University of Stavanger

Faculty of Science and Technology

MASTER'S THESIS

Study program/ Specialization: **Offshore Technology/ Subsea Technology**	**Spring semester, 2014** **~~Open~~ / Restricted access**
Writer: **Wenhui Zhu**	…………………………………………… (Writer's signature)
Faculty supervisors: **Ljiljana D. Oosterkamp (University of Stavanger, Stavanger)** **Ove T. Gudmestad (University of Stavanger, Stavanger)** External supervisor: **Birger A. Etterdal (DNV GL, Høvik)**	
Thesis title: **Ship Anchor Interference with Offshore Pipelines**	
Credits (ECTS): **30**	
Key words: Subsea pipeline, Hooking, Anchor, Abaqus, FEM, Local buckling	Pages: ……71…… + enclosure: …13…… Stavanger, 12/06/2014

Master thesis spring 2014

For student Wenhui Zhu

Ship Anchor Interference with Offshore Pipelines

1. Background for the thesis:

Several anchor-hooking have recently caused severe damages to offshore pipeline. Such event imposes high risk both related to operation of the pipeline and to the ship and crew itself. There are indications that this occurs more frequent than anticipated in the design of the pipeline.

2. Goal for the thesis:

The main goal is to identify the most important parameters with respect to damage extent. We have seen that the damage severity differs a lot from case to case even though they have been subjected to same type and size of anchors. Among the parameters that have to be addressed are:

- Pipeline diameter
- Pipeline wall thickness
- Steel material properties
- Water depth
- Pipeline protection (depth of burial, rock dumping, etc.)
- Pipe / soil interaction properties

3. Scope (description of content, theoretical foundation and literature):
    a. Literature study: results from investigations and assessment of anchor hooking events are available in the public domain (e.g. 30” Kvitebjørn Pipeline, 20” Oil Export Gorm/Filsø, Cats Pipeline). The damage extent to the pipeline shall be summarized and value of important parameters tabulated. DNV may also provide details for some cases that are not public available (upon client acceptance)
    b. Familiarisation with pipeline analysis using Abaqus FE-tool: non-linear FE analyses are commonly used to simulate the behaviour of pipeline exposed to functional loads (pressure & temperature) as well as external loads, e.g. trawl

or anchor interference. DNV will provide a general FE-model of a pipeline as a starting point. For this study, it is proposed to use beam-elements (not shell or solid-elements).

c. Define failure criterion based on DNV-OS-F101: an acceptance or failure criteria for the FE-simulation has to be defined. It is proposed to use a strain criterion for this study where the allowable strain is estimated from formulations given in DNV-OS-F101.
d. Initial parameter study to define the important parameters: an initial study shall be performed to identify the most important parameters.
e. Comprehensive parameter study on the important parameters: a more comprehensive study shall be conducted by varying the most important parameters. Trends shall be identified and the results must be discussed.

Abstract

The main purpose of this thesis was to identify and study important parameters related to hooking incidents. Criteria of local buckling in DNV-OS-F101 were used to judge the results of FE analysis acceptable or not.

In this report, several known hooking incidents were briefly described. Some aspects related to risk assessment were discussed together with some prevention approaches. Large anchors were identified to be more likely to hook a specific pipeline than small anchors. What's more, chain length and tow velocity were discovered to decide the depth an anchor could reach.

Simulations using Abaqus were conducted to explore parameters, like magnitude of load, hooking duration, friction coefficient, which might have significant influences on the response of pipeline. In addition, a pipeline together with a chain was built in Abaqus to investigate the response of pipeline besides applying hooking load directly onto a pipeline.

The parameters studied in this thesis were all proved to affect the response of pipeline. The final configuration of pipeline by applying hooking load directly onto it was found relying on the style of load history. By setting a velocity on top of a chain, the result of FE analysis matched the survey well. Thus, efforts on adjusting the load history were avoided. Additionally, low velocities of the chain implied lower risks than high velocities.

