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TECHNICAL REPORT

Offshore Anchor Data for Preliminary Design of Anchors of Floating Offshore Wind Turbines

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Prepared by

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Table of Contents

List of Tables iii

List of Figures iv

Executive Summary v

1 Introduction 1

2 Definition of Applicable Anchors for FOWTs 2

2.1 Anchor Types 2

2.2 Anchor Design Load 2

2.3 Soil Conditions 5

3 Drag Anchor Design Data 6

3.1 Vryhof Anchors 6

3.2 Bruce Anchors 10

3.3 Drag Anchor Data in API RP 2SK 13

4 Vertically Loaded Anchor (VLA) Design Data 14

4.1 Vryhof Stevmanta VLA 14

4.2 Bruce Dennla VLA 16

5 Pile Anchor Design Data 17

5.1 Pile Anchor Design Approach 17

5.1.1 Design Cases 17

5.1.2 Soil Properties 19

5.1.3 Anchor Pile Geometry and Material 20

5.2 Pile Anchor Design Data 22

6 Use of the Derived Anchor Design Data 27

6.1 Application of Anchor Type 27

6.2 Anchor Sizing Procedure 28

6.3 Limitations of the Derived Anchor Design Data 30

7 Typical Anchor-Mooring Line Connections 31

7.1 Typical Connections for Drag Anchors and VLAs 31

7.2 Typical Connections for Pile Anchors 34

8 References 35

List of Tables

Table 2.1 Definition of Clay Type Based on the ASTM and BS Standards [7] 5

Table 3.1 Design Equations for Vryhof Drag Anchors 6

Table 3.2 Design Equations for Bruce Drag Anchors 10

Table 4.1 Design Equations for Vryhof VLAs for Permanent Moorings 15

Table 5.1 Pile Anchor Design Cases 17

Table 5.2 Definition of Clay Properties for Deriving Pile Anchor Design Data...................... 19

Table 5.3 Definition of Sand Properties for Deriving Pile Anchor Design Data 20

Table 5.4 Target Pile Anchor *L/D* and *D/T* Ratio.. 21

Table 5.5 Design Equations for Pile Anchors of the Spread Mooring System (Metric Units) . 25

Table 5.6 Design Equations for Pile Anchors of the Spread Mooring System (US Customary Units).. 25

Table 5.7 Design Equations for Pile Anchors of the TLP Tendon System (Metric Units)....... 26

Table 5.8 Design Equations for Pile Anchors of the TLP Tendon System (US Customary Units).. 26

Table 6.1 Typical Application of Anchor Types.. 27

Table 6.2 Drag Anchor Capacity Reduction Factor for Non-zero Uplifting Angles 27

Table 6.3 Safety Factors Specified in the ABS Guide [1] for FOWT Anchor Design............... 29

List of Figures

Figure 2.1 Maximum Line Top Tension (Normal vs. Abnormal) under the Storm Conditions..3
Figure 2.2 Minimum Line Top Tension (Normal vs. Abnormal) under the Storm Conditions...4
Figure 3.1 Design Curves for Vryhof Stevin Mk3[7]....7
Figure 3.2 Design Curves for Vryhof Stevpris Mk5[7]....8
Figure 3.3 Design Curves for Vryhof Stevpris Mk6[7]....9
Figure 3.4 Design Curves for Bruce FFTS Mk4 [5]....11
Figure 3.5 Design Curves for Bruce PM Anchor [6]....12
Figure 3.6 Design Curves for Bruce FFTS GP Anchor [4]....13
Figure 4.1 Vryhof Stevmanta VLA[7]....14
Figure 4.2 Vryhof Stevmant VLA Design Curves....15
Figure 4.3 Bruce Dennla VLA [2]....16
Figure 5.1 Typical Pile Anchor Ultimate Holding Capacity Envelope....18
Figure 5.2 Definition of Pile Anchor Geometry....21
Figure 5.3 Example Pile Anchor Design Curves for the Spread Mooring System (Driven Piles in Very Soft Clay)....23
Figure 5.4 Example Pile Anchor Design Curves for the TLP Tendon System (Suction Piles in Medium Clay)....24
Figure 7.1 Typical Connections for Drag Anchors and VLAs [7]....31
Figure 7.2 Typical Mooring Components Connected to Anchor Shackles [7]....32
Figure 7.3 Typical Anchor Shackles [7]....33
Figure 7.4 H Shackles/Links....33
Figure 7.5 Typical Pile Anchor and Mooring Line Connection....34
Figure 7.6 Typical Suction Anchor Pile and Mooring Line Connection (API RP 2SK)....34

Executive Summary

This report presents the development of offshore anchor data sets which are intended to be used to develop a database that allows preliminary selection and sizing of anchors for the conceptual design of floating offshore wind turbines (FOWTs). The study is part of a project entitled "*Development of Mooring-Anchor Program in Public Domain for Coupling with Floater Program for FOWTs (Floating Offshore Wind Turbines)*", under the direction of Dr. Moo-Hyun Kim at the Texas A&M University and with the sponsorship from the US Department of Energy (Contract No. DE-EE0005479, CFDA # 81.087 for DE-FOA-0000415, Topic Area 1.3: Subsurface Mooring and Anchoring Dynamics Models).

The ABS project team collected and analyzed specifications of various types of generic offshore anchors that are available in the public domain. For pile anchors, the empirical design equations for initial sizing are derived using a pile-soil finite element analysis program based on the recommended design methods for pile foundations in API RP 2A. Typical combinations of soil properties and load conditions are applied in the derivation of the pile anchor design equations.

The design data and equations are derived for four types of commonly use offshore anchors, including

- Drag anchors
- Vertical Loaded Anchors (VLAs)
- Suction pile anchors
- Driven pile anchors

A brief guidance on the application and limitation of the derived anchor design data is provided. Typical anchor-mooring line connections are also reviewed and documented.

1 Introduction

This study is to collect, analyze and document specifications and main design parameters of generic offshore anchors. These data are intended to be used to develop an anchor database that enables the users to perform a preliminary anchor selection and sizing based on global performance analysis results and additional input such as soil conditions. Once completed, the database will be made available in the public domain as a part of the mooring analysis program module that can be integrated into design software for floating offshore wind turbines (FOWTs).

The study is divided into six tasks as summarized in the following:

1. Definition of applicable anchors for FOWTs (Section 2)
    - Review existing floating wind turbine designs
    - Determine types of applicable anchors
    - Estimate the range of anchor loads to be covered by the derived anchor design data
    - Develop typical soil profiles for which anchor design data will be generated
2. Drag anchor design data (Section 3)
    - Review drag anchor data in existing design guidelines such as API RP 2SK
    - Collect drag anchor data from Vryhof and Bruce for commonly used offshore drag embedment anchors such as Stevpris Mark 6 and Bruce FFTS Mark 5
    - Generate drag anchor design data
3. Vertically Loaded Anchor (VLA) design data (Section 4)
    - Collect VLA performance data from the manufacturers (Vryhof and Bruce)
    - Generate design data for VLAs based upon available information
4. Pile anchor design data (Section 5)
    - Generate design data for suction pile anchors in accordance with API RP 2A
    - Generate design data for driven pile anchors in accordance with API RP 2A
5. Guidance on application of the derived anchor design data (Section 6)
6. Typical connections between the anchor and the mooring line for various anchor types (Section 7)

The references are listed in Section 8.

2 Definition of Applicable Anchors for FOWTs

2.1 Anchor Types

A state-of-the-art review of various designs, prototypes and concepts of floating offshore wind turbines (FOWTs) was performed in the BSEE TA&R Project No. 669 [8]. Numerous publications have been reviewed and commented. It was found that, in general, the stationkeeping systems employed by the existing design concepts of FOWTs include the spread mooring (catenary, taut-line or semi-taut-line) system and the tension leg system. The design and selection of the stationkeeping systems of FOWTs are mostly based on experience from the offshore oil and gas industry. For the spread mooring system, four typical anchor types, including drag anchors, VLAs, conventional piles anchors and suction pile anchors are commonly adopted, depending on the configuration of mooring system, floating support structure type, soil conditions, maximum line tensions, installation considerations, as well as costs. For the tension leg system, conventional pile anchors or suction pile anchors are typically used because of the requirement of high axial holding capacity.

The anchor design data presented in this report are generated for typical offshore anchors with consideration of the effect of floating support structure types, soil properties, and maximum line tension ranges. Four types of commonly used offshore anchors are covered in this study, which include:

- Drag anchors
- Vertical Loaded Anchors (VLAs)
- Suction pile anchors
- Driven pile anchors

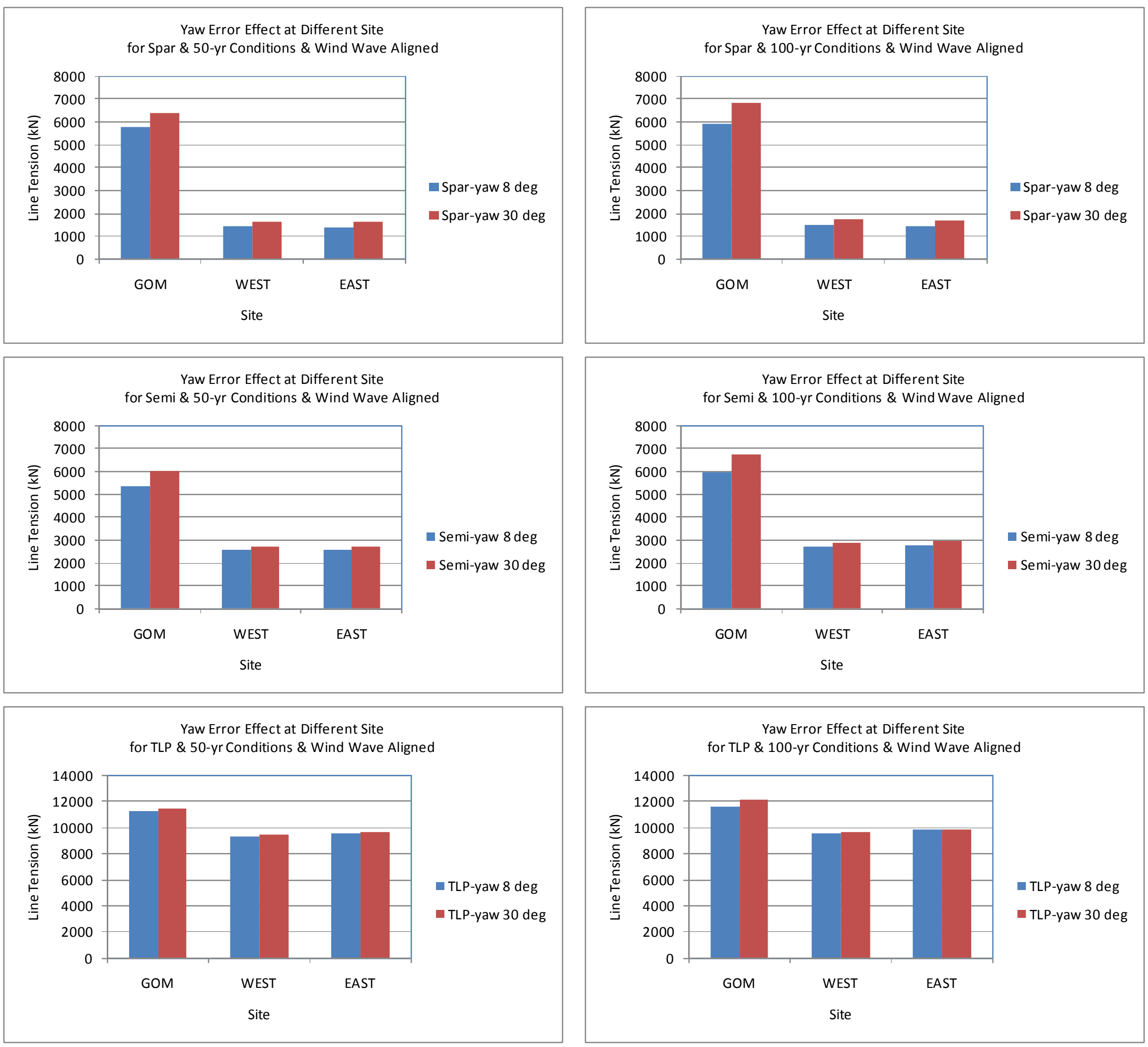
Other anchor types, such as the gravity anchor and foundation template, could also provide alternative solutions for a specific FOWT design. These special anchors are not addressed by this study as they have to be custom-designed based on specific project requirements and there is no generic design that could be derived.

