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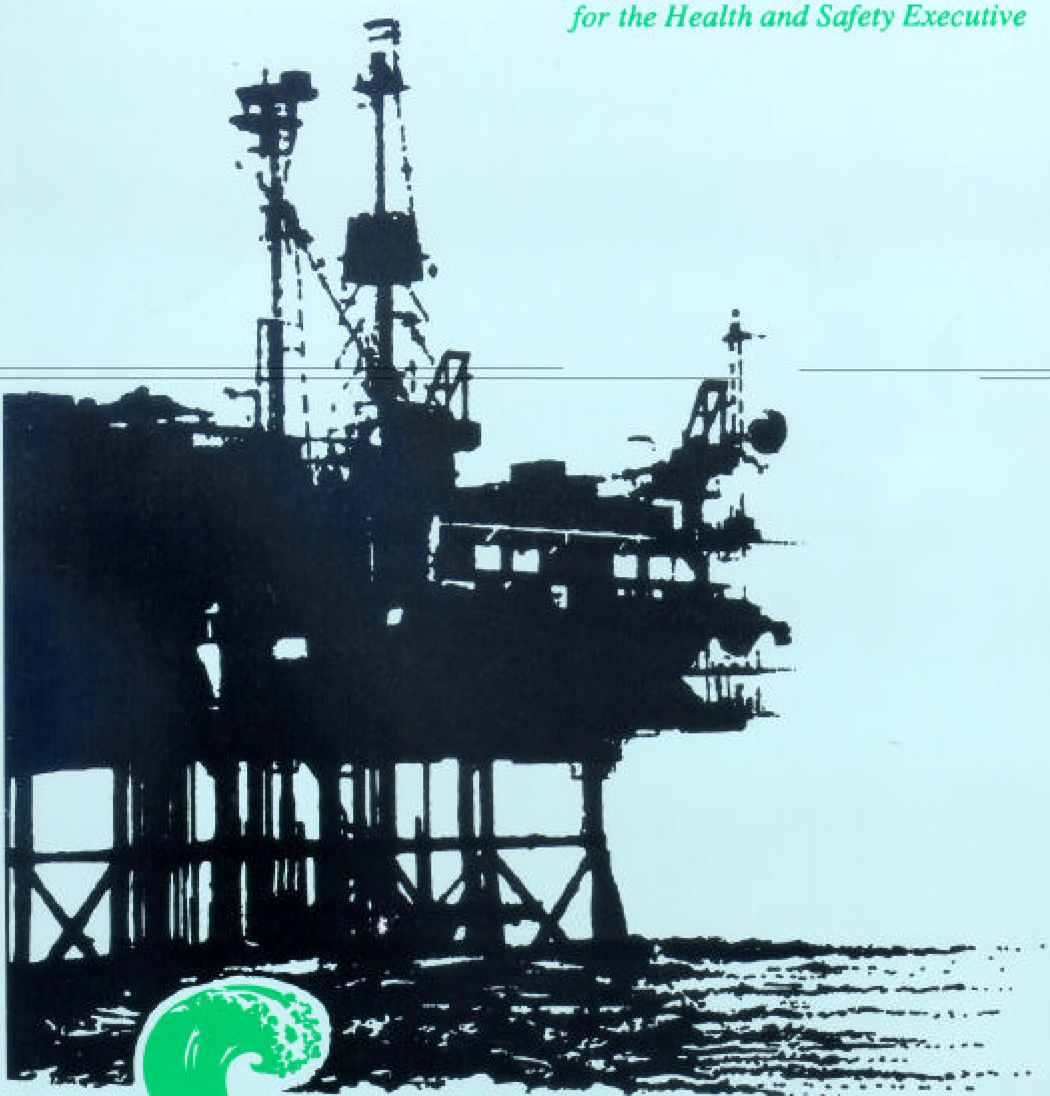
DRAG ANCHORS FOR FLOATING SYSTEMS

Prepared by MSL Engineering Limited
for the Health and Safety Executive



Offshore Technology Report

Health and Safety Executive

OTH 93 395

DRAG ANCHORS FOR FLOATING SYSTEMS

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HSE BOOKS

Health and Safety Executive - Offshore Technology Report

First published 1993
ISBN 0 7176 0642 2

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Results, including detailed evaluation and, where relevant, recommendations stemming from their research projects are published in the OTH series of reports.

Background information and data arising from these research projects are published in the OTI series of reports.

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SUMMARY

This document presents the findings of a study of **Drag Anchors for Floating Systems**. The objective of this study was to review the current use of drag anchors offshore. The study established current practice with respect to drag anchor usage, including anchor selection, deployment and recovery methods, survey and inspection, handling difficulties, and anchor failures. Information was gathered on anchor shapes, dimensions, fabrication methods, reliability and holding power.

Information for the study was obtained by two primary methods. The first method was a substantial literature survey, which encompassed technical journals, conference proceedings, design codes and guidelines, and manufacturer's data. The second method of gathering data was to circulate questionnaires to organisations in the offshore industry with significant experience of specifying and using drag anchors, and then to follow up these questionnaires by interviews. A considerable quantity of data was gathered by these two means. This data is presented in detail in the report.

A number of important safety and reliability related conclusions are drawn from the information collected and collated in the report.

The authors wish to extend their thanks to all those individuals and organisations who contributed to the information survey. The authors also wish to express their gratitude for the granting of permissions to reproduce copyright material in this report.

GLOSSARY

Anchor rack:	Anchor storage arrangements on board a vessel.
Fluke:	Component of the anchor which, by virtue of its projected surface area, generates most of the holding capacity of the anchor.
Hawsepipe:	Pipes in bows of ships through which the anchor chains run.
HHP anchor:	High Holding Power anchor.
Holding efficiency:	Holding power/anchor mass (or weight).
Pendant wire:	A wire, permanently attached to the head of the anchor, which is used to assist deployment and recovery of the anchor. Once the anchor is deployed the free end of the anchor is attached to a surface buoy.
Piggyback:	Anchor connected in tandem with the main anchor to increase total holding power.
Ring chaser:	A device used for anchor deployment and recovery. A ring just large enough for the mooring line to pass through, and which can be pulled along the mooring line and onto the anchor shank by a wire to the surface.
Scope:	The ratio of the length of the anchor line to the vertical distance from the fairlead to the seabed.
Shank:	Component of the anchor which transmits the tension force in the anchor line to the flukes.
Soak In:	Increase in holding capacity of a newly installed anchor due to time dependent effects in the disturbed soil adjacent to the anchor.
Stock:	Stabilising bar.

1. INTRODUCTION

This document has been prepared by MSL Engineering Limited and reports the findings of a study on **Drag Anchors for Floating Systems**. The objective of this study, which was commissioned by the Offshore Safety Division of the Health and Safety Executive, was to undertake a state-of-the-art review of present day practices for drag anchors.

Floating offshore structures and vessels are subjected to large environmental forces, and most rely on permanent or temporary moorings to withstand these forces. Some of these floating systems, for example Floating Production Systems (FPSs) and Single Buoy Moorings (SBMs) are required to remain on station for long periods, often several years. Other floating systems, for example Mobile Offshore Drilling Units (MODUs), use moorings which must not only withstand the severest weather conditions, but must also be capable of being rapidly and economically deployed and recovered. Most of these floating systems employ drag anchors as a fundamental part of their mooring systems. The performance of drag anchors therefore has a great influence on the reliability, integrity and operational safety of floating systems.

In the North Sea, the most frequent offshore deployment of drag anchors is by MODUs. More than 60 MODUs are currently in operation in the North Sea, indicating the considerable significance of drag anchors to offshore operations.

Anchors for offshore structures may be divided into four categories: drag anchors, deadweight anchors, pile anchors and embedded plate anchors. Drag anchors generate their holding power by embedding in the seafloor when pulled horizontally, mobilising the shear strength of the soil to resist the pulling force. Deadweight anchors depend primarily on their own mass to provide holding capacity, whilst pile anchors generate their holding power by mobilising lateral earth pressure and skin friction in the surrounding soil. Like drag anchors, embedded plate anchors gain their holding capacity from mobilising the shear strength of the soil, but are distinguished from drag anchors by not being self embedding.

This study has established current practice with respect to drag anchor usage, including anchor selection, deployment and recovery methods, mooring arrangements, survey and inspection procedures, handling difficulties and anchor failures. Information has been gathered on anchor shapes, dimensions, manufacturers, fabrication methods, reliability and holding power.

Information for this study has been obtained by two primary methods. The first method was a substantial literature survey, which included technical journals, conference proceedings, design codes and guidelines, and manufacturers' data. This was supplemented by citation and keyword index searches. The second method of gathering data was to circulate questionnaires to organisations in the offshore industry with significant experience of specifying and using drag anchors, and then to follow up these questionnaires by interviews. The organisations interviewed represented a wide cross section of the industry and included six operators, two drilling contractors, one certifying authority, a marine equipment supplier, a marine contractor and a mooring consultancy. Information was also received from the University of Manchester.

The comments made during the interviews by the various organisations are reproduced herein, without modification or amplification, and with MSL Engineering acting strictly in the capacity of a neutral observer and reporter. Therefore, the views contained herein are attributable solely to the various organisations interviewed. These views, together with the findings from a review of public literature, are used in a later section to draw a series of conclusions.

The findings of the study are reported as follows. Section 2 presents a brief outline of the development of modern drag anchor types and introduces some basic terminology. A representative range of drag anchor types are described and illustrated, with particular emphasis on types commonly used by the offshore industry.

Section 3 presents the results of the literature survey. Published technical literature, design codes and guidelines and manufacturers' data are reviewed in detail. Attention is also directed to the scope and extent of proprietary data, where this is known.

Based on information gathered from the interviews with offshore organisations, an extensive review of current anchor deployment practices is presented in Section 4. Topics covered include anchor selection, bottom surveys, installation and recovery, post-installation proof tests, in-position inspection, inspection and repair between deployments, and corrosion protection.

Sections 5, 6 and 7 are also based on the information gathered from the interviews. Section 5 discusses anchor handling difficulties. The effect of dragging on the subsequent holding power of anchors is examined in Section 6, and Section 7 discusses anchor failures.

Conclusions are presented in Section 8. References are tabulated in Section 9.

2. CURRENTLY EMPLOYED DRAG ANCHOR TYPES

There are several types of drag anchor in common use by the offshore industry. These are part of a much larger range of drag anchor types which are employed by merchant ships, naval ships, fishing boats and pleasure craft, as well as for special purposes such as permanent inshore moorings. Figure 1 shows anchors of the types most typically used offshore, plus a number of other anchor types of interest with respect to design or application. Note that none of the anchors is shown embedded.

The stock anchor is an old design, familiar as the anchor fitted to many 19th century sailing ships. A bar (the “stock”) fitted through the anchor’s shank close to the shackle stabilises the anchor, so that the anchor generally embeds irrespective of its orientation on arrival at the seabed. On the stock anchor the flukes, the surface areas of an anchor which contribute to the greater part of its holding power, are carried on two curved arms set at right angles to the stock. Only one of these arms embeds and because the flukes have a small area, the stock anchor has a limited holding power for its mass. The stock anchor is no longer used on large vessels and is included here only for information. However folding forms of this anchor are still used on many small fishing boats and pleasure craft.

The stockless anchor was invented in 1821, and gained popularity at the turn of the century because of the ease with which it can be stowed in the hawsepipes of steel ships. The head of the anchor, to which are attached its flukes, is pivoted about the shank in the plane of the flukes. Projections on the head of the anchor, known as tripping palms, are intended to catch in the soil, rotating the head so that the ends of the flukes point downwards into the soil and the anchor commences to embed. Because the anchor is symmetrical, it will embed whichever side first comes to rest on the seabed. Stockless anchors, differing in detail and manufactured under a variety of commercial names including Hall, Baldt, Union and Spek, are still widely used on merchant ships and Naval vessels. However their poor stability when embedding and low holding power for a given mass, have limited the offshore use of this type of anchor.

Stockless anchors have been further developed by the lateral extension of the crown to form short, broad stabilisers, intended to improve the stability of the anchor. The Stokes type is typical: other similar types include the Admiralty AC14 design. These improved stockless anchors are used on both merchant ships and Naval vessels.

The AC14 and Stokes improved stockless anchor designs are recognised by Certifying Authorities as High Holding Power (HHP) anchors. To be accepted as a HHP anchor, an anchor design must demonstrate a holding power at least twice that of a standard stockless anchor of the same mass, in a range of seabed conditions.

The Danforth (Meon) articulated stock anchor was developed in 1939 and other similar articulated stock designs, such as the US navy LWT and the Stato were developed subsequently. In this type of anchor the head and flukes of the anchor are pivoted about the shank, as for the stockless anchor. However a long bar is fitted through the head of the anchor. This bar performs the dual functions of pivot pin and stock, and is often referred to as the stabilising bar. The anchor is symmetrical and will embed whichever way up it arrives at the seabed.

Articulated stock anchors have been and are very widely used offshore, most notably by Mobile Offshore Drilling Units (MODUs). Their holding efficiency (ratio of holding capacity to anchor weight) is typically around 8 in clay and 10 in sand (**NCEL [1972]**) for an anchor of 35,000 lbs (15.9 tonnes) mass. The equivalent figures for a stockless anchor of the same mass are 2 and 4.

An interviewed mooring contractor indicated that for most MODUs, anchors of between 30,000 lbs (13.6 tonnes) and 40,000 lbs (18.1 tonnes) mass are fairly standard.

The Stevin, Boss, Delta and Bruce single shank anchors were developed with the intention of obtaining improved performance over Danforth/LWT type anchors.

The Stevin anchor was first used in dredging operations, and subsequently for offshore applications. The flukes of the Stevin anchor are articulated about the stock.

The Delta anchor has a single fluke fixed to the shank and will only embed if it arrives at the seabed in the correct orientation. It follows that the Delta anchor must be lowered by a second line in addition to the anchor line, making it necessary to employ an Anchor Handling Vessel (AHV) or an anchor barge to assist in laying this anchor.

The Bruce anchor has a single crow's foot shaped fluke fixed rigidly to a cranked shank. However due to the shape of its fluke it is self-righting, that is if dropped on the seabed up-side-down it will turn upright, embedding as it does so, when tension is applied to the anchor line.

More recently higher performance anchor types have been developed for offshore use. These higher performance anchors include the Bruce twin shank, Stevpris and Flipper-Delta types. Available in large sizes, and with claimed high efficiencies, these anchors offer the possibility of very high holding capacities. The term higher performance anchors has been adopted here as a generic term for these recently developed types of anchor.

The Bruce twin shank has the same arrangement of fixed fluke with self-righting capability as the Bruce single shank anchor. The anchor chain attached to the Bruce twin shank anchor shown in Figure 1 is fitted with Bruce chain depressors, which are intended to augment the performance of the anchor.

The Stevshark is a Stevpris anchor with modifications for very hard soil conditions. The Stevin and Stevshark are non-self-righting designs with fixed flukes and therefore the assistance of an AHV is essential when laying these anchors.

The head and flukes of the Flipper-Delta anchor are pivoted about its shank. Large tripping palms and stabilising surfaces are attached to the head in an open box-like arrangement. The anchor is symmetrical and, like the Danforth/LWT type anchors, will embed whichever way up it arrives at the seabottom.

A summary of the anchor types carried as original equipment on the vessels listed in the 1990-91 Lloyd's Register of Offshore units is represented in Table 1. This summary of fitted anchor types must be treated with some caution, as the type of anchor is frequently not reported with exacitude, LWT for example being used as a generic name for any articulated stock anchor. Also, as reported below, on some MODUs the fitted complement of anchors are rarely used, being substituted for by higher performance anchors brought out on AHVs to the site where the MODU is to be moored.

Table 1
Summary of anchor types (1990-91 Offshore Register)

TYPE	**Anchors**		**Units**	
	Number	**%**	**Number**	**%**
LWT	788	31	130	32
Flipper Delta	384	16	63	15
Danforth	373	14	59	14
Stevin	245	9	37	9
Bruce	194	7	31	8
Moorfast	130	5	18	4
Baldt	127	5	25	6
Offdrill	112	4	15	4
Stevpris	84	3	10	2
Stevfix	82	3	14	3
Vicinay	56	2	7	2
Stato	20	1	3	1
Totals	**2595**	**100**	**412**	**100**

Here the convention has been used of applying the term articulated stock anchor to denote a general type of anchor, rather than following the widespread practice of using LWT as a generic name. It should be appreciated when reading the information presented in Sections 4 to 7 that it was sometimes not clear from the interviews whether LWT was being used as a specific or a generic term, and consequently it has been necessary to exercise judgement in these instances.

Four other types of anchor, the Mushroom, Clump, Kite and Single Fluke, are shown for information in Figure 1. The first two may occasionally be encountered offshore. The Mushroom anchor, which is fabricated from either steel or reinforced concrete, is used for lightships and other permanent moorings. Clump anchors are made of concrete and represent a cross between drag and deadweight anchors, their holding capacity coming from a combination of their weight and their tendency to embed when dragged. Clump anchors are also used for permanent moorings.

Kite anchors and Single Fluke anchors, such as the Navy Single Fluke shown in Figure 1, have not been used offshore to any significant extent. The Kite anchor is mainly suitable for use in mud. It has been stated that when used in these soils, the Kite anchor can generate holding capacities up to one hundred times its own weight. Single fluke anchors are used for permanent moorings, but have limited holding capacities.

3. REVIEW OF PUBLISHED DATA AND INFORMATION

3.1 INTRODUCTION

Information for this study has been obtained by two primary methods. The first method was a substantial literature survey, which included technical journals, conference proceedings, design codes and guidelines, and manufacturer's data, and which was supplemented by citation and keyword index searches

A considerable amount of information (in excess of twenty references) related to drag anchors has been found from the technical literature. The majority of this information was found from a simple search of conference proceedings, technical journals and offshore industry publications, carried in most cases back to 1982. The following were included in this search:-

Conference Proceedings

- Offshore Technology Conference
- Behaviour of Offshore Structures
- Offshore Mechanics and Arctic Engineering
- Offshore Engineering
- International Symposium on Offshore Petroleum Engineering
- Floating Structures and Offshore Operations

Technical Journals

- Journal of Offshore Mechanics and Arctic Engineering
- Applied Ocean Research
- Journal of Offshore Petroleum Engineering

Offshore Industry Publications

- North Sea Newsletter
- Offshore Engineer

These were followed up by a search based on the references quoted in the papers found from this initial simple search. A keyword search using the London Science Reference Library scientific and technical index yielded a further two references. Finally a citation index search was conducted, based on the previously discovered references, and extending back to 1985. This citation index search yielded two new references. The scope of work and results of each of the technical references is summarised in Section 3.2.

Through interviews with several operators, it is apparent that some proprietary data on drag anchor performance exists, outside of tests conducted by anchor manufacturers. Also some research and experimentation is underway or recently completed in the USA. However, because of the proprietary nature of this data, the findings and results are not known, and only brief details are presented below.

A review of the drag anchor manufacturer's data has been conducted from a cross-section of manufacturers within the UK and The Netherlands. This is presented in Section 3.4. Manufacturers generally provided the following data for their anchors: dimensions, proof loads and holding power in a range of seafloor conditions.

The most significant codes and regulations related to drag anchors have been reviewed. These include:-

- DEn Guidance Notes (4th edition)
- Statutory Instruments
- API Recommended Practice
- DnV Rules
- Lloyd's Regulations

Some are comprehensive, but others give only outline guidance. Detailed reviews are presented in Section 3.5.

3.2 PUBLISHED TECHNICAL LITERATURE

Results of an experimental study of the behaviour, during embedment, of Stock, Stockless, Danforth and Delta anchors are discussed by **Klaren [1971]**. The study was particularly directed towards the Delta anchor. Both model and full scale embedment tests were conducted, the former in a water filled tank, the latter in he Rotterdam and Europort docks. Photographs taken during the model tests are presented to illustrate the embedment of each anchor type.

Klaren states that the Danforth anchor has a high holding power in good holding ground. However he suggests that it can easily be obstructed by debris. He states that the flukes will not dig in on a hard seabed, and that in clay, the Danforth embeds very deeply, with the result that the force required to break out the anchor is sometimes as large as its holding power.

The Delta anchor is stated by Klaren to have a high holding efficiency of 15, which is achieved in most types of soil. He also suggests that the Delta anchor embeds within a very short distance, and has high stability. The breakout force for the Delta anchor is claimed by Klaren to be small.

Model tests were also undertaken with piggybacked anchors. Klaren states that these tests showed that if there is enough slack to allow the main anchor to embed, it will start to rotate and break loose immediately the piggyback anchor starts to offer resistance. Alternatively, if the piggyback anchor starts to embed before the main anchor, the flukes of the main anchor will not be able to open. Klaren recommends that, if it is necessary to use a piggyback arrangement, the better anchor should always be used as the rear anchor (*presumed to mean the piggyback anchor*).

Van den Haak [1972] reviews the characteristics of a number of types of anchor, including the LWT, Stevin, Danforth, Delta and Stato types. Performance data for these and other anchor types is summarised in Figure 2.

He suggests that good types of holding ground are normal clay, hard sand and soft lime. He lists fine gravel and coarse sand as poor holding ground, and coarse gravel, shells, soft sand, hard clay, stone and rock as extremely poor holding ground.

Van den Haak discusses in detail the breaking out of anchors, with particular reference to dredger operations.

Results of several series of performance tests of MODU anchors are reported by **Beck [1972, 1974]**. The following designs were tested; an articulated stock anchor similar to the LWT, articulated stock anchors similar to the Stato type, and the BOSS anchor. (The BOSS anchor design is similar in appearance to an articulated stock anchor, with the exception that the two flukes are merged to form a single fluke, which articulates on only one side of the shank). Tests were conducted in the Gulf of Mexico and also on a beach and in a lake. The test sites encompassed a range of seabed conditions from very soft mud through to firm mud, and also sticky clay and hard, fine grained sand. Several different sizes of anchor were tested, ranging from under two kilograms up to 10 tonnes.

In the tests mentioned above, Beck observed several different types of anchor behaviour, which are illustrated in Figure 3. The LWT type anchors were found to be prone to the flukes failing to trip in mud, (B) of Figure 3. This problem did not affect the Stato type anchors. When balling up occurs, (C) in Figure 3, a large ball of mud becomes trapped between the shank and the anchor flukes, causing the anchor to lose holding power. Beck states that it was found that balling up could occur for the LWT type anchors at any stage as they embedded. The Stato type anchors were found only to ball up after they had developed substantial holding power.

The results of each of the test series are described in detail by Beck. The performance of the BOSS anchor was found to be generally better than that of the LWT and Stato type anchors. It was noted that the LWT type anchor had an erratic performance in mud, whilst the Stato type anchor failed to embed properly in hard sand. Table 2 summarises the performance of each anchor type in Gulf of Mexico mud bottoms (type 1 and type 2 are the LWT and Stato types, respectively). Figure 4 shows a direct comparison of performance at a soft mud test site in the Gulf of Mexico.

Table 2
Anchor performance in Gulf of Mexico mud bottoms
(from Beck, 1974)

	800 lb class anchors		
	Type 1	**Type 2**	**Boss**
Total tests in mud	17	15	13
Number of failures to dig in	6	0	0
Number of ball-ups	6	10	0
Average holding power for all tests, kips	15.3	23.0	34.0

Tests were conducted with various fluke angles for each anchor type. In mud, the performance of the BOSS anchor was found to be strongly dependent on the fluke angle, as may be seen from Figure 5. Beck concludes that, for each of the anchor types tested, improved holding power in soft mud can be obtained by increasing the fluke angle. Beck further concluded that in sand, the anchors tested fail to embed properly when the fluke angle exceeds a critical value. This critical value is usually in excess of 34° for medium grained sand. However for hard fine grained sands this critical angle may be less than 30°.

Klaren [1973] discusses the results of an experimental investigation of piggybacking. The tests were carried out in dry sand, using two model Delta anchors and a model Danforth anchor. The model anchors had masses of 0.35 kg, 0.36 kg and 0.30 kg, respectively. A number of different piggybacking arrangements were investigated, including:-

- The two Delta anchors piggybacked together.
- The Danforth as the main anchor, and a Delta anchor as the piggyback anchor.
- A Delta anchor as the main anchor, and the Danforth anchor as the piggyback anchor.

When a Delta anchor was used as the main anchor, two attachment points for the chain to the piggyback anchor were investigated. The first was a padeye on the top of the shank, near to the anchor shackle, and the second was a padeye on the head of the anchor. A first set of tests was conducted with the angle of the tension force on the main anchor to the horizontal in the range 5° to 15°. A second set of tests was then conducted in which this angle was 0°.

Klaren states that when the line from the piggyback anchor was attached to the padeyes on the heads of the Danforth or Delta anchors, the tension force from the piggyback anchor caused the main anchor to rotate and break out. He notes that if the main anchor has articulated flukes, then the flukes will subsequently be constrained to remain parallel to the shank, and the main anchor will not embed again.

When a Delta anchor was used as the main anchor, and the line from the piggyback anchor was attached to the padeye on the top of the shank of the Delta anchor, both the main and the piggyback anchors embedded fully. The holding power of the piggyback arrangement was found to be equal to the sum of the holding powers of the two individual anchors. This piggyback arrangement is shown in Figure 6.

Klaren recommends that a padeye should only be fitted on top of the shank if the anchor has a fixed fluke. He suggests that for articulated fluke anchors there is a danger that a line attached at this point on the anchor would become entangled.

Puech [1978] presents the results of two series of anchor tests. The first series of tests was intended to investigate the influence of parameters such as fluke area and shank shape on anchor performance, and made use of 0.1 tonne anchors with simplified configurations. The second series of tests was conducted to compare the performance of a number of commercially available anchors. For this second set of tests, 0.1 tonne anchors of the following types were used: GS articulated stock anchor, Hall stockless anchor, Stevin, Bruce, Flipper-Delta, Delta Triple.

