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Vertical Loads on Drag Embedment Anchors

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ABSTRACT

As industry moves into deeper water and economical solutions for mooring systems are sought, anchor systems capable of withstanding vertical loads are needed. Current industry standards and API recommendations constrain a mooring line to be tangent to the seabed when a drag embedment anchor is used.

This paper shows that current High Holding Power (HHP) anchors such as the Bruce FFTS and Vryhof Stevpris can withstand significant vertical loads. By introducing a mooring line angle at the seabed, the vertical load at the anchor only increases slightly. The technical feasibility and economic benefits of this concept are described. New types of drag embedment anchors specifically designed to withstand vertical loads are also discussed.

DRAG ANCHOR TYPES

Drag anchors can be grouped in many different categories. For simplicity, they are grouped in this paper into three categories: "old" style "low" efficiency anchors (e.g., LWT, Danforth, Stockless, Bruce Cast), High Holding Power (HHP) anchors (e.g., Bruce FFTS, Vryhof Stevpris), and new generation Vertically Loaded Drag Embedment Anchors (VLA) (e.g., Bruce DENLA, Vryhof Stevmanta), see Figures 1 and 2.

The discussion is limited to deeply embedded HHP and VLA anchors in soft cohesive soils. Many of the ideas presented are applicable to anchors in harder soils. It is shown that HHP anchors can resist loading of around 30-40 times their weight, including substantial vertical loads. It is also shown that VLA anchors, after they have been "tripped" or "keyed", can perhaps resist 100-200 times their weight at any angle.

CURRENT DESIGN PRACTICES

Current mooring design practices for drag anchors require the mooring line always to have tangential contact with the seabed. Reference 1 states "If drag anchors are used, the outboard mooring line length should be sufficient to allow the lines to come tangent to the ocean bottom at the anchor when the system reaches the maximum anticipated offset under the damaged condition". Reference 2 includes a very similar statement.

The U.S. Navy's mooring design manual, Reference 3, states "Drag-embedment anchors are designed to resist horizontal loading. A near-zero angle between the anchor shank and the seafloor (shank angle) is required to assure horizontal loading at the anchor.... As the shank angle increases from zero, the vertical load on the anchor increases and the holding power of the anchor decreases". However, one design office in the Department of the Navy typically uses a seabed line angle of 3° as a maximum with no anchor performance reduction.

References, tables, and figures at end of paper.

A recent departure from the traditional no uplift at the seabed approach has been ABS approval of a Floating Production System mooring designed to have a seabed line angle of 3.5° in the damaged condition (one-line damaged - 100 year hurricane). ABS stated, however, they would not allow a seabed line angle in the intact condition (no damaged lines - 100 year hurricane).

DRAG ANCHOR DESIGN TOOLS

There are four main methods for designing or sizing drag embedment anchors: NCEL holding power curves (Reference 4), manufacturer's analysis, the anchor prediction program *STA ANCHOR*, and full scale or reduced scale testing.

The NCEL curves for anchor performance in soft soils are based on tests of small anchors in one soil condition with a chain forerunner. The tests were performed on anchors weighing approximately 0.5 to 6 kips in a soft cohesive soil with shear strength increasing at a rate of 10 psf/ft with no seabed line angle. The NCEL curves over predict HHP anchor capacities in weaker soils and under predict capacity in stronger soils, where a chain forerunner is used. In cases where a wire forerunner is used, the NCEL curves significantly under predict HHP anchor system capacities in soft soils.

Manufacturer's analyses are largely based on past anchor performance. Most of the data collected by the manufacturers does not include information on the ultimate capacity of the anchors because in very few situations have anchors been pulled to failure while loads were being measured. The manufacturers do use the data from the Gulf of Mexico Large Scale Anchor Tests JIP conducted in 1990, Reference 5 . The manufacturers also take into account soil shear strength and whether the anchor system uses a chain or wire forerunner.

