated penetrometer. The effects of the length of loading time on the pullout capacity of the tested anchor were considered.

II. SIGNIFICANT RELATED WORKS

Many attempts have been made to investigate the pullout capacity of anchors subject to vertical tension loads in both saturated and unsaturated soils. Empirical solutions based on model tests have been proposed by some individuals while others have used full scale tests to obtain reliable values of pullout loads of earth anchors.

According to Baker and Kondner (1965), the methods which are available for calculating the pullout capacity of circular anchors in sand are based on an assumed shape for the failure surface. Specifically these methods are the friction cylinder method, the weight of cone method and a method presented by Balla (1961). In the friction cylinder method, the pullout capacity is computed by assuming that the failure occurs along the surface of a cylinder of soil above the anchor and that the pullout load is equal to the weight of soil plus the frictional resistance of the soil along the surface of the cylinder. The weight of cone method assumes that the pullout load of the anchor is equal to the weight of soil within a truncated cone extending from the perimeter edge of the anchor to the ground surface with an apex angle of $(45° + \phi/2)$, where ϕ is the angle of internal friction of the soil.

Balla's method, which is based on theoretical considerations supplemented by scale model tests and full scale field tests, decrees that the shape of the pulled out soil mass consists of a complex upward-flaring out solid of revolution. The pullout resistance is computed by calculating the weight of the pulled out soil mass and the value of the resulting shear stress acting on the sliding surface. Balla presents formulas for computing the pullout resistance of the anchor which are functions of the third power of anchor depth, the physical characteristics of the soil and of the relationship between anchor depth, D, and the diameter of the anchor, B. The latter relationship is expressed as λ where:

$$\lambda = D/B$$

Balla's model and field tests on non-saturated sands were conducted with $\lambda \leq 4$ which may be a limitation on the formulas which he presents.

Baker and Kondner also feel that the anchor pullout capacity is a function of anchor depth and the diameter of the anchor. However Baker and Kondner state that a distinction should be made between shallow and deep anchors and that in dense sand this distinction occurs at a $\lambda = 6$. Baker and Kondner also conducted model and field tests on non-saturated sands and present two formulas for calculating the pullout resistance, one for $\lambda < 6$ and one for $\lambda \geq 6$.

The U.S. Navy has conducted many field tests to determine the vertical holding power of anchors embedded in the sea floor (Smith, July 1966) (Dohner, 1966). The testing program is possibly based on the philosophy stated in NavDocks DM 7 (1962) with regard to earth anchors that "more reliable values are obtained from pullout tests." The tests were conducted to evaluate specific designs of anchors developed by industry and by the U.S. Navy. However, no attempts to describe the mechanisms of the failures have been cited in the literature.

Several methods exist by which to embed anchors into a saturated sand such as might be found on the ocean bottom. Explosive embedment anchors have been developed and are used successfully, but with the limitations that they are not reliable and are dangerous to arm. Other concepts such as the free fall embedment anchor have proven not to be fruitful. Smith (March 1966) in describing the free fall embedment method states, "In general, test results indicate that energy other than or in addition to free-fall impetus is needed for an anchor to embed to a sufficient depth." Other sources of energy which are available for use are jetting the anchor under high water pressure, use of a pulse jet principle as described by Sea Space Systems, Inc. (1967) and vibration. Vibration has been successfully used in coring and is also under investigation by Ocean Science and Engineering, Inc. (1967) for the U.S. Naval Civil Engineering Laboratory, Port Hueneme, California, as a means of embedding an anchor.

The use of vibration for obtaining cores has been shown by Sanders (1960) and Sanders and Imbrie (1963). Sanders and Imbrie describe the process as one in which, "the vibrating sampling tube penetrates sand by loosening the packing pressure at grain contacts, causing the grains to flow aside as the tube enters; hence the 'space problem' of the entering tube is solved without increasing the packing pressure between all grains in the vicinity to a level where further penetration becomes impossible." Bernhard (1967) discusses the same process for pile driving and refers to it as a fluidization phenomenon, representing the change of soils from a solid to a quasi-fluid state.

The vibratory technique is primarily dependent on the vibration of the combined soil and anchor mass system. This technique differs from the resonant technique used by Sonico, Inc. to drive piles. The latter technique uses an "oscillator to generate a pressure wave which travels down the pile and if the length of the pile is just right (in conjunction with the frequency of the oscillator), the pile will alternately lengthen and shorten elastically at the same frequency as that of the oscillator. The alternating shortening and lengthening of the pile causes the pile to drive, both by reducing side friction and by penetrating the earth at the bottom tip of the pile. The resonant technique is dependent on the natural frequency of the pile which increases as pile length decreases.

It appeared that for this investigation the most efficient way to place an anchor would be to use the vibratory technique for embedment. The anchor, attached to a rigid pipe for vibratory embedment would then be expanded after placement to offer a larger area for pullout capacity.

III. DESCRIPTION OF APPARATUS

A. Test Facility

The test facility consists of two large-scale concrete outdoor test bins, 20 feet by 20 feet in plan and 8 feet deep. The facility is located near the Main Engineering Building of the University of Massachusetts at Amherst. The appurtenances include a movable reaction frame and a wellpoint system for backflushing the test bin (Photos 1 and 2). Pullout loads of the anchors were applied using a hydraulic jack and yoke assembly and were measured using strain gage load cells. The wellpoint system was designed and used as a means of loosening the flooded sand after an anchor test or several anchor tests were performed. The system consists of four 1-1/2 inch diameter wellpoints which are attached to a header pipe. High pressure water available from a nearby fire hydrant is fed to the header pipe and a semi-quick condition occurs in the flooded sand. The system was not quite as efficient as was desired and future changes will include the addition of four more wellpoints and individual shutoff valves for each wellpoint.

B. Soil Properties

The depth of soil in the test bin was approximately 6-1/2 feet. The soil used in this investigation was quarried locally and processed for use as a washed Mason sand. Standard testing methods were utilized as recommended by T. William Lambe (1951) or the American Society of Testing Materials (1958) to obtain the grain size distribution, specific gravity, permeability and angle of internal friction.

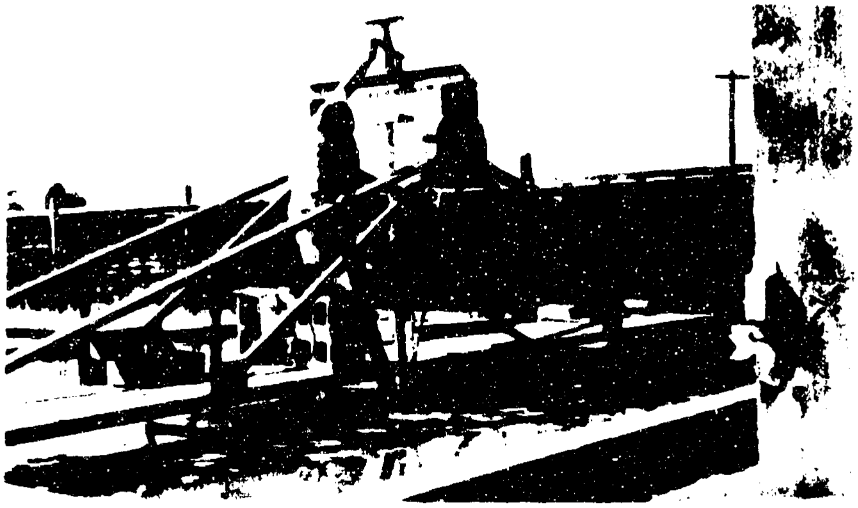


PHOTO 1. VIEW OF TEST FACILITY SHOWING MOVABLE REACTION FRAME AND PULLING OF A TEST ANCHOR.

PHOTO 2. DETAIL OF WELLPOINT SYSTEM USED FOR RECHARGE PURPOSES

The angle of internal friction was found using consolidated drained triaxial tests at confining pressures of 15 and 30 psi. Results of these tests are presented in Table 1 with a grain size distribution shown in Figure 1.

TABLE 1

Engineering Properties of Sunderland Sand

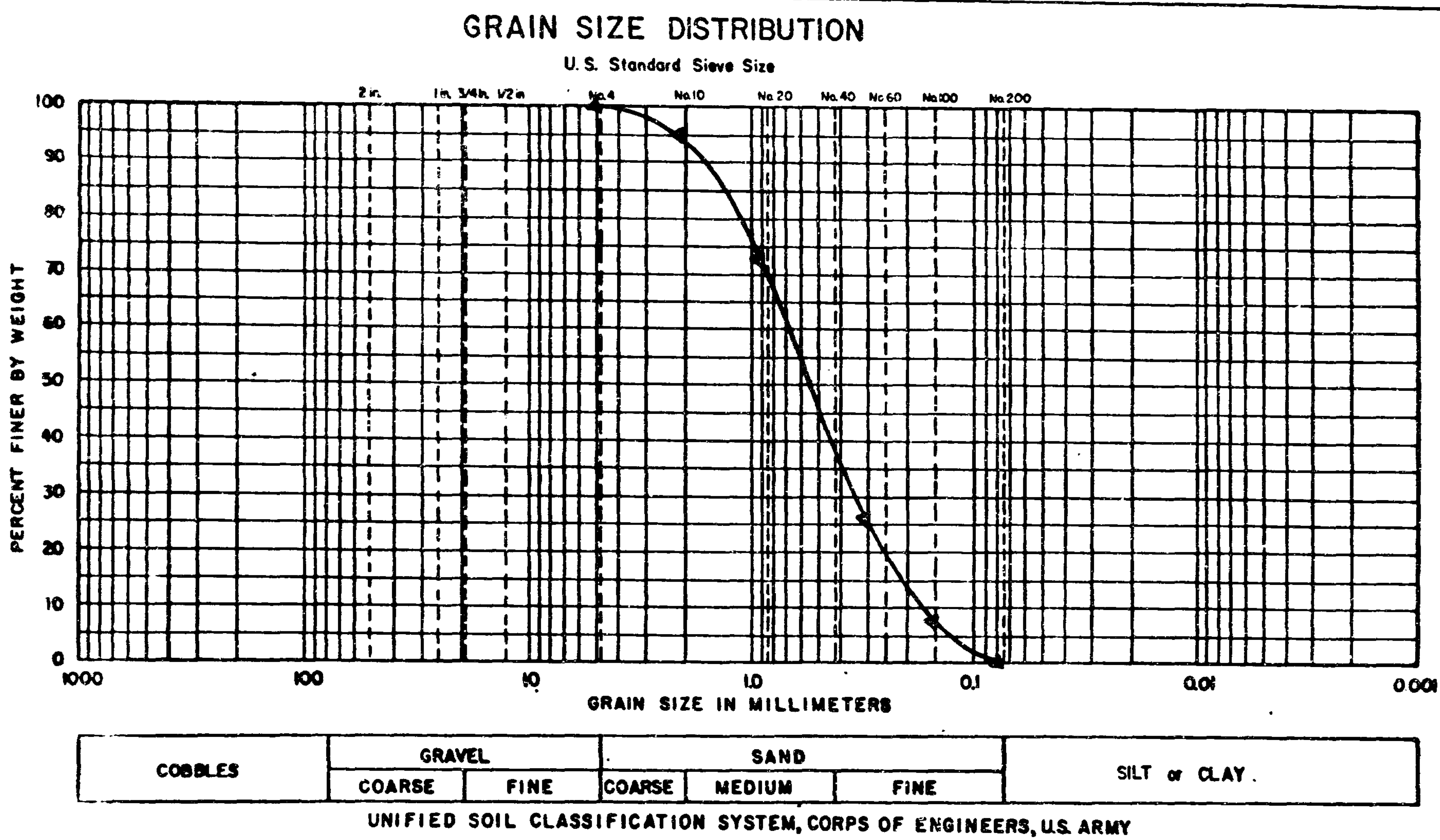
Uniformity Coefficient	4
Specific Gravity	2.68
Permeability (Falling Head, Void Ratio = .7)	$\simeq$ 0.1 ft/min
Effective Stress Angle of Internal Friction	ϕ' = 38 degrees at 100 pcf Dry Density
	ϕ' = 45 degrees at 118 pcf Dry Density

The sand is identified as an SP soil in the Unified Soil Classification System.