The anchor tests mentioned above were conducted at two coastal sites near Brest. The first site is a calcareous sandy beach, having medium grain size, which is covered by a shallow depth (less than 1.0m) of water at low tide. The second site was a tidal mud flat which dries at low tide and is covered by 1.0m to 2.0m of water at high tide. The mud has a surface cohesion of about 50 g/cm^2 and a cohesion gradient of about 30 c/cm^2/m.

The findings of the first set of tests are summarised in Table 3. Typical results from the tests of commercial anchor types are shown in Figure 7.

Table 3
Effects of basic parameters on anchor behaviour
(from Peuch 1978)

Fundamental parameters		**Main functions**				
		Opening	**Penetration**	**Burial**	**Stability**	**Holding Power**
Distribution of masses - rotation axis position		x			x	
Trimming palm area		x				
L/F ratio or fluke spacing					x	
Fluke surface area				x		x
Bearing surface of shank				x		
Shank length	S		x			
Stocks, stabilisers					x	
Fluke-shank angle	α		x	x		
Pulling angle	β					x
Burial depth	D					x
Mechanical properties of soil	ϕ, Cu	x	x	x	x	x
Fluke roughness	δ		x	x		x

Peuch concludes that stockless and articulated stock anchors are poorly suited to offshore use. He further concludes that Stevin, Bruce and Flipper-Delta anchors are well suited to the temporary mooring of barges and MODUs, by virtue of their high reliability and stability when dragged. For the permanent mooring of FPSs he suggests that special anchor types, such as the Delta Triple, can be used to obtain the required high holding capacities, but that the handling of these special types is proportionately more difficult.

Valent, Taylor, Atturio and Beard [1979] consider possible anchor strategies for Ocean Thermal Energy Conversion (OTEC) structures. With reference to drag anchors (they also consider other forms of anchor) their main topic is the extrapolation of holding power and other data for Stato, Bruce and Doris anchors to the extremely large anchor sizes which would be required for an OTEC structure.

Valent et al also give recommendations for the minimum spacing, (b) between piggybacked anchors, and between anchors sited in parallel, to achieve a holding power equal to the sum of the holding power of the individual anchors (Figure 8).

The ratio of (b) to embedment depth is presented as a function of soil shear strength for clay seabeds (Figure 9) and as a function of soil friction angle for sand seabeds (Figure 10). Valent et al derived their recommendations for (b) from consideration of data for groups of embedded plate anchors. They caution that in reality the total capacity of a group of anchors will also depend on the way in which the anchors are installed and connected.

Ura and Yamamoto [1979] propose an approximate method of analysing the behaviour of anchors being dragged through a non-cohensive soil. By way of example, this method was applied to a stockless anchor. Their method makes use of empirically derived expressions for the forces acting on individual components of the anchor. These expressions were obtained by measuring the forces on each component independently.

Most of the anchor components, for example the fluke and shank, were idealised as rectangular plates. The force measurements for these components were then accomplished by dragging rectangular plates of various aspect ratios through a tank of dry sand. Ura and Yamamoto claim that experimental results from dry sand tests can be applied to real anchors in flooded sand if the effective density of the sand is fully considered. They also suggest that the dragging speed has very little effect on the behaviour of anchors, and can be disregarded.

The results of the above mentioned experiments are summarised as a set of vector integral expressions for forces and moments on rectangular plates. These expressions are similar to the expressions for forces and moments on plates due to hydrostatic pressure, except that pressure is replaced by friction tangential to the plate surface. The tangential friction is a function of the normal force coefficient and the effective friction angle. The lateral force and associated moment are additionally a function of the lateral force coefficient. Empirical expressions for the normal and lateral force coefficients and the effective friction angle are derived from the test data.

From the expressions for forces and moments on individual components of the anchor, Ura and Yamamoto derive the equilibrium equation for the stockless anchor. An expression for the maximum holding power is in turn derived from the equilibrium equation, as are expressions for equilibrium anchor inclination and embedment depth. Comparisons are drawn between experimental measurements of maximum holding power, embedment depth and inclination of a 0.92 kg model anchor and the values predicted by the derived expressions. Modification of the derived expressions, by the introduction of empirically derived factors to account for interaction effects between the components of the anchor, is found to significantly improve the correlation between the experimental and numerical values, as may be seen from Figure 11.

Conditions for stability/instability of the anchor are also established from the equilibrium equation. Two instabilities are considered, lifting of the head and rolling about the shank. Lifting of the head is found to depend largely on the length of the shank. Roll instability is shown to be dependent on the stabilising moment generated by the flukes and the stabilising fins. It is suggested that absolute roll stability (which ensures that the anchor will rotate about the shank to its correct orientation whatever angle it starts at) can be achieved by attaching a pair of flat-faced stabilising fins perpendicular to the flukes.

Dove [1980] reviews the historical development of ring chaser systems, and discusses their use for deployment and recovery of anchors. In his historical review Dove first describes extemporised chasing devices, which were used for recovering anchors when difficulties were encountered with a pendant wire system. He then reviews the development of these early chasing devices into permanently installed ring chaser systems, which are used instead of pendant wires on many MODUs.

The method of using ring chasers for the installation and recovery of anchors is described and illustrated (Figure 12) by Dove. He presents an example to show the cost benefits of a permanent ring chaser system over a buoyed pendant wire system, for a MODU capable of drilling in up to 1000 (305 metres) feet of water. He then goes on to discuss the advantages of ring chaser systems over pendant wires for very deepwater drilling (in excess of 305 metres).

Dove notes that if piggyback anchors are used, then a pendant wire system must be deployed, because the chaser cannot be passed over the main anchor. He suggests that chaseable chain depressors, placed on the mooring line inboard of the main anchor, may prove to be an acceptable alternative to piggyback anchors.

Dove [1981] first reviews existing deepwater mooring techniques and then goes on to consider future developments in deepwater mooring technology. He states that for permanent mooring of large floating structures, specialised types of prefabricated anchors, such as the Hook anchor, Delta Triple anchor and Doris anchor are the preferred option. He suggests that the difficulty of installing these specialised anchor types is not generally appreciated, and that the cost of the installation equipment (for example large converted derrick barges) is such that drag anchors will offer little or no cost savings over pile anchors for these applications

Dove also comments that the reliability of drag anchors on the depth, shear strength and homogeneity of the soil in addition to the stability of the anchor. He states that accurate positioning of each anchor in a mooring system is very important for large permanently moored structures, because the mooring line lengths are critical for such structures. He notes that accurate positioning of drag anchors is, however, almost impossible, as the drag distance before the anchor fully embeds is very variable.

In locations where the soil conditions are not well known, or where the seabed is rocky or sloping, Dove considers the reliability of drag anchors to be questionable.

Ura and Yamamoto [1981] apply the analytical procedures outlined in Ura and Yamamoto [1979] to design new types of stockless and single fluke anchors having absolute roll stability. The roll stability of these new designs is demonstrated experimentally.

Taylor [1981] reports the results of a series of US Navy field tests of Stockless and Stato anchors. He also makes mention of tests of Moorfast, Hook, Stevin and Bruce anchors conducted concurrently with the Stockless and Stato anchor tests, but includes no details or results of these tests. Three sizes of Stockless anchor 5000, 9000 and 20000 pounds (2.3, 4.1 and 9.1 tonnes) and three sizes of Stato anchor, 1000, 3000 and 6000 pounds (0.5, 1.4 and 2.7 tonnes) were tested. The tests were conducted at three sites San Diego Harbour, Indian Island and Guam.

The test programme for the Stockless anchors included a number of tests on pairs of anchors in various piggyback arrangements (Figure 13). Piggyback anchors are anchors connected in tandem with the main anchor, with the intention of increasing the overall holding power mobilised on a given mooring line.

For the piggyback tests the flukes of the anchors were welded in the open position, to prevent the flukes of the main anchor being closed by the load of the tandem anchor, and because the flukes of Stockless anchors frequently do not open in soft mud. In the arrangement shown in Figure 13c, the distance between the main and piggyback anchors was sufficient to allow the two anchors to be installed separately.

The seafloor conditions at the test sites were as follows:

- San Diego Harbour — first test site fine sand, second test site 1' to 3' (0.3 to 0.9 metres) of soft silt over dense overconsolidated clayey sand
- Indian Island — highly plastic normally consolidated clay, with a shear strength of 1.4 psi (0.01N/mm^2) at 20' (6.1 metres) below the seafloor
- Guam — a few inches to 7' (2.1 metres) of moderate to high plasticity clay overlying medium density corally sand

One hundred and thirteen anchor tests were completed, distributed between these four test sites. A limited number of these results are presented in tabular form. Graphs are presented showing a range of parameters as functions of anchor drag distance, derived from the tests on single anchors.

Taylor also presents graphs of load against drag distance, derived from piggyback anchor test results. These graphs include results for all three piggyback arrangements tested at the first San Diego test site, Figure 14 (test 1/21 crown to shackle, test 1/22 grounding to shackle, test 2/20 shank to shackle) and for two of the piggyback arrangements tested at Indian Island, Figure 15 (test 11 shank to shackle, test 12 crown to shackle).

Albertsen and Beard [1982] review the current (1982) status of high capacity drag, pile, embedded plate and deadweight anchors. The general characteristics and the advantages and disadvantages of each anchor type are discussed, and several types are illustrated. It is stated that drag anchors will often continue to provide near maximum load resistance even though the anchor continues to slip in the soil. Results are presented of US Navy tests of the holding efficiency (ratio of anchor holding capacity to actual anchor weight) for a number of drag anchor types in two soil types (Table 4). A caution is given that this data is site specific and that performance could vary for other seafloor conditions. It is also noted that the behaviour of drag anchors is erratic in layered seafloors. Test results showing that the embedded length of anchor chain adds significantly to the holding capacity of the anchor are presented. For a Stato anchor in mud the anchor chain is found to have contributed 50% of the total holding capacity. Albertsen et al state that the fluke angle has a major influence on the holding power of an anchor, and that the optimum angles for mud and sand are 50^o and 30^o to 35^o, respectively.

Table 4
Efficiencies of drag embedment anchors in two types of seafloors
(from Albertsen and Beard, 1982)

Anchor type	**anchor weight (lbs)**		**efficiency**	
	Nominal	**Actual**	**Sand**	**Mud/Silt**
Navy Stockless	5,000	5,950	8:1	3:1
Stato	3,000	3,500	18:1	15:1
Stevfix	1,410	1,410	31:1	15:1
Stevdig	2,200	2,560	29:1	-
Stevmud	2,200	2,200	-	20:1
Hook	1,230	1,260	12:1	18:1
Bruce	1,320	1,320	25:1	-
Bruce Twin Shank	750	750	-	12:1

A series of experiments on the holding capacity of circular plate anchors embedded in sand are described by **Sutherland, Finlay and Fadl [1983]**. An approximate expression for the holding capacity of plate anchors is derived from these experimental results. Both shallow and deeply buried plates are considered, the burial depth having a strong influence on the failure surface of the soil at the ultimate capacity of the anchor. Two orientations of the plate are considered, parallel to and inclined to the soil surface. The load on the anchor was applied perpendicularly to the plane of the circular plate.

Measurements of anchor load, anchor displacement and soil surface displacement were made for each experiment. The soil failure surface was recorded by means of tracer layers of cement powder deposited at several depths in the sand.

The relative density of the sand was found to strongly influence the ultimate capacity and displacement behaviour of the plate anchors.

Sutherland et al also observed a marked reduction in the holding capacity of shallow anchors after the ultimate capacity had been reached, particularly in dense sand. They suggest that this effect could be explained by dilitancy effects. This reduction in holding capacity was not observed for deeply buried anchors.

From the experimentally observed shape for the soil failure surface, an approximate expression for the holding capacity of a deeply buried inclined plate anchor in sand is derived. Included in this expression are the effects of the relative density of the sand, and the differences in holding capacity of shallow and deep burial anchors. The soil failure surface and loads assumed in deriving the expression are shown in Figure 16. Expressions for the holding capacity of horizontal and shallow buried plates are derived by simplification of the expression for the deeply buried inclined plate.

Vold and Eie [1983] report the results of field tests of four types of 3 tonne drag anchors in the Norwegian Trench. The anchors tested were a Stevin, a Flipper-Delta, a Bruce Mark 2 and a Baldt stockless anchor. Geotechnical data for the soil in the test area are shown in Figure 17. The upper 8m of the soil consisted of normally consolidated clay of high plasticity with an undrained shear strength increasing with depth from approximately 2.5 kN/m^2 to 12.5 kN/m^2. The fluke angle was set to 45^o for the Stevin and Baldt anchors, 50^o for the Flipper-Delta anchor and 13^o to 16^o for the Bruce anchor.

Instrumentation on each anchor included a pair of inclinometers to measure anchor orientation, a load cell in the anchor shackle, a depth gauge and a trailing wire device intended to record the distance the anchor was dragged.

Two AHVs were employed to carry out the field tests. The first, which was moored to a buoy anchored by a 12 tonne anchor, provided the winch to pull the test anchors. The second AHV was used to lower the test anchors to the seabed, and to recover them after the tests. The anchors were installed and recovered using a 57mm diameter pendant wire attached to the nose shackle of the anchor. A 2400m long 57mm diameter wire cable was used to pull the test anchors. The water depth was 300m.

Twelve tests were conducted in which the anchors were lowered slowly to the seabed, then pulled until they dragged. No mention is made of a "soaking-in" period. Readings were taken from all of the instrumentation in these tests. The results of these tests are summarised in Table 5. The following observations were made:-

- the Stevin anchor exhibited good penetration and holding capacity, but had a tendency to roll when dragging (ie it was not perfectly stable)
- the Flipper-Delta anchor exhibited good penetration and holding capacity, and was stable when dragging
- the Bruce anchor penetrated much less and generated only one quarter of the measured holding capacity of the Stevin or Flipper-Delta types, but was quite stable when dragging
- the Baldt anchor generated a holding capacity half that of the Stevin and Flipper-Delta types, but was very unstable when dragging, rolling through a 29^o angle about the shank.

Figure 18 shows tension at the anchor shackle, embedment depth and inclination plotted against drag length measured in particular tests, for each of the four anchors.

Table 5
Summary of instrumented tests
(from Vold and Eie, 1983)

Test No.	Anchor Type	Anchor line tension (kN) at anchor shackle/at winch [a)]			Max. Drag dist.	Duration of drag	Max. penetr-ation [b)]	Final inclination (deg)	
		25 m drag	50 m drag	Maxi-mum	(m)	(min)	(m)	Long.	Transv.
1		-	-	470/620	-	14	10.6	38	20 [c)]
2	Stevin	210/350	380/500	420/540	80	17	-	32	52
3		-	-	330/460	-	9	-	30	-23
4		210/300	390/490	400/500	65	12	10.8	46	6
5	Flipper-	370/490	430/530	460/540	75	16	-	48	11
6	Delta	-	-	470/620	-	19	-	48	0
7		90/200	105/200	110/210	130	11	-	8	-3
8	Bruce	90/200	100/210	110/220	130	8	5.0	8	0
9		90/200	110/210	120/220	100	7	-	8	12
10		180/260	190/260	210/280	130	9	6.0	38	49
11	Baldt	-	-	170/270	-	14	8	37 [c)]	47
12		145/240	150/245	180/270	130	13	-	39 [c)]	37 [c)]

Notes: *a) For tests in which dragometer did not function, only maximum tensions are given.*
b) Penetration refers to depth of anchor shank top below seabed.
c) A higher numerical inclination value than the final one was recorded during the test.

A further set of ten tests were conducted in which the anchors were lowered much more quickly to the seabed, and for which the instrumentation pack was removed from the anchors. Table 6 summarises the results of these tests. In two of the four tests on the Stevin anchor in this set of tests, the Stevin anchor lost stability and holding force. Vold et al ascribe this to the pendant line fouling the flukes of the anchor. In one of this second set of tests, the Bruce anchor generated a maximum capacity more than double that seen in the rest of the tests on the Bruce anchor. This higher capacity was only achieved after prolonged dragging of the anchor, during which 580m of the anchor cable was hauled in. Vold et al suggested that the increase in capacity resulted from the Bruce anchor embedding more deeply, after dragging for a long period in a stalled attitude.

Two approaches to extrapolating the experimental data to larger anchors are considered:

- conventional approach, using the empirical expression

  holding capacity = c_1.(anchor weight)^b

  where c_1 and b are empirical coefficients dependent on anchor type and soil conditions

- geotechnical approach, using an expression based on an analogy to the end bearing capacity of a pile

  holding capacity = c_2.A.s_u

where A and s_u are, respectively, the projected area of the anchor flukes and the undrained shear strength of the soil, and c_2 is an empirical coefficient.

Table 6
Summary of drop tests
(from Vold and Eie, 1983)

Test No.	Anchor Type	Max. anchor line tension at winch (kN)	Duration of drag (min)	Total length of anchor line pulled in during test (m)
15	Stevin	590	14	450
16		400 decr. to 140 [a)]	9 to 18	330
17		230 decr. to 130 [a)]	3 to 11	360
18		500	26	510
19	Flipper-Delta	560	21	560
20		570	27	500
13	Bruce	210	14	350
14		220	6	350
23		490 [b)]	41	580
21	Baldt	300	22	480
22		280	19	500

Notes: *a)* *Tension loss apparently caused by fouling of pennant line around anchor.*
b) *Maximum tension reached after 35 minutes.*

From these expressions, the size of Stevin or Flipper-Delta anchor to give a working capacity of 1500 kN is compared with the anchor manufacturers recommendations for these anchor types. The conventional approach indicates a weight of 34 tonnes or 19 tonnes, depending on whether b is assumed to be 0.75 or 1.0. No comment is made on the assumptions behind these values for b. The geotechnical approach and the manufacturers data for the Stevin anchor indicate an anchor weight of 18 to 19 tonnes. he manufacturers data for the Flipper-Delta anchor suggest a weight of 15 tonnes.

Puech [1984] gives a comprehensive assessment of drag anchors in his book, under the following main chapters:-

- history of anchors
- high-capacity anchoring systems
- kinematics of anchors
- holding power of anchors
- anchoring site surveys
- choice of an anchor
- anchoring tests

It is considerence that this reference is a very useful general introduction to drag anchors.

Zumwait [1986] discusses deepwater mooring operations on the continental slope of the Gulf of Mexico. He notes that the mooring of rigs in 600 to 2000 feet (180 - 610 metres) water depths on the Gulf of Mexico continental slope, is now a routine operation. Recent improvements in mooring procedures and technology which have been bought about by the need to moor in these deeper waters are discussed under a number of headings.

Suggesting that the safety record of MODUs with respect to moorings has been good, with only one mooring failure incident being significant enough to be reported, Zumwait goes on to state that anchor line failures which delay mooring operations but do not become safety hazards will generally not be reported.

Zumwait reports that the seafloor on the Gulf of Mexico continental slope is a weak Holocene unconsolidated clay layer, which overlies firmer Pleistocene era clay, sand and gravel deposits. In some areas coral is found beneath the Holocene clay layer. he notes that an anchor's holding capacity in these conditions is primarily dependent on the cohesiveness of the seabed soil: where the bottom is very soft clay or silt, the anchor may have to penetrate in excess of 100 feet (30 metres) to achieve a percentage of its normal holding capacity.

Estimated holding capacities for a range of anchors in soft silt or clay, and in sands (stated to be of lesser interest for Gulf of Mexico conditions) are presented in Figure 19. Zumwait notes that to avoid applying uplift forces on anchors, long anchor lines are commonly used. He suggests that these long scopes have the redeeming feature that they contribute an additional holding capacity which for chain is about 55% of the immersed weight of the chain. Referring to the use of piggyback anchors, he states that the length of anchor line between the primary and piggyback anchors is usually two to three times the water depth, to allow them to be handled separately. He adds that up to three piggybacks have occasionally been used on a single line in very poor holding ground.

In discussing the use of permanent chain chasers Zumwait points out that the maximum loading on the chaser and its pendant wire will occur when dislodging the embedded anchor. He states that the force required to do this can exceed the maximum horizontal force to which the anchor has been subject whilst in position.

The preferred specifications for AHVs intended for deepwater Gulf of Mexico mooring work are listed. The preferred deck equipment specification for such vessels is summarised in Figure 20.

Dutta [1988] discusses a numerical method for determining the configuration of a mooring chain with an embedded attachment point subject to a horizontal tension force at its free end. His numerical method uses a finite segment approach, in which the chain is modelled as a series of line segments connected by frictionless nodes. All forces, both external and internal, act on the chain numerical mode through these nodes. The numerical model provides a method of determining the tension at the embedded attachment point for a given tension on the free end of the chain. The numerical procedure is validated by comparison with published experimental data.

The design, installation and testing of a temporary mooring system for the Gullfaks A Condeep concrete platform is described by **Røraas and Hagen [1989]**. They explain that an eight line mooring system was required to hold the Gullfaks platform in position whilst it was completed at a deepwater site on the Norwegian coast. Five of these lines were taken to shore. The remaining three lines were secured by drag anchors designed to withstand a maximum pull of 15000 kN each. Røraas et al note that there was a complete lack of rules regulations and experience relevant to the design and installation of anchors having a holding capacity of this magnitude.

The soil conditions at the sites of the three drag anchors are detailed in Table 7. Røraas et al state that a decision was made to carry out small scale field tests, using 3 tonne anchors, at the planned anchor locations. They indicate that two anchor manufacturers were involved in the small scale test programme, and that the anchor types finally chosen were the Stevpris and Stevshark designs produced by Vryhof Ankers. The other manufacturer is not identified. Results of tests at all three sites are given (Figure 21), but it is not clear to which designs of anchor these results refer. The only 3 tonne anchor for which dimensional data is given is a Stevpris anchor. It is stated that the fluke to shank angle was set to 32^o for sand and 50^o for mud. The test anchors were installed using an AHV. The anchor line was then pulled at a speed of less than 5 m/minute. The tensioning of the anchor line was stopped at 40% and at 70% of the maximum predicted holding capacity of the anchor. When the maximum holding power of the anchor was reached, the pulling of the anchor line was stopped for 15 minutes, and the holding capacity was recorded again. Røraas et al note that for the anchor at line 4 location, the anchor became stuck in the rock; the load reached 1500 kN before the test was stopped.

Table 7
Soil conditions at the three locations
(from Røraas and Hagen, 1989)

Line no.	**3**	**4**	**7**
Water depth (metres)	299	102	202
Soil type	very soft clay	soft clay	medium uniform sand
Depth to rock (metres)	40	7 to 11	40
Shear strength (kN/m) [depth in metres]	10 [0-7.5] 15 [-8.5] 20 [-10] 35 [-15]	8 [0 - 3] 22 [-8.5] 35 [-9] 50 [-10]	
Water content (%)	40 - 45	32 - 45	22 - 27
Angle of internal friction (degrees)	28	28	40
Sensitivity	10 - 15	10 - 15	
Grain size (mm)			0.2 - 0.6

The 3 tonne Stevpris anchor was also subject to mechanical strength tests. These tests are described in detail by Røraas et al, who note that the anchor was found to fail by buckling of the shank members when subject to a 1412 kN load applied as a point load at the fluke tips.

Røraas et al report that based on the field tests, together with the mechanical test data and the results of a strength analysis of the proposed anchors, Stevpris anchors of 65 and 40 tonnes were chosen for line locations 3 and 7 respectively, and a Stevshark anchor of 60 tonnes was chosen for location 4. They present data showing the tensioning to proof load of the three anchors (Figures 22 and 23). For each of the anchors tensioning to proof load was carried out over a number of days.

The three anchors were recovered after use. The anchor at line position 3 is noted by Røraas et al to have required an uplift force of approximately 11000 kN to dislodge it. A previous attempt to move this anchor had failed, and a steady vertical pull was subsequently put on it for a day. Røraas et al state that the anchors at the other two sites were easy to retrieve.

Dutta and Degenkamp [1989] present the results of an experimental investigation of the embedment of mooring chains during chain tensioning. Although their work is directed primarily towards chains attached to pile anchors, they suggest that their findings are also applicable to mooring chains connected to drag anchors.

The experiments, which were carried out at a small scale, were conducted by attaching one end of an anchor chain to a fixed point beneath the soil surface. A horizontal pull force was then applied to the free end of the chain, causing more of the chain to become embedded as the embedded part of the chain was displaced from a vertical position. The experimental apparatus is shown schematically in Figure 24. Three different sizes of chain and two different saturated clays were used. The chains were studless and had nominal diameters of 6.4mm, 9.5mm and 16mm. One of the two clays was very soft, having an undrained shear strength of 4.52 kN/m^2. The other clay was firm, having an undrained shear strength of 33.9 kN/m^2. The following parameters were recorded as the tension on the free end of the chain was steadily increased:-

- Forces/chain tension at the fixed attachment point.
- Embedded chain length.
- Chain angle at the fixed attachment point.

Figure 25 shows the variation of chain tension an angle at the attachment point with horizontal pull force, for the soft clay, when the fixed attachment point was 1.008m below the soil surface. Figure 26 compares the horizontal and vertical chain forces obtained in the soft clay with that obtained in the hard clay, for fixed attachment point depths below the soil surface of 0.135m and 0.407m (chain diameter 6.4mm).

Dutta et al concluded that the chain tension at the fixed attachment point varied linearly with the horizontal pull force, whereas the chain angle decreased non-linearly with increasing pull force.

Degenkamp and Dutta [1989] describe a numerical model for the configuration of a mooring chain attached to a point below the surface of a soft clay seabed. Their numerical model employs an incremental integration technique to derive the equilibrium equations for the chain. The effective width of the chain, which is used in calculating soil resistance in bearing and friction, was determined from the model tests reported in Dutta and Degenkamp [1989]. The proposed numerical model is applied to determine the tension load at the embedded attachment points of the moorings of a Catenary Anchor Leg Mooring (CALM) buoy installed in 77m of water in the Adriatic.

One anchor manufacturer has produced an anchor manual (**Van den Haak [1990]**) which in addition to describing the manufacturer's products, gives advice on anchor handling procedures, soil surveys and anchor sizing. A brief review of anchor design requirements is presented, as is a summary of chaser types and handling methods.