STA ANCHOR is an anchor performance prediction program developed and calibrated from the data collected in Reference 5. This program uses theoretical soil resistance calculations along with calibration coefficients to determine anchor performance parameters. The theoretical basis of this program is described in Reference 6. Currently, the program is calibrated for use with the Bruce FFTS and Vryhof Stevpris anchors in a soft cohesive soil.

Full scale anchor testing at the final mooring site is the most accurate way to size anchors; however, the cost for performing these tests is very high. Reduced scale tests at the mooring site would be nearly as good, if carefully conducted (and interpreted) and the soil parameters are well known. Again, these tests can be very expensive.

ANCHOR FORERUNNERS-CHAIN VS. WIRE

The reason current HHP and new generation VLA anchors achieve high efficiencies is they bury very deep in soft soils, reaching relatively high shear strength soil. Deep penetration, combined with high soil shear strength, results in high anchor capacity. The depth of anchor penetration is strongly influenced by the type and size of the anchor forerunner.

The anchor forerunner geometry in the soil is in the form of an inverted catenary. The smaller the size of the forerunner the less soil resistance there is on the forerunner. The less resistance there is on the forerunner, the deeper the anchor will bury.

A well designed anchor will continue to bury deeper in a soft cohesive soil while an increasing horizontal load is applied at the anchor shackle. Burial rate slows as the vertical component of force (from the forerunner/soil interaction) at the shackle increases. Eventually, an equilibrium burial depth is reached. The anchor will then drag horizontally without further capacity increase.

For example, assume a 4 inch diameter spiral strand forerunner is needed with a break strength of 1960 kips. If chain were used, 3⅞ inch diameter ORQ +20% would be approximately equivalent. The bearing area of the forerunner is calculated as if the forerunner were a cylinder. The wire would have an equivalent diameter of 4 inches, and the chain would have an equivalent diameter of 2.6 times the bar stock, or just over 10 inches.

An analysis was performed with *STA ANCHOR* to show this effect. A 25 tonne anchor was analyzed at its ultimate capacity with both wire and chain forerunners with no vertical uplift at the seabed. Table 1 summarizes the results of the analysis. As can be seen, although the chain forerunner resistance has a greater percentage of the total anchor system capacity than the wire forerunner, the wire forerunner anchor system holds much more load because the anchor buries deeper.

IMPACT OF SEABED LINE ANGLE ON HHP ANCHORS

The basis for requiring no mooring line angle at the seabed, as currently stipulated in widely used codes and practices, stems from times when embedment depths were shallow. This was common for normal drilling rig anchors such as the Moorfast, Danforth and LWT, which had low fluke areas that did not embed very deeply on proof tensioning (typically

300 to 500 kips at the fairlead). The current high efficiency HHP anchors typically used for floating platforms have fluke areas considerably greater than conventional drilling rig anchors of the same weight. The combination of a very large fluke area and high proof tensioning on the order of 1,000 kips (at the fairlead) results in the anchor being deeply embedded in the soft cohesive soils that exist in most deep water sites. Analysis, scale and field tests have shown that when the anchor is proof tensioned the anchor forerunner will take on an inverse catenary, as shown in Figure 3. The embedded anchor in its equilibrium position is rotated so the fluke is nearly horizontal. This implies that even if the mooring line is completely tangent to the seabed when fully loaded, the anchor would experience and resist significant horizontal and vertical loads. There is a negligible loss of holding capacity as the line is allowed to attain small angles at the seabed, mainly as a result of the reduced length of embedded wire.

In a conventional mooring analysis the anchor point is assumed to be at the mud line; therefore, an angle of the line at the seabed anchor point implies an angle or vertical load on the anchor. In a more rational analysis, one would first determine the touchdown point of the line, then add an additional distance to the anchor point, accounting for the inverse catenary and anchor embedment depth. An angle at the line touchdown point does not imply a corresponding angle on the anchor. The small loss in holding capacity due to reduced embedded line length is compensated for by increasing anchor size.

