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Anchor Loads on Pipelines

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MASTER THESIS

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Abstract:

Anchor hooking on a subsea pipeline has been investigated in this thesis. Anchor loads on pipelines is in general a rarely occurring event, however, the severity when it occurs could easily jeopardize the integrity of any pipeline. It is considered as an accidental load in the design of pipelines.

Pipeline Loads, limit state criteria and anchor categories are defined by the DNV standards. For pipeline, DNV-OS-F101 (08.2012), Submarine Pipeline Systems is adopted. Offshore standard DNV-RP-E301 Design and Installation of Fluke Anchors and DNV-OS-E301 Position Mooring are adopted for the anchor system analysis.

SIMLA models are established to check whether the pipelines can be hooked by anchors. A short rigid model is established first, which allows efficient parameter studies with respect to pipe diameter, span height, anchor size and chain length to find the circumstances where hooking can take place. Then "long" pipe models are investigated for selected cases to show the pipeline response curves.

Keyword:

Acidental load
Anchor hooking

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THESIS WORK DESCRIPTION

MASTER THESIS SPRING 2015
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Anchor loads on pipelines
Ankerlaster på rørledninger

Anchor loads on pipelines is in general a rarely occurring event, however, the severity when it occurs could easily jeopardize the integrity of any pipeline. It is considered as an accidental load in the design of pipelines. In the Norwegian Sea there are several locations where the subsea pipeline density is high, also in combination with high vessel density. The vessels usually know where pipelines are located and avoid anchoring, but anchors might be dropped in emergencies, lost in bad weather or due to technical failures. In these cases, the drop might not be noticed before the anchor hooks, e.g. in a pipeline.

The master course is to be based on the project work carried out in the fall semester 2014 which included the following activities:

1. Literature study on pipeline technology, relevant standards for pipeline design, with particular focus on impact loads. Aspects related to vessel size, frequencies and corresponding anchor equipment is to be included.
2. Study the theoretical background for and get familiarized with the computer program SIMLA
3. Define the basis for a case study considering anchor geometry, pipeline mechanical properties, soil interaction parameters, wire chain capacity, water depth and hydrodynamic coefficients
4. Establish a SIMLA model for the hooking event and perform simulations to demonstrate the performance of the model

From that basis, the study is extended to include:

1. Establish a short generic model that allow efficient parameter studies with respect to pipe diameter, span height, anchor size, water depth, chain length to find the circumstances where hooking can take place (the pipe might be short and rigid)

2. Then make “long” models for selected cases and establish the pipeline response curve until the anchor chain fails.
3. Conclusions and recommendations for further work

All necessary input data are assumed to be delivered by Statoil.

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)

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Deadline: Juni 10, 2015

Trondheim, Januar, 2015

Svein Sævik

Candidate – date and signature:

15, 01, 2015

PREFACE

This master thesis is performed as a part of my Nordic Master degree in Marine Technology, with specialization in Ocean Structures. The thesis accounts for 30 credits in the spring semester.

My supervisor of NTNU is Professor Svein Savik, I would like to thank him for the excellent guidance during my thesis work. Especially his guidance for the software Simla helps me a lot for modeling and code debugging. My supervisor of Aalto is Professor Romanoff Jani, I would like to thank him for the answers of my questions. I would also like to thank Naiquan Ye from MARINTEK for the installation of software and Eril Levold from Statoil for the model data.

The main objective of this thesis is to establish hooking models by Simla to perform the simulation. The main content includes the DNV standard to define loads, limit criteria and theoretical understanding of hooking scenarios. In addition, modelling process and results are presented.

CONTENT

NOMENCLATURE

P_{min}	Minimum internal pressure
α_{fab}	Fabrication factor
M_{Sd}	Design moment
S_{Sd}	Design effective axial force
P_e	External pressure
P_{min}	Minimum internal pressure
P_c	Characteristic collapse pressure
R_c	Characteristic resistance
$f_{c,}$	Characteristic material strength
t_c	Characteristic thickness
f_0	Out of roundness of the pipe, prior to loading
γ_m,γ_{SC}	partial resistance factors
$f_{y,temp}$	De-rating value due to the temperature of the yield stress
$f_{U,temp}$	De-rating values due to the tensile strength
α_U	Material strength factor
Δ	Moulded displacement
A	Projected area
p_i	Internal pressure
p_e	External pressure
D	Outside diameter of pipeline
T	Minimum wall thickness of pipeline
σ_{lh}	Hoop stress
σ_{lb}	Bending stress
σ_{lt}	Thermal stress
σ_{lc}	End cap force induced stress
F_D	Drag force
F_M	Inertial force
F_H	In-line force
F_L	Lift force
P	Density of seawater
U	Water particle velocity

a	Wave induced water particle acceleration
C_D	Drag coefficient
C_M	Inertial coefficient
C_L	Lift coefficient
KC	Keulegan–Carpenter number
T	Wave period
α	Current to wave ratio
k/D	Non-dimensional pipe roughness
M	Anchor mass
v_1	Initial velocity of anchor
v_1	Final velocity of anchor
l	Chain length
h	Water depth
a	A catenary parameter
T_x	Tension in the x-direction
W_c	Total chain weight + anchor weight
S	The 2nd Piola-Kirchoff stress tensor
T	Surface traction vector,
δu	Virtual compatible displacement field
δE	Corresponding virtual Green strain tensor
E	Modules of elasticity
σ	Stress
ε	Strain
M	Global mass matrix
C	Global damping matrix
R^I	Vector with internal forces
R^E	Vector with external forces

FIGURE LIST

TABLE LIST

1 INTRODUCTION

The main purpose of marine pipelines which are laid on the seabed is to transport liquids to land, including gas and oil. When the pipelines are installed in the regions where active marine activity and operations occur, there is risk that anchors of ships may be dropped in emergencies due to bad weather or technical failures, and the pipelines might be hit or hooked by the anchors. Although the probability for the occurrence of this kind of accident is regarded as less than 10^{-2} per year, it could easily jeopardize the pipeline and anchor systems once happened. This kind of accident will cause critical problems to the marine environment and normal operation once the pipeline is hooked by the anchors. Considering this situation and few studies on this subject up to now, this project which focuses on the anchor hooking loads on pipelines provides significant insight for avoiding this kind of accident and potential solutions.

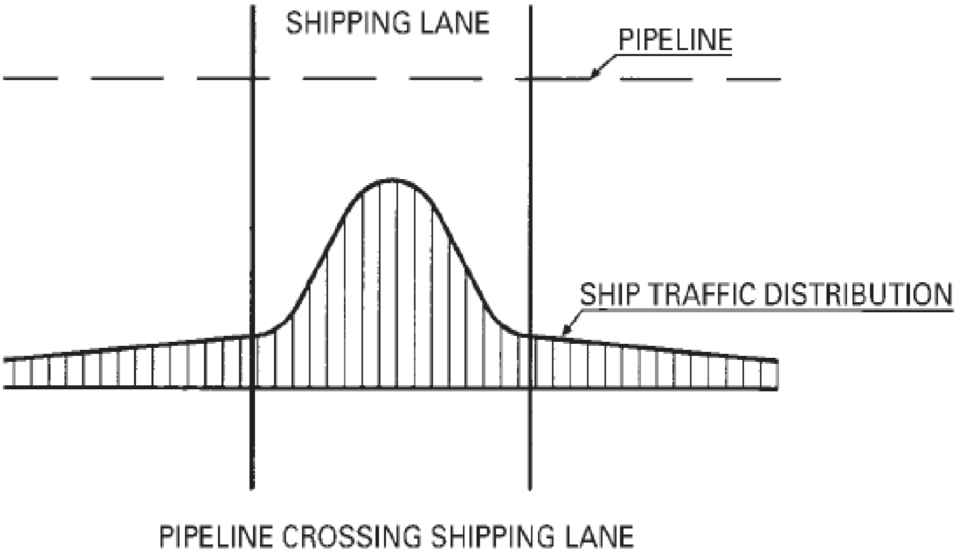


Figure 1 Traffic distribution at shipping lane (1)

With the increasing demand of gas and oil, the amount of subsea pipelines will increase, and it is inevitable to install some pipelines through the shipping lane as is shown in Figure 1. In the Norwegian Sea, there are several locations where the subsea pipeline density is high, also in combination with high vessel density. Though in deep waters, the anchors of commercial ships are not able to reach pipelines, offshore construction vessels which are always equipped with deep water anchors, will still have the risk of hooking the pipelines by the anchors in emergency or accidents. Thus, it is worthwhile to have this study to improve the safety of subsea pipelines and vessel anchors.

1.1 THESIS OUTLINE

- Chapter 2 illustrates the DNV standards which are adopted to analyze the hooking events.
- Chapter 3 illustrates a theoretical background of the pipe forces and mechanical behavior during the impact loading condition. As the pipeline lay in the subsea, the internal and external pressure as well as the environment loads should be considered, while the impact load acting on the pipelines is the most important factor to be considered in this hooking event.
- Chapter 4 presents the SIMLA software to analyze the effect of anchor loads on pipelines. Finite Element Method is also presented briefly.
- Chapter 5 presents the modeling data, including anchor geometry, pipeline parameters and material characteristic. The modeling process is also described in this chapter.
- Chapter 6 presents the SIMLA model results. Hooking and unhooking behaviors of short pipeline models are described to define the hooking scenarios. Then short model results and long model results are analyzed further.
- Chapter 7 presents some conclusions.
- Chapter 8 gives some recommendations for the further work.

2 DNV STANDARDS

In Norwegian Sea, most pipelines and anchor systems are designed by DNV standards. Thus these standards are referred to analyze the hooking events in this report. For pipeline, DNV-OS-F101 (08.2012), Submarine Pipeline Systems is adopted. Offshore standard DNV-RP-E301 Design and Installation of Fluke Anchors and DNV-OS-E301 Position Mooring are adopted for the anchor system analysis.

2.1 PIPELINE

2.1.1 Loads

In DNV-OS-F101 (08.2012), the loads acted on subsea pipelines are divided into function loads, environmental loads, construction loads, interference loads, and accidental loads.

- **Function loads** are defined as Loads arising from the physical existence of the pipeline system, including weights, external hydrostatic pressure, internal pressure, reaction from seabed.
- **Environmental loads** are defined as those loads on the pipeline system which are caused by the surrounding environment including wind loads, hydrodynamic loads, ice loads
- **Construction loads** are defined as a result of the construction and operation of the submarine pipeline system shall be classified into functional and environmental loads
- **Interference loads** are the loads which are imposed on the pipeline system from 3rd party activities shall be classified as interference loads. Typical interference load include trawl interference, anchoring, vessel impacts and dropped objects.
- **Accidental loads** are loads which are imposed on a pipeline system under abnormal and unplanned conditions and with a probability of occurrence less than 10^{-2} within a year including extreme wave and current loads, vessel impact or other drifting items— dropped objects, infrequent internal over pressure, seabed movement and/or mud slides, explosion, fire and heat flux, accidental water filling due to wet buckle, operational malfunction, dragging anchors.

From the above definitions, anchor hooking load is categorized as an accidental load, since the hooking event has often a frequency less than 10^{-2} per year.

2.1.2 Failure modes of pipelines

When the hooking event occurs, the impact loads will introduce large forces and moments on the pipe, which may cause the failures of pipelines. Thus, it is necessary to analyze the capability of the models with respect to the bending moment, internal and external pressure, and axial forces. Pipelines may fail due to different factors, thus there are different failure modes, including local buckling, fracture, fatigue, bursting. The following sections will focus on the failure modes that may be caused by anchor hooking.

2.1.2.1 Local buckling (2)

Local buckling implies gross deformation of the cross section. The following criteria shall be fulfilled:

— System collapse (external over pressure only)

— Propagation buckling (external over pressure only)

— combined loading criteria, i.e. interaction between external or internal pressure, axial force and bending moment.

2.1.2.1.1 System collapse (external over pressure only)

The external pressure at any point along the pipeline shall fulfil the following criterion:

$$P_e - P_{min} \leq \frac{P_e(t_1)}{\gamma_m \cdot \gamma_{SC}} \quad \text{2-1}$$

Where

P_{min} is the minimum internal pressure that can be sustained. This is normally taken as zero for as-laid pipeline.

2.1.2.1.2 Propagation buckling (external over pressure only)

Propagation buckling cannot be initiated unless local buckling has occurred. The propagating buckle criterion reads:

$$P_e - P_{min} \leq \frac{P_{pr}}{\gamma_m \cdot \gamma_{SC}} \quad \text{2-2}$$

Where

$\mathrm{P}_{pr} = 35 \cdot f_y \cdot \alpha_{fab}(\frac{t_2}{D})$

α_{fab} is the fabrication factor.

2.1.2.1.3 Local buckling - combined loading criteria

There are two conditions given in DNV rules

- Load Controlled condition (LC condition)

  A load-controlled condition is one in which the structural response is primarily governed by the imposed loads. It is characterized by that the applied load is independent on the deflection of the pipeline

- Displacement Controlled condition (DC condition).

  A displacement-controlled condition is one in which the structural response is primarily governed by imposed geometric displacements.

In the anchor hooking event, the load controlled condition is adopted, since the pipeline response is primarily governed by the impact and drag of anchor. .

In load controlled condition, pipe members subjected to bending moment, effective axial force and external overpressure shall be designed to satisfy the following criterion at all cross sections:

$$\left\{\gamma_m \cdot \gamma_{SC} \cdot \frac{|M_{Sd}|}{\alpha_c \cdot M_P(t_2)} + \left\{\frac{\gamma_m \cdot \gamma_{SC} \cdot S_{Sd}}{\alpha_c \cdot S_P(t_2)}\right\}^2\right\}^2 + \left(\gamma_m \cdot \gamma_{SC} \cdot \frac{P_e - P_{min}}{P_c(t_2)}\right)^2 \leq 1 \qquad \textit{2-3}$$

Where

M_{Sd} is the design moment

S_{Sd} is the design effective axial force

P_e is the external pressure

P_{min} is the minimum internal pressure that can be sustained.

P_c is the characteristic collapse pressure

2.1.3 Limit State Criteria

2.1.3.1 Limit states of pipeline design

In DNV rules, three limit states are illustrated, including ULS, FLS and ALS. Limit state design implies that the pipeline is checked for all relevant failure modes.

- ULS: Ultimate limit state
- FLS: Functional limit state
- ALS: Accident limit state

FLS and ALS are sub-categories of ULS accounting for accumulated cyclic load effects and accidental loads respectively.

2.1.3.2 Design format

In the rules section5 C100, it illustrates that design load effects, L_{Sd}, do not exceed design resistances, R_{Rd}, for any of the considered failure modes in any load scenario:

$$f\left(\left(\frac{L_{Sd}}{R_{Rd}}\right)_i\right) \le 1 \tag{2-4}$$

Where the fractions i denotes the different loading types that enters the limit state.

$$R_{Rd} = \frac{R_c(f_c, t_c, f_0)}{\gamma_m \cdot \gamma_{SC}} \tag{2-5}$$

Where

R_c is the characteristic resistance
$f_{c,}$ is the characteristic material strength
t_c is the characteristic thickness
f_0 is the out of roundness of the pipe, prior to loading
γ_m and $\gamma_{SC}$are the partial resistance factors, which are checked in the Table 1 and Table 2, the values are 1.15 and 1.26 for high safety level respectively.

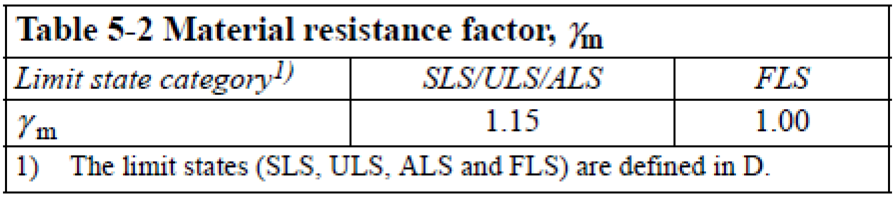


Table 5-2 Material resistance factor, γ_m

Limit state category[1)]	*SLS/ULS/ALS*	*FLS*
γ_m	1.15	1.00

1) The limit states (SLS, ULS, ALS and FLS) are defined in D.

Table 1 Material resistance factor DNV-OS-F101 (08.2012) (2)

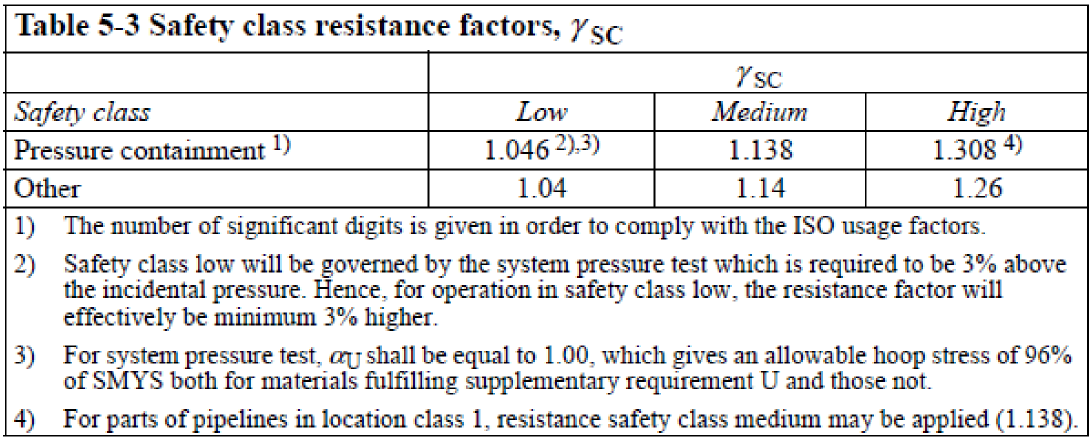


Table 5-3 Safety class resistance factors, γ_{SC}

	γ_{SC}		
Safety class	*Low*	*Medium*	*High*
Pressure containment [1]	1.046 [2),3)]	1.138	1.308 [4]
Other	1.04	1.14	1.26

1) The number of significant digits is given in order to comply with the ISO usage factors.

2) Safety class low will be governed by the system pressure test which is required to be 3% above the incidental pressure. Hence, for operation in safety class low, the resistance factor will effectively be minimum 3% higher.

3) For system pressure test, α_U shall be equal to 1.00, which gives an allowable hoop stress of 96% of SMYS both for materials fulfilling supplementary requirement U and those not.

4) For parts of pipelines in location class 1, resistance safety class medium may be applied (1.138).

Table 2 Safety class resistance factors DNV-OS-F101 (08.2012) (2)

The design load effect can be calculated in the following format:

$$L_{Sd} = L_F \cdot \gamma_F \cdot \gamma_C + L_E \cdot \gamma_E + L_1 \cdot \gamma_F \cdot \gamma_C + L_A \cdot \gamma_A \cdot \gamma_C \qquad 2\text{-}6$$

Load effect factors γ_A, γ_E, γ_E and γ_C are checked in the Table 3 and Table 4 respectively

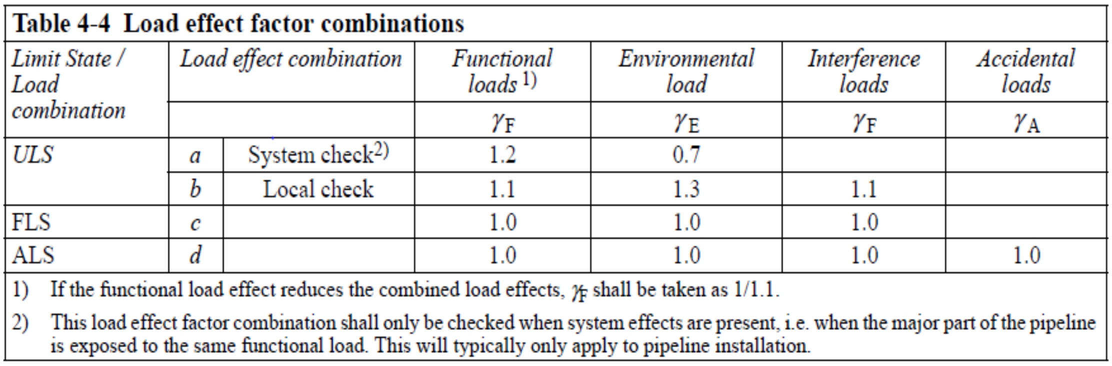


Table 4-4 Load effect factor combinations

Limit State / Load combination	*Load effect 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

1) If the functional load effect reduces the combined load effects, γ_F shall be taken as 1/1.1.

2) This load effect factor combination shall only be checked when system effects are present, i.e. when the major part of the pipeline is exposed to the same functional load. This will typically only apply to pipeline installation.