By comparing with the local buckling criteria, responses of the pipeline with a 10m lateral displacement were found unacceptable by using LC criterion, while the responses satisfied DC criterion well. This conclusion suggested that it was not possible to design out the anchor damage by using ALS LC criterion even faced with a small anchor. Protecting pipelines in areas like anchorages and defining a failure criterion as loss of containment could be reasonable to deal with hooking incidents.

Preface

This thesis was done as part of my master degree specialized in Subsea Technology in University of Stavanger, accounting for 30 credits. All of the work presented henceforth was conducted in DNV GL at Høvik office from January, 2014 to June, 2014.

The high frequency of anchor interference with offshore pipelines has aroused the concern of the industry. Important parameters related to hooking incidents should be identified and studied, which were the objective of this thesis. In addition, criteria of local buckling were used to judge the results. Due to limited information of anchor hooking incidents, a detailed study will give some insights for the future familiarity with this kind of issue.

FE analysis was conducted in Abaqus and results were plotted using Python.

Enclosed with this report is a zip file, which contains all the input files for all simulations that have been conducted in this thesis.

Acknowledgements

Taking a master program in Norway was never in my plan. I had a job in a shipyard, had my family and friends around 2-year back. It took me some time to figure out what kind of life I wished to have. It was exciting to step out of my comfort zone into a brand-new world.

First of all, I would like to thank Afzal Hussain (Høvik, DNV GL) and Jun Liu (Høvik, DNV GL) for giving me this opportunity to work on a topic I am interested in. They offered me a good working environment and access to their facilities.

All the work in this thesis is done under the supervision of Birger Atle Etterdal (Høvik, DNV GL). I would like to express my deepest appreciation to him for his support and advice during the discussion of my work. His excellent expertise in pipeline and his attitude to work have greatly inspired me, no matter what I would be working on in the future. In addition, I would like to thank my advisors Prof. Ljiljana Djapic Oosterkamp (Stavanger, UiS) and Prof. Ove Tobias Gudmestad (Stavanger, UiS) for their generous recommendations and opinions on this thesis. They have taught me so much during the entire master degree. I am so grateful to have them as my teachers.

And I really appreciate the patient help and advice from people, Linlin Jiao, Simen Eldevik, Gaute Kolstad and António Cartaxo in section of Operations Technology, DNV GL. Sincere thanks goes to Sheryl Josdal, who has helped me a lot on the faculty documents and forms.

Finally, I would like to thank my family for their support and company.

Høvik, June 2014

Wenhui Zhu

Contents

List of figures

List of tables

Symbols and abbreviations

C_D	Drag coefficient
D	Outer diameter of a pipe,
D_{chain}	Diameter of chain
D_{max}	Maximum diameter a specific anchor could hook
$D_{max\ modified}$	Modified maximum diameter a specific anchor could hook
E	Young's modulus
E_a	Efficiency of anchor
F	Drag force per unit length
F_{total}	Total drag force
f_y	Yield stress to be used in design
$f_{y.temp}$	Derating on yield stress due to temperature
$f_{u.temp}$	Derating on tensile strength due to temperature
g	Acceleration of gravity
H_c	Average holding capacity of anchor
Δh	Difference of elevation between pressure reference point and local pressure point
L	Length of fluke
L_c	Length of chain
L_{drag}	Dragging length of anchor
M_c	Ultimate bending moment capacity
M_P	Plastic moment
$M_{P,point\ load}$	Plastic moment accounting for point load
M_{Sd}	Design moment
M_{tot}	Total bending moment
m_a	Mass of anchor
m_c	Total mass of chain
m_s	Total mass of ship
n_{RO}	Ramberg-Osgood parameter
p	Pressure acting on the pipe
p_b	Burst pressure
p_d	Design pressure at the pressure reference elevation
p_e	External pressure

p_i	Internal pressure
p_l	Ultimate pressure capacity
p_{min}	Minimum internal pressure that can be continuously sustained with the associated strain
R	Reaction force from point load
S	True longitudinal force acting on the pipe
S_P	Plastic axial force
S_{Sd}	Design effective axial force
t	Wall thickness of a pipe
v	Anchor velocity
v_s	Velocity of ship when casting anchor