2.2 Anchor Design Load

There is limited information about the typical range of maximum mooring line or tendon tension loads. BSEE TA&R Project No. 669 [8] performed extensive case studies using a Spar-type (3-line catenary mooring), a Semisubmersible-type (4-line catenary mooring), and a TLP-type (8-line tendon) floating wind turbines under various storm conditions on the US Outer Continental Shelf. The results of maximum and minimum line tensions in the intact line condition are summarized in Figure 2.1 and Figure 2.2. It is shown that

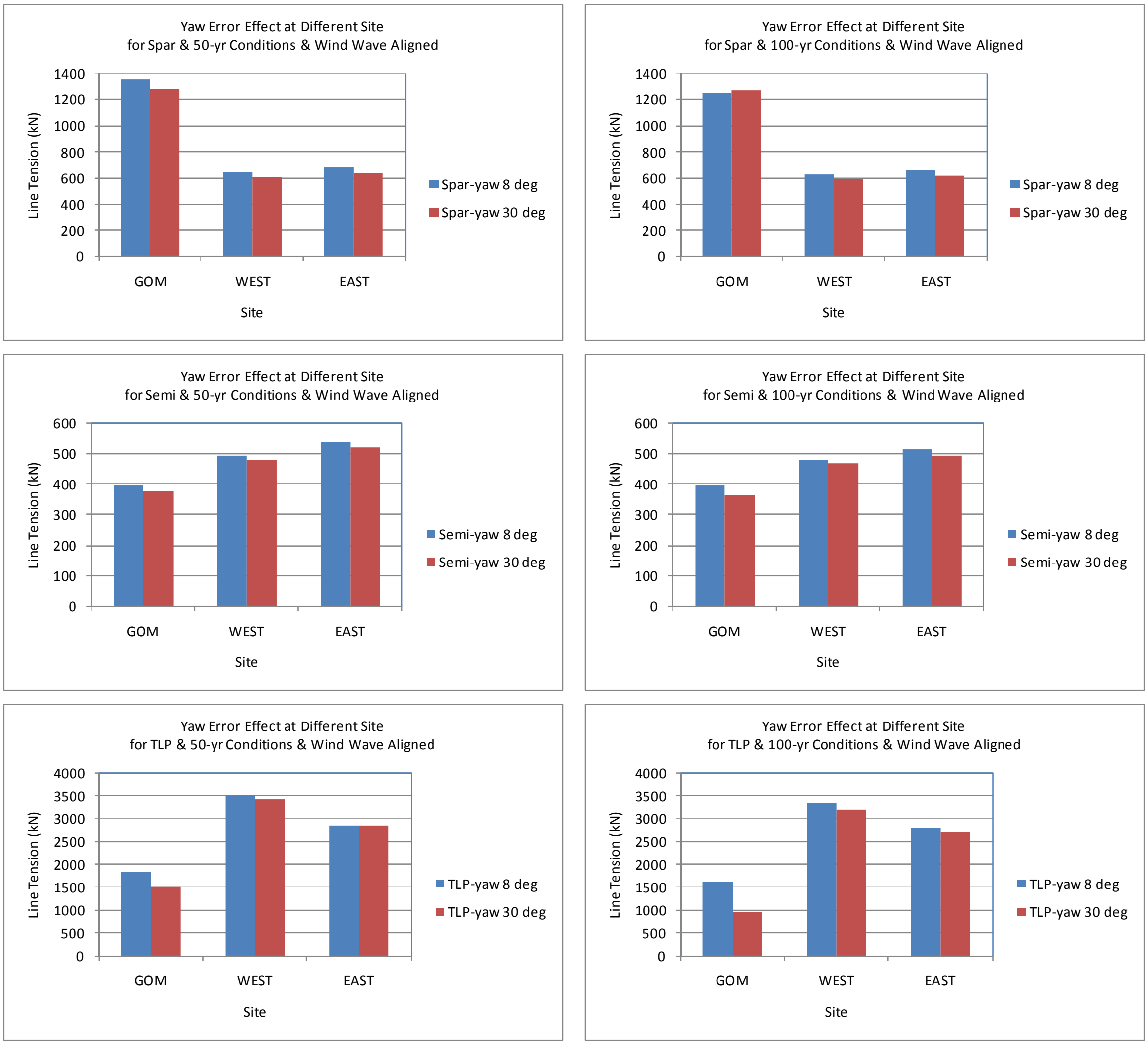
- the maximum line tensions is about 7,000 kN for the Spar and Semisubmersible FOWTs where the catenary mooring system is used; and
- the maximum tendon tension is about 12,000 kN for the TLP FOWT with tendons.

By applying a safety factor of 2.0 to the design of mooring line or tendon in the intact line condition, the anchor design load is estimated to be 14,000 kN (3,147 kips) for the Spar and the Semisubmersible FOWTs equipped with the catenary mooring system and 24,000 kN (5,395 kips) for the TLP FOWT with the tendon system.



50-Year Return Storm Conditions 100-Year Return Storm Conditions

Figure 2.1 Maximum Line Top Tension (Normal vs. Abnormal) under the Storm Conditions



50-Year Return Storm Conditions 100-Year Return Storm Conditions

Figure 2.2 Minimum Line Top Tension (Normal vs. Abnormal) under the Storm Conditions

2.3 Soil Conditions

The preliminary design data derived in this study are intended for worldwide applications, which may include a large variety of soil conditions. With consideration of availability of generic anchor design data and typical applications of offshore anchor, the following soil conditions, in combination with the specific anchor types, are considered in this study:

- Drag anchors: very soft clay, medium clay, hard clay, sand
- VLAs: very soft clay, medium clay
- Suction piles: very soft clay, medium clay
- Driven piles: very soft clay, medium clay, sand

It should be noted that there are no unified definition of representative soil conditions, and that it is beyond the scope of this study to define these terms. For reference, Table 2.1, which is adapted from the Vryhof Anchor Manual [7], provides the definition of clay types obtained using the recommended methods of ASTM and BS standards.

It should also be noted that, for actual site conditions, the soil is not uniform along the depth. For VLAs, conventional driven piles and suction piles, assumptions are made in this study for the undrained shear strength profiles. The detail definitions of soil properties are provided in Section 4 and Section 5, based on which the anchor design data are derived. Although efforts are made to select representative data, the user should be aware that the assumed soil properties are for the purpose of initial anchor sizing for the preliminary/conceptual design of FOWTs. Actual soil properties should be obtained from site assessment and used in detail designs.

Table 2.1 Definition of Clay Type Based on the ASTM and BS Standards [7]

Clay Type	*Undrained Shear Strength (kPa)*	
	ASTM D-2488	*BS CP-2004*
Very Soft	0 – 13	0 – 20
Soft	13 – 25	20 – 40
Firm	25 – 50	40 – 75
Stiff	50 – 100	75 – 150
Very Stiff	100 – 200	150 – 300
Hard	200 – 400	300 – 600
Very Hard	> 400	> 600

3 Drag Anchor Design Data

3.1 Vryhof Anchors

Vryhof has developed and manufactured a number of widely used offshore anchors in the past thirty years. Figure 3.1 through Figure 3.3 provide the anchor drawings and design charts for the three most recent models, *viz.* Stevin Mk3, Stevpris Mk5, and Stevpris Mk6, described in the Vryhof Anchor Manual [7].

The design curve denoted sand represents competent soils, such as medium dense sands and stiff to hard clays and is based on a silica sand of medium density. In sand and hard clay the optimal fluke/shank angle is typically set to 32 degrees.

The design curve denoted medium clay represents such soils as silt and firm to stiff clays. The fluke/shank angle is normally set at 32 degrees for optimal performance.

The design curve denoted very soft clay represents such soils as very soft clays (mud), and loose and weak silts. The curve is applicable in soil that can be described by an undrained shear strength of 4 kPa at the surface increasing by 1.5 kPa per meter depth or in the equation $S_u = 4{+}1.5z$, with S_u in kPa and z being the depth in meters below seabed. In very soft soils the optimum fluke/shank angle is typically 50 degrees.

Table 3.1 summarizes the design equations for Vryhof drag anchors derived based on the design curves in Figure 3.1 through Figure 3.3.

Table 3.1 Design Equations for Vryhof Drag Anchors

Vryhof Anchor	*Soil*	$UHC = a*(W)^b$			
		Metric Unit		*US Customary Unit*	
		• *UHC*: Anchor Ultimate Holding Capacity (kN) • *W*: Anchor Weight (MT) (1 ~ 50 MT)		• *UHC*: Anchor Ultimate Holding Capacity (kips) • *W*: Anchor Weight (kips) (1 ~ 110 kips)	
		a	*b*	*a*	*b*
Stevin MK3	Very Soft Clay	161.23	0.92	17.51	0.92
	Medium Clay	229.19	0.92	24.90	0.92
	Sand and Hard Clay	324.42	0.90	35.80	0.90
Stevpris MK5	Very Soft Clay	392.28	0.92	42.61	0.92
	Medium Clay	552.53	0.92	60.02	0.92
	Sand and Hard Clay	686.49	0.93	73.98	0.93
Stevpris MK6	Very Soft Clay	509.96	0.93	54.96	0.93
	Medium Clay	701.49	0.93	75.60	0.93
	Sand and Hard Clay	904.21	0.92	98.22	0.92