C. Equipment

Small size anchors having net projected horizontal areas of approximately 15, 30, 55 and 110 square inches were fabricated from mild steel and are shown in Photo 3. For insertion the anchors were attached to the lower end of a rigid 2-inch diameter steel pipe and vibrated into place by means of a vibrator unit attached to the upper end.

The 15 and 30 square inch anchors consisted of a fixed horizontal



Uniformity Coefficient = 66/17 $\underset{-}{\sim}$ 4

Figure 1

PROJECT Sunderland Mason Sand

Brown, Mostly Quartz

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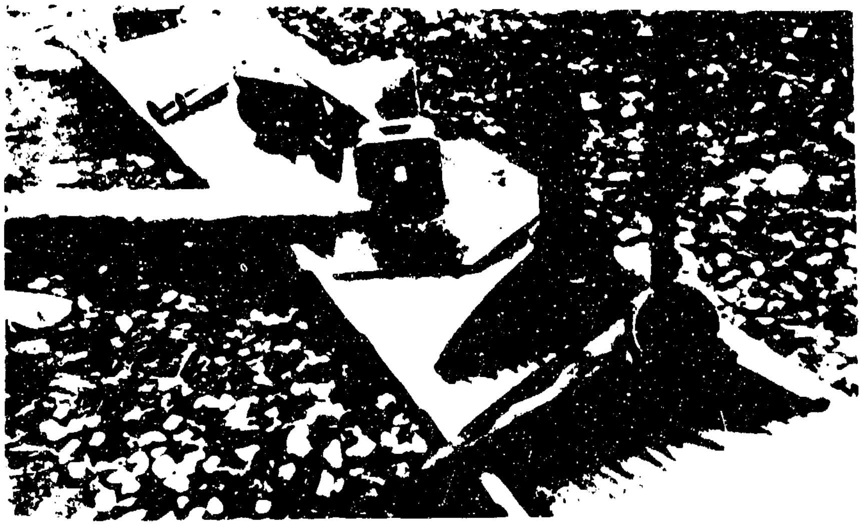


PHOTO 3. ANCHORS USED IN THIS INVESTIGATION. FROM LEFT TO RIGHT, 15 SQ. IN. FIXED, 30 SQ. IN FIXED, 55 SQ. IN. FLAT PLATE, 55 AND 110 SQ. IN. Y-SHAPES. THE 110 SQ. IN. FLAT PLATE IS NOT SHOWN.

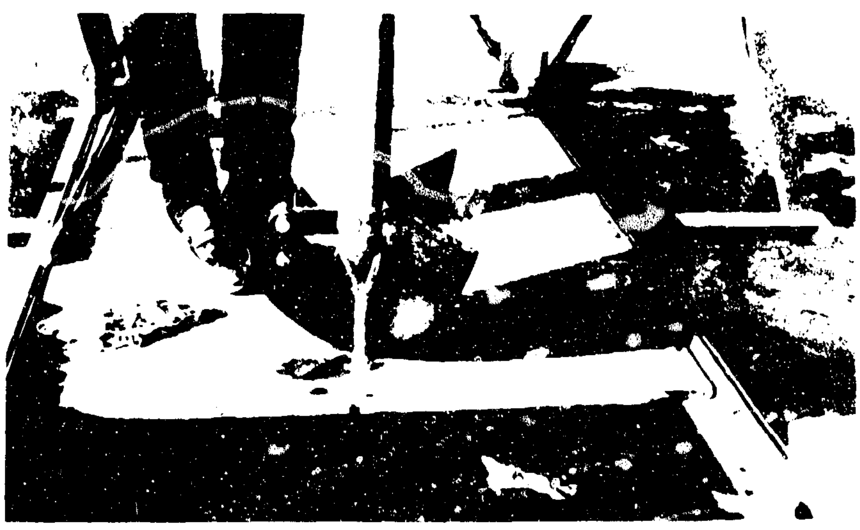


PHOTO 4. THE 120 SQ. IN. Y-SHAPED ANCHOR ATTACHED TO THE 2-INCH DIAMETER DRIVE PIPE PRIOR TO EMBEDMENT.

plate formed to a pyramid for ease of insertion, and attached to the 2-inch diameter pipe by a pipe coupling welded to the square plate. The actual area of the anchors was larger than the nominal 15 and 30 square inches to allow for the area occupied by the pipe.

The 55 and 110 square inch anchors were fabricated in two designs, both having a linkage mechanism which allows the anchor to rotate 90° after insertion (Photos 4 and 5). The 90° rotation of the anchor occurred after pulling was begun and allowed the anchor to present the least horizontal projected area during embedment and the greatest horizontal projected area during pullout. The Y-shaped anchor was based on an anchor designed by Smith of the U.S. Naval Civil Engineering Laboratory (March 1966). Anchor size and weight data is presented in Table 2.

TABLE 2

Anchor Size and Weight Data

Type and Size, sq. in.	$\sqrt{area}$, ft	Dist. from Bottom of Pipe to Top of Anchor, ft	Weight, lbs			Max and Min Dim, ft	
			Shaft	Bottom	Total	Max	Min
Pipe Alone	.100	0	21*	4	25	.23	.23
Fixed 15	.322	.15	21	3	24	.36	.36
Fixed 30	.46	.15	21	4	25	.49	.49
Y 55	.61	.75	29**	12.5	41.5	1.1	.6
Flat 55	.62	.75	29	11	40	.75	.66
Y 110	.87	1.05	29	20	49	1.4	.8
Flat 110	.88	.75	29	26.5	45.5	1.08	.92

*Schedule 40 steel pipe

**Schedule 80 steel pipe

PHOTO 5. THE 60 SQ. IN. Y-SHAPED ANCHOR AFTER PULLOUT.

PHOTO 6. THE DOUBLE AND SINGLE ECCENTRIC VIBRATORS SHOWN LEFT TO RIGHT, RESPECTIVELY.

The area of an anchor is determined from the horizontal projected area of the anchor. Standard wall steel pipe (Schedule 40) was used as a drive pipe for the 15 and 30 square inch anchors while heavy wall steel pipe (Schedule 80) was used for the 55 and 110 square inch anchors. For the pipe alone tests, the standard wall steel pipe was tipped with a cone-shaped point for insertion.

A horizontally canceling double eccentric vibrator and a single eccentric vibrator shown in Photo 6 were employed. Both units were attached to the anchor pipe by means of a 2-inch pipe floor flange.

The double eccentric vibrator was available in the Civil Engineering Department of the University of Massachusetts. The plans for the double eccentric vibrator were adapted from a vibrator used by E. O. Davis (1942) during his Master's work at the Massachusetts Institute of Technology. The vibrator is a two mass oscillator, with the masses rotating in opposite directions so as to cancel the dynamic force in the horizontal direction and add in the vertical direction. The double eccentric vibrator is approximately 6" x 6" x 5" in size and weighs 31 pounds. Each eccentric mass weighs about 1.5 pounds with a center of mass 1.05 inches from the center of the shaft.

The single eccentric vibrator was adapted from a standard 4 HP soil compaction machine used to compact backfill around pipes and culverts, and was modified for use as a vibrator for anchor emplacement. The vibrator weighs 35 pounds and is 12 inches long and 4 inches in outer diameter. The eccentric is 6" x 1-1/2" x 3/4" in size and weighs 1.8 pounds with a center of mass of 1-3/16 inches from the center of the shaft.

The vibrator units were connected to a variable speed alternating current motor with a flexible shaft. The speed of the motors could be varied from 500 to 5000 rpm by a dial selector. The ability to dial any speed from 500 rpm to 5000 rpm was a necessity since the desirable vibration frequency of the anchor and adjacent soil mass which would allow easy penetration was not known beforehand. Initially a 3/4 HP motor was used but, due to overloading of the 3/4 HP motor, a 1 HP motor was used in later tests. The variable speed motors and flexible shaft are available from Sears Roebuck and Company. The rpm dial selectors on the motors were calibrated and errors up to 25% of the indicated speed were found to exist. These errors did not effect the tests since the exact rpm of the motor was not of significance for the tests in this investigation.

IV. TESTING PROCEDURE

A. Field Tests

A total of thirty-six field tests were conducted in the fall of 1968 with the various shapes and sizes of anchors. These anchor tests were conducted at different depths of embedment and varying densities of the test soil.

The test bin was flooded using the wellpoint system to insure saturation of the sand, until approximately 4 to 6 inches of water covered the sand. The reaction frame was positioned over the area in which the anchor was to be tested. The location of the anchor in the test bin was such that the wall effects on the pullout capacity of the anchor would be minimized. The smaller size anchors were embedded at least 3 feet from the nearest wall while the larger size anchors were embedded at least 5 feet from the nearest wall.

The relative density of the flooded sand was then determined using a Proctor needle penetrometer which had been modified by the addition of a six-foot, 1/2-inch diameter shaft. The end of the shaft was fitted with a 1/2-square inch circular tip. Readings of the amount of force in pounds to insert the penetrometer a distance of 3 inches were taken from 2 feet below the top of the sand to 6 feet below the top of the sand (see Photo 7). Similarly, two to four soundings of density were taken after the anchors were embedded. Relative density of the flooded sand was then determined from the classification given in Table 3. No attempt was made to correlate these arbitrarily selected relative density groups with the actual net density of the sand.

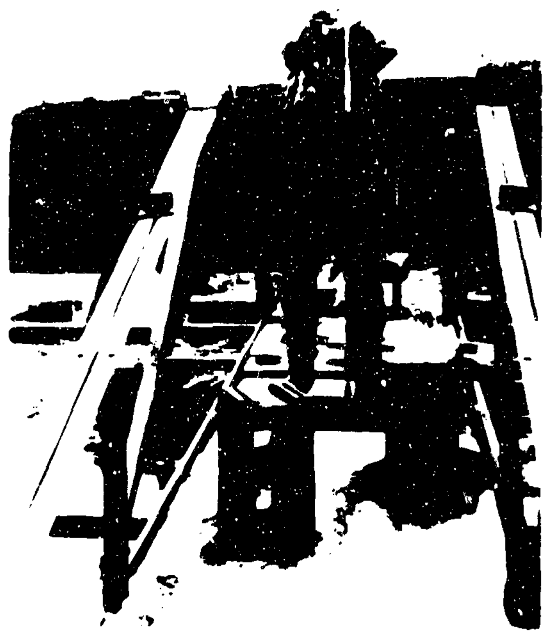


PHOTO 7. THE RELATIVE DENSITY OF THE FLOODED SAND BEING MEASURED USING A PROCTOR NEEDLE PENETROMETER.

TABLE 3

Relative Density of Flooded Sand

Time of Reading	Penetrometer Readings		
	Loose	Medium	Dense
Before Anchor Emplacement	< 40	40-80	> 80
After Anchor Emplacement	< 80	80-130	> 130

The anchor to be tested was attached to the drive pipe and then set in position. In early tests of the 55 square inch Y-shaped and flat plate anchors, it was thought that a shear pin was required to keep the anchor from rotating as it was being emplaced. In six tests the anchor did not key due to shear pin problems; the results of those tests are not presented in this investigation. Several methods of installing a shear pin were tried, all offering considerable difficulty. Subsequent tests without any shear pin showed that the pin was not required during emplacement. However, in ocean applications a method will have to be designed to hold the anchor fluke in place at least until penetration has begun.

Either the single eccentric or double eccentric vibrator unit was then attached to the top of the pipe. The variable speed motor was positioned in a convenient location and the flexible shaft connected to the vibrator unit as shown in Photo 8. In some tests a guide template was used to position the anchor while it was being embedded; however, it was found that guidance was best achieved by having a man's hand guide the vibrator unit.

