Reliability of drag embedment anchors for applications in Canadian deep offshore

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ABSTRACT
Reliability analysis was applied to calculate the failure probability of drag embedment anchors for intact catenary mooring lines (ULS). The probabilistic characterization of the seabed soil condition and environmental loading was associated to the Newfoundland and Labrador's (NL) deepwater sites (e.g. the Flemish Pass Basin). The ultimate holding capacity of the anchor was modeled using plastic yield loci incorporating the profile and frictional capacity of the embedded anchor chain. The dynamic line tensions were extracted from time domain analyses of a generic floating system subjected to environmental loadings. The reliability analysis was performed using First-order reliability method (FORM).

RÉSUMÉ
Une analyse de fiabilité a été appliquée pour calculer la probabilité de défaillance des ancrages traînée pour les lignes caténaire intactes (ULS). La caractérisation probabiliste de l'état du sol du fond marin et de la charge environnementale a été associée aux sites d'eau profonde de Terre-Neuve-et-Labrador (TNL) (par ex. Le bassin du col Flemish). La capacité de rétention ultime de l'ancre a été modélisée en utilisant des locus de rendement en plastique incorporant le profil et la capacité de frottement de la chaîne d'ancrage intégrée. Les tensions de ligne dynamiques ont été extraites d'analyses temporelles d'un système flottant générique soumis à des charges environnementales. L'analyse de fiabilité a été effectuée en utilisant la méthode de fiabilité du premier ordre.

1 INTRODUCTION

Drag embedment anchors have been widely used in station-keeping systems of drilling and production vessels. These anchors are usually implemented along with catenary mooring lines, which arrive the seabed horizontally to withstand the large horizontal offsets of the floating unit due to the environmental loads. A drag anchor is mainly comprised of shank, fluke, padeye, and forerunner (the anchor chain embedded in the soil) and is pulled in to the seabed to reach its ultimate resistance. Several parameters such as anchor geometry, soil characteristics, applied loads, and type of mooring line can affect the performance and capacity of the drag anchor (Vryhof Anchors 2010). The uncertainties associated with these parameters, as well as difficulties in inspection and maintenance of embedded facilities in deepwater sites indicate the necessity of reliability based design and analysis of drag anchors.

A review of the previous studies shows that several researches have been conducted on reliability assessment of suction caissons both numerically and experimentally. Clukey et al. (2000) conducted the reliability analysis of suction caissons for catenary and taut-leg mooring systems for lateral and axial failure modes using FORM and SORM. Choi (2007) studied the reliability of suction caissons by estimating the caisson capacity at the padeye using the upper bound plastic limit equation proposed by Aubeny et al. (2003a) and considered the soil-chain interaction based on the Neubecker and Randolph (1995a) formulation. Valle-Molina et al. (2008) modeled the suction caisson capacity for a Floating Production Storage and Offloading (FPSO) vessel based on the plastic limit equations proposed by Aubeny et al. (2003a, 2003b, and 2003c) and applied Monte Carlo simulation for reliability assessment. Silva-Gonzalez et al. (2013) evaluated the reliability of suction caissons using FORM through probabilistic modelling of caisson capacities and formulated a linear relationship between caisson height and probability of failure.

Despite suction caissons, there is a considerable gap in reliability assessment of drag embedment anchors and only one study has been conducted in this area. Moharrami and Shiri (2018) assessed the reliability of drag anchors for catenary mooring lines using FORM. The authors developed an Excel spreadsheet Visual Basic Application (VBA) Macro based on a limit equilibrium model proposed by Neubecker and Randolph (1995b) and a yield loci approach proposed by O'Neil et al. (2003) to calculate the anchor capacity taking into account the soil-chain interaction effect. They used response surface method to express the line tensions as a function of uncertain metocean variables and studied the relative reliability of drag anchors and suction caissons.

The present study deals with reliability analysis of drag embedded anchors used in the Flemish Pass Basin located in offshore Newfoundland and Labrador (NL), Canada. During past decades, offshore NL has been of great interest for oil and gas exploration and production projects. The unique metocean and geotechnical characteristics of this region, however, has caused further complexity to the design and installation of drilling and production facilities. Flemish Pass is a north-south trending, mid-slope basin with a water depth ranging from 500 to 1500 m located over 450 km off the east coast of NL between the Grand Banks and the Flemish Cap (Figure 1). With an area of approximately 30,000 km^2, the Flemish Pass is a region of active hydrocarbon exploration including three recent discoveries; Mizzen, Bay du Nord, and Harpoon. Based on geophysical studies, the seabed of Flemish Pass Basin is mainly composed of large debris flow deposits (Brown et al. 2016).