3.3 PROPRIETARY DATA

Certifying authorities are almost invariably closely involved with the installation and testing of the moorings of structures intended to remain on their moorings on a long term basis (such as FPSs and loading buoys). As a result they hold a quantity of proprietary data from installation tests of these mooring systems.

Within the scope of a joint industry funded project, a field test programme with a planned test matrix of some 30 tests was recently completed in the Gulf of Mexico. Bruce FFTS IV, Stevpris and Vicinay Norshore anchors, in 2 tonne and 7 tonne sizes, were planned to be tested. It is understood, however, that a number of experimental problems were encountered and that as a result, only of the order of one quarter of the planned matrix of tests were actually completed. The planned deliverable from this JIP was a program to compute anchor burial, drag distance holding power and an expression for holding power based on anchor geometry.

A centrifuge test technique has been employed by one operator in the US to carry out a series of small scale model tests on drag anchors in soft clays. This technique, has previously been applied to the experimental investigation of a range of other soil mechanics problems.

3.4 MANUFACTURER'S DATA

Information in the form of product catalogues and data sheets was sought from five anchor manufacturers chosen to be a representative cross-section of the European anchor manufacturing industry. The information which follows is drawn from the information received from these manufacturers in reply.

The anchors discussed here are those which are of particular relevance to offshore use. Several manufacturers also produce other types of anchors, including types intended primarily for yachts, small commercial boats, fish farming, inshore permanent moorings, or naval use.

Isiah Preston (UK) manufacturer the Meon Mk3 anchor for offshore use. This particular design of anchor was previously known as the Danforth anchor. The Meon Mk3 anchor is approved as a HHP anchor by Lloyd's, Germanisher Lloyd and Bureau Veritas, each allowing a 25% weight reduction relative to a standard stockless anchor. The American Bureau of Shipping (ABS) allow a 20% weight reduction. Figure 27 shows the manufacturer's performance data for this anchor, which is manufactured in a range of weights up to 50,000 lbs (22.68 tonnes). The fluke angle is set to 32^{o}.

Isiah Preston also produce the Stokes HHP stockless anchor. The fluke angle is normally 40o, but this may be set to a different value during manufacture. The manufacturer's performance data for this anchor are shown in Figure 28. The largest catalogued anchor of this type is 50,000 lbs (22.68 tonnes) but larger sizes are stated to be available. The Stokes anchor is approved as an HHP anchor (25% reduction in weight) by Lloyd's, Germanisher Lloyd, Bureau Veritas, Registro Italiano Navale (RINa) and Det Norske Veritas (DnV). The ABS allows a 20% weight reduction.

Bruce International (UK) manufacture two types of anchor in sizes appropriate for offshore use. These are the FFTS Mk4, and the TS, both of which are of welded construction. The FFTS and TS anchors are manufactured in weights of up to 60 tonnes and 25 tonnes, respectively. The fluke angle of both types may be adjusted. On the TS anchor this adjustment is achieved by means of a bolt arrangement, whilst on the FFTS plain pins are used. Both anchors are self-righting. Figure 29 shows manufacturer's performance data for the FFTS anchor.

Anker Advies Bureau (The Netherlands) manufacture the Flipper-Delta anchor for offshore use. Flipper-Delta anchors are stated to be proof tested as HHP anchors in accordance with certifying body requirements. Anchors with weights of up to 75 tonnes are catalogued. The fluke angle is normally set to 36º, but can be increased to 50º for very soft clay and mud conditions, and reduced to 28º for hard seabeds such as rock or cemented sand. Adjustment of the fluke angel is achieved by cutting out or welding in small spacing pieces. Performance charts are not given, it is simply recommended that the anchor weight should be 10% of the maximum holding load required.

Vryhof Anker (The Netherlands) produce three anchors for offshore use, the Stevin, Stevpris and Stevshark types. All three are stated to be certified by a range of certifying authorities, including Lloyd's, Germanisher, Lloyd, Bureau Veritas, RINa, ABS and DnV.

The Stevin anchor has hinged anchor flukes and can be dropped without the assistance of an AHV. Weights of up to 30 tonnes are catalogued. The manufacturer's performance chart for this anchor is shown in Figure 30.

The Stevpris anchor has fixed anchor flukes, the angle of which can be adjusted to 50º for mud and 32º for sand. Adjustment is facilitated by moving a pair of plain pins, which are held in place by welded keeper plates. The manufacturer's performance chart for the Stevpris anchor is shown in Figure 31. Weights of up to 65 tonnes are catalogued.

The Stevshark anchor is an adaptation of the Stevpris anchor for use in very soils and some rock seabeds. The anchor is fitted with a serrated shank, and is reinforced, particularly at the fluke points. Other details of this anchor are similar to those for the Stevpris anchor.

Vlaardingen Oost (The Netherlands) produce Danforth anchors with a maximum size of 30000 lbs (13.61 tonnes). They also manufacture several types of stockless anchors, including Baldt anchors of up to 35000 lbs (15.87 tonnes) and Hall anchors of up to 29 tonnes. These anchors are stated to meet the requirements of a number of certifying bodies, including Lloyd's, Germanisher Lloyd, Bureau Veritas, RINa, ABS, and DnV. Performance data are not given in this manufacturer's catalogue.

3.5 CODES AND REGULATIONS

DEn Offshore Installations: Guidance on Design, construction and certification. 4th edition, 1990.

Section 30: Floating Installations

This section requires that an investigation of the planned operating site be made, to ascertain whether the floating structure can operate safely at the site, before the structure is moved to the site. For an anchored platform the investigation is to include an appropriate survey of the seabed.

Section 32: Station Keeping

It is required that moorings should accommodate the failure of one line without causing conditions in the other lines which would endanger the security of the anchors.

In addition, the selection of anchor strength and type should be based on consideration of the mooring pattern to be used, the expected sea bottom conditions and the anticipated environmental conditions. Anchors are to be tested and marked in accordance with “Anchors and Chain Cables Rules 1970 (SI 1970/1453”).

The Operations Manual is to include details of the holding power and weight of the anchors, plus a plan showing a typical mooring arrangement. For mobile units the operations manual is also to include procedures for the deployment and recovery of moorings and requirements for pre-tensioning.

Anchors and Chain Cables Rules 1970 (SI 1970/1453)

This Statutory Instrument specifies the mechanical proof load to be achieved by anchors of a given weight (see below). To pass, an anchor must not, in the opinion of the representative of the Certifying Body witnessing the tests, show material deformation, flaw or weakness after the test.

For a stockless anchor the weight of the anchor is to include both the weight of the anchor and its shackle. For a stock anchor the weight of the anchor is to include the weight of the anchor and its shackle but exclude the weight of the stock. If a special design of anchor has been accepted by a certifying authority as being as effective as a conventional anchor of greater weight, then at the request of the person seeking the certification of the anchor, this special anchor design may be tested at a proof load appropriate to an anchor of greater weight. The special anchor design is not to be tested at a proof load greater than the proof load for an anchor weight more than one third greater than the actual weight of the anchor.

Anchors which pass the proof test must be marked with the name of the certifying authority and the number of the test certificate. The test certificate is to include details of the dimensions and type of anchor, the proof load, the name of the test house and the name of the certifying authority.

Lloyd's Register Rules and Regulations for the Classification of Mobile Offshore Units, 1989

Part 2, Chapter 2, High Holding Power anchors and Special Quality Chain Cable

The rules and regulations state that cast and forged anchor components and plate material for anchors are to be fabricated in compliance with Lloyd's "Rules for the Manufacture, Testing and Certification of Materials", (see below).

Proof loads for High Holding Power (HHP) anchors are specified for anchors of 50 kg (test load 29.5 kN) to 36000 kg (test load 2730 kN). For HHP anchors with a mass greater than 35000 kg the proof load is to be:

$$\text{Proof load, (kN)} = 2.452 \times (\text{mass of anchor in kg})^{2/3}$$

but not less than 2730 kN. Each anchor to be used on a platform must be subject to a proof test. On completion of the test an inspection is required and must show the anchor to be free from significant defects. In particular the permanent set of the anchor must not exceed 20 mm.

The rules in this chapter are directed primarily towards HHP anchors. However the proof loads specified may also be applied to ordinary ship-type stockless anchors

by using the proof load specified for an anchor having a mass three quarters that of the actual mass of the ship anchor. Anchors may also be proof tested to higher loads than tabulated in the Rules, provided that the anchor design has been especially approved for higher loads.

Marking of the certified anchor is to include either the letters "Lloyd's" or "LR", he proof test load and, when appropriate, the letters "HHP". Also, each major component of the anchor which is either cast or forged is to be marked as such.

Part 3, Chapter 4 Mooring Equipment

This chapter deals with temporary mooring equipment, which is defined as mooring equipment for use during voyages or changes of position. Compliance with the Rules for temporary mooring equipment is not compulsory, but vessels which do comply are awarded a classmark signifying their compliance.

The Rules note that mooring equipment intended primarily for positional mooring will only be accepted as additionally fulfilling the requirements for temporary mooring if the equipment arrangement is such that it can be efficiently used in this second role.

To satisfy the Class regulations regarding temporary mooring a minimum of two anchors are required, arranged so that they can quickly be dropped. The mass of these anchors is determined by an expression dependent on the displacement of the vessel and the surface area of the vessel over which wind forces act. It is assumed that the anchors will be HHP anchors. However, anchors which must be laid the right way up, or which require the fluke angles to be altered for different soil conditions are not acceptable.

For an anchor design to gain approval as a HHP anchor, it must generate a holding capacity at least twice that generated by a standard stockless anchor of the same mass, tested at the same time in field tests conducted at sea. The field tests must be carried out on at least three types of seabed, preferably soft mud or silt, sand or gravel, and hard clay. The anchor line must have a scope of at least six, preferably ten, and the same scope is to be used for both the potential HHP anchor and the standard stockless anchor. The anchor line used for the tests may be either chain or wire.

If approval is sought for a range of sizes of anchor, a minimum of two sizes of anchor must be field tested. The larger of these two test anchors must be at least one tenth of the mass of the largest anchor for which approval is desired. The smaller of the two test anchors must have a mass of at least one tenth of the larger test anchor.

HHP anchors are required to embed and remain stable for pulls up to twice the capacity of the equivalent weight standard stockless anchor, regardless of the orientation at which they first settle on the seabed when dropped from a hawsepipe or anchor rack.

<u>Part 6, Chapter 7 Rules for the Classification of Positional Mooring Systems and Thruster Assisted Mooring Systems</u>

This chapter presents rules for positional mooring equipment. Positional mooring is defined as the deployment of an array of anchor lines, to enable a vessel to keep station at a particular site. As for temporary mooring equipment, compliance with the rules for positional mooring equipment is not compulsory, but vessels which comply are awarded a classmark signifying their compliance.

The operations manual for the vessel must include instructions on laying and pre-tensioning the mooring system, adjusting the tension, and the procedure to be followed in the event of a failure of the mooring system.

The positional mooring system is to be designed to withstand environmental conditions with a return period equal to or greater than fifty years, the vessel being in survival mode. The mooring lines are required to have sufficient scope to ensure that uplift forces are not exerted on the anchors in this case, even when one of the mooring lines has failed.

It is stated that the anchors used in the positional mooring system must be sufficient in number, holding power and mechanical strength, to fulfil their intended function. It is stressed that the responsibility of the vessel owners to ensure that the holding power of the anchors is sufficient for each particular site.

The anchors used for positional mooring are to be of an approved design, fabricated in accordance with Part 2, Chapter 2, as discussed above. The mechanical proof load applied to the anchors is to be either half of the minimum breaking strength of the mooring line to which the anchor is to be attached, or the proof load specified in Part 2, Chapter 2, whichever is the greater.

Lloyd's Register Rules for the Manufacture, Testing and Certification of Materials, 1984

Lloyd's "Rules and Regulations for the Classification of Mobile Offshore Units" make reference to the following chapters of the Materials Rules:-

- Chapters 3.2 and 3.3. These chapters define the required mechanical properties and test procedures for plate steel.
- Chapters 4.1 and 4.2. These chapters lay down requirements for the manufacture and testing of steel castings.
- Chapters 5.1 and 5.2. These chapters specify the mechanical properties and testing procedures for steel forgings.

DnV Rules for the Classification of Mobile Offshore Units

<u>Part 3, Chapter 2 Special Designs, Equipment and Stability</u>

This chapter sets out requirements for temporary and emergency mooring equipment. Temporary mooring equipment is defined as equipment for use in harbours and sheltered anchorages. Emergency mooring equipment is defined as equipment for use in bad weather conditions during transit movements of the vessel, and is to be capable of preventing the vessel from drifting in an uncontrolled manner in bad weather. The requirements for temporary and emergency mooring equipment may usually be fulfilled by equipment fitted for positional mooring purposes.

For temporary or emergency mooring the vessel must be fitted with at least two anchors. These must start to fall under their own weight when the brakes of the anchor winches are released. The minimum size requirements for these anchors is determined from an expression involving the displacement of the vessel and the projected area of the surfaces of the vessel exposed to the wind. The anchor size requirements are based on stockless anchors, but either stocked or HHP anchors may be used instead. The following points are noteworthy:-

- For stockless anchors the mass of the heads must not be less than 60% of the total specified anchor mass of the heads must not be less than 60% of the total specified anchor mass.
- If stocked anchors are used their mass, not including the stock, must be at least 80% of the mass specified for stockless anchors (the stock itself must be 25% of the mass of the test of the anchor).
- If HHP anchors are used, their mass must be at least 75% of the mass specified for stockless anchors.
- If wire anchor lines are used, the anchor mass must be increased by at least 25%.

The anchor size requirements are based on the use of two anchors. Three or four anchors may be used instead, in which case each anchor may be one third or one fourth, respectively, of the total mass of the two anchors.

Mechanical proof testing is specified for both ordinary and HHP anchors. The necessary proof load is tabulated for anchor masses between 2.2 tonnes and

4.8 tonnes. For stockless anchors the proof load is to be chosen based on the total mass of the anchor, but for stocked anchors the proof load is to be based on the mass of the anchor minus its stock. For HHP anchors the proof load is based on a nominal mass which is 4/3 of the total mass of the anchor.

The proof load is applied on the flukes at a position which is 2/3 of the distance from the crown of the anchor to the tip of the fluke. To pass anchors must display no indication of defects after the proof test.

If the design of anchor to be used has not previously received type approval as an HHP anchor, strength calculations for the anchor and its shackle must be submitted for approval.

The requirements which an anchor design must satisfy in order to gain type approval as an HHP anchor are detailed. These relate to both the behaviour and field testing of the anchor design, and are essentially the same as the approval requirements for HHP anchors set out in Part 3, Chapter 4 of the Lloyd's Rules for Mobile Offshore Units. The DnV rules do however differ from the Lloyd's Rules with respect to the type and length of anchor line to be used in the test. DnV require that the anchor line is to be chain of the diameter specified in equipment tables listed in the chapter. DnV also specify that if the pull on the test anchors is measured by reference to the propeller revolutions of the AHV, the minimum water depth in which the field tests may be conducted is 20m.

Anchors which have been satisfactorily proof tested are to be marked with DnV's stamp, the anchor mass, the test certificate number and date of test, and when appropriate, the letters "HHP".

Material (plate, forgings, castings) requirements are specified within Part 2 of the Rules.

<u>Part 6, Chapter 2 Position Mooring</u>

This chapter lays down requirements for positional mooring equipment which apply to both single point and spread moored vessels.

All anchors must be proof tested. The proof test procedure is the same as for temporary mooring equipment, discussed in Part 3, Chapter 2 of the Rules. However the proof load is required to be 50% of the minimum breaking strength of the anchor line to which the anchor will be attached.

Anchors must be designed such that additional (piggyback) anchors may be attached.

Anchors and anchor shackles must be designed to withstand a load equal to the minimum breaking strength of the strongest anchor line that will be used. For anchor designs which have not previously received type approval, strength calculations must be submitted. Type approval for an HHP anchor design must be obtained by following the procedures outlined in Part 3, Chapter 2 of the Rules.

<u>Part 2, Chapter 1 Steel and Iron</u>

Cast anchor components are to be made to "special quality" specification. The requirements for special quality castings include specified minimum Charpy test results in addition to the tensile strength and yield stress specifications for "normal quality" castings.

API Recommended Practice for Analysis of Spread Mooring Systems for Floating Drilling Units, RP 2P, 1987

Mooring design is based on environmental criteria which have a 99.9% probability of not being exceeded in an average year.

It is stated that in order to provide information from which anchor performance may be estimated, bottom soil conditions at the intended drilling site should be investigated. The possibility of piggybacking being required when the seabed is very soft is noted. It is also suggested that pile anchors may have to be used instead of drag anchors when the seabed is very hard.

The factors influencing anchor holding power are listed under headings of anchor type, bottom soil conditions and anchor behaviour during deployment. It is noted that prediction of anchor holding power is difficult, because of the considerable variability in these factors. Further, it is suggested that the exact holding power can only be determined after the anchor is deployed and tested.

When attempting to predict the anchor holding power for a new site, it is recommended that wherever possible reference should be made to performance data for the given anchor type in similar bottom soils to those at the new site. Graphs of holding capacities for several types of anchor in sand and mud soils are given, which may be used when more specific data is not available (Figures 32, 33 reproduced from API RP2P). These graphs are based on US Navy test data and it is noted that the design of some of the anchors covered has been modified since the tests were conducted. A caution is also given that performance data from other sources can vary significantly both from the US Navy data and between each other.

The holding capacity of the embedded length of mooring line adjacent to the anchor is expressed as:

$$\text{Holding capacity (Newtons)} = f.L.w$$

Where f is the coefficient of friction between the mooring line and the sea bottom and L, w are, the length of mooring line in contact with the seabed (m) and the submerged unit mass of the mooring line (kg/m), respectively. The coefficients of friction for chain and wire mooring lines aer given in Table 8, as reproduced from API RP2P.

Table 8
Coefficient of friction for chain and wire rope
(from API RP2P: Analysis of spread mooring system for floating drilling units, 1987)

	Starting	**Sliding**
Chain	1.0	0.7
Wire rope	0.6	0.25

The lengths of the mooring lines are to be such that they approach the seabed at a tangent to the bottom, when the platform is at its maximum predicted offset.

API Draft Recommended Practice for Design, Analysis and Maintenance of Mooring for Floating Production Systems RP2FP1, 1991

With respect to drag anchors, the provisions of this draft recommended practice are essentially similar to the guidance on drag anchors presented in API RP2P. The following modifications and additions to the provisions of RP2P should be noted:-

- Mooring design is to be based on 100 year return period environmental criteria, although scope is made for modifying the return period where this can be justified by a risk analysis.
- The graphs of anchor capacity in sand and mud included in API RP2P have been revised (Figures 34 and 35 as reproduced from API RP2FP1).
- Drag anchors are to be designed with a factor of safety of 1.5 for the maximum storm load and all mooring lines intact, and a factor of safety of 1.0 when one line is broken.

API Recommended Practice for In-Service Inspection of Mooring Hardware for Floating Drilling Units, RP2I, 1987

Procedures for the inspection of mooring equipment on floating drilling units are detailed. It is stated that some of these procedures are also applicable to the moorings of other floating structures such as Floating Production Systems, pipelaying barges and crane barges.

Visual inspection of anchors is recommended, directing particular attention to the welds and corners, and to areas of high stress. Visual inspection of anchor shackles is suggested, supplemented by Magnetic Particle Inspection (MPI) of the inside bend region and the circumstances of the holes for the shackle pin.

When the inspection is conducted offshore it is suggested that the anchor is either hauled on board an AHV or lifted onto the deck of the platform by crane.

API Recommended Practice for Qualification Testing of Steel Anchor Designs for Floating Structures, API RP2M, 1980

This recommended practice details qualification (type approval) tests for drag anchors. The test procedures are stated as being suitable for conventional anchors with flukes, shank, stock and padeye. Qualification testing is only necessary for one anchor of each design.

The first test consists of the application of a proof load to the anchor flukes. The proof load, sufficient to produce a moment at the pivot of 184000 Nm/tonne times the anchor weight in tonnes, is applied by pulling on the anchor shackle, with the anchor flukes supported at either their tips or at two thirds of the way along their length (Figure 36 as reproduced from API RP2M). A number of strain gauges are mounted at prescribed positions on the anchor. The anchor is deemed to have failed the proof test if one of the strain gauges shows a strain in excess of 0.001 mm/mm before the proof load is reached, or if the anchor exhibits any permanent deformation or cracking at the conclusion of the test.

The anchor shackle and crown padeye are tested by applying a tension load to the anchor by means of the shackle and padeye. Values for this tension load are specified for anchors of 9.07 tonnes to 13.61 tonnes. The anchor is deemed to have failed this test if any permanent deformation or cracking is apparent at the conclusion of the test.

Anchor stocks, when fitted, are tested by supporting the anchor at points a third of the way from the end of each arm of the stock, whilst applying a tension load to the shackle of the anchor. Proof loads are listed for anchors of 9.07 tonnes to 13.61 tonnes.

The final test consists of hammering the suspended anchor to check for inclusions or voids in the metal.

As part of the information gathering exercise, interviews were held with several organisations including operators, drilling contractors and certifying authorities. A number of comments were received with respect to codes and regulations.

From the proceeding sections, it is noted that the codes and regulations give detailed methods and rules for material and mechanical testing of drag anchors, and procedures for classification of non-standard anchors. However, little or no guidance is available for anchor specification/selection procedures for particular sites, and for anchor handling activities. The lack of guidance in this area was confirmed by those interviewed. Some of those interviewed expressed opinions to leave the specification of anchor types to certifying authorities and not define anchor usage in guidelines, where site specific assessments would be inappropriate and difficult to implement.

It was confirmed through many interviews that there were no guidelines for handling anchors offshore, and a drilling contractor noted that much reliance was placed on previous experience.

4. CURRENT DEPLOYMENT

4.1 ANCHOR SELECTION

4.1.1 Use of drag anchors

All those interviewed stated that MODUs, crane barges, flotels and pipelay barges almost invariably use drag anchors. Drag anchors are chosen for these applications in preference to other types of anchor because of their mobility (ease of deployment/recovery). It was also remarked that jackups use drag anchor based temporary moorings to assist them in positioning correctly, preparatory to jacking up close to a jacket, or when re-entering an existing wellhead.

Floating Production Systems (FPSs), Single Buoy Moorings (SBMs) and storage buoys may make use of either drag anchors or pile anchors. Bottom conditions are always important in determining which is chosen: piles will be used if the soil is considered to be too soft for long term mooring using drag anchors. Cost considerations are another factor influencing the decision between drag anchors and piles. Drag anchors were said to be more expensive to buy than piles, but much cheaper to install. It was commented that the for SBMs the choice between drag anchors and piles depends on the water depth and consideration of the length of the SBM is to be in place: for short term installations drag anchors would always be chosen. The mooring consultants interviewed stated that they would also recommend pile anchors for any structure intended to be moored in the same position for “prolonged periods”.

Deadweight anchors have been used for at least one storage buoy in the North Sea. The persons interviewed were not aware of the reasons why deadweight anchors were chosen in preference to drag anchors for this buoy.

4.1.2 Choice of drag anchor type

Several organisations stated that a high proportion of MODUs had been fitted with articulated stock anchors when built, and still retained these anchors as normal equipment (the LWT articulated stock anchor was mentioned in particular as being a common fitting on US built MODUs). However, although articulated stock anchors are very common equipment on MODUs, both their holding power and their durability were widely criticised (see below).

The consensus was that the modern Bruce, Stevpris and Flipper-Delta types are all satisfactory anchors, with a performance normally well in excess of the articulated stock anchors.

When a MODU is engaged to work at a given site or in a given area, one of two different approaches may be taken in deciding what type of drag anchors the MODU will use when carrying out the work:-

- The first approach is to use whatever anchors are carried on the MODU (typically low performance articulated stock types) accepting that it may be necessary to piggyback one or more anchors onto some or all of the mooring lines in order to achieve the required holding power. Extra anchors for piggybacking are taken to the new worksite on the decks of the AHVs which are to assist in mooring the MODU. Typically, at least four extra anchors will be taken out speculatively to any new worksite. When the new worksite is known to be on bad holding ground, as many as eight extra anchors may be taken out.

- The second approach is to decide from the start to substitute higher holding power anchors for the articulated stock anchors fitted to the MODU. High performance anchors, usually of the Stevpris, Bruce or Flipper-Delta types, are then taken out to the new worksite on the decks of the AHVs and attached directly to the mooring lines of the MODU, in place of its fitted anchors.

The approach adopted is dependent on the operator to whom the MODU is contracted, and on the proximity of the anchor positions to pipelines. It was suggested that several operators are prepared to accept the articulated stock anchors carried on the majority of MODUs, with the likelihood of having to piggyback some or all of them, possibly with more articulated stock anchors.

Further, it was stated that large operators are much less inclined to accept articulated stock anchors and may insist on high performance anchors to substitute the anchors carried on the MODU. Alternatively, they ay decide on the provision of high performance anchors as backup anchors for piggybacking.

Whichever case applies, the supply of the necessary piggyback or high performance anchors is normally the responsibility of the operator. Some operators own their own stocks of anchors for this purpose. The required anchors are otherwise hired from marine equipment suppliers.

The purchase (or hire) price of the Bruce/Stevpris/Flipper-Delta type anchors is usually higher than that of articulated stock anchors. It was commented by one source that this higher price is usually offset by the reduction in MODU downtime during a change in worksite, because the high performance anchors do not normally need to be piggybacked. However another source considered that it was always cheaper to piggyback low performance anchors.

Piggybacking is usually avoided when the anchor points are close to pipelines. Instead, a typical action would be to substitute large high performance anchors for the low performance anchors fitted to the MODU, for example 40 tonne Flipper-Deltas might be used to replace 20 tonne LWTs.