Field tests and experience have shown current HHP anchors can withstand large vertical loads in soft cohesive soils. Drilling rigs using this anchor type often experience difficulty recovering their anchors. During field tests (Reference 5) it was found that HHP anchors withstood a vertical pull out load on the same order as the horizontal ultimate capacity. One anchor manufacturer warns that the vertical pull out load may be equal to the drag embedment (horizontal) load (Reference 7).

Centrifuge tests conducted by Exxon (Reference 8) showed a mooring line angle did not reduce the peak capacity of deeply embedded anchors in cohesive soils. The peak capacity in these tests was defined as the applied line tension at the seabed. The tension remained constant as the line angle increased to a maximum of 30° during the final stages of the tests.

SAMPLE ANALYSIS-HHP ANCHORS

Two analyses using *STA ANCHOR* to analyze the anchor system are presented here. The first shows the difference in anchor performance parameters of a 25 tonne HHP anchor with seabed line angles of 0° to 20° in 5° increments. The second analysis is for a "typical" FPS mooring system in 3,000 ft of water with 0°, 5° and 10° seabed line angle. In each case the anchor embedment trajectory was computed and maximum capacity determined by applying and increasing line tension to the anchor system while keeping the seabed line angle constant.

Table 2 and Figures 4 and 5 show anchor performance parameters for the 25 tonne HHP anchor with various seabed line angles. Figure 6 shows the inverse catenary formed by the wire forerunner for 0°, 10° and 20° uplift. As can be seen, the total system capacity, horizontal and vertical applied anchors loads decrease only slightly as the angle at the seabed is increased. Also, the angle the wire makes with the anchor changes very little. The most dramatic effect of allowing a seabed line angle is the amount of wire buried in the soil. This analysis not only shows that anchor performance is not radically reduced by allowing a seabed line angle, but shows that an anchor is resisting a substantial vertical load when there is no seabed line angle. For example, for the case with no seabed line angle, the horizontal applied load at the anchor is 1360 kips and the vertical applied load is 916 kips.

Three different mooring lines were designed to demonstrate the impact of allowing a mooring line angle at the seabed using current HHP anchors. The analysis assumes the design maximum horizontal load is 1,000 kips at the fairlead. The mooring system is a 12 point system. Catenaries were designed with 0°, 5° and 10° mooring line angle at the seabed. The systems are for a "typical" Floating Production System mooring system in 3,000 ft of water. One mooring line is shown in Figure 3 and consists of a platform section of chain, a submersible buoy, a catenary section of spiral strand, a dip zone section of chain, and ground wire and anchor forerunner wire of spiral strand.

Table 3 presents the summary results of the analysis. Again, the main impact of allowing a mooring line angle at the seabed is an increase in the horizontal load at the anchor due to the decrease in load resisted by the anchor forerunner. From the table it can be seen by allowing a 10° seabed line angle instead of no angle, 14,640 ft of chain and 5,880 ft of wire are saved for the mooring system. The anchor size only increases by 1.25 tonnes.

A component cost estimate was prepared for each system. Only the differing components of the mooring system (dip zone chain, ground wire, and anchor) were costed. Table 4 and Figure 7 shows a per leg cost breakdown. For a 12 leg system it can be seen, the cost savings is approximately $3.2 million.

VERTICALLY LOADED ANCHORS

Vertically Loaded Anchors (VLAs) are drag embedment anchors specifically designed to withstand very high vertical loads. The VLAs have a very high holding capacity to anchor weight ratio (efficiency). Since the anchors are currently being developed, no independent tests of the anchors have been conducted other than very small scale tests in synthetic clay, although testing is planned (Reference 9). Manufacturer's tests and claims along with analytical calculations show the anchors have an efficiency in soft cohesive soils of at least 100, and perhaps as high as 200.

