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Abstract:

Ship interaction in terms of anchor hooking on a subsea pipeline has been investigated in this thesis. An attempt has been made to predict the most probable anchor interaction loads on the Kvitebjørn gas pipeline in the North Sea if anchor hooking were to occur, and evaluate the structural consequences of an anchor hooking incident.

By utilization of AIS ship data provided by the Norwegian Coastal Administration it has been found that 7160 cargo, tanker and tug ships passed the Kvitebjørn gas pipeline from March 2010 to March 2011. These ships have been evaluated with respect to anchor equipment, ship mass and velocity by use of a developed computer script in the computer code MATLAB. It has been found from geometrical evaluations of anchor hooking that anchors above 3780 kg will have large enough dimensions to hook pipeline. Anchor tow depth analyses predict that stabilization depth of a towed anchor arrangement is about 1/3 of the chain length for velocities around 15 knots. The geometrical evaluations and the tow depth analyses have been included in the computer script, and ships not able to hook pipeline have been separated out.

Results predict that 237 of the total 7160 evaluated cargo ships, tankers and tugboats possess the necessary hooking parameters. These ships have large enough anchor for the pipeline to get stuck, and ship velocity low enough that the anchor will touch seabed if dropped. Ship traffic has been found to be largest over pipeline sections with a water depth of around 300 meters. Due to this large water depth only ships with large anchors sizes around 10 tons and above will be able to touch down on the seabed.

The most frequently observed anchor equipment and velocities of the ships found to be able to hook the pipeline have been determined. In order to predict the structural consequences of anchor hooking a model in the computer code SIMLA has been developed. The most frequently observed anchor equipment and ship velocities from the AIS studies performed have been included in the SIMLA analyses.

Results from the analysis predict that very large strain levels will be observed as a result of anchor hooking. Strains have been found to exceed design strains for interaction by the most frequently observed anchor systems and the pipeline would need extensive reparations due to utilization of the plastic capacity of the cross section beyond capacity corresponding to Specified Minimum Tensile Strength (SMTS).

Keyword:

3. party accidental loads, anchor hooking.

Advisor:

Prof. S. Sævik , Dr Ing. Hagbart S. Alsos

THESIS WORK DESCRIPTION

STUD. TECH. STIAN VERVIK

PIPELINE ACCIDENTAL LOAD ANALYSIS

Subsea pipelines with OD ≥ 16" are normally left exposed on the seabed during the operational phase. Hence there is a risk for interaction loads due to both trawl gear and anchor handling operations, where the latter normally is considered as a rare event that can be treated as an accidental load.

The thesis work focus on the consequence in terms of pipeline response due to an anchor that is dragged along the seabed and hitting the pipeline addressing the following items:

1. Literature study, including pipeline technology, failure modes and design criteria, relevant stress components and effects, methods and techniques for response analysis of such structures. This is to give a good basement for understanding the response and failure of pipelines exposed to such loads. This will be followed by a literature study into load characterization relevant for the Norwegian Sector of the North Sea, investigating anchor design, associated chain capacities, ship frequency versus size and associated anchors and considering the pipeline grid.
2. Establish an analytical model considering the pipe diameter and the different anchor designs. Which are the circumstances in terms of diameter and anchor design need to be fulfilled in order for the anchor to be hooked to the pipeline? Considering the ship traffic and pipeline grid: what are the risks in terms of annual probabilities?
3. Familiarize with the software SIMLA, establish a global model representing a ship anchor being dragged along the seabed and hitting the pipeline. Two cases to be considered, one with mimimum diameter, the other with large diameter.
4. Perform non-linear static and dynamic time domain analysis using the SIMLA program system until chain breakage or full axial plastification.
5. Perform non-linear static and dynamic time domain analysis using the SIMLA program system until chain breakage or full axial plastification.
6. Familiarize with the software ABAQUS and establish a local model for the chain breakage case. Expose the local model to the relevant global load time histories from SIMLA and estimate the local damage level.
7. Perform ABAQUS parameter study of scaled versions of the SIMLA load history to evaluate which anchor designs that would be acceptable.
8. Conclusions and recommendations for further work

The project assumes that all necessary input data are provided by REINERTSEN. The work scope may prove to be larger than initially anticipated. Subject to approval from the supervisors, topics may be deleted from the list above or reduced in extent. In the thesis the candidate shall present his personal contribution to the resolution of problems within the scope of the thesis work. Theories and conclusions should be based on mathematical derivations and/or logic reasoning identifying the various steps in the deduction. The candidate should utilise the existing possibilities for obtaining relevant literature.

THESIS FORMAT

The thesis should be organised in a rational manner to give a clear exposition of results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.

The thesis shall contain the following elements: A text defining the scope, preface, list of contents, summary, main body of thesis, conclusions with recommendations for further work, list of symbols and acronyms, references and (optional) appendices. All figures, tables and equations shall be numerated. The supervisors may require that the candidate, in an early stage of the work, presents a written plan for the completion of the work. The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

The report shall be submitted in two copies:

- Signed by the candidate
- The text defining the scope included
- In bound volume(s)
- Drawings and/or computer prints which cannot be bound should be organised in a separate folder.

OWNERSHIP

NTNU has according to the present rules the ownership of the thesis. Any use of the thesis has to be approved by NTNU or Reinertsen As. The department has the right to use the thesis as if the work was carried out by a NTNU employee, if nothing else has been agreed in advance.

PREFACE

This report is the result of my master thesis at the Department of Marine Technology at the Norwegian University of Science and Technology (NTNU). The thesis accounts for 30 credits in the spring semester.

First of all I would like to thank my main supervisor, Professor Svein Sævik for helpful and encouraging guidance throughout the semester. I would also like to thank co-supervisor Dr. Ing Hagbart S. Alsos at Reinertsen AS for valuable guidance and motivational input.

The scope of work has been changed during the thesis work in consultations with the supervisors Dr. Ing. Hagbart S. Alsos and Prof. Svein Sævik. In agreement we have decided to focus some more attention to the anchor load categorization part of the thesis. A significant amount of work has been performed in part 1 and 2 of the work description and the focus has been turned more towards the anchor interaction load part of the problem. The local model described in point 6 and 7 of the work description has not been performed due to this shift of attention.

Attention has been given especially to the Kvitebjørn gas pipeline, and the structural analyses performed in the thesis are based on parameters from this pipeline. Point 2 of the work description has been modified and only the 30 " Kvitebjørn gas pipeline is considered for the analyses.

Trondheim, June 2011

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Stian Vervik

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FIGURES

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NOMENCLATURE

An attempt has been made to explain all symbols as they appear in formulas. This list is included to explain the relevant abbreviations and important symbols.

S_{hp}	Circumferential hoop stress
S_{lp}	Longitudinal stress
r_0	Pipeline outside diameter
P	Internal pressure in pipe
M_y	Bending moment around Y axis
M_z	Bending moment around Z axis
S_{by}	Bending stress Y axis
S_{bz}	Bending stress Z axis
Z	Section modulus
σ_{SMYS}	Specified Minimum Yield Strength
σ_{SMTS}	Specified Minimum Tensile Strength
$d\varepsilon^e$	Elastic strain increment
$d\varepsilon^p$	Plastic strain increment
M_p	Plastic moment capacity
N_p	Ultimate axial force capacity
p_y	Critical burst pressure
D	Nominal pipe diameter
t	Wall thickness
p_{burst}	Critical burst pressure
F_t	Critical tensile load
A	Area of the pipe cross-section
R_c	Resistance in each failure mode
γ_m	Material resistance factor
γ_m	Safety class factor
L_{sd}	Design load in each failure mode
p_{min}	Minimal internal pressure that can be continuously sustained
γ_ε	Strain resistance factor
α_h	Material factor
α_{gw}	Girth weld factor
EN	Equipment number
Δ	Displacement in sea water
D_{max}	Maximum outer pipeline diameter that can be hooked by anchor
α	Angle between anchor shank and fluke
F_D	Drag force
v	Fluid velocity
E_{kin}	Kinetic energy of reference ships
m	Reference ship mass
a	Added mass reference ship, assumed to be 10 % of m
v_{ship}	Ship velocity

1 INTRODUCTION

Subsea pipelines carrying oil and gas from offshore field developments on the Norwegian shelf are located off the Norwegian coast and run through sectors with significant ship traffic. Pipelines with an outer diameter of 16'' and higher are normally left exposed on the seabed during operational phase. Third party accidental loads in terms of accidental anchor drop under vessel transit and hooking of the exposed pipelines may occur. The imposed load on the pipeline may be of a critical magnitude for the operational integrity of the subsea production system.

During a routine inspection performed on the 30 '' Kvitebjørn gas and condensate pipeline located off the coast off Bergen, severe anchor interaction damage was discovered on the pipeline system. The pipeline itself had been struck by a 10 ton anchor and dragged approximately 53 meters from its initial position. The anchor impact load was later estimated to be around 500 tons or 5000 KN and this load induced large deformations and strains in the pipeline (Gjertveit). The retrieved ship anchor found on the impact site is presented in Figure 1.

FIGURE 1 RETRIEVED ANCHOR FROM THE KVITEBJØRN GAS PIPELINE ANCHOR HOOKING INCIDENT

Ship traffic along the coast of Norway consists of several vessel types such as fishing vessels, tankers, cargo ships, tug boats and offshore supply vessels. Some areas of the North Sea may be more susceptible to third party loads than others due to a higher frequency of ship traffic over the pipeline grid. On the basis of this it is assumed that it would be of great relevance for the industry if a tool for evaluation of ship traffic over subsea pipelines were developed, and this has been a motivation for the work performed in this thesis. Ship parameters such as ship velocity, anchor chain and anchor dimension are parameters which will be examined in order to predict the consequences of anchor hooking on a subsea pipeline.

Several parameters need to be fulfilled in order to get anchor hooking. Anchor dimensions need to be large enough for the evaluated pipeline to get stuck between the anchor shank and teeth (Nord Stream). The vessel velocity must be of a magnitude such that the towed anchor arrangement sinks down to the pipeline at seabed. All these parameters will be discussed in great detail throughout the thesis.

Some work has been performed to determine the structural consequences of an anchor impact on a subsea pipeline. In a study performed by (Sriskandarajah) typical ships sizes and corresponding anchor equipment have been included in finite element simulations of pipeline models in order to predict typical pipeline response. Based on the methodology of this paper, a more extensive study has been performed in this master thesis, but with focus especially on the North Sea and the Kvitebjørn gas pipeline.

THESIS OUTLINE

The objective of the first part of the thesis has been to develop a tool for prediction of the most probable ship sizes and corresponding anchor equipment for specific areas in the North Sea. Attention has been given specifically to the Kvitebjørn area and an attempt has been made to predict the most frequent ship sizes and anchor equipment passing this specific pipeline. The second objective has been to model the Kvitebjørn gas pipeline in the computer code SIMLA in order to predict pipeline response and strains. Ship parameters such as velocity and anchor equipment determined in the first part of the thesis have been included in the SIMLA model in order to predict typical pipeline strains and responses due to ship anchor interaction.

Chapter 2 presents the theory applied in the structural analysis part, with emphasis on plasticity and cross-sectional capacities. Codes and guidelines presented by DNV will be briefly reviewed in order to familiarize with pipeline design methodology.

Chapter 3 presents anchor equipment systems with focus on anchor geometry and hooking properties of a typical anchor. An investigation on the towing depths for various anchor equipment and ship velocities is performed.

Chapter 4 presents an investigation of the ship traffic over the Kvitebjørn gas pipeline. Historical ship data over 1 year has been processed in order to predict the most frequent ships and corresponding anchor equipment passing sections of the Kvitebjørn gas pipeline. MATLAB has been the preferred tool for data processing and an overview of the data processing script is given in terms of a flow chart and descriptions of the various subroutines. Results in terms of the most frequent anchor parameters observed on ships passing the Kvitebjørn gas pipeline, and an estimated annual number of ships able to hook the pipeline in 1 year are presented.

Chapter 5 presents a structural evaluation of the Kvitebjørn gas pipeline if anchor hooking on the pipeline were to occur. Parameters such as anchor chain strength, ship velocities, section water depth and anchor mass determined from the study performed in chapter 4 have been included in the analyses.

Chapter 6 presents a discussion on the basis of the results obtained in chapter 4 and 5. A discussion with regards to impact point bending moments, membrane forces and strains is performed in order to evaluate the structural consequences if anchor hooking were to occur.

Chapter 7 presents a preliminary conclusion based on the results obtained in chapter 4, 5 and 6 and sums up the findings in this thesis.

Chapter 8 gives some recommendations for further work on the subject.

2 THEORY

The structural response of a subsea pipeline subjected to an anchor impact is a complex matter. The forces and moments from a ship anchor hooking onto a subsea pipeline will induce large reaction forces in the pipeline. The behavior of the pipeline will be governed by elastic bending for smaller displacements but for larger displacement of the pipeline plastic behavior such as plastic bending and large axial membrane forces are introduced (Vagnildhaug). A subsea pipeline experiences two main categories of stresses. The first category of stresses comes from pressures, either internal or external pressure. The second category comes from external forces and moments acting on the pipeline.

PIPELINE STRESSES

STRESSES DUE TO INTERNAL PRESSURE

When a pipe is pressurized the inside surface is exposed to the same pressure in all directions. A pressurized pipe will stretch in all directions, and due to the symmetry of a circular cross section of a pipe the stress components may be divided into two principal stresses, the circumferential hoop stress S_{hp} and the longitudinal stress S_{lp} as shown in Figure 2.

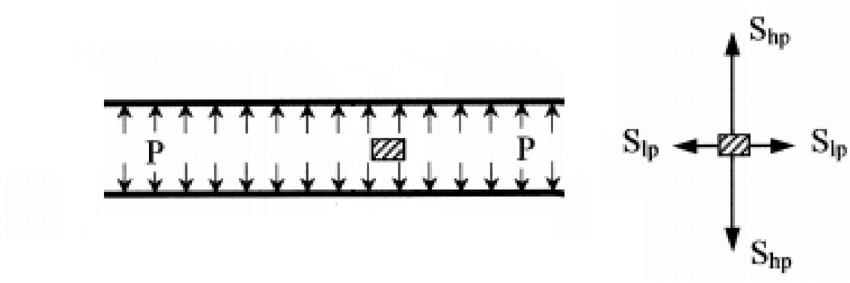

FIGURE 2 STRESS COMPONENTS DUE TO INTERNAL PRESSURE (PENG)

By assuming uniform stress distribution over the thickness in both circumferential and longitudinal direction the following expressions for S_{hp} and S_{lp} may be derived

$$S_{lp} = \frac{r_0 P}{2t} \tag{2.1}$$

$$S_{hp} = \frac{r_0 P}{t} \tag{2.2}$$

Where t is the pipe thickness, r_0 is the pipeline outside diameter and P is the internal pressure.

STRESSES DUE TO FORCES AND MOMENTS

External forces and moments may induce significant stresses in subsea pipelines. Thermal expansion, hydrodynamic loads, weight of content and third party loads such as dragged anchors are some examples of the loads which may be inflicted on the pipeline.

Forces acting on a pipeline may be divided into shear forces acting perpendicular to the pipe axis, and axial forces acting in the axial direction of the pipe. The transverse forces acting on the pipeline section induces shear stresses in the cross section with distributions presented in Figure 3. The shear stress has its maximum value at the diametrical centerline transverse to the force. Moment loads are divided into bending moments and torsion moments. The bending moments M_y and M_z induces linear stress distributions around Y and Z axes respectively. The stress distributions are presented in Figure 3 below.

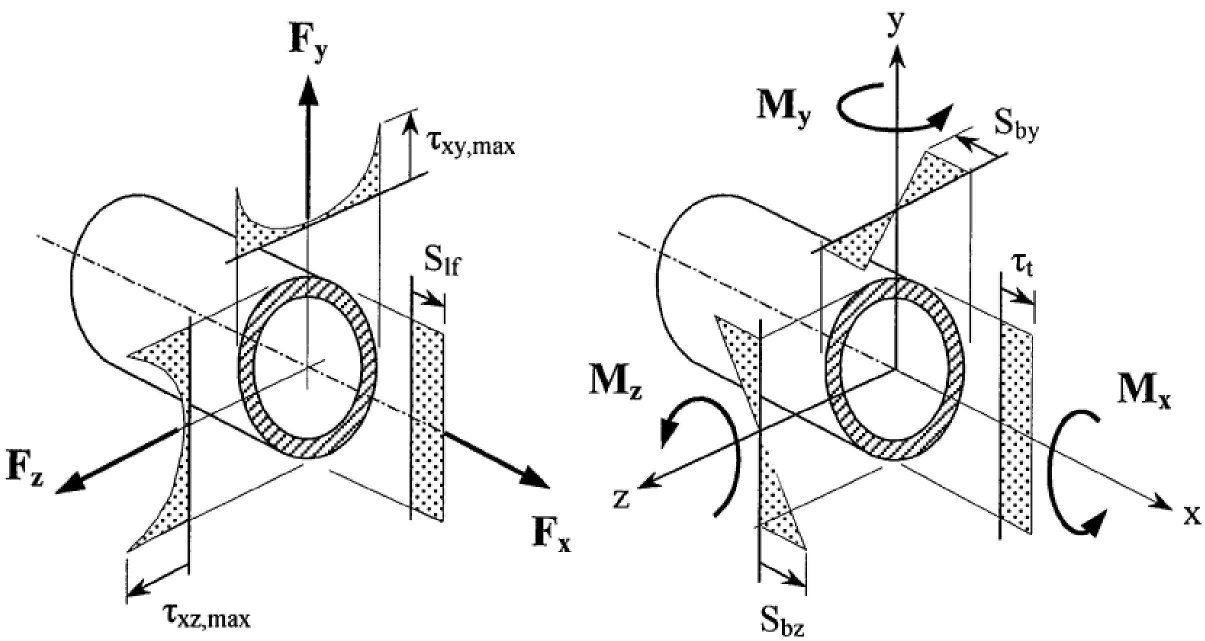

FIGURE 3 FORCES AND MOMENTS ACTING ON PIPELINE CROSS SECTION (PENG)

$$S_{by} = \frac{M_y}{Z} \qquad S_{bz} = \frac{M_z}{Z} \qquad S_{bx} = \frac{M_x}{Z} \tag{2.3}$$

$$Z = \frac{\pi}{4r_o}({r_o}^4 - {r_i}^4) \tag{2.4}$$

$$S_b = \sqrt{{S_{by}}^2 + {S_{bz}}^2} \tag{2.5}$$

Where S_{by} , S_{bz} and S_{bx} are given as the bending stresses around the respective axes. S_b is given as the total bending stress and Z is section modulus.

PLASTICITY

Very large responses may be observed for pipelines subjected to anchor hooking (Gjertveit). Due to this the cross-sectional capacities may be utilized well out into the plastic range and an outline of the mechanisms involved in plasticity must be given.

STRESS STRAIN RELATIONSHIP

A nonlinear stress – strain curve for a typical steel material is presented in Figure 4. The linear part of the curve is defined as the linear elastic region where no permanent deformation occurs when unloading is performed. The nonlinear region of the curve symbolizes the plastic region of the material. An increment of stress produces a permanent deformation and, as the strain increase the increment of stress needed to produce an increment of strain is reduced.