With respect to the comments reported above, it should be understood that the type of anchor carried by a MODU is not usually an important factor to an operator who is considering whether to hire the MODU.

A number of reasons were advanced as to why articulated stock anchors had been fitted as original equipment on many MODUs, despite the widespread dissatisfaction with this type of anchor. The most frequently mentioned was the lower purchase cost of articulated stock anchors compared to more modern types such as the Bruce, Stevpris or Flipper-Delta anchors. With reference to US built MODUs, it was suggested that articulated stock anchors had proved to be satisfactory for Gulf of Mexico conditions.

There is an extreme reluctance to completely replace the anchors equipping a MODU by higher performance anchors, because of the very high costs involved. In addition to the actual cost of the replacement anchors, the fitting of a new type of anchor is likely to require the anchor racking arrangements to be revised, a task needing dockyard facilities.

Bruce anchors are commonly used for SBMs, although recourse is also made to other anchor types. The choice of anchor type is dependent on price and availability, but is influenced by a general practice of over designing the anchors for an SBM.

Anchors for FPSs will typically be high performance types, because of the cost implications if there is a problem with obtaining the required holding capacity at installation time.

4.1.3 Sizing of anchors

The Operators Manual for a MODU includes details of the approved operating envelope for that MODU. Before moving to a new site it is the responsibility of the drilling contractor (MODU owner) to ensure that the conditions at the new site fall within the operating envelope. This will be confirmed by a warranty surveyor, who will give location approval for the new site. The operator is responsible for providing the drilling contractor with sufficient site information to enable the drilling contractor to obtain location approval from the warranty surveyor.

The warranty surveyor should use the site information, particularly the bottom survey data, to decide what maximum post-installation test tension is required for each anchor. However one source suggested that it is questionable how much attention is paid to the bottom survey data, an felt that there is a tendency to simply ask for a high post-installation test load.

The preceding comments on the post-installation test load should be considered in conjunction with Section 4.4 below.

A quasi-static mooring analysis is usually considered to be adequate for MODUs. When a MODU is to work at several sites in the same general area, the mooring analysis is based on the assumption of a standard mooring pattern and 50 year storm conditions for the general area in which the MODU is to drill. In a site-specific analysis, separate analyses are carried out for each worksite, using the conditions peculiar to that particular site. Whether area-specific or site-specific analyses are carried out when the MODU is to work at unobstructed sites, is dependent on the operator and on the drilling contractor. A site-specific mooring analysis is always carried out for a MODU which is to moor in a sensitive position, such as close to a jacket or over pipelines.

It was stated that some operators take an active interest in ensuring that the mooring performance of a MODU is adequate for the required purpose, whereas other operators consider that it is the task of the drilling contractor to ensure that the mooring system will be adequate.

The lack of independent, reliable anchor holding efficiency data was widely remarked on. It was noted that the available data is limited to a small amount of published data, the most important part of which comes from US Navy tests (NCEL [1987]), and to the manufacturers own test data. Much of the published data is quite old, and consequently relates to articulated stock anchors or to higher holding power anchors of designs which have now been superseded. A number of further problems with the published data were highlighted by one operator (these observations follow a recent review of the database of published test information undertaken by this operator):-

- Almost all published test data have been obtained using anchors of very much lesser mass than the anchors used offshore. This is done to reduce test costs: minimising the size of the test anchor reduces the winch capacity required to pull the anchor to failure. The few large anchors tested have not been pulled to failure.
- Similarly, most published anchor tests have been done in very soft soils, because this minimises the winch capacity required to pull the anchor to failure, and thereby reduces the cost of the test. These tests are inappropriate to the greater part of the North Sea, because only the Witch ground, which constitutes just 10 to 15% of the area of the northern North Sea, consists of very soft to soft clay. The remainder of the northern North Sea is stiff to very stiff clay, with, in some areas, an overlying layer of sand. The seabed in the southern North Sea is sand.
- A number of tests of anchors in sand have been done by pulling a test anchor along partially saturated sand on a beach. This gives an erroneous result because the dilation effects are different when the sand is fully saturated. The holding capacity is actually likely to be greater when the sand is fully saturated, because the sand dilation forces can then be fully mobilised.
- Data on the soils in which anchor tests were conducted is generally very badly reported in the test literature. In many instances inappropriate tests were used to quantify the soil properties.

The operator further suggested that as a minimum, the following data was required to quantify the soil in which an anchor test is conducted:-

for clays
- shear strength variation with depth

for sands
- grain size analysis
- angle of friction from shear box tests
- cone penetration tests

The operator commented that to predict the holding capacity of a 30 tonne anchor in stiff northern North Sea clay, from the published test data available at the time of their review, would have involved a tenfold extrapolation with respect to mass, and a sevenfold extrapolation with respect to soil stiffness.

Several of the organisations interviewed stated that they made use of the manufacturer's data to size anchors. However the majority of these organisations expressed a lack of confidence in this data. The following were mentioned as reasonable working estimates of holding efficiency, 8 for articulated stock anchors and 15 for high performance anchors. It was suggested that the actual value for high performance anchors is in excess of 20.

Ease of handling was also mentioned as a consideration when sizing anchors. Thus original equipment MODU articulated stock anchors will typically be chosen to have masses in the range 30,000 lbs (13.61 tonnes) to 40,000 lbs (18.14 tonnes), because anchors which are bigger than this become difficult to handle on deck.

One operator indicated that their usual approach to improving the anchor holding power of a MODU fitted with articulated stock anchors, which will be of a size already approved by a certifying authority, is to substitute higher performance anchors of the same mass as the articulated stock anchors. The Certifying Authority is then approached to get area approval for the new anchors.

Flotels and tender-assist units will generally be moored close to jackets and as a consequence will have been the subject of a site-specific mooring analysis. Their moorings are arranged so that by hauling in and paying out appropriate lines, they can move away from the jacket when environmental conditions demands. The stand-off distance between jacket and semisubmersible which can be achieved in this way will typically be 600 feet (180 metres) for flotels and similar units, and 1000 feet (305 metres) fro crane vessels and other large semisubmersibles.

Jackups are typically fitted with relatively low performance anchors. When a jackup is being installed, tugs usually provide backup to the jackup's own moorings. However, despite this, the low performance anchors on jackups are frequently substituted by higher holding power types, particularly when the jackup is to be positioned close to a jacket. Further to this, one operator mentioned that they are keen to encourage jackup owners to improve the mooring equipment on jackups.

An interviewed classification society stated that they would usually require the loads on a SBM to be determined by model tests.

The mooring analysis for an FPS will almost invariably be dynamic. In respect of the anchor performance data used to design FPS moorings, the Classification Society suggested that the best solution would be to test a slightly subsize anchor of the chosen type on the actual site. However they commented that it was very rare that this level of information was forthcoming from the operator seeking certification of the FPS, and that often not even performance data from an equivalent site is made available.

4.2 PRE-INSTALLATION BOTTOM SURVEY

The general practice is to carry out a bottom survey for each new site at which a MODU is to work. The information gathered will typically include seabed soil type, water depth contour lines, and any obstructions or debris on the seabed. One operator also mentioned making checks for shallow gas as part of the bottom survey.

The bottom survey is the responsibility of the operator, and is often carried out in conjunction with geotechnical surveys of the area. In some instances, seabed information is extracted from previous geotechnical surveys. Seabed data are also exchanged between operators. It was suggested by one interviewee that the diligence with which the seabed survey is carried out varies from operator to operator.

The information from the seabed survey should be an important input to anchor selection and sizing activities discussed in the preceding section. In addition, the findings of the survey may prompt the fluke angle of the anchors to be changed, or the mooring pattern to be modified.

Several types of anchor make provision for the fluke angle to be altered by the user, depending on the type of soil in which the anchor is to be used. However the majority of the organisations interviewed stated that they rarely or never alter the fluke angle, preferring to leave the angle at a general compromise setting. It was suggested that the seabed conditions are often locally very "patchy", and so it is not straightforward to determine the type of soil an anchor will enter.

The mooring pattern will be modified, by changing the length or direction of certain mooring lines, in order to avoid obstructions or seabed debris, and sometimes to avoid bad holding ground

The certifying authority stated that for an FPS it would expect the pre-installation seabed survey to include, as a minimum, several boreholes and a side scan sonar survey.

4.3 INSTALLATION METHOD

4.3.1 General

MODUs and flotels require the assistance of AHVs to install their mooring spread. A typical operation sequence is shown in Figure 25. To save time some MODUs will lay the first anchor of their mooring spread themselves. Some support vessels are able to lay their complete mooring spread without assistance, by manoeuvring on their thrusters.

The interviewed marine contractors commented that to self lay an anchor, the anchor should be lowered with the anchor winch under power. They stated that simply releasing the brake on the winch and letting the anchor drop does not improve the likelihood of the anchor biting, as is popularly believed. Moreover, simply releasing the anchor in this manner is likely to result in coils of the anchor line landing on top of the anchor and becoming entangled with it, and can also result in mechanical damage to the anchor (particularly to the stock of articulated stock anchors). They also suggested that an anchor laid by an AHV is much more likely to embed satisfactorily than a self laid anchor. This is because the orientation of the anchor when it reaches the seabed, will be better.

Anchors laid with the assistance of AHVs are laid using either a ring chaser or a pendant wire system. Whichever system is used, each anchor is taken out to its designated position by the AHV. The anchor is then lowered to the seabed by either the wire attached to the ring chaser, or the pendant wire. If a ring chaser is being used, it is then taken back to the rig by the AHV, which pulls the ring back along the mooring line by the line attached to it. If a pendant wire is being used, the free end of the wire is attached to a buoy, and left in position.

Chain moored MODUs operating in the North Sea are more often equipped with permanent ring chasers than pendant wires. It was suggested that ring chasers are liable to cause damage to wire mooring lines, and a pendant wire system is therefore more suitable for wire moored MODU's.

If no problems are encountered, a full MODU anchor spread can be run in six hours. However, if problems with achieving adequate holding capacity are encountered it may take days to fully install the anchor spread.

Three AHVs will normally be used to install the moorings of a MODU or flotel Four AHVs are used for some flotels which have combination (chain/wire) moorings. For certain self-powered MODUs, two AHVs are considered to be sufficient, but this is unusual.

The AHVs used for MODU moves range in size from around 8500 HP (100 tonne bollard pull) to around 12,000 HP (160 tonne bollard pull). The bigger AHVs have two advantages. Firstly they are able to pull out a greater length of chain from the MODU; a smaller AHV may be unable to overcome the resistance of the length of chain on the seabed, when the anchor lines are long. Secondly, bigger AHVs are more stable, making anchor handling on deck easier.

Smaller AHVs are considered adequate for the small mooring systems of jackups.

The anchors for SBMs are typically lowered into position by AHVs, using pendant wires on the anchors, before the SBM is installed. After the anchor has been placed on the seabed, the pendant wires are removed by divers.

4.3.2 Piggybacking

MODUs rely very heavily on the possibility of piggybacking anchors. The anchors used for piggybacking are typically articulated stock types. It was noted that the large market in piggyback anchor rental implies that many MODUs do not have adequate anchors.

Piggybacking anchors is a time consuming procedure. For this reason piggybacking is usually only resorted to after it has become clear that the main anchor will not be capable of holding the post-installation test tension without assistance. The following was suggested as a useful rule of thumb. If an anchor drags 500 feet (150 metres) during the post-installation tensioning without achieving the required holding capacity, then the anchor is rerun. If the anchor still fails to hold after hauling in 500 feet (150 metres) then a piggyback anchor is added.

If the combined holding power of the main and piggyback anchors is still insufficient to resist the post-installation test tension, a second piggyback anchor is added. On some occasions even more piggyback anchors may be added (see Section 5).

The length of the line between the main and piggyback anchors is chosen to be sufficient to allow the piggyback anchor to be worked on, on the deck of the AHV, without disturbing the main anchor. Typical values used for the length of this line include the water depth plus 50m, and the water depth plus 20%.

Buoyed pendant wires have been used on all piggyback anchors, as it is not feasible to use ring chasers.

It was commented that whilst piggybacking works, in that it generally increases the total holding power, it is not clear how it works, as the addition of a piggyback anchor is believed to reduce the holding power of the main anchor, by preventing it from embedding properly.

It was also commented that Flipper-Delta type anchors should not be piggybacked, because the padeye for piggybacking is situated on the head of the anchor, and the load of the piggyback anchor will pull the flukes closed.

4.4 POST-INSTALLATION HOLDING CAPACITY TESTS

After a drag anchor mooring system has been installed, the mooring lines are usually subject to a tension test load, to embed the anchors and test their holding capacity. This test is normally witnesses by the operator's representative and on occasion, by the warranty surveyors. On MODUs, flotels and similar vessels the test tension is applied by tensioning diagonally opposite mooring lines against each other. Occasionally, a higher test tension is applied to a critical anchor by tensioning it against two or three of the other anchors of the vessel's mooring system. To tension pre-installed moorings, such as those for an SBM, special tensioning equipment is available from some anchor manufacturers.

For MODUs the post-installation tension test is standard practice. However, there are variations both in the way this tension is applied, and the basis for the magnitude of the proof tension. These factors are dependent on which operator/drilling contractor is involved.

On some MODUs the proof tension is applied immediately after the anchors have been installed. On others, the proof tension is applied only after the MODU has ballasted down. There are two points to note in respect of this difference in procedure. Firstly, ballasting down takes approximately six hours, during which time the anchors will "soak-in" to some extent. Secondly, if proof tensioning is carried out before the MODU is ballasted down, any anchor which fails to hold can be brought back to the MODU for inspection.

A third approach to applying the proof tension is to deliberately "soak-in" the anchors for four to six hours with some tension on, before applying the full test tension.

The proof tension is generally applied for a period of fifteen minutes. Various bases for the magnitude of the proof tension were quoted by the organisations interviewed including, for chain moorings:

- the stall load of the anchor winches, stated to be in the range 350 to 400 kips (1555 to 1780 kN)
- The figure defined in the operating manual for the MODU, usually around 350 kips (1555 kN)
- 33% of the breaking load of the mooring system

and for wire moorings:

- 33% of the breaking load of the mooring wire (380 kips) (1690 kN).

The certifying authority commented that the basis for the tension test load is a vexed question, and that the tension test load is never as high as the design ultimate load. Consequently, as the 100 year storm conditions are approached, it is never certain how the anchors will perform. The specification of a tension test load which is less than the design ultimate load is defended on two counts. Firstly "soak-in" will improve the performance of the anchors subsequent to the tension test. Secondly, there is a belief that anchors are better able to withstand occasional high loads than steady tensions.

The certifying authority stated that they would like anchors to be tested to the 100 year storm load. However, they pointed out that difficulties could be experienced in attempting to impose such high test tensions. (A MODU was damaged by an attempt to impose such a tension test load which was 50% of the breaking load of its mooring lines).

4.5 RECOVERY PROCEDURE

MODUs and flotels require the assistance of AHVs to recover their anchors. The recovery procedure depends on whether the rig is equipped with ring chasers or buoyed pendant wires.

To recover an anchor using a ring chaser, the line attached to the chaser is passed from the rig to the AHV. The AHV then pulls the chaser along the mooring line out to the anchor. When the chaser reaches the anchor, the AHV lifts the anchor by the wire attached to the chaser. The rig can then haul in the mooring line.

To recover an anchor fitted with a buoyed pendant wire, the AHV picks up the buoy, and lifts the anchor by pulling on the pendant wire. The rig then hauls in the mooring line.

Even when it is fitted with ring chasers, a MODU or flotel will normally resort to using buoyed pendant wires if it has to moor near or over pipelines. This is done because when using a ring chaser to recover an anchor, there is always the possibility of picking up a bight of chain with the chaser, and thereby dragging the anchor over a pipeline.

Using larger AHVs anchor recovery can be achieved more rapidly. Taken in conjunction with the advantages of larger AHVs for anchor installation, there is a move in the industry towards employing larger AHVs for relocation of MODUs.

The anchors of an SBM are typically recovered by detaching, in turn, each one of the SBM's mooring chains, and passing the end to an AHV. The AHV then retrieves the anchor by hauling on the mooring chain.

4.6 IN-POSITION INSPECTION PROCEDURES

The interviewed certifying authority stated that they would be strongly in favour of ROV surveys being conducted on newly installed drag anchor mooring systems as a general practice. They now insist on post-installation inspection, by ROV or diver, of the anchors of any FPS which they are asked to certify. The reason for their insistence on post-installation inspection for FPSs is that recently they have been involved in two or three installations in which the anchors failed to embed completely in sand seafloors, and were therefore vulnerable to subsequent scour.

For applications other than FPSs, in-position inspection is most usually limited to monitoring the tensions in the mooring lines of the vessels or structure.

The general opinion was that the accurate monitoring of anchor line loads was important. The primary reason cited for its significance was the need to balance loads between mooring lines during storms.

Two of the operators interviewed considered that the tension monitoring equipment on MODUs is most usually of very low accuracy. Reinforcing this view, one of the drilling contractors interviewed said that they had put considerable effort into improving the tension monitoring systems originally fitted to their MODUs.

A third operator was of the opinion that the chain tension gauges on MODUs are accurate to within 10%. This operator checks the calibration of the chain load gauges against winch motor power during the post-installation tensioning of anchors.

4.7 INSPECTION AND REPAIR BETWEEN DEPLOYMENTS

All comments regarding the inspection of the anchors of MODUs between deployments were in accord. Inspection is visual, and is carried out on the deck of the AHV by the crew of the AHV. Inspection is carried out both when the anchors are deployed and when they are recovered. Some visual inspection is also performed from the deck of the MODU, using field glasses, when the anchors have been recovered onto their racks.

The interviewed marine contractor stated that their anchors were always subjected to a Classification Society check before re-use. It should be noted that this interviewee usually deploys anchors for longer periods than would be the case for a typical MODU.

One operator reported carrying out regular three yearly inspections of their stock of backup anchors. In these inspections, visual inspection of the anchor is supplemented by NDT inspection of the anchor shackles.

Below are presented comments regarding wear and tear damage, as might be discovered by routine inspection between deployments. Data regarding damage caused by handling, and damage sufficient to cause failure of the anchor, are included in Sections 5 and 7 respectively.

The comments regarding wear and tear damage were mixed:-

- One drilling contractor and one operator stated that damage to anchors was rare, damage to the mooring system being chiefly confined to the chains and wires.
- Two operators and the marine contractor reported occasional damage, most usually to the flukes and stocks of articulated stock type anchors.
- Problems which could be directly ascribed to wear were only reported by two of the interviewees. The problems were heavy wear of the blocks limiting maximum fluke angle, ovalisation of the hole in the shank for the anchor shackle, wear of the anchor shackle pin, and distortion of stocks and flukes.
- Single instances of bent shanks on an articulated stock anchor and on one of the higher performance anchor types were also reported.

It was suggested that the problem of wear and tear damage was worst for pipelay barges, on which the anchors are moved very frequently.

Damage at the welds of fabricated anchors is occasionally encountered. This damage was ascribed to dropping the anchor from too great a height above the seafloor in excess of 50 feet (15 metres).

The interviewed marine contractor stated if an anchor is repairable, the repair is subcontracted to a specialised engineering repair company. The Classification Society is then asked to re-certify the anchor.

The marine equipment supplier considered damage to anchors to be fairly unusual, and usually to be confined to bent anchor flukes. These tend to happen most often when anchoring in boulder clay. It was stated that to repair bent flukes on anchors is unusual, and the anchor should for preference be replaced. Alternatively, for some types of anchor, new flukes can be obtained from the anchor manufacturer. They stated that they are reluctant to repair anchors and will only do so to Certifying Authority approval. They suggested that in the past, some anchor users have tried to carry out their own repairs to anchors, to save money. They think that such repairs are probably no longer undertaken. These comments should be read in conjunction with Section 7.

One of the operators indicated that any of their stock of backup anchors which was severely damaged was scrapped. Twelve anchors had been scrapped in the last two years, mainly of the articulated stock type.

4.8 CORROSION PROTECTION

All parties interviewed agreed that corrosion was not an issue. The marine equipment supplier commented that anchors generally last a long time, unless mechanically damaged. By way of example they cited a stockless ship’s anchor in their possession which although admittedly now little used, is still in good condition despite being at least 46 years old.

Typical practice is to occasionally shot blast and repaint anchors. On ships, spare anchors are often simply repainted over the old paint, with no prior cleaning down. The marine equipment supplier commented that as a result, such anchors frequently have an extremely thick coating of paint.

5. ANCHOR HANDLING DIFFICULTIES

5.1 MECHANICAL DAMAGE

Several comments were made concerning mechanical damage to anchors during installation and recovery. In the main, these comments were directed towards articulated stock anchors, the stocks of which were stated to be easily bent. Occasional instances of flukes being bent, particularly in boulder clay, were also remarked on. One operator said that they experienced one or two instances a year of anchors being damaged during installation.

Articulated stock anchors were also said to be prone to falling apart when hit by ring chasers during the anchor recovery operation.

5.2 HANDLING ON DECK

Articulated stock anchors are generally found to be simple to handle on the AHVs deck.

Some difficulties were noted with handling certain of the higher performance anchors. One type has been found to be difficult to pull onto the deck of an AHV. Another type presents problems on two counts. Firstly, because this anchor stands on its fluke, the shank is at a considerable height above the deck of the AHV, which makes the attachment of the mooring chain a difficult operation. This problem is often overcome by leaving a tail of chain attached to the anchor. Secondly, on older patterns of this type of anchor, the shank is attached to the fluke by four bolts, which must be removed to alter the fluke angle. This operation was stated to be very awkward and required perfect weather conditions. It was further stated to be much easier to change the fluke angle on anchors for which the adjustment is made by cutting out or welding in packing blocks.

Operations which require the AHV crew to move around an anchor on the deck of the AHV generally represent a safety problem, because of the possibility of the anchor moving. During certain stages of the anchor laying and recovery procedures, the AHV crew must be on deck to handle the wire. However there should be no need for the crew to leave the protection of the safety barriers on the deck of the AHV during the stages of the laying and recovery procedures when the wire is under high tension.

5.3 INSTALLATION AND RECOVERY

Very frequently when installing a mooring system, it is found that one or two of the anchors drag when the test tension is first applied. Although this may reflect poor holding conditions, it is also strongly dependent on the skill of the master of the AHV:

- He may not place the anchor on the sea bed correctly.
- He may apply too much tension to the chaser wire (when recovering the chaser) and thus lift the anchor.
- He may snag the chaser on the anchor or the chain. Then when trying to return the chaser to the rig he will drag the anchor back towards the rig.

- He may let the chaser wire go too slack. The ring chaser will then sit on the chain at too oblique an angle, which is likely to make it jam. The anchor will then be dragged back towards the rig.

When the holding conditions are poor, it is often found that the proof tension can be approached when the anchor is first tensioned, but that the tension cannot be held. Instead the tension gradually falls back.

Typical procedure, if an anchor fails to hold on first applying the test tension, is to:-

(i) re-install the anchor

If this fails,

(ii) re-install at a different bearing from the rig,

If the anchor still fails to hold,

(iii) piggyback the anchor.

Almost invariably it is articulated stock anchors rather than the higher performance Bruce, Stevpris and Flipper-Delta types which must be piggybacked. The frequency with which piggybacking is found to be necessary is high. One operator had piggyback anchors on ten out of twelve MODUs offshore at the time of the interview, and considered that on a typical MODU move, one to five anchors would have to be re-installed and up to four piggyback anchors would be needed. Another operator estimated that 20% of all anchors set require piggybacking.

It is not unusual for more than one piggyback anchor to be put on an individual mooring line in order to achieve the required proof tension. It is also not uncommon for several of a MODU's mooring lines to be piggybacked. For one MODU, operating on an area of hard clay overlaid with highly plastic clay, it was found necessary to put five piggyback anchors on a single mooring line (in addition to the main anchor) in order to achieve the required test tension. Another MODU operating in poor holding conditions needed a total of thirty eight anchors (main anchors plug piggyback anchors).

Piggybacked anchor systems are awkward to install and recover. One problem mentioned was that tensioning the piggybacked mooring line can cause other mooring lines to drag. These in turn then have to be reset and it may take days to fully install the complete mooring system.

It was suggested that difficulties can be experienced in recovering any type of anchor, and that perseverance is required. Problems which may occur include:-

- the chaser wire may break,
- a chain link may break, and thereby lose the anchor, as a result of accidental application of a bending load on the link with the chaser,
- the ring chaser may snag on the shackles at the end of the chain, and therefore fail to slide onto the anchor shank.

Particular difficulties have been experienced in recovering the higher performance anchors. On some occasions pulls of 100 tonnes have been needed to break-out these anchor types. Certain of the fixed fluke designs of higher performance anchor were mentioned as being the most difficult to recover.

Two solutions were suggested for recovering one of these fixed fluke anchor types. The first was to apply a steady tension on the chaser wire for an hour. The second was to ensure that the chaser is pulled right down to the angle in the shank, and then use a long chaser wire to pull at a large angle to the anchor.

Mooring chains can sometimes be very difficult to pull out, particularly in certain blocks in the North Sea where the seabed comprises is very sticky mud. In these areas, 350 kip (1555kN) tensions have on occasion been required just to haul in chain. The embedding of long lengths of mooring lines alters the response of rigs operating in these areas, requiring ring chasers to be sent down the mooring lines every two weeks to free the chains.

Mushroom anchors and single fluke stock anchors were stated to be very difficult to use.

6. EFFECT OF ANCHOR DRAGGING ON SUBSEQUENT HOLDING POWER

The occurrence of anchor dragging was reported by several of the interviewees. The severity of the anchor dragging, and its effect on the subsequent holding power of the anchor, differed from report to report. There was also some divergence in the frequency with which anchor dragging was reported to occur. The comments made by interviewees were directed towards MODUs and flotels

One interviewee stated that during storms anchors drag short distances (of the order of a few metres). Mooring line tensions are restored after the storm by hauling in a short length of the mooring lines.