Figure 1. Location of the Flemish Pass Basin (http://www.ceaa-acee.gc.ca/050/evaluations/proj/80129)

2 CAPACITY ASSESSMENT

Simulations of anchor capacity were conducted at mudline using the Excel spreadsheet VBA Macro developed by Moharrami and Shiri (2018). The Excel spreadsheet estimates the anchor holding capacity based on a limit equilibrium model (LEM) originally proposed by Neubecker and Randolph (1995b) and a yield locus approach proposed by O'Neill et al. (2003).

The effects of soil-chain interaction were taken into account for two reasons. First, the friction between soil and the embedded chain will reduce the tension load transferred from mudline to the padeye and can have a slightly large contribution to the ultimate holding capacity of the anchor. Neubecker and Randolph (1995b) developed the following equation to calculate the frictional capacity along the chain incorporating the self-weight of the chain into the total tension capacity:

$$T = T_a\, e^{\mu(\theta_a - \theta)} + \mu\, w\, s \quad [1]$$

where T is the tension in the chain, T_a is the chain tension at the anchor padeye, μ is the soil-chain friction coefficient, θ_a is the chain inclination at the anchor padeye, θ is the chain angle at any given point, w is the chain self-weight per unit length, and s is the length of the embedded chain.

The second reason for considering the soil-chain interaction is that it affects the loading direction at the padeye and consequently the holding capacity of the anchor. To calculate the loading angle at the padeye, an expanded form of the equation proposed by Neubecker and Randolph (1996) was used:

$$\theta_a = \left[\frac{2\, b_c\, N_c\, d_a\left(s_{u0} + 0.5\, s_{ug}\, d_a\right)}{T_a}\right]^{0.5} \quad [2]$$

where b_c is the effective width of the anchor chain, N_c is the bearing capacity factor, d_a is the padeye embedment depth, s_{u0} is the surface undrained shear strength, and s_{ug} is the undrained shear strength gradient with depth.

The anchor holding capacity and the fluke tip depth obtained from the developed Excel spreadsheet (Moharrami and Shiri 2018) were compared with those from finite element analysis (O'Neil et al. 2003), test results (Neubecker and Randolph 1996), and practical anchor design charts (Vryhof Anchors 1990) based on the input parameters given in Table 1. Figure 2 and Figure 3. illustrate the results of comparisons.

Table 1. Parameters used in yield locus analysis for a 32 t MK5 Vryhof Stevpris anchor (Moharrami and Shiri 2018)

Parameter	Value
Fluke length, L_f (m)	4.97
Fluke width, b_f (m)	4.23
Fluke thickness, d_f (m)	0.71
Bearing capacity factor, N_c	9
Undrained shear strength at mudline, s_{u0} (kPa)	0
Undrained shear strength gradient, s_{ug} (kPa/m)	1.5