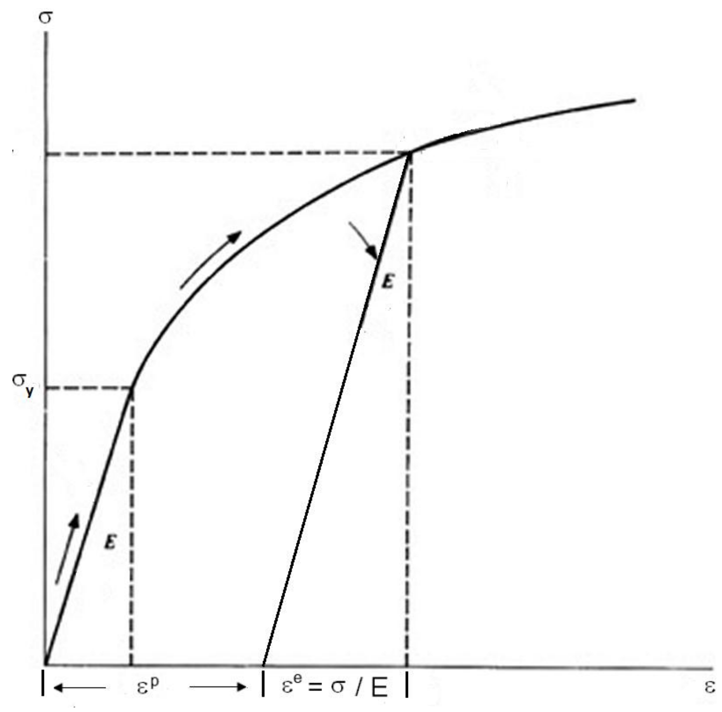

FIGURE 4 TYPICAL STRESS STRAIN RELATION FOR STEEL MATERIAL

The yield stress is given in the figure as the transition point between the linear elastic region and the nonlinear plastic region. For engineering purposes other material strength terms have been developed. The *Specified Minimum Yield Strength* σ_{SMYS} corresponds to the stress associated with a strain level of 0.5 %. *Specified Minimum Tensile Strength* σ_{SMTS} corresponds to a strain level of 20 % (Bai). Typically in the industry a value of strain between 10 – 20 % corresponds to σ_{SMTS} .

Pipeline materials may experience very large strain levels as an effect of anchor hooking, and it is convenient to show the relationship between stress and strain in the plastic range. A simplified stress-strain relationship with linear hardening for a material is presented in Figure 5.

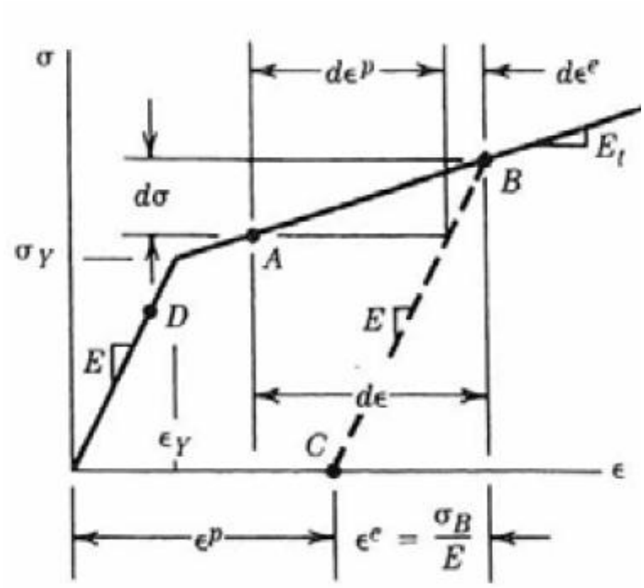

FIGURE 5 SIMPLIFIED STRESS STRAIN RELATION WITH LINEAR HARDENING

$$d\sigma = E d\varepsilon^e = E(d\varepsilon - d\varepsilon^p) \tag{2.6}$$

A strain increment from point A to point B consists of an elastic component $d\varepsilon^e$ and a plastic component $d\varepsilon^p$. The plastic component $d\varepsilon^p$ represents a permanent deformation in the material and $d\varepsilon^e$ represents the recoverable elastic deformation of the material. The stress increment will however always be determined be determined from the elastic strain (Vagnildhaug)

Plastic capacity of the cross section

A dragged anchor hooking onto a subsea pipeline may introduce very large forces and moments on the pipeline cross section. In order to evaluate consequences of anchor hooking it is of great importance to determine the cross-sectional capacities of the pipeline with regards to bending moment, internal pressure and tension.

Failure modes

Pure bending

For large bending moments the pipeline cross section experiences deformations. Ovalisation of the ring shape may occur and hence the cross-sectional moment of inertia of the cross section is reduced. A study performed by (Bai) suggests that up to a certain level of ovalisation the decreased moment of inertia will be counterbalanced by the increased pipe wall stresses due to strain hardening. It is stated that when the loss in moment of inertia no longer can be compensated for by strain hardening, collapse of the cross section will occur. For low D/t ratios the failure will be initiated on the tensile side of the pipe due to stresses in the outside fibers exceeding the limiting longitudinal stress. For D/t ratios higher than 30 – 35 the failure will be initiated on the compression side of the pipe, e.g. local buckling of the cross section. The plastic moment capacity of a pipe presented in (Bai) is shown in 2.7.

$$M_p = \sigma_{SMYS} D^2 t \tag{2.7}$$

Where M_p is the plastic moment capacity, *D* is the nominal diameter *t* is the wall thickness and σ_{SMYS} is the Specified Minimum Yield Strength.

PURE INTERNAL PRESSURE

For pure internal pressure the failure mode of the cross section will be bursting. Due to pressure forces a pressurized pipe will expand and the wall thickness of the pipeline cross section will decrease. Hoop stress in the pipe wall will increase due to the reduced thickness of the cross section. It is stated in (Bai) that when the strain hardening no longer can compensate for pipe wall thinning the maximum internal pressure has been reached and the pipe will burst. According to (Bai) the burst pressure may be written as presented in equation 2.8.

$$P_{burst} = 0.5 \cdot (\sigma_{SMYS} + \sigma_{SMTS}) \cdot \frac{2t}{D} \tag{2.8}$$

Where P_{burst} is the critical burst pressure, σ_{SMYS} is the Specified Minimum Yield Strength, σ_{SMTS} is the Specified Minimum Tensile Strength, *D* is the nominal diameter and *t* is the wall thickness

PURE TENSION

For pure tension the failure of the pipe will be a result of wall thinning. When the longitudinal tensile force is increased the pipe wall thickness will narrow down as a result of the Poisson's effect. The expression shown in equation 2.9 is presented by (Bai)

$$F_t = 0.5 \cdot (\sigma_{SMYS} + \sigma_{SMTS}) \cdot A \tag{2.9}$$

Where $F$is the critical tensile force, σ_{SMYS} is the Specified Minimum Yield Strength, σ_{SMTS} is the Specified Minimum Tensile Strength, and *A* is the area of the pipe cross section.

COMBINED LOAD INTERACTION

Anchor hooking will introduce large tensile forces and bending moments in the pipeline cross section. However the plastic capacity of the cross section cannot be utilized fully for both tension and bending at the same time. An interaction formula describing the maximum combined bending and tension load in a circular pipe is presented in eq. 2.10 (Søreide). The plastic interaction curve for a circular cross section subjected to a combination of bending moment and axial force is presented in Figure 6.

$$\frac{M}{M_p} - \cos\left(\frac{\pi}{2}\frac{N}{N_p}\right) = 0 \tag{2.10}$$

Where plastic moment capacity $M_p = D^2 t\sigma_y$ and ultimate axial force capacity $N_p = \pi D t\sigma_y$.

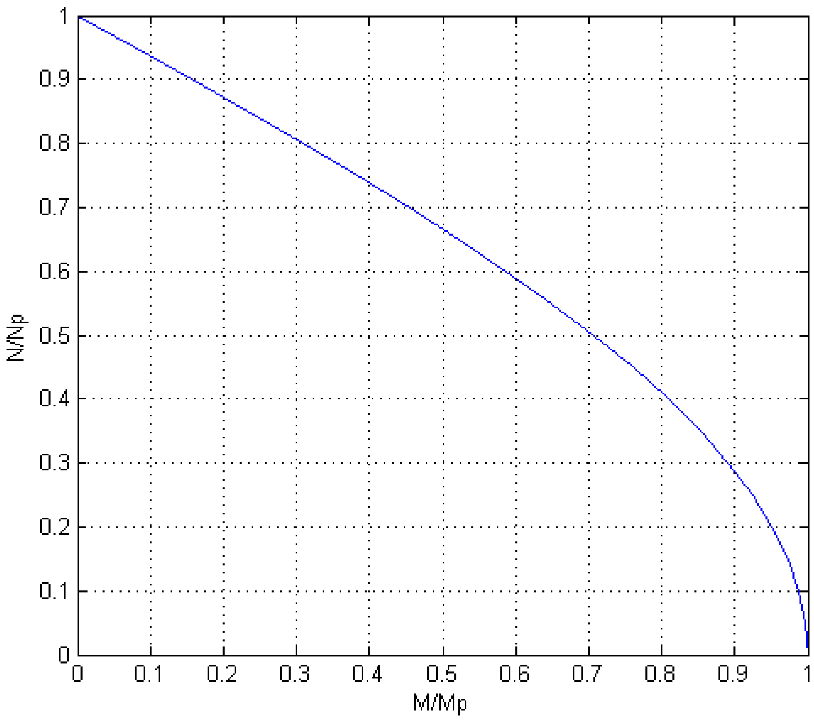

FIGURE 6 PLASTIC INTERACTION CURVE FOR A CIRCULAR SECTION SUBJECTED TO BENDING MOMENT AND AXIAL FORCE

The interaction curve presented in Figure 6 does not account for internal pressure. Subsea pipelines in operation contain pressurized fluids and the internal pressure will have an effect on the plastic interaction curve. A plastic interaction curve including internal pressure is presented in eq. 2.11 (Bai)

$$\frac{M}{M_p} - \sqrt{1 - \frac{3}{4}\left(\frac{p}{p_y}\right)^2} \cos\left(\frac{\pi}{2} \frac{\frac{N}{N_p} - \frac{1}{2}\frac{p}{p_y}}{\sqrt{1 - \frac{3}{4}\left(\frac{p}{p_y}\right)^2}}\right) = 0 \tag{2.11}$$

Where $M_p = D^2 t\sigma_y$ is the plastic moment capacity, $N_p = \pi D t\sigma_y$ is the ultimate axial force capacity and $p_y = 0.5 \cdot (\sigma_{SMYS} + \sigma_{SMTS}) \cdot \frac{2t}{D}$

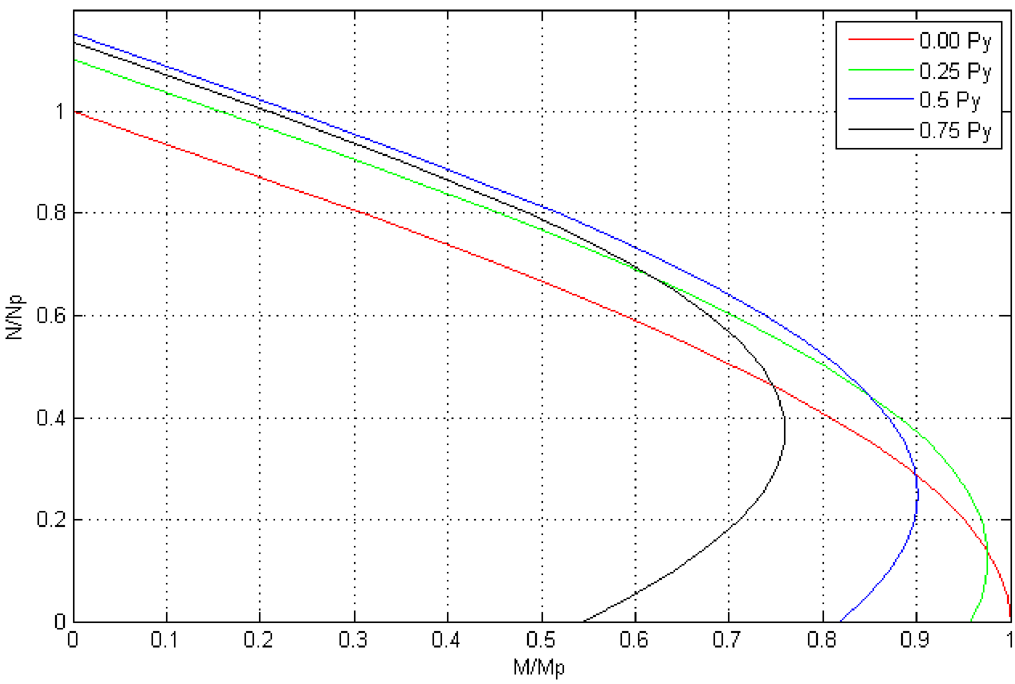

FIGURE 7 PLASTIC INTERACTION CURVE FOR A CIRCULAR CROSS SECTION SUBJECTED TO BENDING MOMENT, AXIAL FORCE AND INTERNAL PRESSURE

The plastic capacity curves presented above have been included to show that some variations exist with regards to the cross-sectional capacities of as pipe. It is seen that the plastic capacities presented by (Søreide) is somewhat different from (Bai) with respect to including internal pressure. Evaluations of the cross-sectional capacity of the Kvitebjørn gas pipeline performed in the forthcoming sections of the thesis will be based on the expressions presented in (Søreide), i.e. equation 2.10.

DESIGN CRITERIA

Design codes have been developed by joint projects in the industry in order to make sure that subsea pipelines are properly designed against the mechanical failure modes listed previously. The code applied in this thesis is the DNV-OS-F101 – *Submarine pipeline systems.* This code is general covering almost every aspect of a subsea pipeline system, such as pressure loads, temperature, 3 party interaction loads and so on.

LOADS

In order to predict stresses in a pipeline section one has to know the physical nature of the problem, in terms of loads acting on the pipeline. The loads acting on a pipeline may be classified as follows in DNV- OS-F101.

Functional loads are characterized as the loads from the physical existence of the system.

- Weight of pipe including buoyancy and contents.
- External hydrostatic pressure is given as the pressure loads from the sea environment.
- Internal pressure from internal pressure in tubes.
- Temperature of contents. The operational temperature and fluctuations in temperature must be considered.
- Pre-stressing may be evident due to permanent curvature from installation.

Environmental loads are the load components acting on the system from the surrounding sea environment

- Hydrodynamic loads given as waves, current, relative pipe motions, and indirect forces from vessel motions. Typical return period wave loads is 10^{-2}. Drag and lift forces, inertia forces, VIV, slamming, buoyancy variation.

Accidental loads are loads under abnormal and unplanned conditions with probability less than 10^{-2} of occurrence

- Extreme wave and current loads
- Vessel impact
- Dropped objects
- Explosion
- Dragging anchors

LIMIT STATE DESIGN

The principle of limit state design is that the loads are combined into three different limit states which have to be satisfied in order to approve the design. It is shown in (DNV101) that the three limit states are given as

- ULS Ultimate limit state
- FLS Functional limit state
- ALS Accidental limit state

From (DNV101) we have the following limit states:

Load effect factors and load combinations						
Limit State / Load combination	*Design load combination*		*Functional loads* [1)]	*Environmental load*	*Interference loads*	*Accidental loads*
			γ_F	γ_E	γ_F	γ_A
ULS	*a*	System check[2)]	1.2	0.7		
	b	Local check	1.1	1.3	1.1	
FLS	*c*		1.0	1.0	1.0	
ALS	*d*		1.0	1.0	1.0	1.0

FIGURE 8 LIMIT STATES (DNV101)

Design loads are calculated utilizing the safety factors presented in Figure 8 in accordance with ULS, FLS and ALS and design methodology.

DESIGN CHECK

Structural resistance R_{Rd} is calculated for all the relevant failure modes. The design check is performed by stating the following :

$$f\left(\left(\frac{L_{Sd}}{R_{Rd}}\right)\right) \le 1 \quad \text{where the resistance is given as} \quad R_{Rd} = \frac{R_c}{\gamma_m \cdot \gamma_{SC}}$$

- L_{sd} is the design load in each failure mode.
- R_c is the calculated resistance in each failure mode.
- γ_m is a material resistance factor with a typical value 1.15 for SLS/ULA/ALS/ and 1 for FLS
- γ_{SC} is a safety class factor corresponding to the level of safety required, typically 1.26 for a high safety level.

DESIGN CRITERIA

The principle of the design check is to use formulas given in the standard for each failure mode to calculate a structural resistance value for a given failure mode to be evaluated. Then state that the load corresponding to this failure mode has to be less than or equal to the structural resistance.

With regards to local buckling a displacement based criteria and a load based criteria is given in (DNV101).

- **Combined load criteria**
  - **Load controlled condition**
    - A condition where the structural response is primarily governed by the imposed loads on the structure. Loads corresponding to the relevant limit states i.e. ULS are checked against a yield criterion where combined loads are included
  - **Displacement controlled condition**
    - A condition where the structural response is governed by the imposed geometric displacements. Strains are checked according to yield criteria as a function of strains

DISPLACEMENT CONTROLLED CONDITION

With regards to local buckling a strain based criteria has been proposed in (DNV101). Local buckling is assumed to be the most relevant failure mode as a result of anchor hooking. The design strain criterion against local buckling for a pipeline is presented in eq. 2.13. This expression is presented to illustrate how design strains are calculated but will not be used further in the thesis as local buckling will not be considered.

$$\varepsilon_{Sd} \leq \ \varepsilon_{Rd} = \frac{\varepsilon_c(t, p_{min} - \ p_{min})}{\gamma_\varepsilon}\ , \qquad \frac{D}{t} \ \leq 45, \qquad p_i \geq \ p_e \tag{2.12}$$

$$\varepsilon_c(t, p_{min} - \ p_{min}) \ = 0.78 \left(\frac{t}{D} - 0.01\right) \cdot (1 + 5.75 \cdot \ \frac{p_{min} - \ p_e}{p_{b(t)}}) \cdot {\alpha_h}^{-1.5} \cdot \alpha_{gw} \tag{2.13}$$

Where p_{min} is the minimal internal pressure that can be continuously sustained with the associated strains, γ_ε is the strain resistance factor, α_h is a factor considering material and α_{gw} is a girth weld factor.

3 Anchor systems

Mooring equipment

All registered ships operating in the North Sea have to fulfill mooring rules and regulations provided by the classification societies such as DNV or Lloyd. The classification societies provide guidelines for making sure that vessel mooring equipment is properly dimensioned to withstand loads experienced during operation. The vessels are assigned an equipment number or letter that sets the minimum weight and size of the mooring equipment. From guidelines provided in (DNV301) an expression for calculation of equipment number is given as follows:

$$\mathrm{EN} = \Delta^{2/3} + A \tag{3.1}$$

Where Δ is the moulded displacement in salt water on maximum draught and A is the projected area of all wind exposed surfaces in a plane normal to the wind.

Mooring equipment corresponding to the calculated equipment number for any given vessel may be found in equipment tables provided in (DNV301). Chain diameter, length of the anchor chain and anchor mass are found in the tables.