Other interviewees reported that on infrequent occasions the tension in one of a MODU's mooring lines will drip markedly during or immediately after severe weather. The tension may for example fall from around 130 tonnes to around 90 tonnes. Another organisation commented that such incidents are very rare and that tension can usually be recovered by hauling in the slack mooring line (typically around 100 feet (30 metres) of line must be hauled in). However, yet another of the organisations interviewed stated that once or twice a year, within a fleet of nine or ten MODUs, a loss of line tension occurs which cannot be recovered by hauling in on the mooring line. The anchor must then be hauled back to the rig and reinstalled. It was claimed by another organisation that once an anchor starts to drag, it will continue to do so.

A comment regarding the frequency of anchor dragging incidents was that it is occasionally necessary to retension the mooring lines of a MODU, subsequent to post-installation tensioning, but that there is a less than 10% probability of having to do this during the period of any particular deployment.

Concerning an incident in which a MODU lost some of its mooring lines and was driven off station by the severe storm of December 1990, it was stated that the MODU's anchors had dragged 100 feet (30 metres) under a 1000 kips (4450 kN) tension. When the MODU returned to station, the dragged anchors were found to be still capable of sustaining the post-installation test tension.

Data on anchor dragging incidents sufficiently serious to compromise station-keeping is discussed further in Section 7.

7. ANCHOR FAILURES

Articulated stock type anchors are prone to coming apart because of failure of the stock. The stock frequently becomes bent on these anchors. This may in itself be sufficient to cause the anchor to fail. If it is not, straightening of the stock can make it brittle and likely to snap at a later date.

The problem is exacerbated on many articulated stock anchors by the way in which the stock is located in the head of the anchor. A fixed ring on the stock sits at one side of the head. A loose retaining washer is placed at the other side, and held in place by a block welded to the stock. The stock may be removed in order for it to be straightened, for a new stock to be substituted, or to allow a bent fluke to be straightened. If, when the stock is replaced, the block is not welded on adequately, the block can be knocked off if the anchor falls on the end of the stock. The anchor is then likely to fall apart. If the weld is extended completely round the washer, the stock is made brittle and will subsequently snap, again causing the anchor to come apart.

The interviewed marine equipment suppliers provide less than one replacement stock a month for articulated stock anchors.

Data on anchor dragging incidents which are sufficiently serious to compromise stationkeeping, are limited, and usually quite vague. Opinions varied as to the frequency of serious anchor dragging incidents, from very rare to many cases. The certifying authority interviewed has received no reports of dragging of anchors on the vessels which it classifies, but is aware of a small number of serious anchor dragging incidents which have occurred to vessels classed by other certifying authorities.

Specific examples of serious dragging incidents include the following:

- A flotel which dragged all of its anchors during a storm. It is believed this resulted from insufficient penetration of its anchors.
- A support vessel which apparently dragged all of its anchors. It is believed that this vessel was fitted with high performance anchors at the time.
- The incident mentioned in Section 6 in which a MODU was driven off station.
- An example of a piggybacked MODU anchor dragging 200 feet (60 metres) under a tension of around 500 kips (2225 kN).

The moorings of crane and pipelay barges are not designed for storm conditions. It was suggested, however, that there is a tendency for these vessels to continue to work for as long as possible as the weather worsens, with the result that they experience dragged anchors and broken mooring wires.

In some areas, such as the Forties field, anchors hold well under steady tension, but the soil becomes more fluid when subject to shock loads. Anchors can pull out in storms as a result of this fluidisation.

MODUs in confined positions sometimes have problems with anchors dragging across pipelines. The situation can arise that the weatherside mooring lines cannot be adjusted to the extent desired because of the confined space, whilst the leeside mooring lines cannot be slackened off because of their proximity to pipelines.

8. CONCLUSIONS

The findings of a detailed assessment of current practices for drag anchors have been presented. The investigations have yielded a significant number of interesting aspects from which the following general conclusions have been drawn:

- Available experimental test results on drag anchors are dated, and based on small scale anchors. They do not reflect present day high holding power requirements of the North Sea offshore industry. Furthermore, tests have been conducted in clays and muds which are generally inappropriate to the seabed conditions that exist in the North Sea. In many instances, poor testing methodology has been adopted.

  Therefore application of available test data requires large magnitude extrapolation with respect to size of anchor and strength of soil.

- In general, codes and regulations are consistent with each other, but some cover the subject of drag anchors in a very piecemeal and disjointed manner. Although the codes provide guidance on mechanical proof testing of anchors and rating of HHP anchors, no explicit guidance is provided with respect to anchor handling or level of tension load for post-installation proof tension tests.

- Piggybacking anchors is very common practice in the North Sea. Surprisingly however, there are no set procedures or guidelines for piggybacking.

  The performance of articulated stock anchors is marginal for applications in the North Sea and since many MODU's operating in the North Sea are equipped with articulated stock anchors, piggybacking of anchors is very frequently necessary to achieve post-installation test tension loads.

  Sometimes, higher performance anchors are deployed instead of piggybacking articulated stock anchors. However, the hire or purchase cost of higher performance anchors is significantly greater than that of articulated stock anchors. The permanent replacement of a vessel's articulated stock anchors by higher performance anchors requires costly modifications to the MODU's anchor racking system.

- A detailed search of technical literature has revealed that virtually no numerical analyses have been conducted for drag anchors and almost all investigations have been experimental in nature.

- Inadequate information exists to allow a systematic selection of a drag anchor for a particular site. Much reliance is placed on manufacturer's data and NCEL test data. The NCEL data is not applicable to many of the more recent anchor types.

  Manufacture's data provide guidance on the setting of fluke angles for certain seabed conditions, and the manufacturer's anchor performance data are based on these settings. However, in general it was suggested that when these anchors are deployed, the setting requirements are often disregarded, and an average fluke angle adopted.

- Pre-installation surveys take the form of seabed contour plots, detection of obstructions, for example pipelines, and soil-type identification. Only one organisation added that shallow gas detection is carried out.

- In most cases, an AHV is required to position the anchors on the seabed. The ease with which the anchors can be handled depends on the type and size of the anchor, the size of the AHV and the skills of the master of the AHV. The consensus was that certain of the higher performance anchor types present the greatest difficulty with respect to anchor handling.

  Higher performance anchors are frequently difficult to recover, and either very large, or long duration application of loads may be necessary, to dislodge them from the seabed.

- If problems with achieving adequate holding capacity are encountered it may take days to fully install the anchor spread.

- It was noted that in-position inspection procedures are applied only in the case of FPSs. In most other cases "inspection" is based on line tension alone.

- In general, the anchors are only visually inspected between deployments. Damage, if any, usually results from the installation or recovery stages. Corrosion of the steel is not a problem.

- Certifying authorities hold considerable proprietary data through their involvement in certification of permanently moored systems.

  A joint industry funded project has recently completed drag anchor tests in the Gulf of Mexico. Although the tests considered articulated stock and higher performance anchors, the tests have been carried out in soil conditions unrepresentative of soil conditions in the North Sea.

- Some research has been done on small scale tests on drag anchors using the centrifuge method. This method uses acceleration forces to model the behaviour of true-size drag anchors, and is claimed to provide useful information with respect to failure mechanisms.

- Conflicting views were expressed on the holding power of an anchor after dragging. Some organisations stated that holding power was recovered after dragging, but others found that total loss of tension resulted.

- A number of anchor failures have been reported. Most of these relate to articulated stock anchors, which are prone to fall apart from failure to adequately locate the retaining washer on the stock. Alternatively, failure may occur due to excessive welding to locate the retaining washer.

This study has concluded that drag anchors are widely deployed in the North Sea offshore industry. The findings of current day practices in the use of drag anchors reveal that further investigations in some areas are necessary to ensure the safe and reliable use of drag anchors.

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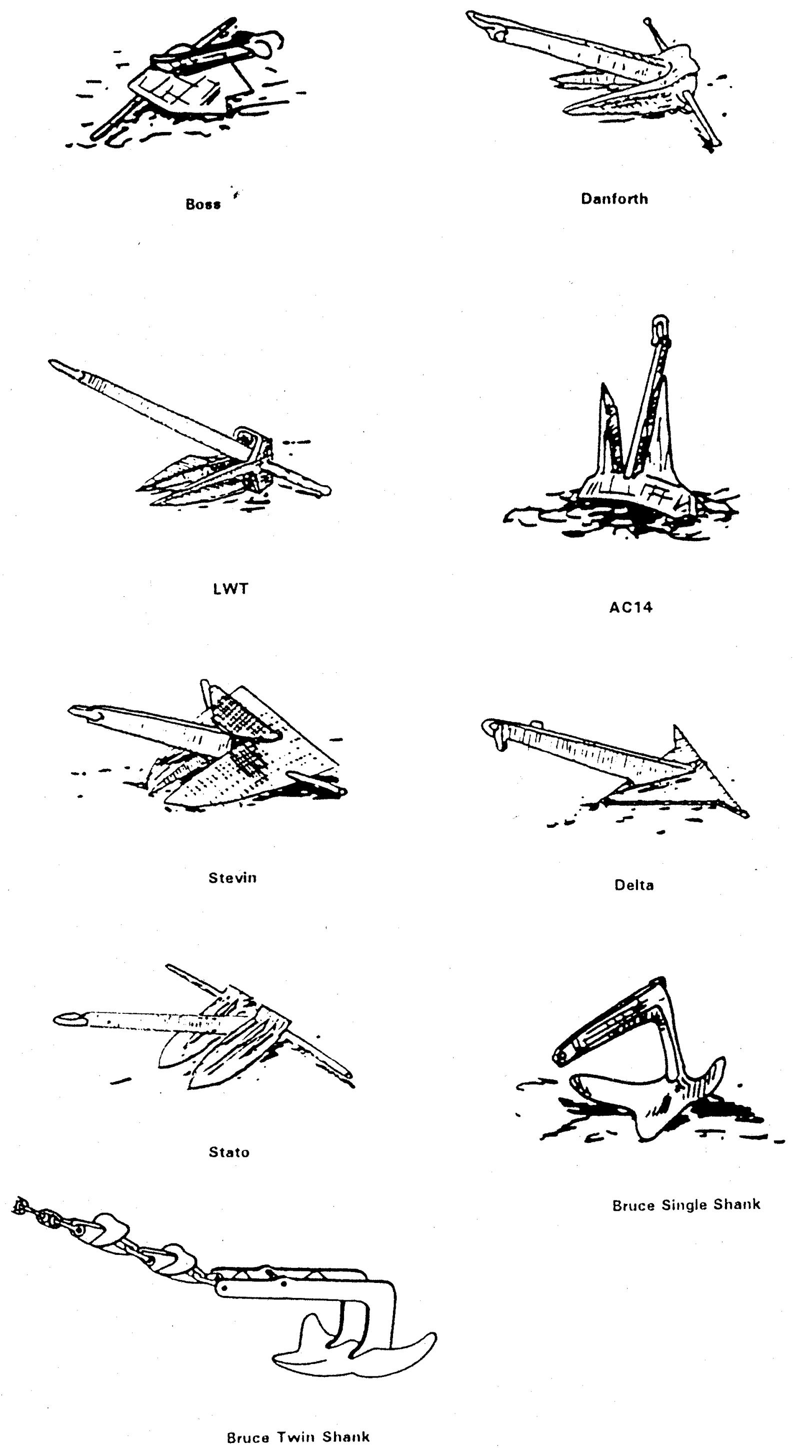

Figure 1a Typical anchor types (after Van den Haak [1990], Van den Haak [1972], also manufacturers data sheets for Bruce, Stevpris and Flipper-Delta anchors)

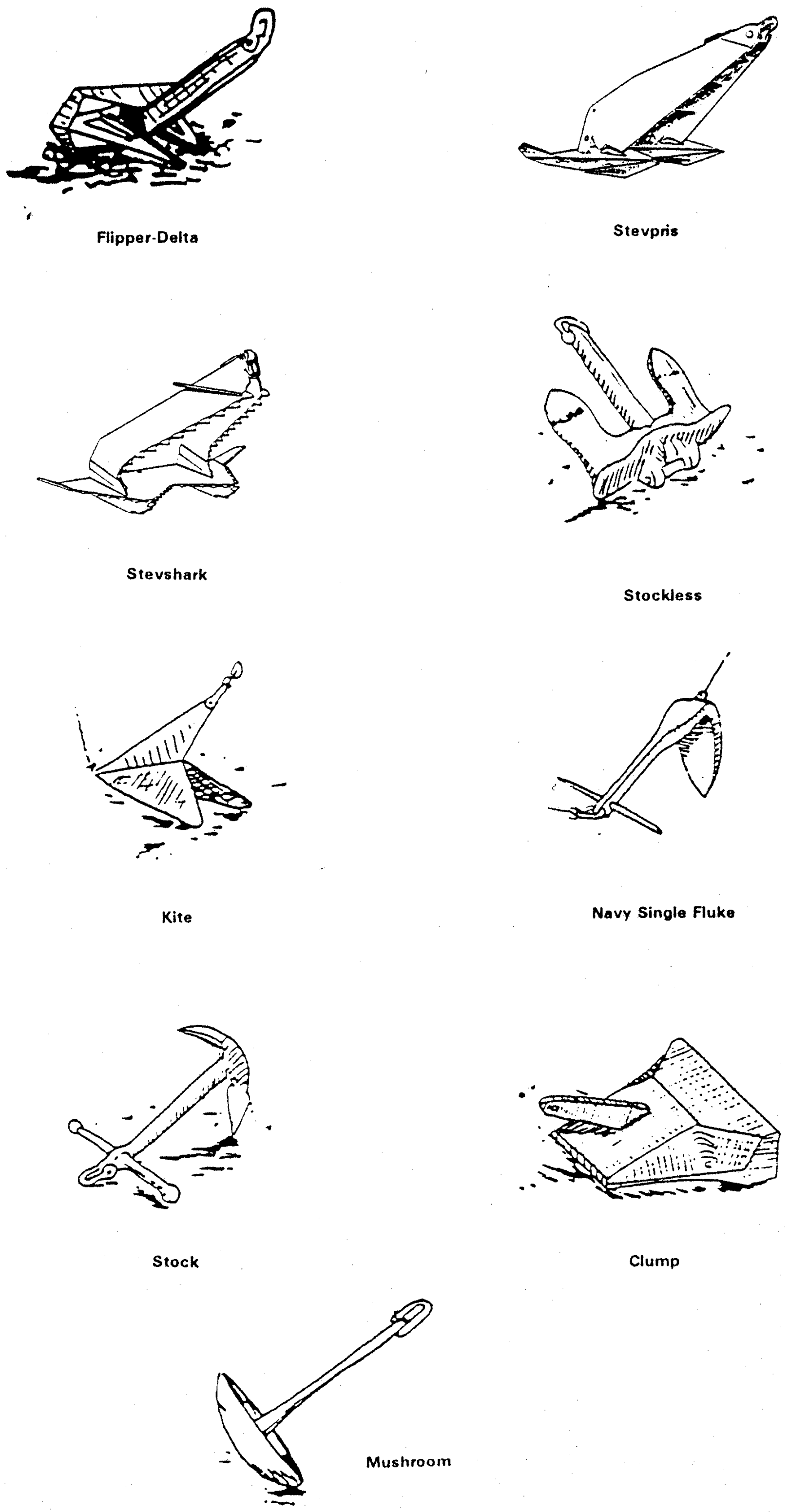

Figure 1b Typical anchor types (after Van den Haak [1990], Van den Haak [1972], also manufacturers data sheets for Bruce, Stevpris and Flipper-Delta anchors)

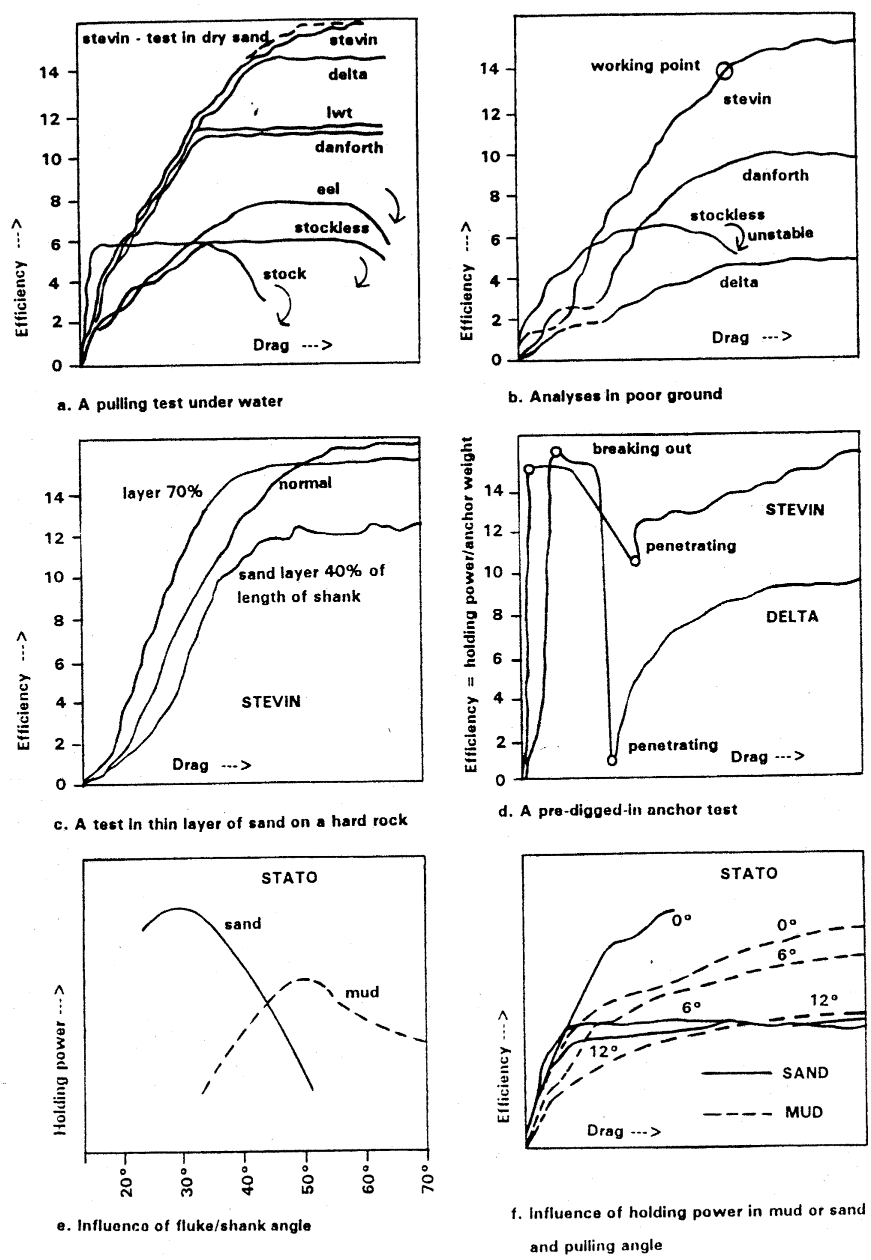

Figure 2 Holding power of various anchors (from Van den Haak, 1972)

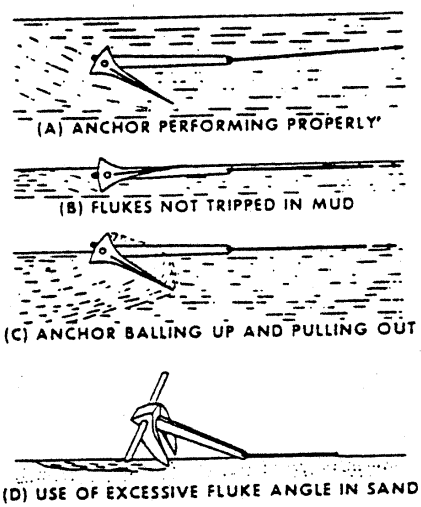

Figure 3 Various types of anchor behaviour (from Beck, 1974)
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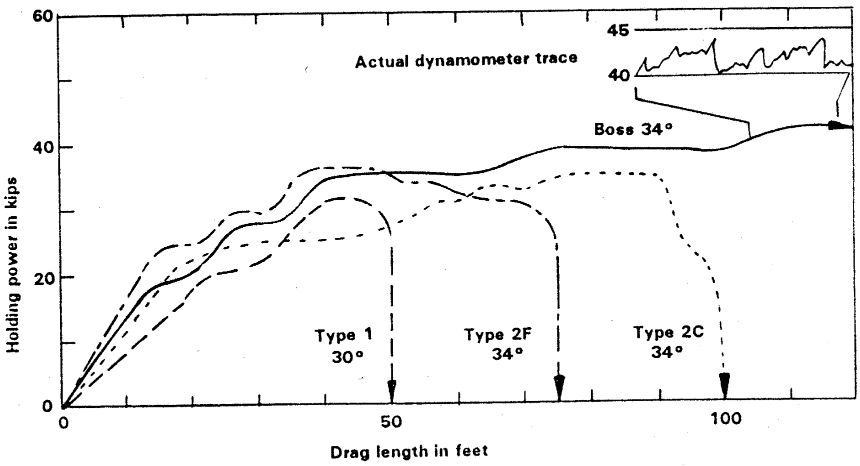

Figure 4 Anchor performance at soft mud site 2 (from Beck, 1974)
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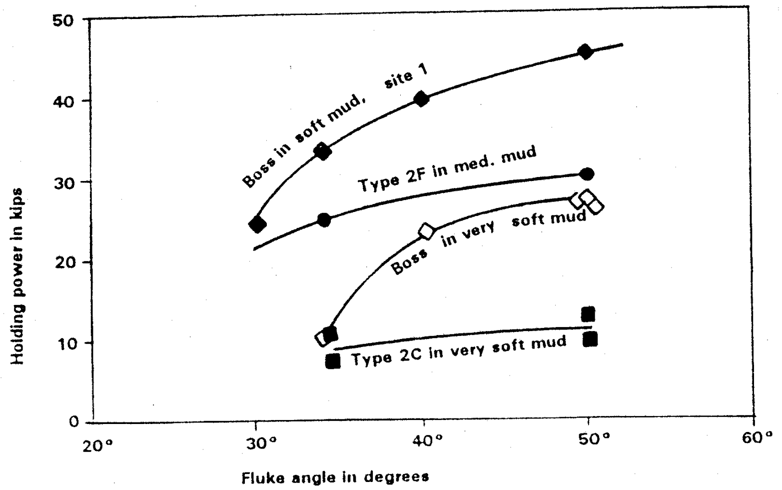

Figure 5 Effects of fluke angle on holding power in mud (from Beck, 1974)
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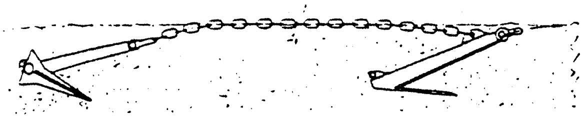

Figure 6 Pennant-chain connected to padeye (from Klaren, 1973)

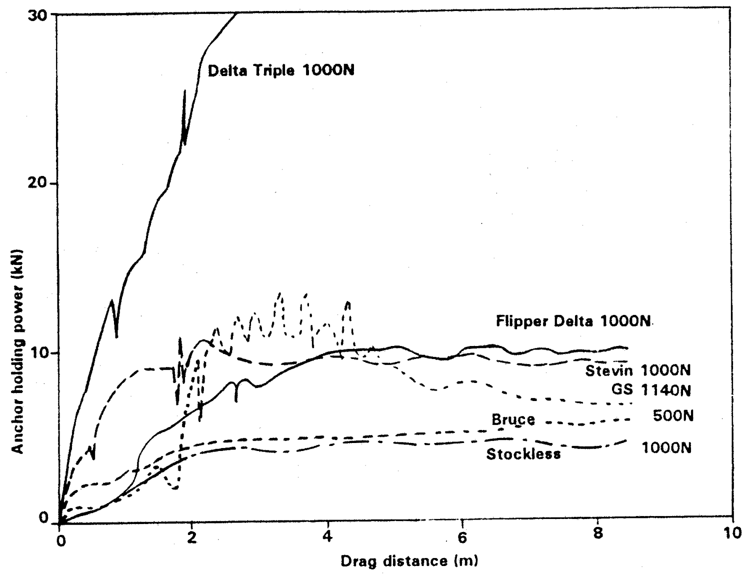

Figure 7a Comparative tests in sand: typical holding power - distance of drag records (from Puech, 1978) © *OTC 1978*

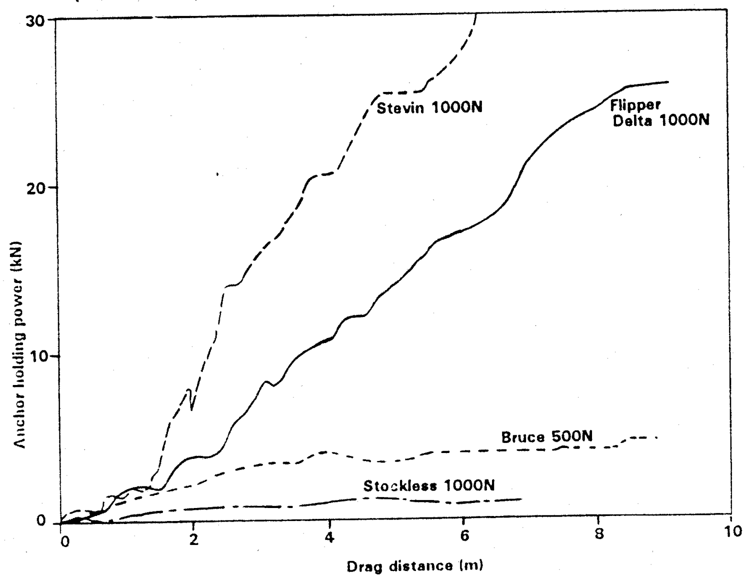

Figure 7b Comparative tests in mud: typical holding power - distance of drag records (from Puech, 1978)
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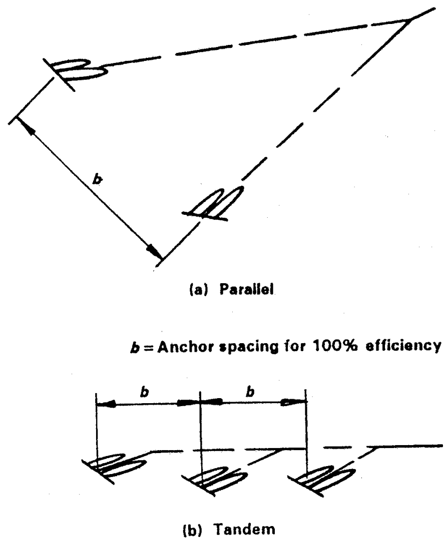