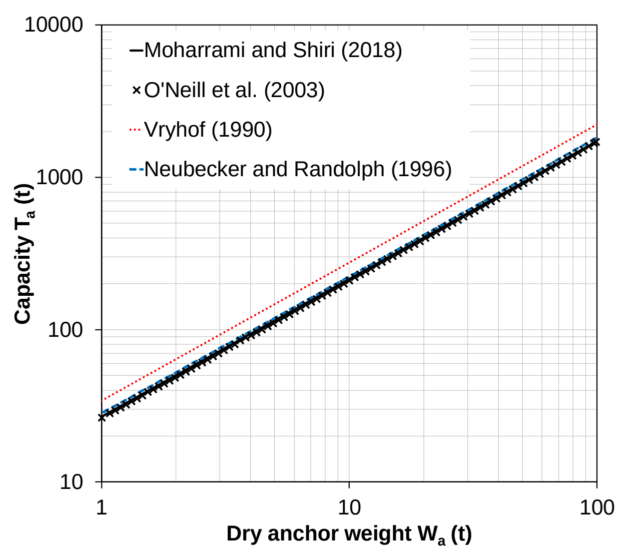

Figure 2. Comparison of anchor capacity in soft clay

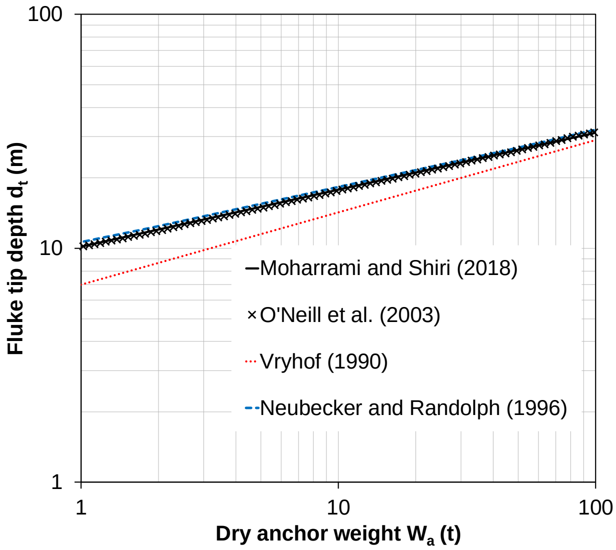

Figure 3. Comparison of fluke tip depth in soft clay

3 LOAD ASSESSMENT

A semisubmersible platform with catenary mooring system was modeled using finite element analysis (FEA) to calculate the line tensions applied to the anchor. The mooring system consists of four (2×4) groups of lines as shown in Figure 4. Each line has a combination of upper chain, middle wire, and bottom chain. The spacing between each group is 90 degrees and each line in the same group is separated by 45 degrees spacing. The extreme sea states of the Flemish Pass Basin with 100 years return period and a water depth of 700 m were considered to calculate the environmental loads on the platform and the resultant mooring line tensions.

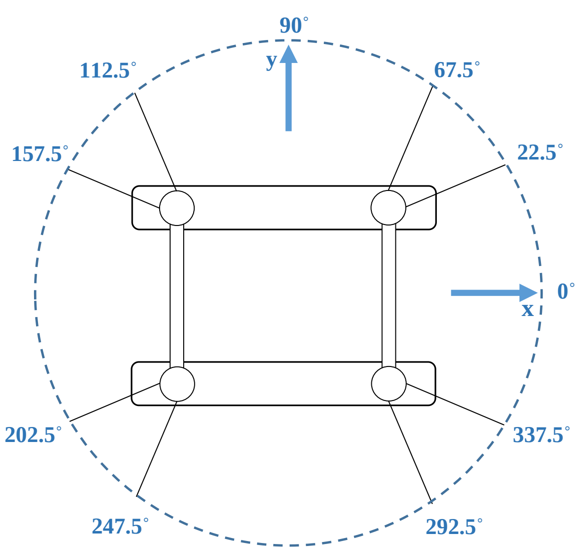

Figure 4. Catenary mooring system pattern

The line tensions were estimated at touchdown point through 3 h time histories and were expressed in terms of mean and expected value of maximum dynamic tension. Assuming the dynamic tension as a Gaussian process, the expected maximum dynamic line tension was calculated based on the model proposed by Davenport (1964):

$$E[T_{dyn,max}] = \left[\sqrt{2\ \ln\left(v\ \Delta t/2\right)} + \frac{0.5772}{\sqrt{2\ \ln\left(v\ \Delta t/2\right)}}\right]\sigma \qquad [3]$$

where Δt is the duration of the extreme sea state, and σ and v are the standard deviation and the mean-crossing rate of the dynamic tension, respectively.

4 RELIABILITY ANALYSIS

Reliability analysis of drag embedment anchors was performed using FORM. In this method, the uncertainties associated with both environmental loadings and anchor capacity are taken into account to determine the failure probability of drag anchor. The failure is related to exceeding a limit state i.e. line tension exceeding the anchor resistance.

The drag anchor was designed based on the recommended practice of Design and Installation of Fluke Anchors published by Det Norske Veritas, DNV-RP-E301 (DNV 2012). The holding capacities were calculated for four Mk5 Vryhof Stevpris anchors with a fluke length-fluke thickness ratio of 6.67. The main dimensions of a typical drag anchor are shown in Figure 5, where F represents the fluke thickness. Table 2 summarizes the characteristics of the anchor.