The variable speed motor was then turned on and the speed was

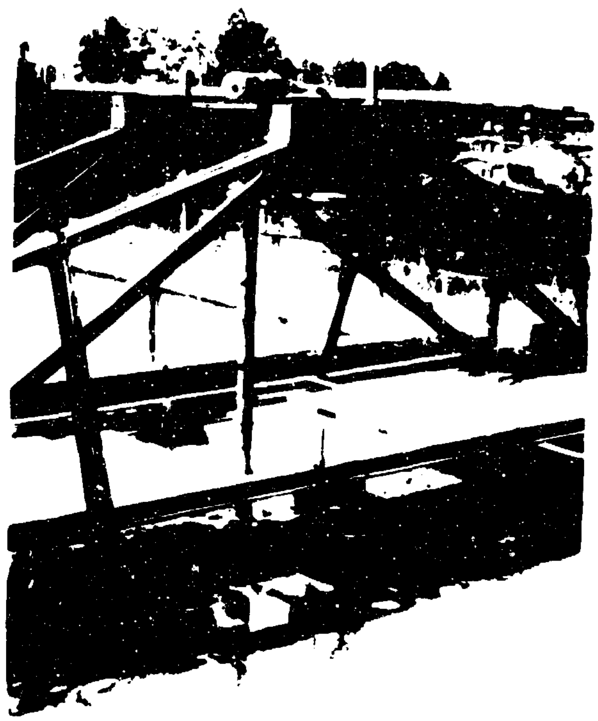


PHOTO 8. ANCHOR IN POSITION PRIOR TO EMPLACEMENT WITH GUIDE TEMPLATE FIXED TO LOWER CHORDS OF THE TEST FRAME.

slowly increased to approximately 2,500 rpm. The vibrator was guided as the anchor penetrated. When the penetration of the anchor began to slow or stop it was necessary to increase the speed of the vibrator. This was done in steps of approximately 500 rpm to a maximum of 4,500 rpm. In tests of the 110 square inch anchors or in dense soil it was necessary to place additional weight on the vibrator unit or to turn on the well-point system at a slow rate in order to achieve the desired penetration of the anchor. It should be noted that the 30 square inch fixed anchor was more difficult to embed than the rotating 55 square inch Y-shaped and flat plate anchors. The speed of vibration and the time to embed the anchor were recorded on the field data sheets, however, they are not presented in this investigation.

The hydraulic load apparatus and yoke assembly was then positioned over the anchor pipe and a strain gage load cell was connected in the chain between the yoke and the anchor as shown in Photo 1. The hydraulic load apparatus was jacked until a movement of the anchor occurred and a measurement of pullout capacity was recorded by reading the SR-4 strain indicator. The distance from the bottom of the pipe to the ground surface was used as the reference measurement for the depth of the anchor. In tests of the 55 and 110 square inch anchors, sufficient movement of the drive pipe had to occur for the flukes to rotate. A sketch of the fluke is shown in Figure 2. This rotation of the fluke is referred to as keying.

After initial loading of the anchor, the load apparatus was jacked in 3-inch increments and a measurement of pullout capacity was recorded. After six inches of movement, the load on the anchor had to be released and the jack reset due to the limitation of a 6-inch piston in the hydraulic jack. This loading in 3-inch increments was continued until the bottom of the pipe was within 9 inches of the surface.

When the pulling of the anchor was complete, the frame was repositioned for the start of a new test. After four or five tests were completed the test bin was recharged using the wellpoint system described in Chapter II.

B. Laboratory Tests

Laboratory tests were conducted to determine the effect of length of loading time on the pullout capacity of the anchor and to determine the soil movement around and above the anchor. The 55 square inch flat plate anchor was buried in a depth of 15 inches in a loosely placed flooded sand and in a dry sand.

The sand used in the laboratory tests came from the same quarry as the sand used in the field tests and has similar engineering properties. A half-height 55-gallon drum was used for a test bin. Reference probes were placed on, above and around the anchor to record anchor movement and soil movement. A constant load apparatus with a yoke assembly was placed over the anchor and a proving ring was placed between the load apparatus and the yoke assembly. The constant load apparatus uses an air regulator to keep a constant load on a piston and therefore a constant pull on the anchor. A 3/16-inch diameter wire cable was used to connect the anchor and yoke assembly. The apparatus is shown in Photo 9.

Anchor movement, soil movement and time to failure of the anchor were recorded versus load on the anchor. The results of the effects

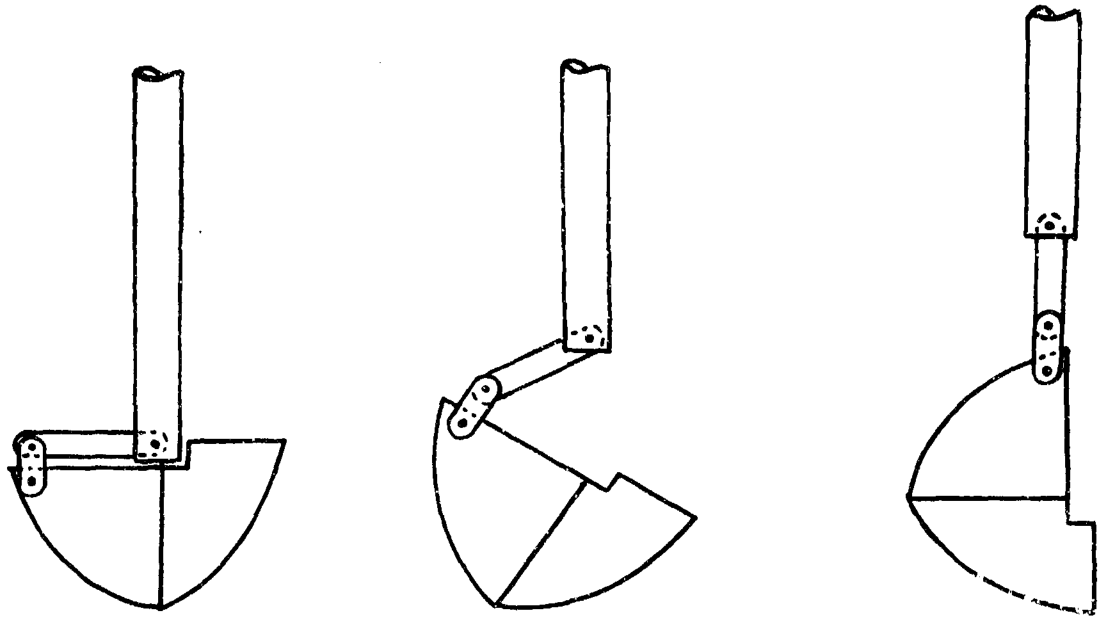


FIGURE 2. SCHEMATIC DRAWING OF EMBEDMENT AND OPENING OF Y-SHAPED ANCHOR

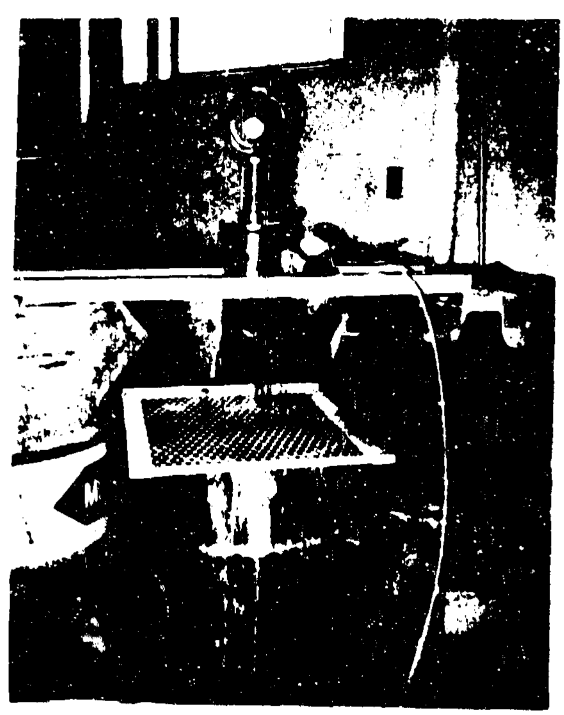


PHOTO 9. LABORATORY TESTS OF 55 SQ. IN. FLAT PLATE ANCHOR WITH CONSTANT LOAD APPARATUS

of length of loading time are presented in Chapter V. The soil movement tests were not conclusive enough to merit discussion in this presentation.

V. PRESENTATION AND DISCUSSION OF TEST RESULTS

The pullout capacity of the anchor was plotted versus the depth to the bottom of the pipe for each test conducted in the investigation. These graphs are presented in Figures 3 through 9 and represent the data recorded in the field tests for short lengths of loading time. The bottom of the pipe was used as a reference in all field tests and to find the pullout capacity at a given depth of anchor, a correction factor equal to the distance from the bottom of the pipe to the top of the anchor plate must be subtracted from the depth of the opened anchor. These correction factors are given in Table 2. For example, if it is desired to find the pullout capacity for a 55 square inch flat plate anchor in dense sand at a depth of 3 feet, Figure 8 must be entered at (3' - .75' = 2.25') and the pullout capacity would be 800 pounds. The pullcut capacity given in these figures and in Figures 11 through 15 are the total load on the anchor and include the weight of the pipe and anchor, the friction resistance load on the pipe, and the resistance load of the anchor. The relative density of the flooded sand before and after each field test and the type of vibrator used for emplacement are presented on the graphs.

The maximum pullout capacity and the corresponding total vertical movement to develop it are shown in Figures 5 through 9 for the 55 and 110 square inch anchors. A total vertical movement consists of the movement required for keying plus the movement required for developing the load on the anchor. The term "developing the load" is used to describe the movement necessary to attain maximum pullout