VLAs are embedded in the seabed in a manner similar to conventional drag embedment anchors with a horizontal pull. After embedment, the line pull direction is changed to vertical or any intermediate angle. Prior to this, the anchors are "tripped" by some method, allowing the shank to rotate relative to the fluke from a embedment shank-fluke angle of approximately 50° to 90°. (This method varies by anchor type and some additional methods are being developed.) The following two paragraphs briefly describe the two major concepts being developed. It should be noted that both anchors are in continuing development and the descriptions provided are as they are currently configured.

The DENLA anchor has an extremely slender shank similar in concept to that of many conventional drag embedment anchors. It has a removable lever and wedge device that is detached after embedment to allow the shank to rotate to become perpendicular to the fluke. The lever is removed by heaving in on a pendant line that shears a pin connecting the lever to the shank. The lever and pendant can be recovered or the lever can be attached to the rear of the anchor and pendant line dropped or buoyed off. This pendant may then be used in recovering the anchor if necessary. The DENLA may then be loaded at any angle, and it will "key" or rotate to be perpendicular to the applied load. The fact that the DENLA's embedment wire is also used for final loading, and it can be recovered with a load about 25% of its vertical capacity, are major advantages.

The Stevmanta employs a wire rope bridle arrangement attached to the fluke instead of a shank. After the Stevmanta is embedded, the embedment wire is either released and recovered or abandoned. Anchor loading is accomplished by using another wire rope. Other alternatives are being developed to make use of the same embedment and loading wire. The Stevmanta may also be loaded from any angle.

VLAs are ideal anchors for taut leg moorings (TLM) for small moorings (e.g., supply boat back-down systems) to large mooring systems (e.g., large floating production systems). The economic benefits of TLMs for deep water platforms have been pointed out by many papers and studies, including Reference 10. The benefit for supply boat mooring systems is that the mooring component lengths can be reduced to a point where they approximately equal the water depth. Also, the anchor weight for such a mooring would only be 1 to 2 tonnes.

VLAs also have a major benefit in that they do not need to be embedded in the same direction in which they are to be loaded. Conventional drag embedment anchors have to be loaded in the same (or very close to the same) direction from which they are embedded. The idea of installing a VLA from any direction could be a major benefit if the mooring site is cluttered with other mooring systems, pipelines, or well templates.

The ultimate holding capacity of a VLA is fairly simple to calculate if the depth of penetration and soil parameters are known, using conventional plate anchor calculations. To date, the embedment characteristics of VLAs are not well understood. Once these characteristics (embedment depth, embedment load, and drag distance) are better known, using VLAs will be more practical.

DESIGN, FACTOR OF SAFETY AND PROOF LOADING CONSIDERATIONS

A factor of safety of 1.5 (relative to the maximum intact, or non-damaged, design mooring load at the seafloor) is recommended for all drag embedment anchors. The anchor should be sized, together with the forerunner, to achieve this factor of safety, whether or not uplift at the seabed is anticipated. If the soil shear strength is weaker than that for which the NCEL curves were developed, and if a chain forerunner is used, the anchor size should be larger than shown on the NCEL curves, with the mooring line having a tangential touchdown to the seabed.

If a wire forerunner is used, and the touchdown line angle is horizontal, the minimum safe anchor size is likely to be smaller than that found in the NCEL curves in soft soils, regardless of whether the soil is weaker or stronger than the NCEL test soil, provided a rational analysis (or model testing or previous experience) is used.

It should be shown (analysis, experience and/or model tests) that the anchor can resist the design load (intact or non-damaged mooring line tension at the seabed) x 1.5 when the line load is applied at the design angle at the seabed. If the design angle is large, even with a wire forerunner, the anchor may be larger than predicted by the NCEL curves. This is unlikely, however, for design angles at the seabed less than 10°.