Table 3 Load effect factor combinations DNV-OS-F101 (08.2012) (2)

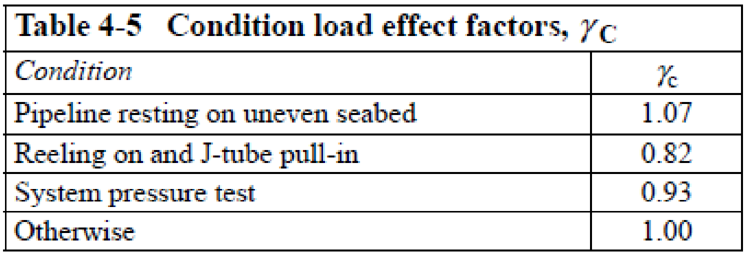


Table 4-5 Condition load effect factors, γ_C

Condition	γ_C
Pipeline resting on uneven seabed	1.07
Reeling on and J-tube pull-in	0.82
System pressure test	0.93
Otherwise	1.00

Table 4 Condition load effect factors DNV-OS-F101 (08.2012) (2)

2.1.3.3 Characteristic material properties

In the rules section5 C300, characteristic material properties shall be used in the resistance calculations. The yield stress and tensile strength in the limit state formulations shall be based on the engineering stress-strain curve. The characteristic material strength fy and fu, values to be used in the limit state criteria are:

$$f_y = (SMYS - f_{y,temp}) \cdot \alpha_U \tag{2-7}$$

$$f_u = (SMTS - f_{U,temp}) \cdot \alpha_U \tag{2-8}$$

Where

$f_{y,temp}$ and $f_{U,temp}$are the de-rating values due to the temperature of the yield stress and the tensile strength respectively.

α_U is the material strength factor.

2.1.3.4 Stress and strain calculations

Plastic strain shall be calculated from the point where the material stress-strain curve deviates from a linear relationship. The yield stress is defined as the stress at which the total strain is 0.5%, shown in Figure 2.

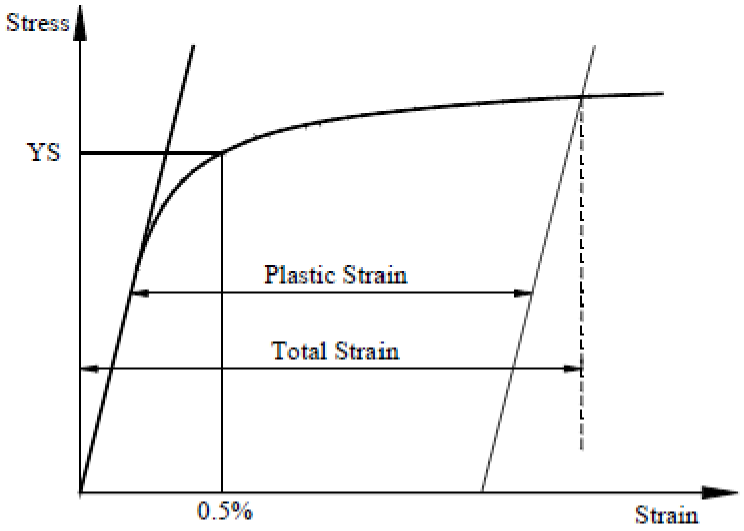


Figure 2 Reference for plastic strain calculation DNV-OS-F101 (08.2012) (2)

2.2 ANCHOR SYSTEM

2.2.1 Mooring Equipment

In DNV standards, vessel mooring equipment are assigned equipment letters that imply the requirements of dimensions, including anchor mass, chain length. Equipment for temporary mooring shall in general be selected in accordance with the requirements given in Table 5.

Equipment letter can be obtained by calculating the equipment number that is given by the formula:

$$EN = \Delta^{2/3} + A \tag{2-9}$$

Δ = Moulded displacement (t) in salt waters (density 1.025 t/m3) on maximum transit draught

A = projected area in m^2 of all the wind exposed surfaces above the unit's light transit draught, in an upright condition, taken as the projection of the unit in a plane normal to the wind direction. The most unfavorable orientation relative to the wind shall be used taking into account the arrangement of the mooring system.

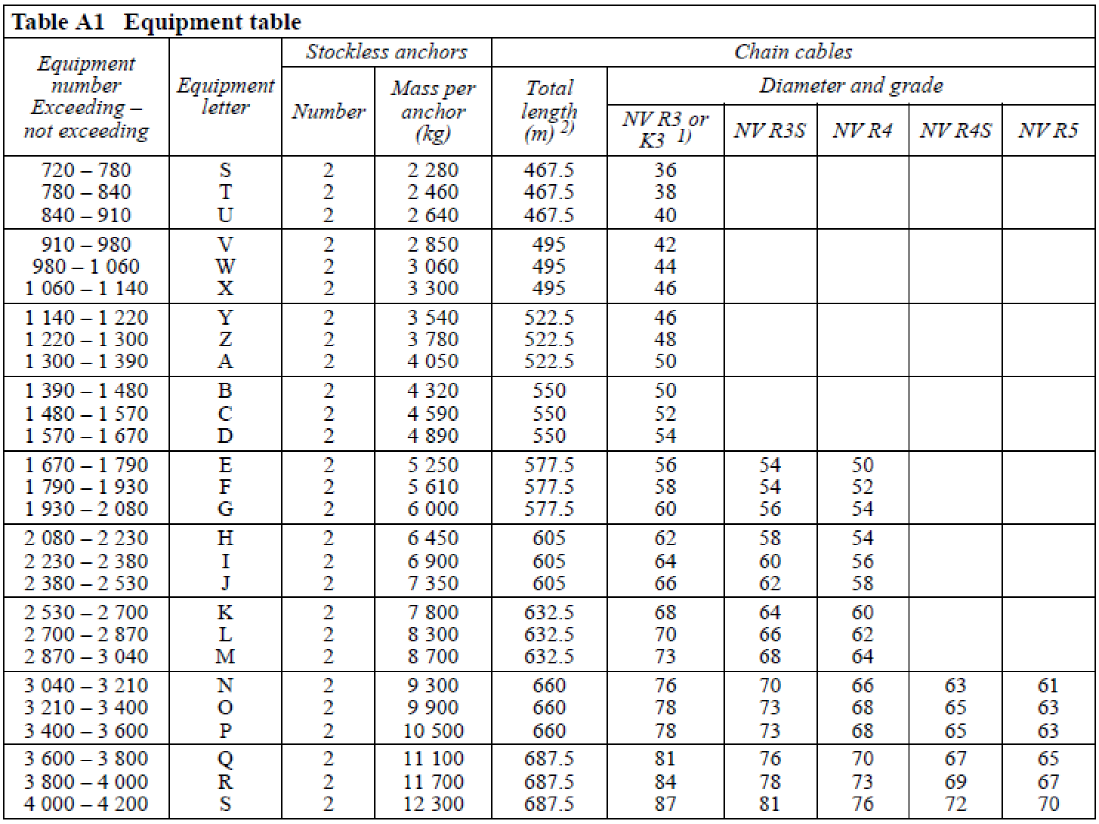


Table A1 Equipment table

Equipment number Exceeding – not exceeding	*Equipment letter*	*Stockless anchors*		*Chain cables*					
		Number	*Mass per anchor (kg)*	*Total length (m) 2)*	*Diameter and grade*				
					NV R3 or K3 1)	*NV R3S*	*NV R4*	*NV R4S*	*NV R5*
720 – 780	S	2	2 280	467.5	36				
780 – 840	T	2	2 460	467.5	38				
840 – 910	U	2	2 640	467.5	40				
910 – 980	V	2	2 850	495	42				
980 – 1 060	W	2	3 060	495	44				
1 060 – 1 140	X	2	3 300	495	46				
1 140 – 1 220	Y	2	3 540	522.5	46				
1 220 – 1 300	Z	2	3 780	522.5	48				
1 300 – 1 390	A	2	4 050	522.5	50				
1 390 – 1 480	B	2	4 320	550	50				
1 480 – 1 570	C	2	4 590	550	52				
1 570 – 1 670	D	2	4 890	550	54				
1 670 – 1 790	E	2	5 250	577.5	56	54	50		
1 790 – 1 930	F	2	5 610	577.5	58	54	52		
1 930 – 2 080	G	2	6 000	577.5	60	56	54		
2 080 – 2 230	H	2	6 450	605	62	58	54		
2 230 – 2 380	I	2	6 900	605	64	60	56		
2 380 – 2 530	J	2	7 350	605	66	62	58		
2 530 – 2 700	K	2	7 800	632.5	68	64	60		
2 700 – 2 870	L	2	8 300	632.5	70	66	62		
2 870 – 3 040	M	2	8 700	632.5	73	68	64		
3 040 – 3 210	N	2	9 300	660	76	70	66	63	61
3 210 – 3 400	O	2	9 900	660	78	73	68	65	63
3 400 – 3 600	P	2	10 500	660	78	73	68	65	63
3 600 – 3 800	Q	2	11 100	687.5	81	76	70	67	65
3 800 – 4 000	R	2	11 700	687.5	84	78	73	69	67
4 000 – 4 200	S	2	12 300	687.5	87	81	76	72	70

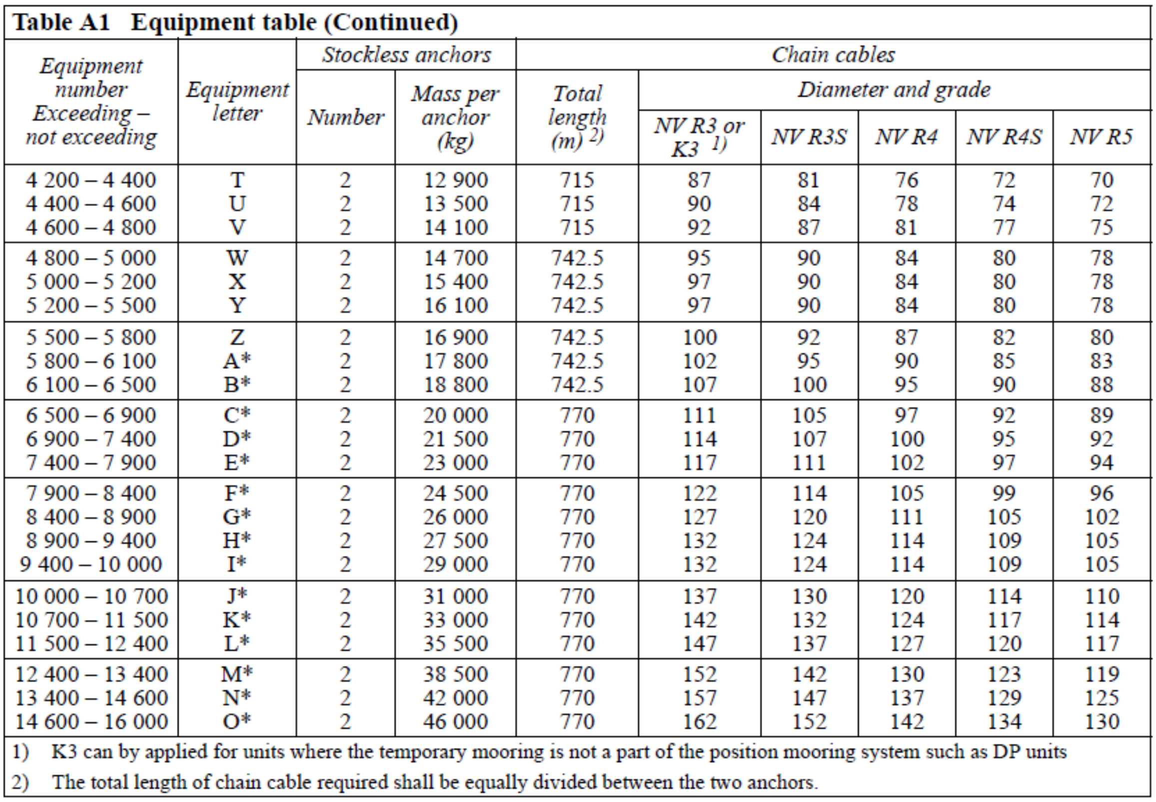


Table A1 Equipment table (Continued)

Equipment number Exceeding – not exceeding	*Equipment letter*	*Stockless anchors*		*Chain cables*					
					Diameter and grade				
		Number	*Mass per anchor (kg)*	*Total length (m)* 2)	*NV R3 or K3* 1)	*NV R3S*	*NV R4*	*NV R4S*	*NV R5*
4 200 – 4 400	T	2	12 900	715	87	81	76	72	70
4 400 – 4 600	U	2	13 500	715	90	84	78	74	72
4 600 – 4 800	V	2	14 100	715	92	87	81	77	75
4 800 – 5 000	W	2	14 700	742.5	95	90	84	80	78
5 000 – 5 200	X	2	15 400	742.5	97	90	84	80	78
5 200 – 5 500	Y	2	16 100	742.5	97	90	84	80	78
5 500 – 5 800	Z	2	16 900	742.5	100	92	87	82	80
5 800 – 6 100	A*	2	17 800	742.5	102	95	90	85	83
6 100 – 6 500	B*	2	18 800	742.5	107	100	95	90	88
6 500 – 6 900	C*	2	20 000	770	111	105	97	92	89
6 900 – 7 400	D*	2	21 500	770	114	107	100	95	92
7 400 – 7 900	E*	2	23 000	770	117	111	102	97	94
7 900 – 8 400	F*	2	24 500	770	122	114	105	99	96
8 400 – 8 900	G*	2	26 000	770	127	120	111	105	102
8 900 – 9 400	H*	2	27 500	770	132	124	114	109	105
9 400 – 10 000	I*	2	29 000	770	132	124	114	109	105
10 000 – 10 700	J*	2	31 000	770	137	130	120	114	110
10 700 – 11 500	K*	2	33 000	770	142	132	124	117	114
11 500 – 12 400	L*	2	35 500	770	147	137	127	120	117
12 400 – 13 400	M*	2	38 500	770	152	142	130	123	119
13 400 – 14 600	N*	2	42 000	770	157	147	137	129	125
14 600 – 16 000	O*	2	46 000	770	162	152	142	134	130

1) K3 can by applied for units where the temporary mooring is not a part of the position mooring system such as DP units

2) The total length of chain cable required shall be equally divided between the two anchors.

Table 5 Equipment table DNV-OS-E301 (3)

2.2.2 Limit State Criteria

2.2.2.1 Limit states of mooring system design

In DNV rules, the design criteria of mooring system are formulated in terms of three limit states ULA, ALS and FLS.

- ULA: An ultimate limit state to ensure that the individual mooring lines have adequate strength to withstand the load effects imposed by extreme environmental actions.
- ALS: An accidental limit state to ensure that the mooring system has adequate capacity to withstand the failure of one mooring line, failure of one thruster or one failure in the thrusters' control or power systems for unknown reasons. A single failure in the control or power systems may cause that several thrusters are not working.
- FLS: A fatigue limit state to ensure that the individual mooring lines have adequate capacity to withstand cyclic loading.

From the definitions above, hooking event should focus on ALS, since the interaction force between anchor and pipeline may cause failures of anchor chain. The limit state is formulated as a design equation in the form:

$$Design\ capacity - Design\ load\ effect \geq 0 \qquad \text{2-10}$$

If hooking event occurs, anchor chain is considered a failure when its tension exceed its strength.

3 LITERATURE STUDY

The objective of this section is to show a theoretical understanding of the pipe forces and mechanical behavior during the impact loading condition. As the pipelines lay in the subsea, the internal and external pressure as well as the environment loads should be considered, while the impact load acting on the pipelines is the most important factor to be considered in this hooking event.

3.1 PIPELINE STRESSES (4)

Pipelines are submerged in the sea, and gas or oil will flow in the pipe, thus the internal pressure and external pressure will be different. In addition, the geometry and temperature also have effects on pipelines. Considering this situation, hoop stress and longitudinal stress will be displayed first.

3.1.1 Hoop Stress

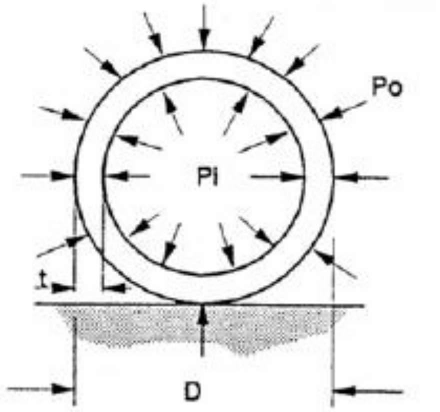


Figure 3 Pipe pressure (4)

The hoop stress is the stress exerted circumferentially (perpendicular both to the axis and to the radius of the object) in both directions on every particle in the cylinder wall, which should not exceed a certain fraction of the Specified Minimum Yield Stress (SMYS), depending on standard (4).

The hoop stress can be determined using the equation:

$$\sigma_h = (p_i - p_e)\frac{D-t}{2t} \qquad 3\text{-}1$$

Where:

p_i: Internal pressure

p_e: External pressure

D: Outside diameter of pipeline

t: Minimum wall thickness of pipeline

3.1.2 Longitudinal Stress

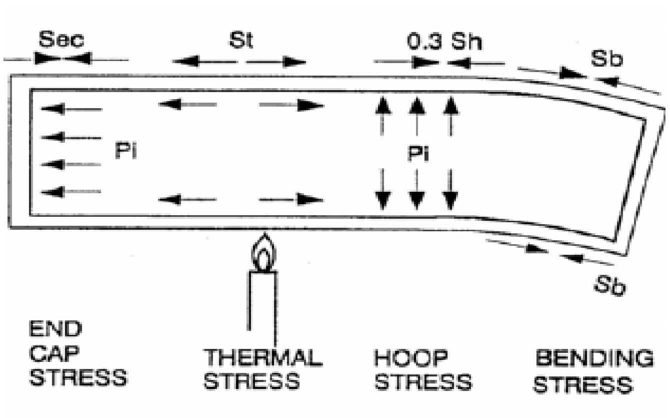


Figure 4 Longitudinal stress (4)

The longitudinal stress (σ_l) is the axial stress experienced by the pipe wall, and consists of stresses due to hoop stress, bending stress thermal stress and end cap force induced stress (4).

The longitudinal stress can be determined using the equation (4):

$$\sigma_l = 0.3\sigma_{lh} + \sigma_{lb} + \sigma_{lt} + \sigma_{lc} \tag{3-2}$$

Where:

σ_{lh}: Hoop stress

σ_{lb}: Bending stress

σ_{lt}: Thermal stress

σ_{lc}: End cap force induced stress

3.2 ENVIRONMENTAL LOADS

3.2.1 Hydrodynamic forces

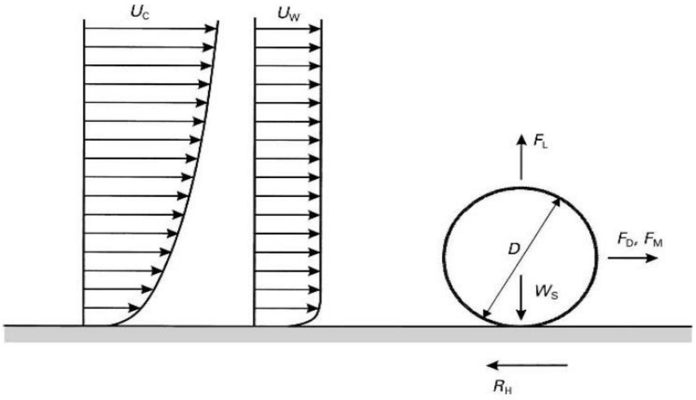


Figure 5 Forces on a submarine pipeline exposed to wave and current action (1)

Pipelines are submerged in the sea which may generate current and waves, thus hydrodynamic forces should be considered. In current, the components of hydrodynamic forces can be expressed by the drag force which is in the same direction of flow and the lift force which is perpendicular to the flow. In waves, expect drag and lift forces, there is also an inertial force which is composed of Froude-Krylov term and added mass term. Those forces can be determined by the below equations:

Morison equation: $$F_H = F_D + F_M = \frac{1}{2}\rho D C_D U|U| + \frac{\pi}{4}\rho D^2 C_M a \qquad \textit{3-3}$$

Lift: $$F_L = \frac{1}{2}\rho D C_L U^2 \qquad \textit{3-4}$$

Where

F_D	Drag force
F_M	Inertial force
F_H	In-line force
F_L	Lift force
P	Density of seawater
U	Water particle velocity, i.e. sum of wave and current induced velocity $\mathrm{Uw(t)} + \mathrm{Uc}$
a	Wave induced water particle acceleration
C_D	Drag coefficient
C_M	Inertial coefficient

C_L Lift coefficient

3.2.1.1 Hydrodynamic force coefficient

The force coefficients cannot be found using analytical methods only, model tests or complex numerical flow simulations are required, The coefficients depend on a number of parameters, for example, the relative pipe roughness (k/D), the relative amplitude of water motion (or the Keulegan–Carpenter number, KC), and the ratio between the steady current and the wave velocity.