FIGURE 3

PLOT OF PULLOUT CAPACITY VERSUS
DEPTH TO BOTTOM OF PIPE
FOR A 15 SQ. IN. ANCHOR

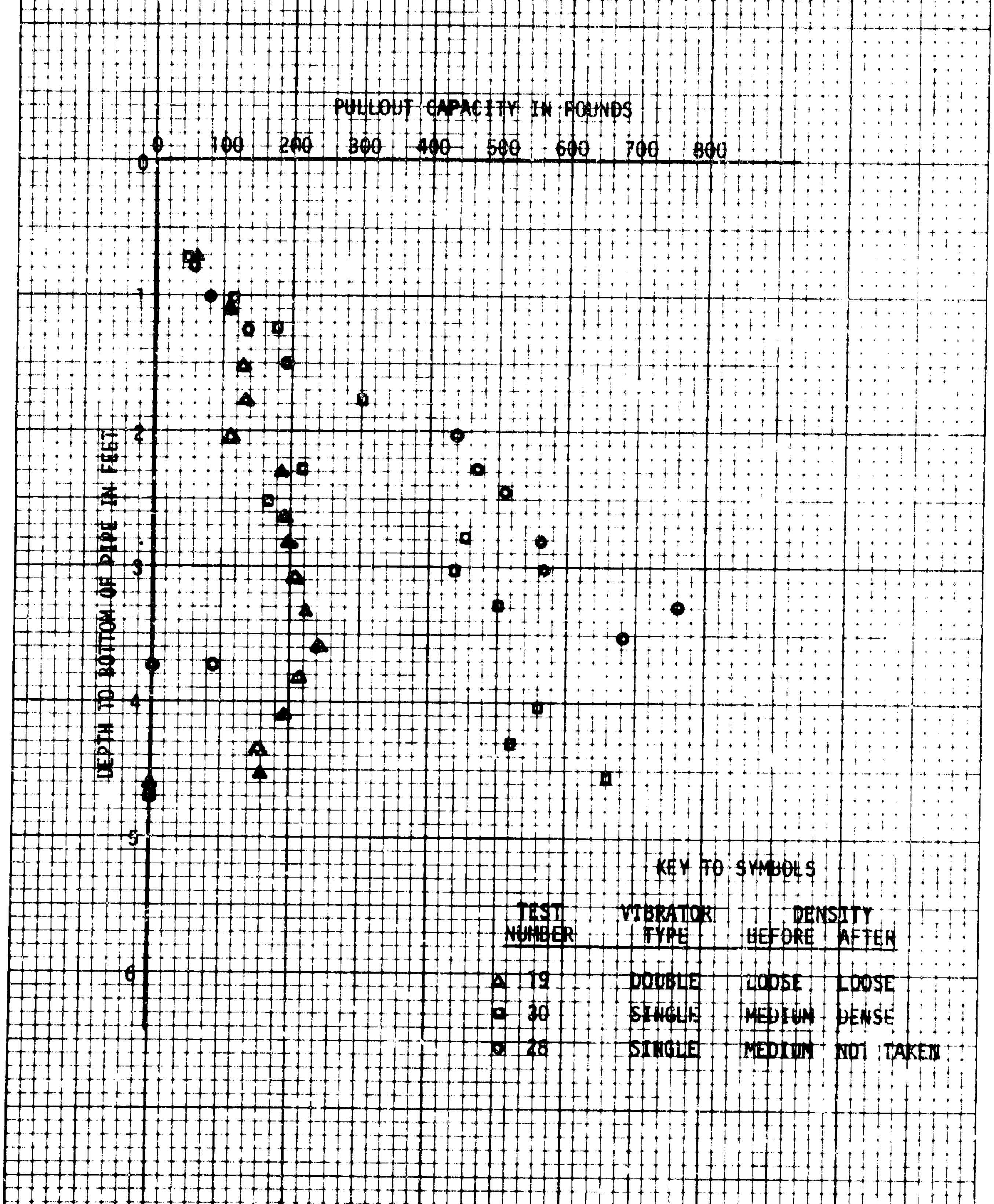
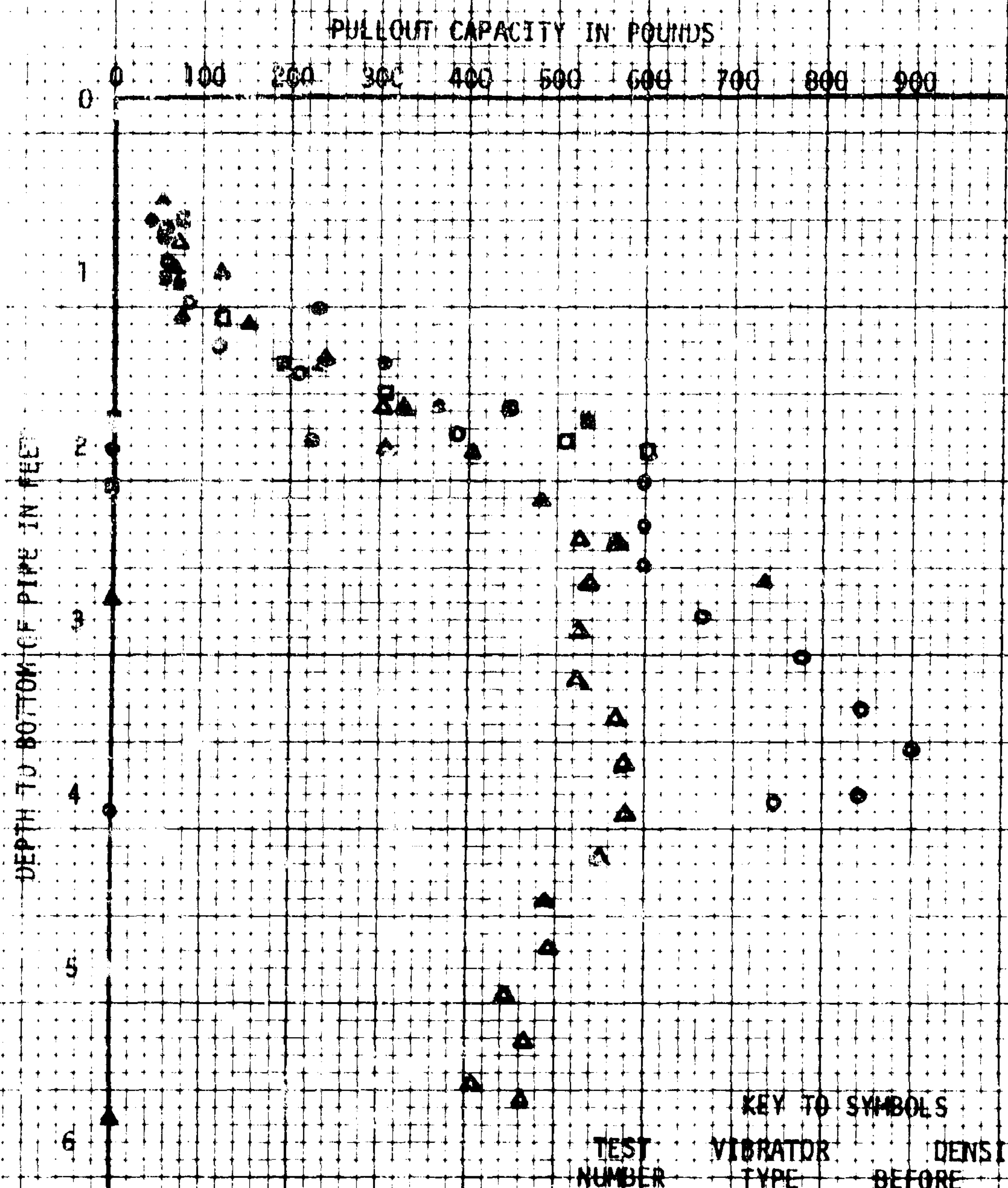


FIGURE 4
PLOT OF PULLOUT CAPACITY VERSUS
DEPTH TO BOTTOM OF PIPE
FOR A 30 SQ. IN. ANCHOR



KEY TO SYMBOLS

TEST NUMBER	VIBRATOR TYPE	DENSITY BEFORE	DENSITY AFTER
△ 33	SINGLE	LOOSE	LOOSE
■ 18	SINGLE	LOOSE	DENSE
▲ 17	SINGLE	LOOSE	DENSE
● 21	SINGLE	LOOSE	DENSE
□ 20	DOUBLE	MEDIUM	NOT TAKEN
● 15	SINGLE	DENSE	DENSE

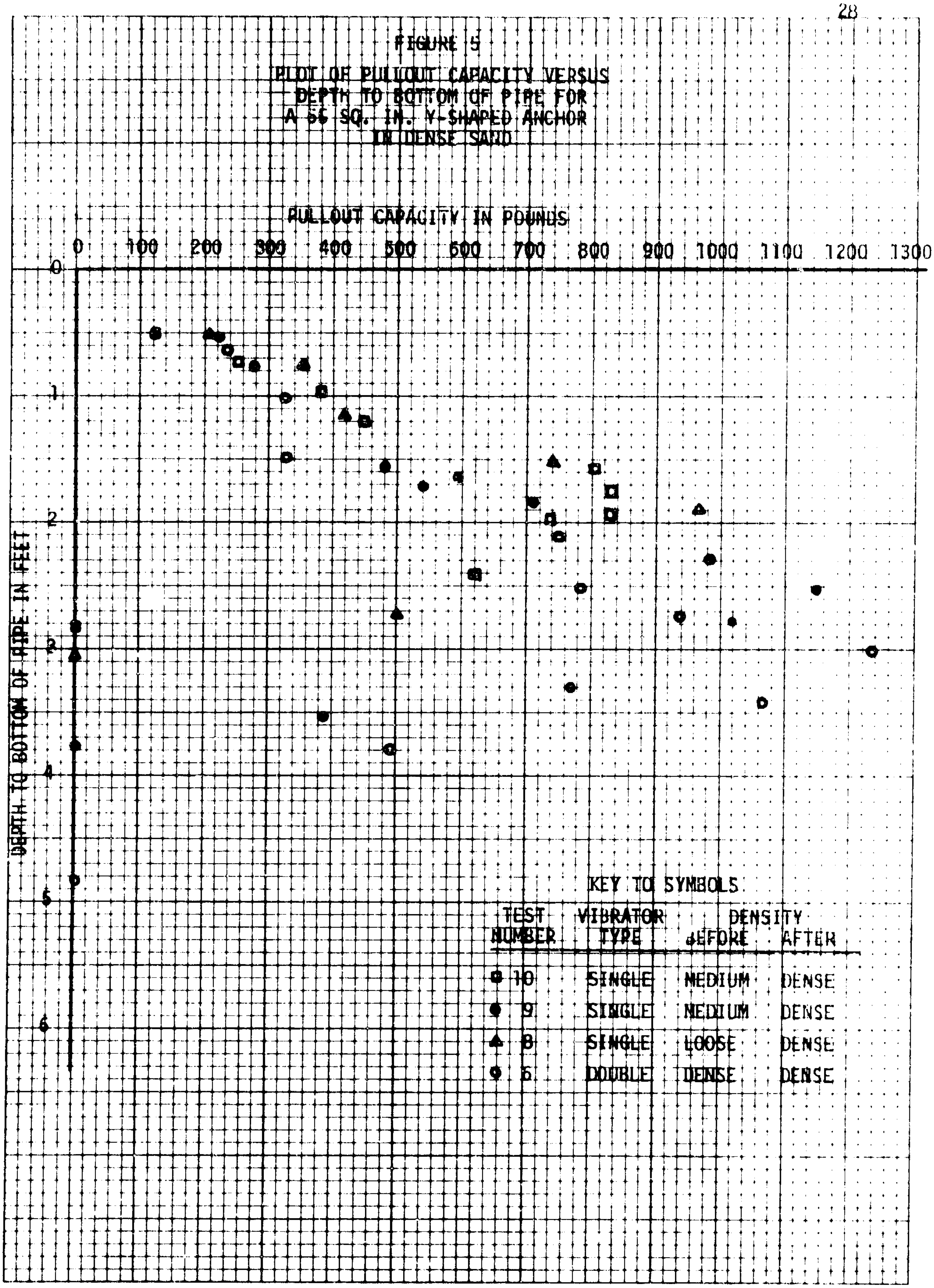


FIGURE 5
PLOT OF PULLOUT CAPACITY VERSUS
DEPTH TO BOTTOM OF PIPE FOR
A 56 SQ. IN. Y-SHAPED ANCHOR
IN DENSE SAND
PULLOUT CAPACITY IN POUNDS
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300
DEPTH TO BOTTOM OF PIPE IN FEET
0 1 2 3 4 5 6
KEY TO SYMBOLS
TEST NUMBER
VIBRATOR TYPE
DENSITY
BEFORE
AFTER
10 SINGLE MEDIUM DENSE
9 SINGLE MEDIUM DENSE
8 SINGLE LOOSE DENSE
6 DOUBLE DENSE DENSE