Conventional installation procedures for drag embedment anchors involve applying 100% of the maximum design load (intact load) to the mooring line and holding this tension for a reasonable amount of time. The anchor embeds, a section of line lies along the seabed and a factor of safety of 1.5 is anticipated to have been achieved.

A similar anchor embedment procedure is proposed for drag embedment anchors intended to resist a small amount of uplift at the seabed. Instead of the proof loading being applied horizontally, the line angle at the seabed should reach the design maximum uplift angle. The 100% design load should be held at this angle for a reasonable amount of time, if practical. The actual anchor embedment can be performed either with the line tangential to the seabed or with the design line angle (or somewhere between).

For certain mooring systems, it may be difficult to proof load a system in the manner suggested above. An alternative method for anchor proof loading systems with small angles could be to proof load the anchor with a horizontal load (perhaps more than the design load) and show either from testing or analytical methods that the anchor can resist the design load and angle without additional dragging. For large angles, it may be necessary to proof load at the design angle, until there is more experience with large seabed angles.

For the case of an anchor with no uplift, if the line load exceeds the proof load (in service during storm conditions), it is generally agreed that a correctly sized anchor will dive deeper and hold more load up to the factor of safety of 1.5. The same should hold true for an anchor system designed to take uplift at the seabed. If the design load is exceeded, the anchor should dive deeper and hold more load, up to the 1.5 factor of safety.

Experience with field and model tests (References 5 and 8) and analytical approaches, confirm this is indeed the case with a rationally designed anchor system. Industry is encouraged to gain confidence in the ability of anchors to accept uplift at the seabed and for rational design to include this condition.

CONCLUSIONS

1. An anchor system designed with a wire forerunner has a considerable increase in holding capacity compared to a system designed with a chain forerunner, due to the increase in embedment depth.

2. Conventional HHP anchors resist a large amount of vertical load when adequately embedded in soft soils due to the inverted catenary of the anchor forerunner, even when the line pull at the seabed is horizontal.

3. Small uplift angles (0° to 10°) at the seabed result in very small changes in the forces applied (via the anchor forerunner) to HHP anchors.

4. Large uplift angles at the seabed can be tolerated by HHP anchors when properly designed. A small increase in anchor size over that required for similar line loads with no uplift results.

5. Use of NCEL curves for anchor design is only rational if the design has conditions similar to the NCEL tests.

6. When uplift angles at the seabed are included in the HHP anchor design, proof loading should be at the design angle.

7. Significant deep water mooring system cost savings, as a result of the reduction of wire and chain lengths required, can be achieved by designing HHP anchor systems with an uplift angle at the seabed.

8. VLAs potentially offer a cost effective and technically beneficial means to resist high loads at any angle. Their main benefit is their very high efficiency compared to HHP anchors and their ability to resist vertical loads as efficiently as horizontal loads. Their embedment characteristics are currently unpredictable, however, this science is evolving rapidly.

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TABLE 1
Chain vs. Wire Comparison

Case	Wire	Chain
Anchor Size (tonnes)	25	25
Anchor System Capacity (kips)	1875	1050
Hor. Applied Anchor Load (kips)	1359.8	680.7
Vert. Applied Anchor Load (kips)	916.2	508.7
Hor. Anchor Capacity (kips)	1359.8	685.6
Vert. Anchor Capacity (kips)	1019	515.1
Forerunner Hor. Capacity (kips)	515.2	369.3
Anchor Embedment (ft)	118.5	55.5
Forerunner Length (ft)	953	448
Total % Held by Anchor	87.4%	80.9%
Hor. % Held by Anchor	72.5%	64.8%
Total % Held by Forerunner	12.6%	19.1%
Hor. % Held by Forerunner	27.5%	35.2%