The force coefficients are plotted as functions of (1):

KC Keulegan–Carpenter number ($U_w T/D$)
T Wave period
α Current to wave ratio ($U_c/(U_c + U_w)$)
k/D Non-dimensional pipe roughness

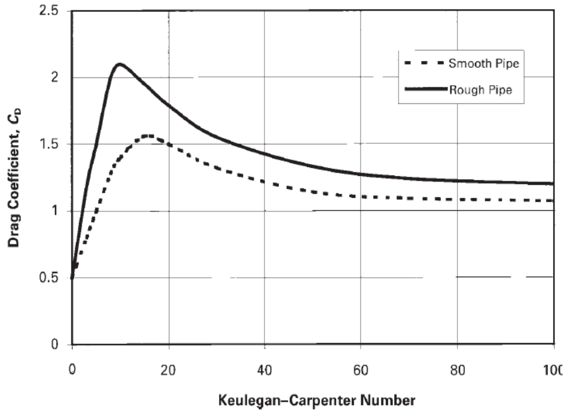


Figure 8 Drag coefficient against Keulegan–Carpenter number – pure wave flow (1)

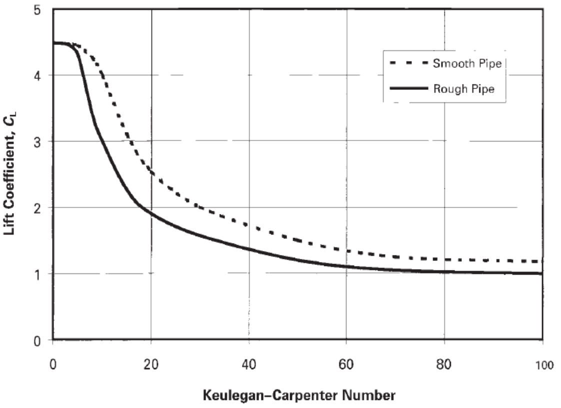


Figure 9 Lift coefficient against Keulegan–Carpenter number – pure wave flow (1)

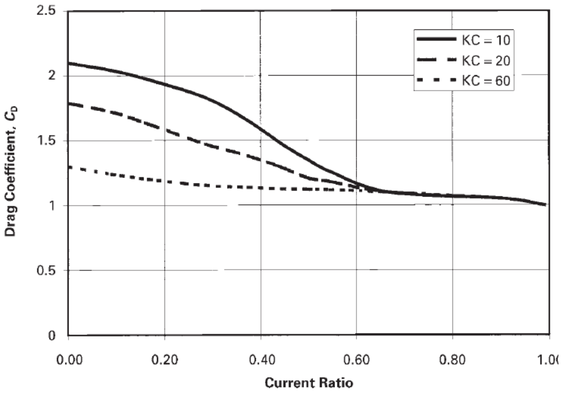


Figure 7 Drag coefficient against current ratio, combined wave and current flow. Values for rough pipe are presented (k/D ≈ 10^{-2}) (1)

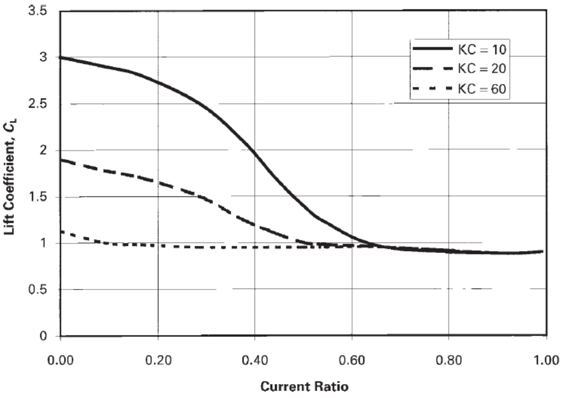


Figure 6 Lift coefficient against current ratio, combined wave and current flow. Values for rough pipe are presented (k/D ≈ 10^{-2}) (1)

3.3 ACCIDENTAL LOADS - IMPACT LOADS

In the DNV rules, the impact loads are considered as accidental loads, as they occur with the probability of less than 10^{-2} per year. When an anchor is dropped to the seabed, it may hit the pipeline directly or hook it with one forward velocity to move. In this project, this thesis will focus on the hooking events.

3.3.1 Anchor direct impact loading

Direct impact load on the pipe is represented by an impulse loading I (5), which is equal to integral of impact load F over the entire duration from time t1 to t2:

$$I = \int_{t_1}^{t_2} F\, dt = mv_2 - mv_1 \tag{3-5}$$

Where:

M: Anchor mass
v_1: Initial velocity of anchor
v_1: Final velocity of anchor

3.3.2 Anchor Hook Loading

When an anchor moves along the seabed and hits the pipeline, the anchor may hook the pipeline, then drag it along the seabed as the vessel moves in the sea surface which can transfer the velocity to the anchor. At the same time, the current and wave drift force will enforce this situation. A simplified case of tension load is considered where the applied transverse load is assumed to be in the upward vertical direction. The applied tension could be evaluated using the following procedure (6): Calculate the downstream excursion x_t in the longitudinal direction from the anchor chain with (5):

$$sinh\left(\frac{x_t}{2a}\right) = \frac{11}{2a}\sqrt{l^2 - h^2} \tag{3-6}$$

Where

l: Chain length
h: Water depth
a: A catenary parameter which is defined as $a = T_x / W_c$

T_x: Tension in the x-direction (= drag force on the vessel in the longitudinal direction)

W_c: Total chain weight + anchor weight

Knowing x_t, the applied tension may be evaluated with:

$$T = aW_c[l + (sinh(\frac{x-x_1}{a})^2)^{0.5}] \qquad 3\text{-}7$$

Where

$$x_1 = x_r - x_t$$

$$x_r = a\, tanh^{-1}\left(\frac{h}{L}\right) + (\frac{x_t}{2})$$

The anchor hook loading function applied on a pipeline as an example is shown in the Figure 10.

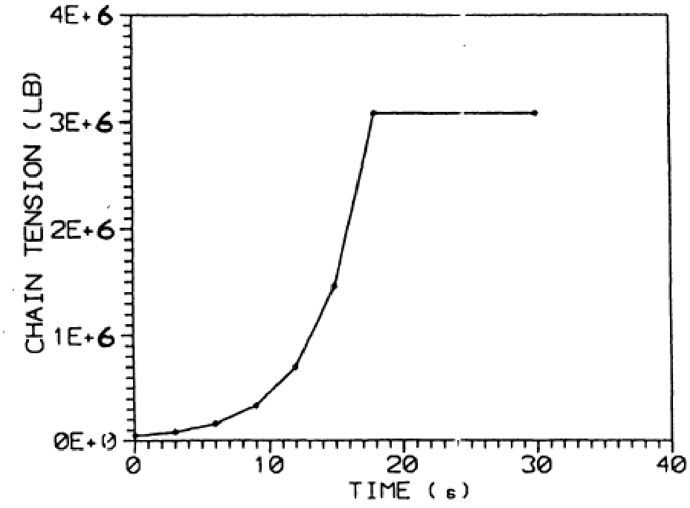


Figure 10 Anchor hook loading function applied to a pipeline (5)

4 SIMLA

This project uses Simla software to analyze the effect of anchor loads on pipelines. Simla is a nonlinear 3D FEM static and dynamic analysis tool, which can simulate the pipes efficiently.

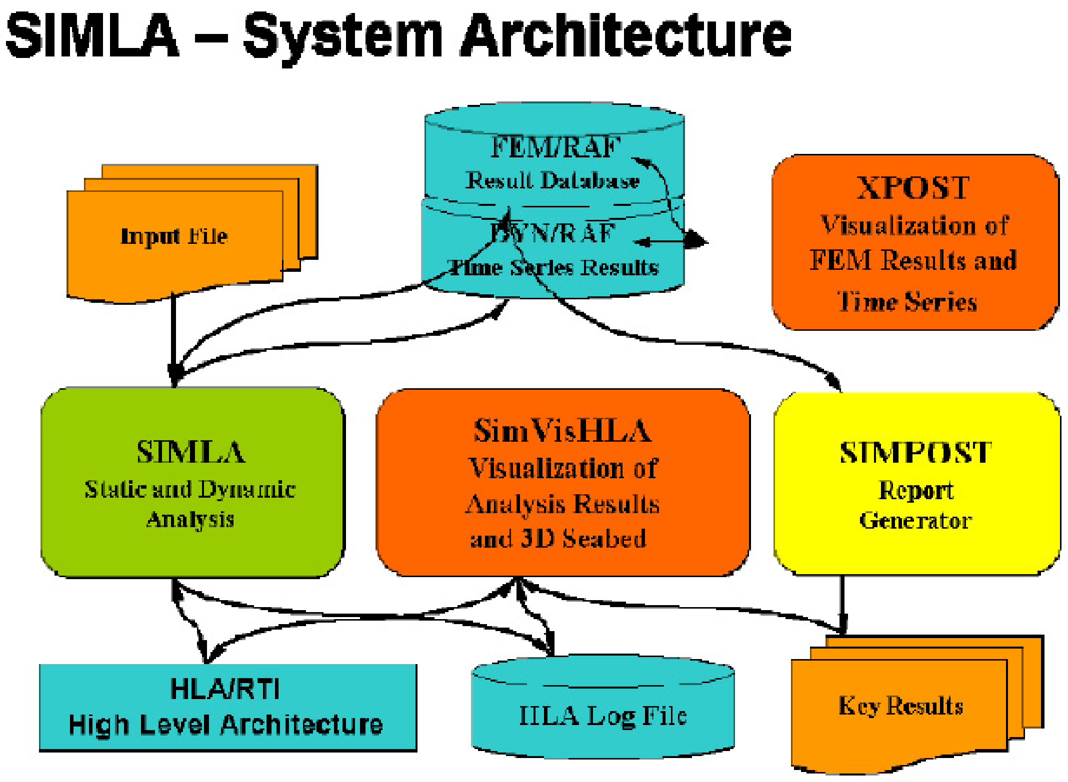


Figure 11 SIMLA-System Architecture (7)

Simla allows for both nonlinear static and dynamic analysis. In both cases the time domain is used to describe the load histories and the analysis sequence. The sequence of analysis is controlled by the TIMECO card, which defines a set of time intervals where different properties may apply with respect to step length, time interval for restart info and result storage, type of analysis in terms of static or dynamic and result exchange with other applications (the HLA concept). The program may be run in different ways as indicated in Figure 11. (7)

The input is provided for by an ASCII input file, which is text string based. Depending on the time sequence defined, results may be stored/exchanged in different ways. For the typical batch job the procedure the will be as follows (7):

1. Define input file with an analysis sequence. Typically static analysis is used in the first sequence and dynamic in the second sequence.

2. Define time interval for restart info storage to the .raf data base, see Figure 11. If a 3D visual model is required, the command VISRES must be activated. If not, only numerical data will be stored on the .raf file. The contour plot is obtained by using the post program which also enables to create animations which may be imported directly into PowerPoint.

3. For the steps at which restart info is stored, access to the binary .raf data base numbers is provided for by the SimPost program that enables fairly general user defined x-y plots which is stored on .mpf ascII-files. The plots can then be imported into the MatrixPlot program, for visualization and pasting into reports.

4.1 FINITE ELEMENT METHOD

Finite element method is widely used in structural analysis to solve complicated geometries and boundaries with relative ease. Simla uses this method to do the numerical simulations for models.

4.1.1 Basic principles (8)

In linear elastic structural analysis, three basic principles are followed:

- Equilibrium (in terms of stresses)
- Kinematic compatibility (expressed by strains obtained from continuous displacements)
- Stress-strain relationship

Nonlinearities can also be classified into three principles in structural behavior:

- Geometry (affect equilibrium and kinematic compatibility)
- Material (stress—strain relationship)
- Boundary condition

4.1.1.1 Equilibrium

The method of the Principle of Virtual Displacements is adopted to describe equilibrium in SIMLA. In the formulation of SIMLA the volume forces are neglected while initial stresses are accounted for (9). The Principle of Virtual Displacements expressed by tensors for the static case can then be written as (10)

$$\int_{V_0}(S - S_0) : \delta E dV - \int_{\partial V_0} t \cdot \delta u dS = 0 \qquad 4\text{-}1$$

Where

Subscript 0 refers to the initial state
S is the 2nd Piola-Kirchoff stress tensor.
t is the surface traction vector.
δu is a virtual compatible displacement field.
δE is the corresponding virtual Green strain tensor.

4.1.1.2 Kinematic compatibility

The kinematic compatibility states that material is continuous and the adjacent sections displacements are same when beam deforms. In SIMLA the pipe elements follow that principle. In SIMLA the Green strain definition is applied and the 2nd order longitudinal engineering strain term is neglected (11),

$$E_{xx} = u_{,x} - yv_{,xx} - zw_{,xx} + \frac{1}{2}\left(v_{,x}^2 + w_{,x}^2\right) + \theta_{,x}\left(yw_{,x} - zv_{,x}\right) + \frac{1}{2}\theta_{,x}^2(y^2 + z^2) \qquad 4\text{-}2$$

In 4-2 the neutral axis coincides with the x-axis. u, v and w are the axial, horizontal and vertical displacements respectively. θ is the torsional rotation of the neutral axis.

4.1.1.3 Stress-strain relationship

Linear material law shows the relation between stress and strain in the elastic condition by below equation:

$$\sigma = E \cdot \varepsilon \qquad 4\text{-}3$$

Where

E: Modules of elasticity
σ: Stress
ε: Strain

If a linear relationship between stress and strain exists, the material is said to be in the linear elasticity area. While, if the strain exceeds elastic limit, there will be a permanent strain in the material after unloading. In this case the pipe experiences two different strains; True strain that occurs at loading moment and the permanent strain that occurs after removing the load. Yield stress is defined by the interaction point between the strain-stress curve and the drawn line with the slope equaling E from the offset strain value point in strain axis. The relation between strain and stress can be checked by the figure 12. (12)

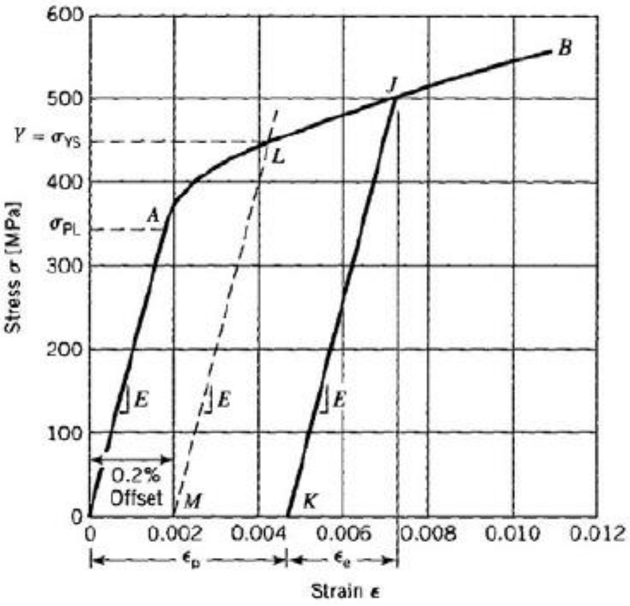


Figure 12 Strain-Stress relation for steel material (12)

Material characteristic strain-stress plot can be idealized as Figure 12 to display the main features of material, including yield condition, hardening rule and flow rule. (8)

- The yield criterion illustrates that yielding begins when $|\sigma|$ reaches σ_Y. The plastic deformation will alter the stress needed to produce continued yielding.

- A hardening rule, which contains isotropic hardening rule and kinematic hardening rule, describes the yield criterion and changes by the history of plastic flow. In Figure 13, Assume that unloading occurs from point B and progresses into a reversed loading. If the yielding is assumed to occur at $|\sigma| = \sigma_B$, it follows the isotropic rules. For common metals, yielding reappears at a stress of approximate magnitude $\sigma_B - 2\sigma_Y$ when loading is reversed. Accordingly, it follows the “kinematic hardening” rule, which says that a total elastic range of $2\sigma_Y$ is preserved.

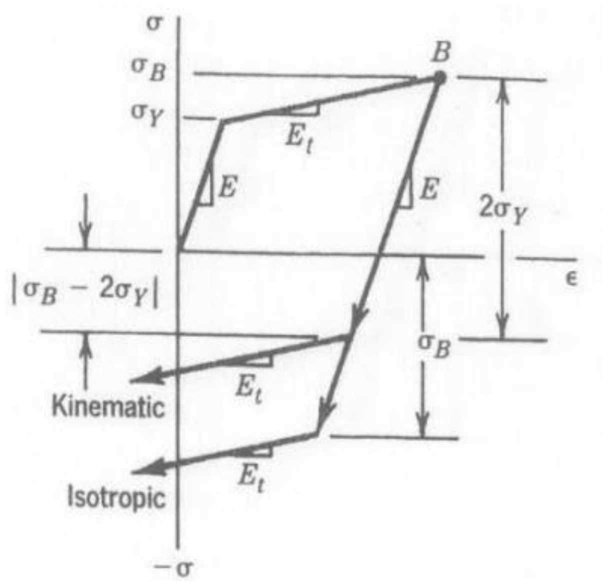


Figure 13 Kinematic and isotropic hardening rules (8)

- A flow rule leads to a relation between stress increments $d\sigma$ and strain increments $d\varepsilon$. In uniaxial stress this relation is $d\sigma = E_t\, d\varepsilon$, which describes the increment of stress produced by an increment of strain.

4.2 STATIC ANALYSIS

The static solution procedure is based on defined load control with Newton-Raphson equilibrium iteration at each load step. This is illustrated in Figure 14 below where the load increment $\Delta \mathrm{R}$ is given from Equlibrium state I given by load R^{I} to equilibrium state II given by load R^{II} . The load increment $\Delta \mathrm{R}$ results in a displacement increment $\Delta \mathrm{r}$ at iteration 0. The internal load vector and the stiffness matrix is updated and iterations are repeated until convergence has been obtained. The procedure can be written as (9):

$$\Delta r_{k+1}^{i} = K_{T,k+1}^{-1i} \Delta R_{k+1}^{i} \qquad \text{4-4}$$

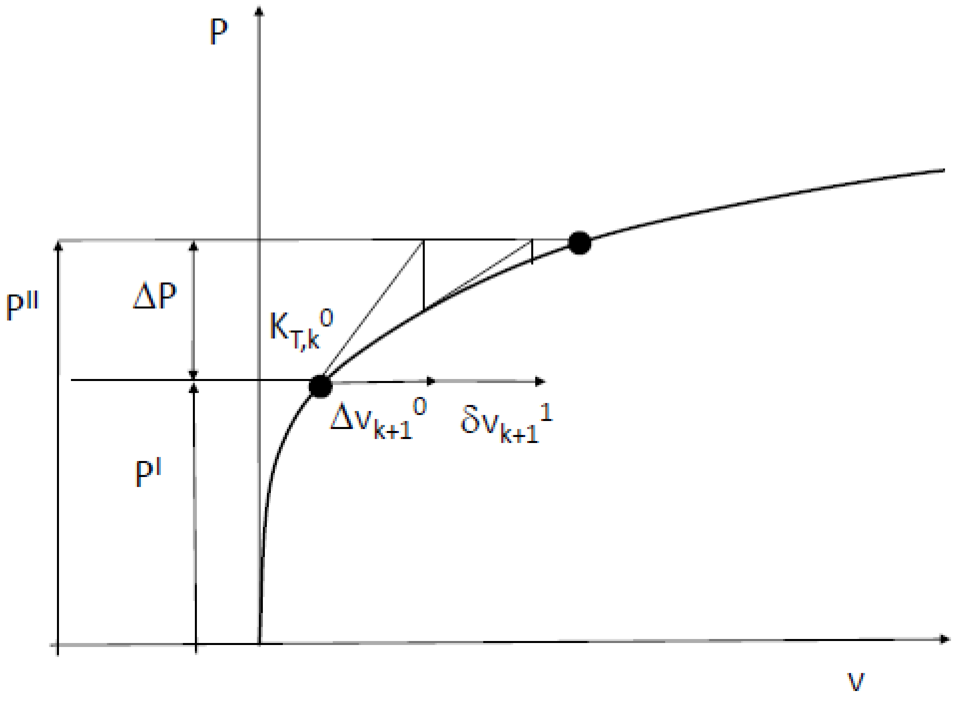


Figure 14 Illustration of Newton Raphson iteration (11)

4.3 DYNAMIC ANALYSIS

The general dynamic equilibrium is shown in below equation

$$M\ddot{r} + C\dot{r} + R^I = R^E \qquad 4\text{-}5$$

Where：

M is the global mass matrix
C is the global damping matrix
R^I is a vector with internal forces
R^E is a vector with external forces

Nonlinear dynamic solution can be performed using direct time integration either by an explicit method or an implicit method, as it cannot use modal superposition (11) In Simla, the implicit method is used.