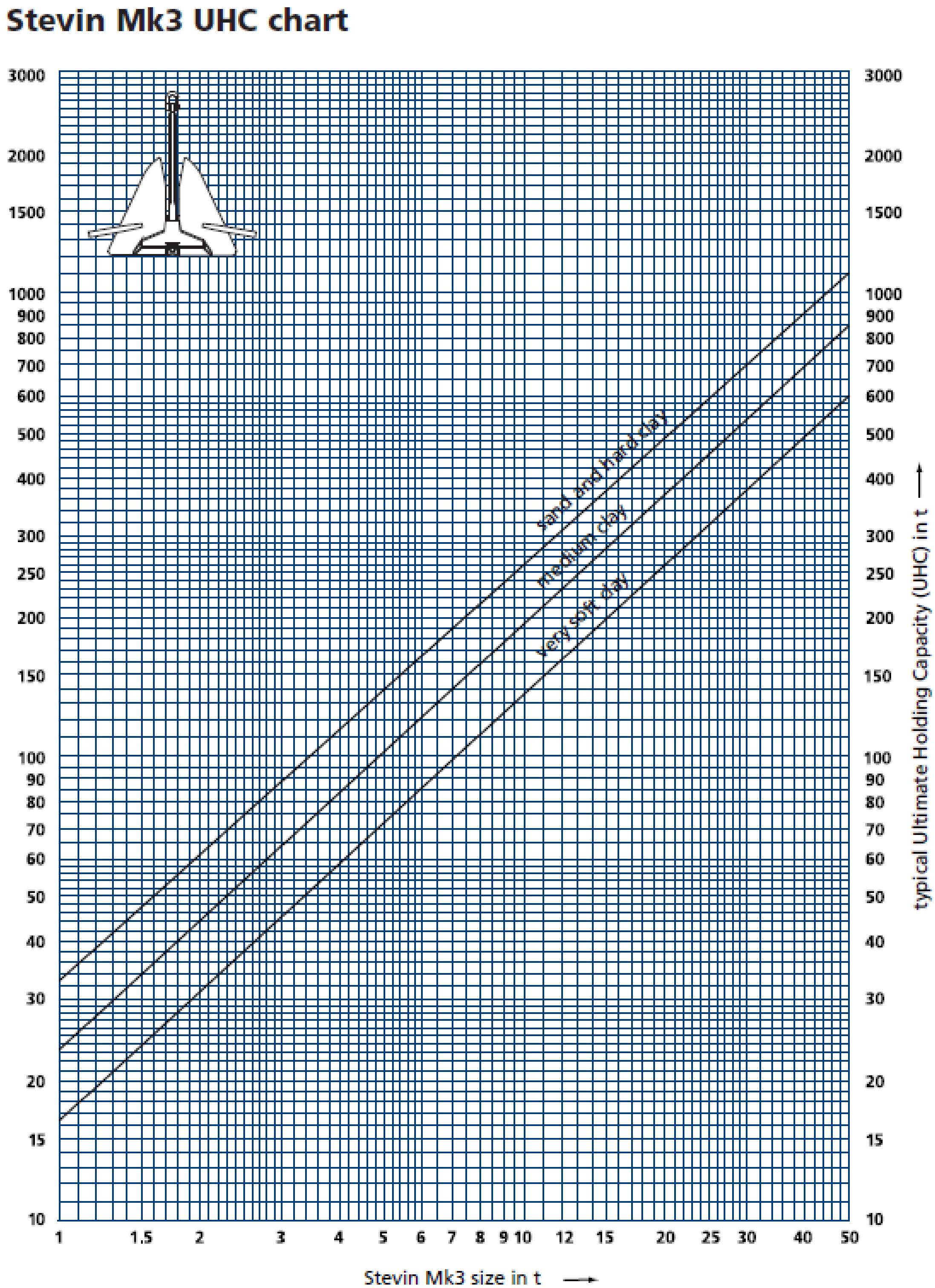


Figure 3.1 Design Curves for Vryhof Stevin Mk3[7]

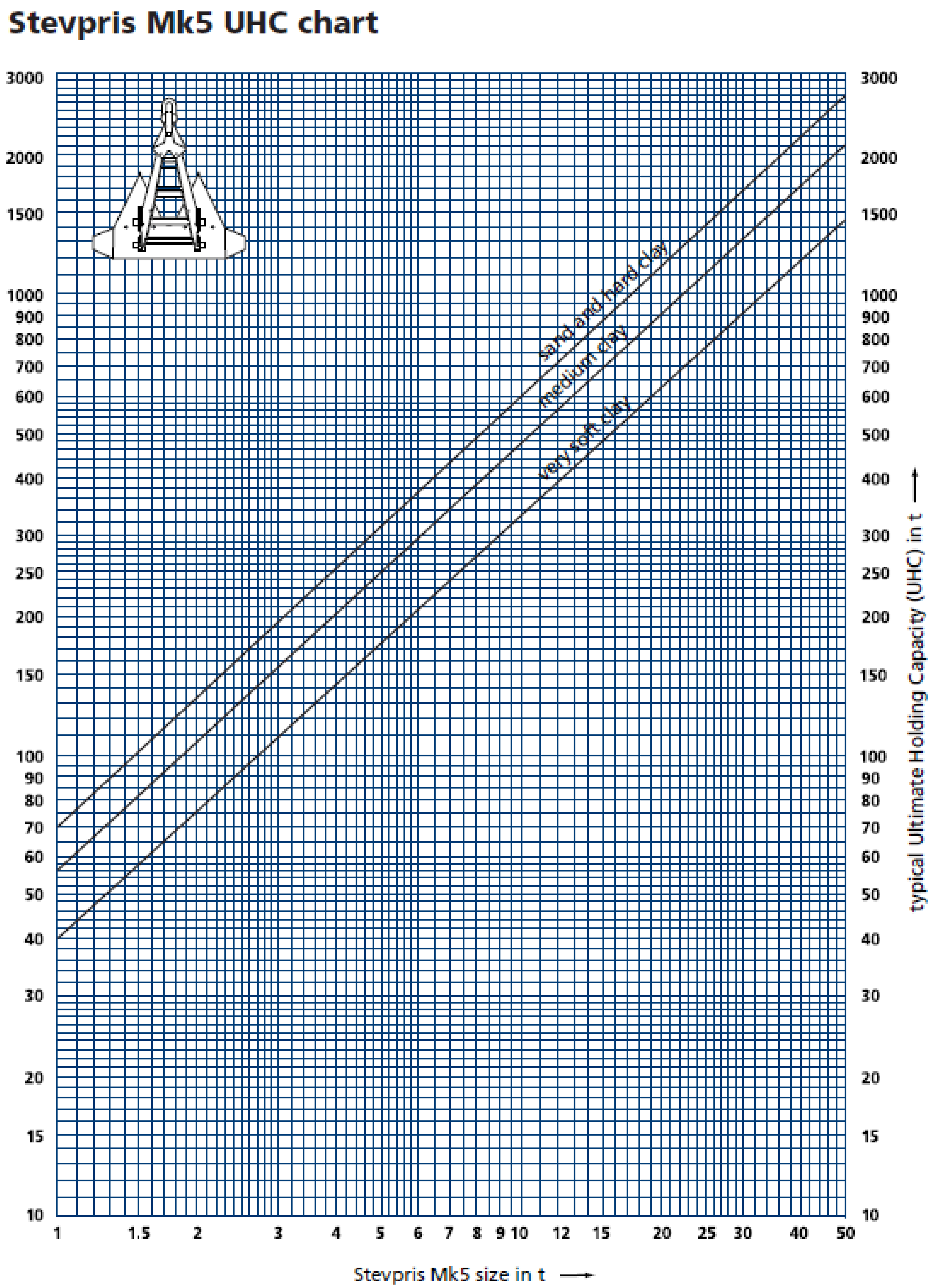


Figure 3.2 Design Curves for Vryhof Stevpris Mk5[7]

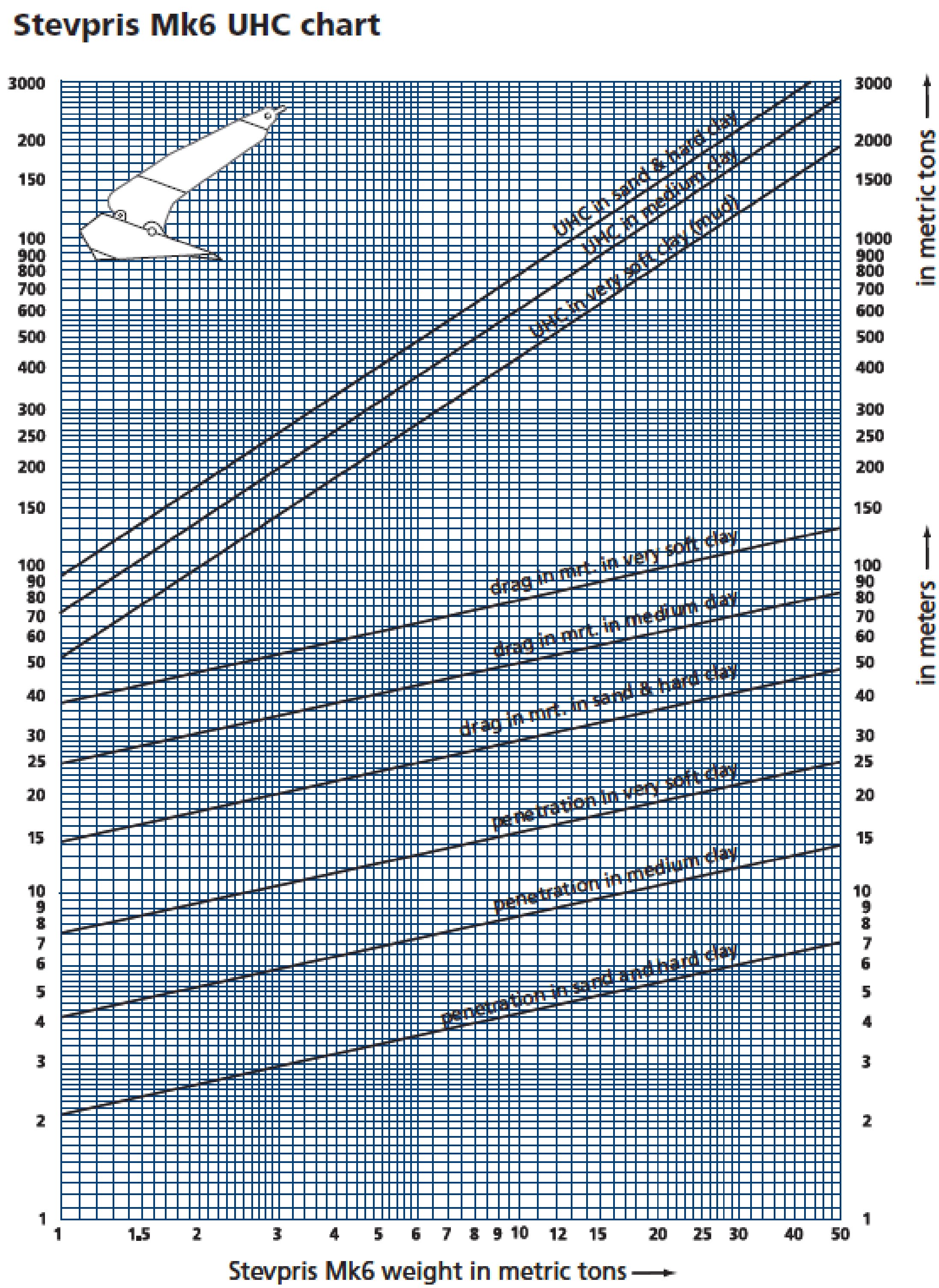


Figure 3.3 Design Curves for Vryhof Stevpris Mk6[7]

3.2 Bruce Anchors

Similar to Vryhof, Bruce Anchor Group is another major supplier of offshore anchors. Figure 3.4 through Figure 3.6 depict the design charts and equation for the three recent models including FFTS Mk4 [5], PM (Permanent Mooring) [6], and FFTS GP (General Purpose) [4], respectively. It should be noted that the Bruce anchor design data include the effect of the forerunner (chain or wire rope). The fluke angle is typically set at 30 degrees for sand and 50 degrees for soft clay.

Table 3.2 summarizes the design equations for the Bruce drag anchors based on the design curves in Figure 3.4 through Figure 3.6.