α	Angle between shank and fluke
α_c	Flow stress parameter
α_u	Material strength factor
α_s	Strength anisotropy factor
α_{gw}	Girth weld factor
α_h	Max. yield to tensile ratio
α_p	Factor accounting for effect of D/t ratio
α_{pm}	Plastic moment reduction factor accounting for point load
α_{RO}	Ramberg-Osgood parameter
β	The angle between horizontal direction and chain
$\gamma_A, \gamma_C, \gamma_E, \gamma_F$	Safety factors
γ_{inc}	Incidental to design pressure ratio
γ_ε	Strain resistance factor related to safety class
ε	True strain
ε_c	Strain capacity
ε_E	Engineering strain
ε_p	True plastic strain
ε_{Rd}	Design resistance strain,
ε_{Sd}	Design compressive strain
ρ	Density of pipeline content
ρ_{chain}	Density of chain per unit length
ρ_{water}	Density of seawater
σ	True stress

σ_0	True yield strength
σ_E	Engineering stress
σ_Y	Yield stress

ALS	Accidental limit state
DAF	Damping amplification factor
DC	Displacement controlled
ESF1	Effective axial force
Fp	Horizontal component of hooking force
Fz	Vertical component of hooking force
LC	Load controlled
Max.	Maximum
Min.	minimum
PL-MODEL	Model used for FE analysis which is based on a real case
SF1	Axial force
U2	Displacement in Y direction
U3	Displacement in Z direction
ULS	Ultimate limit state
Y displacement	Lateral displacement
@Peak	Instant of removing load or velocity
@Stable	Instant when pipeline being stable

1. Introduction

Offshore pipelines are used for transporting hydrocarbon products and produced water etc., connecting offshore platforms and onshore facilities. The network of the subsea pipelines is crucial concerning Oil & Gas activities and HSE aspects. Furthermore, on the Norwegian Continental Shelf, there are frequent fishing activities, shipment transporting, Oil & Gas activities and so on. There is an increasing concern about ship interference on offshore pipelines thinking of possible hazards to the third party, pipeline's integrity and environment. Hence, to establish a good understanding of the pipelines which are under risks of ship interference is of great significance.

Incidents of anchor hooking onto pipelines were supposed to be a rarely occurring event, because during the design phase, the pipeline requires a clearance about 2km radius away (Karunakaran, 2013) from possible anchor spreads. Even in some exclusive zones, 3rd party activities are prohibited. However, hooking incidents happened more frequently than expectation, causing damages ranging from slight scratches of the coating to large deformation of the pipeline. In addition, during hooking incidents, it is possible to break the chain or anchor fluke, which leads to a loss of the capacity of mooring system. Such incidents have significant consequences varying from repair and shutdown of the pipeline to potential risks regarding pollution and loss of lives. As for the 3rd party, there could be a need to change a new anchor and possibly abort the mission because of the loss of mooring capacity.

DNV GL has been involved in several projects in recent years related to 3rd party interference. A seminar on anchor threats on pipelines was launched with participants from industry in December, 2013. One of the main needs from industry representatives is to establish better understanding of the underlying factors of observed incidents, including the load effects on pipeline (Afzal, 2014).

1.1 Previous works

The open literature provides studies on anchor hooking incidents, mainly in 3 categories: reports on known hooking incidents, risk assessments of hooking incidents and structural analysis of pipeline being hooked.

Several reports have been published describing the details of the hooking incidents. Also the damages were expatiated, which have aroused the attention of the industry. Some of the reports have mentioned the remedial approaches in order to recover the production after the hooking incidents. More details about the reports were discussed in Chapter 2.

As for the articles related to risk, like HSE (2009) , Hvam et al. (1990) and Anonymous (2006), consequences of hooking incidents were discussed. Some aspects related to the frequency of hooking incident were investigated as well. For example, in the work of Vervik (2011), statistical study of the traffic over a certain offshore field was carried out.