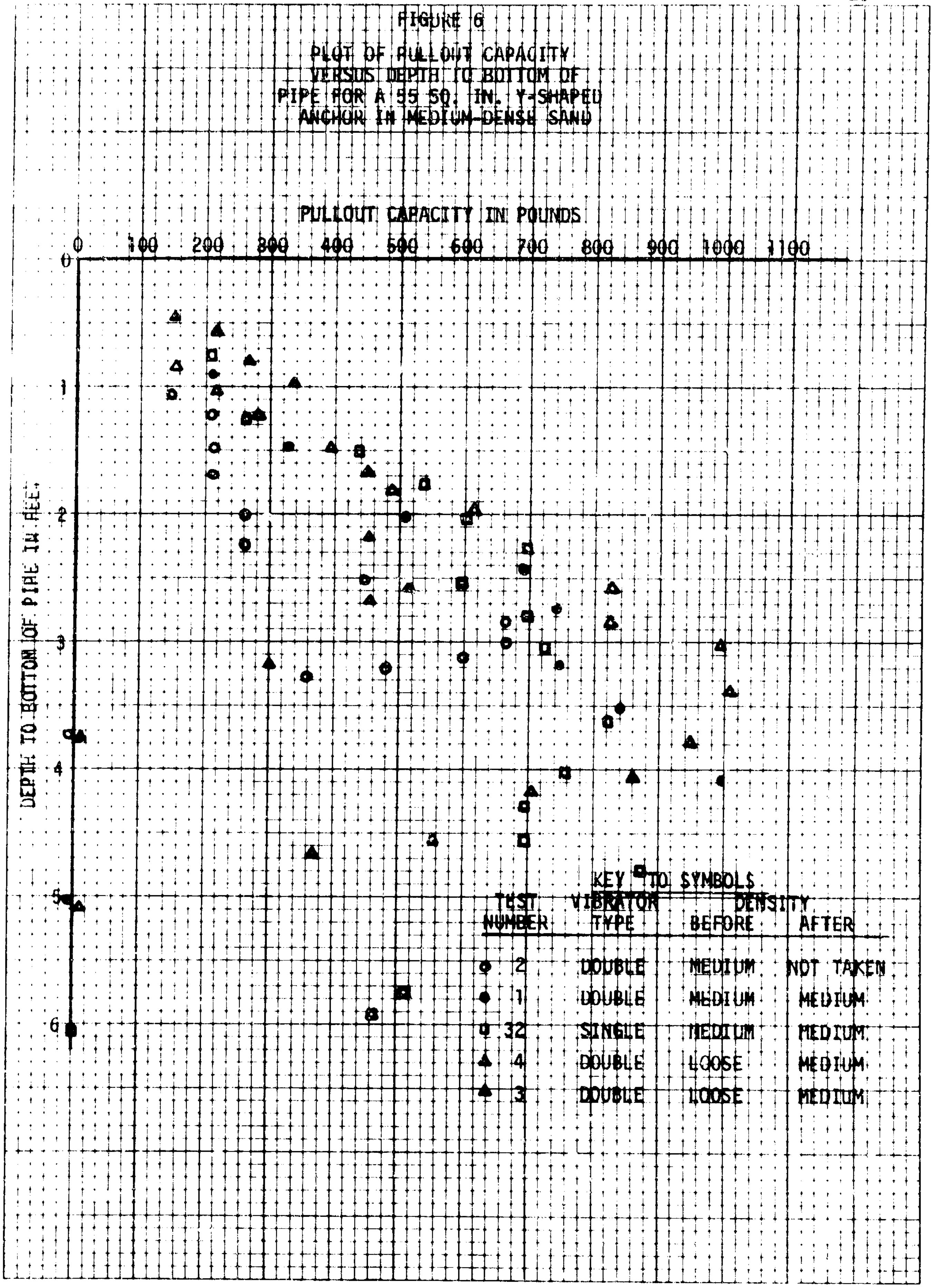


FIGURE 6
PLOT OF PULLOUT CAPACITY
VERSUS DEPTH TO BOTTOM OF
PIPE FOR A 55 SQ. IN. Y-SHAPED
ANCHOR IN MEDIUM-DENSE SAND
PULLOUT CAPACITY IN POUNDS
0 100 200 300 400 500 600 700 800 900 1000 1100
DEPTH TO BOTTOM OF PIPE IN FEET
0 1 2 3 4 5 6
KEY TO SYMBOLS
TEST NUMBER
VIBRATOR TYPE
DENSITY
BEFORE
AFTER
2 DOUBLE MEDIUM NOT TAKEN
1 DOUBLE MEDIUM MEDIUM
32 SINGLE MEDIUM MEDIUM
4 DOUBLE LOOSE MEDIUM
3 DOUBLE LOOSE MEDIUM

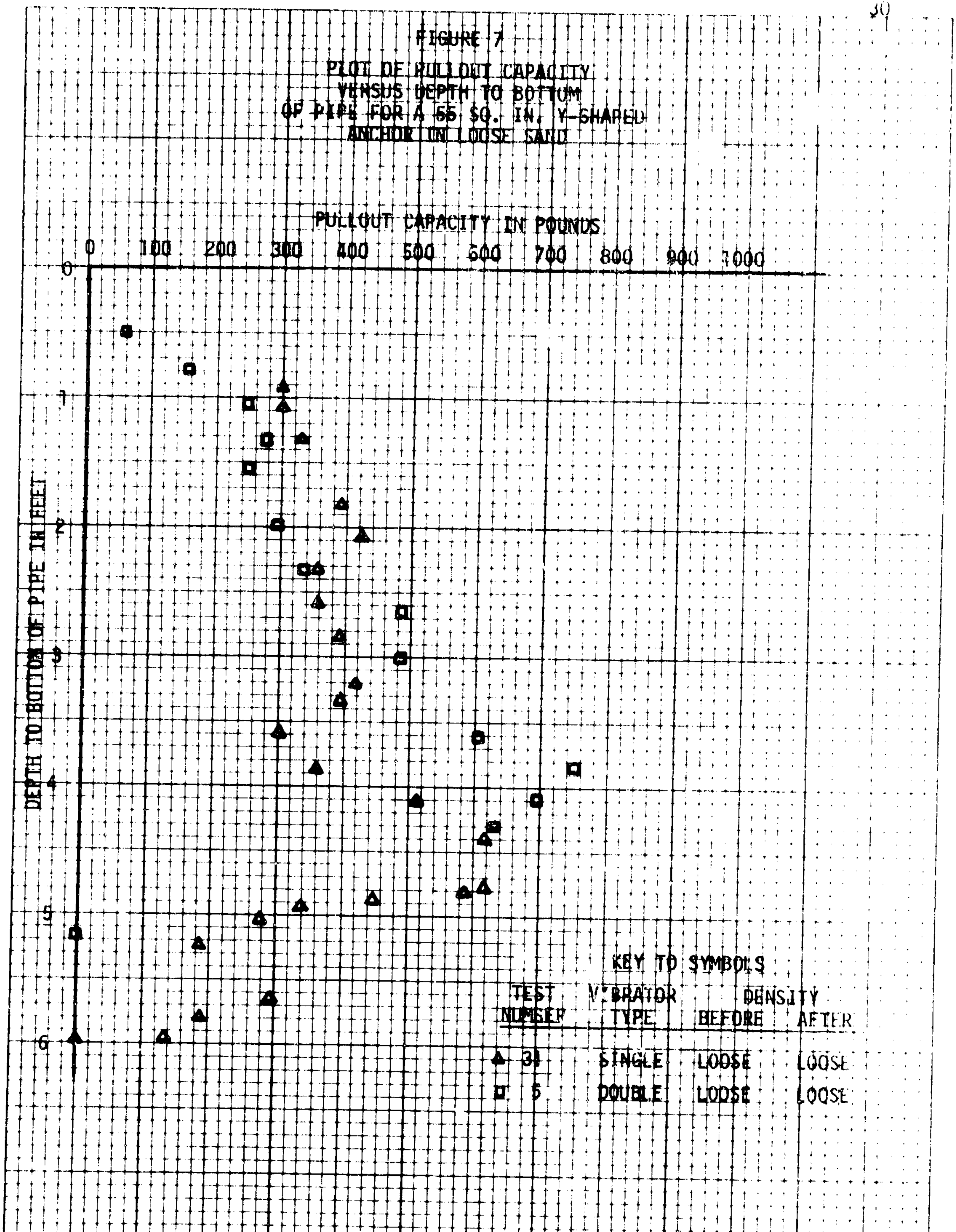


FIGURE 7
PLOT OF PULLOUT CAPACITY
VERSUS DEPTH TO BOTTOM
OF PIPE FOR A 55 SQ. IN. Y-SHAPED
ANCHOR IN LOOSE SAND
PULLOUT CAPACITY IN POUNDS
0
100
200
300
400
500
600
700
800
900
1000
DEPTH TO BOTTOM OF PIPE IN FEET
0
1
2
3
4
5
6
KEY TO SYMBOLS
TEST NUMBER
VIBRATOR TYPE
DENSITY
BEFORE
AFTER
3
SINGLE
LOOSE
LOOSE
5
DOUBLE
LOOSE
LOOSE

FIGURE 8
PLOT OF PULLOUT CAPACITY VERSUS
DEPTH TO BOTTOM OF PIPE
FOR A 55 SQ. IN. FLAT PLATE
ANCHOR

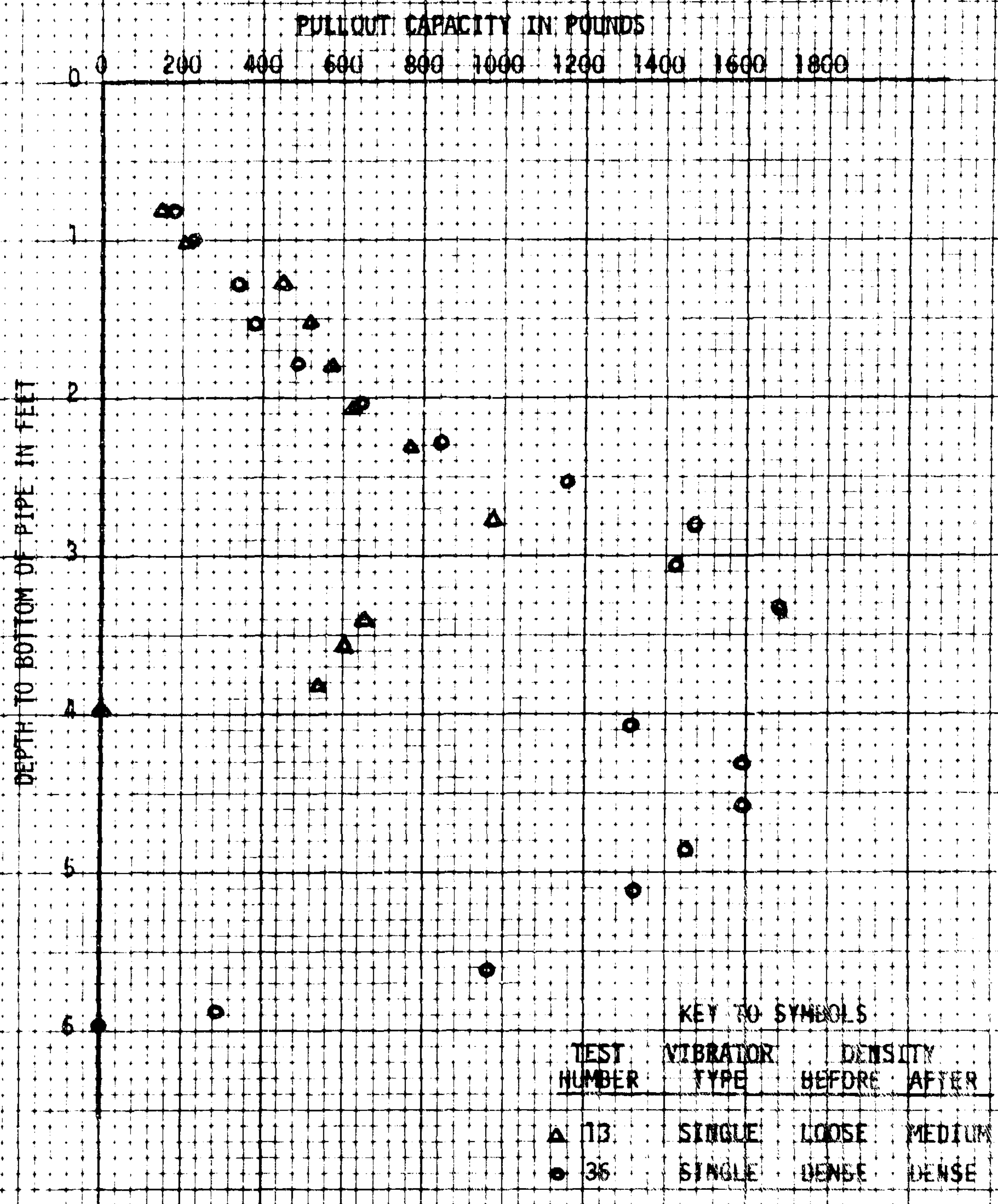
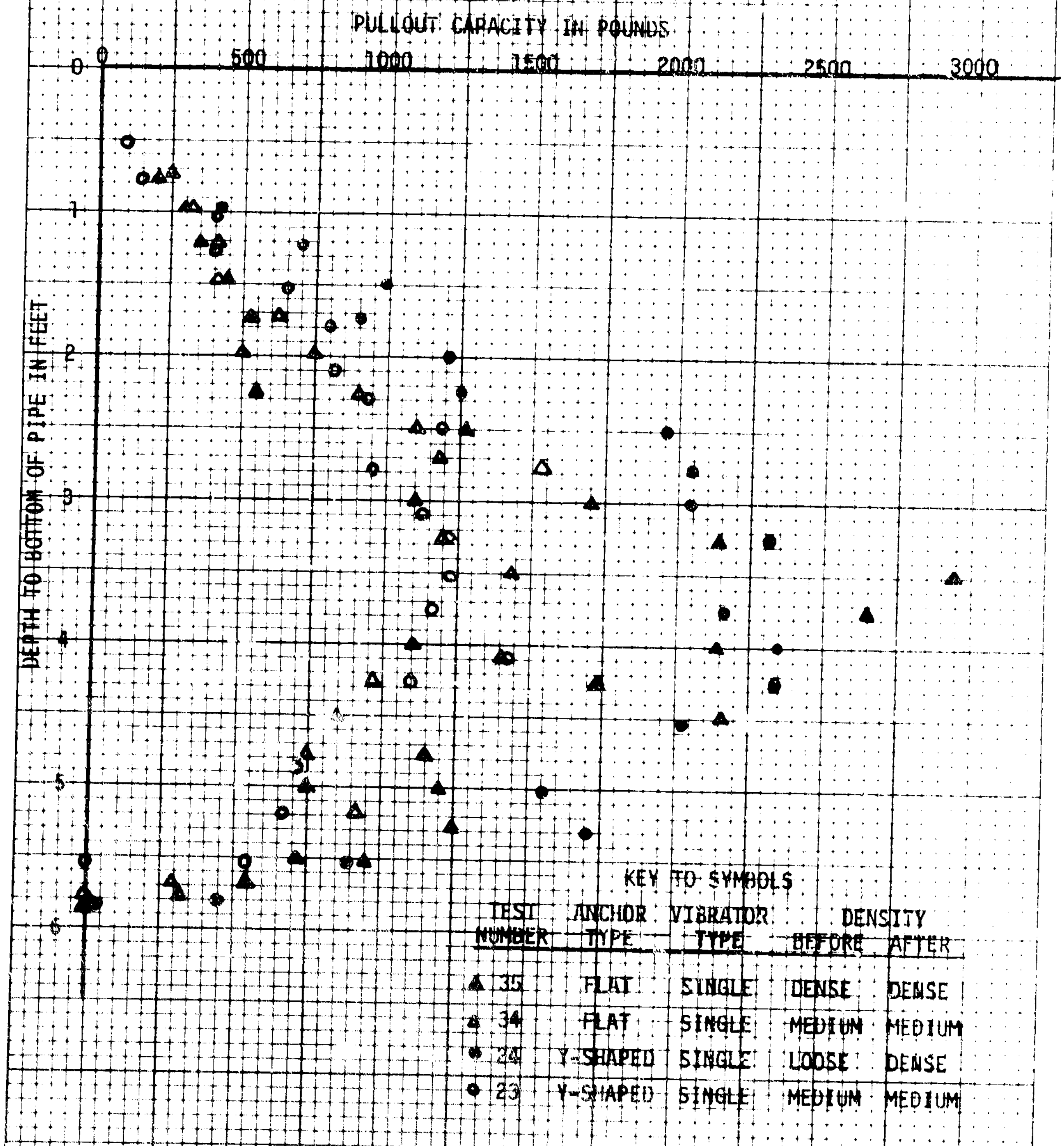