Table 3.2 Design Equations for Bruce Drag Anchors

Vryhof Anchor	*Soil*	*Fore-runner*	$UHC = a*(W)^b$			
			Metric Unit		*US Customary Unit*	
			• *UHC*: Anchor Ultimate Holding Capacity (kN) • *W*: Anchor Weight (MT) (1 ~ 45 MT for FFTS MK4) (1 ~ 45 MT for PM) (1 ~ 20 MT for FFTS GP)		• *UHC*: Anchor Ultimate Holding Capacity (kips) • *W*: Anchor Weight (kips) (2 ~ 99 kips for FFTS MK4) (2 ~ 99 kips for PM) (2 ~ 44 kips for FFTS GP)	
			a	*b*	*a*	*b*
FFTS MK4	Soft Clay	Chain	391.79	0.92	42.56	0.92
	Soft Clay	Wire	487.02	0.92	52.90	0.92
	Sand	Chain	459.56	0.94	49.14	0.94
PM	Soft Clay	Chain	450.53	0.92	48.94	0.92
	Soft Clay	Wire	560.08	0.92	60.84	0.92
	Sand	Chain	597.44	0.94	63.88	0.94
FFTS GP	Soft Clay	Chain	636.67	0.92	69.16	0.92
	Soft Clay	Wire	791.42	0.92	85.97	0.92
	Sand	Chain	746.80	0.94	79.85	0.94

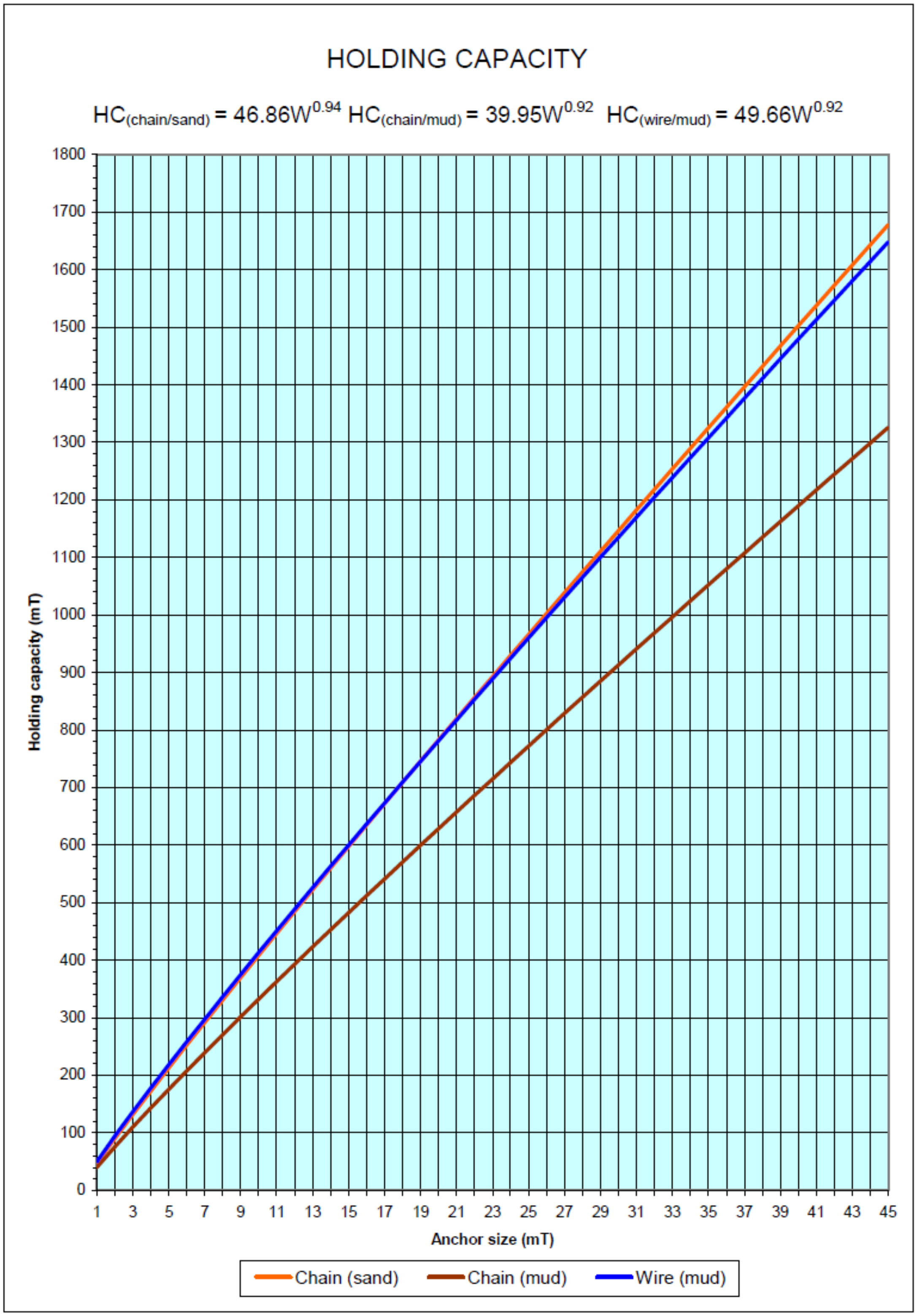


Figure 3.4 Design Curves for Bruce FFTS Mk4 [5]

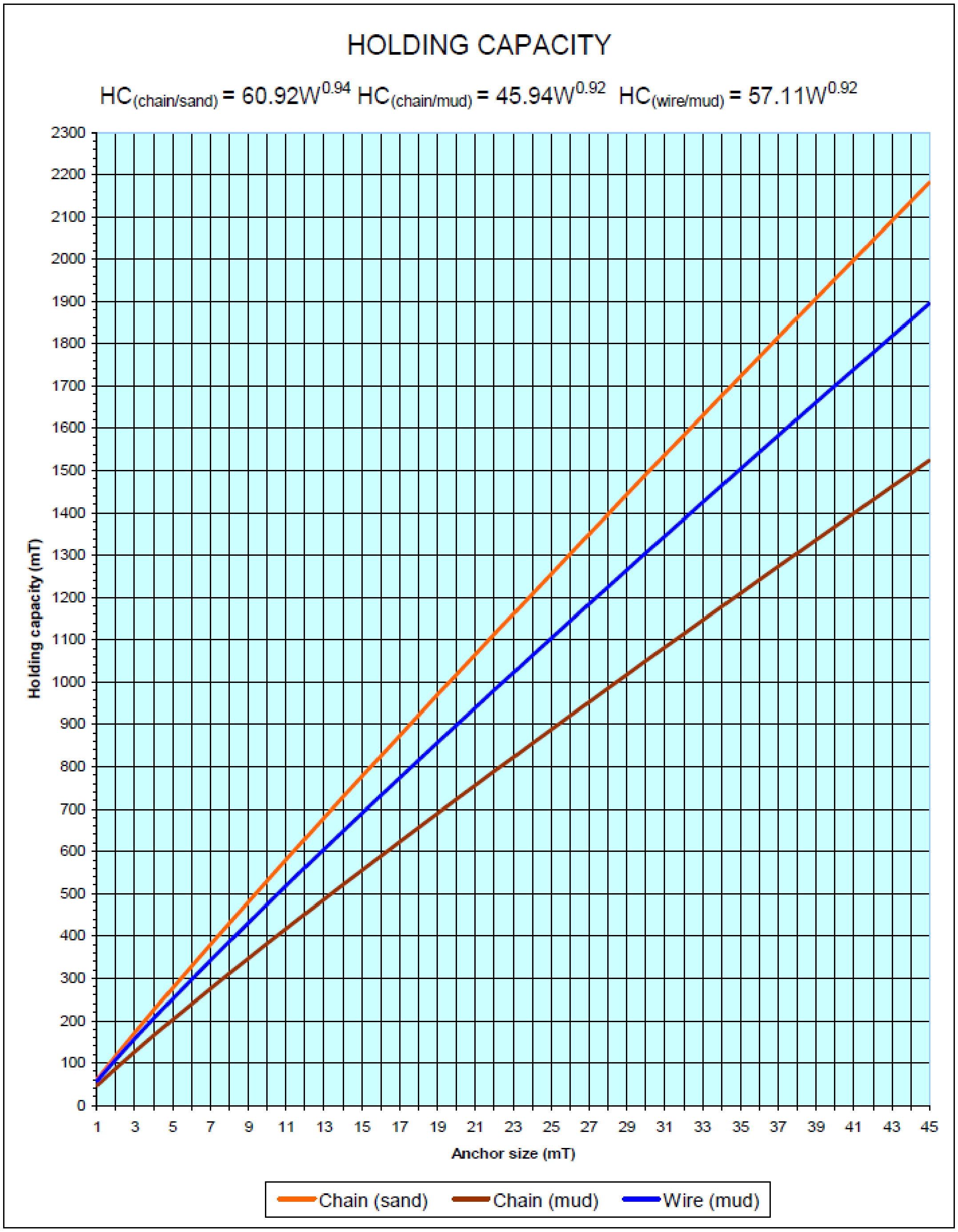
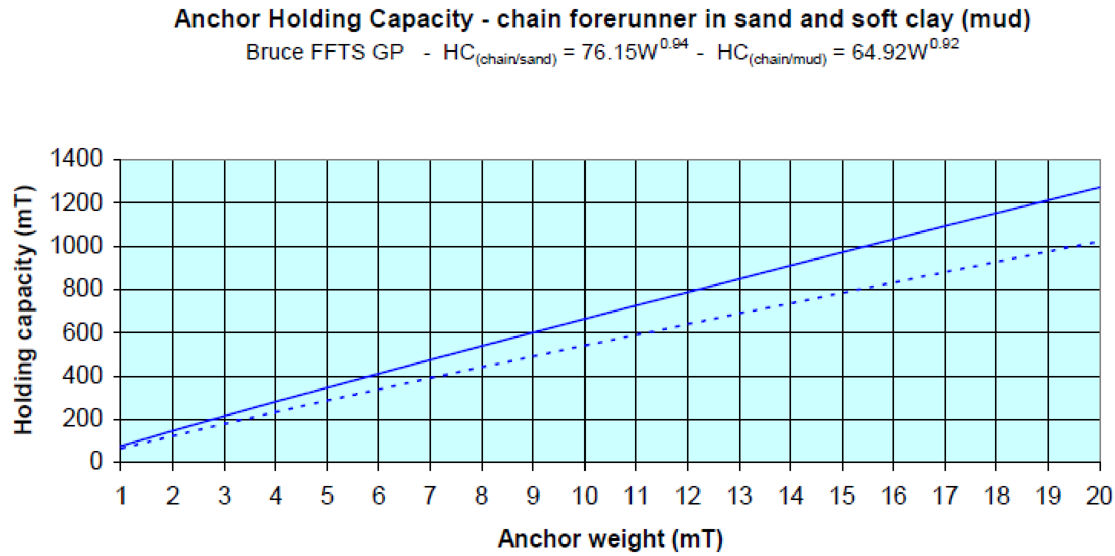


Figure 3.5 Design Curves for Bruce PM Anchor [6]



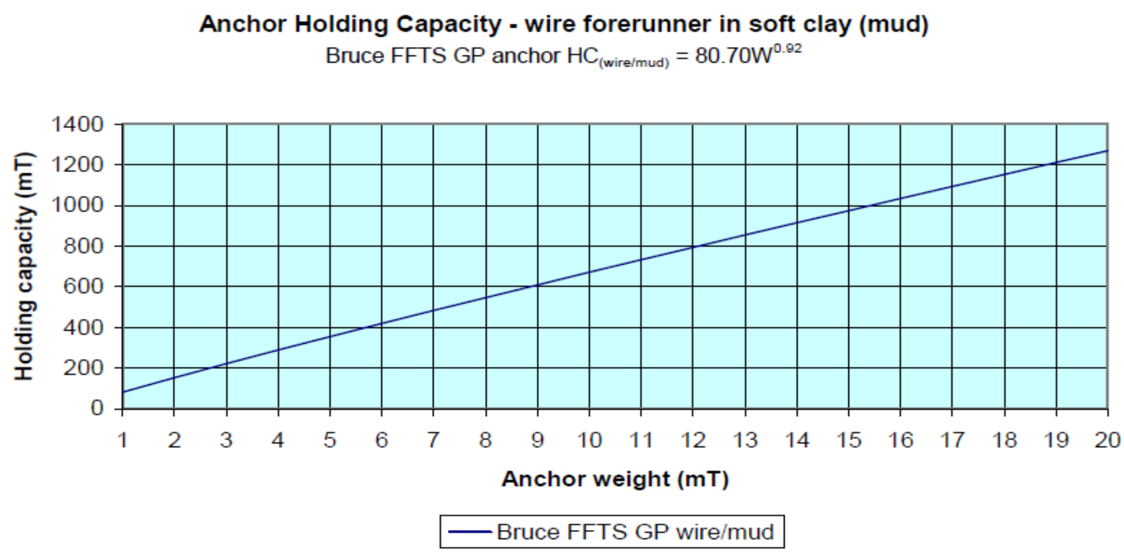


Figure 3.6 Design Curves for Bruce FFTS GP Anchor [4]

3.3 Drag Anchor Data in API RP 2SK

API RP 2SK [3] provides design charts for a number of old drag embedment anchors, which have much lower holding capacities. Most of these drag anchors are no longer in production and, therefore, their design data are not included in the present study.