4.3.1 Explicit Methods

Explicit methods can be expressed as equation 4-6. In this equation displacements at the next time step will be determined on the current and previous time steps. Explicit methods are conditionally stable, thus very small time steps should be used during calculations. If these methods are formulated in terms of lumped mass and lumped damping matrices it is not necessary to solve a coupled equation system in the time march (11). This results in very small computational efforts per time step. In analysis of impulse type response it is necessary to use small time steps in order to achieve sufficient accuracy. Thus explicit methods are typically used in explosion and impact analysis.

$$r_{k+1} = f\,(\ddot{r}_k, \dot{r}_k, r_k, r_{k-1}, \dots) \qquad 4\text{-}6$$

4.3.2 Implicit Methods

Implicit methods can be expressed as equation 4-7. Displacements in this equation are determined by quantities at the next and the current step. Since implicit methods use the next time step, they have better numerical stability than explicit methods. If the acceleration varies between time steps, the implicit methods will be different. For instance, if acceleration is constant average between time steps, the method will be unconditionally stable, which means that numerical stability is regardless of time step size. Therefore, this method is beneficial to long analysis durations. When using implicit methods, a coupled equation system should be solved at every time step, and they will become uneconomical if short time steps are unavoidable due to accuracy. In case of nonlinear systems the guarantee of unconditional stability does not hold, but in practical cases this is not considered to be an issue (11).

$$r_{k+1} = f(\ddot{r}_{k+1}; \ddot{r}_k; \dot{r}_{k+1}; \dot{r}_k; r_k; \dots) \qquad 4\text{-}7$$

In a dynamic analysis the response of high frequency modes are usually not of interest and are described with less accuracy than the lower modes. Therefore it is desirable to remove these modes and at the same time describe the lower modes with good accuracy. It can be shown that increasing the damping ratio or introducing Rayleigh damping in the well-known Newmark- β method will damp out mainly the medium modes, leaving lower and higher modes almost unaffected. Higher modes can however be damped out by numerical damping. In the Newmark- β method numerical damping can be introduced at the cost of reducing the accuracy from 2nd order to 1st order. The drawback of reduced accuracy can however be eliminated by applying the implicit HHT- α method proposed by Hilbert, Hughes and Taylor. The HHT- α method will damp out high frequency modes and at the same time retain 2nd order accuracy (11).

5 MODELING

In this section, input data and process of modelling by Simla software will be presented. First, a short rigid model is established, which allows efficient parameter studies with respect to pipe diameter, span height, anchor size and chain length to find the circumstances where hooking can take place. Then "long" pipe models are investigated for selected cases to show the pipeline response curves.

5.1 INPUT DATA

5.1.1 Anchor geometry

Anchor geometry is an important factor in analyzing hooking events, as only the anchors with parameters that are suitable to the pipelines can cause hooking. Spek anchor shown in Figure 15 is used in this case which is always equipped on the vessels in the North Sea. The dimensions of Spek anchor are shown in Table 6

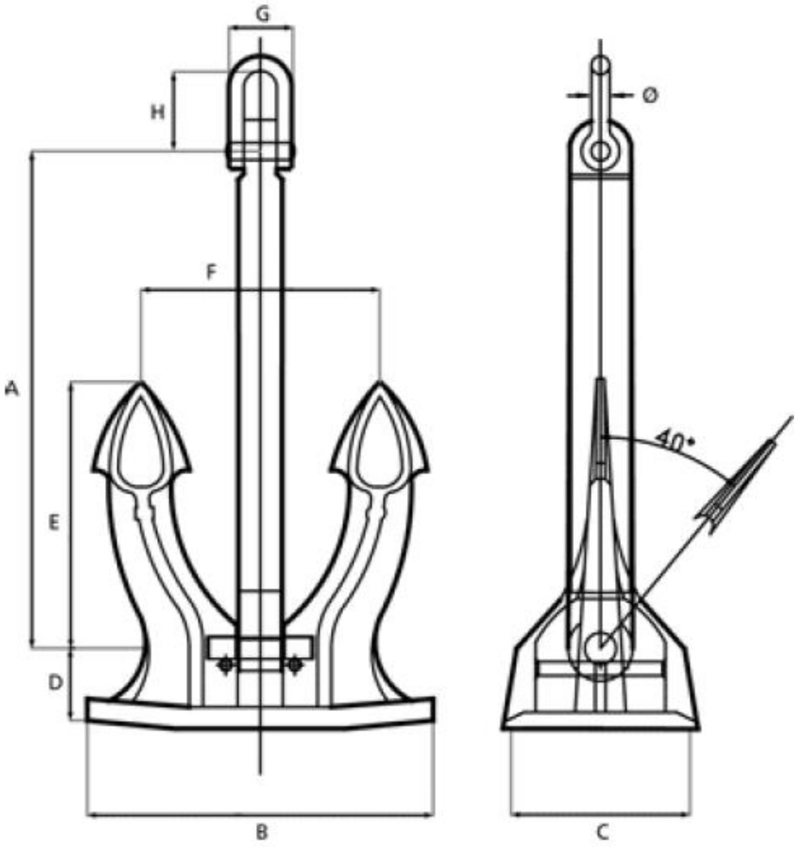
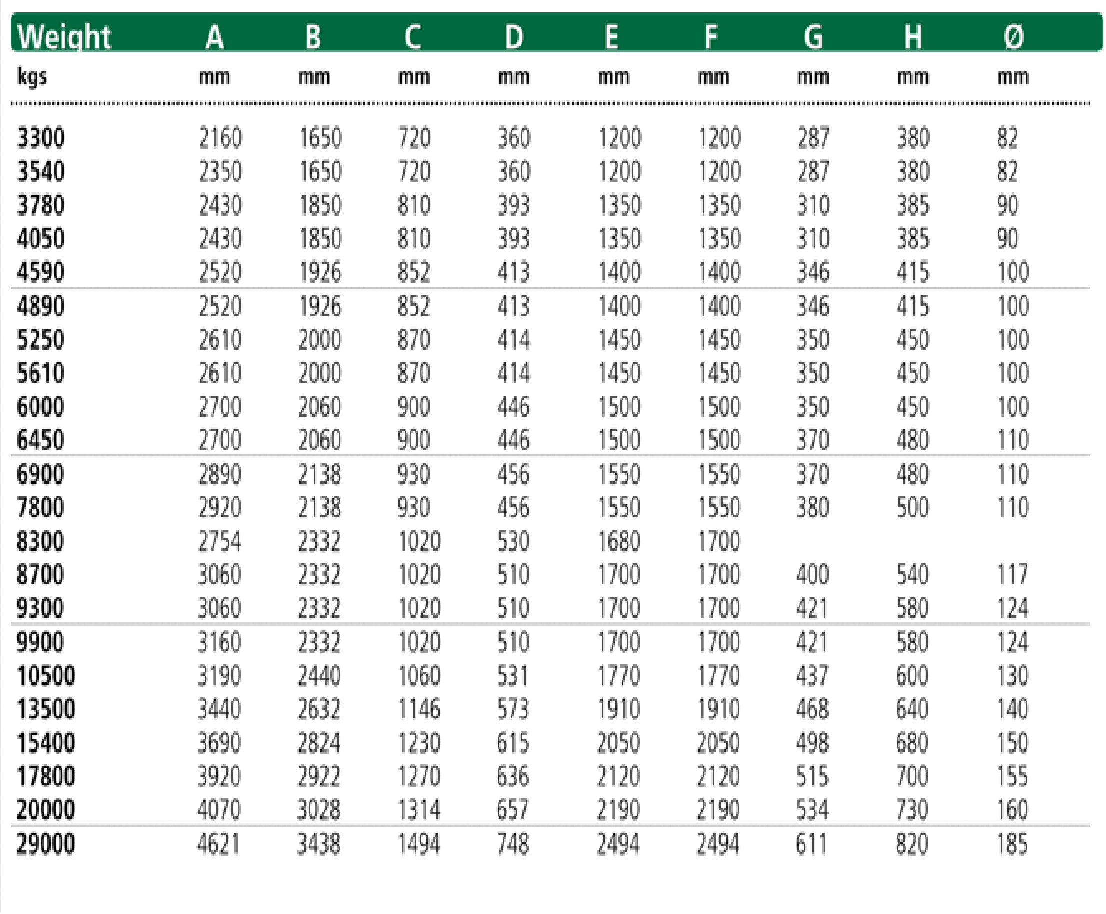


Figure 15 Geometry of spek anchor (13)



Weight kgs	A mm	B mm	C mm	D mm	E mm	F mm	G mm	H mm	Ø mm
3300	2160	1650	720	360	1200	1200	287	380	82
3540	2350	1650	720	360	1200	1200	287	380	82
3780	2430	1850	810	393	1350	1350	310	385	90
4050	2430	1850	810	393	1350	1350	310	385	90
4590	2520	1926	852	413	1400	1400	346	415	100
4890	2520	1926	852	413	1400	1400	346	415	100
5250	2610	2000	870	414	1450	1450	350	450	100
5610	2610	2000	870	414	1450	1450	350	450	100
6000	2700	2060	900	446	1500	1500	350	450	100
6450	2700	2060	900	446	1500	1500	370	480	110
6900	2890	2138	930	456	1550	1550	370	480	110
7800	2920	2138	930	456	1550	1550	380	500	110
8300	2754	2332	1020	530	1680	1700			
8700	3060	2332	1020	510	1700	1700	400	540	117
9300	3060	2332	1020	510	1700	1700	421	580	124
9900	3160	2332	1020	510	1700	1700	421	580	124
10500	3190	2440	1060	531	1770	1770	437	600	130
13500	3440	2632	1146	573	1910	1910	468	640	140
15400	3690	2824	1230	615	2050	2050	498	680	150
17800	3920	2922	1270	636	2120	2120	515	700	155
20000	4070	3028	1314	657	2190	2190	534	730	160
29000	4621	3438	1494	748	2494	2494	611	820	185

Table 6 Anchor dimensions (13)

5.1.2 Hooking frequency

Considering the multi dimensions of anchors, the anchors that have high frequencies to pass pipelines are used in analysis to narrow the scope of research. In addition, Spek anchor passing frequency has been summarized in Stian Vervik Master Thesis (14). The result is shown in Figure 16.

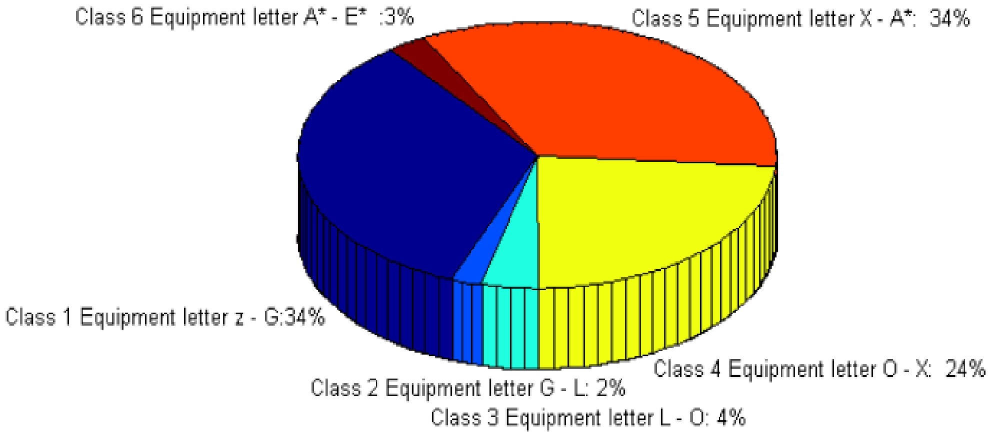


Figure 16 Distribution of total number of ships in each class pipeline in 1 year (14)

Anchors are divided into 6 classes by equipment letters defined by DNV rules. From Figure 16, it is obvious that class 1, 4, 5 occupy larger proportion. Thus, four anchor dimensions are selected from the three classes for the following research. The corresponding equipment letter can be found in Table 7.

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 7 Anchor classes

Combine Table 5 and Table 6, the selected anchor sizes and the associated chain parameters are presented in Table 8

Equipment letter	Chain length [m]	Chain diameter [mm]	Anchor mass [kg]	Chain strength [kn]
z	522.5	48	3780	1810
G	577.5	60	6000	2770
O	660	78	9900	4500
X	742.5	97	15400	6690

Table 8 Selected anchor parameters

5.1.3 Pipelines parameters

4 pipe diameters are selected to do the parameter study: 0.4 m, 0.6 m, 0.8 m, and 1.0 m. Other parameters of pipelines make some references to the master thesis Pipeline Accidental Load Analysis of Stian Vervik, which are shown in Table 9.

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	$11.7E^{-6}k^{-1}$
Content properties	
Content pressure	100 Bar
Content temperature	15 ℃
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	150KN/mm
Axial friction coefficient	0.44
Lateral friction coefficient	0.67

Table 9 Model properties

5.1.4 Material Mechanical Data of Pipelines

In order to survey the pipeline, it is recommended to consider a steel grade material that is used a lot in oil and gas industry. Thus X65 is chosen, its elastic plastic stress strain relationship for the material is presented in Figure 17.

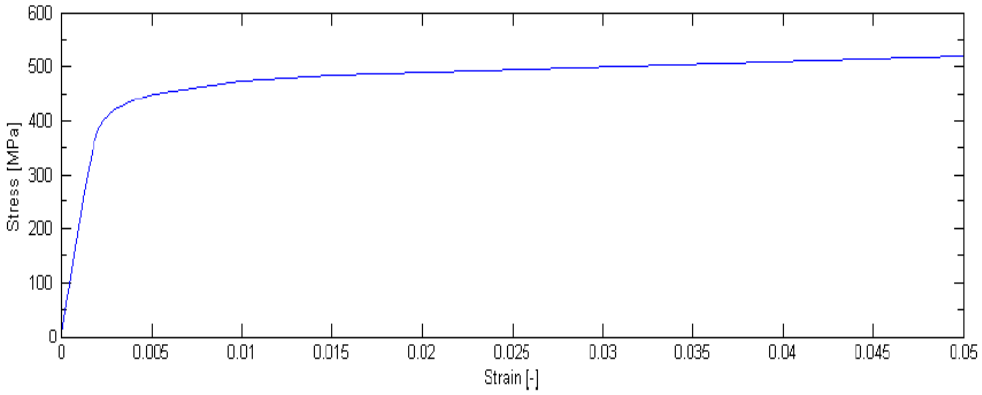


Figure 17 Material data X65 steel (14)

In short model, linear material was used at the first stage, since it is more efficient to run the Simla code and the exact result is not required in this stage. Then nonlinear material is used in long model to analyze the pipeline bending moments.

5.2 CASES DEFINITION

The pipeline response due to anchor hooking is dependent of parameters such as pipeline diameters, hooking angle, span height, vessel velocity and chain length. All the parameters are ranged to do the efficient parameter studies. Variables are shown in Table 10. Meanwhile, there are two scenarios in the efficient parameter study. Scenario 'a' means vessel moves with 12 knots velocity and anchor chain is modeled with full length. Scenario 'b' means vessel moves with 6knots velocity and anchor chain length is 300.

Variables	Number	Values			
Anchor mass [Kg]	_X000	① 3780	② 6000	③ 9900	④ 15400
Pipe diameter D [m]	_0X00	① 0.4	② 0.6	③ 0.8	④ 1.0
Hooking angle [°]	_00X0	① 90	② 100	③ 110	④ 120
Span height/D	_000X	① 0	② 1	③ 2	④ 3

Table 10 Model variables

Each case is assigned a number YXXXX that consists one letter and four digits, the letter presents the scenarios, a or b. The first digit presents anchor mass, the second digit presents pipe diameter D, the third one presents the hooking angle, the last one presents the ratio of Span height and pipe diameter. For instance, a1234 means the model is in scenario a, anchor mass is 3780 kg, pipe diameter is 0.6 m, hooking angle is 110° , ratio of span height and pipe diameter is 3.

5.3 MODEL PROCESS

In the process of establishing hooking events, five main parts are simulated, including pipeline, anchor, cable, seabed and roller. The model is shown in Figure 18.

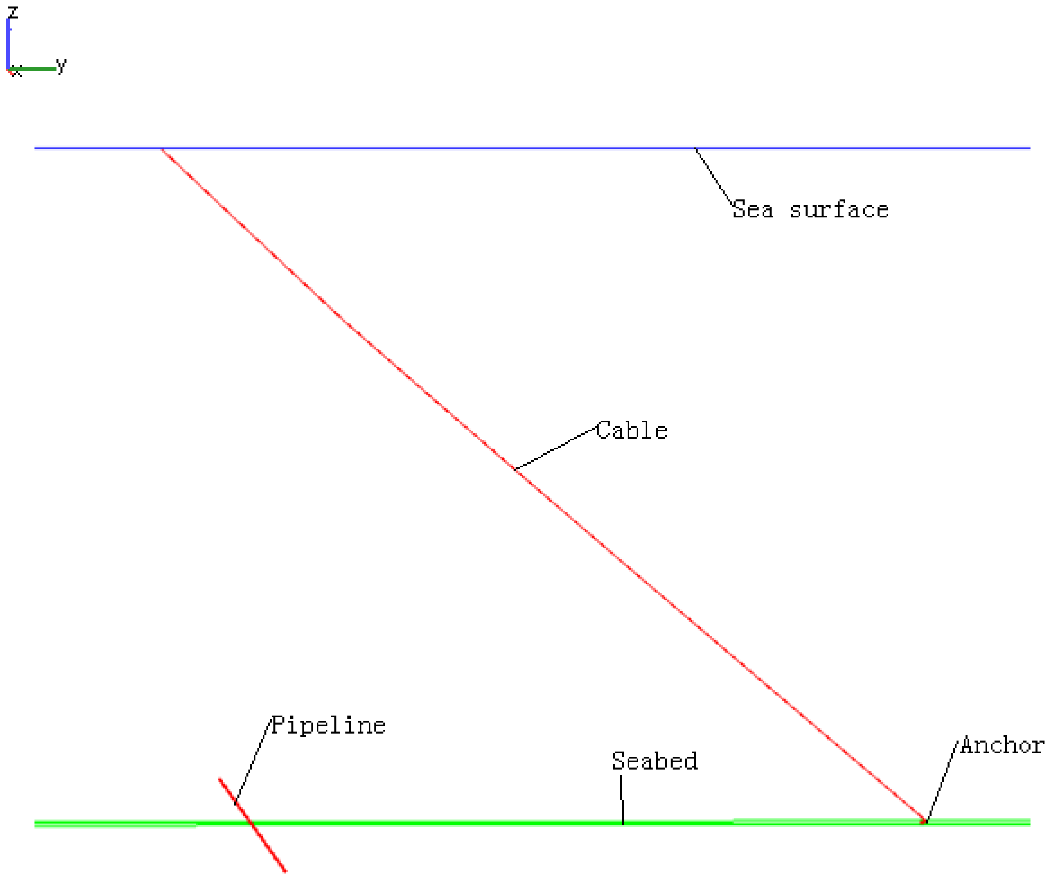


Figure 18 Simla model

5.3.1 Pipeline

In the first stage, the objective of simulation is to check whether the pipe can be hooked by anchor, thus the modelled pipeline that is located along x axis is short and rigid, only 10 meters long and it is assumed to be restrained against all degrees freedom at the end nodes. It consists one element and two nodes. The pipe is built in code PIPE31, which can simulate the 3D beam constant axial strain and torsion by linear material type.

In the second stage, the objective of simulation is to show the pipeline response curves, thus the 10.68 km pipeline section has been modeled which is 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 1 meter at the anchor impact section as shown in Table 11.

Sections	**x-coordinates**		**element length [m]**
1	-5240	-240	10
2	-240	-160	8
3	-160	-120	4
4	-120	-100	2
5	-100	300	1
6	300	320	2
7	20	360	4
8	360	440	8
9	40	5440	10

Table 11 Element lengths

5.3.2 Anchor

In order to model the different geometry, anchor part is divided into two groups and both groups are built in code PIPE31. Group 1 is the fluke part which contains 20 elements and 21 nodes. Group 2 is shank part which contains 10 elements and 11 nodes. The fluke geometry is modified by the NODPROP command, which allows the user to specify bellmouth or bend stiffener geometries, overruling the concept of constant geometry properties per group.

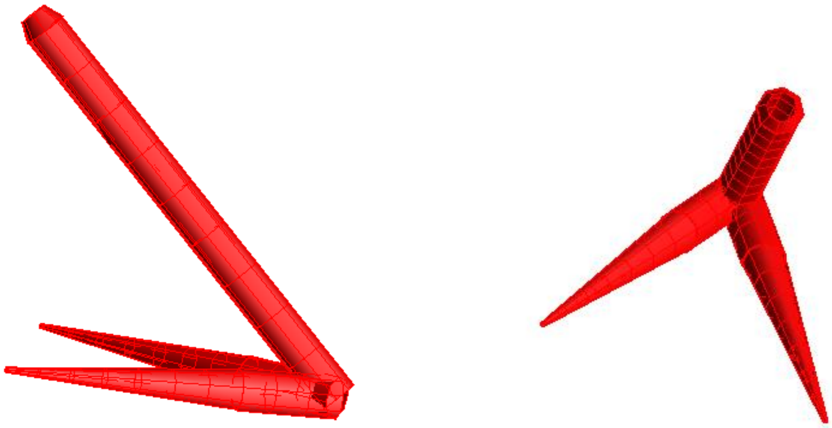


Figure 19 Anchor model

5.3.3 Cable

Cable model is also built in code PIPE31 and it consists of 200 elements and 201 nodes. The Node 50201 remains on the sea surface. Other nodes are assumed to be restrained against x direction motions. Since the end of cable will contact with the pipeline, the elements are refined at this part.