FIGURE 9

PLOT OF PULLOUT CAPACITY VERSUS DEPTH TO BOTTOM OF PIPE FOR A 110 SQ. IN. Y-SHAPED AND FLAT PLATE ANCHORS



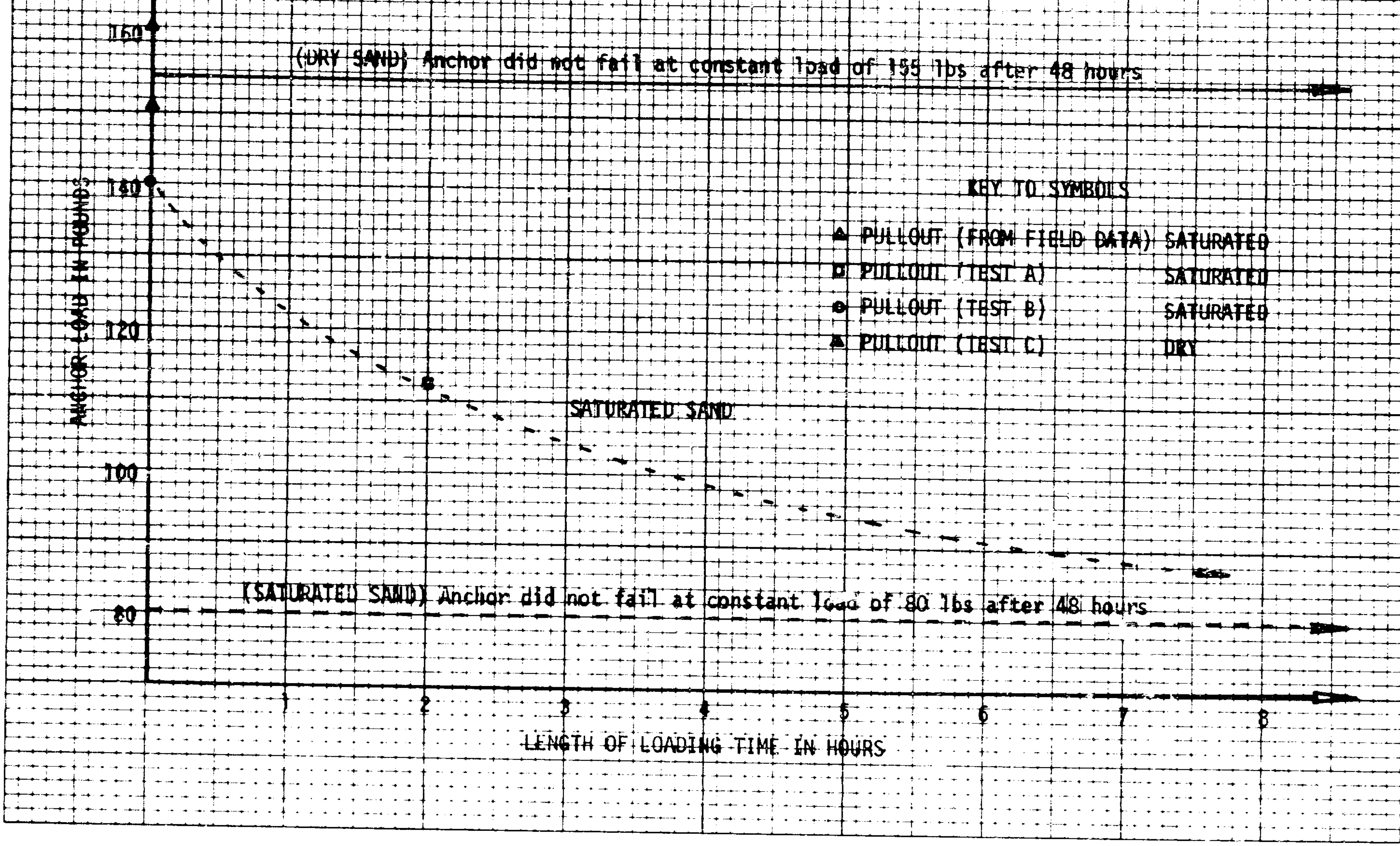
capacity and it is in addition to the keying movement. It is due to the strain required by the soil to develop the pullout resistance. In examining Figures 3 through 9, some discontinuities can be observed in the curves. It is felt that these increases or decreases in pullout capacity are due to local layers of dense or loose soil through which the anchor is being pulled. It should also be noted that the discrepancies between the pullout capacity of a similar anchor in a similar density of soil were due to the inexactness of the control on density.

The pullout capacity shown in Figures 3 through 9 represents the effect of a short loading time on the anchor. A series of laboratory tests was conducted in a flooded sand and in a dry sand to determine the effect of length of loading time on the pullout capacity of an anchor. The permeability of the sand was about 0.1 feet per minute. The results of these tests are shown in Figure 10 and indicate that the effect of length of loading time should be considered in analyzing anchor pullout capacity in a flooded sand soil. In Figure 10, the anchor load includes only the weight of the anchor and the resistance load of the anchor due to the soil mass.

The change in pullout capacity is associated with the dissipation of negative pore pressure. For example, negative pore pressures commonly develop instantaneously in a soil mass subjected to shearing stresses whenever those stresses tend to cause a volumetric expansion of the soil mass. In a flooded sand this volumetric expansion is accompanied by the desire of the soil mass to draw water into the voids of the sand. The rate at which this occurs depends upon the permeability

FIGURE 10

PLOT OF ANCHOR LOAD VERSUS LENGTH OF LOADING TIME FOR 55 SQ. IN. FLAT PLATE ANCHOR BURIED AT 15 INCHES IN FLOODED SAND



of the sand and upon the geometry of the anchor. The temporary negative pore pressures have the effect of creating equal temporary additional effective stresses and thus create a temporary larger pullout capacity. In the dry sand tests, the pore pressures are always zero and therefore the pullout capacity is not time-dependent. Considering the small size of the anchor used in the test to obtain Figure 10 and the high permeability rate of the sand, the 48-hour loading period is deemed adequate to dissipate the negative pore pressure.

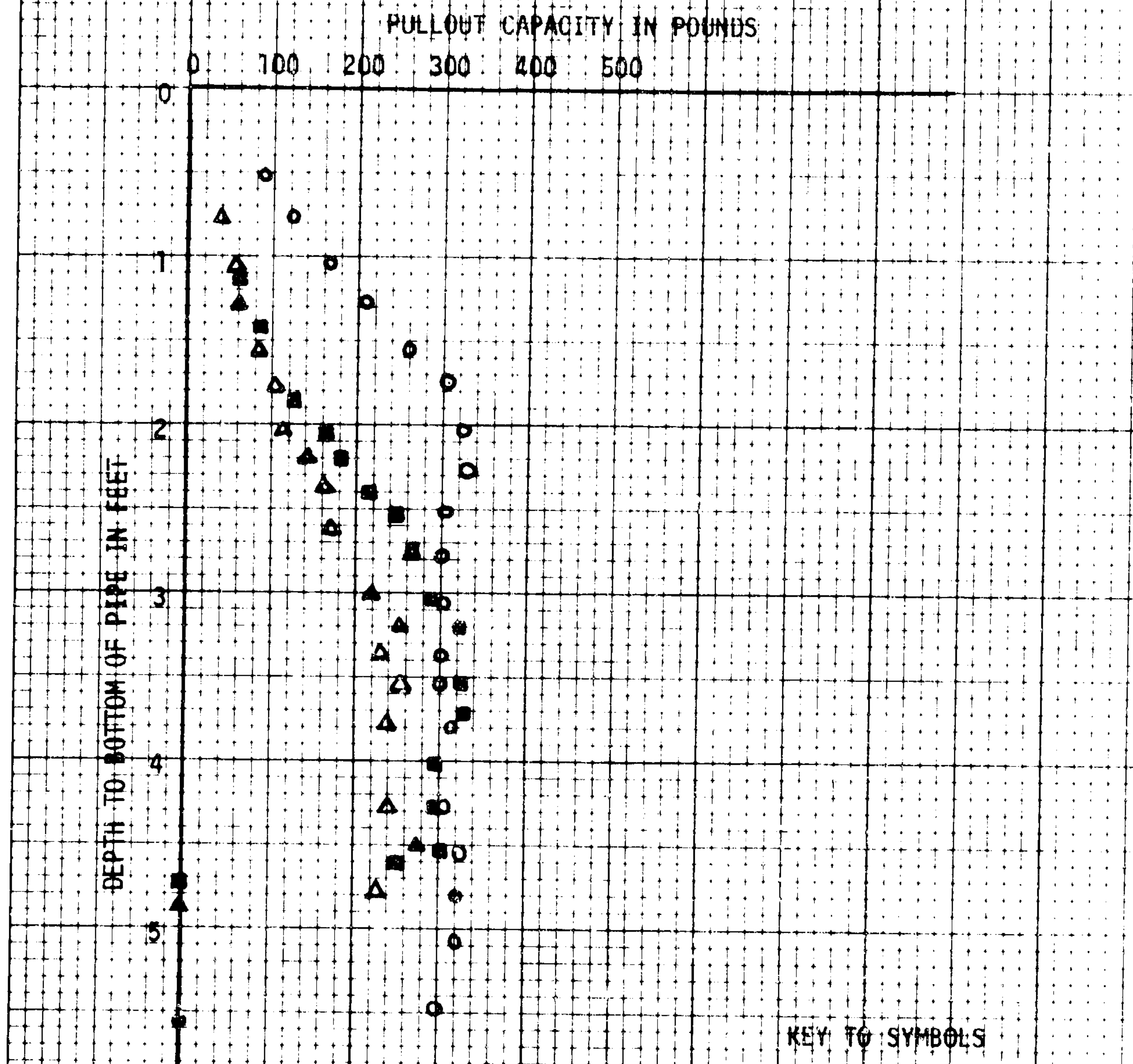
From Figures 3 through 9 it can be observed that the pullout capacities of an anchor at shallow depths of burial will follow the curves of deeper anchor tests. This is useful in predicting the failure load of a shallow anchor from deep anchor tests and this has been done in preparing Figures 12 through 15.