TABLE 2
25 tonne Anchor Performance Comparison vs. Uplift Angle

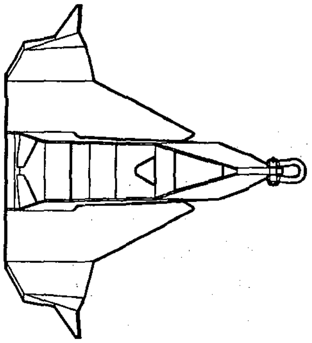
Seafloor Angle (deg)	0	5	10	15	20
Anchor System Capacity (kips)	1875	1860	1820	1745	1585
Hor. Applied Anchor Load (kips)	1359.8	1377.5	1354.7	1301.8	1188.3
Vert. Applied Anchor Load (kips)	916.2	935.2	952.4	951.4	896.4
Hor. Anchor Capacity (kips)	1359.8	1380.2	1357.9	1301.9	1189.3
Vert. Anchor Capacity (kips)	1019	1033.5	1017.5	978	898.1
Forerunner Hor. Capacity (kips)	515.2	475.4	437.7	383.7	301.1
Anchor Embedment (ft)	118.5	118.4	118.3	112.9	101.3
Forerunner Length (ft)	952.7	500.1	376.1	295.7	228.2

TABLE 3
Summary of 3,000 ft FPS Mooring Analysis

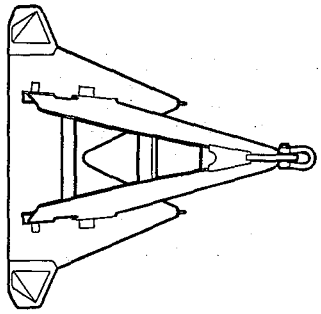
Seafloor Angle (deg)	0	5	10
Anchor Size (tonnes)	19.75	20.25	21
Hor. Applied Anchor Load (kips)	1068.3	1101	1123.3
Vert. Applied Anchor Load (kips)	744.5	771.1	808.1
Hor. Anchor Capacity (kips)	1071.3	1106.7	1127.6
Vert. Anchor Capacity (kips)	802.9	829.1	845.6
Forerunner Hor. Capacity (kips)	426.7	339.3	377.5
Anchor Embedment (ft)	108.7	110.6	109.9
Forerunner Length (ft)	835	450	345
Dip Zone Chain Length (ft)	3400	2750	2180

TABLE 4
Component Cost Summary

Seafloor Angle (deg)	Chain Cost Per Leg (x 1,000)	Wire Cost Per Leg (x 1,000)	Anchor Cost Per Leg (x 1,000)	Total Anchor + Wire Cost Per Leg (x 1,000)	Savings for 12 Leg System (x 1,000)
0	671.8	$50.1	$76.2	$798.2	NA
5	543.4	$27.0	$78.1	$648.5	$1,795
10	430.8	$20.7	$81.0	$532.5	$3,188