Table C1 Equipment table, general (Continued)

Equipment number	*Equip-ment letter*	*Stockless bower anchors*		*Stud-link chain cables*			
		Number	*Mass per anchor*	*Total length*	*Diameter and steel grade*		
					NV K1	*NV K2*	*NV K3*
			kg	*m*	*mm*	*mm*	*mm*
910-979	v	2	2850	495	54	48	42
980-1059	w	2	3060	495	56	50	44
1060-1139	x	2	3300	495	58	50	46
1140-1219	y	2	3540	522.5	60	52	46
1220-1299	z	2	3780	522.5	62	54	48
1300-1389	A	2	4050	522.5	64	56	50
1390-1479	B	2	4320	550	66	58	50
1480-1569	C	2	4590	550	68	60	52
1570-1669	D	2	4890	550	70	62	54
1670-1789	E	2	5250	577.5	73	64	56
1790-1929	F	2	5610	577.5	76	66	58
1930-2079	G	2	6000	577.5	78	68	60

Table 1 Equipment table presenting anchor equipment dimensions corresponding to equipment number (DNV)

ANCHORS

Vessels operating in the North Sea are usually equipped with stockless anchors such as Hall or Spek anchors (SOTRA). By visual inspection of the retrieved anchor from the Kvitebjørn gas pipeline hooking incident it has been found that the ship anchor hooking the pipeline was a Spek anchor. In order to perform a geometrical anchor hooking evaluation it has been assumed that the Spek anchor represents typical ship anchor geometry. The specific geometrical measures of the Spek anchor presented in Figure 9 are shown in Table 2.

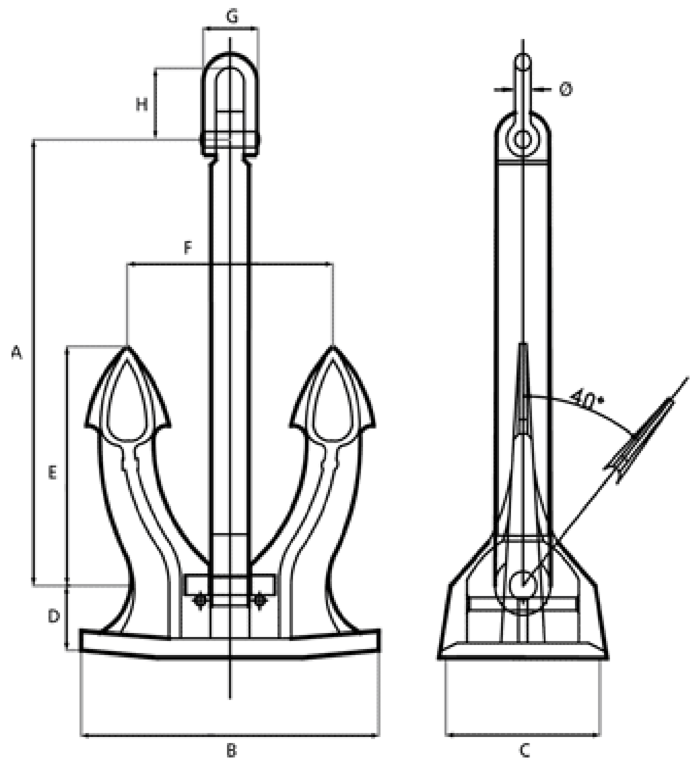

FIGURE 9 GEOMETRY OF SPEK ANCHOR(SOTRA)

Weight [Kg]	A [mm]	B [mm]	C [mm]	D [mm]	E [mm]	F [mm]	G [mm]	H [mm]	Ø [mm]
2460	2010	1514	660	324	1100	1100	260	340	74
3060	2160	1650	720	360	1200	1200	284	360	82
3780	2430	1850	810	393	1350	1350	310	385	90
4590	2520	1926	852	413	1400	1400	346	415	100

TABLE 2 ANCHOR SIZES AND DIMENSIONS

HOOKING PROPERTIES

Several parameters need to be fulfilled in order to get anchor hooking on a subsea pipeline. The pipeline diameter versus the length between anchor shank and tip of the anchor fluke is very important (Nord stream). Intuitively it is assumed that a small size anchor will not be able to hook onto a large diameter pipeline due to the fact that the pipeline simply will not fit between the anchor fluke and shank. This must be shown mathematically. A principle sketch is shown in Figure 10.

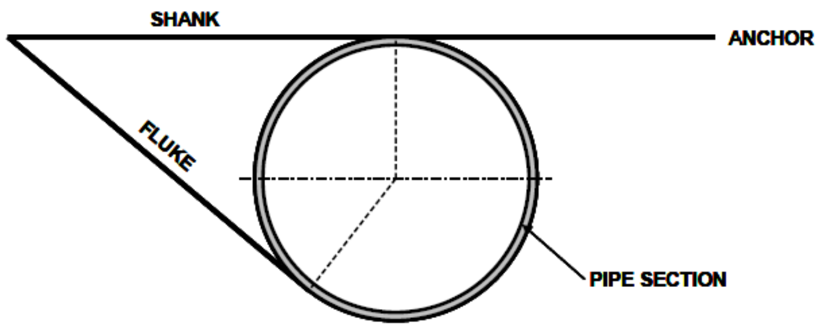

FIGURE 10 HOOKED PIPE SECTION (NORD STREAM)

It is seen from the sketch presented in Figure 11 that the maximum diameter of the hooked pipeline is dependent of the fluke length *L* and angle α between fluke and shank. A geometrical consideration of the problem has been performed in (Nord stream). The geometry of a typical anchor and a pipeline is shown in Figure 11.

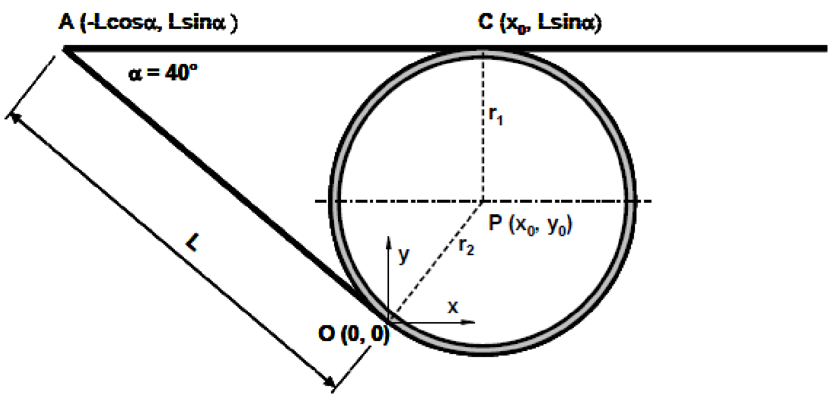

FIGURE 11 ANCHOR HOOKING GEOMETRY (NORD STREAM)

Considering Spek anchor dimensions and that the opening angle between the anchor fluke and shank is constant and equal to 40 degrees, the maximum diameter that can get stuck between the anchor fluke and shank is presented in equation 3.2

$$D_{max} = \frac{2L(1-\cos\alpha)}{sin\alpha} \tag{3.2}$$

The basis for this formula is that the anchor shank and fluke does not have any significant width. For the fluke this is assumed to be a valid assumption, as the tip of the fluke is very thin as seen in Figure 9. From Figure 9 it has been found that the anchor shank has a wide profile, which will affect the anchor hooking properties. Due to the wide anchor shank the maximum pipeline diameter which the anchor is able to hook will be slightly reduced as presented in Figure 12. The red circle represents the maximum hooking diameter expression presented above with the length E presented in Figure 9. The blue circle shows how the hooked pipeline diameter decreases when the shank width is included.

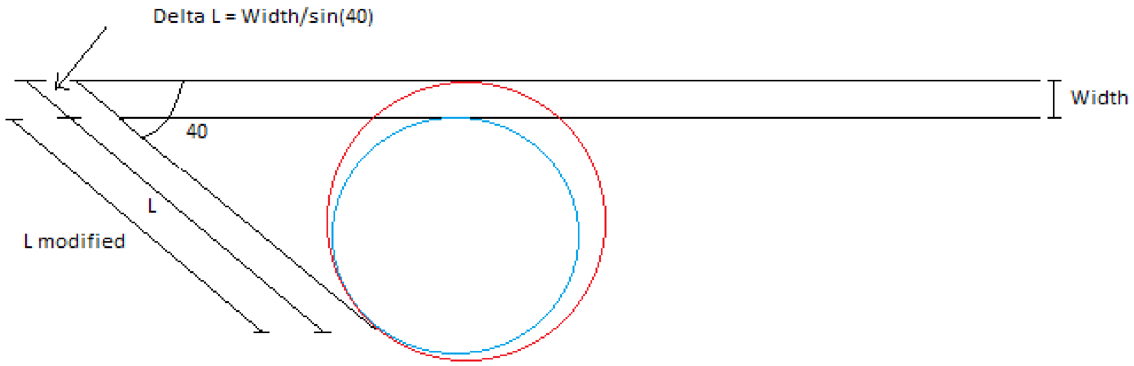

FIGURE 12 EFFECT OF INCLUDING ANCHOR SHANK IN THE MAXIMUM PIPELINE HOOKING DIAMETER CALCULATION

L modified is calculated as ***L*** – ***Delta L*** where ***Delta L*** is given as the shank width divided by sin(40). The width of the shank is not presented as a measure in Figure 9 so an assumption has been made that the shank width is about 1/7 of the length C in Figure 9. Dimensions and maximum calculated hooking diameter *Dmax* for various sizes of a Spek anchor are presented in Table 3. ***L modified*** has been used as ***L*** in equation 3.2.

Anchor weight [Kg]	Fluke angle [deg]	E [mm]	L modified [mm]	C [mm]	SHANK width [mm]	Delta L [mm]	*Dmax [mm]*
2460,0	40	1194,0	1065,7	660,0	94,3	146,7	762,4
3060,0	40	1283,0	1143,0	720,0	102,9	160,0	817,5
3780,0	40	1350,0	1140,0	810,0	115,7	180,0	851,7
4590,0	40	1400,0	1210,6	852,0	121,7	189,4	881,3

TABLE 3 MAXIMUM HOOKING DIAMETER FOR VARIOUS SIZES OF SPEK ANCHORS

In order for a ship anchor to hook the Kvitebjørn pipeline the anchor needs to be of such a size that the pipeline can get stuck between the anchor shank and fluke. A study has been performed in the previous section where the maximum pipeline hooking diameter was determined for various Spek anchors. The specific outer diameter of the kvitebjørn gas pipeline is 860.4 mm. From the results on the maximum hooking diameter presented in Table 3 it is seen that an anchor able to hook the Kvitebjørn gas pipeline falls between the two anchor sizes 4590 Kg and 3780 Kg. Due to some uncertainty with respect to the determination of the shank width it has been decided that the borderline minimum anchor size able to hook the pipeline is set to be 3780 Kg. A variety of anchor sizes and the associated chain parameters are presented in Table 4. These selected anchors will form the basis for further evaluation of the anchor interaction on the Kvitebjørn gas pipeline.

Equipment letter	Chain length [m]	Chain diameter [mm]	Grade	Anchor mass [Kg]	Chain strength [KN]
z	522,5	48	K3	3780	1810
G	577,5	60	K3	6000	2770
L	632,5	70	K3	8300	3690
O	660,0	78	K3	9900	4500
X	742,5	97	K3	15400	6690
A*	742,5	102	K3	17800	7320
E*	770,0	117	K3	23000	9300

TABLE 4 EQUIPMENT LETTER PARAMETERS

The anchor parameters presented in Table 4 are combined into anchor equipment classes presented in Table 5. The application of these anchor equipment classes will be explained in the forthcoming sections of the thesis.

Anchor class	Equipment letter
Class 1	z- G
Class 2	G - L
Class 3	L -O
Class 4	O-X
Class 5	X -A*
Class 6	A* - E*

TABLE 5 ANCHOR CLASSES

Anchor tow depth studies

A towed anchor arrangement from a vessel in transit will stabilize at a certain water depth where drag forces on the anchor arrangement are in equilibrium with gravity forces. Drag forces on the anchor chain and anchor are described by Morison's equation given in equation 3.3.

$$F_D = \frac{1}{2}\rho C_D D|v|v \tag{3.3}$$

Where C_D is the drag coefficient presented in Table 6, D is the anchor chain link diameter presented in Figure 15, and v is the fluid velocity.

As seen by the equation 3.3 the drag forces acting on the anchor and anchor chain are proportional to velocity squared. This implies that the drag forces are more evident for large tow velocities and that the stabilization tow depth is dependent on tow velocity. This effect is illustrated in Figure 13 where the different colors represent a typical anchor for towing velocities between 2 (blue) and 17 (green) knots. From the figure below it is seen that the tow depth is less for high velocities than for low velocities.

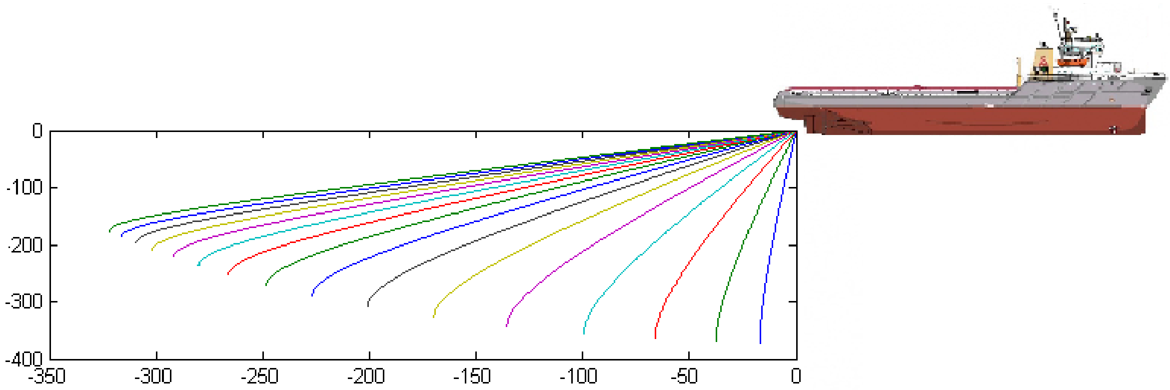

FIGURE 13 TYPICAL ANCHOR TOW DEPTH SHOWING VARIATIONS FOR VELOCITIES 2-17 KNOTS

The drag force on the towed anchor arrangement consists of a transverse and a longitudinal force component. Drag coefficients for transverse and longitudinal direction are found from (DNV301).

	Transverse	Longitudinal
Stud - link chain	2.6	1.4
Stud less chain	2.4	1.2

TABLE 6 DRAG COEFFICIENTS FOR STUD-LINK AND STUD LESS CHAIN

An investigation of the tow depth for each of the 7 equipment letters described in earlier sections has been performed. An effort has been made to develop a computer model for prediction of the tow depth of a towed anchor using the computer code SIMLA. The tow depths for each of the 7 equipment letters described in Table 4 have been established for vessel velocities between 2 and 17 knots. It has been assumed that the most common anchor chain type is the stud - link anchor chain (SOTRA). Results from the analyses are presented in Figure 14 and Figure 16. The typical trend shown in the figures is that for large vessel velocities the anchor chain will experience large drag forces and the stationary anchor tow depth will correspond roughly to a water depth of 1/3 of the chain length. This is a very important result and will be discussed in more detail further on throughout the thesis.

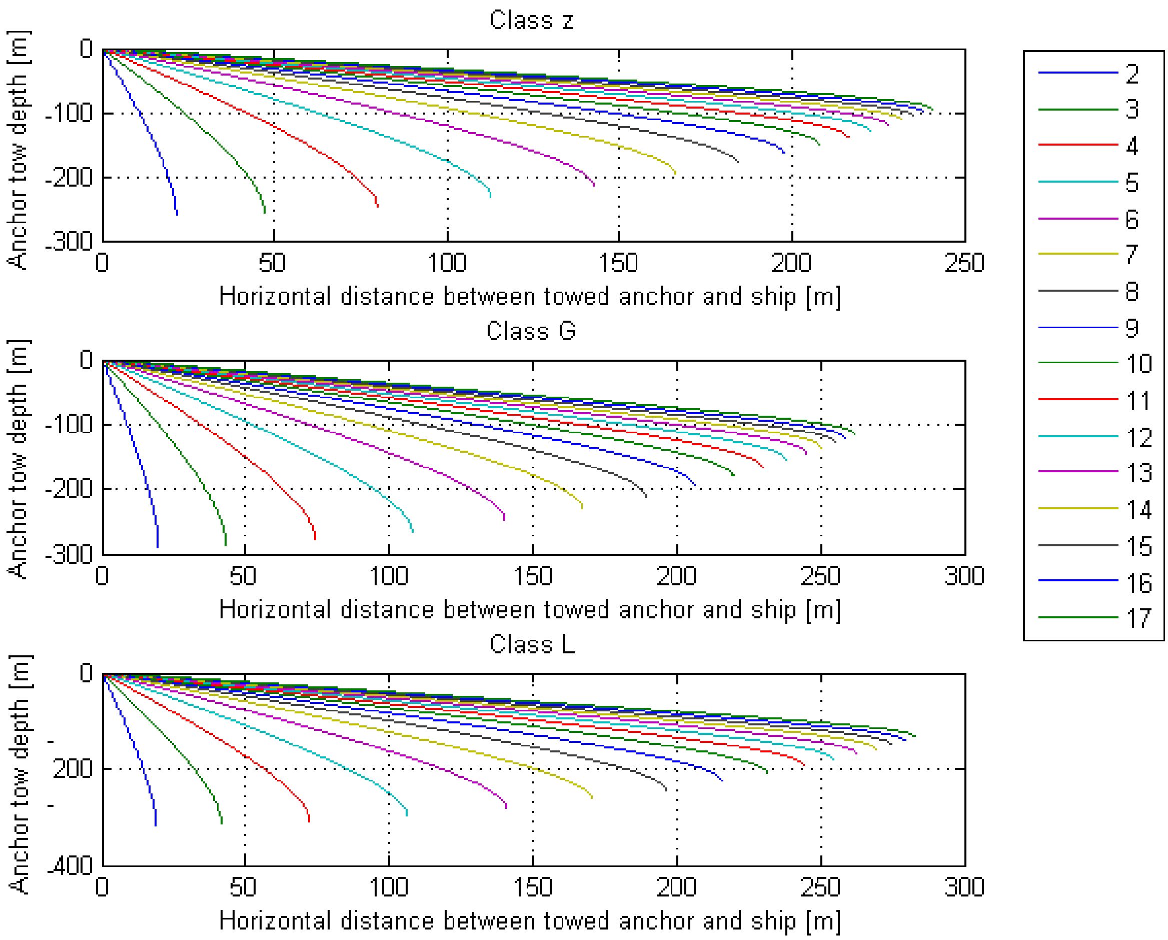

FIGURE 14 ANCHOR TOW DEPTH FOR ANCHOR CLASS Z, G, AND L FOR VELOCITIES 2 - 17 KNOTS

Drag coefficients corresponding to the stud - link chain have been included in the SIMLA input file. It is very important to notice that the drag coefficient correspond to the stud - link chain diameter D presented in Figure 15 below.