5.3.4 Seabed

Seabed is modeled as a simple flat surface, which contacts with pipe and anchor by code CONT126. The CONT126 code is 3D Seabed contact element which is for general pipe-soil interaction modelling on original seabed. The contact between the pipe and the seabed occurs when a pipe node penetrates the seabed.

5.3.5 Roller

In order to make the anchor hooking event occur, roller contact elements should be modelled along the pipeline model where is assumed to be hit by anchor.

In this case, three roller groups are modeled to connect the pipe with two anchor flukes and one shank separately. The contact code CONT164 is adopted, which is used for 3D stinger cable or roller contact element. One roller group contains 1 roller with the same diameter as the pipe.

During the hooking process, the cable of anchor is possible to touch the pipe, thus one roller is modelled for the cable.

6 RESULTS

6.1 "SHORT" PIPE MODEL SIMLA RESULT

When the analysis starts, the distance between the anchor and the pipe is 150 meters in y direction. First, the static simulation is applied, the static loads consist of weight, internal pressure, external pressure and temperature load. When the static mode computation is completed successfully, the dynamic analysis is applied and the anchor boundary conditions are released. The anchor moves to the pipe along seabed. There are two results, hooking or unhooking for short pipe model. The results are defined in the following sections.

6.1.1 Hooking behavior

The straight pipe case imposes restrictions on x direction movement for anchor and cable, while the diagonal pipe case releases this boundary condition when anchor approaches the pipeline, thus hooking cases are defined in two behaviors.

6.1.1.1 Straight pipe case (90 ° hooking angle)

When anchor hits the pipe which is straight along the x direction without any rotation angle, the anchor is stuck by the pipe, this behavior is defined as hooking case. Case a2112 is shown in Figure 20 and Figure 21 as an example. When hooking occurs, the force of the cable element which is connected to the anchor will increase dramatically at the hooking time, shown in Figure 22.

Case a2112	
Anchor mass	6000 kg
Pipe diameter	0.4 m
Hooking angle	90
Span height/Pipe diameter	1

Table 12 Case a2112 input data

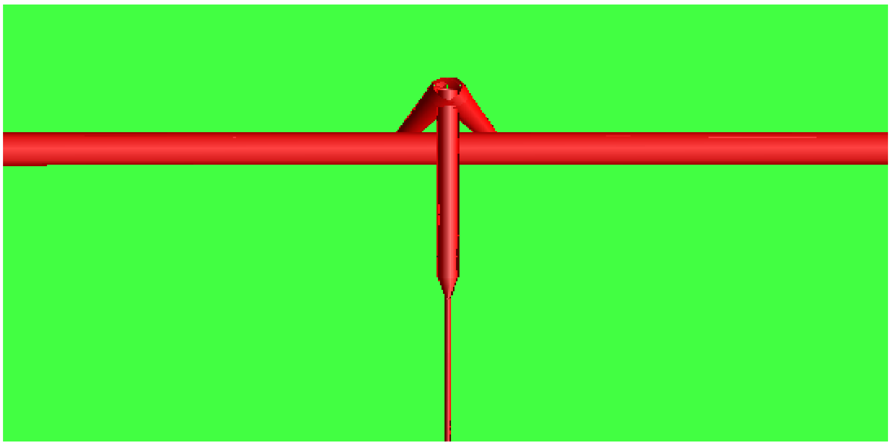
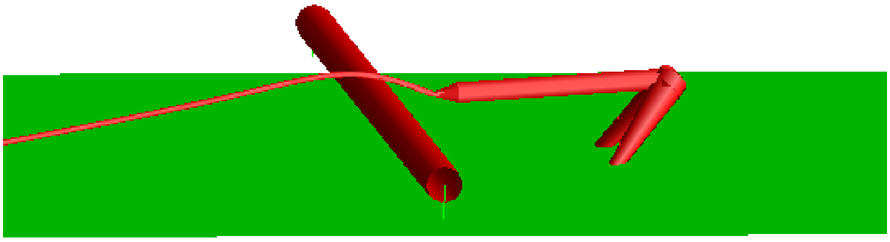
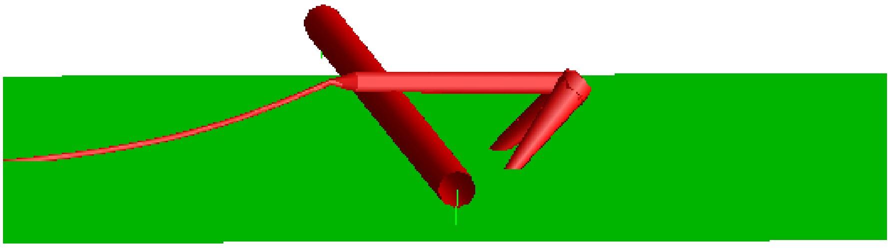


Figure 20 Case a2112 vertical view

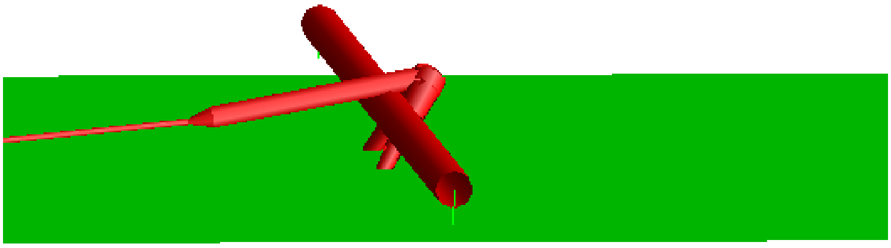


(a) t = 33.4s

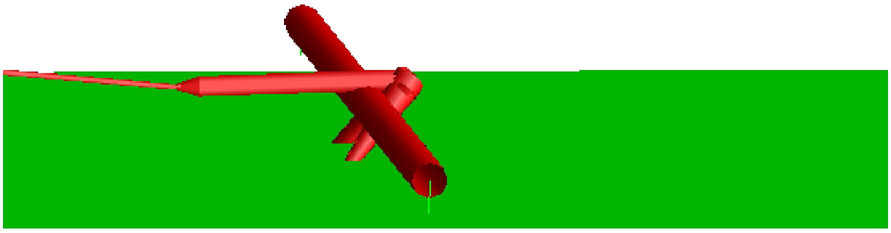


(b) t = 33.6s

(c) t = 33.8s



(d) t = 34.0s



(e) t = 34.5s

Figure 21 Case a2112 Hooking model

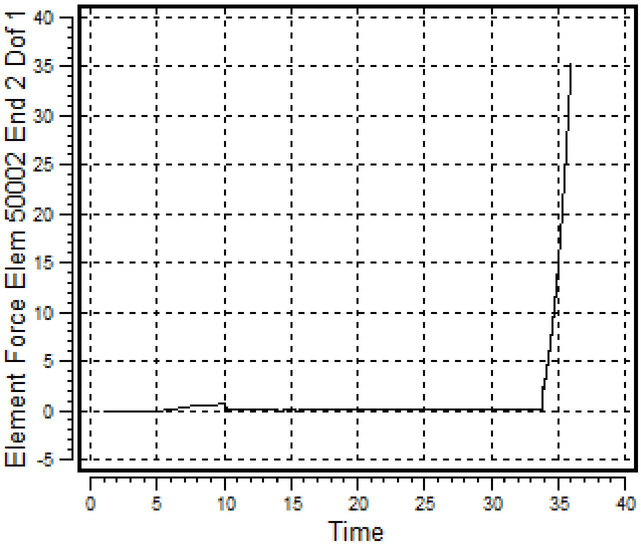


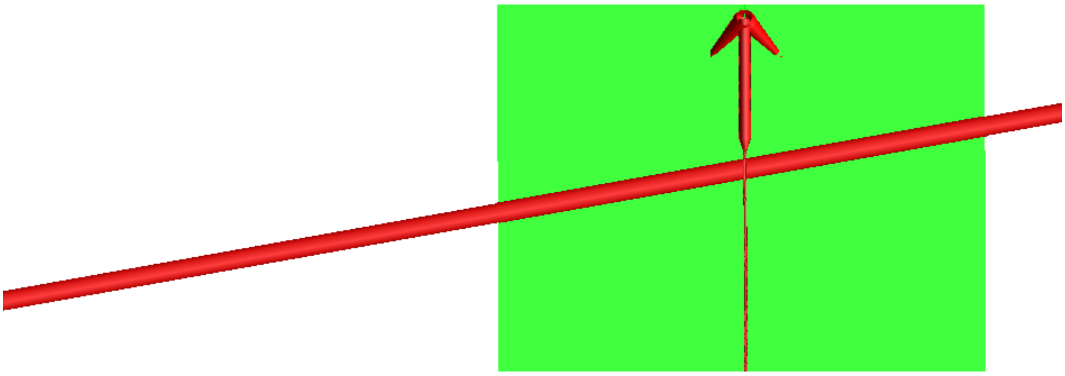
Figure 22 Case a2112 Element force of cable end

6.1.1.2 Diagonal pipe case (hooking angle > 90°)

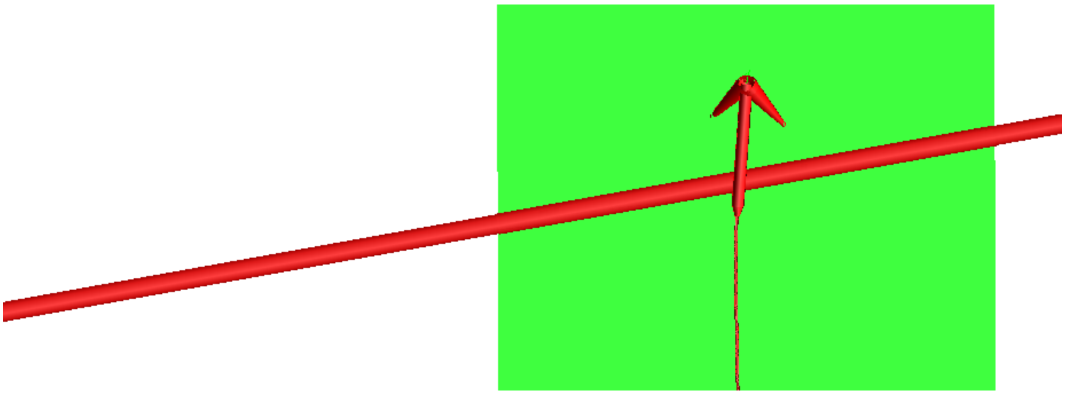
Since all boundary conditions of anchor and cable are released before the anchor hooks the pipe, anchor will slide along the pipeline when hooking case occurs, the hooking process of case a 2122 is shown in Figure 23 as an example. The force of the cable end will increase significantly at the hooking time, shown in Figure 24.

Case a2122	
Anchor mass	6000 kg
Pipe diameter	0.4 m
Hooking angle	100
Span height/Pipe diameter	1

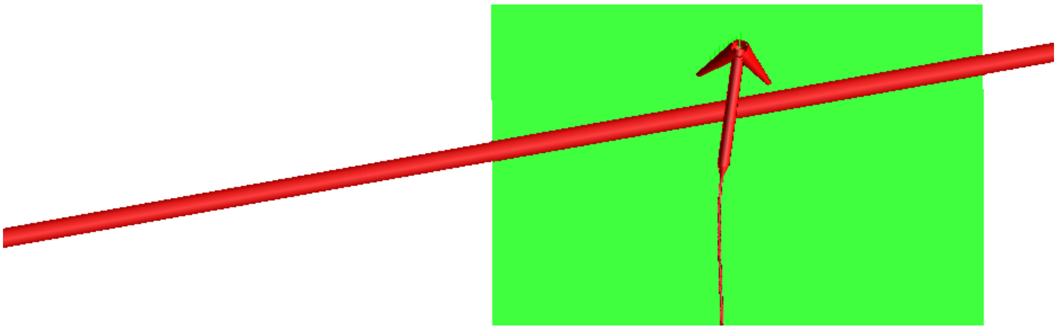
Table 13 Case a2122 input data



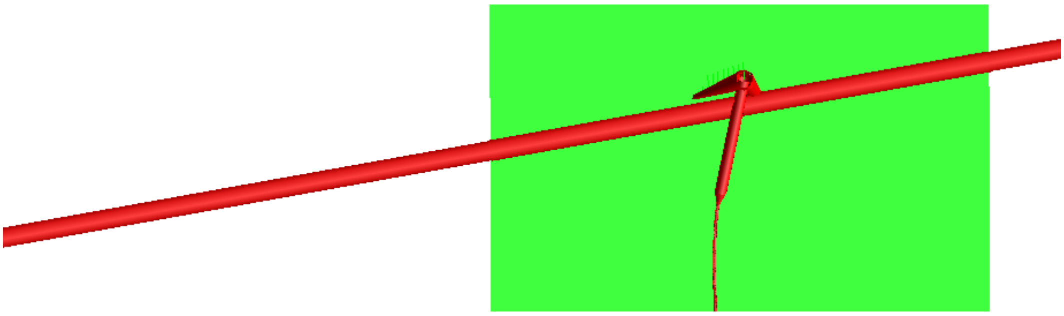
(a) t = 33.3 s



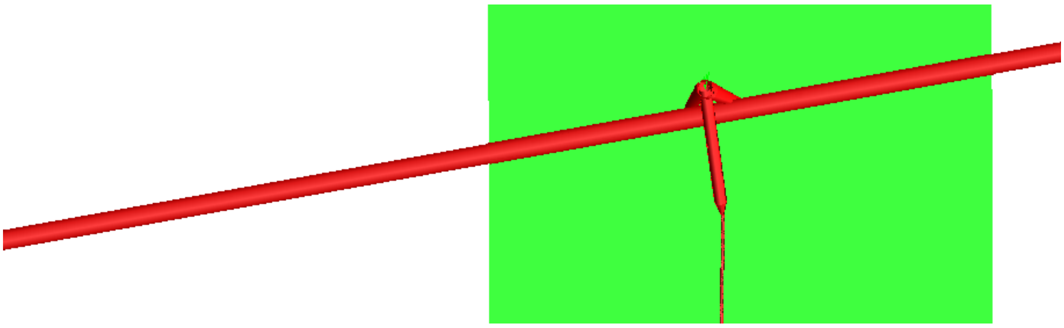
(b) t = 33.5 s



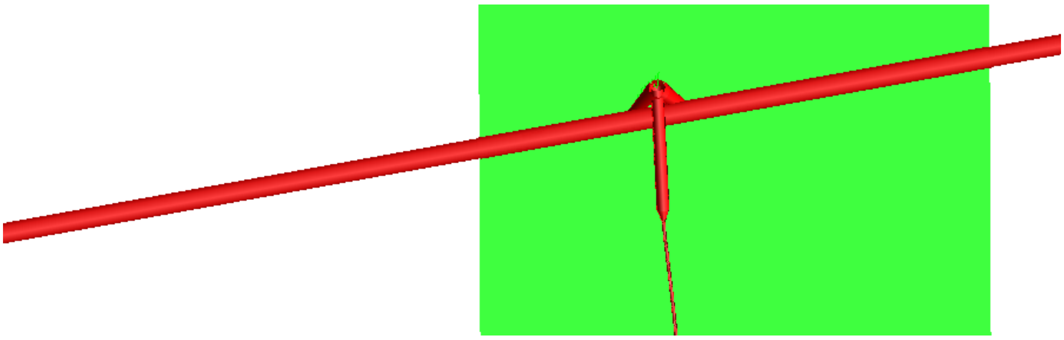
(c) t = 33.6 s



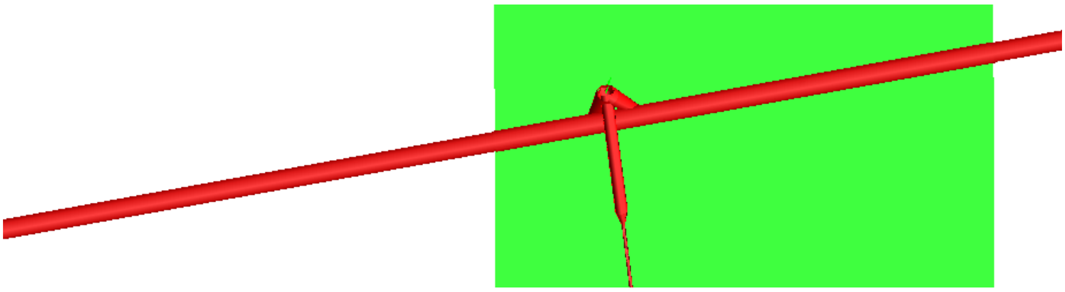
(d) t = 33.7 s



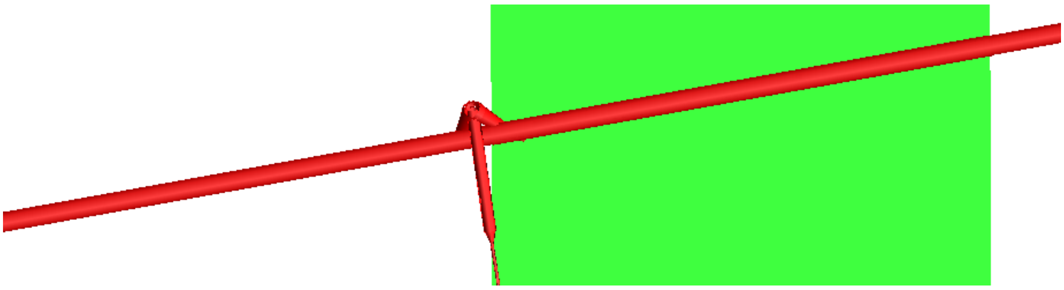
(e) t = 33.8 s



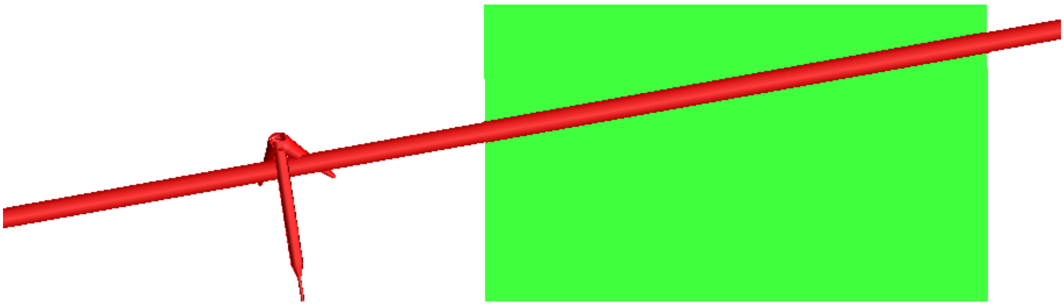
(f) t = 33.9 s



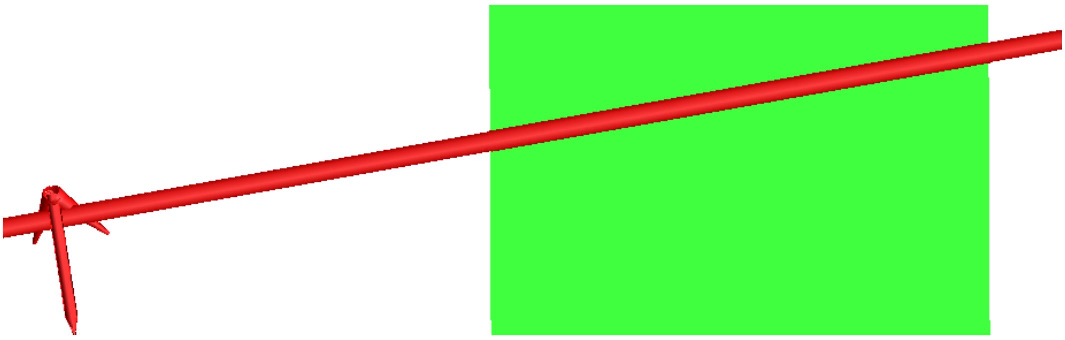
(g) t = 34.0 s



(h) t = 34.2 s



(i) t = 34.5 s



(j) t = 35.0 s

Figure 23 Case a2122 Hooking model

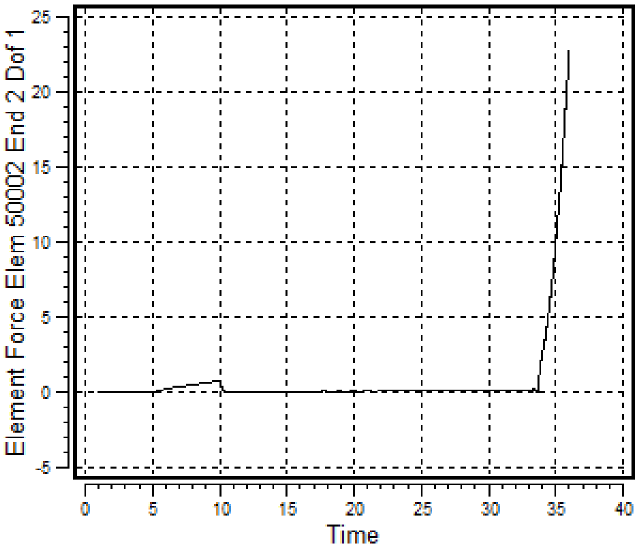


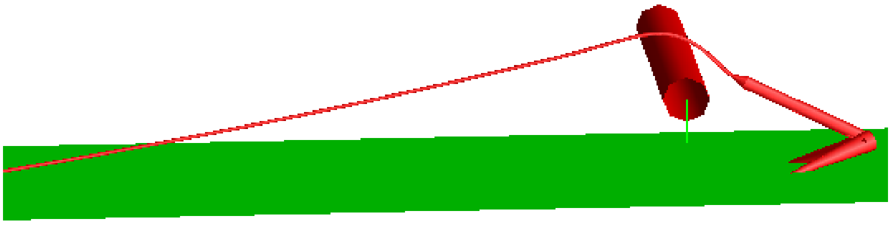
Figure 24 Case a2122 Element force of cable end

6.1.2 Unhooking behavior

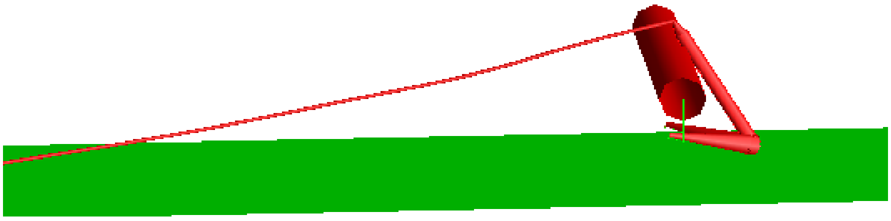
When anchor hits pipe and bounces off the pipe, the case is defined as unhooking case. Case a2313 is shown in Figure 25 as an example. The element force of cable end shows fluctuations within a narrow range, see Figure 26.