As for the structural analysis, in the work of Sriskandarajah and Wilkins (2002), they considered that a pipeline which is hooked by an anchor rests on a continuous seabed and is partially buried. Anchor force is determined after calculating environmental forces. To be more specific, the environmental forces exerted onto the vessel are translated through the mooring system to the anchor. In their work, dynamic force from environment is calculated including the effect of the DAF. By subtracting a part of ultimate anchor holding capacity from the dynamic force, force applied on pipeline is then got related to different types of vessels. In an FE model, a prescribed lateral displacement is applied at the anchor hooking point after applying essential forces on the pipeline. Actually, anchor could drag a pipeline in both lateral and vertical direction. It’s possible that anchor lifts the pipeline off seabed and drags it along the direction which the vessel is heading to.

In the work of Vervik (2011), he used a linear spring to connect pipeline and chain in a dynamic FE analysis. The spring has a maximum force as the chain capacity. As far as I am concerned, once the stiffness of the spring is defined, the time of interaction between chain and pipeline is then determined. Based on the information we have already got, when an anchor hooking incident happens, we usually get a break-off fluke instead of an entire anchor, which indicates the chain capacity is way larger than the fluke could withstand. Hence, if using this model for a parameter study, it could have satisfying result. However, there is little information about how the analysis matches the real situation, like final configuration of pipeline.

These works play a significant role in future investigation on anchor hooking incidents. The study could be more reasonable if comparing the analysis with a real case more exhaustively.

1.2 Scope and objectives

This thesis focused on anchor hooking incidents. Investigations and assessments of several anchor hooking incidents need to be summarized. During the literature study, some important parameters which could influence the response of pipeline need to be identified and be studied in subsequent FE analysis. The objective was to find if the results were acceptable by using a strain criterion given in DNV-OS-F101 (DNV, 2013b). In addition, bending moment capacity was used as another failure criterion, even though it wasn’t within the scope of this thesis originally. Anyway, it could give the industry an insight into future practice.

1.3 Structure of thesis

This paper started with a literature study (see Figure 1-1). Several cases had been studied focusing on short descriptions of the incidents, summary of the damage extents and related remedial approaches. Here also presented a methodology of judging if anchor interference on offshore pipeline could happen, which was discussed mainly about geometrical aspects that influence the anchor hooking issue, such as anchor size, tow depth, and drag distance of anchor. Prevention approaches were then generally introduced to shed some light to future countermeasures on hooking incidents. The following content was a theoretical study of mechanics by presenting material properties, mechanical model, failure mode and design criteria.