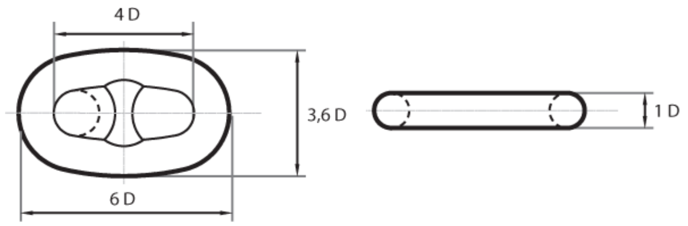

FIGURE 15 DIAMETER OF STUD LINK CHAIN

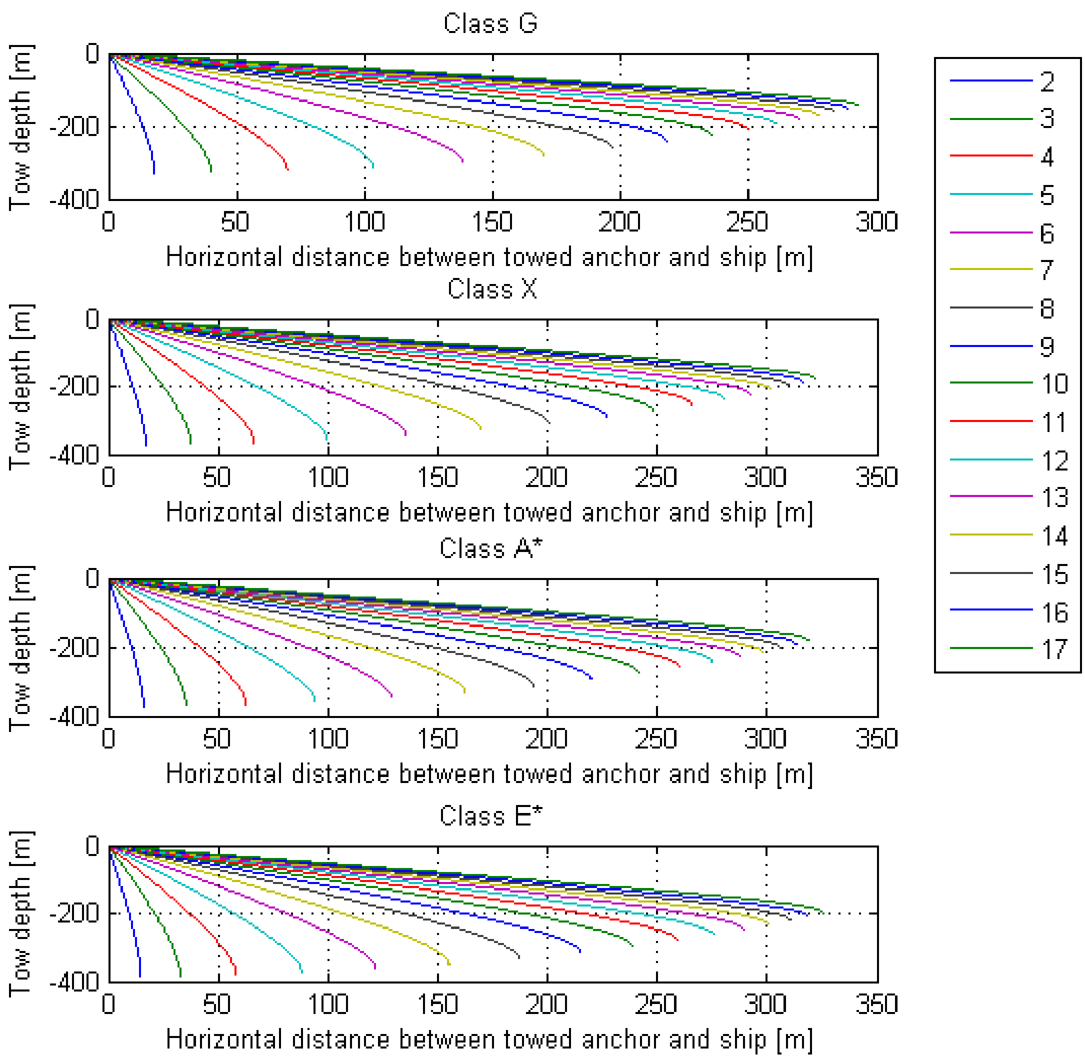

FIGURE 16 ANCHOR TOW DEPTH FOR ANCHOR CLASS G,X,A* AND E* FOR VELOCITIES 2 - 17 KNOTS

From the plots presented above it is seen that the anchor tow depth varies for the different equipment configurations presented in Figure 14 and Figure 16. In order to determine a tow depth for each anchor equipment class presented in Table 5 the mean tow depth between the two equipment letters in each class have been calculated. Typically for class 1 the mean tow depth between equipment letter z and G has been calculated for vessel velocities 2 – 17 knots. The same procedure has been applied to find the maximum anchor tow depth for all the anchor equipment classes 1-6.

The maximum tow depths for each class are presented in Figure 17. It is seen from the figure that the anchor classes with larger anchor parameters have a larger maximum tow depth. This is due to the fact that the mass of both the anchor and the anchor chain increase more rapidly than the belonging projected surfaces of the anchor and chain.

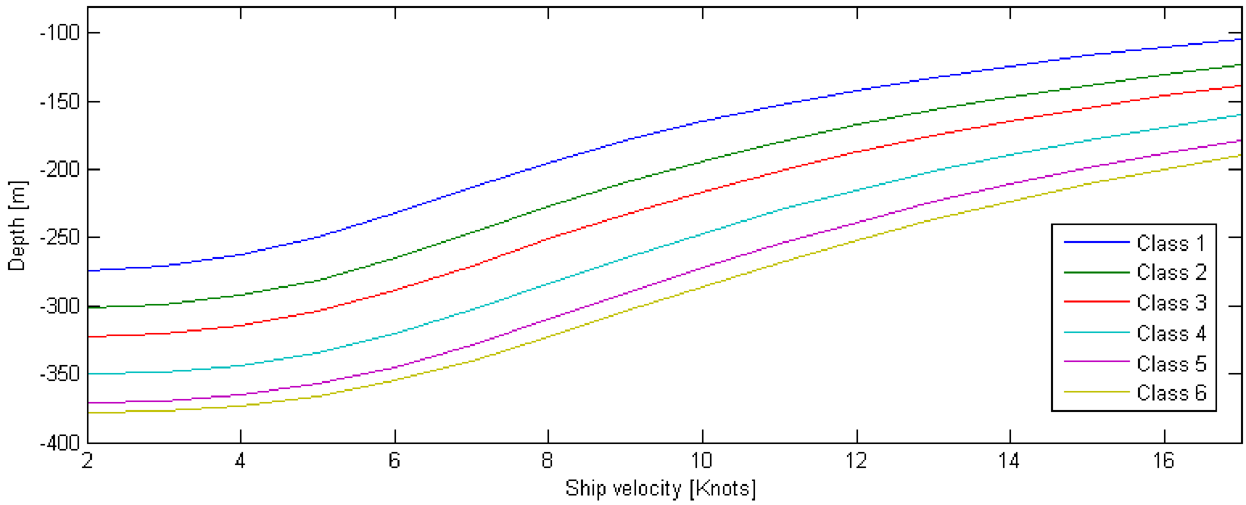

Figure 17 Maximum anchor tow depth versus ship velocity 2- 17 knots

4 Third party load investigation

Scope

The damage inflicted to a pipeline due to a dragged anchor is assumed to be dependent of parameters such as anchor mass, chain length versus water depth, vessel velocity, chain breaking strength and the pipeline size. In order to do a structural evaluation of the hooking scenario in terms of determination of the response of the Kvitebjørn pipeline these parameters will have to be evaluated. An attempt has been made to predict the most frequent anchor equipment and ship velocity for ship traffic over the Kvitebjørn gas pipeline. The specific scope of the third party load investigation is presented below.

1. Determine ship traffic over 5 km sections of the pipeline and determine sections with highest ship frequencies.
2. Classify ships into anchor equipment classes presented in Table 5 using reference ships
3. Determine the most frequent anchor chain length, chain breaking strength and chain dimension for ships passing each 5 Km section of the pipeline.
4. Determine number of ships able to hook pipeline, corresponding anchor equipment class of the ships and the ship velocities for the ships able to hook pipeline.

Automatic identification system (AIS)

The Norwegian Coastal Administration (NCA) has provided access to a database containing historical Automatic Identification System (AIS) data from the Norwegian sector of the North Sea. Vessels equipped with this system send out live signals containing information such as speed over ground, ship length breadth and draft etc. The following ships are to be equipped with the AIS system:

- Tankers
  - All in international operation
  - All within EU
- Cargo ships
  - Over 300 GT in international operation
  - Over 300 GT within EU

Due to this it has been assumed that all ships in transit in Norwegian coastal areas are equipped with this system, and that all the ships able to hook the Kvitebjørn gas pipeline are equipped with this system.

Sectioning of the Kvitebjørn pipeline and exporting AIS data

The Norwegian Petroleum Directorate provides a map in the AIS user interphase showing the pipeline grid and names of the different pipelines. The user interface is set up in such a manner that it is possible to export historical ship data for any given area of the Norwegian sector in the North Sea. By use of this map it is possible to draw pass lines over a specified pipeline section of the map and export historical AIS data containing all the vessels passing this line over a certain period in time. A typical pass line has been drawn in red in Figure 18 to demonstrate the user interface of the AIS database. The user has to define the start and end point of the pass line using longitudinal and latitudinal coordinates.

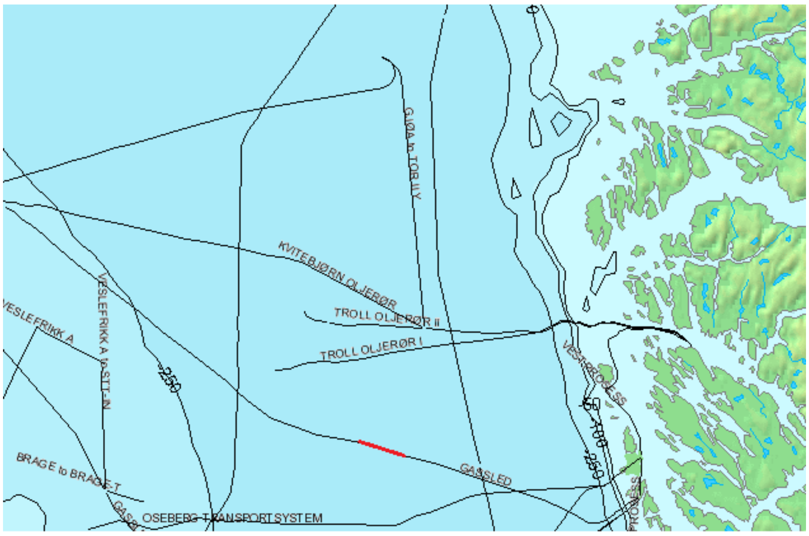

Figure 18 AIS database view presenting various pipelines and a pipeline section of Kvitebjørn marked with red

In order to evaluate the ship traffic passing the Kvitebjørn gas pipeline the pipeline has been divided into 29 sections of 5 Km each, and historical ship data between March 2010 and March2011 has been exported. Data files containing ship information such as dimensions and velocities for ships crossing each individual pipeline section have been exported. A small part of one of the exported *.tsv files is presented in Figure 19.

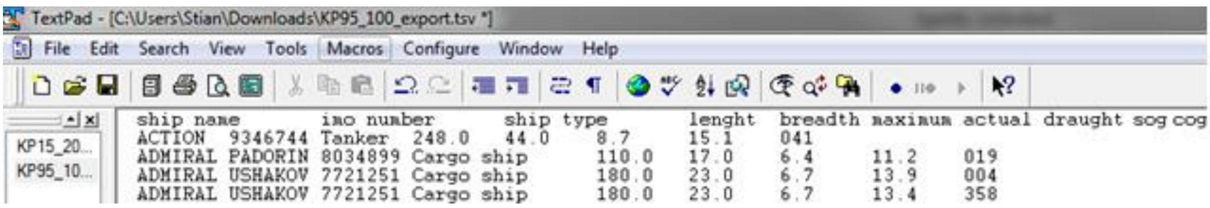

Figure 19 Example of an exported .tsv ship data file for a section of the pipeline

CLASSIFICATION OF SHIPS

As mentioned in the previous section ship parameters such as length, breadth, and draft have been exported from the AIS database. A significant effort has been made to locate relevant reference ships so that it is possible link the ships in the exported data files to the correct anchor equipment. This is a very important part of the study, and various ways of linking ships to anchor equipment have been investigated. As seen in the previous section the exported AIS files contain information about the ship type such as tanker, cargo ship or tug boat for each ship in the AIS file. It has been found that the best way to classify the ships is to use reference ships for each ship type, i.e. to use cargo reference ships to classify cargo ships and tanker reference ships to classify tankers.

Reference Ships Cargo

NAME	IMO	L [m]	B [m]	D [m]	EQ LETTER	Anchor total length [m]	D Chain [mm]	Anchor mass [Kg]	Chain Strength [KN]	DWT [ton]
BERGE ATLANTIC	9164184	**291,75**	**48,00**	**17,10**	**Z**	**742,00**	**100,00**	**16900**	**7060,00**	**172704,00**
JACK D	7915632	**250,00**	**41,50**	**11,40**	**W**	**742,50**	**95,00**	**14700**	**6440,00**	**98358,00**
HARDANGER	9079119	**213,40**	**31,00**	**12,00**	**O**	**660,00**	**78,00**	**9900**	**4500,00**	**44251,00**
BARSAM	8107581	**199,50**	**29,00**	**11,74**		**632,50**	**70,00**	**8300**	**3690,00**	**44441,00**
ROYAL DIAMOND	8300391	**160,00**	**25,20**	**9,81**	**G**	**577,50**	**60,00**	**6000**	**2770,00**	**25407,00**
FAR SEARCHER	9388950	**93,00**	**21,00**	**6,20**	**B**	**550,00**	**50,00**	**4320**	**1960,00**	**5200,00**

TABLE 7 REFERENCE SHIPS CARGO

Reference Ships Tankers

NAME	IMO	L [m]	B [m]	D [m]	EQ LETTER	Anchor total length [m]	CHAIN diameter [mm]	Anchor mass [Kg]	Chain Strength [KN]	DWT [ton]
ARCTIC DISCOVERER	9276389	**289,50**	**48,50**	**11,56**	**E***	**770,00**	**117,00**	**23000**	**9300,00**	**75485,00**
SALLIE KNUTSEN	9169627	**277,00**	**50,00**	**16,00**	**A***	**742,50**	**102,00**	**17800**	**7320,00**	**153617,00**
NANSEN SPIRIT	9438860	**249,00**	**43,82**	**15,00**	**X**	**742,50**	**97,00**	**15400**	**6690,00**	**109239,00**
CLIPPER SKY	9277943	**205,00**	**32,23**	**12,00**	**O**	**660,00**	**78,00**	**9900**	**4500,00**	**44617,00**
BW HEDDA	9014420	**170,00**	**27,50**	**8,00**	**L**	**632,50**	**68,00**	**7800**	**3500,00**	**25926,00**
BRO DEVELOPER	9160932	**144,00**	**24,00**	**7,00**	**F**	**577,50**	**58,00**	**5610**	**2600,00**	**14737,00**
BERGESTRAUM	9108740	**123,00**	**16,00**	**5,50**	**z**	**522,50**	**48,00**	**3780**	**1810,00**	**9494,00**

TABLE 8 REFERENCE SHIPS TANKERS

An effort has been made to select reference ships directly from the exported AIS data files, in order to get as much similarity as possible to the evaluated ships in the AIS data files. Several cargo ships and tankers from the AIS data files have been used as reference ships. By utilization of the ship IMO number the correct anchor equipment letter has been found for these ships using the DNV Exchange database. The cargo reference ships are presented in Table 7 and tanker reference ships in Table 8. It has been found that the best way to compare ships in the data files to the reference ships is to use the ship length in the classification. Table 9 below shows how the ships from the AIS data files are classified using the length of the ship as classification parameter.

Anchor class	Tanker		Cargo		Equipment letter
	L low	L high	L low	L high	
Class 1	123	144	93	160	z- G
Class 2	144	170	160	199,5	G - L
Class 3	170	205	199,5	213,4	L -O
Class 4	205	249	213,4	250	O-X
Class 5	249	277	250	291,75	X -A*
Class 6	277	-	291,75	-	A* - E*

TABLE 9 CLASSIFICATION OF SHIPS BY USE OF SHIP LENGTH

A number of tests have been performed to validate the classification method. This has been done by checking some of the classified ships against the DNV Exchange database. The model seems to put the ships in the correct class and is found to be valid. In order to get a feel for the anchor parameters corresponding to each of the equipment letters a description of the different anchor classes was presented in Table 4.

For tug boats it has been assumed by inspection of the vessels from AIS files that tug boats below 84 meters of length are equipped with equipment letter smaller than z and will not be able to hook pipeline. Tug boats with a length larger than 84 meters have been assigned into class 1 anchor equipment.

MATLAB SCRIPT FOR DATA PROCESSING

An effort has been made to develop a computer code and an analysis methodology which may be used for evaluation of ship traffic over pipelines in the North Sea.

SCOPE

The scope of the programming work has been to develop a script for processing of the data files exported from the AIS database. The exported AIS data files contain a significant amount of ship data and if the data were to be organized manually by hand the process would have been very time consuming. MATLAB has been the preferred computer code for the data processing due to its endless possibilities with regards to plotting, calculations and matrix operations. The desired operations performed by the computer script are presented below.

- Find maximum tow depth for each equipment letter for velocities 2 – 17 knots from text files containing tow depth information from the SIMLA analyses performed in chapter 3.
- Store **mean value** of maximum tow depth between two equipment letters, typically z and G for class 1, G and L for class 2 and so on.
- Extract tankers, cargo ships and tug boats from data files and store ship information in matrices.
- Assign the correct anchor equipment to each ship utilizing reference ships presented in Table 7, Table 8 and the ship lengths presented in Table 9. Separate out ships with anchor equipment smaller than class 1.
- Store the number of ships in each class 1-6 crossing each 5 kilometer section of the pipeline.
- Store the velocities associated to ships in each class 1-6 crossing each section of the pipeline.
- Link the maximum tow depth from tow depth analyses and the associated velocities for ships in each class for each 5 kilometer section of the pipeline. Compare potential anchor tow depth against depth in the evaluated pipeline section and separate out ships with anchor equipment not able to touch down on seabed and hook pipeline.
- Determine total number of ships in each class able to hook pipeline for each 5 kilometer section of the pipeline.
- Present the information in a clear and structured manner.

A more extensive outline of the specific script layout is presented in a flowchart in next section.

PROGRAM STRUCTURE

In order to demonstrate the structure of the MATLAB script a flow chart is presented in Figure 20. The script utilizes several subroutines to perform the necessary manipulations of the exported data from AIS database and present the results in a systematical manner.