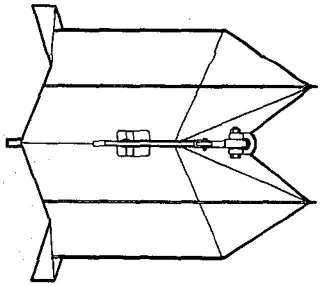
PLAN VIEW OF BRUCE FFTS ANCHOR



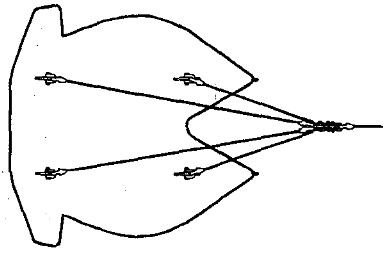
PLAN VIEW OF STEVPRIS ANCHOR

HHP ANCHORS

FIGURE 1



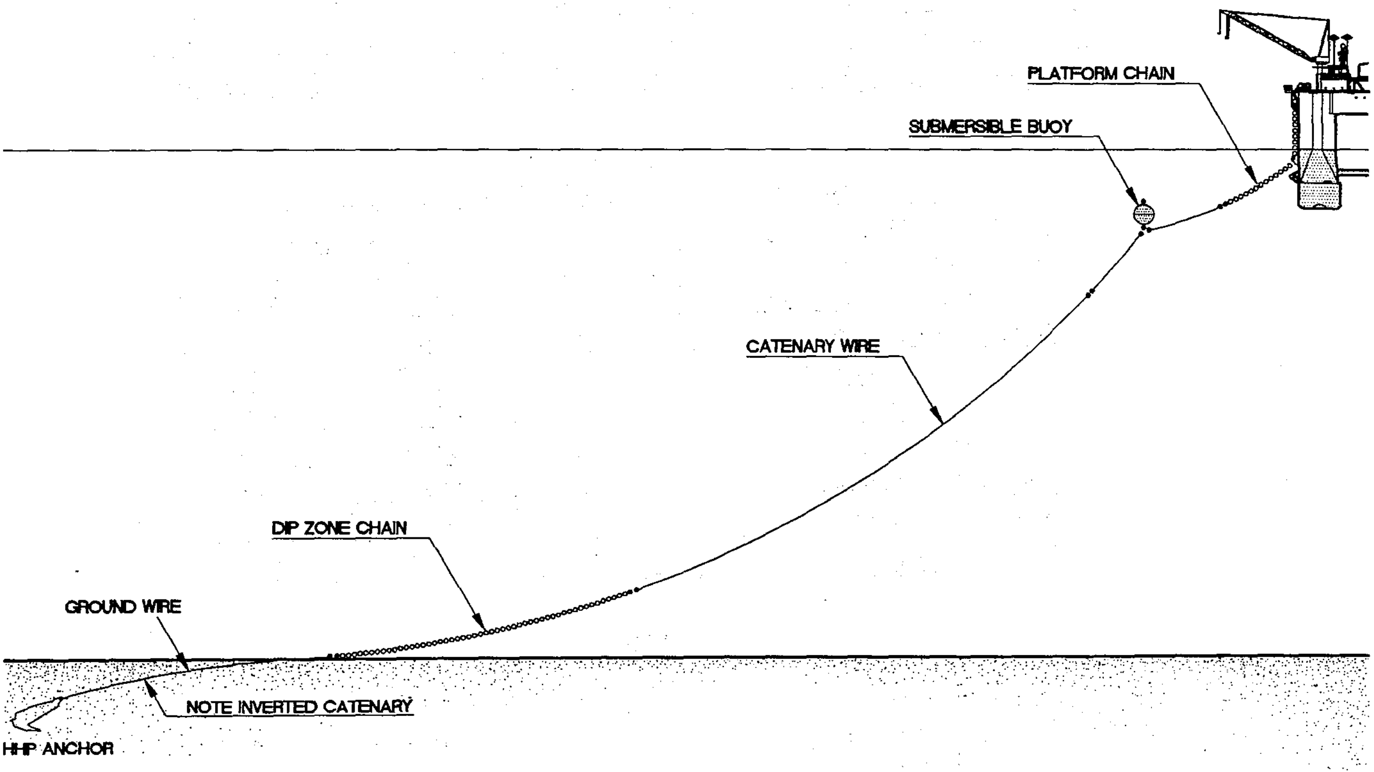
PLAN VIEW OF DENLA ANCHOR



PLAN VIEW OF STEVMANTA ANCHOR

VLA ANCHORS

FIGURE 2



TYPICAL FPS MOORING LEG

FIGURE 3

FIGURE 4
Anchor Parameters vs. Line Angle (1)