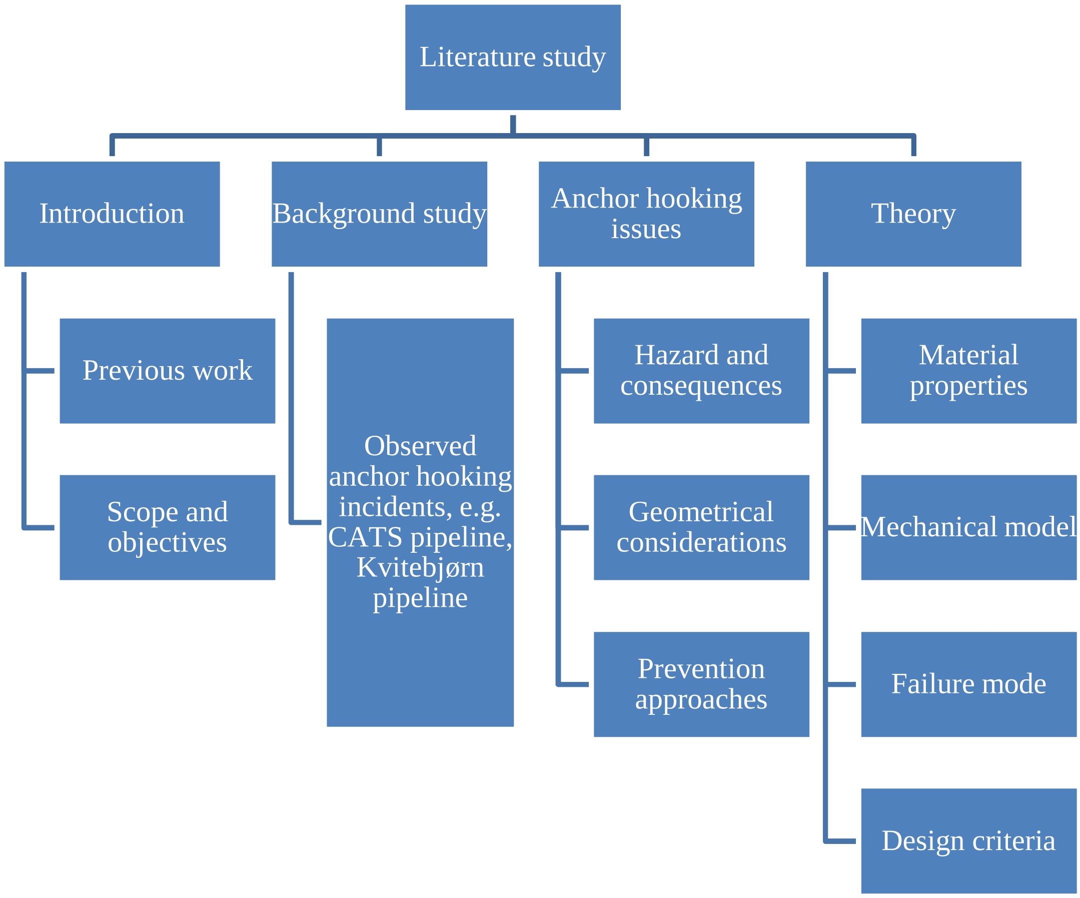


Figure 1-1 Structure of literature study

After literature study, FE analysis (see Figure 1-2) was investigated. The model used in FE analysis was based on a real pipeline hooked by an anchor on Norwegian Continental Shelf. A static model was built to simulate the process of installation operation. Then a dynamic analysis was generated to study the response of this pipeline during hooking incidents. Important parameters being studied in dynamic analysis were to find the sensitive ones. Furthermore, a contrast was made between applying the hooking load directly to the pipeline and applying the load through a chain, i.e. ‘load model’ and ‘velocity model’. Also, acceptable criteria were discussed in view of the results.