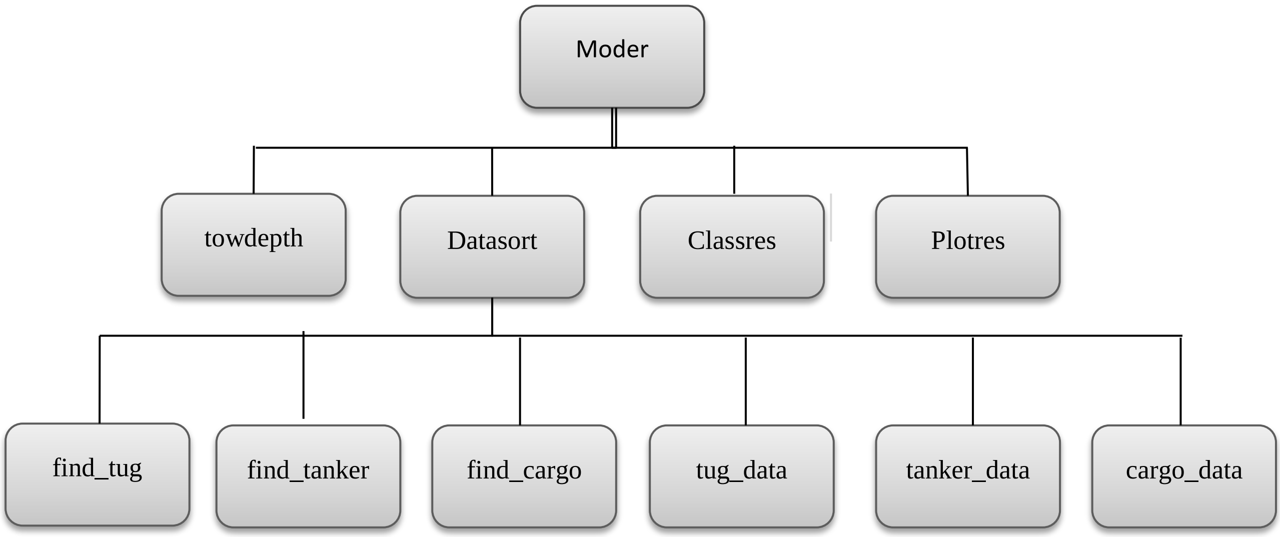

FIGURE 20 FLOW CHART ILLUSTRATING THE STRUCTURE OF THE DEVELOPED SCRIPT FOR SHIP CLASSIFICATION

Descriptions of the main operations performed in the script have been given below.

- The subroutine towdepth.m reads output files from SIMLA tow depth analyses and determines maximum tow depth for anchor equipment letter classes presented in Table 5 for ship velocities 2-17 knots.
- Moder.m run through the 29 sections of the pipeline and perform the following operations
    - Datasort.m utilizes **find_tug.m**, **find_tanker.m** and **find_cargo.m.** The subroutines run through the evaluated AIS data file and find tankers, cargo ships and tug boats. The specific positions of the ships in the data file are saved and returned back to the main program as matrices.

  - The subroutines **tug_data.m**, **tanker_data.m** and **cargo_data** utilize the position matrices provided by the **find_** subroutines to export and sort out the desired ship information from the AIS data files. Ship length, breadth, draught and speed over ground are stored in separate matrices for tankers, cargo ships and tug boats.
  - The subroutine **Data_sort.m** returns one matrix containing tanker ship information sorted by ship length, one matrix containing cargo ship information sorted by ship length and one matrix containing tug boat information sorted by ship length.

- **Classres.m** utilizes reference ships presented in Table 7 and Table 8 to classify the tankers, cargo ships and tugboats into the anchor equipment letter. The length of the ships in the extracted AIS files is compared to the ship lengths presented in Table 9 and the ships are assigned to the correct equipment class. The ship length and ship type have been found to be the best parameters to compare in order to assign ships to the correct anchor equipment letter class.
- **Classres.m** stores the ship velocity when a ship is assigned to an anchor equipment class. By doing this the velocity distribution for the ships in each anchor equipment class may be found.
  - The maximum tow depth for each class 1-6 and the associated velocities for ships in each class are linked in main.m and compared to the water depth at the evaluated pipeline section. Ships with anchor equipment able to touch down on seabead and hook pipeline are stored in a matrices with information about anchor equipment class and velocity.

- **Plotres.m** plots the relevant results.

SHIP FREQUENCIES

The annual ship traffic over the Kvitebjørn gas pipeline has been evaluated utilizing the computer code described in the previous section. The total number of cargo ships, tankers and tug vessels passing the pipeline between March 2010 and March 2011 has been found from the extracted AIS data files to be 7160. As presented in geometrical considerations chapter, anchors with dimensions lower than class 1 will not be able to hook the 30 inch pipeline. Class 1 may be seen as a lower limit for anchor hooking to happen. Figure 21 below presents the distribution of ships with anchor dimensions lower than class 1 not able to hook the pipeline, and ships with anchor dimensions large enough to hook the pipeline. As seen from the figure about 58 % of the ships passing the pipeline have large enough anchor dimensions to hook the pipeline.

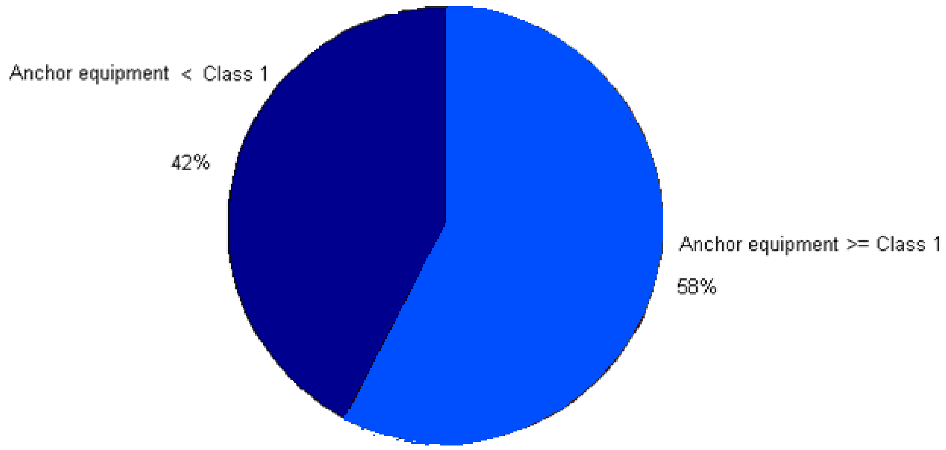

FIGURE 21 SEPARATION OF SHIP BASED ON LARGE ENOUGH ANCHOR TO HOOK THE PIPELINE

The 58 % of the ships with anchor dimensions large enough for the ship anchor to hook onto the pipeline have been separated from the total number of ships and forms the basis for further anchor hooking evaluations.

The next step has been to assign the ships passing each 5 Km section of the pipeline into the correct anchor equipment classes 1 – 6 presented in Table 5. The total number of ships passing each section of the pipeline and the specific distribution of the anchor equipment associated with these ships are presented in Figure 22. KP 1 represents the start of the pipeline at the Kvitebjørn field while KP 145 represents the last point on the pipeline at Kollsnes.

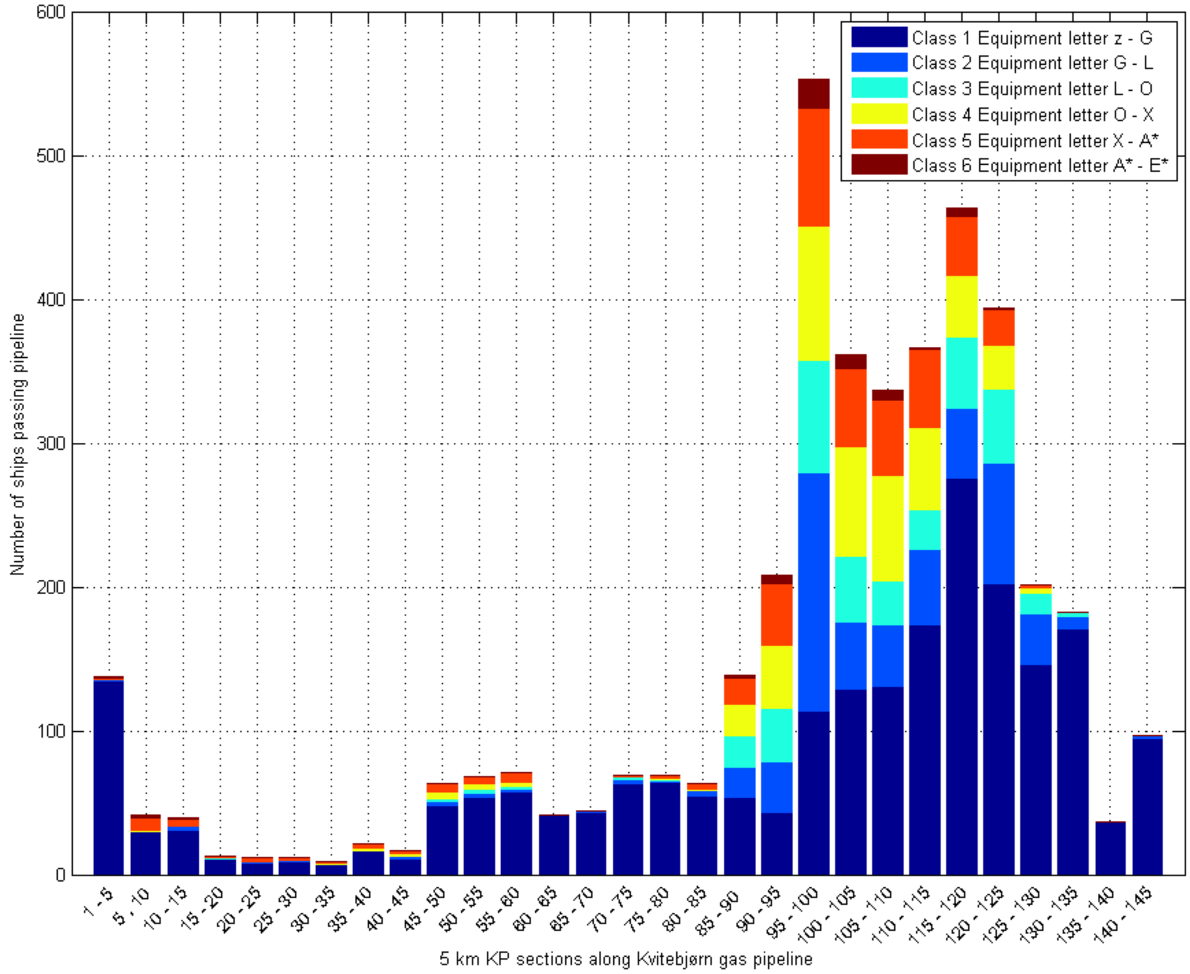

FIGURE 22 TOTAL NUMBER OF SHIPS PASSING PIPELINE WITH ANCHOR LARGE ENOUGH TO HOOK THE PIPELINE

From Figure 22 it may be seen that the main ship traffic is situated between KP sections 85 – 135. Based on evaluation of Figure 22 it is seen that the main ship line falls between these points and one may conclude that this is the area of the pipeline which is most susceptible to anchor hooking. In addition it is seen from the distribution of the ships that a significant number of the ships passing these sections have been assigned with anchor equipment class 2 and higher. Class 2 and the higher classes represent a real threat to the pipeline survival if ship anchor interaction were to happen. A link may be drawn to the Kvitebjørn anchor hooking incident where the ship hooking the pipeline would fall into the class 4 anchor equipment class.

In order to get a feel on the distribution of ships in each anchor class with respect to all the pipeline sections a pie diagram is presented in Figure 23. It is seen from the distribution that there is a strong representation of ships with class 1 anchor equipment which accounts for 55 % of the ships able to hook the pipeline. 14 % of the ships fall into class 2 and class 3, 4, and 5 are represented by around 10 %. Only 1 % of the ships fall into class 6.

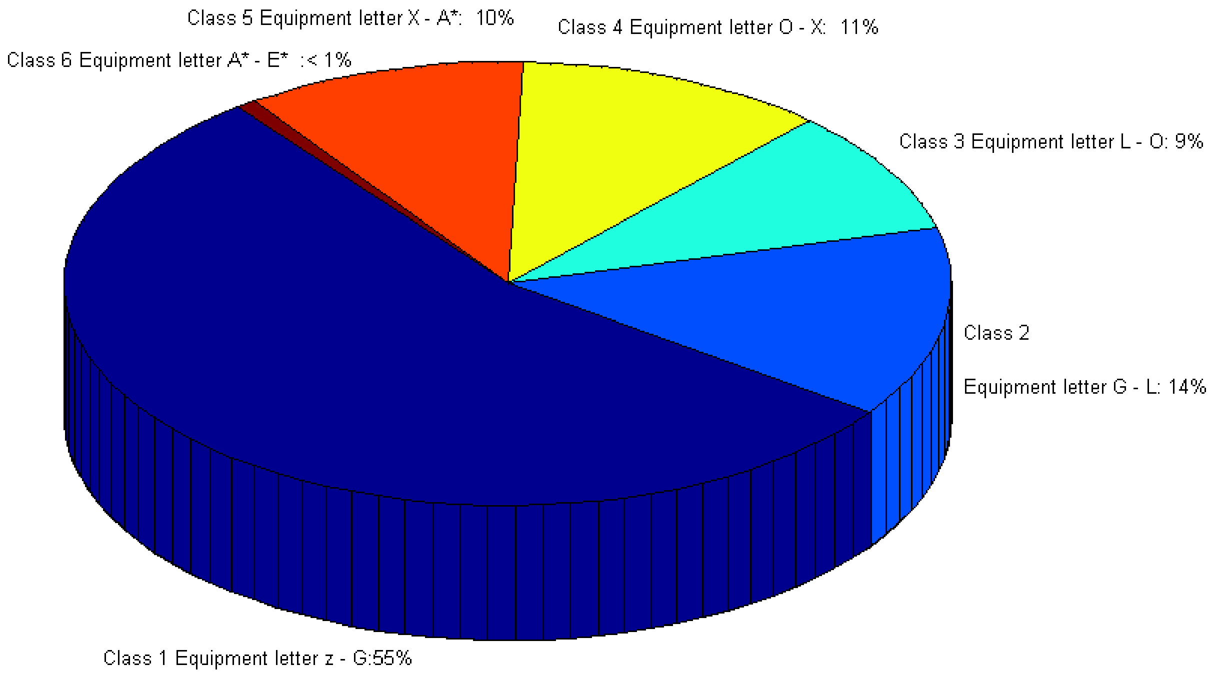

FIGURE 23 DISTRIBUTION OF SHIPS ABLE TO HOOK PIPELINE IN DIFFERENT SHIP CLASSES

By visual inspection of Figure 23 one may conclude with the fact that the most probable anchor interaction on the pipeline will be from a class 1 ship. However more parameters need to be evaluated in order to draw a conclusion. The anchor tow depth study performed in chapter 3 of the thesis will now be applied to link the velocity of the ships presented in Figure 22 , the maximum tow depth corresponding to these velocities and the specific water depth of the evaluated section of the pipeline.

SHIP VELOCITY DISTRIBUTIONS OF PIPELINE SECTIONS

The velocities of the ships passing each section of the pipeline will with reference to Figure 17 be of significant importance in terms of the possibility of anchor hooking. The anchor equipment class tow depth is highly dependent on ship velocity and it was seen that the maximum tow depth for large velocities is around 1/3 of the chain length. The main ship traffic is situated between section 85 and 135. Section KP 95 – 100 is the section of the pipeline which experiences the most ship traffic. Figure 24 presents the velocities of the ships in each class passing the pipeline over the KP section 95- 100. It is seen from the bar plot that the ship velocities are generally quite high and that the majority of the ships passing this section are found to have a velocity above 10 knots.

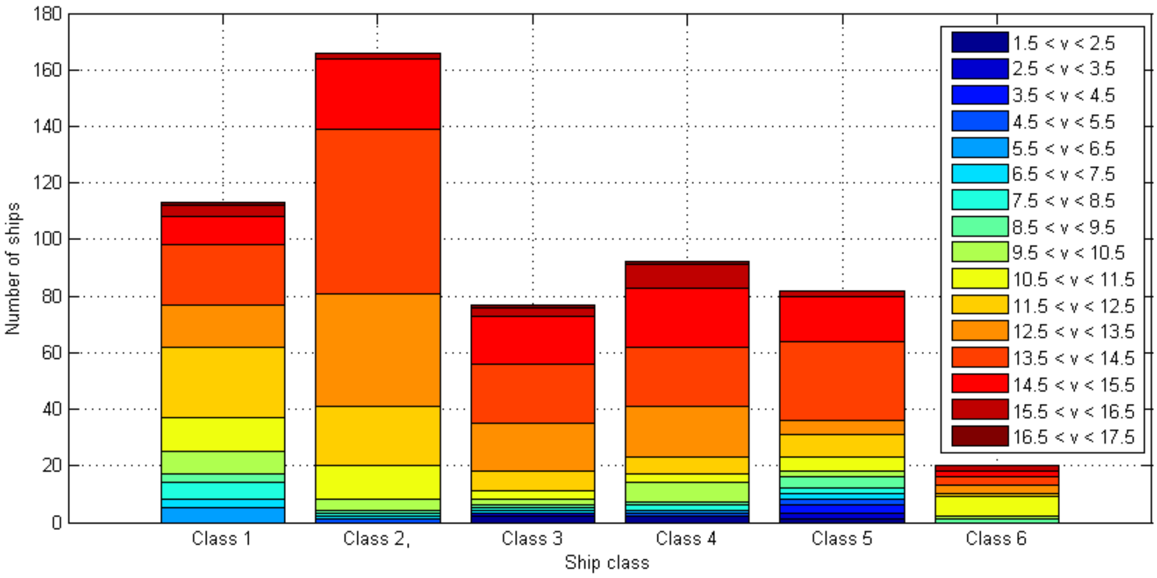

Figure 24 Velocity distribution of ships passing section KP 95-100. The different colors on the bars represent different velocities in knots.

Figure 25 represent the velocities of ships passing the section KP 1-5. This velocity distribution has been included to show that there is somewhat variation of the ship velocities for the different sections of the pipeline. If a comparison is done between Figure 24 and Figure 25 it is seen that the class 1 velocity is somewhat smaller in Figure 25.

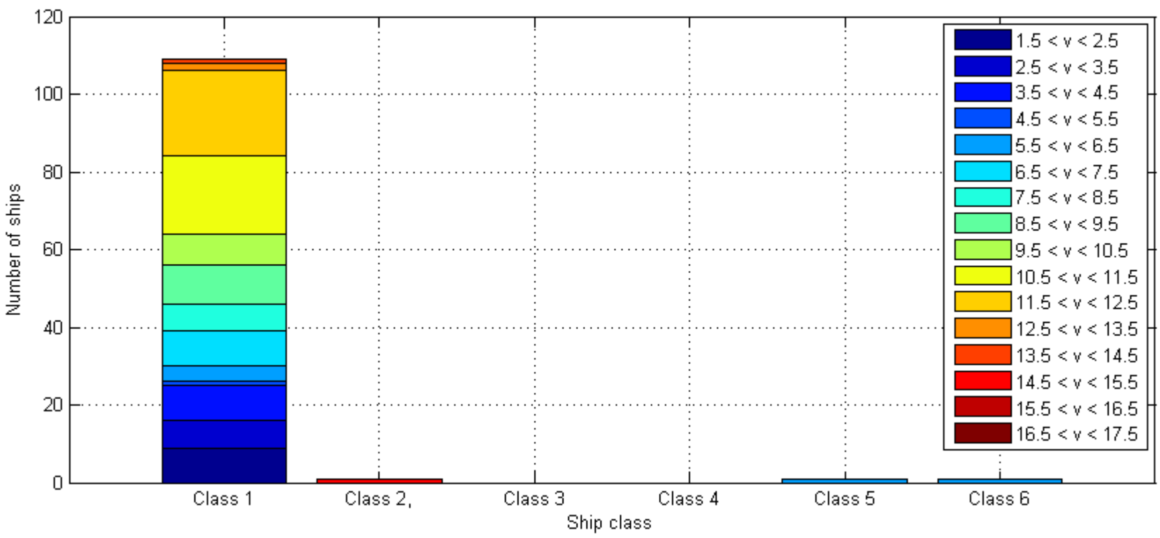

Figure 25 Velocity distribution of the ships passing Section KP 95-100. The different colors on the bars represent different ship velocities in knots.