Case a2313	
Anchor mass	6000 kg
Pipe diameter	0.8 m
Hooking angle	90
Span height/Pipe diameter	2

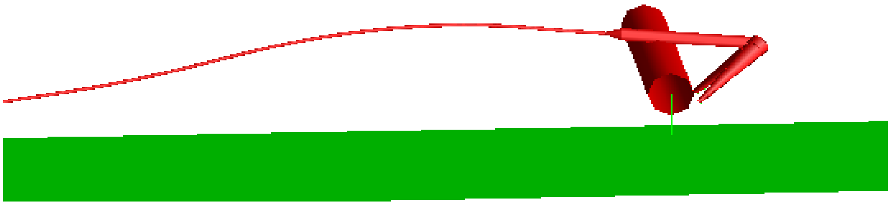
Table 14 Case a2313 input data



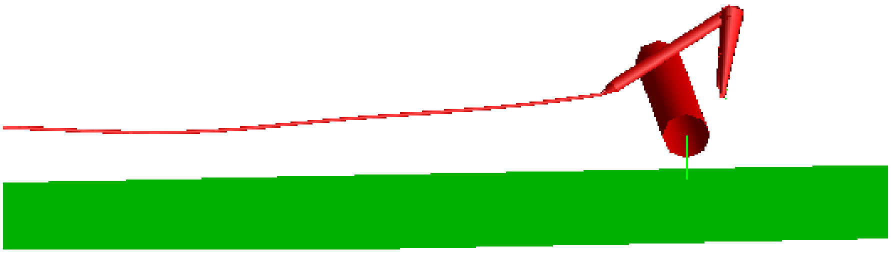
(a) t = 33.3 s



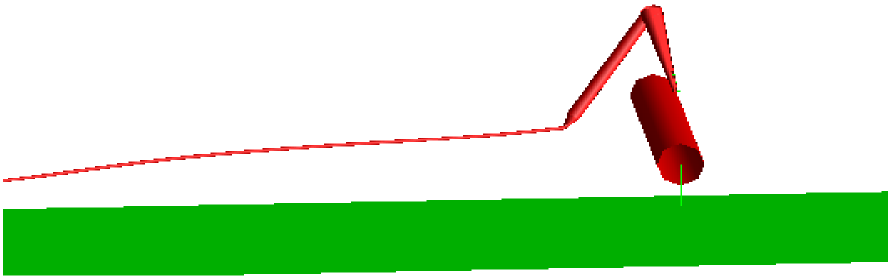
(b) t = 33.5 s



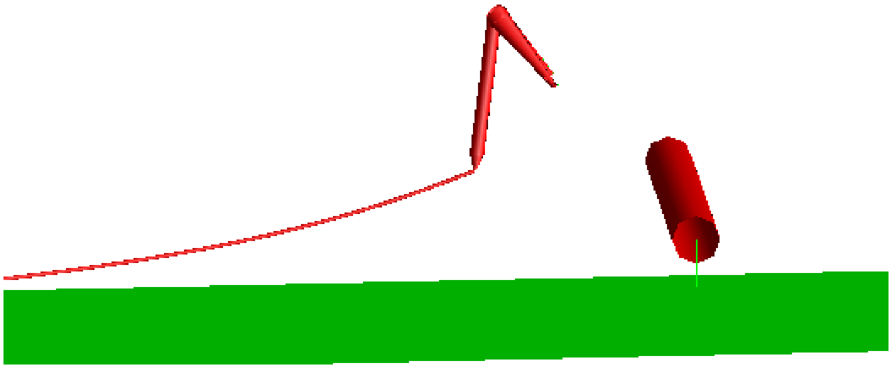
(c) t = 33.7 s



(d) t = 33.8 s



(e) t = 33.9 s



(f) t = 34.2 s

(k) t = 35.0 s

Figure 25 Case a2313 Unhooking model

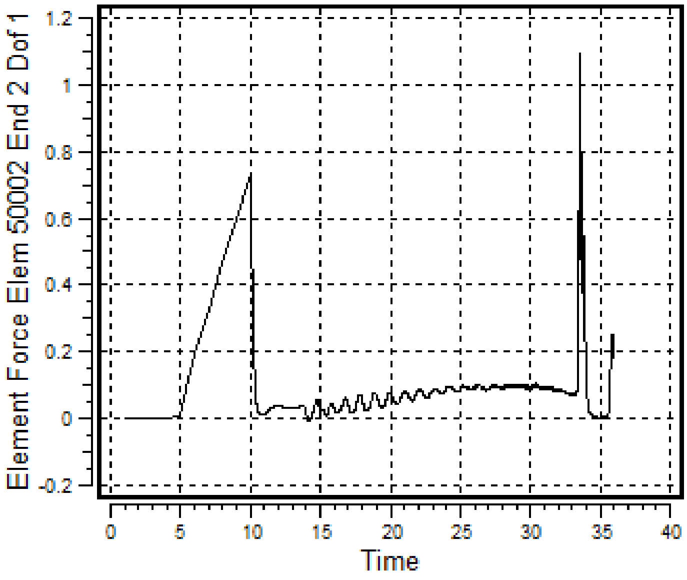


Figure 26 Case a2313 Element force of cable end

6.1.3 Simulation results

There are 512 cases simulated by Simla to check the influencing factors of hooking, including anchor mass, pipe diameter, hooking angle, span height and vessel velocity. Detailed results of scenario a straight pipe cases are shown in Table 15 . Other results are attached in appendix.

Anchor mass 3780 kg			
Number	**Result**	**Number**	**Result**
a1111	Hook	a1311	Hook
a1112	Hook	a1312	No
a1113	Hook	a1313	No
a1114	No	a1314	No
a1211	Hook	a1411	No
a1212	No	a1412	No
a1213	No	a1413	No
a1214	No	a1414	No
Anchor mass 6000 kg			
Number	**Result**	**Number**	**Result**
a2111	Hook	a2311	Hook
a2112	Hook	a2312	No
a2113	Hook	a2313	No
a2114	Hook	a2314	No
a2211	Hook	a2411	Hook
a2212	Hook	a2412	No
a2213	No	a2413	No
a2214	No	a2414	No
Anchor mass 9900 kg			
Number	**Result**	**Number**	**Result**
a3111	Hook	a3311	Hook
a3112	Hook	a3312	No
a3113	Hook	a3313	No
a3114	Hook	a3314	Hook
a3211	Hook	a3411	No
a3212	Hook	a3412	No
a3213	Hook	a3413	No
a3214	No	a3414	No
Anchor mass 15400 kg			
Number	**Result**	**Number**	**Result**
a4111	Hook	a4311	Hook
a4112	Hook	a4312	Hook
a4113	Hook	a4313	No
a4114	Hook	a4314	No
a4211	Hook	a4411	Hook
a4212	Hook	a4412	No
a4213	Hook	a4413	No
a4214	No	a4414	No

Table 15 Simla results - Scenario a, 90 hooking angle

6.2 “SHORT” PIPE MODEL RESULTS ANALYSIS

In this section, the influencing factors of hooking are analyzed for scenario a and scenario b respectively. Influencing factors are anchor mass, pipe diameter, hooking angle and span height. Hooking ratio is adopted to do the analysis.

$$Hooking\ ratio = \frac{Hooking\ cases}{Total\ cases} \times 100\% \qquad 6\text{-}1$$

6.2.1 Scenario a

In scenario a, vessel moves with 12 knots velocity and anchor chain is modeled with full length.

6.2.1.1 Anchor mass

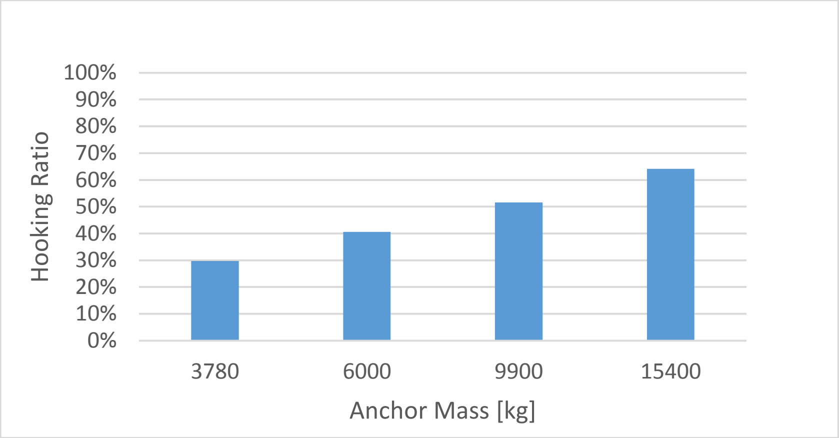


Figure 27 Relationship of anchor mass and hooking ratio in Scenario a

4 anchors with different masses and dimensions are simulated by Simla. The results show that hooking ratio increases with the increase of anchor mass, shown in Figure 27. It is due to the dimensions of heavy anchor are larger than those of light anchor, the dimensions are shown in Table 6 Anchor dimensions. It is obviously that larger anchors can hook more pipes than the smaller ones.

6.2.1.2 *Pipe diameters*

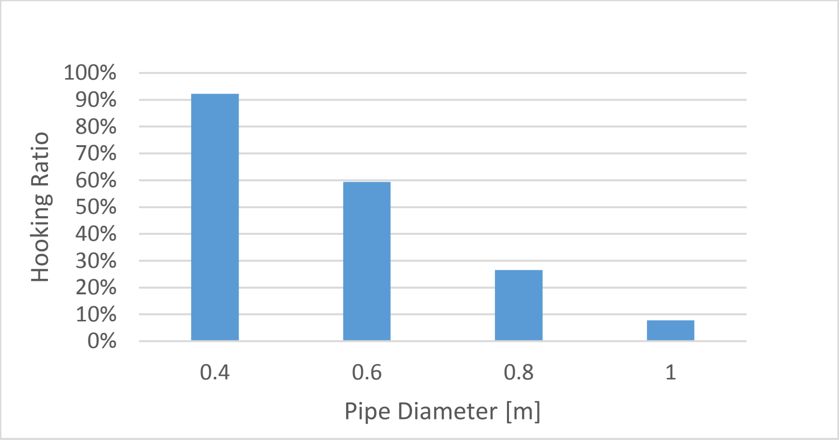


Figure 28 Relationship of pipe diameter and hooking ratio in Scenario a

Pipe diameter has an obvious effect on the simulation results, small pipe diameters are more easily to be hooked by the anchors. This is still due to the anchor dimensions.

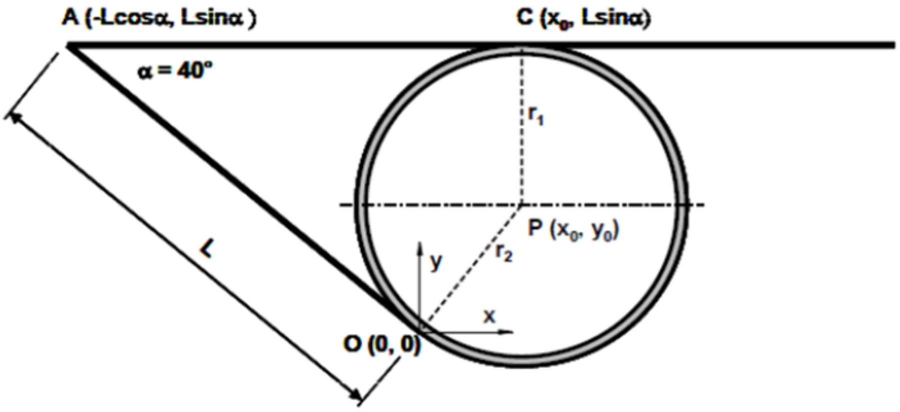


Figure 29 Anchor hooking geometry (15)

The diameters of pipelines can determine if the hooking events may occur. Some pipelines are too large to be hooked. Assume that the anchor hits the pipeline by flukes and shank when hooking occurs. When an anchor hooks on a pipeline, the maximum diameter of pipeline can be calculated by the below equation

$$D_{max} = \frac{2L(1-cos\alpha)}{sin\alpha} \qquad 6\text{-}2$$

The maximum pipeline diameters that may be hooked by selected anchors are shown in Table 16.

Anchor weight [kg]	angle α [deg]	L [m]	Dmax [m]
3780	40	1.35	1.0
6000	40	1.5	1.1
9900	40	1.7	1.3
15400	40	2.05	1.5

Table 16 Relation between anchor weight and maximum pipe diameter in straight pipe cases

6.2.1.3 Hooking angle

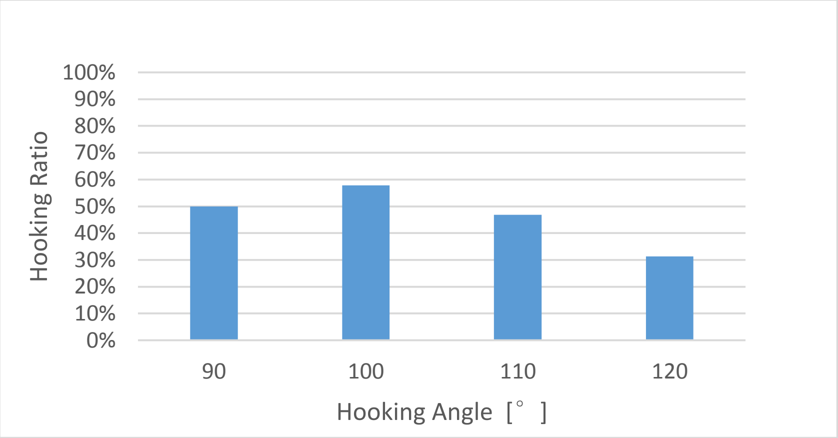
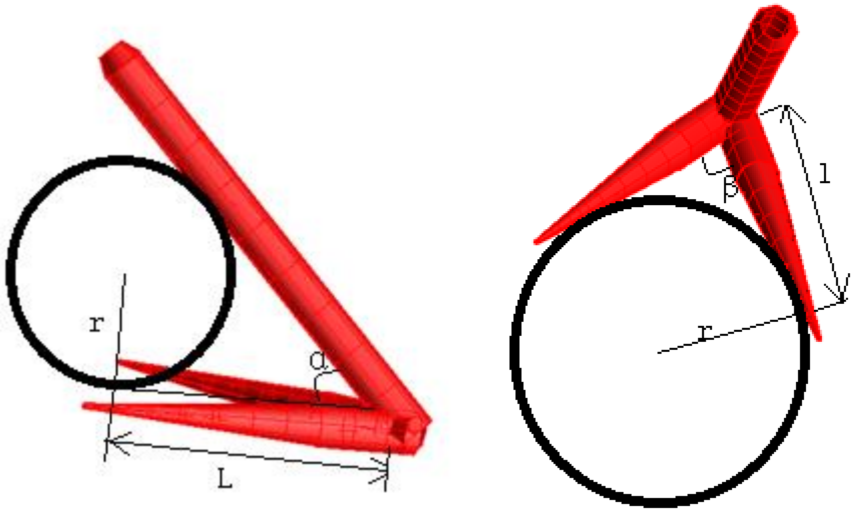


Figure 30 Relationship of hooking angle and hooking ratio in Scenario a

The results show that the hooking ratio of pipe with hooking angle 100° is a little higher than the straight pipe with 90° degrees angle. In the 90° hooking angle cases, the anchor is restricted in x direction movement, thus the anchor cannot rotate along y axis. Pipes can only be hooked by the area which is composed of flukes and shank, shown in Figure 31 a. The maximum pipe diameters that can be hooked by anchors are determined by fluke length and the intersection angle α of shank and flukes, the diameters are calculated in section 7.2.1.2 and shown in Table 16.



(a) (b)

Figure 31 Hooking geometry

In diagonal pipe cases, all the freedom degrees of anchor and cable are released before the anchor hits the pipe, the anchor can rotate along the y axis to hook the pipe, then the pipe can be hooked by the area composed of two flukes, shown in Figure 31 b. The maximum pipe diameters are determined by the intersection angle β of two flukes and the fluke length, they can be calculated by below equation.

$$D_{max} = \frac{2l(1-cos\beta)}{sin\beta} \quad 6\text{-}3$$

Anchor weight [kg]	angle β [deg]	l[m]	Dmax [m]
3780	53	1.51	1.5
6000	53	1.68	1.6
9900	53	1.90	1.8
15400	53	2.29	2.2

Table 17 Relation between anchor weight and maximum pipe diameter in nonzero hooking cases

Compare Table 16 and Table 17, the anchors of diagonal pipe cases can hook larger pipes than those of straight pipe cases. Thus more hooking cases occur in the 100 degrees hooking angle cases.

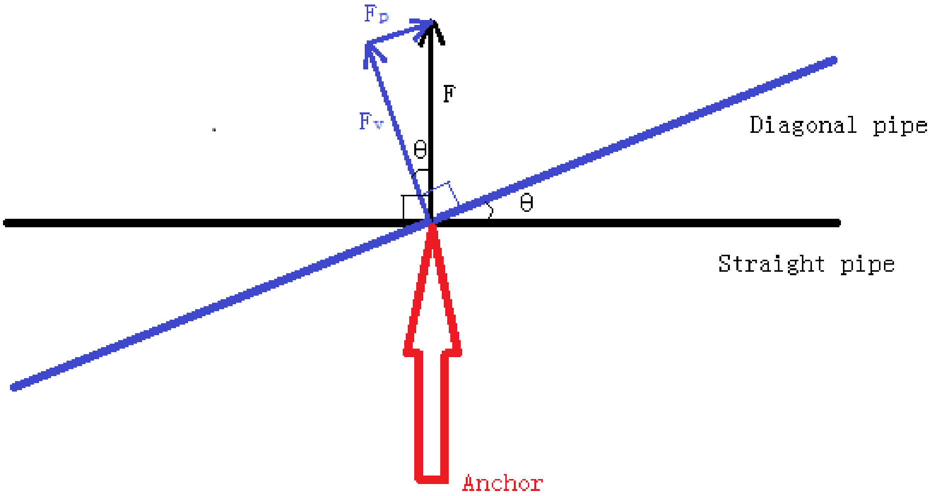


Figure 32 anchor loads on pipeline

However, for the cases with diagonal pipes, the hooking ratio is decreased with the increase of hooking angle. This is due to composition and separation of mechanics, shown in Figure 32. When anchor hits diagonal pipe, the impact force $\vec{F}$ can be separated into the forceF_v which is perpendicular to the pipe and the force F_p which is parallel to the pipe.

$$\vec{F} = \overrightarrow{F_v} + \overrightarrow{F_p} \tag{6-4}$$

$$F_v = F \cdot \cos\theta \tag{6-5}$$

$$F_p = F \cdot \sin\theta \tag{6-6}$$

When angle θ $(0 < \theta < 90)$ increases, the perpendicular force F_v decreases, thus the anchor cannot hook the pipes for some cases.