4 Vertically Loaded Anchor (VLA) Design Data

4.1 Vryhof Stevmanta VLA

Figure 4.1 depicts the Vryhof Stevmanta VLA[7], which is one of the popular choices of VLAs in the offshore industry for permanent moorings.

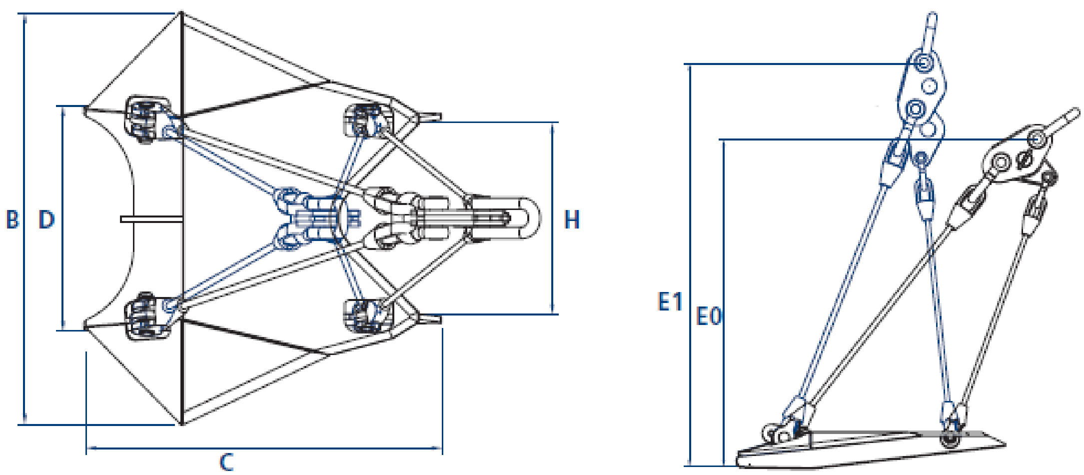


Figure 4.1 Vryhof Stevmanta VLA[7]

Typical Ultimate Pull-out Capacity (UPC), according to the Vryhof Anchor Manual [7], can be expressed in the equations as stated below:

$$UPC = N_c * S_u * A$$

where,

UPC	= Ultimate Pull-out Capacity (kN)
N_c	= bearing capacity factor
A	= fluke area (m^2)
S_u	= undrained shear strength of clay (kPa)
	= $k * D$
D	= penetration depth (m)
	= $1.5 * k^{0.6} * d^{-0.7} * A^{0.3} * [\tan(\alpha)]^{1.7}$
k	= quotient undrained shear strength of clay (kPa/m)
d	= mooring line or installation line diameter (m)
α	= fluke-shank angle (deg)

To derive the design data, typical values of the following parameters are applied:

d = diameter of a wire rope which has the MBS equivalent to twice the UPC

$N_c = 10$

$\alpha = 50°$

The design curves and equations are presented in Figure 4.2 and Table 2.1 for various quotient undrained shear strength (*k*) of clay. The undrained shear strength of clay (S_u) is defined above.

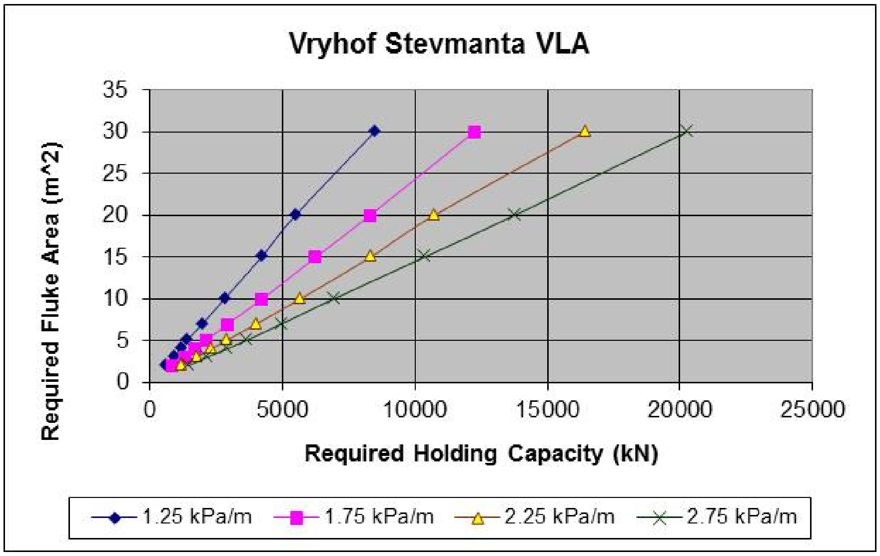


Figure 4.2 Vryhof Stevmant VLA Design Curves

Table 4.1 Design Equations for Vryhof VLAs for Permanent Moorings

*A = c*UHC + d*					
Metric Unit US Customary Unit			*Metric Unit US Customary Unit*		
Soil Quotient Undrained Shear Strength k (kPa/m)	• *A*: Required fluke area (m²) (1 ~ 30 m²) • *UHC*: Required Anchor Holding Capacity (kN)		*Soil Quotient Undrained Shear Strength k (psf/ft)*	• *A*: Required fluke area (ft²) (10 ~ 320 ft²) • *UHC*: Required Anchor Holding Capacity (kips)	
	c	*d*		*c*	*d*
1.25 (very soft)	0.003581	-0.1094	8 (very soft)	0.1715	-1.177
1.75 (very soft)	0.002461	-0.2847	11 (very soft)	0.1178	-3.065
2.25 (medium)	0.001857	-0.3259	14 (medium)	0.0889	-3.509
2.75 (medium)	0.001489	-0.3176	18 (medium)	0.0713	-3.419

4.2 Bruce Dennla VLA

Figure 4.3 shows a picture of the Bruce Dennla VLA, which is also well accepted for use in mooring operations. However the manufacturer, Bruce Anchor Group, does not provide the design information for this VLA and therefore the anchor design data cannot be generated.

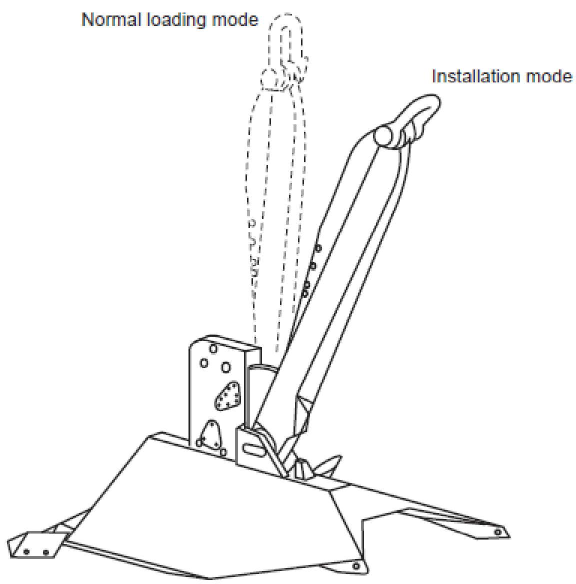


Figure 4.3 Bruce Dennla VLA [2]

5 Pile Anchor Design Data

5.1 Pile Anchor Design Approach

Based on the estimated maximum design loads in Section 2.2, the pile anchor design data are derived to accommodate the maximum design load up to 16,000 KN or 3,500 kips for FOWTs with the spread mooring system, and 27,000 KN or 6,000 kips for TLP-type FOWTs with the tendon system.

The pile anchor design data are derived in accordance with the pile foundation design procedure outlined in API RP 2A [2]. The finite element method for beam-columns is used to calculate the pile deflection, bending stresses, shear force, axial stress, and soil deformation.

5.1.1 Design Cases

There are many parameters for pile anchor design, such as type of mooring, anchor type, soil type, anchor load direction, anchor padeye location, and anchor dimension ratio, etc. With consideration of typical pile anchor configurations and their intended applications, the pile anchor design data are derived for the cases listed in Table 5.1.

Table 5.1 Pile Anchor Design Cases

Mooring Type	*Anchor Type*	*Soil*	*Load Direction from Horizontal*
Spread Mooring System (Semisubmersible, Spar, etc.)	Suction Pile	Very Soft Clay Medium Clay	40º
Spread Mooring System (Semisubmersible, Spar, etc.)	Driven Pile	Very Soft Clay Medium Clay Sand	40º
Tendon System (TLP, etc.)	Suction Pile	Very Soft Clay Medium Clay	90º
Tendon System (TLP, etc.)	Driven Pile	Very Soft Clay Medium Clay Sand	90º

In the global performance analysis, the mooring line typically ends on the seafloor so the buried section of mooring line connecting to the padeye is not included. The buried section of mooring line is approximately in an inverse catenary shape in the case of catenary mooring. See Figure 7.6 for an example. As a result, the vertical load on a pile anchor always exist in reality, even if the mooring line load obtained from the global performance analysis is horizontal (i.e. in parallel to the seafloor). In many cases, the optimal utilization of pile anchor capacity is achieved when the direction of maximum loading at the padeye, i.e. *Θ* in Figure 5.2, is approximately 35-45 degrees from the horizontal direction. Figure 5.1 depicts a typical ultimate holding capacity envelope for pile anchors. It shows that when the loading angle at the padeye is smaller than 40 degrees, the pile holding capacity is determined by the pile's lateral capacity, while for a loading angle larger than 40 degrees, the pile's axial capacity will govern. Recommendations on the use of the derived pile anchor data for various loading angles are provided in Section 6.2.

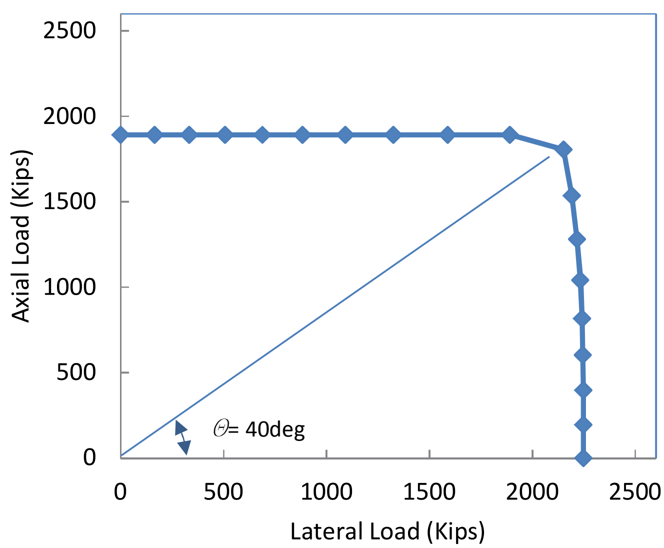


Figure 5.1 Typical Pile Anchor Ultimate Holding Capacity Envelope

5.1.2 Soil Properties

Table 5.6 and Table 5.7 list the representative soil properties for very soft clay, medium clay, and sand used in the derivation of the pile anchor design data.