Linking ship velocity, anchor tow depth and section water depth

The depth profile of the Kvitebjørn gas pipeline is presented in Figure 26, and it is seen from the plot that about 2/3 of the pipeline is situated around 300-350m water depth which implies that only the ships with the largest anchor equipment and low transit velocity will be of relevance.

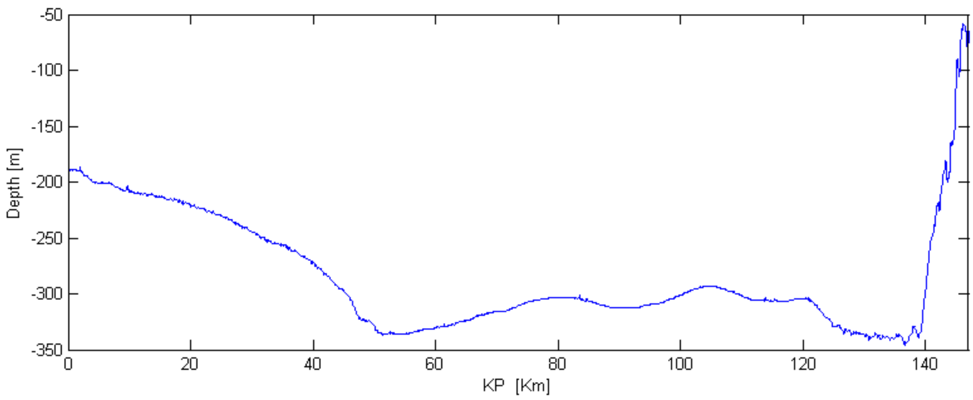

Figure 26 Depth profile for the Kvitebjørn pipeline (Data provided by Statoil)

In order to define the water depth in each 5 Km section of the pipeline, the median water depth between kilometer points 5 Km apart has been applied. This is assumed to be the best way to determine a representative depth for each 5 Km section of the pipeline as the depth varies over the section. The median water depth for the Kvitebjørn pipeline sections are presented in Table 10.

KP	**1-5**	**5-10**	**10-15**	**15-20**	**20-25**	**25-30**	**30-35**	**35-40**	**40-45**	**45-50**	**50-55**	**55-60**	**60-65**	**65-70**	**70-75**
Depth	194	204	211	217	226	238	253	264	285	322	336	333	329	320	314
KP	**75-80**	**80-85**	**85-90**	**90-95**	**95-100**	**100-105**	**105-110**	**110-115**	**115-120**	**120-125**	**125-130**	**130-135**	**135-140**	**140-145**	
Depth	305	304	311	313	308	296	297	306	307	313	334	339	337	192	

Table 10 Median water depth of the Kvitebjørn pipeline sections

As an example, lines representing the water depth of KP section 1-5 (194 m) and the water depth of KP section 95-100 (308 m) have been included in maximum tow depth presentation in Figure 27. This has been done to illustrate which of the anchor classes are able of hooking at these water depths and the towing velocities associated with hooking.

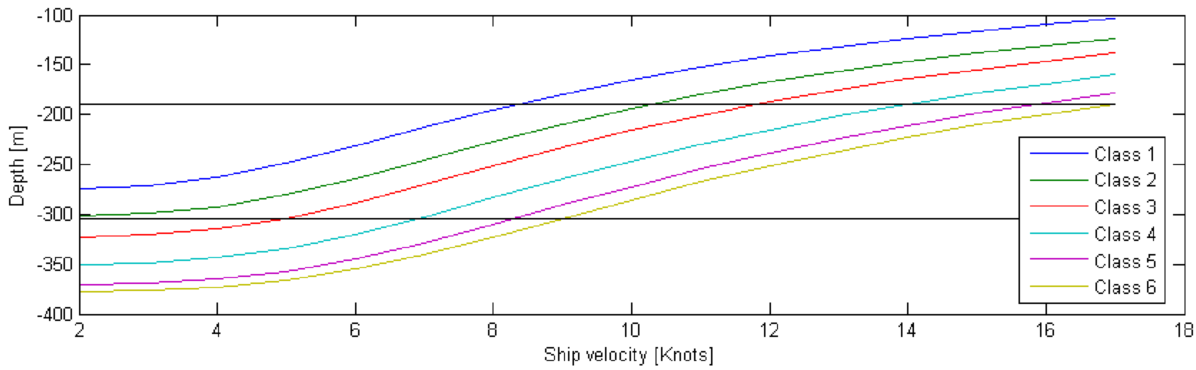

Figure 27 Tow depth with lines showing water depth of 194 m and 308 m

For water depth of 194 m it is seen from the graph that anchor touchdown on the seabed and anchor hooking is relevant for all the classes below 8 knots and that the larger anchor classes such as class 6 will touch the seabed even at 17 knots. For the case where the water depth is 308 meters only the larger anchor classes poses a threat to the pipeline due to the fact that smaller anchor classes simply will not reach down to the seabed, not even for very low velocities.

The link between ship velocity and maximum tow depth has been included in the AIS analysis. This means that the ship velocities of **every ship** with corresponding anchor equipment class in **each section** of the pipeline has been linked with the corresponding maximum tow depth of the anchor equipment class and velocity. By doing this the potential number of ships that will represent a threat to the pipeline in terms of anchor hooking is significantly reduced, due to the fact that for many of the ships travelling with large velocity the potentially dragged anchor arrangement will not reach down to the seabed.

The anchor that hit the Kvitebjørn gas pipeline probably came from 80 – 100 000 DWT vessel and the anchor weight was 10 tons (Gjertveit). This anchor size falls within the Class 4 represented in Table 9. According to (Gjertveit) the anchor had its first touchdown point at 240 meters of water depth and was dragged up to 210 meters where the anchor hooked on to the pipeline. It is seen from Figure 27 that the vessel velocity corresponding to class 4 ship and 240 m tow depth may be found to be around 11 knots which corresponds well to 80 – 100 000 DWT ship.

ANCHOR HOOKING RESULTS

The desired scope of work for this part of the thesis has been to investigate the ship traffic over the Kvitebjørn pipeline sections. The focus has been to predict the annual number of ships able to hook the pipeline, and determine the most probable anchor parameters such as anchor mass, anchor chain strength, chain length and vessel velocity if hooking were to occur. The predicted annual numbers of ships able to hook the Kvitebjørn gas pipeline in each pipeline section are presented in Figure 28.

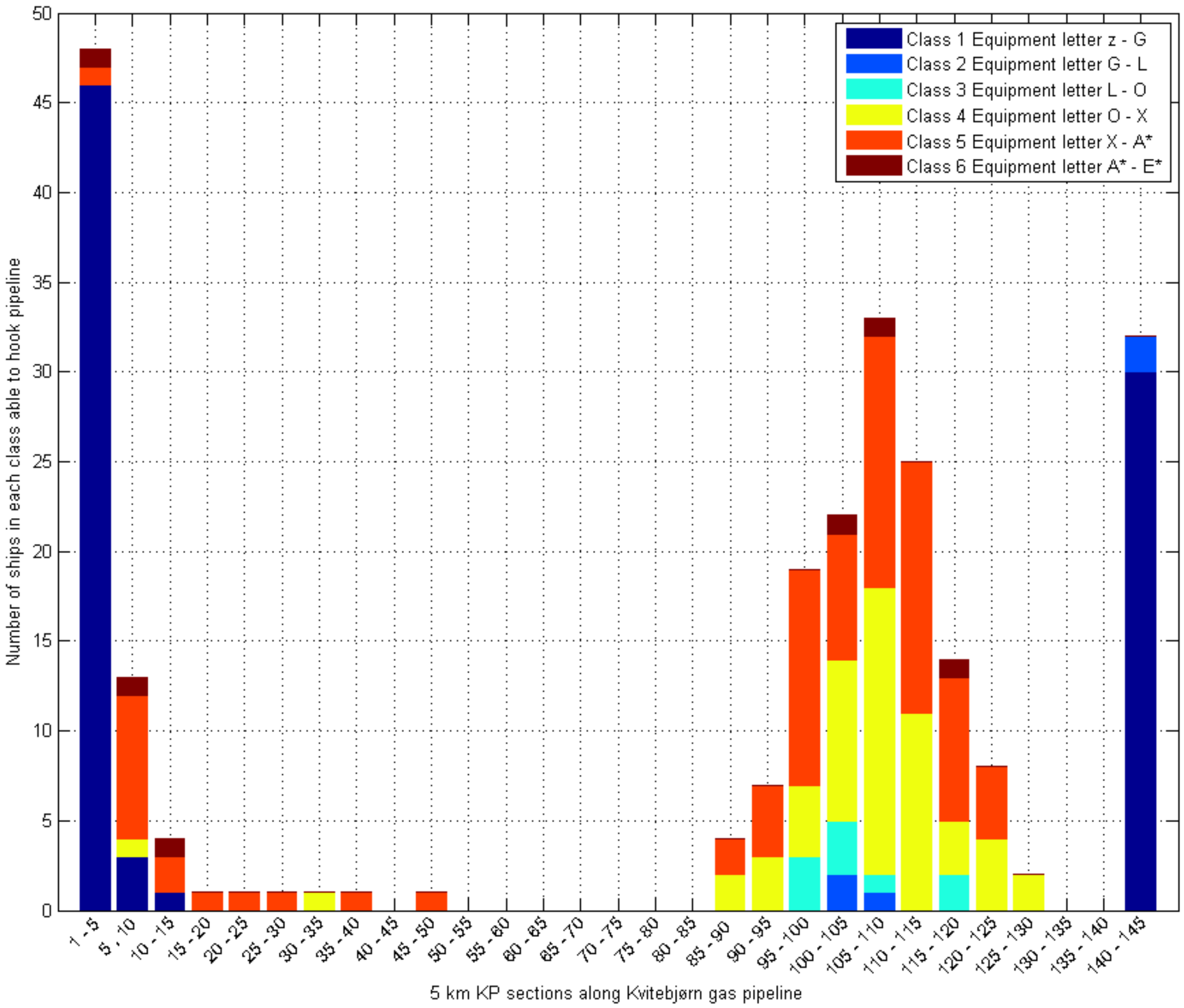

FIGURE 28 ANNUAL NUMBER OF SHIPS ABLE TO HOOK KVITEBJØRN PIPELINE IN EACH 5 KM SECTION

There seems to be a large number of ships falling into class 1 and able to hook the pipeline at section KP 1-5. This is partly due to the fact that this is a section with water depth around 190 meters, and that some of the ships in this section have a very low velocity. A bar plot showing the different velocities of the ships able to hook the pipeline in section KP 1-5 is presented in Figure 29, KP 5-10 in Figure 30 and KP 105 - 110 in Figure 31.

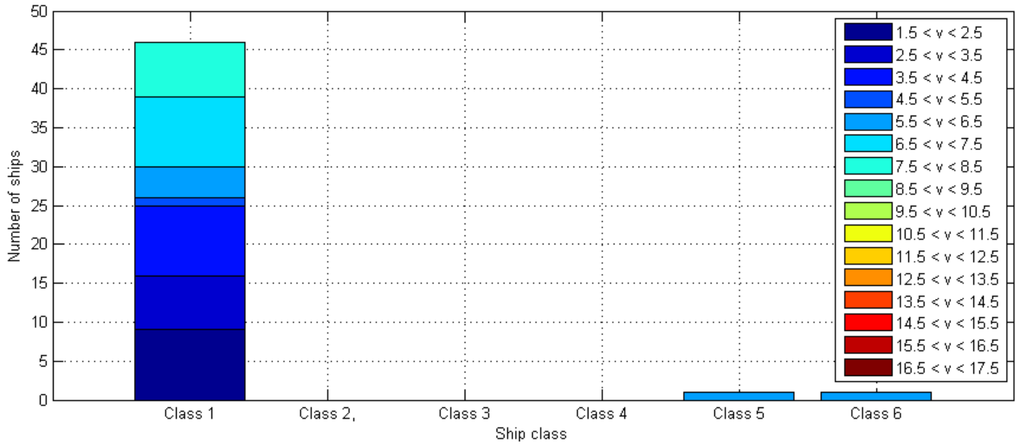

Figure 29 Potential hooking velocity 1-5. Colors represent potential ship hooking velocities in knots.

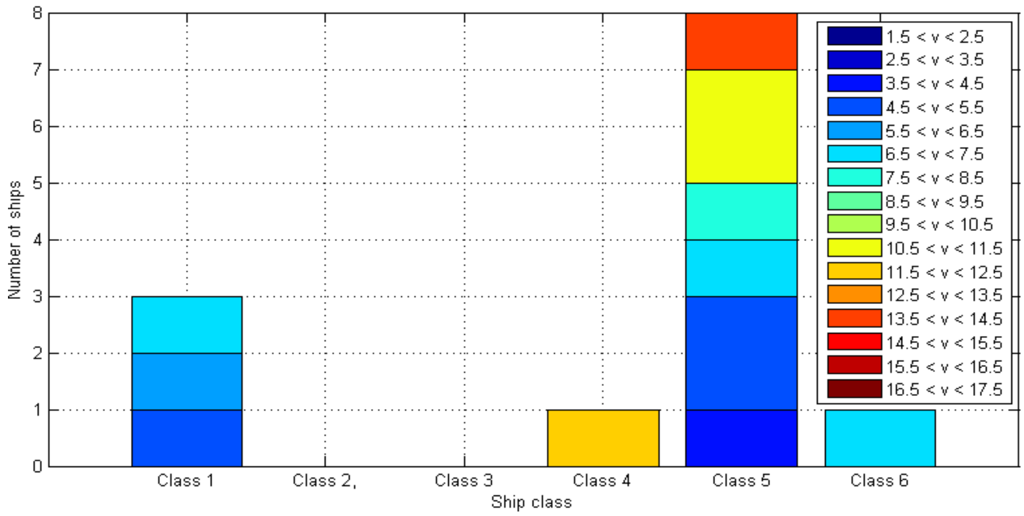

Figure 30 Potential hooking velocity section 5-10. Colors represent potential ship hooking velocities in knots.

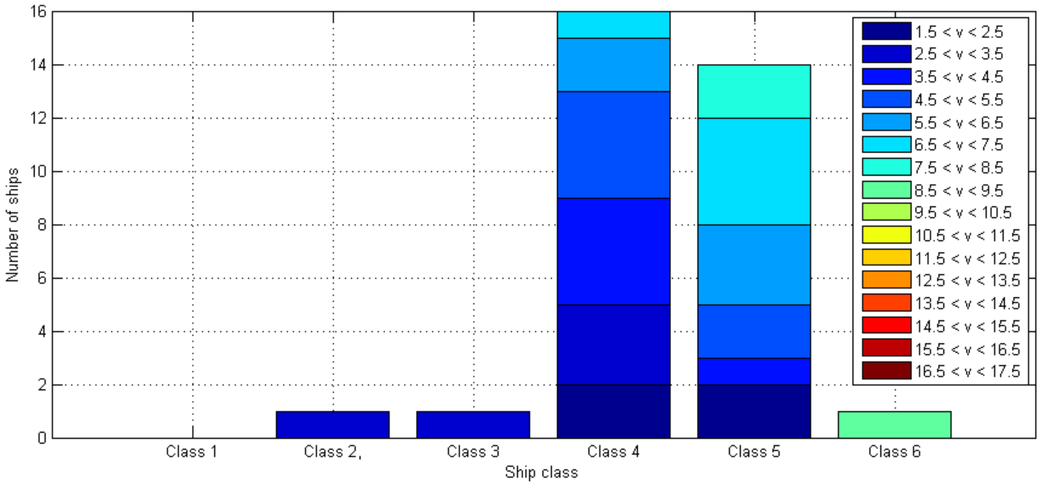

Figure 31 Potential hooking velocity section 105 – 110. Colors represent potential ship hooking velocities in knots

The ships presented in Figure 28 have been summed for the full pipeline length in order to determine the annual number of ships able to hook the pipeline. The total number of ships has been found to be 237 and a distribution of these ships is presented in Figure 32. It is seen that Class 1, Class 4 and Class 5 is represented strongly. 237 out of 7160 (3,3%) fulfill the hooking properties described in the previous sections.

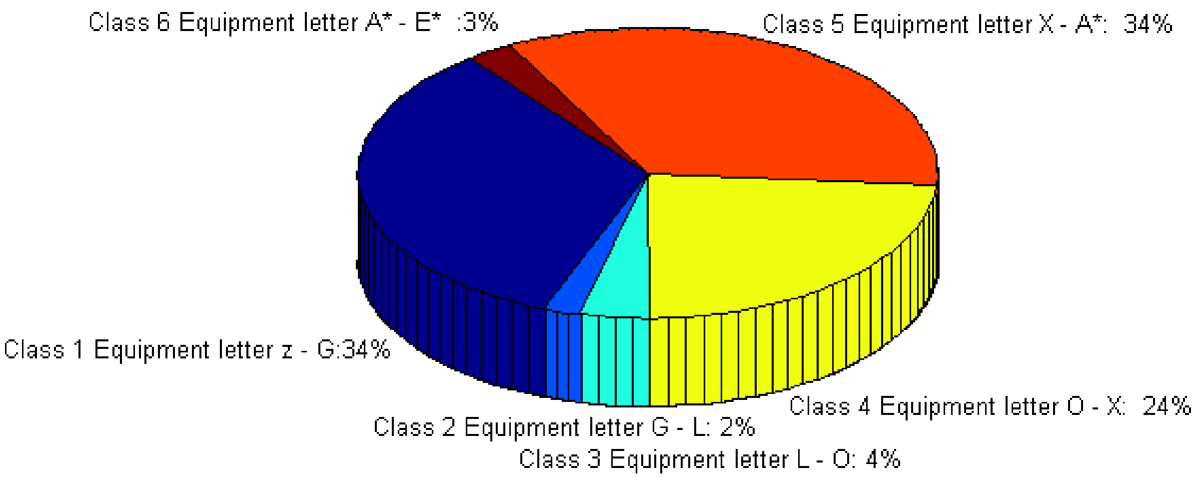

Figure 32 Distribution of total number of ships in each class passing pipeline in 1 year

In order for anchor hooking to happen the ship anchor must be accidentally dropped from a ship in the vicinity of the pipeline. A lot of uncertainty is connected with the probability of anchor drop during transit and this has not been investigated in the thesis. The focus in this thesis has been to determine the most probable consequences if anchor hooking were to occur.

Ship headings when crossing the pipeline sections have not been investigated in the thesis. It is reasonable to assume that ships passing the pipeline with headings almost parallel to the pipeline will not hook the pipeline. Due to this it is reasonable to believe that the annual predicted number of ships able to hook the pipeline will be even lower than 3,3 %.

PARAMETERS FOR STRUCTURAL EVALUATION OF THE PROBLEM

The pipeline response due to anchor hooking is dependent of parameters such as section water depth, anchor chain length, anchor chain strength and vessel velocity. These parameters have been shown to vary for the different pipeline sections, due to the difference in water depth and ship traffic for each pipeline section. Sections with most probable anchor interaction have been found to be section 1-5 and 105-110 and these sections will form the basis for the further structural pipeline model analyses performed in SIMLA.