6.2.1.4 Span height

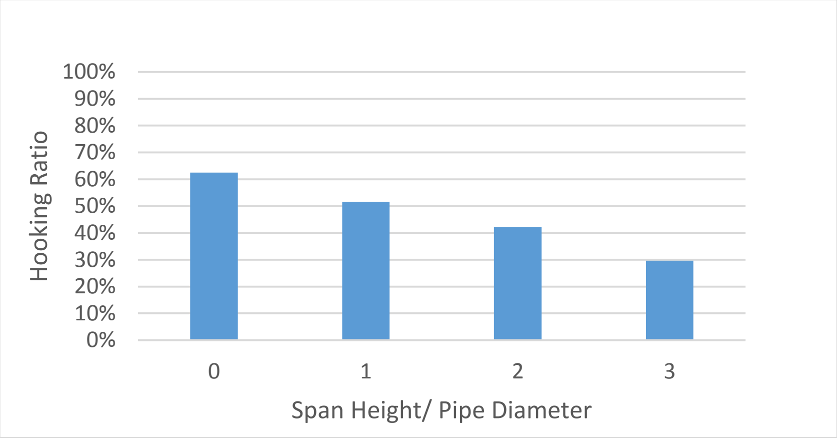
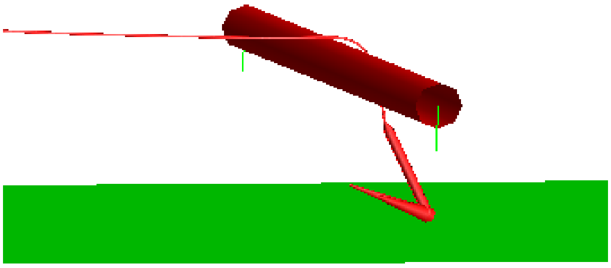
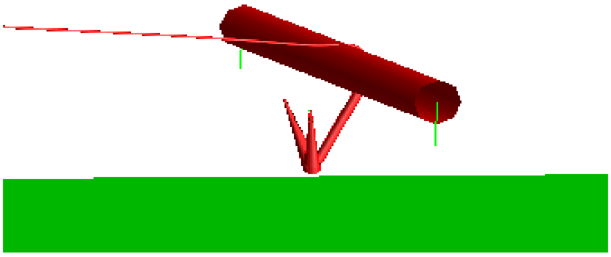


Figure 33 Relationship of span height and hooking ratio in Scenario a

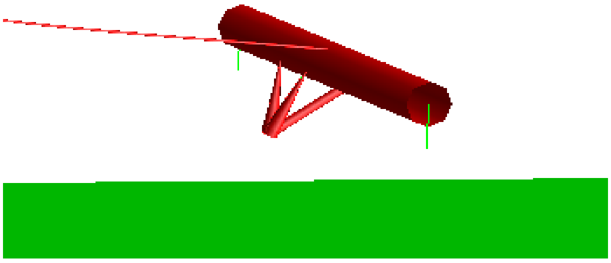
In the span height analysis, the results show that heigher span heights decrease the hooking ratio. In the high span cases, inertia causes the anchor keeps moving along the y axis after the cable touches the pipe, then span provides enough space for the anchor to twine the pipe. Afterwards, the interaction force bounces off the anchor. Thus, in the large span height cases, hooking ratio is lower. The process is shown in Figure 34.



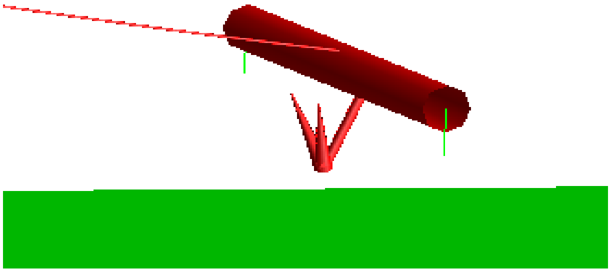
(a) t = 34.1



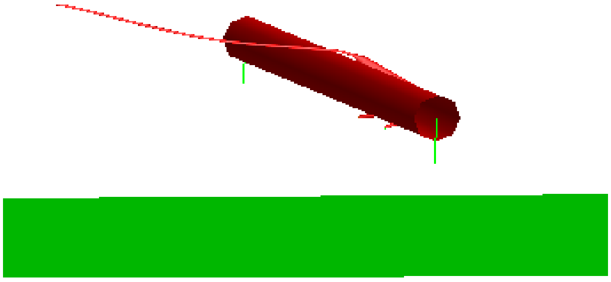
(b) t = 34.3



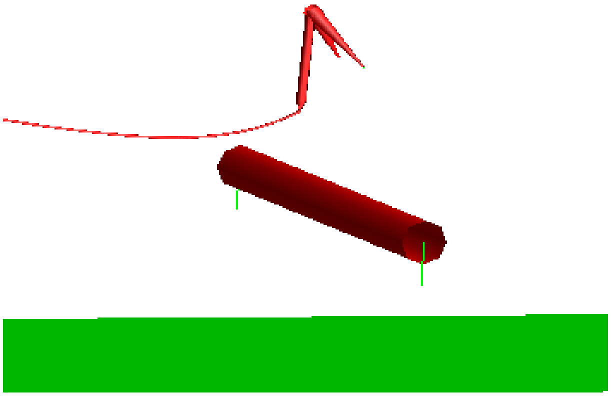
(c) t = 34.4s



(d) t = 34.5s



(e) t = 34.6s



(f) t = 34.8s

Figure 34 Unhooking case of large span

6.2.2 Scenario b

In scenario b, vessel moves with 6 knots velocity and anchor chain length is 300 meters.

The Simla results of scenario b shown in following sections are similar with those of scenario a, thus the reasons to cause those results can follow scenario a.

6.2.2.1 Anchor mass

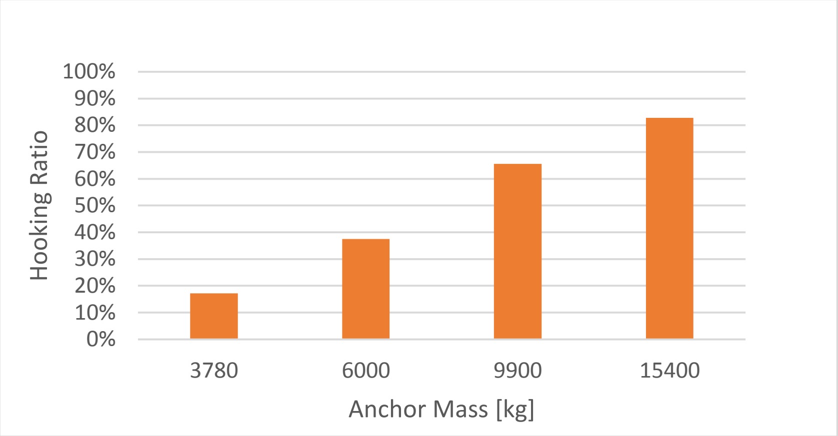


Figure 35 Relationship of anchor mass and hooking ratio in Scenario b

6.2.2.2 Pipe diameter

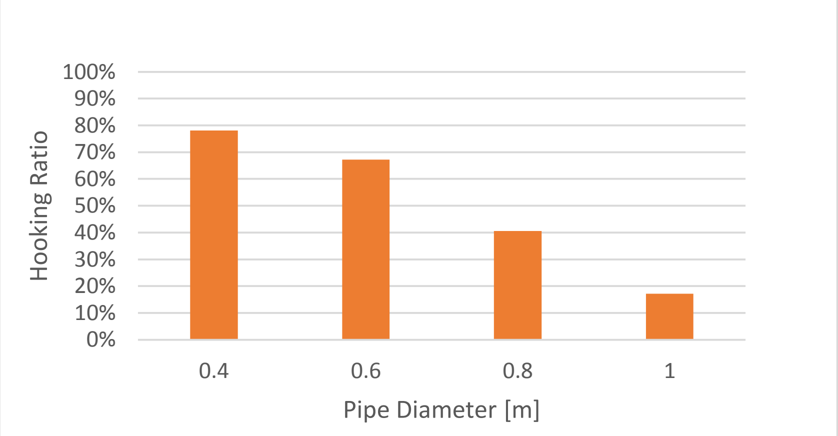


Figure 36 Relationship of pipe diameter and hooking ratio in Scenario b

6.2.2.3 Hooking angle

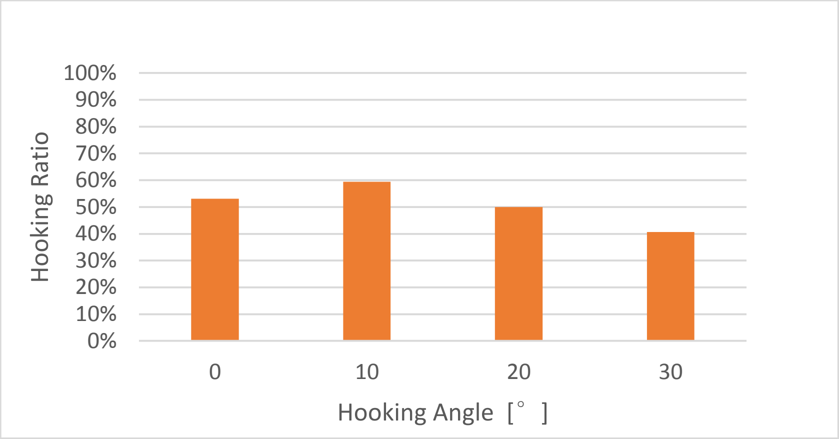


Figure 37 Relationship of hooking angle and hooking ratio in Scenario b

6.2.2.4 Span height

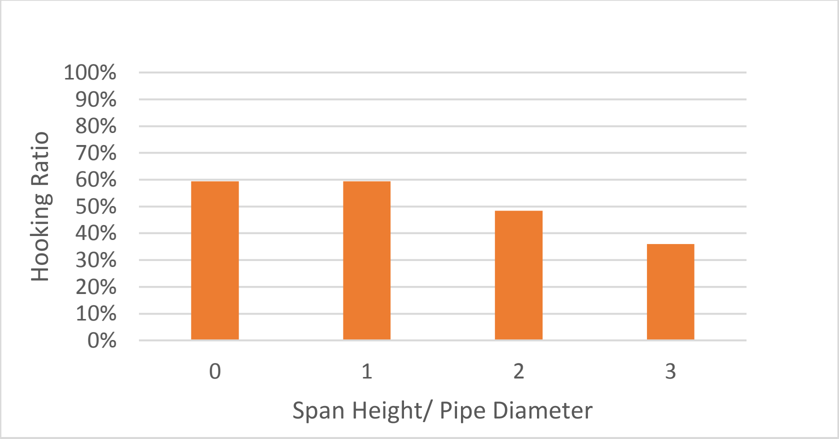


Figure 38 Relationship of span height and hooking ratio in Scenario b

6.2.3 Comparison of scenario a and b

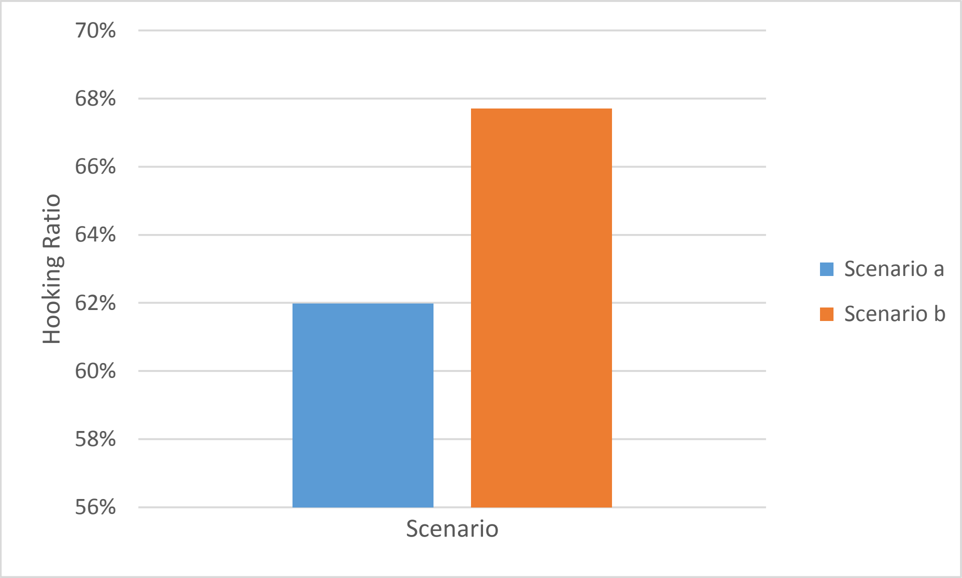


Figure 39 Hooking ratio comparison of scenario a and scenario b

In Figure 39 it can be found that hooking ratio of scenario b is higher than that of scenario a. This is due to anchor velocity of scenario b is slower than scenario a velocity. In Chapter 3, section 3.3.1 can be used to explain this phenomenon.

Direct impact load on the pipe is represented by an impulse loading I (5), which is equal to integral of impact load F over the entire duration from time t1 to t2:

$$I = \int_{t_1}^{t_2} F\,dt = mv_2 - mv_1 \qquad 6\text{-}7$$

First anchor moves to pipe with velocity v_1, then it hits the pipe with velocity v_2, thus $v_2 - v_1 < 0$, the impact load F is negative due to equation 6-7. The impact load can be increased by increasing the difference value of v_1 and v_2. Then the anchor will be bounced off the pipe when the load is large enough. Thus the faster anchors cause lower hooking ratio.

6.3 "LONG" PIPE MODEL SIMLA RESULTS

Short pipe with linear material is replaced by long pipeline with elastoplastic material to investigate typical pipeline responses when subjected to anchor hooking. Four hooking cases of scenario b straight pipe cases with highest span height are selected in this section. When the pipe is hooked by the anchor, the model shows an obvious bending, shown in Figure 40. Bending moments versus cable forces at the impact sections on the pipelines are plotted in the following sections.

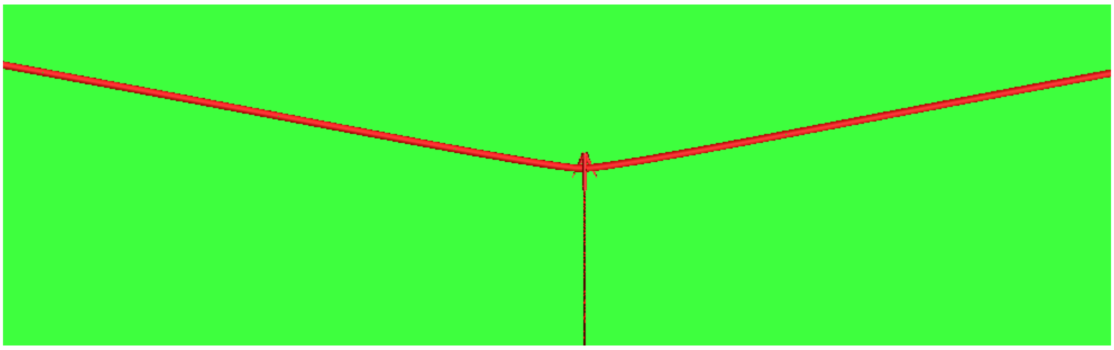


Figure 40 long pipeline model

6.3.1 Case l1114

Case l1114	
Anchor mass	3780 kg
Pipe diameter	0.4 m
Hooking angle	90
Span height/Pipe diameter	3

Table 18 Case l1114 input data

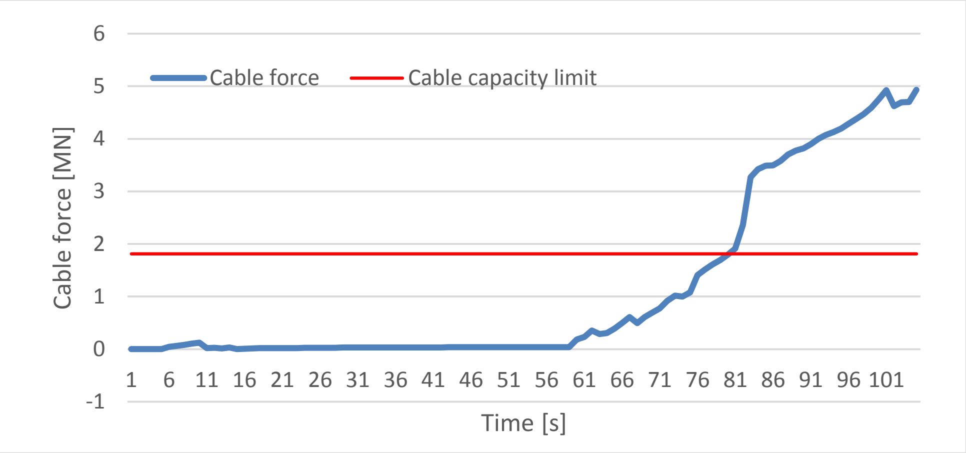


Figure 41 Case l1114 cable force and the capacity limit

Figure 41 shows that the cable force reaches the capacity limit at 81 s, thus the cable fails at that time.

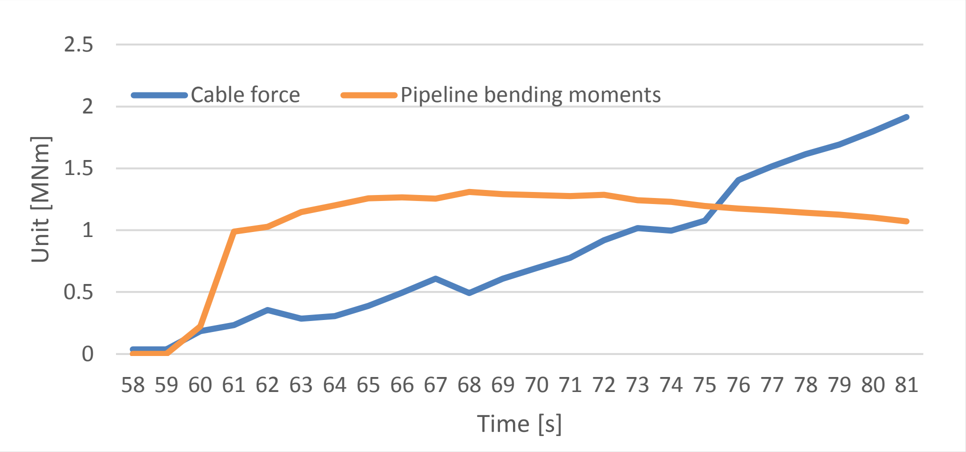


Figure 42 Case l1114 cable force and pipeline bending moments under cable capacity limit

6.3.2 Case l3114

Case l3114	
Anchor mass	9900 kg
Pipe diameter	0.4 m
Hooking angle	90
Span height/Pipe diameter	3

Table 19 Case l3114 input data

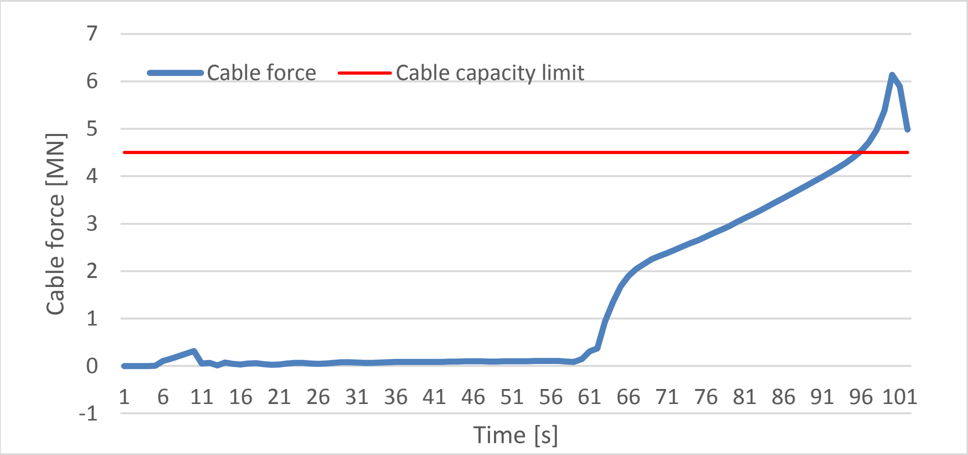


Figure 43 Case l3114 cable force and the capacity limit

Figure 43 shows that the cable force reaches the capacity limit at 96 s, thus the cable fails at that time.