Table 5.2 Definition of Clay Properties for Deriving Pile Anchor Design Data

Unit System	*Soil Property*	*Unit*	*Soil Type*	
			Very Soft Clay	*Medium Clay*
Metric Units	k_0	kPa	2.39	23.94
	k	kPa/m	1.41	2.67
	γ	kN/m^3	4.71	9.43
	ε_{50}	-	0.02	0.01
	m	-	0.33	0.25
US Customary Units	k_0	psf	50	500
	k	psf/ft	9	17
	γ	pcf	30	60
	ε_{50}	-	0.02	0.01
	m	-	0.33	0.25

Notes:

- k_0 Undrained shear strength at the seafloor
- k Quotient undrained shear strength
- γ effective unit weight
- ε_{50} 50% of the strain at the ultimate soil resistance
- m Exponential constant defining the shape of the p-y curve

Table 5.3 Definition of Sand Properties for Deriving Pile Anchor Design Data

Unit System	*Soil Property*	*Unit*	*Soil Type*
			Sand
Metric Units	ϕ	deg	30
	γ	kN/m^3	8.64
	C_1	-	1.9
	C_2	-	2.7
	C_3	-	27
	k	kN/m^3	13573
	A	-	0.9
US Customary Units	ϕ	deg	30
	γ	pcf	55
	C_1	-	1.9
	C_2	-	2.7
	C_3	-	27
	k	lb/in^3	50
	A	-	0.9

Notes:

ϕ angle of internal friction

γ effective unit weight

k initial modulus of subgrade reaction

A coefficient for dynamic loading (see API RP 2A [2])

C_1, C_2, C_3 coefficients determined in accordance with API RP 2A [2]

5.1.3 Anchor Pile Geometry and Material

Figure 5.2 depicts the definition of anchor pile geometry. Table 5.8 contains the target ratios of L/D and D/T, where L is the pile length; D is the outer diameter; and T is the wall thickness. These target ratios are determined based on common design practice of offshore pile anchors for permanent mooring systems. In the calculation of pile size for each design case, the target ratios are used to generate initial pile dimensions used in the design iteration. The actual ratio of L/D and D/T may slightly differ from the target values.

The pile top is assumed at the mud line (i.e. $d = 0$ as shown in Figure 5.2) in the derived design data. Additional pile length above the seafloor may be added to the calculated pile length in the case that the anchor top is above the seafloor.

The location of the padeye for mooring line connection is assumed to be

- 50% L of a driven pile from the pile top at the mud line and;

- 70% L of a suction pile measured from the pile top at the mud line.

These padeye locations can in general provide most efficient soil resistance to the anchor load. The padeye location does not apply to the pile anchor of the TLP tendon system.

The piles are assumed to be constructed using mild steel with a specified minimum yield strength of 36 ksi (248 MPa). To the extent of this study, the yield strength is found having no impact on sizing driven piles of the TLP tendon system or suction piles of the spread mooring system, because the bending stress in these cases is very low and the total stress is well below the yield strength. It is possible that the material yield strength may affect the design of driven piles of the spread mooring system. However, use of higher yield steel would not significantly change the anchor size since the anchor geometry is also affected by the *L/D* and *D/T* ratios.

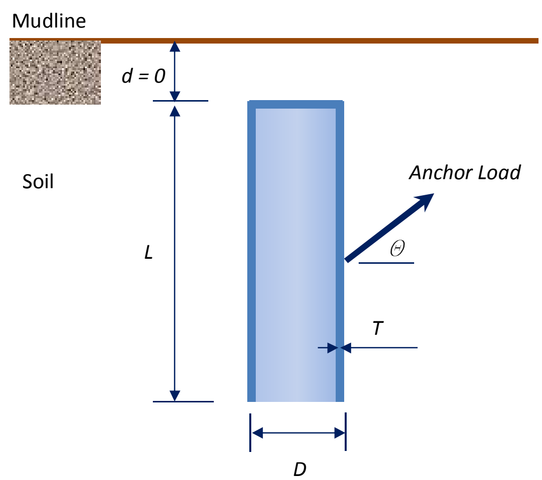


Figure 5.2 Definition of Pile Anchor Geometry

Table 5.4 Target Pile Anchor *L/D* and *D/T* Ratio

Mooring	*Pile Anchor*	*L/D*	*D/T*
Spread Mooring System	Driven Pile for Very Soft Clay	30	30
	Driven Pile for Medium Clay	30	30
	Driven Pile for Sand	40	25
	Suction Pile for Very Soft Clay	6	150
	Suction Pile for Medium Clay	6	150
TLP Tendon System	Driven Pile for Very Soft Clay	50	40
	Driven Pile for Medium Clay	50	40
	Driven Pile for Sand	50	40
	Suction Pile for Very Soft Clay	6	150
	Suction Pile for Medium Clay	6	150

5.2 Pile Anchor Design Data

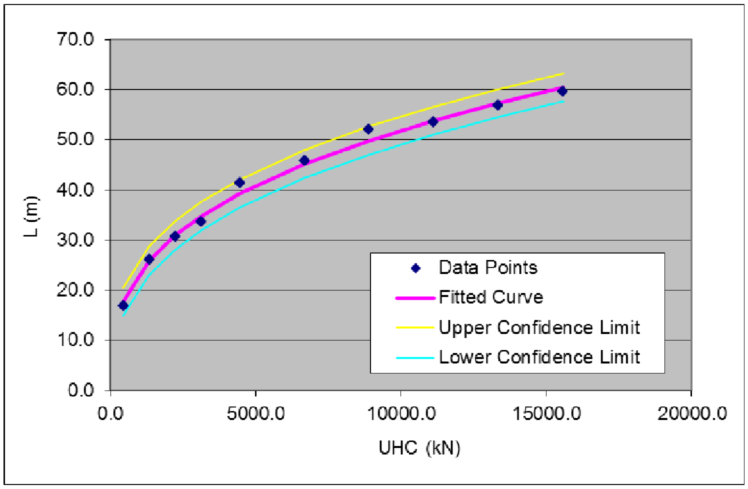
The derivation of pile anchor design data follows the pile foundation design method recommended by API RP 2A. The analysis method for piles of TLP tendon systems is the same as that used for piles of spread mooring systems, except that the loading angle is set to 90 degrees and, therefore, the lateral soil resistance is not utilized.

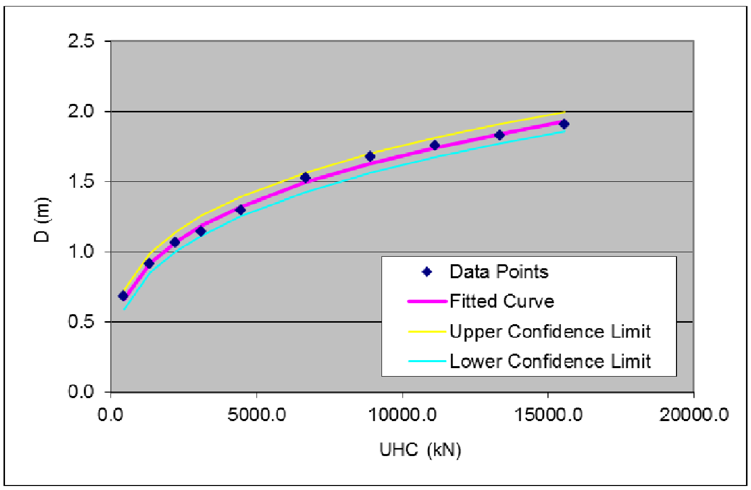
Figure 5.3 presents an example of the design curves for the driven pile anchor of the spread mooring system in medium clay. For this particular example, 10 design loads are selected for the calculation of required geometry of the driven pile. Curve fitting is used to generate the design curves and the 95% confidence level limits. Another example of the design curves for the suction pile anchor of the TLP tendon system is shown in Figure 5.4, where 15 design loads are selected for generating the design data points.

Table 5.5 and Table 5.6 provide the design equations expressed in the metric units and the US customary units, respectively, for the pile anchors of the spread mooring system.

Table 5.7 and Table 5.8 present the design equations expressed in the metric units and the US customary units, respectively, for the pile anchors of the TLP tendon system.

It should be noted that these pile design equations are derived without applying any safety factors. In this regard, the required holding capacity or the design load is the same as the anchor's ultimate hold capacity.





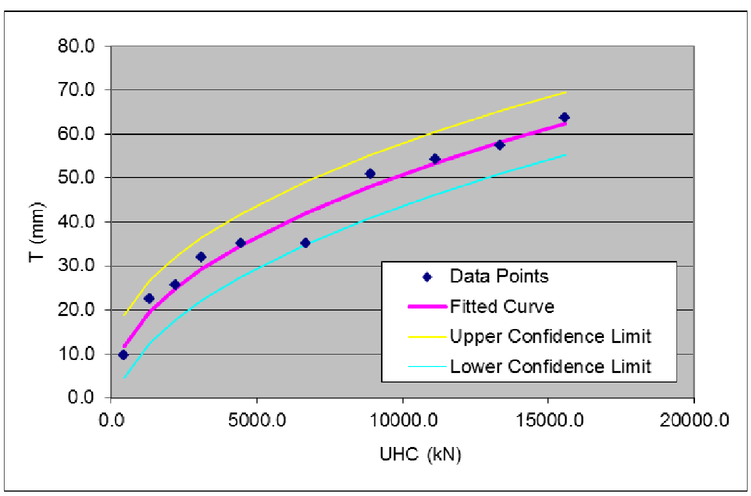


Figure 5.3 Example Pile Anchor Design Curves for the Spread Mooring System (Driven Piles in Very Soft Clay)

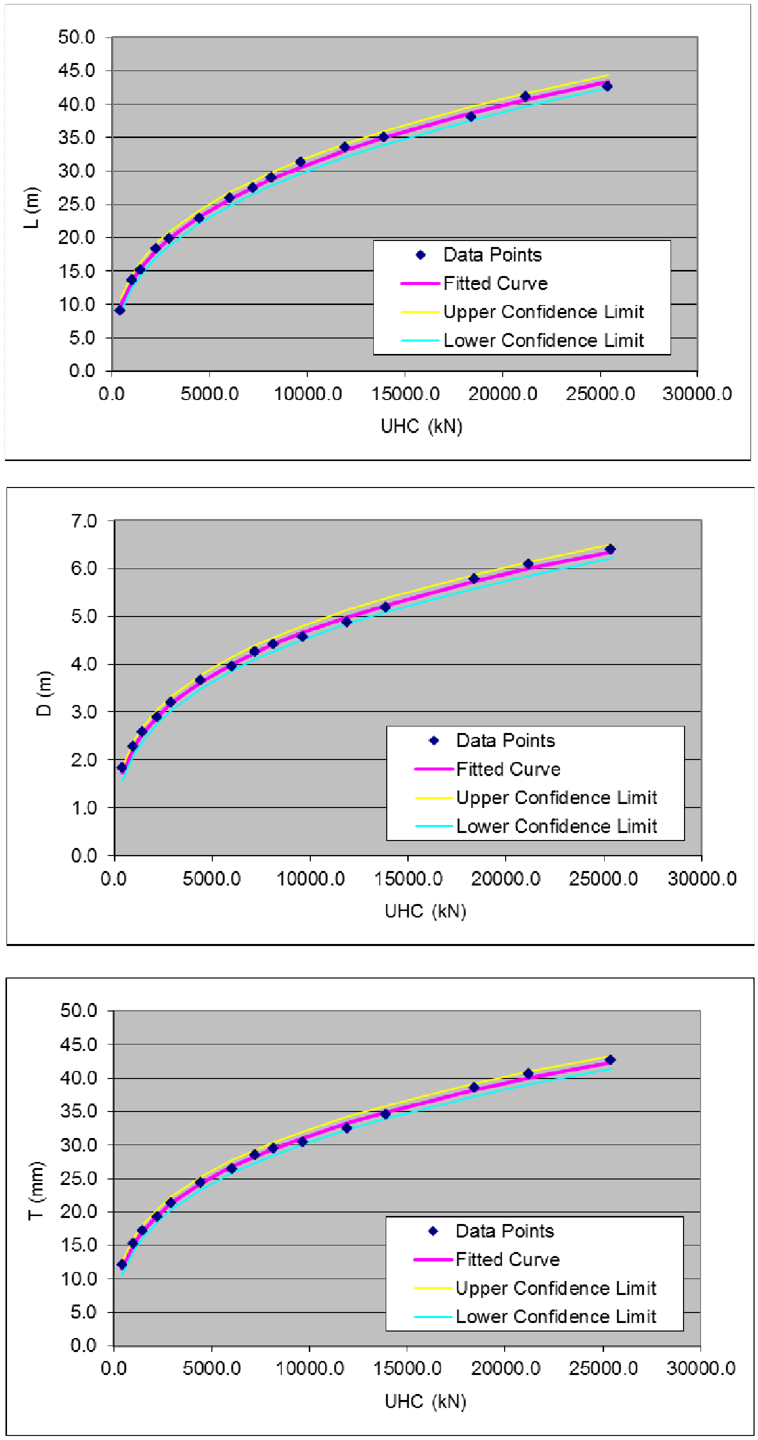


Figure 5.4 Example Pile Anchor Design Curves for the TLP Tendon System (Suction Piles in Medium Clay)