Figure 8 Tandem and parallel anchor configuration (from Valent et al, 1979)

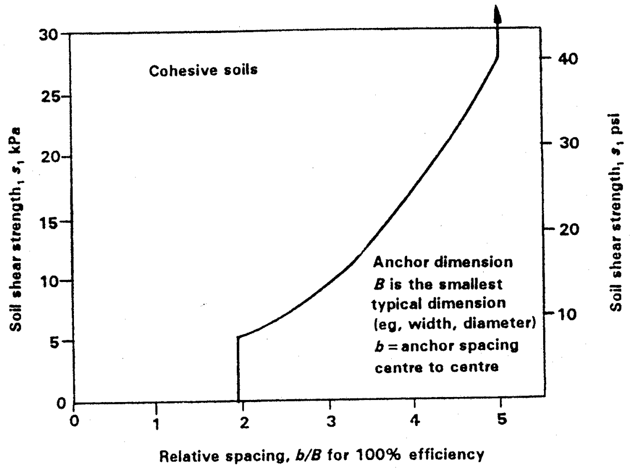

Figure 9 Minimum spacing of embedded anchor flukes for cohesive soils to realise 100% group efficiency (from Valent et al, 1979)

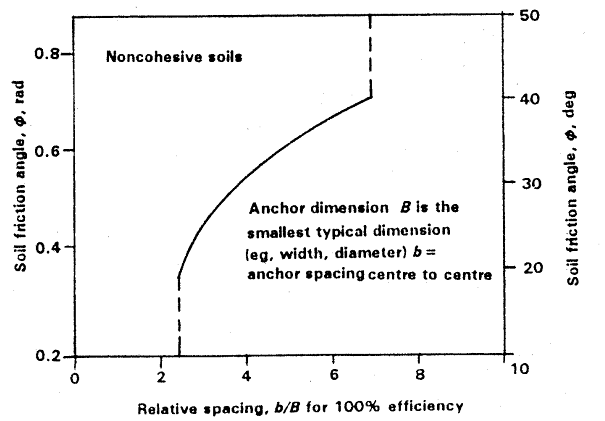

Figure 10 Minimum spacing of embedded anchor flukes for non-cohesive soils to realise 100% group efficiency (from Valent et al, 1979)

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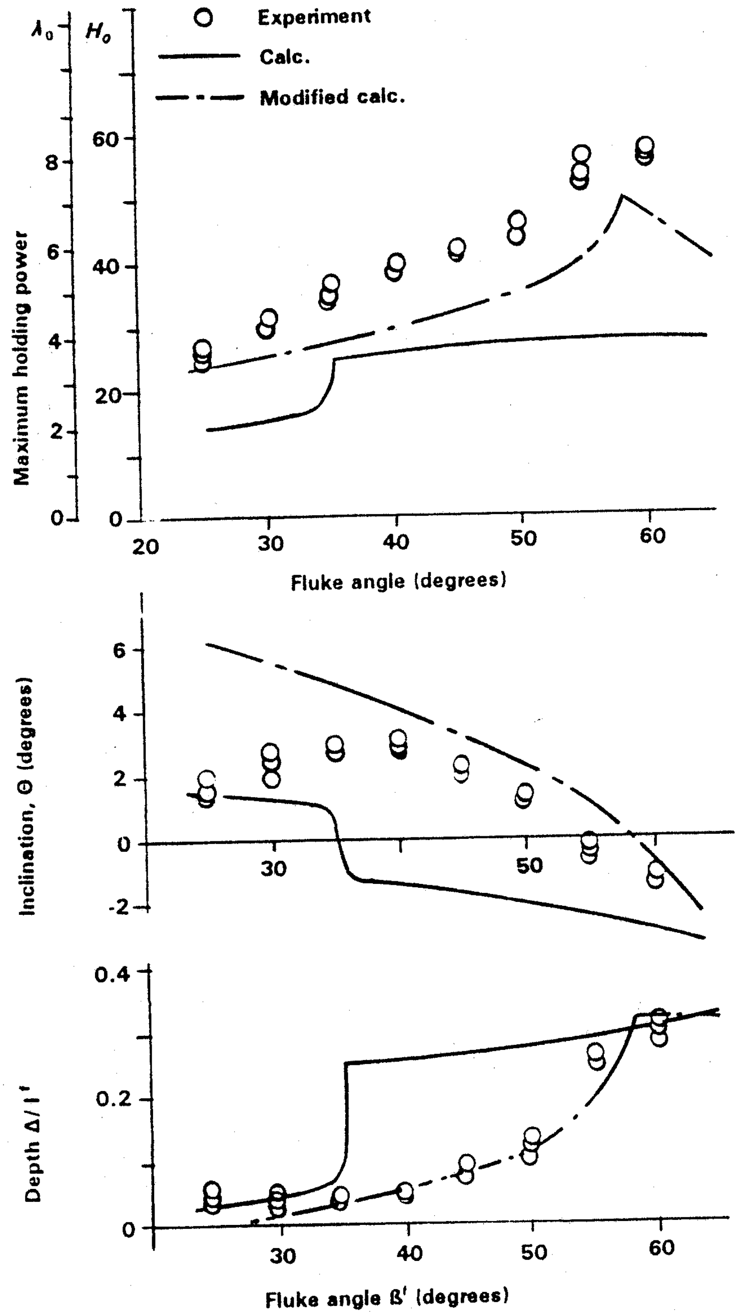

Figure 11 Maximum holding power ratio, inclination and embedment depth (from Ura et al, 1979)

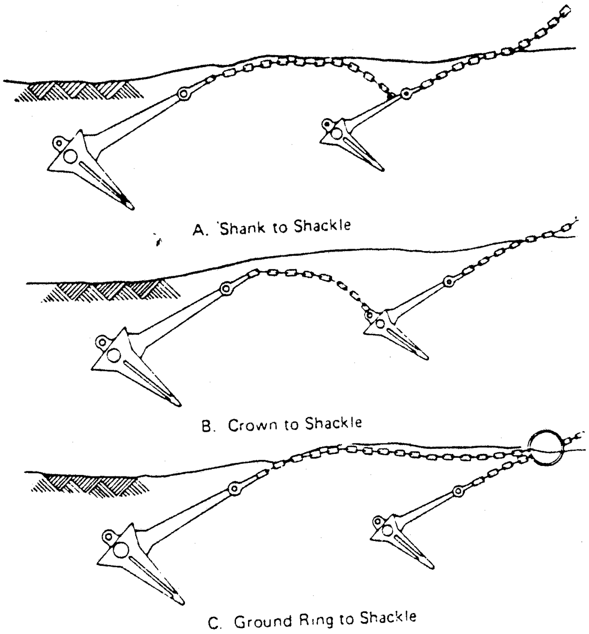

Figure 13 Test tandem rigging techniques with stockless anchor (from Taylor, 1981) © *OTC 1981*

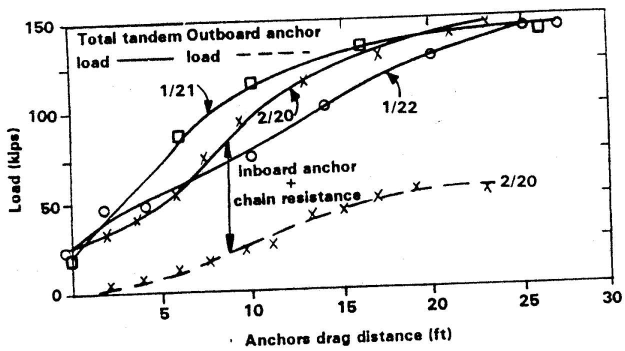

Figure 14 Load versus drag distance for 3 tandem rigging procedures with 5K stabilised stockless anchor, San Diego sand (from Taylor, 1981) © *OTC 1981*

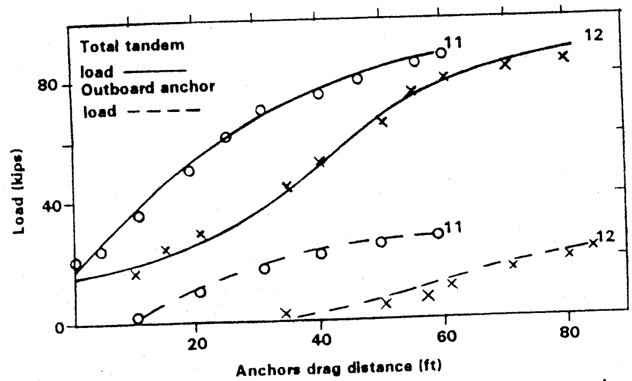

Figure 15 Load versus drag distance for 2 tandem rigging procedures with 5K stabilised stockless anchors, Indian Island mud (from Taylor, 1981) © *OTC 1981*

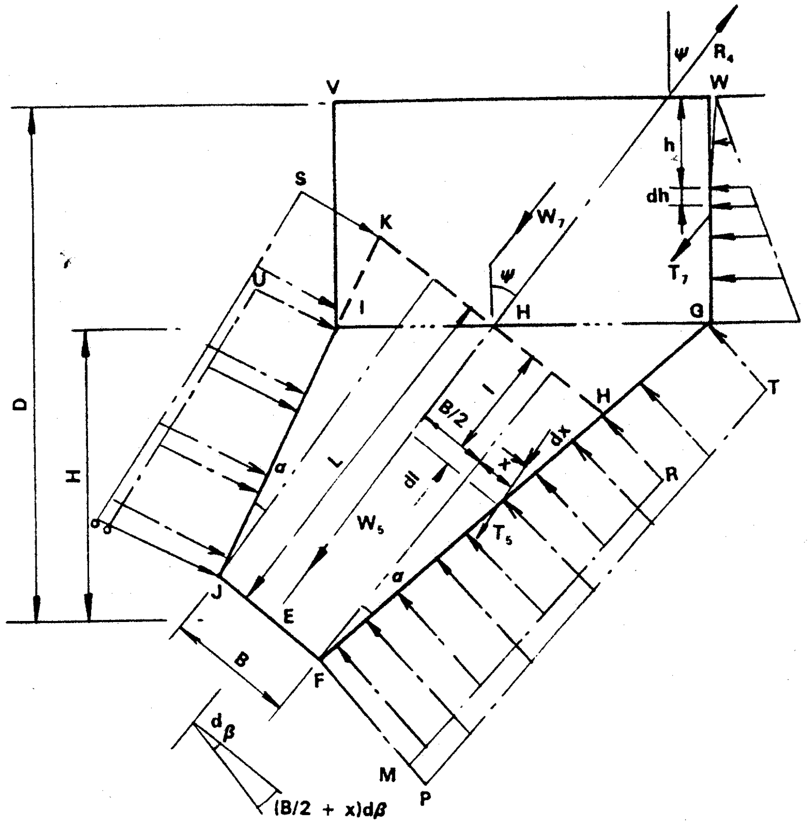

Figure 16 Deep inclined anchor, forces contributing to uplift resistance (from Sutherladn et al, 1983)

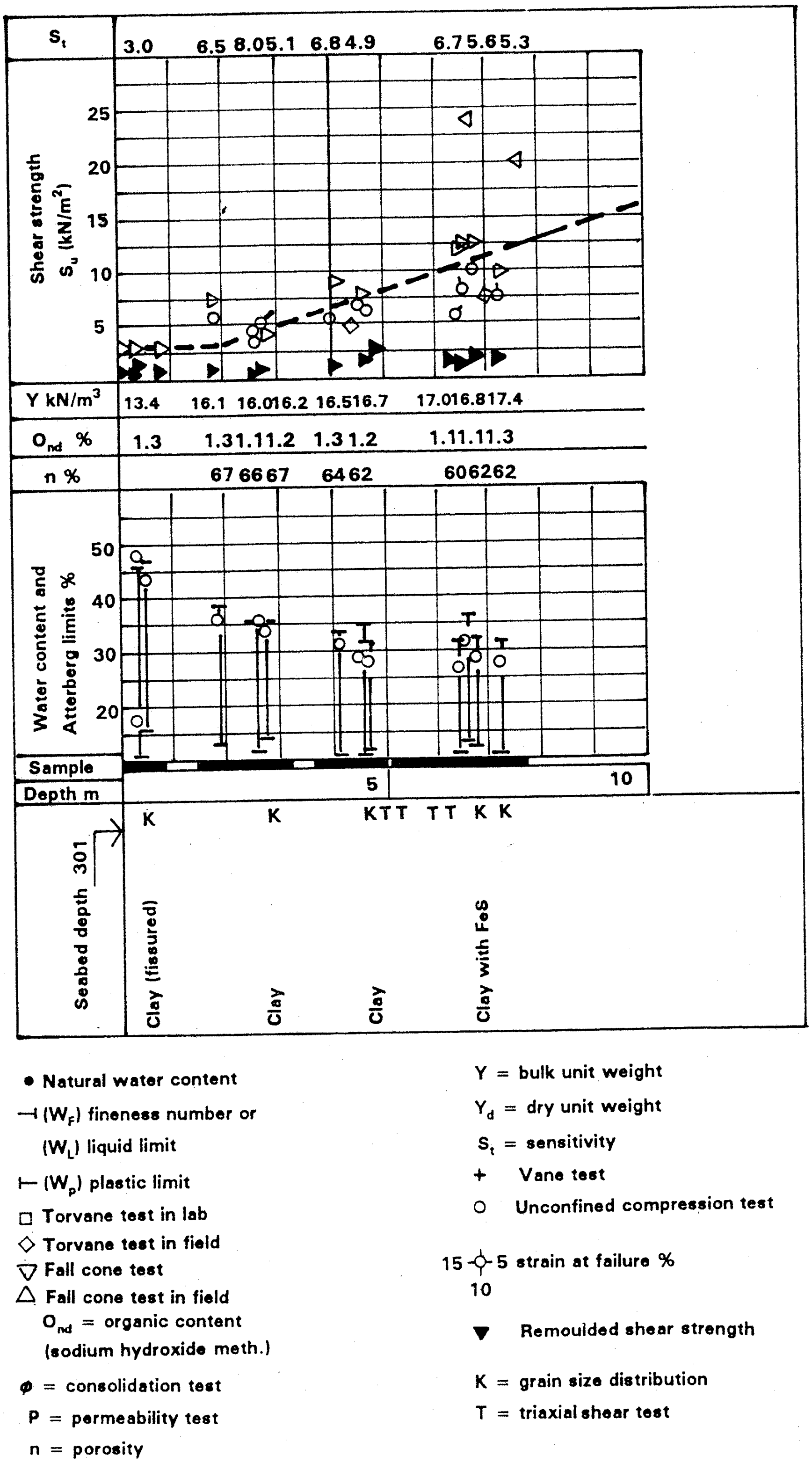

Figure 17 Geotechnical data obtained from gravity cores
(from Vold and Eie, 1983)
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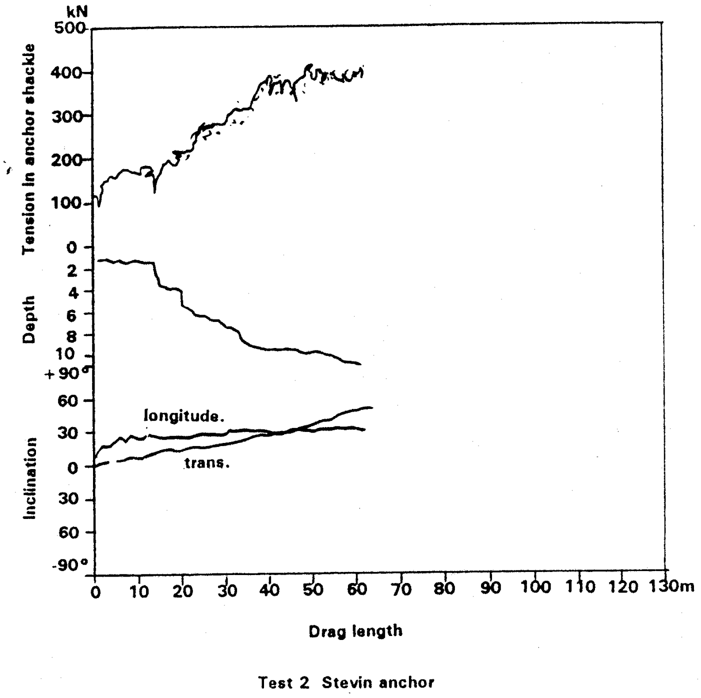


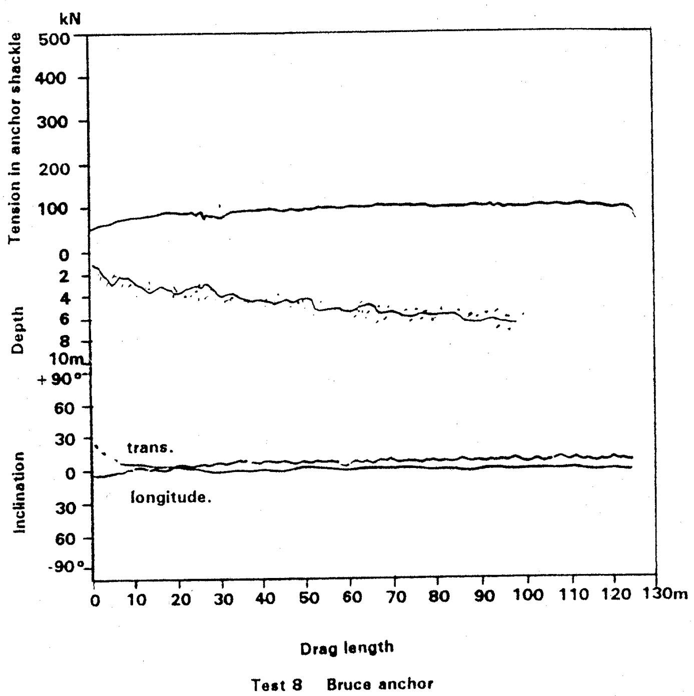
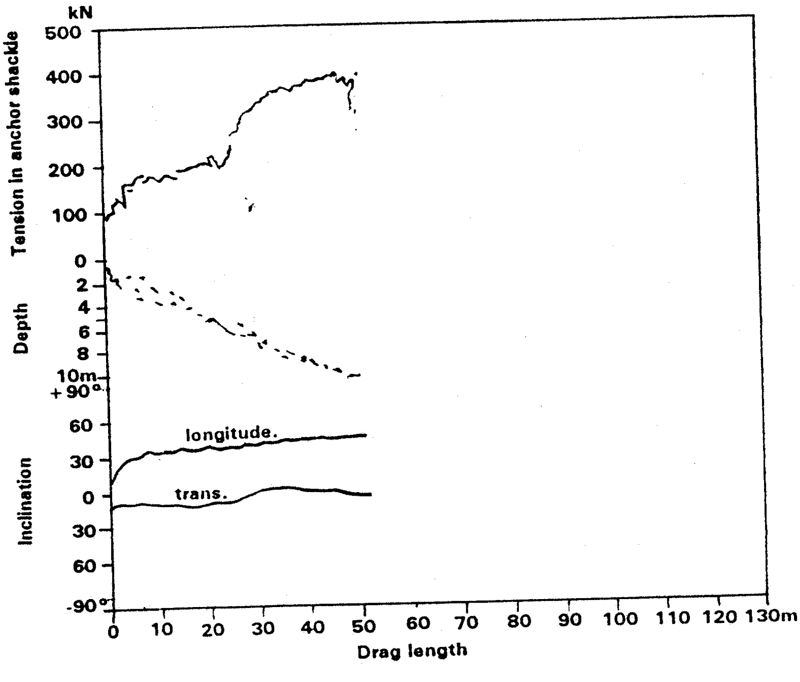
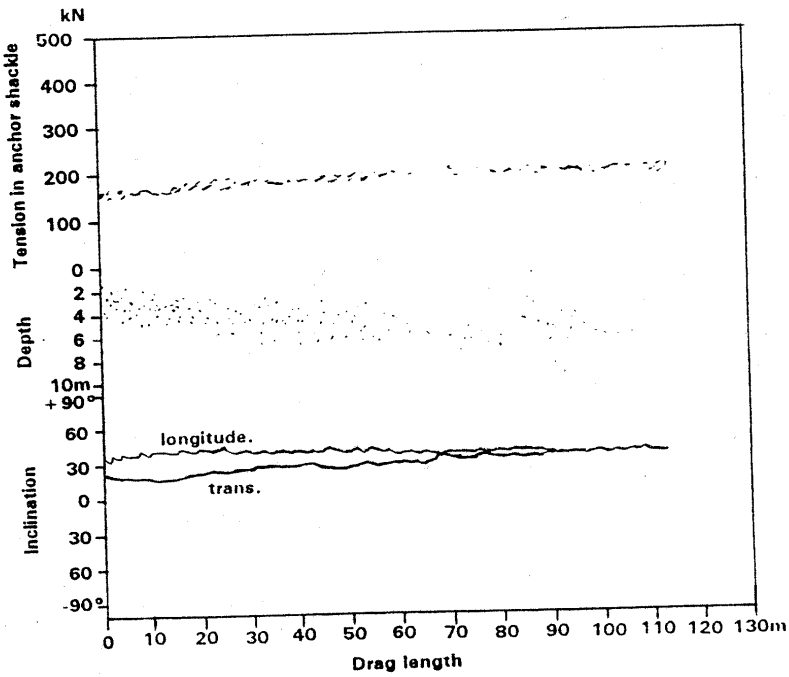


Figure 18a Tension at anchor shackle, embedment depth and inclination, versus drag length (from Bold and Eie, 1983)



Test 4 Flipper-Delta anchor



Test 10 Baldt anchor

Figure 18b Tension at anchor shackle, embedment depth and inclination, versus drag length (from Vold and Eie, 1983)

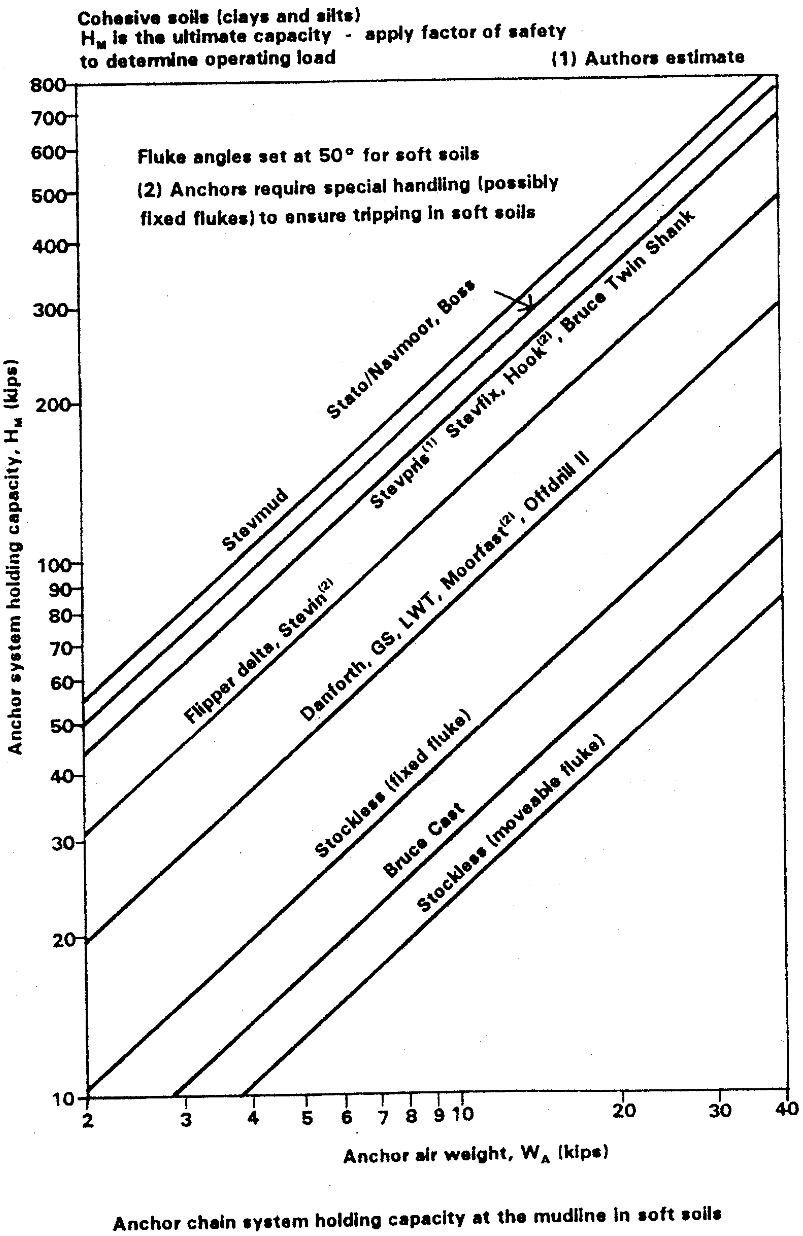


Figure 19a Anchor chain system holding capacity at the mudline
(from Zumwait, 1986)