The load to pull the pipe alone versus depth to bottom of pipe is shown in Figure 11. The tip used to embed the pipe was slightly larger than the outside pipe diameter and offered 1.5 square inches of additional horizontal surface area. It is apparent that the pullout capacity is due to the frictional resistance of the pipe and the weight of the pipe and tip rather than due to any resistance from the soil mass on the small horizontal surface area. Figure 11 also indicates that a maximum pullout capacity for the pipe is essentially reached at a depth of embedment of 3 feet and that the pullout capacity is almost constant below this depth.

The increase in load gained by placing the anchor at the bottom of the pipe is evident in Figures 3 through 9. It does not appear correct to subtract the resistance load for the pipe alone from the pullout capacities of the anchors. The basis for this reasoning is that the

FIGURE 11

PLOT OF PULLOUT CAPACITY VERSUS DEPTH TO BOTTOM OF PIPE FOR DRIVE PIPE



failure of the soil mass above the fluke may significantly affect the pullout capacity of the pipe alone.

Figures 12 and 13 were plotted to show the effects of anchor size and shape on pullout capacity for a given density. These graphs were plotted using average values obtained from Figures 3 through 9. Figures 12 and 13 indicate a difference in the failure mechanism of the soil mass for anchors at shallow and deep depths of embedment. This can be observed by the location of the inflection point of the pullout capacity versus depth of embedment curves. The failure mechanism which develops for an anchor at a shallow depth of embedment involves the lifting up of the soil mass between the anchor and the ground surface and is akin to the failure mechanism described by Balla (1961).

The concept of different failure mechanisms for shallow and deep anchors is in agreement with Baker and Kondner (1965) who stated that modes of failure for shallow ($\lambda < 6$) and deep ($\lambda \geq 6$) anchors in dense unsaturated sand are distinct and require separate analysis. The term λ refers to the ratio of depth of embedment, D, to the diameter of the anchor, B. The dimensionless parameters of $F/BD^2\gamma$ and B^2/D^2 as described by Baker and Kondner where:

F = pullout capacity

D = depth to anchor

B = diameter of anchor

γ = density of soil

were plotted for the 55 and 110 square inch Y-shaped and flat plate anchors. The square root of the area of the anchor was used in lieu of the diameter of the anchor. From this plot it was found that the λ

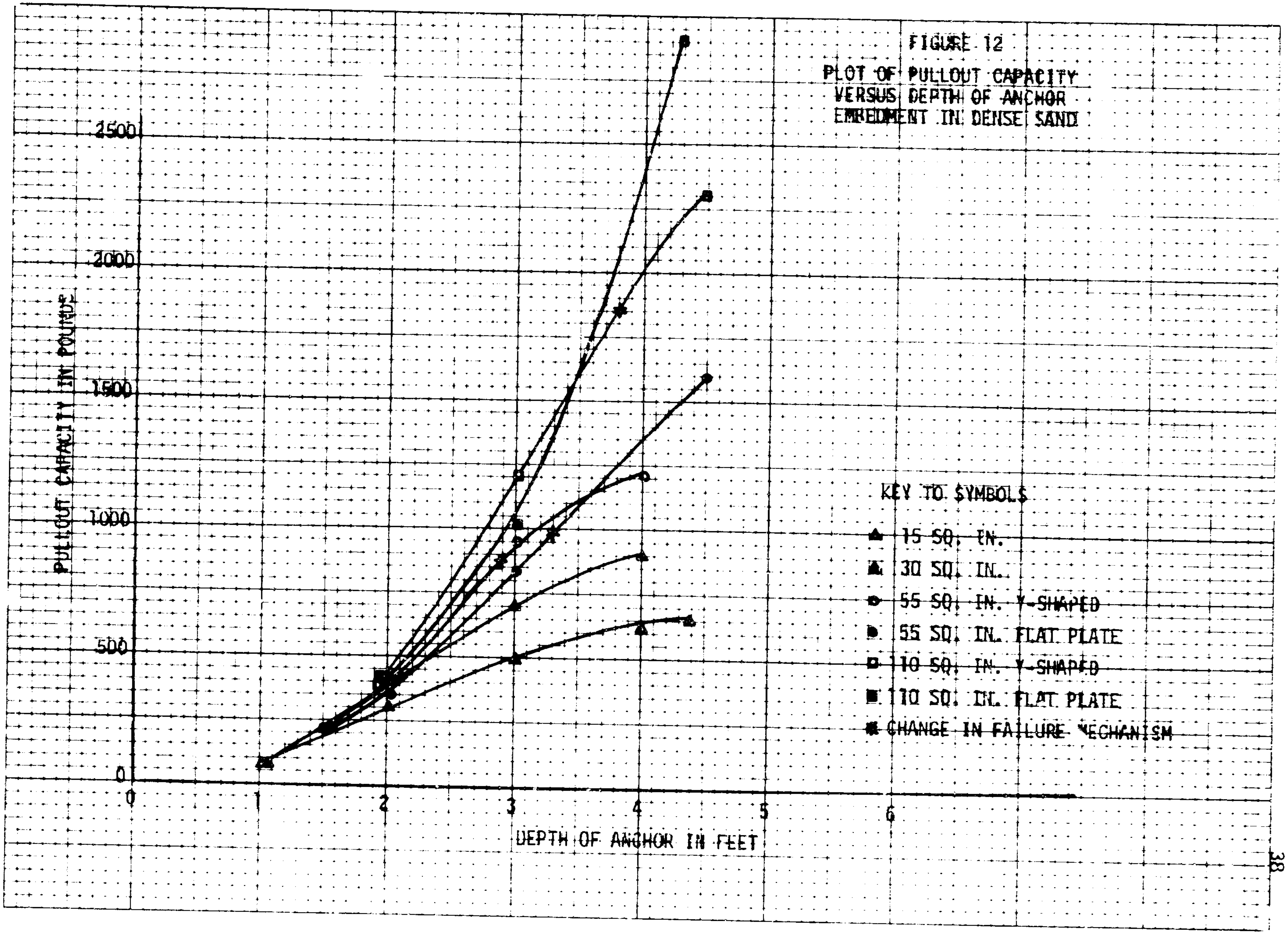
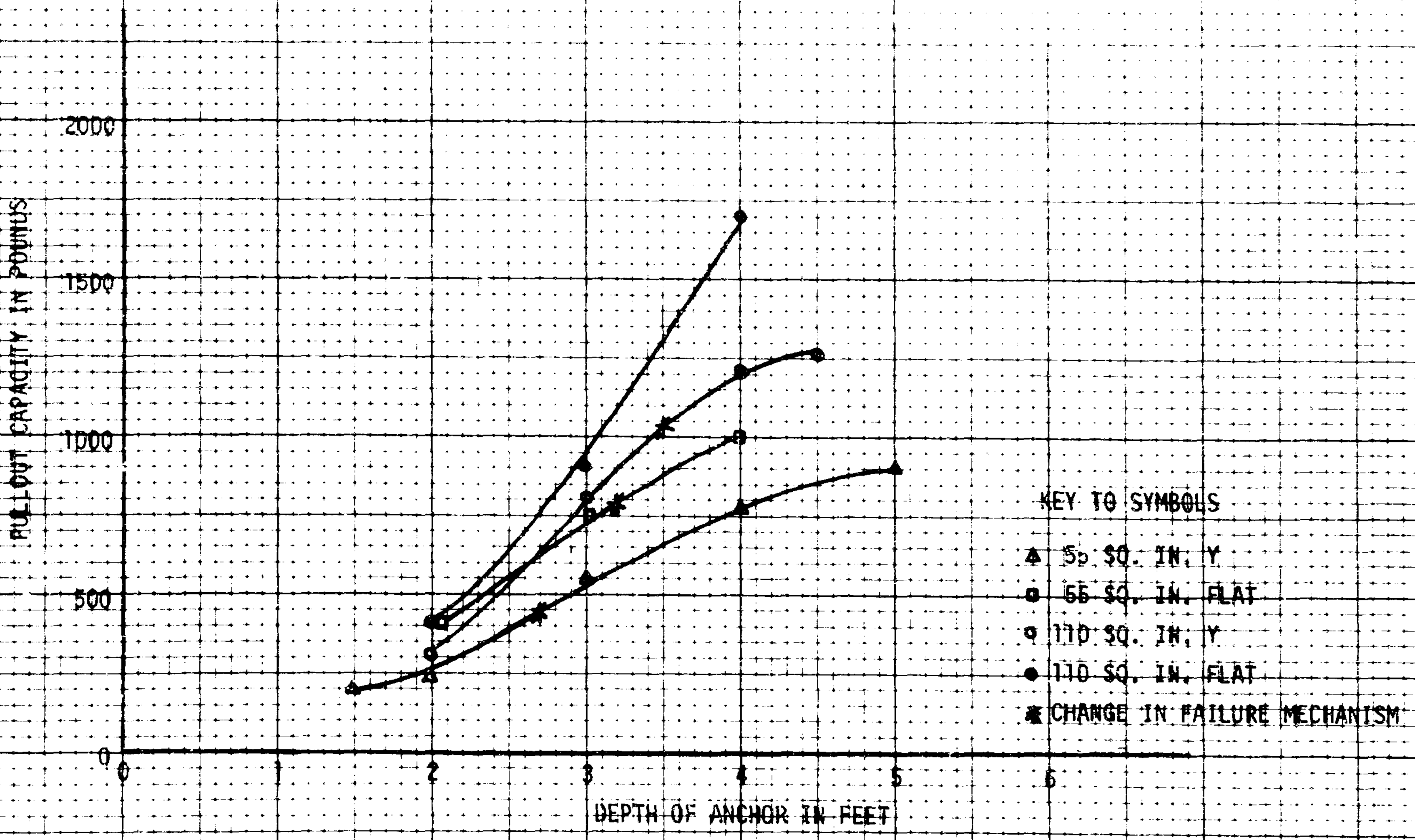


FIGURE 12

PLOT OF PULLOUT CAPACITY VERSUS DEPTH OF ANCHOR EMBEDMENT IN DENSE SAND

FIGURE 13

PLOT OF PULLOUT CAPACITY VS. DEPTH OF ANCHOR EMBEDMENT IN MEDIUM DENSE SAND



ratio for a change in the failure of the soil mass occurred in the range of λ = 4 to 6. The points where the change in failure mechanism occurred are labeled in Figures 12 and 13.

The crossing of the curves in Figures 12 and 13 of the Y-shaped anchor and the flat plate anchor are indicative of the effect of the shape of the anchor on pullout capacity. For these anchors it appears that it is more advantageous to use the Y-shaped anchor at shallow depths and flat plate anchor at deeper depths of embedment. The change in failure mechanism also occurs at a different depth of embedment even though the anchor area is approximately the same.

The effect of density on the pullout capacity of the anchor for the 55 square inch Y-shaped anchor is shown in Figure 14. The results are what would be expected, that is, a definite increase in pullout capacity as density of the soil is increased. The change in failure mechanism occurs at slightly greater depths of embedment for increasing soil density.

Figure 15 was constructed for design purposes and represents the pullout capacity of the anchors tested versus area of anchor for different λ values in the flooded sand soil. The reader is reminded that these curves are for short lengths of loading time and that the magnitude of the ordinate of this curve will be reduced for long lengths of loading time.