SECTION 1-5

From the bar plot presented in Figure 29 is seen that around 2/3 of the ships passing this section with potential of hooking have a velocity between 3.5 and 8.5 knots, so velocities between this interval will be used in the SIMLA analyses. In addition the class 1 anchor properties such as anchor chain strength and chain length will be included in the model, together with the section water depth.

SECTION 5-10

Parameters from this section will be included in the analyses as this is the section where the 10 ton dragged anchor hit the pipeline. It is seen from the velocity distribution presented in Figure 30 that the main part of the ships able to hook the pipeline in this section are class 1, 4 and 5 ships with a velocity between 5 and 14 knots.

SECTION 105 - 110

The main part of ships with potential of anchor hooking in this section is found to be class 4 or class 5 ships. The velocities of the ships are presented in Figure 31. It is seen from the figure that the velocities of the class 4 and class 5 ships vary between 3 and 9 knots.

Based on the results from the sections above it has been decided that the SIMLA model should have a water depth of 201 meters, and ship hooking velocities set to be 5, 8 and 11 knots in the analyses. On the basis of the sections above anchor equipment corresponding to class 1, 4 and 5 have been chosen for the analyses.

5 KVITEBJØRN GAS PIPELINE GLOBAL MODEL ANALYSIS

A global finite element model has been applied to simulate the global response of a subsea pipeline subjected to anchor hooking. The scope of the analysis has been to predict bending moments, axial forces and strains in the Kvitebjørn pipeline when subjected to anchor hooking. The computer code SIMLA has been the preferred alternative in the structural analysis due to its low user threshold and short finite element computational time.

MODEL PROPERTIES

Relevant pipeline properties applied in analyses are presented below:

Pipeline dimensions	
Type of pipeline	30 inch gas pipeline
Steel outer diameter	748.4 mm
Wall thickness steel	19.2 mm
Corrosion coating outside diameter	760.4 mm
Concrete coating outside diameter	860.4 mm
Material Properties	
Steel Density	7850 Kg/m^3
Corrosion coating density	1300 Kg/m^3
Youngs modulus	207 GPa
σ_{SMYS}	450 Mpa
σ_{SMTS}	535 Mpa
Thermal expansion coefficient	11.7 E^{-6} K^{-1}
Content properties	
Content pressure	100 Bar
Content temperature	15 °C
Content density	130 Kg/m^3
Seawater properties	
Seawater density	1025 Kg/m^3
Submerged weight and buoyancy	
Submerged weight empty	103.4 Kg/m
Submerged weight operation	154.9 Kg/m
Buoyancy	595.95 Kg/m
Pipe soil interaction properties	
Vertical stiffness	50 KN/m/m
Axial friction coefficient	0.44
Lateral friction coefficient	0.67

TABLE 11 MODEL PROPERTIES (AGREED WITH SUPERVISORS)

MATERIAL MODEL

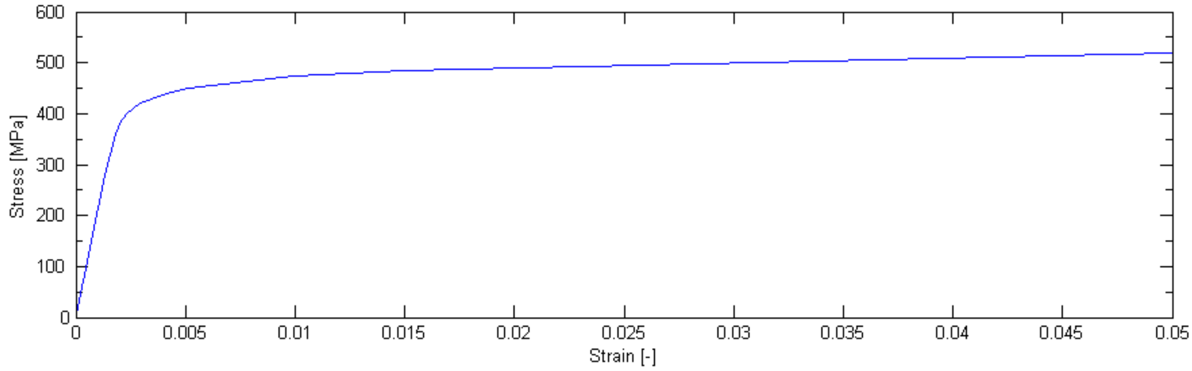

FIGURE 33 MATERIAL DATA X65 STEEL

X65 steel has been used to model the pipeline and an elastic plastic stress strain relationship for the material has been presented in Figure 33. The material yield point is defined at 0.002 % strain and σ_{SMYS} corresponding to 0. 5 % strain is presented in Figure 33 as 450 MPa. σ_{SMTS} for the x65 steel material used in the analysis is 535 MPa and correspond to 10 % strain.

OPERATIONAL CONDITIONS

Operational conditions for the Kvitebjørn gas pipeline are given in Table 11. From Table 11 it is seen that the pipeline flow is assumed to have a density of 130 kg/m^3. Typical pressure in the pipeline during operation is assumed to be 100 bar and a temperature of 15 degrees is assumed for the content. The external water pressure is assumed to be of insignificant magnitude as the water depth of the pipeline is maximum 350 meters.

Global finite element model

A global finite element model has been developed in the computer code SIMLA. The intention for developing this model has been to investigate typical pipeline responses of the Kvitebjørn gas pipeline when subjected to anchor hooking. This section will explain the global model and how the specific analyses are performed in the computer code SIMLA.

Pipeline model

The 10.8 km pipeline section has been modeled using built in pipeline element PIPE33 in the SIMLA software. The element is able to describe nonlinear plastic and elastic behavior and accounts for internal and external pressure. The length of the pipeline elements varies over the modeled pipeline sections from 10 meters at end section, to 0.5 pipeline outer diameter at the anchor impact point as shown in Table 12.

A more refined pipeline mesh will not provide more accurate results on the pipeline strain. This is due to the fact that very small elements will imply excessive strains due to point load singularity. SIMLA does not account for local pipeline cross-sectional deformations such as denting an ovalisation, so if these effects are to be investigated a local model must be developed. This will not be done in this master thesis. The 10.8 km long pipeline has been modeled with 1300 PIPE33 elements. The specific element sections of the pipeline are presented in Table 12

Section	X coordinate		Element length
1	0	5000	10
2	5000	5100	5
3	5100	5150	2.5
4	5150	5200	1.25
5	5200	5215	0.6
6	5215	5235	0.37
7	5235	5250	0.6
8	5250	5300	1.25
9	5300	5350	2.5
10	5350	5450	5
11	5450	10800	10

Table 12 Element lengths

Anchor interaction on the pipeline has been modeled by use of a linear spring between the anchor node and a pipeline node. Resistance properties in the spring increase linearly until it reaches a cut-off value representing anchor chain break load, as presented in Figure 35.

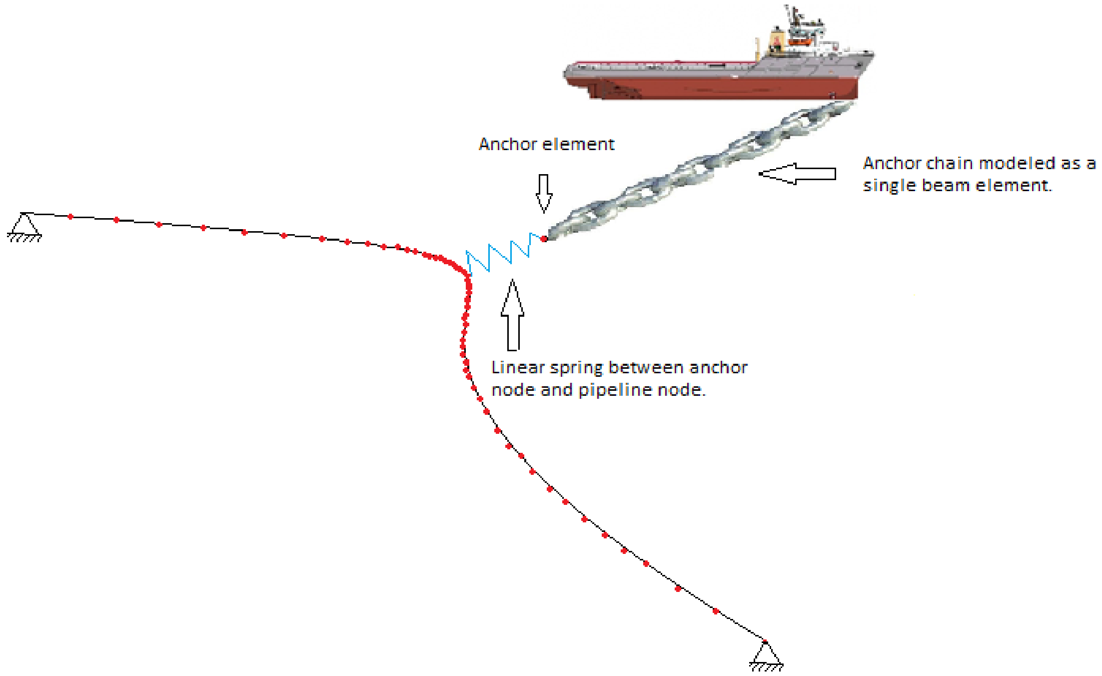

FIGURE 34 SCHEMATIC ILLUSTRATION OF THE ANCHOR HOOKING PROBLEM

The anchor has been modeled as a beam element around 1 meter long and with characteristics corresponding to the evaluated anchor size. Anchor chain has been modeled as a single beam element with axial stiffness corresponding to the evaluated anchor chain size. The element has been given low bending stiffness to represent the bending flexibility of an anchor chain.

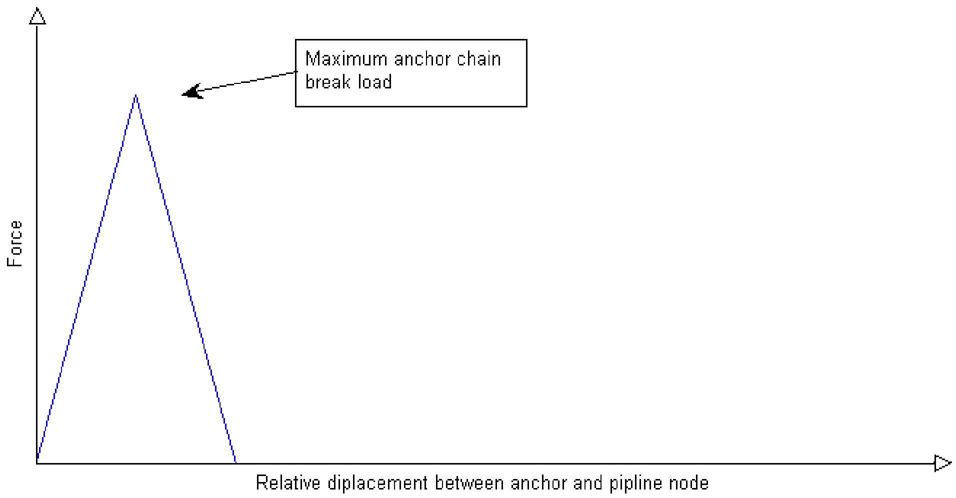

FIGURE 35 SPRING RESISTANCE PROPERTIES

SEABED

The pipeline sections with the largest number of ships able to hook the pipeline have been found to be between KP 1 and 10 and KP 85 – 135. Water depths in these sections are roughly 200 and 300 meters respectively, and quite flat. In order to limit the number of analysis parameters a water depth of 201 meters has been chosen as the model water depth.

PIPE SOIL INTERACTION

Contact elements have been used to model contact between seabed and pipeline. The contact between the pipe and the seabed occurs when a pipe node penetrates the seabed. Frictional parameters in lateral and axial direction are given in Table 11 as 0.67 and 0.44 respectively. These parameters correspond to the friction experienced by the pipeline when it slides on the seabed. A more accurate representation of the frictional coefficients accounting for an initial peak frictional resistance is presented in Appendix A. Vertical stiffness of the contact simulates the vertical resistance of the seabed.

BOUNDARY CONDITIONS

The ends of the pipeline have been fixed in the axial direction and in torsional direction. This is a valid assumption for heavy pipelines which are assumed to be unaffected by axial forces at model ends. For very large anchor interaction loads boundary effects may be encountered in the model ends due to large membrane forces in the pipeline.

PARAMETER VARIATION

In order to limit the analysis variation matrix a number of anchor equipment key parameters based on the AIS study have been selected for variation in the analysis. Ship velocity is also assumed to be a key parameter due to the fact that for large ship velocities inertia and drag reaction forces on pipeline will be more significant.

VELOCITY VARIATION

It has been found from the AIS studies that the most probable velocities of the ships with anchor hooking potential are between 5 and 11 knots. The ship velocities for the analyses have been selected as 5, 8, and 11 knots which are in correspondence with the most frequent potential hooking velocities presented in Figure 29, Figure 30 and Figure 31.

ANCHOR AND CHAIN VARIATION

It has been found from the AIS studies that the most frequent anchor equipment classes represented in Figure 32 are class 1, class 4 and class 5. Anchor parameters from these classes have been included in the analyses and the specific analyses performed are presented in Table 13.

Analysis	Anchor weight [Kg]	Chain length [m]	Chain breaking strength [KN]	Water depth [m]	Velocity [Knots]
1	3780	261.25	1810	201	5
2	3780	261.25	1810	201	8
3	3780	261.25	1810	201	11
4	6000	288.75	2770	201	5
5	6000	288.75	2770	201	8
6	6000	288.75	2770	201	11
7	9900	330.00	4500	201	5
8	9900	330.00	4500	201	8
9	9900	330.00	4500	201	11
10	15400	371.25	6690	201	5
11	15400	371.25	6690	201	8
12	15400	371.25	6690	201	11
13	17800	371.25	7320	201	5
14	17800	371.25	7320	201	8
15	17800	371.25	7320	201	11

TABLE 13 ANALYSIS PARAMETERS

GLOBAL MODEL RESULTS

The scope of the analysis work has been to determine the bending moment, axial force and maximum strain in the modeled pipeline at the anchor impact point. A total of 15 separate SIMLA input files based on the analysis parameters presented in Table 13 have been developed and run. MATLAB has been the preferred tool for result presentation.

PIPELINE RESPONSE

The pipeline responses in terms of vertical and lateral displacement for the different anchor equipment letters evaluated are presented in Figure 36 and Figure 37. It is seen from the plots that pipeline displacement increases when ship velocity decreases. Large displacements of the pipeline are observed, and from Figure 36 it is seen that the pipeline is lifted a significant distance above seabed. Large lateral displacements are seen in Figure 37 and a significant difference in response with regards to hooking velocity is observed.

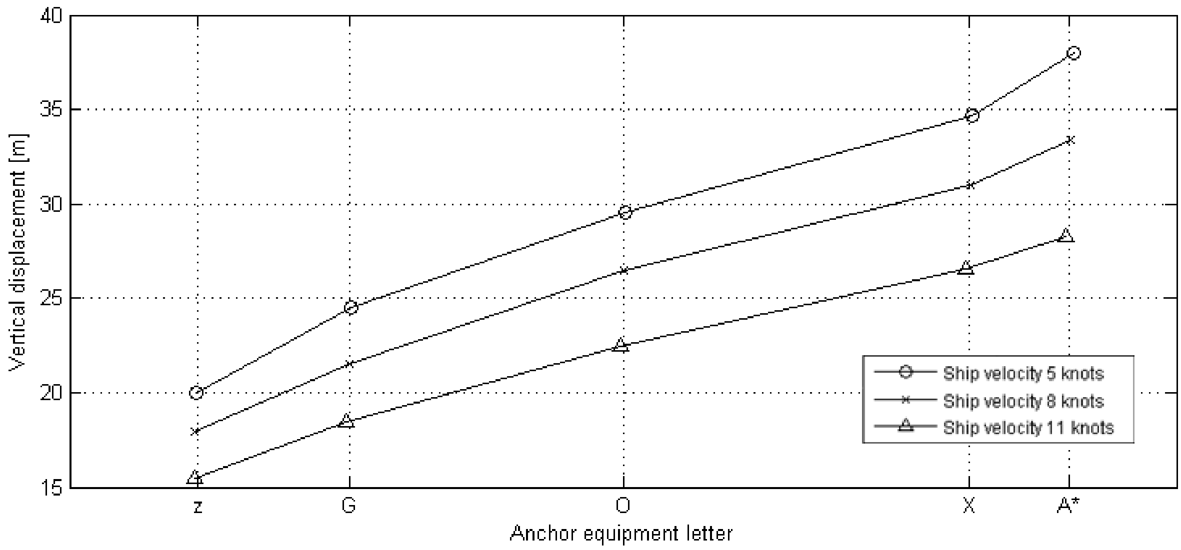

FIGURE 36 PIPELINE VERTICAL DISPLACEMENT FOR EQUIPMENT LETTERS z, G, O, X AND A* FOR VELOCITES 5, 8 AND 11 KNOTS

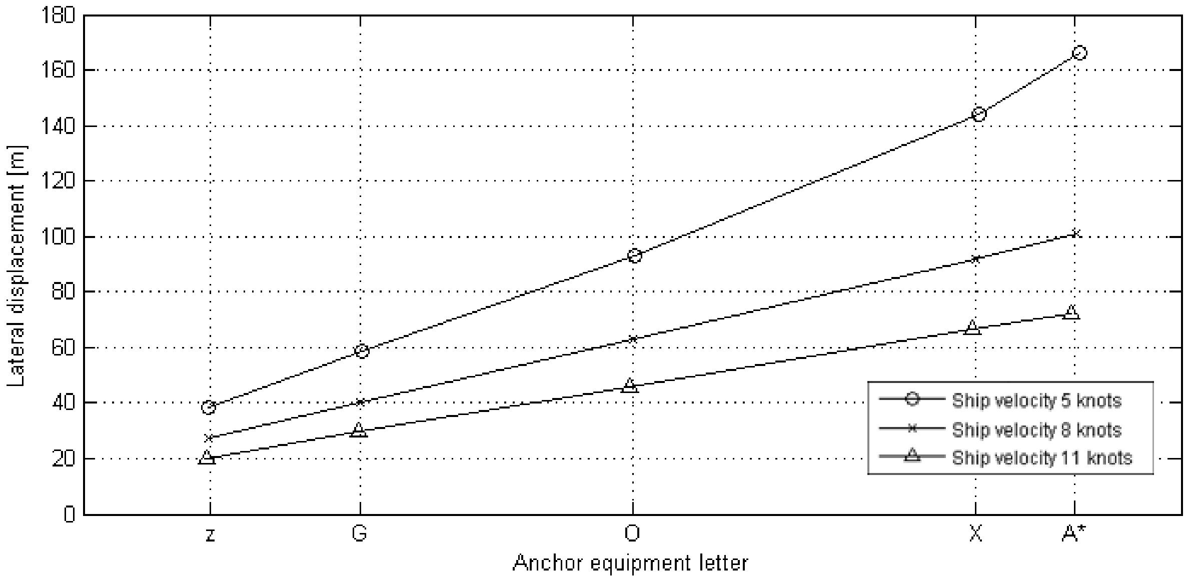

FIGURE 37 PIPELINE LATERAL DISPLACEMENTS FOR EQUIPMENT LETTERS z, G, O, X AND A* FOR SHIP VELOCITIES 5, 8 AND 11 KNOTS.