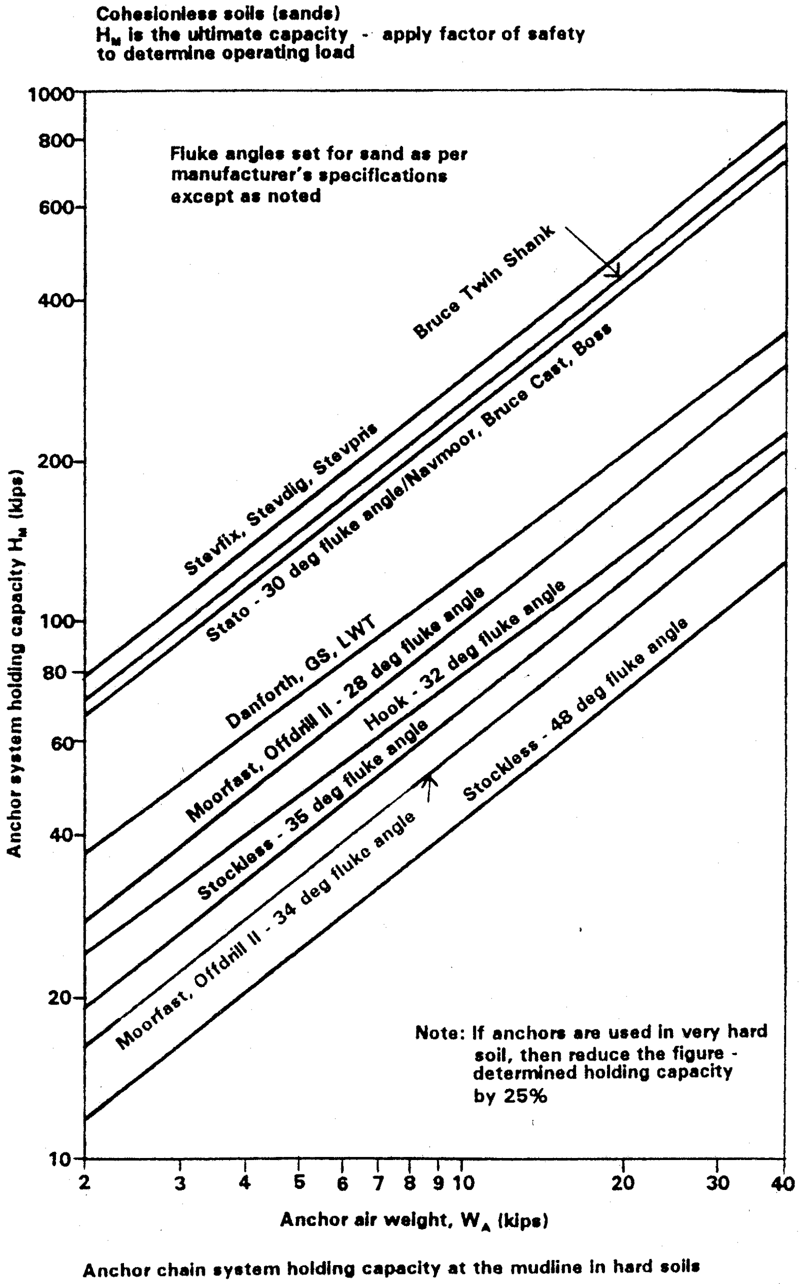


Figure 19b Anchor chain system holding capacity at the mudline
(from Zumwait, 1986)

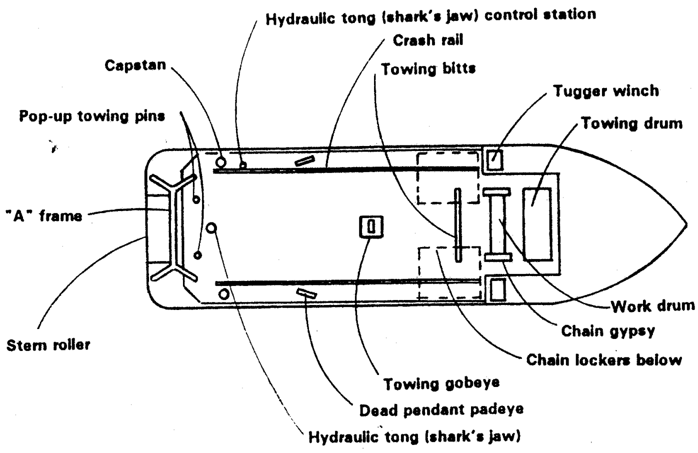


Figure 20 Deepwater anchor boat (from Zumwalt, 1986)
© *OTC 1986*

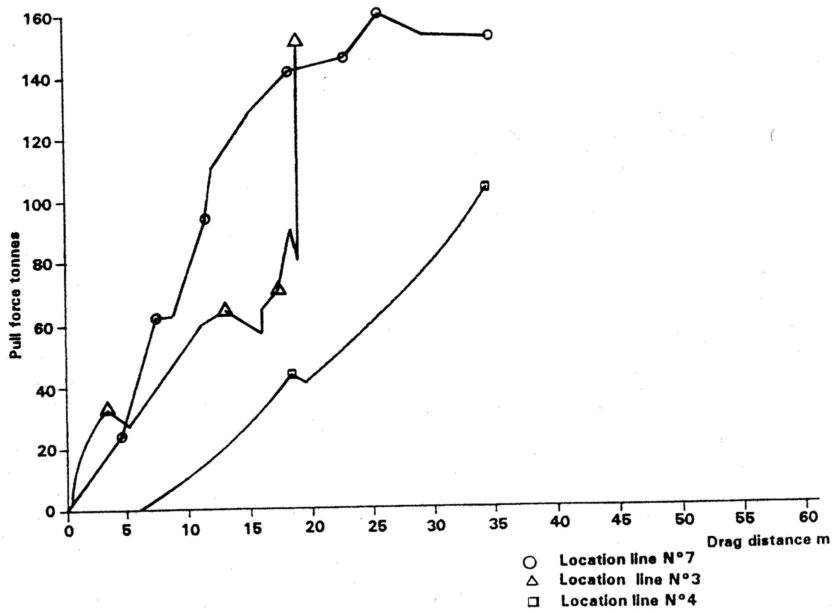


Figure 21 Test results from small scale anchors (from Røraas and Hagen, 1989)
© OTC 1989

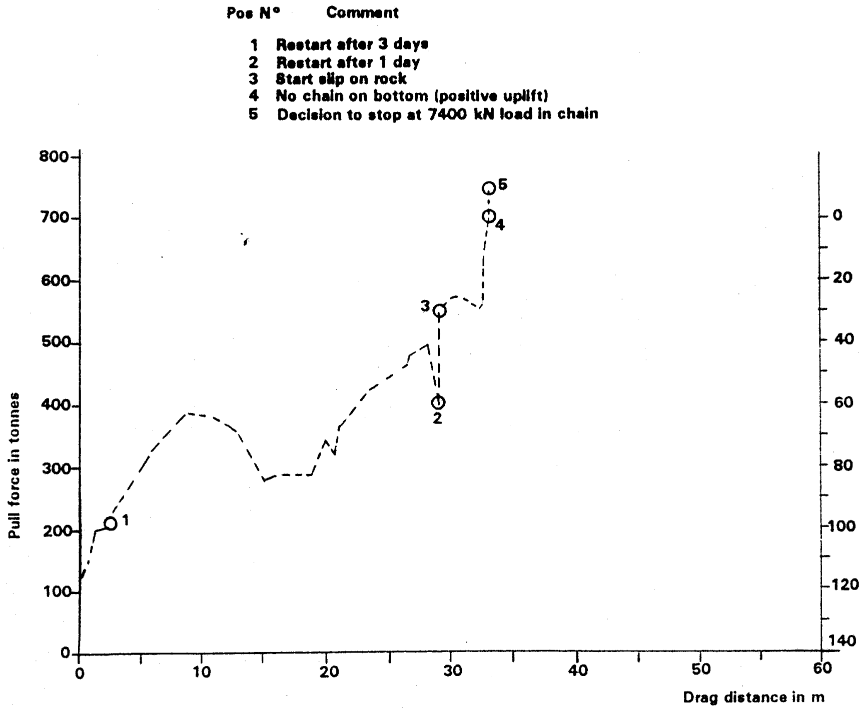


Figure 22 Test results from 40-tonne anchor installation at location N°4 (from Røraas and Hagen, 1989) © *OTC 1989*

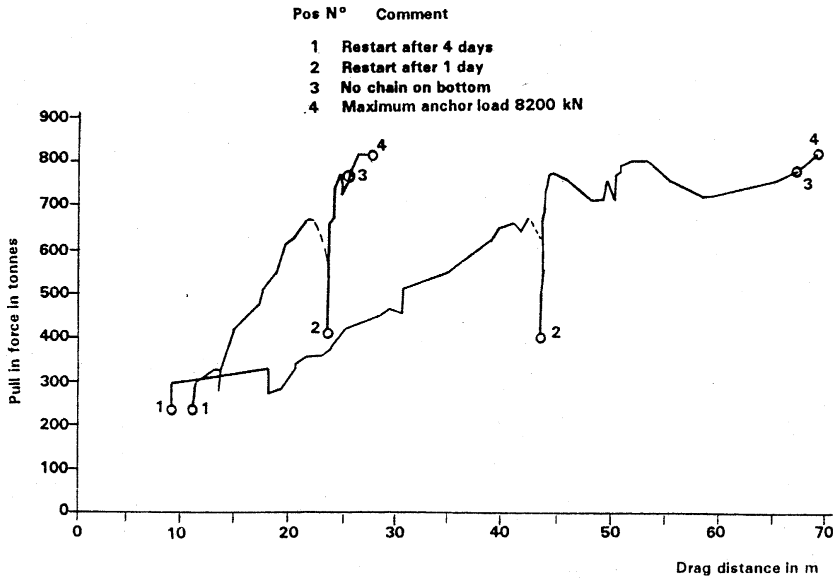


Figure 23 Test results from 60 and 65 tonne anchor installations at location No. 3 and No. 7 (from Røraas and Hagen, 1989)
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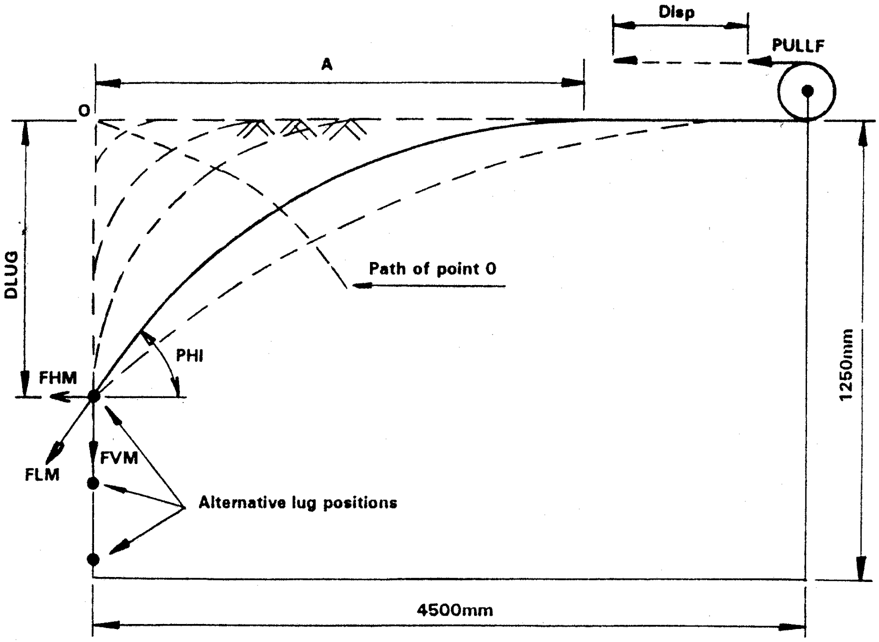

Figure 24 Schematic presentation of testing set-up
(from Dutta and Degankamp, 1989)
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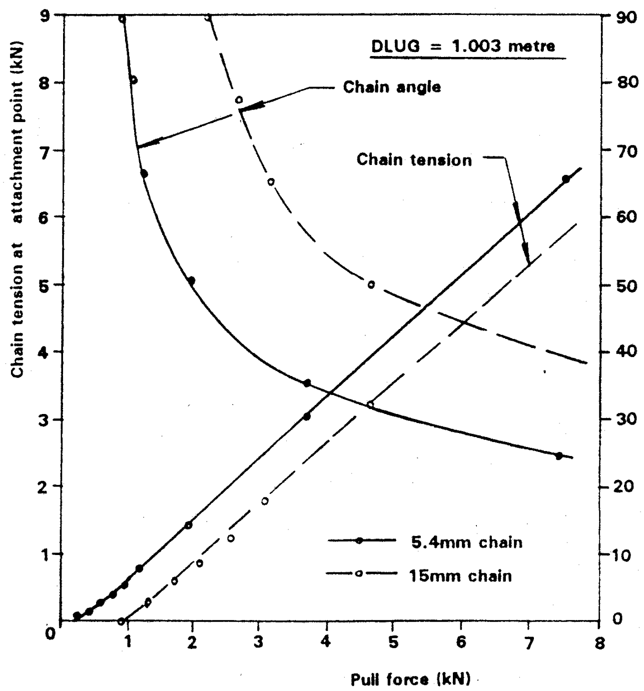


Figure 25 Variation of chain testing and chain angle at the attachment point with pull force (from Dutta and Degenkamp, 1989)
© OTC 1989

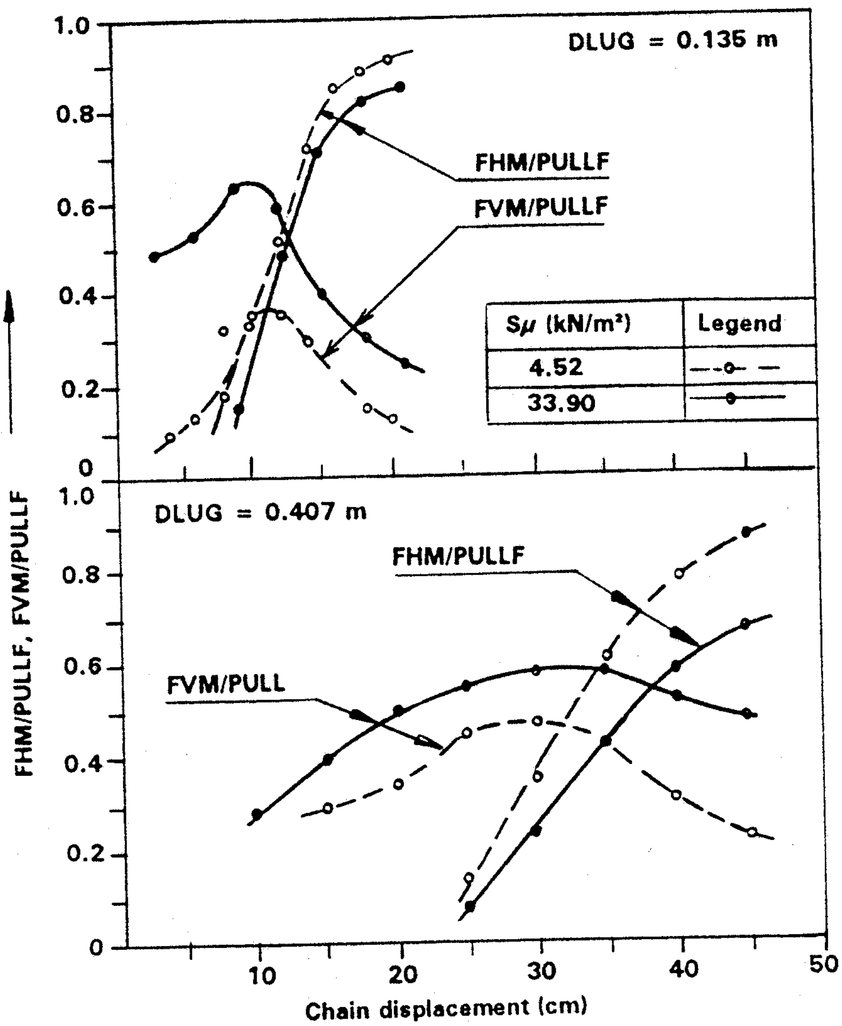


Figure 26 Effects of changing undrained shear strength of clay on chain forces at the attachment point (from Dutta and Degenkamp, 1989)

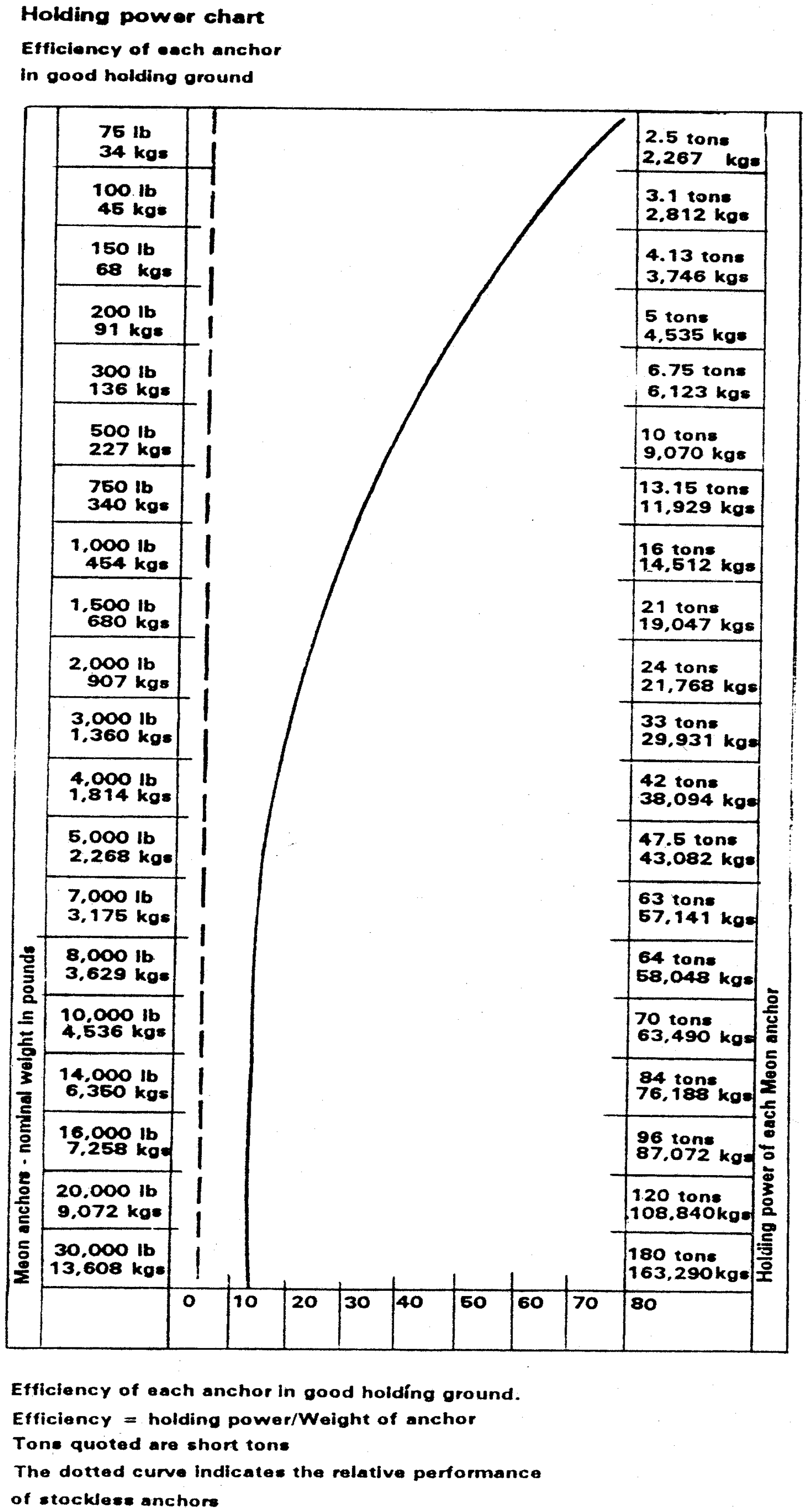


Figure 27 Manufacturer’s performance curve for Meon Mk3 anchor

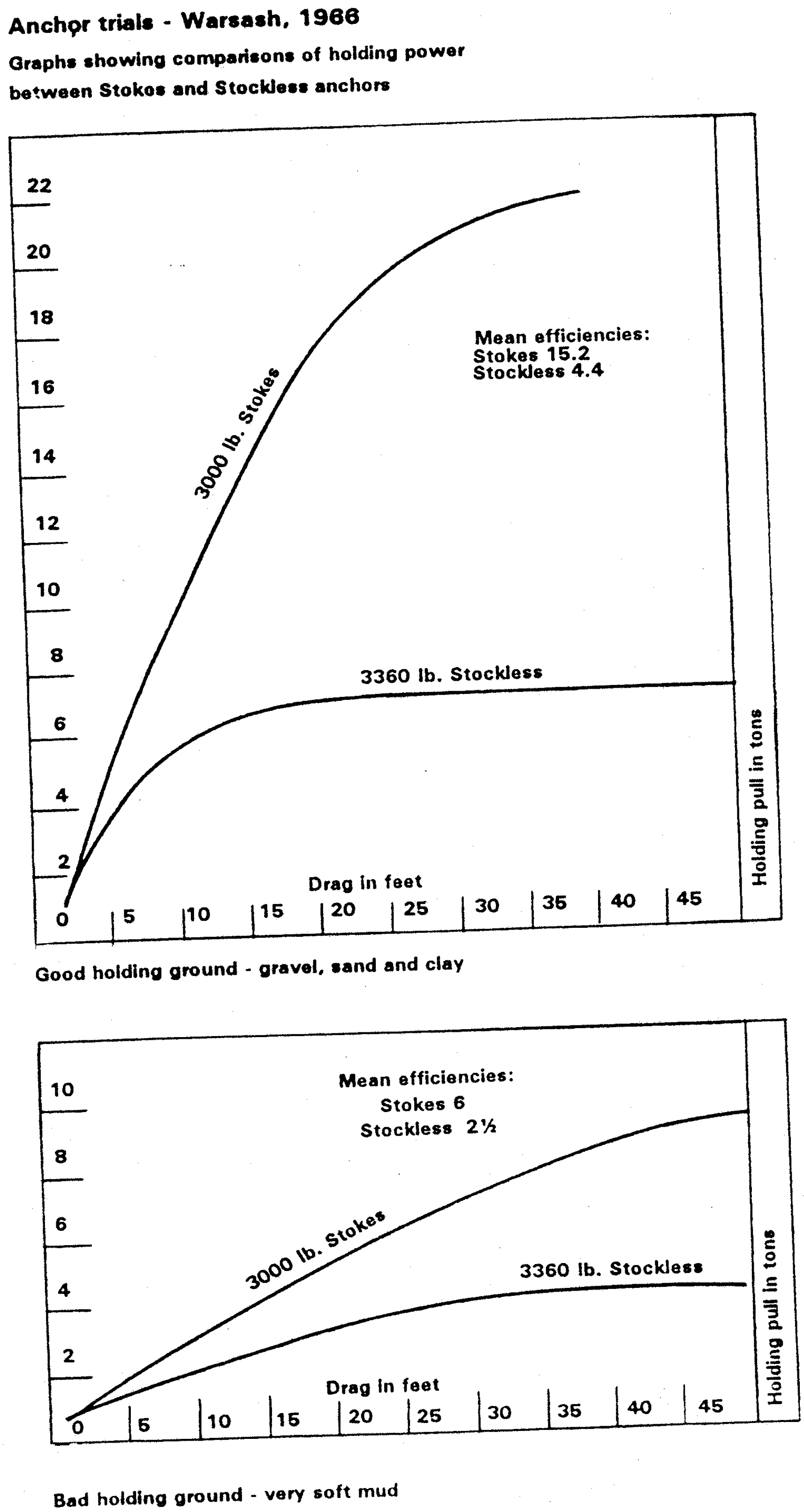


Figure 28 Manufacturer’s performance curve for Stokes HHP stockless anchors

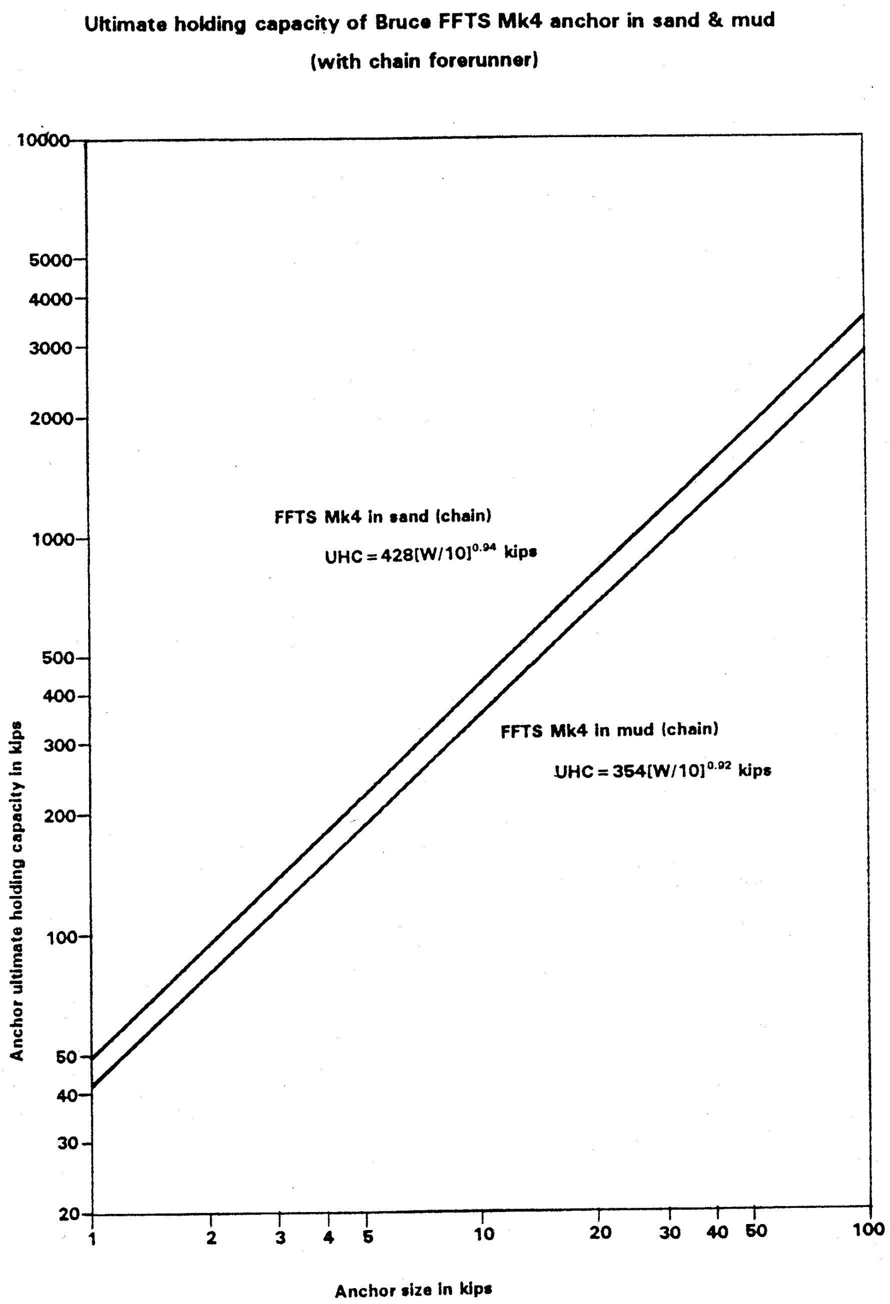


Figure 29 Manufacturer's performance curve for Bruce FFTS Mk4 anchor in sand and mud