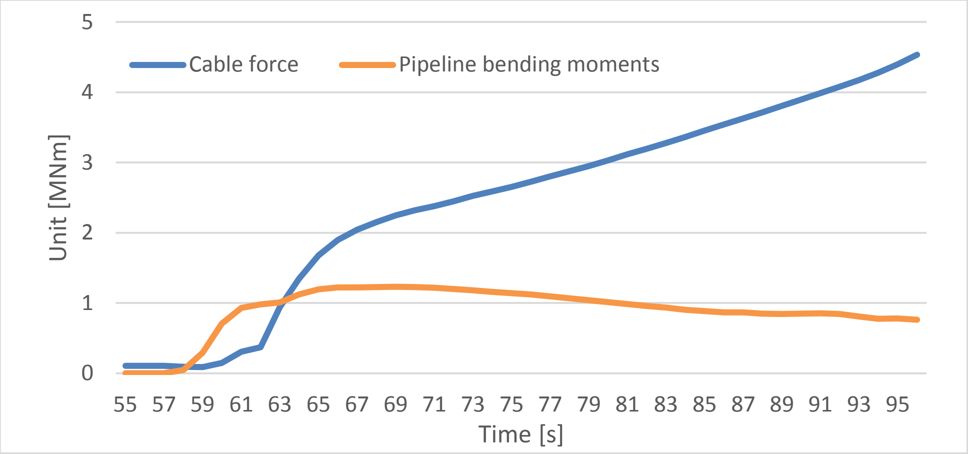


Figure 44 Case l3114 cable force and pipeline bending moments under cable capacity limit

6.3.3 Case l4114

Case l4114	
Anchor mass	15400 kg
Pipe diameter	0.4 m
Hooking angle	90
Span height/Pipe diameter	3

Table 20 Case l4114 input data

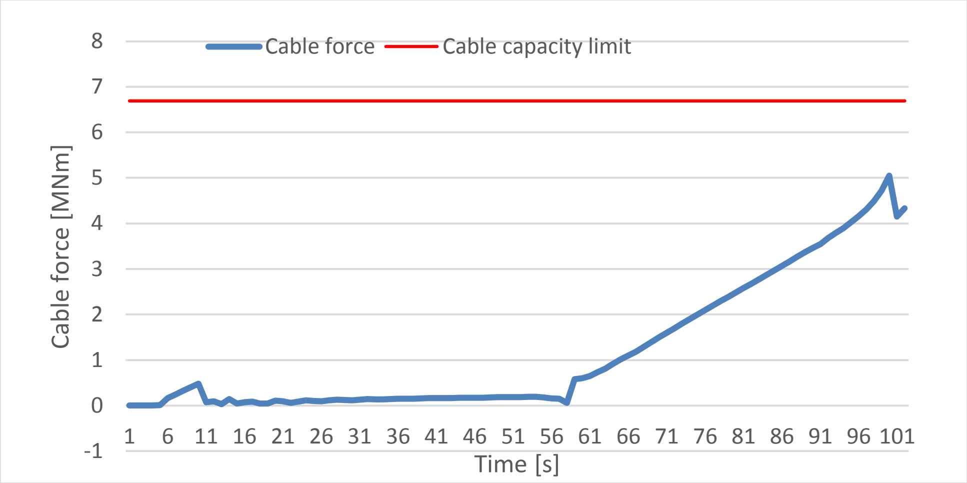


Figure 45 Case l4114 cable force and the capacity limit

Figure 45 illustrates the cable force does not reach the capacity, thus the pipeline ruptures before the cable line fails.

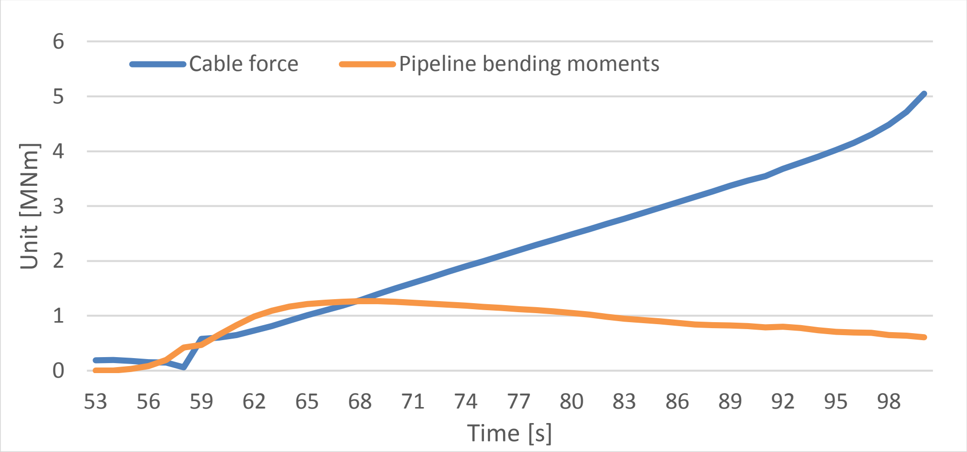


Figure 46 Case l4114 cable force and pipeline bending moments before pipe ruptures

6.3.4 Case l4214

Case l4214	
Anchor mass	15400 kg
Pipe diameter	0.6 m
Hooking angle	90
Span height/Pipe diameter	3

Table 21 Case l4214 input data

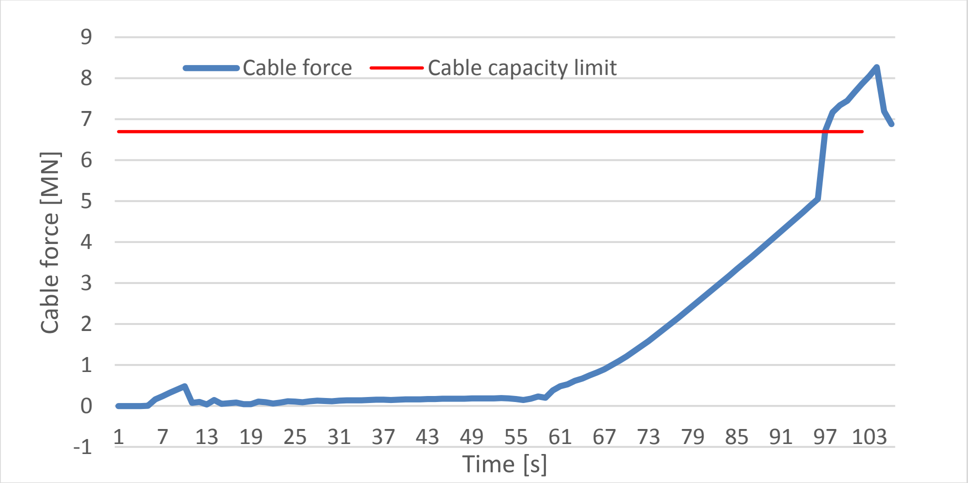


Figure 47 Case l4214 cable force and the capacity limit

Figure 47 shows that the cable force reaches the capacity limit at 97 s, thus the cable fails at that time.

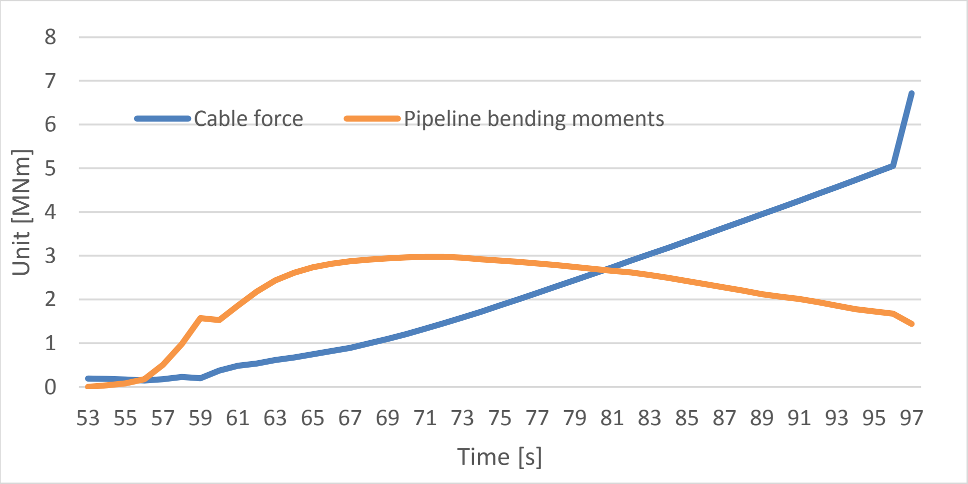


Figure 48 Case l4214 cable force and pipeline bending moments under cable capacity limit

6.4 "LONG" PIPE MODEL SIMLA RESULTS ANALYSIS

Cable force increases at a near-linear trend during hooking process until the cable reaches the capacity limits. The cable with lower capacity will fail earlier than others. All the four cases shows that the pipeline bending moment variation trends are similar when anchor hooking occurs, the bending moment experiences linear increase at the beginning of hooking , then turns into a slow growth until it reaches peak, after that, the bending moment starts to decrease slowly. This phenomenon can be explained by material characteristic strain-stress relationship. Strain increases linearly with the increase of stress until yielding occurs. The pipe experiences two different strains; True strain that occurs at loading moment and the permanent strain that occurs after removing the load. In addition, the largest bending moments of same pipe diameter are almost equal and larger diameter will cause larger bending moments.

7 CONCLUSION

This thesis focuses on anchor loading on pipelines, 512 short pipe models and 4 long pipe models have been investigated for analyzing hooking circumstances and pipeline responses respectively. The following conclusions are drawn from the thesis work.

- The anchors that move with lower velocities can hook more pipelines than those move with higher velocities.
- The span heights of pipeline have the effect on the hooking ratio that higher span heights represent lower hooking ratio.
- The hooking ratio is decreased with the increasing hooking angle due to composition and separation of mechanics.
- Anchor mass has a significant effect on the hooking results, heavier anchors that owns larger dimensions are able to hook more pipes. In addition, the cable capacity limits of heavier anchors are higher, thus the cable of heavy anchor is not easy to fail when the hooking event occurs.
- Pipe diameters also have effects on the hooking cases that: larger pipe diameters cause lower hooking ration. In the long pipeline models, the results show that larger diameter cause larger bending moments.

8 RECOMMENDATIONS FOR FURTHER WORK

Only several circumstances limits were selected for investigation in this project due to a large number of hours needed to run cases. However, the real sea circumstances are more complex, thus more situations should be selected to do the sensitivity study in the further work, including water depth, other vessel velocities, and other seabed conditions.

In this project, only global analysis is performed. Local analysis should be further carried out in the future.

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APPENDIX

Short pipe model SIMLA results:

Anchor mass 3780 kg			
Number	**Result**	**Number**	**Result**
a1111	Hook	a1311	Hook
a1112	Hook	a1312	No
a1113	Hook	a1313	No
a1114	No	a1314	No
a1211	Hook	a1411	No
a1212	No	a1412	No
a1213	No	a1413	No
a1214	No	a1414	No
Anchor mass 6000 kg			
Number	**Result**	**Number**	**Result**
a2111	Hook	a2311	Hook
a2112	Hook	a2312	No
a2113	Hook	a2313	No
a2114	Hook	a2314	No
a2211	Hook	a2411	Hook
a2212	Hook	a2412	No
a2213	No	a2413	No
a2214	No	a2414	No
Anchor mass 9900 kg			
Number	**Result**	**Number**	**Result**
a3111	Hook	a3311	Hook
a3112	Hook	a3312	No
a3113	Hook	a3313	No
a3114	Hook	a3314	Hook
a3211	Hook	a3411	No
a3212	Hook	a3412	No
a3213	Hook	a3413	No
a3214	No	a3414	No
Anchor mass 15400 kg			
Number	**Result**	**Number**	**Result**
a4111	Hook	a4311	Hook
a4112	Hook	a4312	Hook
a4113	Hook	a4313	No
a4114	Hook	a4314	No
a4211	Hook	a4411	Hook
a4212	Hook	a4412	No
a4213	Hook	a4413	No
a4214	No	a4414	No

Anchor mass 3780 kg			
Number	**Result**	**Number**	**Result**
a1121	Hook	a1321	No
a1122	Hook	a1322	No
a1123	No	a1323	No
a1124	Hook	a1324	No
a1221	Hook	a1421	No
a1222	Hook	a1422	No
a1223	No	a1423	No
a1224	No	a1424	No
Anchor mass 6000 kg			
Number	**Result**	**Number**	**Result**
a2121	Hook	a2321	Hook
a2122	Hook	a2322	No
a2123	Hook	a2323	No
a2124	Hook	a2324	No
a2221	Hook	a2421	No
a2222	Hook	a2422	No
a2223	No	a2423	No
a2224	No	a2424	No
Anchor mass 9900 kg			
Number	**Result**	**Number**	**Result**
a3121	Hook	a3321	Hook
a3122	Hook	a3322	Hook
a3123	Hook	a3323	Hook
a3124	Hook	a3324	No
a3221	Hook	a3421	No
a3222	Hook	a3422	No
a3223	Hook	a3423	No
a3224	Hook	a3424	No
Anchor mass 15400 kg			
Number	**Result**	**Number**	**Result**
a4121	Hook	a4321	Hook
a4122	Hook	a4322	Hook
a4123	Hook	a4323	Hook
a4124	Hook	a4324	No
a4221	Hook	a4421	Hook
a4222	Hook	a4422	Hook
a4223	Hook	a4423	Hook
a4224	Hook	a4424	No

Anchor mass 3780 kg			
Number	**Result**	**Number**	**Result**
a1131	Hook	a1331	No
a1132	Hook	a1332	No
a1133	Hook	a1333	No
a1134	No	a1334	No
a1231	Hook	a1431	No
a1232	Hook	a1432	No
a1233	No	a1433	No
a1234	No	a1434	No
Anchor mass 6000 kg			
Number	**Result**	**Number**	**Result**
a2131	Hook	a2331	No
a2132	Hook	a2332	No
a2133	Hook	a2333	No
a2134	Hook	a2334	No
a2231	Hook	a2431	No
a2232	Hook	a2432	No
a2233	Hook	a2433	No
a2234	No	a2434	No
Anchor mass 9900 kg			
Number	**Result**	**Number**	**Result**
a3131	Hook	a3331	No
a3132	Hook	a3332	Hook
a3133	Hook	a3333	No
a3134	Hook	a3334	No
a3231	Hook	a3431	No
a3232	Hook	a3432	No
a3233	Hook	a3433	No
a3234	Hook	a3434	No
Anchor mass 15400 kg			
Number	**Result**	**Number**	**Result**
a4131	Hook	a4331	Hook
a4132	No	a4332	Hook
a4133	Hook	a4333	Hook
a4134	Hook	a4334	No
a4231	Hook	a4431	No
a4232	Hook	a4432	No
a4233	Hook	a4433	No
a4234	No	a4434	No

Anchor mass 3780 kg			
Number	**Result**	**Number**	**Result**
a1141	Hook	a1341	No
a1142	Hook	a1342	No
a1143	Hook	a1343	No
a1144	Hook	a1344	No
a1241	No	a1441	No
a1242	No	a1442	No
a1243	No	a1443	No
a1244	No	a1444	No
Anchor mass 6000 kg			
Number	**Result**	**Number**	**Result**
a2141	Hook	a2341	No
a2142	Hook	a2342	No
a2143	Hook	a2343	No
a2144	Hook	a2344	No
a2241	No	a2441	No
a2242	No	a2442	No
a2243	No	a2443	No
a2244	No	a2444	No
Anchor mass 9900 kg			
Number	**Result**	**Number**	**Result**
a3141	Hook	a3341	No
a3142	No	a3342	No
a3143	Hook	a3343	No
a3144	Hook	a3344	No
a3241	No	a3441	No
a3242	Hook	a3442	No
a3243	No	a3443	No
a3244	No	a3444	No
Anchor mass 15400 kg			
Number	**Result**	**Number**	**Result**
a4141	Hook	a4341	No
a4142	Hook	a4342	No
a4143	Hook	a4343	No
a4144	Hook	a4344	No
a4241	Hook	a4441	No
a4242	Hook	a4442	No
a4243	Hook	a4443	No
a4244	Hook	a4444	No

Anchor mass 3780 kg			
Number	**Result**	**Number**	**Result**
b1111	Hook	b1311	No
b1112	Hook	b1312	No
b1113	Hook	b1313	No
b1114	Hook	b1314	No
b1211	Hook	b1411	No
b1212	Hook	b1412	No
b1213	No	b1413	No
b1214	No	b1414	No
Anchor mass 6000 kg			
Number	**Result**	**Number**	**Result**
b2111	Hook	b2311	Hook
b2112	Hook	b2312	No
b2113	Hook	b2313	No
b2114	No	b2314	No
b2211	Hook	b2411	No
b2212	Hook	b2412	No
b2213	Hook	b2413	No
b2214	No	b2414	No
Anchor mass 9900 kg			
Number	**Result**	**Number**	**Result**
b3111	Hook	b3311	Hook
b3112	Hook	b3312	Hook
b3113	Hook	b3313	No
b3114	Hook	b3314	No
b3211	Hook	b3411	No
b3212	Hook	b3412	No
b3213	Hook	b3413	No
b3214	No	b3414	No
Anchor mass 15400 kg			
Number	**Result**	**Number**	**Result**
b4111	Hook	b4311	Hook
b4112	Hook	b4312	Hook
b4113	Hook	b4313	No
b4114	Hook	b4314	No
b4211	Hook	b4411	Hook
b4212	Hook	b4412	Hook
b4213	Hook	b4413	No
b4214	Hook	b4414	No

Anchor mass 3780 kg			
Number	**Result**	**Number**	**Result**
b1121	Hook	b1321	No
b1122	Hook	b1322	No
b1123	No	b1323	No
b1124	No	b1324	No
b1221	No	b1421	No
b1222	Hook	b1422	No
b1223	No	b1423	No
b1224	No	b1424	No
Anchor mass 6000 kg			
Number	**Result**	**Number**	**Result**
b2121	Hook	b2321	Hook
b2122	Hook	b2322	No
b2123	Hook	b2323	No
b2124	No	b2324	No
b2221	Hook	b2421	No
b2222	No	b2422	No
b2223	Hook	b2423	No
b2224	No	b2424	No
Anchor mass 9900 kg			
Number	**Result**	**Number**	**Result**
b3121	Hook	b3321	Hook
b3122	Hook	b3322	Hook
b3123	Hook	b3323	Hook
b3124	Hook	b3324	No
b3221	Hook	b3421	Hook
b3222	Hook	b3422	Hook
b3223	Hook	b3423	No
b3224	Hook	b3424	No
Anchor mass 15400 kg			
Number	**Result**	**Number**	**Result**
b4121	Hook	b4321	Hook
b4122	Hook	b4322	Hook
b4123	Hook	b4323	Hook
b4124	Hook	b4324	Hook
b4221	Hook	b4421	Hook
b4222	Hook	b4422	Hook
b4223	Hook	b4423	Hook
b4224	Hook	b4424	Hook

Anchor mass 3780 kg			
Number	**Result**	**Number**	**Result**
b1131	Hook	b1331	No
b1132	No	b1332	No
b1133	No	b1333	No
b1134	No	b1334	No
b1231	No	b1431	No
b1232	Hook	b1432	No
b1233	No	b1433	No
b1234	No	b1434	No
Anchor mass 6000 kg			
Number	**Result**	**Number**	**Result**
b2131	Hook	b2331	No
b2132	Hook	b2332	No
b2133	No	b2333	No
b2134	No	b2334	No
b2231	Hook	b2431	No
b2232	No	b2432	No
b2233	No	b2433	No
b2234	No	b2434	No
Anchor mass 9900 kg			
Number	**Result**	**Number**	**Result**
b3131	Hook	b3331	Hook
b3132	Hook	b3332	Hook
b3133	Hook	b3333	Hook
b3134	Hook	b3334	Hook
b3231	Hook	b3431	No
b3232	Hook	b3432	No
b3233	Hook	b3433	No
b3234	Hook	b3434	Hook
Anchor mass 15400 kg			
Number	**Result**	**Number**	**Result**
b4131	Hook	b4331	Hook
b4132	Hook	b4332	Hook
b4133	Hook	b4333	Hook
b4134	Hook	b4334	Hook
b4231	Hook	b4431	Hook
b4232	Hook	b4432	Hook
b4233	Hook	b4433	No
b4234	Hook	b4434	No

Anchor mass 3780 kg			
Number	**Result**	**Number**	**Result**
b1141	No	b1341	No
b1142	No	b1342	No
b1143	No	b1343	No
b1144	No	b1344	No
b1241	No	b1441	No
b1242	No	b1442	No
b1243	No	b1443	No
b1244	No	b1444	No
Anchor mass 6000 kg			
Number	**Result**	**Number**	**Result**
b2141	Hook	b2341	No
b2142	Hook	b2342	No
b2143	Hook	b2343	Hook
b2144	Hook	b2344	No
b2241	Hook	b2441	No
b2242	Hook	b2442	No
b2243	Hook	b2443	No
b2244	No	b2444	No
Anchor mass 9900 kg			
Number	**Result**	**Number**	**Result**
b3141	No	b3341	No
b3142	Hook	b3342	No
b3143	Hook	b3343	Hook
b3144	Hook	b3344	No
b3241	No	b3441	No
b3242	Hook	b3442	No
b3243	Hook	b3443	No
b3244	Hook	b3444	No
Anchor mass 15400 kg			
Number	**Result**	**Number**	**Result**
b4141	Hook	b4341	No
b4142	Hook	b4342	Hook
b4143	Hook	b4343	Hook
b4144	Hook	b4344	Hook
b4241	Hook	b4441	No
b4242	Hook	b4442	No
b4243	Hook	b4443	No
b4244	Hook	b4444	No