STRAIN

Maximum tensile strain at the anchor impact point is presented in Figure 38. It is seen from the figure that the maximum tensile strain increases for increasing anchor equipment and anchor chain capacity. Ship velocities of 5, 8 and 11 knots have been evaluated and it is seen from Figure 38 that the maximum predicted strain in the pipeline decreases for increased ship velocity. The same effect is also seen in (Vagnildhaug) , i.e. quasi-static versus dynamic analysis.

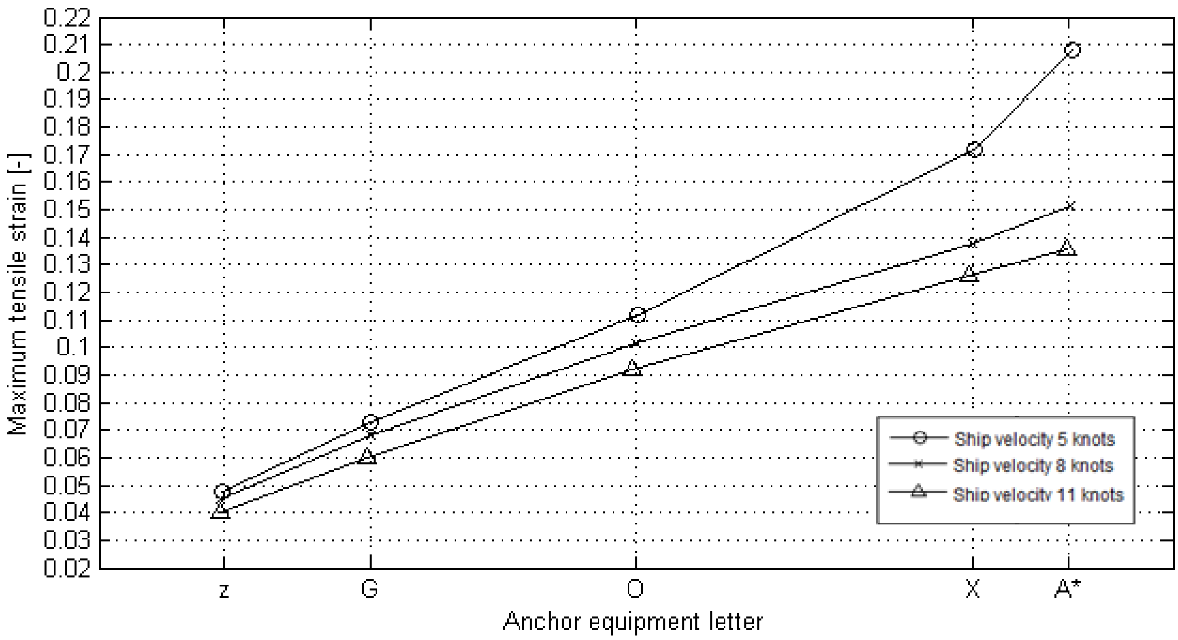

FIGURE 38 PIPELINE STRAIN FOR EQUIPMENT LETTERS z, G, O, X AND A* FOR SHIP VELOCITIES 5, 8 AND 11 KNOTS

Bending moment versus axial force at the impact point on the pipeline has been plotted in Figure 39. Plastic interaction curves according to eq. 2.10 are presented in black in the figure with the outer line corresponding to σ_{SMTS} and the inner line corresponding to σ_{SMYS}. It is seen for equipment letter O, X and A* in Figure 39 that the combined bending moment and axial force in the cross section exceeds the plastic capacity corresponding to σ_{SMTS}.

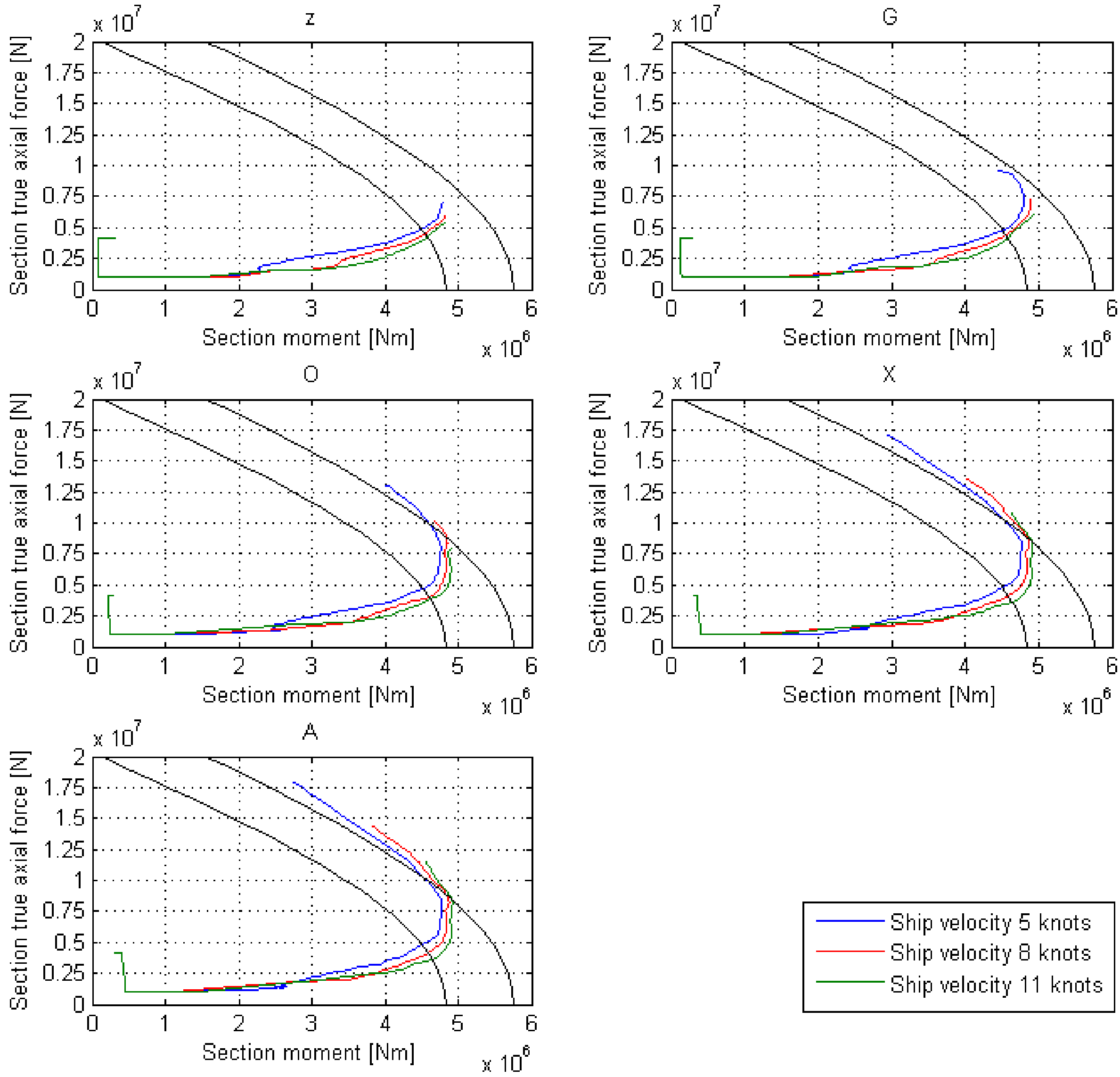

FIGURE 39 MOMENT VERSUS AXIAL FORCE AND PLASTIC INTERACTION CURVES FROM EQ 2.10 CORRESPONDING TO SMYS AND SMTS. ANCHOR EQUIPMENT LETTERS z, G, O, X AND A* ARE PRESENTED FOR VELOCITIES 5, 8 AND 11 KNOTS

6 Discussion

Results obtained in the analysis part of the thesis have been evaluated and the findings are presented below.

Velocity variation

Large pipeline strains and displacements have been observed in the analyses results in the previous section. A relationship between the ship hooking velocity and the observed pipeline strains and displacements is evident. For larger ship hooking velocities the reaction forces from drag and inertia is more significant than for low velocities. Due to this effect larger displacements and strains have been observed for ship hooking velocity of 5 knots compared to 11 knots. It is seen from Figure 38 that the pipeline strains associated with equipment letter A* is found to be 0.21 for 5 knots and 0.14 for 11 knots which is a very large difference. From this it may be concluded that it is conservative to use low hooking velocities in order to determine pipeline strains and response.

The development of the bending moment and axial force in the pipeline has been presented in Figure 39. The observed effect in Figure 39 is that the anchor hooking load is initially supported by the cross-sectional bending moment capacity of the pipeline. As displacements of the pipeline increase, membrane forces in the pipeline become more evident. It is seen from Figure 39 that the membrane forces increase steadily until the break load of the anchor chain is reached and no more force is applied to the pipeline. From Figure 39 it is observed that the combined load line follows a slightly different path when the hooking velocity is increased. A larger bending is moment observed to occur on the pipeline for increased velocity, and this is assumed to be another effect from the drag and inertia reaction forces developed at higher hooking velocities.

It is seen that for velocities 8 and 11 knots the strains follow what seems to be close to a linear relationship to the anchor equipment letters evaluated in Figure 38. For 5 knots the line seems to follow a linear relation for equipment letters z – O, but from this point on the strains increase more rapidly for increased equipment letter.

ANCHOR EQUIPMENT VARIATION

The strain values presented in Figure 38 correspond to the anchor equipment letters z, G, O, X and A*, and it is observed from the figure that large strain values will occur in the pipeline if an anchor of dimensions corresponding to these equipment letters were to hit the pipeline.

By inspection of Figure 38, it has been found that the strain levels predicted for anchor equipment letter O for a velocity of 8 knots is 10 %. In the material model used for the analyses 10 % strain corresponds to σ_{SMTS} value of 535 Mpa. By inspection of equipment letter O in Figure 39 it is seen that the end point on the red line corresponding to 8 knots is located just outside the plastic capacity curve corresponding to σ_{SMTS}. Good correspondence between the predicted strains and the observed bending moments and axial force is observed.

From Figure 38 and Figure 39 it may be concluded with that the pipe would definitely not survive an impact of equipment letter O and larger causing strain levels above 10 % and crossing of the plastic capacity curve corresponding to σ_{SMTS} presented in Figure 39. Reparations will have to be performed on the pipe if an anchor of such dimensions would hit the pipe. For equipment letter z and G it is seen that the strain levels fall below 10 % and the bending moment versus axial force lines presented for equipment letter z and G fall within the plastic interaction curve corresponding to σ_{SMTS}.

STRUCTURAL CONSEQUENCES

In order to draw a final conclusion in terms of pipeline survival after anchor interaction from class z and G the cross-sectional strains need to be evaluated on a local level. A local model of the impact section of the pipeline with end moments and axial forces extracted from the SIMLA model is a good alternative for evaluation of local damage. This has not been performed in this thesis.

HOOKING ENERGY

An interesting question which has come to mind during this thesis work has been the energy involved in an anchor hooking incident. Significant pipeline displacements combined with a large anchor chain pull force implies that the energy involved is large, as the energy is proportional with the area under the force displacement curve. The energy associated with the pipeline displacement for each of the 15 performed analyses have been calculated in MATLAB by utilization of the trapezoidal rule on the anchor chain pull force versus total pipeline displacement curves from analyses. The work done on the pipeline is presented in Table 14.

Equipment letter	Energy W (5 knots) [MJ]	Energy W (8 knots) [MJ]	Energy W 11 knots [MJ]
A*	674,9	391,2	285,8
X	514,9	323,3	240,6
O	218,9	153,0	116,5
G	88,1	64,5	51,1
z	39,6	31,5	25,9

TABLE 14 WORK DONE ON PIPELINE FOR EACH EQUIPMENT LETTER AND FOR VELOCITIES 5, 8 AND 11 KNOTS

A comparison between the work done on the pipeline and the kinetic energy of the reference ships has been done. The kinetic energy of the reference ships has been calculated by use of the formula presented in equation 6.1.

$$E_{kin} = \frac{1}{2}(m + a){v_{ship}}^2 \tag{6.1}$$

A block coefficient for the reference ships has been assumed to be 0.9, and by utilization of this weight estimates of the reference ships presented in Table 15 have been calculated as $L \cdot B \cdot D \cdot \rho \cdot 0.9$. Added mass has been assumed to be 10 % of the ship weight. The kinetic energy for the reference ships calculated for ship velocities 5, 8 and 11 knots is presented in Table 15.

Name	L [m]	B [m]	D [m]	Weight [ton]	Energy 5 knots [MJ]	Energy 8 knots [MJ]	Energy 11 knots [MJ]	Equipment letter
SALLIE KNUTSEN	277	50	16	204426	744	1904	3600	A*
NANSEN SPIRIT	249	44	15	150973	550	1406	2659	X
CLIPPER SKY	205	32	12	73141	266	681	1288	O
ROYAL DIAMOND	160	25	10	36488	133	340	642	G
BERGESTRAUM	123	16	6	9985	36	93	176	z

TABLE 15 KINETIC ENERGY OF REFERENCE SHIPS

Ratios between the calculated kinetic energy of the reference ships and the work done in the analyses are presented in Table 16. For 5 knots it is seen that the energy ratios are close to 1 for all of the reference ships. One should be careful with concluding too much on the basis of these rough calculations, but it is seen that the energy ratio decreases significantly when ship velocity is reduced. A link may be drawn to drifting ships where drifting velocity may be assumed to be around 2 knots. From the ratios presented in Table 16 it may be assumed that drifting vessels will not provide energy enough to reach the anchor chain break load and the damage inflicted on the pipeline can be assumed to be lower.

Equipment letter	Ekin/W 5 knots	Ekin/W 8 Knots	Ekin/W 11 Knots
A*	1,10	4,87	12,60
X	1,07	4,35	11,05
O	1,22	4,45	11,06
G	1,51	5,27	12,57
z	0,92	2,95	6,79

TABLE 16 RATIO BETWEEN KINETIC ENERGY OF REFERENCE SHIP AND THE WORK NEEDED TO DISPLACE THE PIPELINE

For the ships travelling at 8 and 11 knots the ratio is around 5 and 11 respectively and due to the large ratio it is assumed that the ship would have enough energy to displace the pipeline.

7 CONCLUSIONS

Due to its rare occurrence subsea pipelines are not dimensioned against anchor hooking. Very large uncertainty is associated with prediction of anchor hooking probabilities and structural consequences if anchor hooking were to occur. The following conclusions are drawn from the thesis work.

- It has been found that anchor dimensions must be larger than equipment letter z in order for the Kvitebjørn pipeline to get stuck between the anchor shank and fluke of a dragged ship anchor.
- The predicted maximum tow depth of an anchor arrangement is dependent of ship velocity. Analyses performed predict that anchor will sink down to roughly 1/3 of the chain length for large velocities. Considering anchor chain lengths it has been found that only very large anchors such as dimensions corresponding to equipment letter O and larger will pose a threat to pipelines situated at 300 m of water depth and larger.
- Kvitebjørn pipeline sections with largest ship traffic is located on 300 meters water depth and it has been found that only large ships, with anchor equipment larger than equipment letter O poses a real threat to the pipeline in these sections. Potential hooking velocities of the ships have been found to be low and in order of 5 – 8 knots in these section.
- The annual number of ships able to hook the pipeline has been found to be a very modest number compared to the total number of ships (237/7160). Due to the very low probability of an anchor drop during transit and even lower probability of dropping the anchor exactly in the area where the pipeline is located it is concluded with the fact that this is a very low probability event.
- Results from the global analysis indicate that the typical response due to anchor hooking is dominated by plastic bending and development of large membrane forces.
- Anchor hooking structural consequences have been found to be dependent of ship velocity, and pipeline response has been predicted to be larger for ships hooking at larger velocity than for lower velocity. It is conservative to use low hooking velocities in analyses.
- Structural consequences in terms of an anchor hooking incident have been found to be of a serious magnitude, and most likely reparations must be performed on the pipeline if anchor hooking were to occur.

8 Recommendations for further work

The methodology of analyzing historical ship data developed in this thesis may be utilized for other parts in the North Sea as well. Some areas will be more susceptible to anchor hooking than others and it is reasonable to assume that it would be of interest to the pipeline owners to know something about the risk of anchor hooking on pipelines in other areas as well.

With reference to the structural parts of the thesis some more work has to be performed to evaluate the structural consequences of anchor hooking. A local model must be developed in order to evaluate local buckling of the pipeline due to anchor hooking. The bending moments and axial forces predicted from the SIMLA analyses may be included in a local model in the computer code ABAQUS or LS DYNA.

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APPENDICES

APPENDIX A

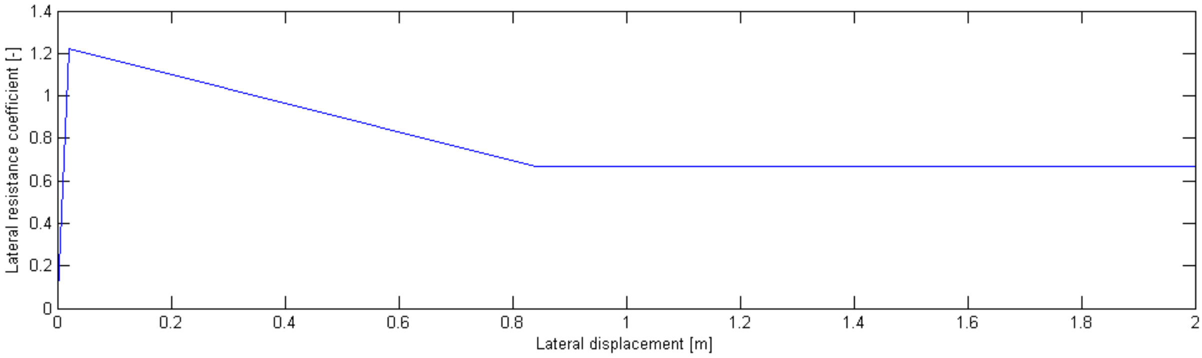

FIGURE 40 SOIL PARAMETERS FOR SIMLA ANALYSIS, LATERAL DISPLACEMENT

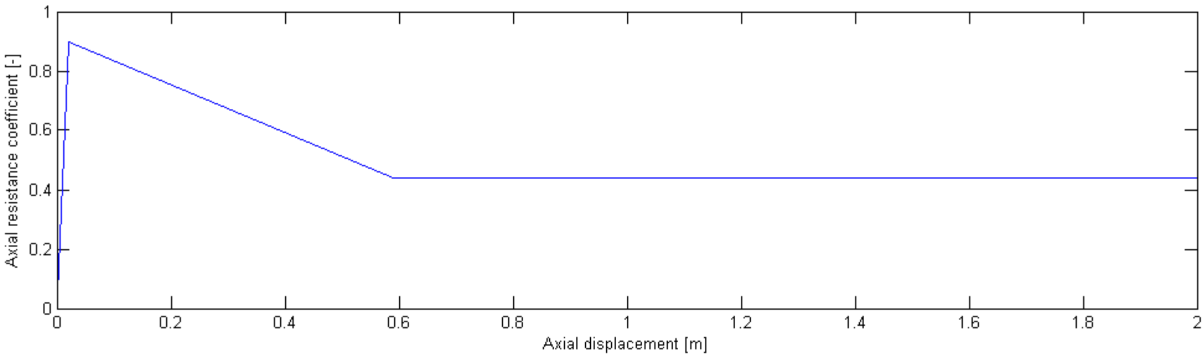

FIGURE 41 SOIL PARAMETERS FOR SIMLA ANALYSIS AXIAL DISPLACEMENT