The limit state function was formulated at mudline, and the effects of soil-chain interaction were taken into account only in calculation of the ultimate holding capacity. In such case, the extreme complexity of reliability analysis due to the dependence between applied load and anchor capacity is neglected. Furthermore, the effect of frictional capacity of the embedded chain is properly associated with the ultimate holding capacity of the anchor, and the uncertainties of the chain are ignored. A similar method was used before in reliability assessment of suction anchors and drag embedment anchors (Choi 2007, Gonzalez et al. 2013, and Moharrami and Shiri 2018).

DNV (2012) presents two limit states to be considered for geotechnical design of fluke anchors:

1) Ultimate Limit State (ULS) to ensure that each mooring line can withstand the extreme environmental loads that it is subjected to. The ULS design requires individual mooring lines to be analyzed under extreme loading in the intact condition.
2) Accidental Limit State (ALS) to ensure that the mooring system can withstand the failure of one mooring line due to unknown reasons. The ALS design requires the analysis of damaged mooring system with one line removed.

Two failure consequence classes are possible for each limit state; consequence class 1 in which failure is unlikely to cause unacceptable consequences i.e. life lost, collision or uncontrolled oil and gas production, and consequence class 2 in which failure may cause unacceptable consequences. The target annual probability of failure for each limit state and consequence class is given in Table 3.

Based on DNV (2012), the limit state equation is expressed in terms of anchor holding capacity and mooring line tension at mudline:

$$G = R_d - T_d \qquad [4]$$

where G is the limit state function, R_d is the design capacity of anchor-chain system at mudline, and T_d is the design line tension at mudline which can be expressed as follows:

$$T_d = T_{mean\text{-}C}\ \gamma_{mean} + T_{dyn\text{-}C}\ \gamma_{dyn} \qquad [5]$$

where $T_{mean\text{-}C}$ is the characteristic mean line tension due to pretension and mean environmental loads, $T_{dyn,\text{-}C}$ is the characteristic dynamic line tension due to low frequency and wave frequency motions, γ_{mean} is the load factor on the mean tension, and γ_{dyn} is the load factor on the dynamic tension. Table 4 presents the load factors for ULS and ALS conditions.

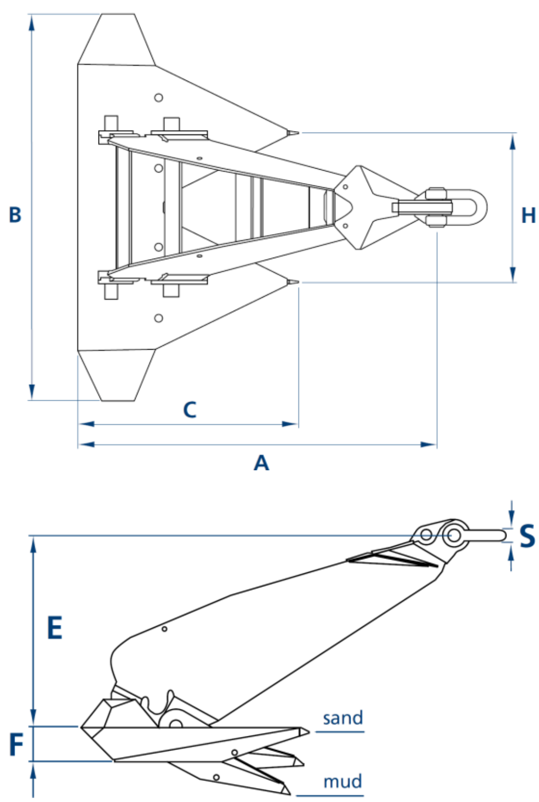

Figure 5. Anchor dimensions (Vryhof Anchors 2010)

Table 2. Main dimensions for Mk5 Vryhof Stevpris 22 t (Vryhof Anchors 2010)

Parameter	Value
A	7230 mm
B	7794 mm
C (L_f)	4436 mm
E	3684 mm
F (d_f)	665 mm
H	3011 mm
S	200 mm

Table 3. Target annual probability of failure (DNV 2010a)

Limit state	Consequence class 1	Consequence class 2
ULS	10E-4	10E-5
ALS	10E-4	10E-5

Table 4. Partial safety factors for dynamic analysis (DNV 2012)

Limit state	Consequence class	γ_{mean}	γ_{dyn}
ULS	1	1.10	1.50
ULS	2	1.40	2.10
ALS	1	1.00	1.10
ALS	2	1.00	1.25