The concept of using vibration to embed the anchors worked very well. Some difficulties were encountered with regard to embedding the 30 square inch fixed and the 110 square inch Y-shaped and flat plate

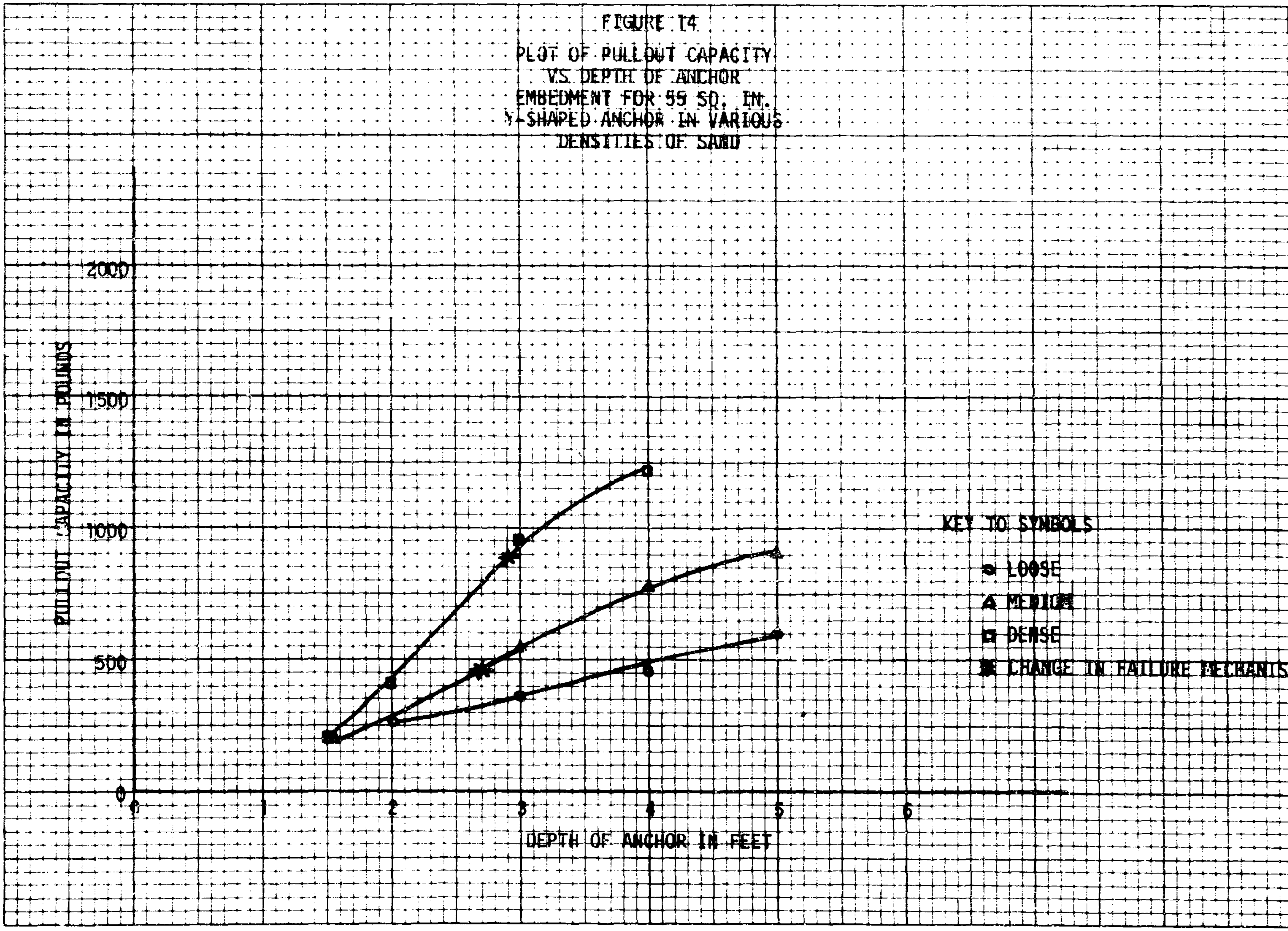
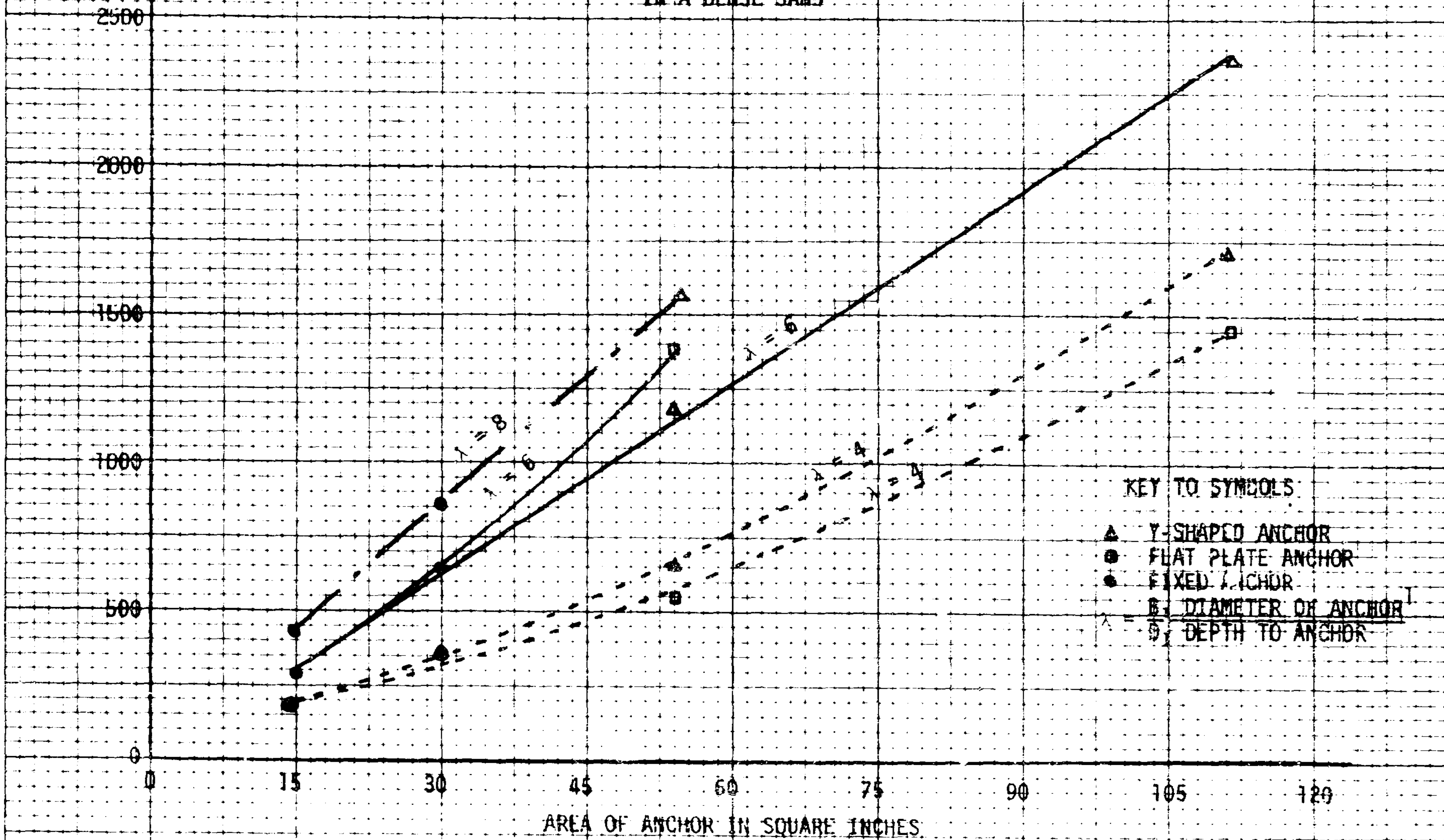


FIGURE 14
PLOT OF PULLOUT CAPACITY
VS DEPTH OF ANCHOR
EMBEDMENT FOR 55 SQ. IN.
Y-SHAPED ANCHOR IN VARIOUS
DENSITIES OF SAND
PULLOUT CAPACITY IN POUNDS
0
500
1000
1500
2000
DEPTH OF ANCHOR IN FEET
0
1
2
3
4
5
6
KEY TO SYMBOLS
LOOSE
MEDIUM
DENSE
CHANGE IN FAILURE MECHANISM

FIGURE 15

PLOT OF PULLOUT CAPACITY VERSUS AREA OF ANCHOR FOR VARIOUS VALUES OF λ IN A DENSE SAND



NOTE: The square root of the area of the anchor was used in lieu of the diameter of the anchor.

anchors in dense soil, however, it is felt that these difficulties could be overcome with the use of a larger vibrator unit. The use of vibration to embed anchors usually offers the advantage of densifying the nearby soil mass while the anchor is being embedded. The change in density from before and after the test may be observed by the reader from the data listed on Figures 3 through 9.

VI. CLOSURE

A. Conclusions

The vertical holding capacity of marine anchors embedded in sand by vibration has been investigated by means of field and laboratory tests. The conclusions based on data presented in this investigation are:

1. The curve of pullout capacity of an anchor embedded at a shallow depth of burial will follow the curve of a deeper anchor test. This relationship is useful for predicting the failure load of a shallow anchor from a deep anchor test if the shape of the pullout capacity versus depth curve is known.
2. There appear to be two separate mechanisms of failure within the soil mass for anchors embedded in flooded sand and subjected to short length of loading time. The particular mechanism which develops is a function of the depth of embedment, size and shape of the anchor, and the density of the flooded sand.
3. The effects of size and shape of anchor, depth of burial and density of sand are presented in Figures 12 through 15.
4. The use of vibration as a source of energy to embed anchors in a flooded sand soil appears to be very feasible. The vibration energy usually has the added effect of densifying the nearby soil mass.
5. The effects of length of loading time on the pullout capacity of the anchor should be considered for anchors embedded in a flooded sand even when the permeability of the soil is as high as 0.1 feet per minute.

B. Recommendations

It is recommended that the following items be given consideration for future work in the field of anchor investigations:

1. The present 55 and 110 square inch Y-shaped and flat shaped anchors should be tested at depths of embedment to a minimum of 8 feet in the flooded sand soil to obtain additional data at higher λ values. The anchor sizes should also be extended to include tests of 220 square inch anchors.
2. The effects of length of loading time should be investigated in the field tests of anchors embedded in the flooded sand soil.
3. The anchors as presently designed should be instrumented with strain gage load cells at the anchor itself and at the top of the drive pipe in order to separate the total resistance load developed by the friction on the pipe from that developed by the lower wider structural element.
4. The failure mechanisms in the soil mass should be more clearly identified as specific functions of anchor size, shape, depth of embedment and density of soil.
5. The vibration energy should be monitored more closely to ascertain the optimum frequency and amplitude of vibration to use in embedding the anchors and to ascertain the amount of energy expended during embedment of the anchors.
6. The present anchors should be tested for use as a foundation component by loading them with vertical downward loads, lateral loads and upward inclined loads.

7. The present anchors should be tested in a predominantly clay soil and in a predominantly silt soil.
8. Other designs of anchors should be investigated in order to optimize the pullout capacity of embedment anchors.

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13. ABSTRACT

This investigation considers the vertical pullout capacity of marine anchors embedded in sand by vibration. Small size anchors having projected horizontal areas of about 15, 30, 55, and 110 square inches were inserted to various depths ranging between 2 feet and 6 feet in a flooded sand soil and load tested for vertical holding capacities. The anchors were tested in a large scale outdoor test bin. For insertion, the anchors were attached to the lower end of a rigid pipe and vibrated into place by means of a vibrator unit attached to the upper end.

Test data indicates that for small size anchors having a short length of loading time, there appear to be two mechanisms of failure within the soil mass in which the anchor is embedded. The mechanism which develops is a function of depth of embedment, size and shape of the anchor, and sand density; and it controls the shape of the curve of pullout load versus anchor depth. The length of the loading time affects the pullout capacity even though the permeability of the flooded sand is 0.1 feet per minute.

The data presented is applicable for the design of anchorages for ocean installations.

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14 KEY WORDS	LINK A		LINK B		LINK C	
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Embedment						
Holding Power						
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