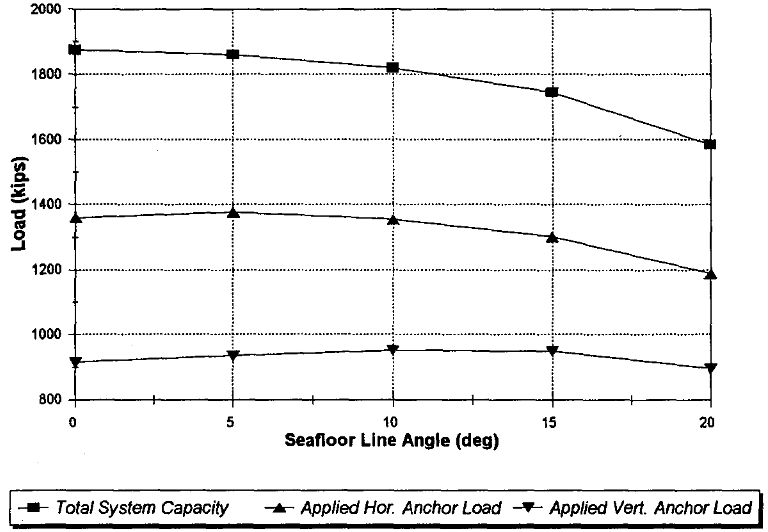


FIGURE 5
Anchor Parameters vs. Line Angle (2)

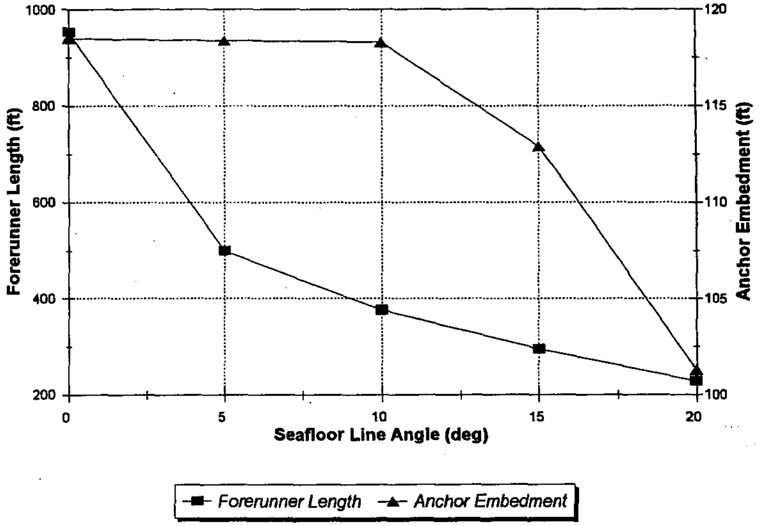


FIGURE 6
Embedded Wire Catenary Comparison

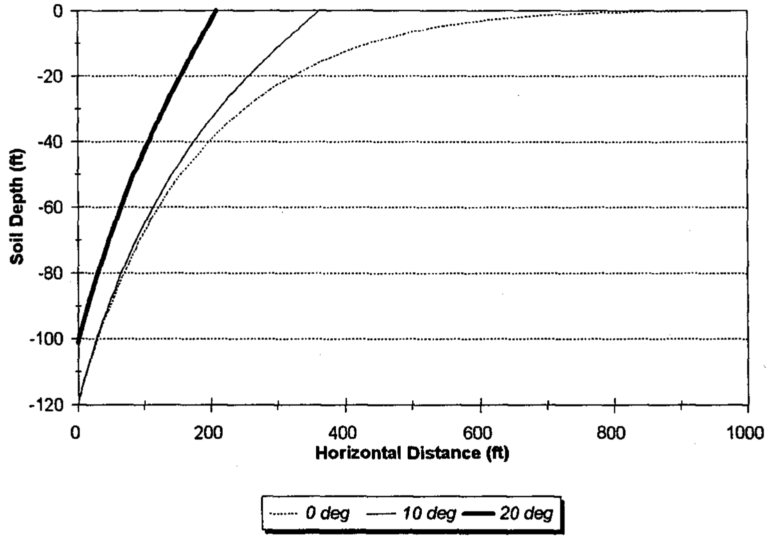


FIGURE 7
Cost vs. Line Angle (Per Leg)