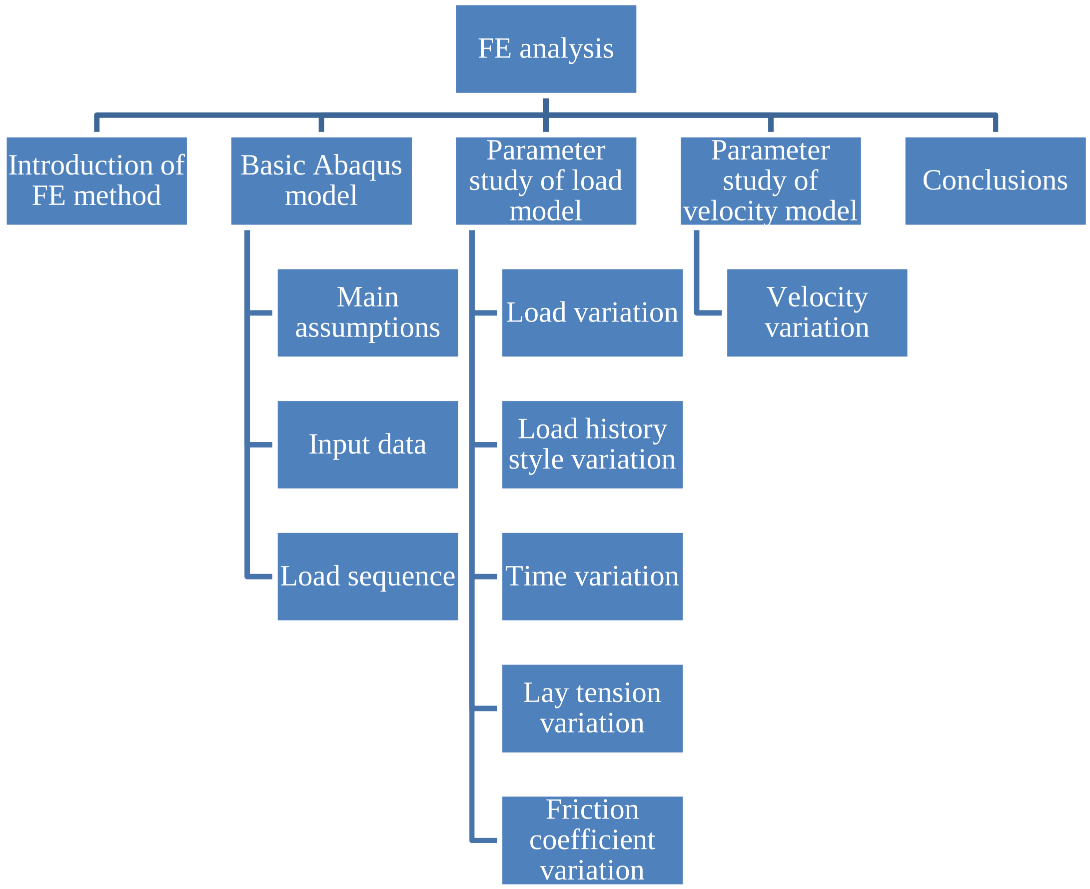


Figure 1-2 Structure of FE analysis

2. Background study

2.1 36" central area transmission system (CATS pipeline)

CATS is a large diameter subsea system in UK sector of the North Sea, which is used for transporting natural gas through a 404km pipeline (see Figure 2-1). The 36" pipeline is, with wall thickness of 28.4mm, coated with 51mm high density concrete. It operates in a dense phase and has a maximum allowable operating pressure (MAOP) of 179barg. In the near shore area, the pipeline is trenched (with natural backfill) for stability and protection. The following description is based on the work of Espiner et al. (2008).