The probability of failure is defined as the probability of design tension exceeding the design holding capacity of the anchor:

$$P_f = P(R_d < T_d) = P(G < 0) \qquad [6]$$

5 RESULTS

The results in this section are presented for reliability of drag embedment anchors in soft clay using FORM. Figure 6 shows the annual reliability index for different anchor geometries as a function of fluke length. Based on the results illustrated in this figure, an average increase of 4.61% in fluke length, which corresponds to an average increase of 14.54% in anchor weight, can increase the reliability index about 11%. This indicates that the anchor weight does not have a significant contribution to the capacity of deeply buried drag anchors in soft clay, and their reliability is considerably affected by the fluke length. Figure 7 shows the variation of annual probability of failure, p_{Fa}, versus fluke length. Based on this figure, in order to achieve a target failure probability between 10^{-4} and 10^{-5}, either the 22 t anchor with a fluke length of 4.436 m, or the 25 t anchor with a fluke length of 4.629 m can be used. This range of target probability of failure is used for the ultimate limit state design of offshore systems (DNV 2010a, 2010b, 2012, and 2013), which corresponds to reliability indices between 3.72 and 4.26.

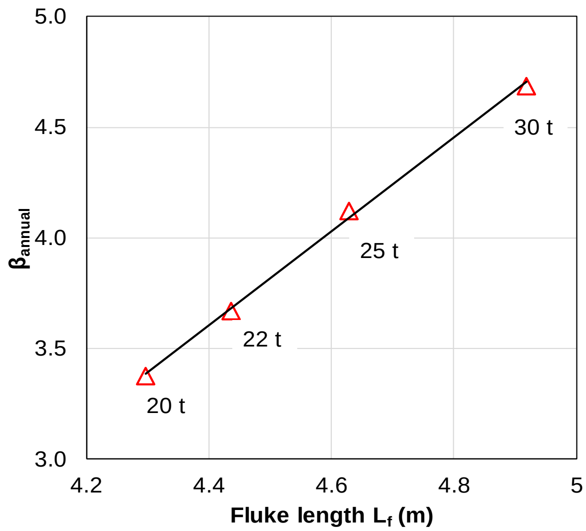

Figure 6. Annual reliability index versus fluke length

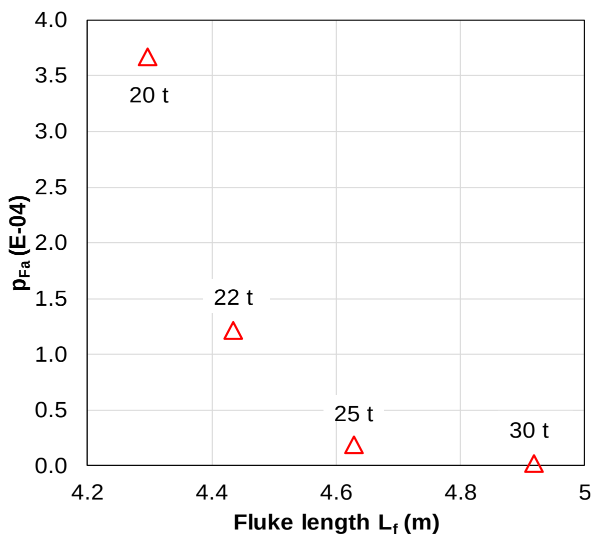

Figure 7. Annual failure probability versus fluke length

6 CONCLUSIONS

In this study, the reliability of drag embedment anchors for catenary mooring systems was analyzed using FORM. The metocean characteristics and soil data of the Flemish Pass Basin in offshore Newfoundland and Labrador (NL), Canada, were used. Four drag anchors with a fluke length-fluke thickness ratio of 6.67 were analyzed. A fully coupled time domain analysis of a semisubmersible platform was performed to determine the line tensions at mudline. An Excel spreadsheet VBA Macro was implemented to estimate the anchor capacities at mudline considering the embedded profile of the chain and the soil-chain interaction. The ultimate limit state equation was formulated at mudline taking into account the uncertainties associated with the soil properties and metocean parameters. The anchor models with reliable performance were determined based on the target failure probability of 10^{-5} for consequence class 2. Annual reliability indices and failure probabilities were expressed in terms of fluke length. The results show that the reliability index of drag anchors embedded in soft clay depends on the fluke length and is largely irrelevant to the anchor weight.

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