Table 5.5 Design Equations for Pile Anchors of the Spread Mooring System (Metric Units)

Pile Anchor Type	*Soil*	$L,D,T = c*(UHC)^d$ • *L:* Pile length (m) • *D:* Pile outer diameter (m) • *T:* Pile thickness (mm) • *UHC:* Required pile ultimate holding capacity (kN) (≤16,000 kN)					
		L (m)		*D* (m)		*T* (mm)	
		c	*d*	*c*	*d*	*c*	*d*
Driven Pile	Very Soft Clay	2.1697	0.3447	0.1049	0.3016	0.6722	0.4694
	Medium Clay	1.2976	0.3733	0.0529	0.3452	1.0531	0.4042
	Sand	2.5296	0.2907	0.0319	0.3700	1.1185	0.3889
Suction Pile	Very Soft Clay	1.1161	0.3442	0.3095	0.2798	2.0580	0.2803
	Medium Clay	0.5166	0.3995	0.1260	0.3561	0.8398	0.3561

Table 5.6 Design Equations for Pile Anchors of the Spread Mooring System (US Customary Units)

Pile Anchor Type	*Soil*	$L,D,T = c*(UHC)^d$ • *L:* Pile length (ft) • *D*: Pile outer diameter (ft) • *T*: Pile thickness (in) • *UHC*: Required pile ultimate holding capacity (kips) (≤3,500 kips)					
		L (ft)		*D* (ft)		*T* (in)	
		c	*d*	*c*	*d*	*c*	*d*
Driven Pile	Very Soft Clay	11.9044	0.3447	0.5398	0.3016	0.0533	0.4695
	Medium Clay	7.4317	0.3732	0.2908	0.3452	0.0758	0.4043
	Sand	12.8039	0.2907	0.1820	0.3700	0.0787	0.3889
Suction Pile	Very Soft Clay	6.1209	0.3442	1.5417	0.2797	0.1231	0.2803
	Medium Clay	3.0754	0.3996	0.7031	0.3561	0.0562	0.3561

Table 5.7 Design Equations for Pile Anchors of the TLP Tendon System (Metric Units)

Pile Anchor Type	*Soil*	$L, D, T = c*(UHC)^d$ • *L:* Pile length (m) • *D:* Pile outer diameter (m) • *T:* Pile thickness (mm) • *UHC:* Pile ultimate holding capacity (kN) (≤27,000 kN)					
		L (m)		*D* (m)		*T* (mm)	
		c	*d*	*c*	*d*	*c*	*d*
Driven Pile	Very Soft Clay	3.2744	0.3374	0.0655	0.3375	1.6390	0.3373
	Medium Clay	2.0402	0.3602	0.0407	0.3604	1.0197	0.3603
	Sand	2.1555	0.3333	0.0431	0.3334	1.0787	0.3332
Suction Pile	Very Soft Clay	1.1037	0.3621	0.2475	0.3200	1.6500	0.3200
	Medium Clay	0.5082	0.4181	0.1509	0.3487	1.0057	0.3487

Table 5.8 Design Equations for Pile Anchors of the TLP Tendon System (US Customary Units)

Pile Anchor Type	*Soil*	$L, D, T = c*(UHC)^d$ • *L:* Pile length (ft) • *D:* Pile outer diameter (ft) • *T:* Pile thickness (in) • *UHC:* Pile ultimate holding capacity (kips) (≤6,000 kips)					
		L (ft)		*D* (ft)		*T* (in)	
		c	*d*	*c*	*d*	*c*	*d*
Driven Pile	Very Soft Clay	17.7810	0.3374	0.3557	0.3374	0.1066	0.3375
	Medium Clay	11.4545	0.3603	0.2291	0.3603	0.0687	0.3603
	Sand	11.6269	0.3333	0.2326	0.3332	0.0697	0.3333
Suction Pile	Very Soft Clay	6.2178	0.3621	1.3091	0.3200	0.1047	0.3201
	Medium Clay	3.1115	0.4182	0.8330	0.3487	0.0666	0.3487

6 Use of the Derived Anchor Design Data

6.1 Application of Anchor Type

Table 6.1 summarizes typical applications of various anchor types.

Table 6.1 Typical Application of Anchor Types

Mooring Type	*Drag Anchor*	*VLA*	*Driven Pile*	*Suction Pile*
Catenary	√		√	√
Taut Leg		√	√	√
Tendon			√	√

In the case of catenary mooring, there must be a sufficient length of mooring line resting on the seafloor such that no uplifting angle occurs under any design conditions. With the use of modern high capacity drag anchors, a small uplifting angle may be acceptable for the catenary mooring although there is no universal criterion as to how large this angle should be allowed. API RP 2SK[3], Appendix D indicates that up to 20 degrees may work fine for those high capacity drag anchors. There are some limitations cautioned in API RP 2SK, including (1) uplifting angle may be acceptable for extreme or damaged conditions, but not for the operational load conditions; (2) sufficient anchor penetration should be achieved such that the application may only be justifiable for very soft clay; (3) an anchor capacity reduction factor as a function of uplifting angle has to be applied, i.e. there is an additional safety factor applied for non-zero uplifting angles; (4) non-zero uplifting angles may only be allowed for certain high capacity drag anchors. For Vryhof and Bruce anchors for which the design data are provided in this report, the following anchor capacity reduction factor adapted from API RP 2SK, Appendix D may be used as an approximation.

Table 6.2 Drag Anchor Capacity Reduction Factor for Non-zero Uplifting Angles

Uplifting Angle (deg)	*Capacity Reduction Factor*
0	1.0
5	0.98
10	0.95
15	0.89
20	0.81

For driven pile and suction anchors used in catenary or taut-leg mooring systems, the padeye are located at certain burial depth below the mud line. The exact location of the padeye should be determined by design optimization. For preliminary sizing of anchor piles, a prescribed typical value may be used instead. The design data provided in Section 5 is derived with the assumption that the padeye is located at 50% of the driven pile length and 70% of the suction pile length below the mud line.

6.2 Anchor Sizing Procedure

A suggested preliminary anchor sizing procedure is outlined as follows:

1. Perform global performance analyses for an FOWT subjected to the design load cases under consideration.

2. Determine the largest value of the maximum mooring/tendon line load times an applicable safety factor among all the design load cases under consideration. Where relevant, consideration should also be given to the maximum mooring line load with a smaller magnitude but acting in a direction where the pile anchor holding capacity is determined by a different failure mode (pull-out due to the insufficient axial capacity or rotation due to the insufficient lateral capacity).

3. Determine the anchor size using the anchor design data in this report.

   - Drag anchor: Use the design equations in Section 3 (Table 3.1 and Table 3.2) to determine the required anchor weight

   - VLA: Use the design equations in Section 4 (Table 4.1) to determine the required fluke area for Vryhof Stevmanta VLA. Design data for Bruce Dennla are not available.

   - Pile Anchor: Use the design equations in Section 5 (Table 5.5 or Table 5.6 for pile anchors of the spread mooring system; Table 5.7 or Table 5.8 for pile anchors of the tendon system) to determine the pile size (L, D, and T). Additional pile length above the seafloor can be added to the calculated pile length if the anchor top is above the seafloor. If the mooring line uplifting angle at the dip-down point on the sea floor is larger than 40 degrees (i.e. in the taut-leg mooring case), the pile holding capacity can be assumed being governed by the axial capacity. The design curves in Table 5.7 or Table 5.8 for piles under axial loading for TLPs should therefore be applied. The anchor design load should be the vertical component of the maximum mooring line load times an applicable safety factor. If the mooring line uplifting angle is equal to or smaller than 40 degrees, the pile holding capacity can be assumed being governed by the lateral capacity. As a slightly conservative approximation, the anchor design load can be taken as the horizontal component of the maximum mooring line load divided by cos(40-deg) times an applicable safety factor. The design curves in Table 5.5 or Table 5.6 for pile anchors subjected to 40-degree loading at the padeye should then be applied.

For reference, the safety factors specified in the ABS Guide [1] for anchors of FOWT stationkeeping systems are quoted in Table 6.3.

Table 6.3 Safety Factors Specified in the ABS Guide [1] for FOWT Anchor Design

Loading Condition	*Redundancy of the Stationkeeping System*	*Anchor Type*	*Design Condition of the Stationkeeping System*	*Safety Factor*
Design Load Cases	Redundant	Drag Anchors	Intact	1.5
			Damaged condition with one broken line	1.0
		Vertically Loaded Anchors (VLAs)	Intact	2.0
			Damaged condition with one broken line	1.5
		Pile Anchors	Intact	To be in accordance with API RP 2T for the tendon foundation or API RP2 SK otherwise
			Damaged condition with one broken line	To be in accordance with API RP 2T for the tendon foundation or API RP2 SK otherwise
		Suction Piles	Intact	1.5 to 2.0* For the tendon foundation, refer to API RP 2T
			Damaged condition with one broken line	1.2 to 1.5* For the tendon foundation, refer to API RP 2T
	Non-redundant	Any Anchor Type	Intact	20% increase in the safety factor required for the redundant system using the same type of anchors and under the intact design condition
Survival Load Cases	Redundant or Non-redundant	Any Anchor Type	Intact	1.05

* *Note:* The safety factor to be used in the design is to be based on the extent of the geotechnical investigation, confidence in the prediction of soil-pile behavior, experience in the design and behavior of suction piles in the area of interest, and the inclination of the mooring line load.

6.3 Limitations of the Derived Anchor Design Data

The derived anchor design data should be used with consideration of the following limitations:

- The anchor design data are derived using
  - the information provided by anchor manufacturers for recent models of drag anchors and VLAs, and
  - the software with simplified anchor and soil models for suction piles and driven piles based on the recommended design method in API RP 2A.
- Generic soil terms are used and defined using representative soil properties. Actual soil properties obtained through the site assessment should be applied in the detail design.
- Representative values for some anchor design parameters are selected based on past experience. No optimization is performed.
- The anchor design data are intended only for preliminary anchor sizing. The results of such preliminary sizing should be considered as indicative values.