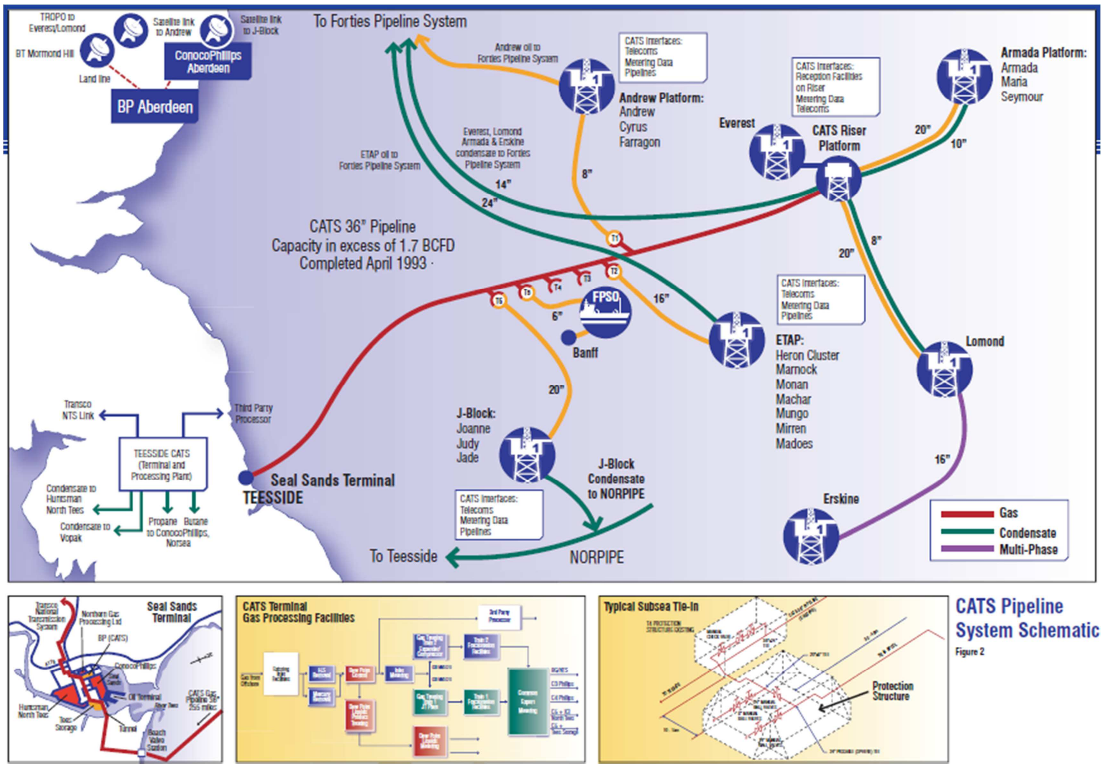


Figure 2-1 CATS pipeline system schematic (Anonymous, 2013)

This pipeline was damaged during an anchor hooking incident in a storm, due to a tanker mooring off anchorage. In an approximate water depth of 32m, the pipeline was lifted off the seabed and dragged away from its designed location. The anchor bent the pipe and deformed it locally.

Based on maritime data, the vessel was drifting at 2 knots. After a structural analysis, the kinetic energy of the anchor was then estimated to be in the order of 10kJ according to the effective mass of the anchor.

After a detailed inspection, it showed gouges in the pipe wall in the longitudinal direction and dents in the pipeline with a depth of 31mm at the deepest point. The pipeline was confirmed that there was no leakage of containment by monitoring the flow rate and pressure after the incident happened.

A grouted sleeve design was decided by BP used for repairing the pipeline. After the pipeline was laid down back to seabed, the damaged section was protected by dumped rock. This pipeline was back to operation after a series of significant inspection, assessment and repair.

2.2 30” Kvitebjørn pipeline

Kvitebjørn is a medium size offshore field located in the Norwegian sector of the North Sea. A 30” gas and condensate pipeline carries the partly processed product to the Kvitebjørn/Troll onshore processing plant at Kolsnes just outside Bergen. The following description is based on the work of Gjertveit et al. (2010).

During a routine inspection performed on this pipeline, severe anchor interaction damage was discovered at 210m water depth. The pipeline itself had been struck by a 10-tonne anchor and dragged approximately 53m from its initial position.

The anchor impact load was later estimated to be around 5000kN and this load had induced large deformations and strains in the pipeline. The damage constituted a localized dent and a 17deg buckle, but no leakage.

Remedial approaches were carried out to Kvitebjørn pipeline. First was a damage survey which including detection and measurement of the external geometry (ovality and deformations) and possible cracks. Then a series of preparations had been made such as exposing pipeline, cutting & relocation, coating removal and longitudinal seam weld cap removal. After preparations were done, procedure of repair was described as follows:

- Adjust pipeline and perform final cut
- Install the Morgrip coupling, first on one end then back over the other end
- Activate the coupling and perform inter seal leak test
- Cut all hydraulic connections and release coupling from installation frame
- Lower pipeline and coupling to seabed, repair completed
- System pressure test and re-commissioning, and start up

2.3 22” Huldra gas export pipeline

Huldra is a wellhead platform located in Norwegian sector of the North Sea. The length of the pipeline is 150km with a nominal diameter of 22”.

During a visual pipeline survey, an anchor was identified near this pipeline in an approximate water depth of 112m. Damages on the concrete coating as well as a lateral shift of the pipeline were discovered. After a detailed visual inspection, the anchor interference caused the pipeline to move laterally about 6.4m over a length of 267m. After the concrete and corrosion coating was removed, ovality due to a dent of 20mm over a length of 1.5m was reported. 80cm long gouges were discovered in the axial direction as well.