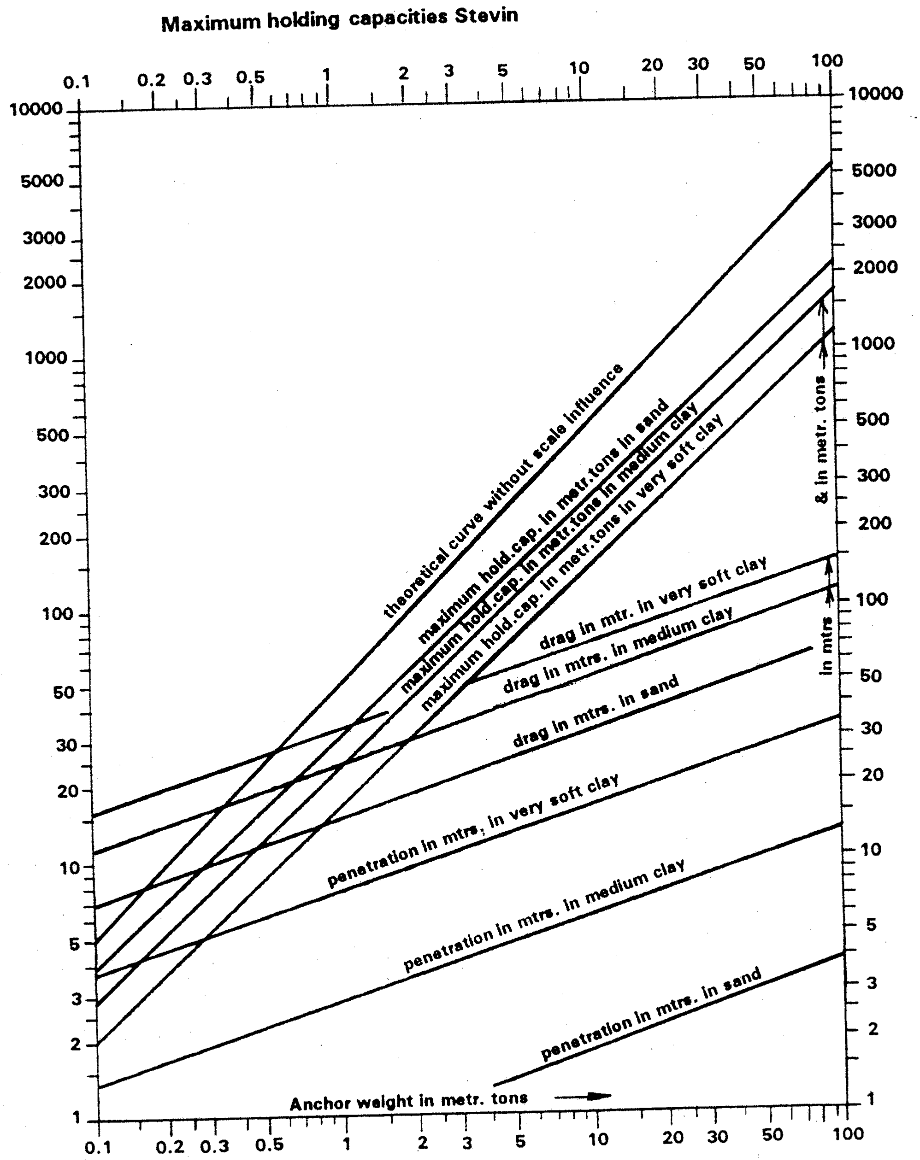


Figure 30 Manufacturer's performance curve for Stevin anchor

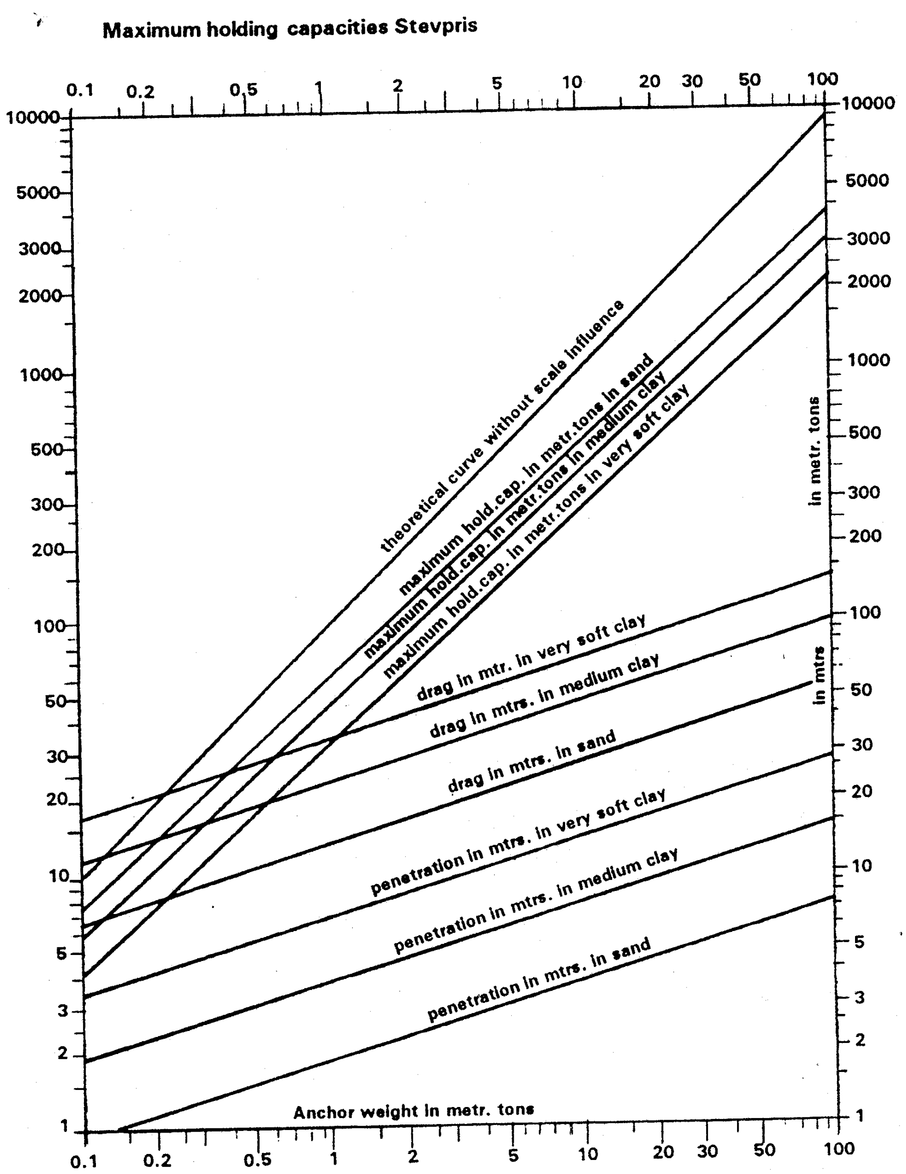


Figure 31 Manufacturer’s performance curve for Stevpris anchor

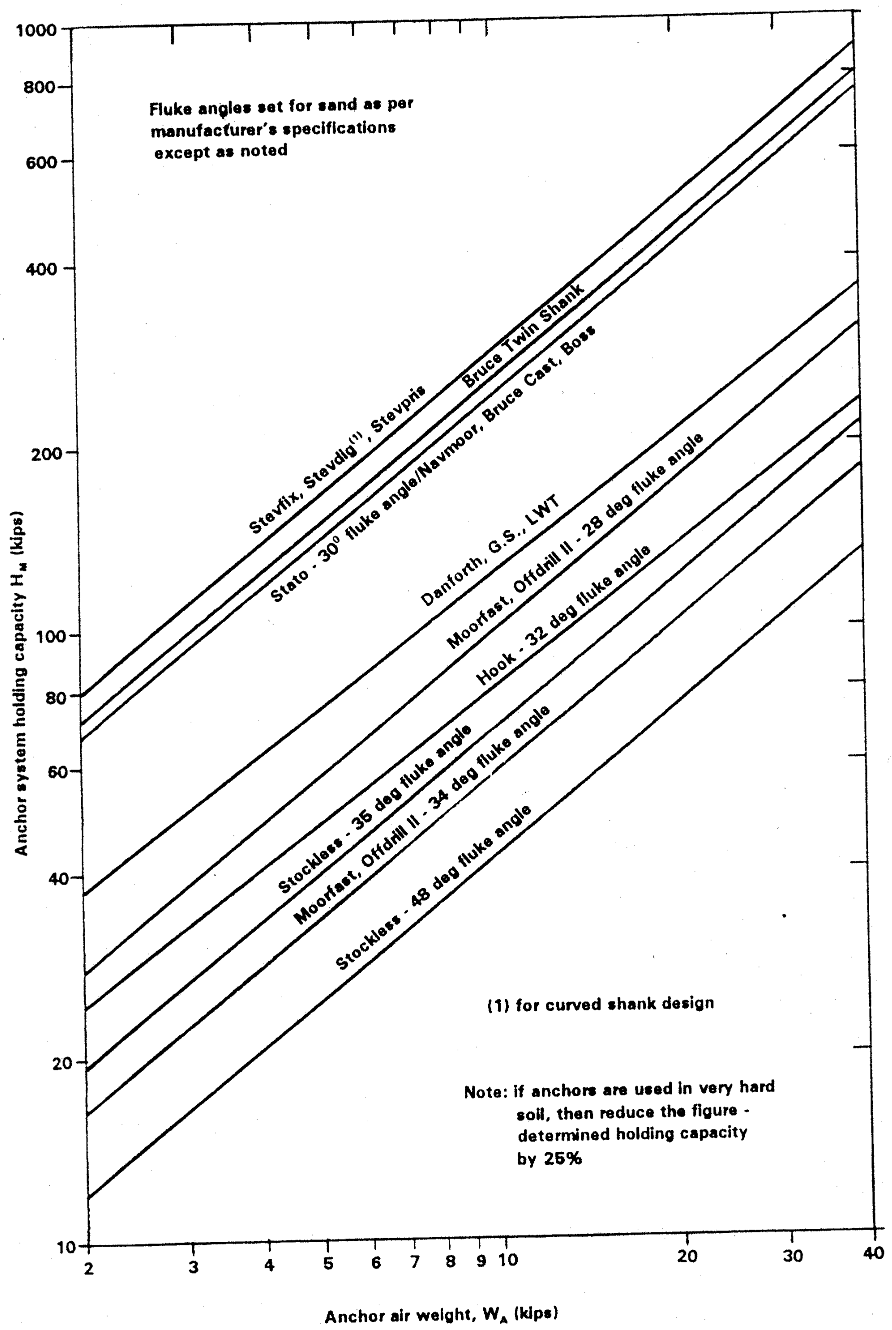


Figure 32 Anchor chain system holding capacity at the mudline in hard soils (sand and stiff clay)
(from API RP2P: Analysis of spread mooring systems for floating drilling units, 1987)

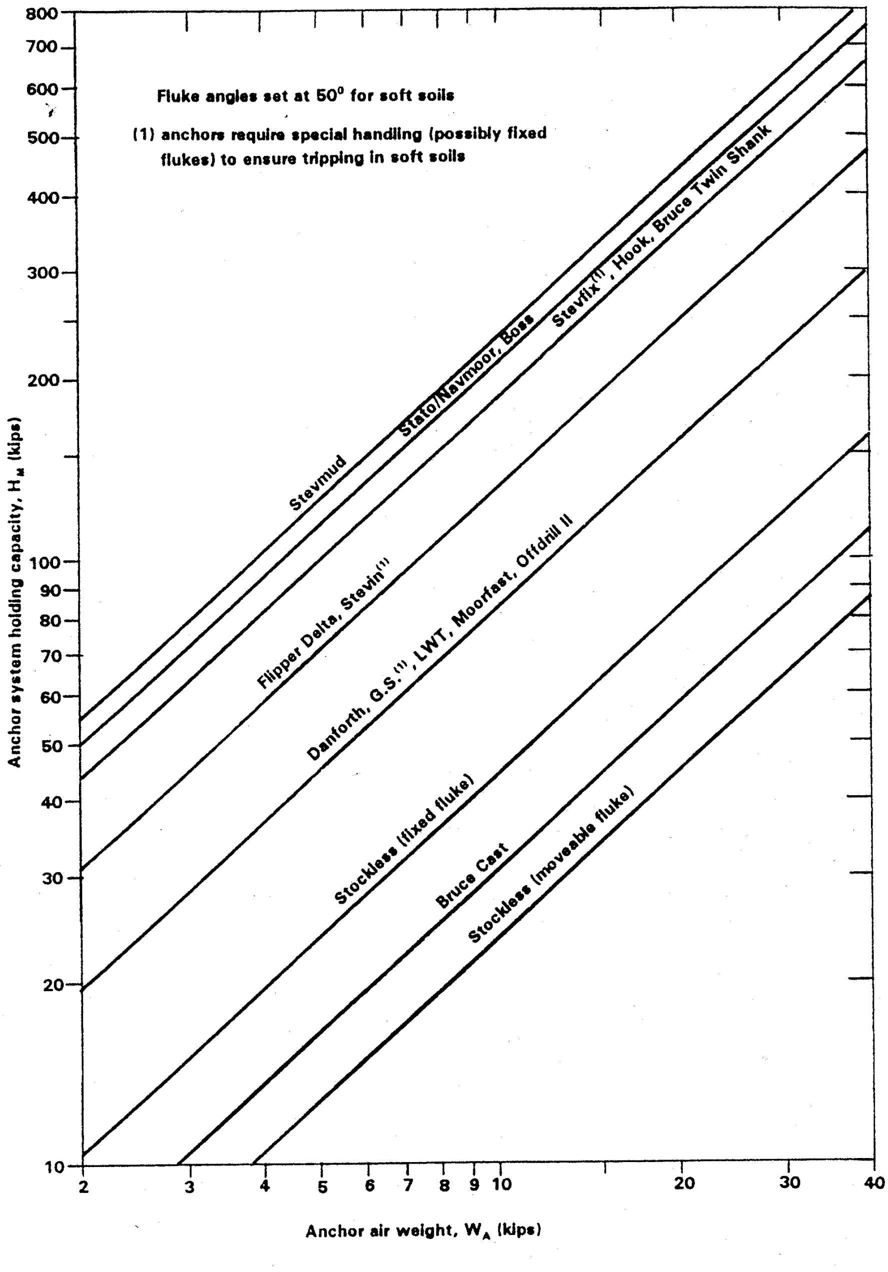


Figure 33 Anchor chain system holding capacity at the mudline in soft soils (silt and clay)
(from API RP2P: Analysis of spread mooring systems for floating drilling units, 1987)

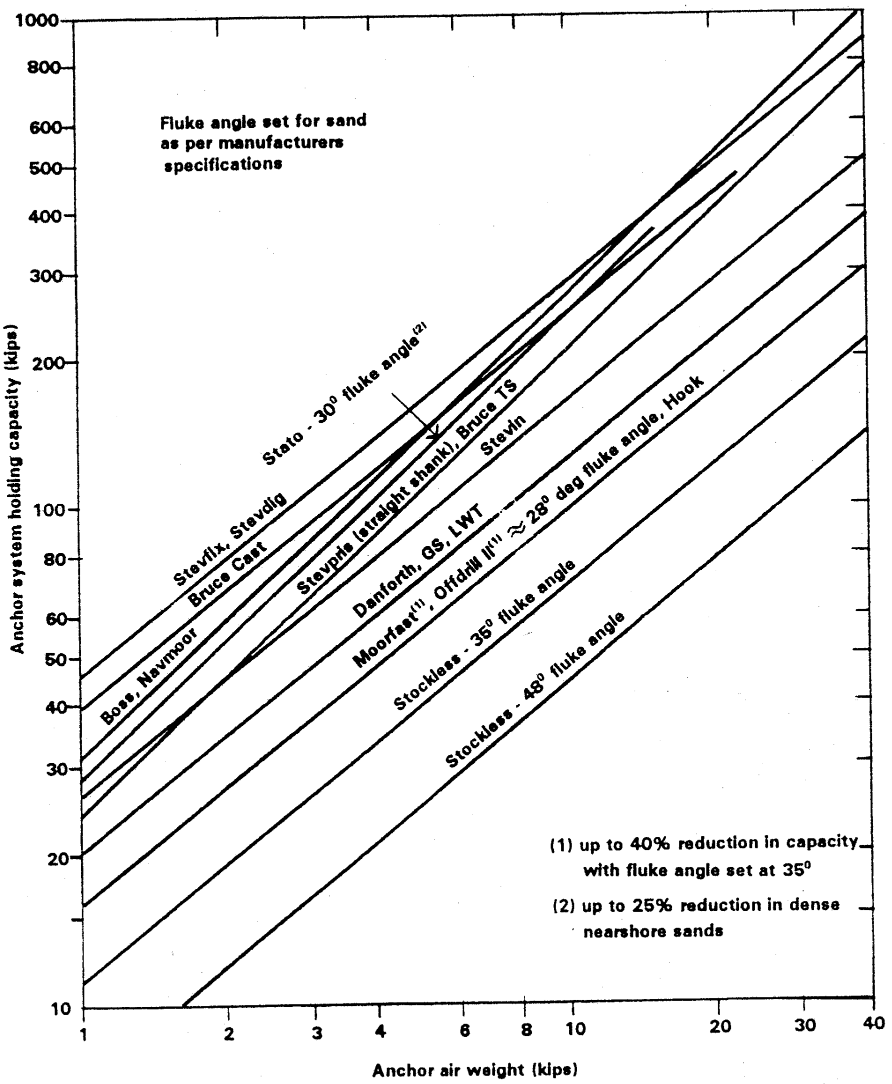
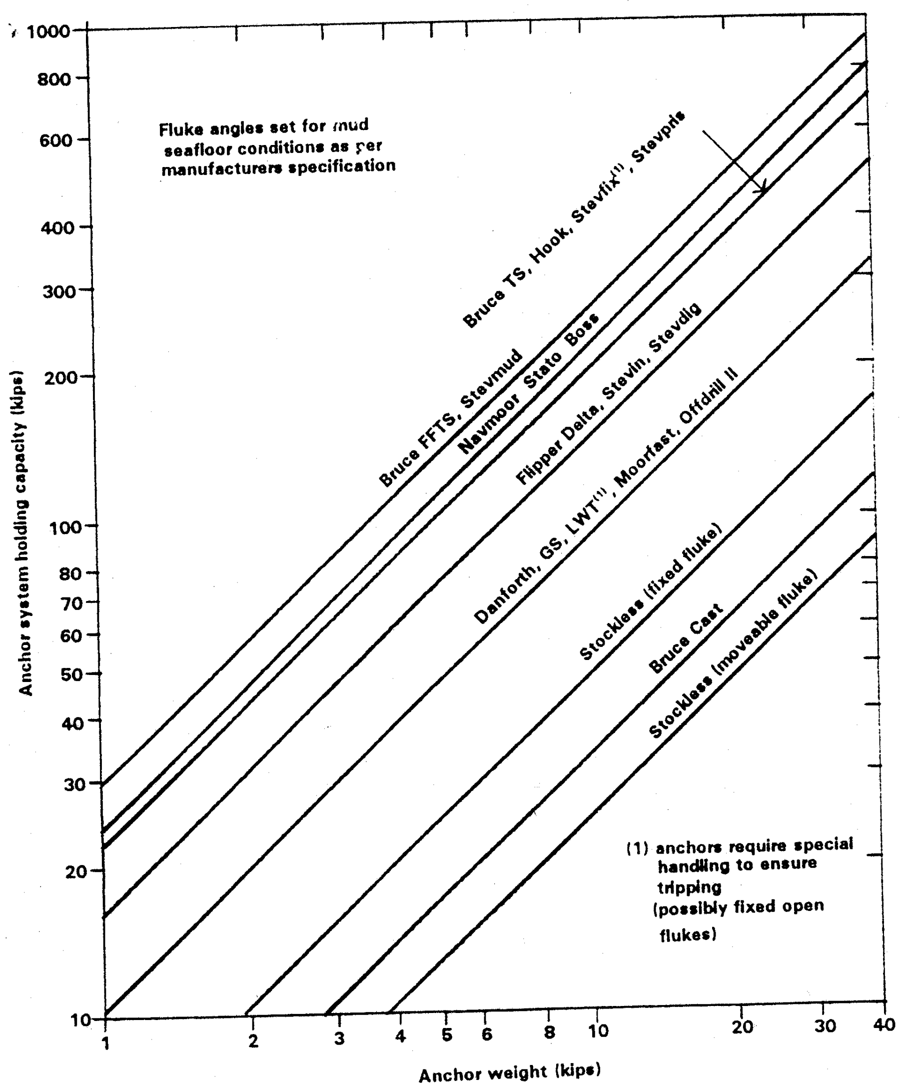
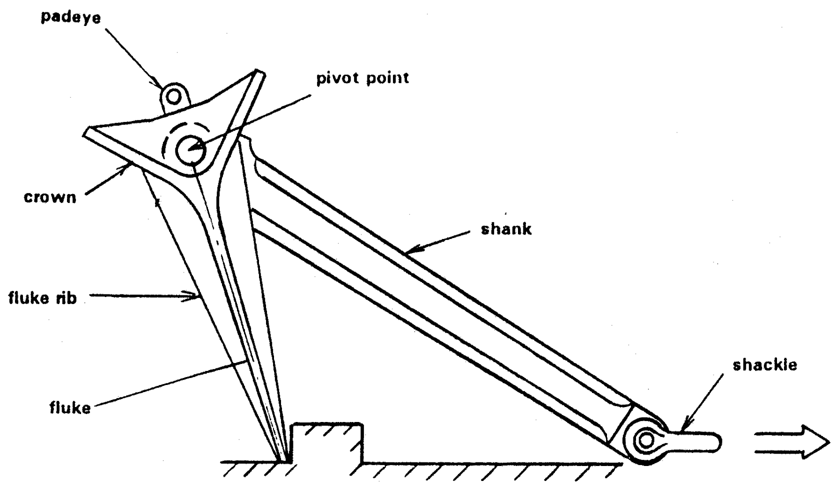


Figure 34 Anchor chain system holding capacity in sand
(from API RP2FP1: Design, analysis and maintenance of mooring for floating production systems, draft 1991)

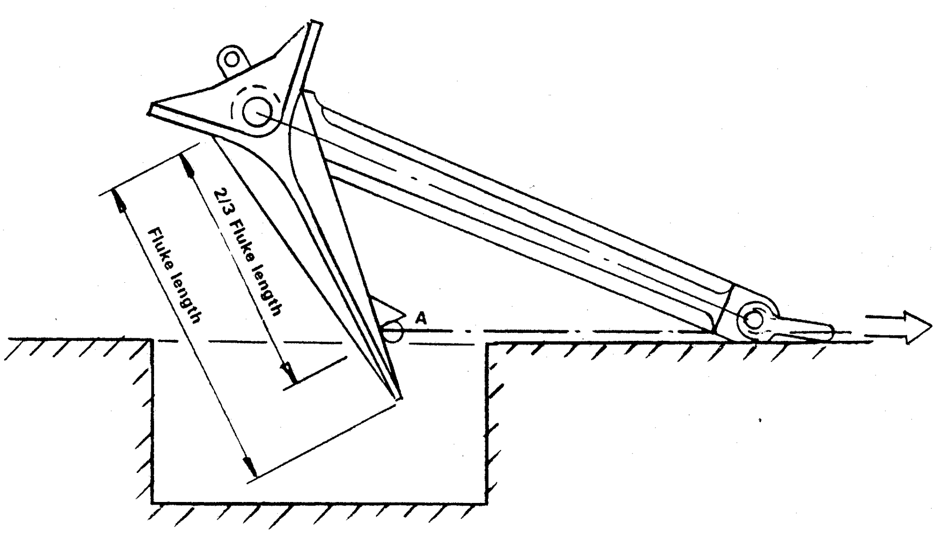


NOTE: Performance curves reflect data valid for anchor designs as of 1987.
The Stevpris and the Bruce FFTS anchor designs have since been modified to enhance their performance in mud; however performance data for these modified designs were not available at this writing.

Figure 35 Anchor system holding capacity in mud (from API RP2FP1: Design, analysis and maintenance of mooring for floating production systems, draft 1991)



a. Fluke tip procedure



b. 2/3 fluke length procedure

Figure 36   Method of proof-test pull from API RP2M: Qualification testing of steel