7 Typical Anchor-Mooring Line Connections

7.1 Typical Connections for Drag Anchors and VLAs

Figure 7.1, which is adapted from the Vryhof Anchor Manual [7], shows typical anchor-mooring connections for drag anchors and VLAs.

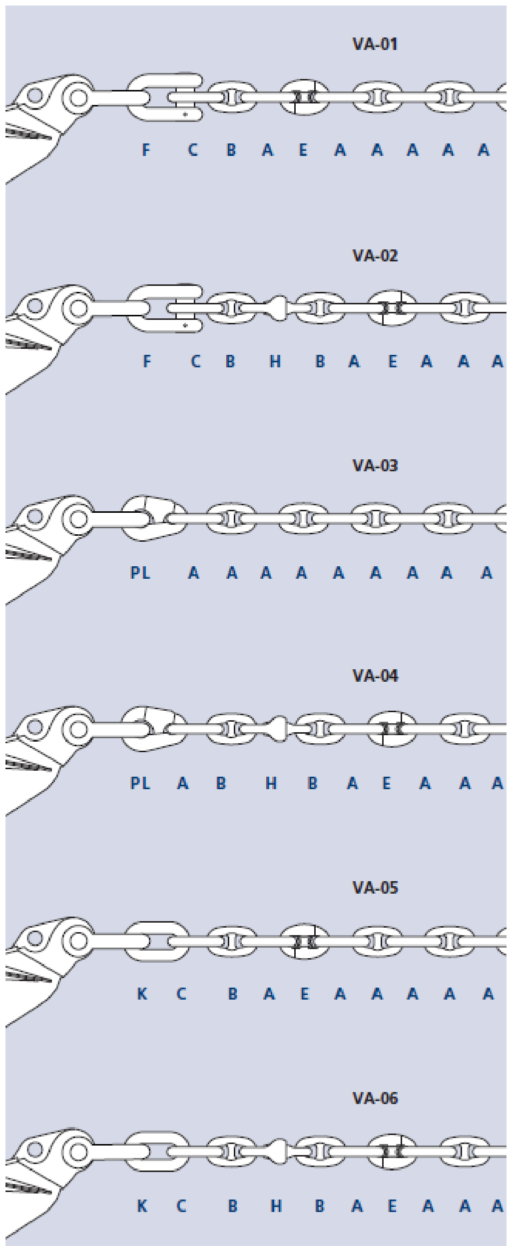


Figure 7.1 Typical Connections for Drag Anchors and VLAs [7]

The typical mooring components and anchor shackles referenced in Figure 7.1 are shown in Figure 7.2 and Figure 7.3, respectively

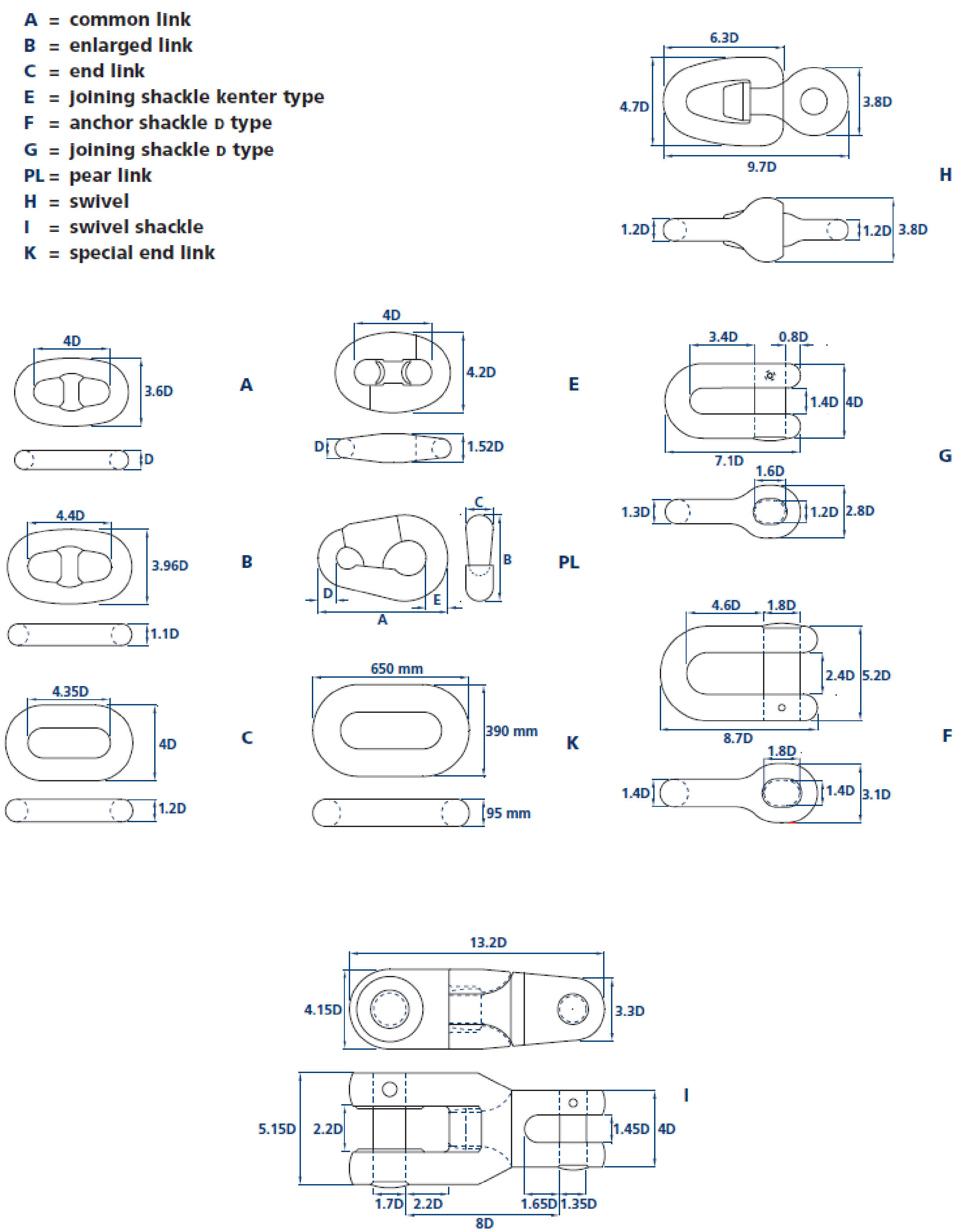


Figure 7.2 Typical Mooring Components Connected to Anchor Shackles [7]

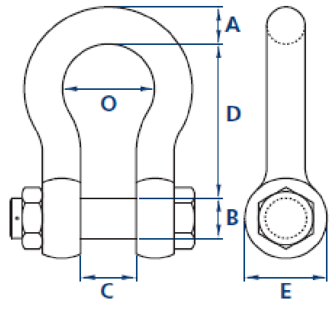
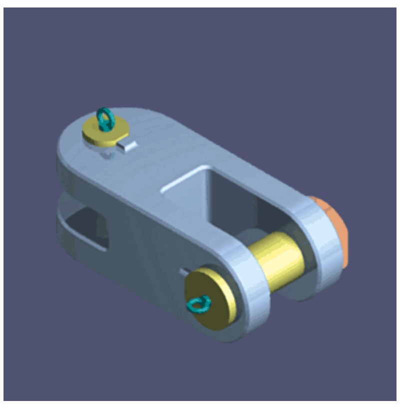


Figure 7.3 Typical Anchor Shackles [7]

In addition to the anchor shackles shown in Figure 7.2 and Figure 7.3, H shackles/links as illustrated in Figure 7.4 have found more and more applications in recent years in permanent offshore mooring systems. These H links are suitable to connect a drag anchors, a VLA, or a pile anchor padeye with the mooring line.



Vicinay Offshore H Link

LeBeon H Link

Figure 7.4 H Shackles/Links

7.2 Typical Connections for Pile Anchors

Typical configurations of pile anchor connection are presented in Figure 7.5 and Figure 7.6, where the anchor shackles are shown in Figure 7.3 and Figure 7.4 and the typical mooring line components connecting to the pile anchor shackle are shown in Figure 7.2.

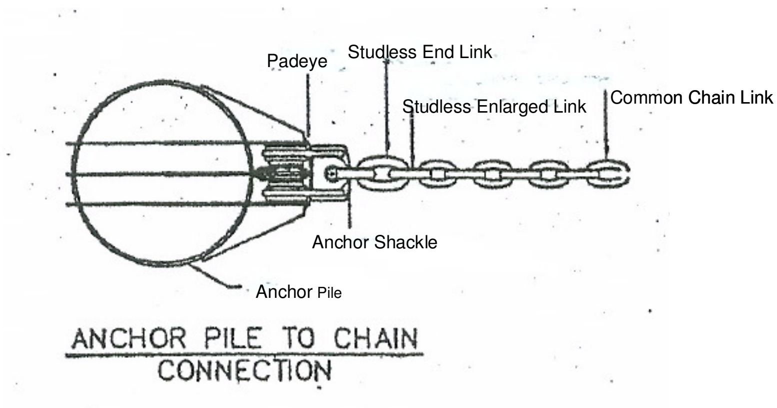


Figure 7.5 Typical Pile Anchor and Mooring Line Connection

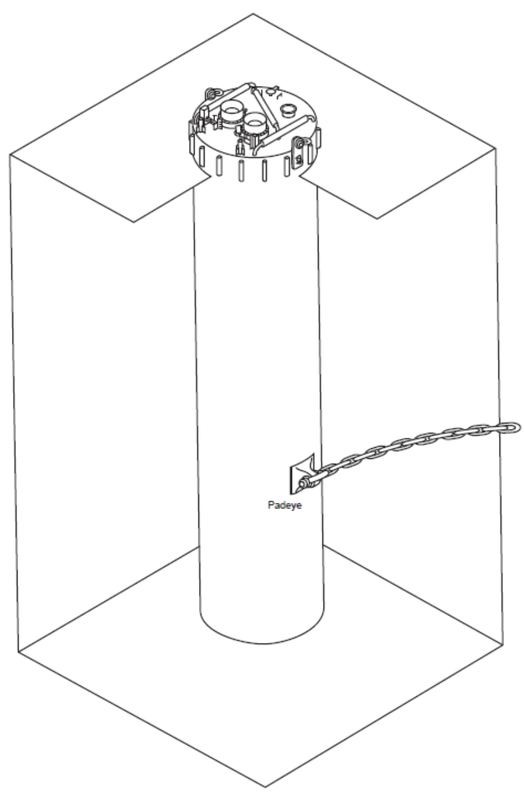


Figure 7.6 Typical Suction Anchor Pile and Mooring Line Connection (API RP 2SK)

8 References

[1]. ABS, 2013. Guide for Building and Classing Floating Offshore Wind Turbine Installations.

[2]. API, 2007. API RP 2A-WSD: Recommended Practice for Planning, Designing, and Constructing Fixed Offshore structures – Working Stress Design, 21st Edition (with Errata and Supplement in 2002, 2005 and 2007).

[3]. API, 2005. API RP 2SK: Recommended Practice for Design and Analysis of Stationkeeping Systems for Floating Structures, 3rd Edition (with Addendum in 2008).

[4]. Bruce Anchor Group. Bruce FFTS GP (General Purpose) Anchor Data Sheet

[5]. Bruce Anchor Group. Bruce FFTS Mk 4 Anchor Data Sheet

[6]. Bruce Anchor Group. Bruce PM (Permanent Mooring) Anchor Data Sheet

[7]. Vryhof Anchors, 2010. Vryhof Anchor Manual

[8]. Yu, Q. and Chen, X., 2012. Floating Wind Turbines. Final Report for BSEE TA&R Project No. 669. Bureau of Safety and Environmental Enforcement (BSEE), U.S. Department of the Interior, Washington, D.C.