After a detailed assessment, the impact energy was estimated at a level less than 40kJ and the static pull force was estimated in a range of 20~50 tonnes. In addition, an anchor with an approximate weight as 1 tonne was identified (Vigsnes et al., 2008).

2.4 20” and 26” Transmediterranean pipeline system

Transmediterranean pipeline system is made up of 5 pipelines, connecting Cap Bon in Tunisia and Mazara del Vallo in Sicily (see Figure 2-2). The following description is based on the work of Orsolato et al. (2011).

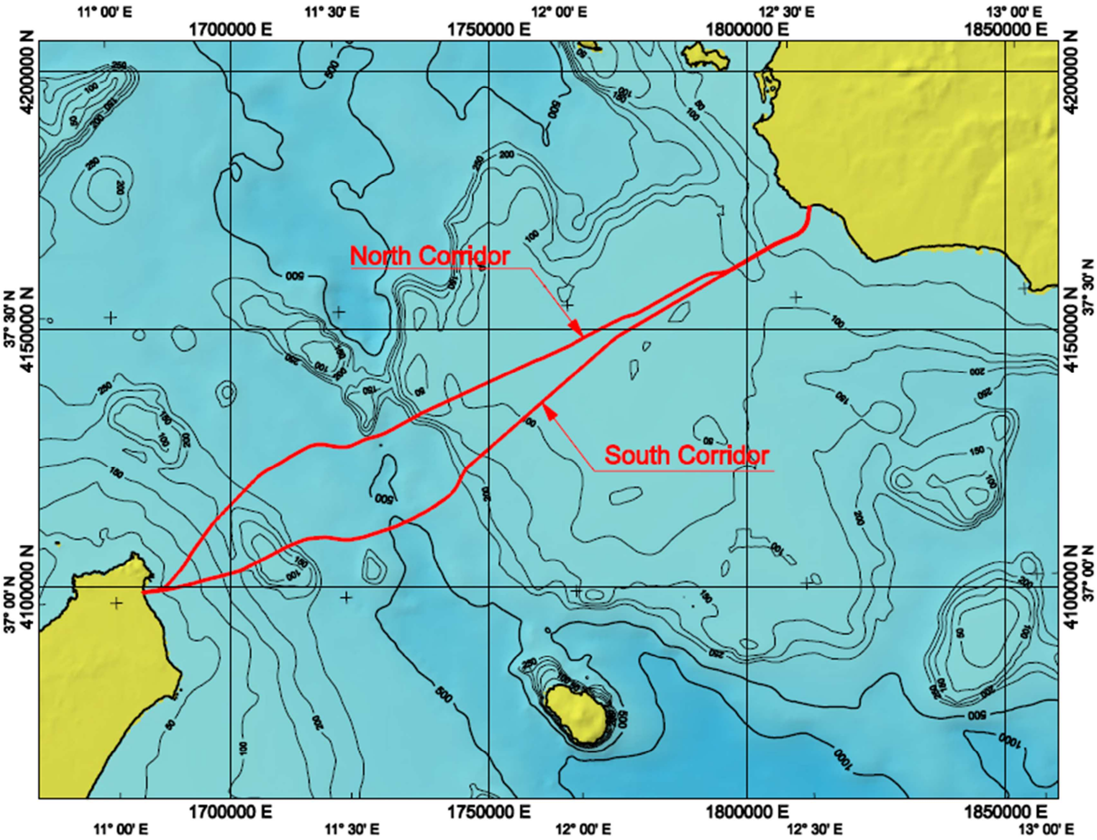


Figure 2-2 Transmediterranean pipeline system schematic (Orsolato et al., 2011)

It was monitored that an 110,000 tonnes tanker sailed across the pipelines’ route with one of her 12 tonnes anchors dragging on the seabed. This event happened at a limited water depth of about 70m. The anchor jumped the first line causing only minor damages, but then a 26’’ line was completely severed with the consequent leakage and moved laterally about 30m. The following 20’’ one was severely bent and displaced about 43m from its route. Since the pulling force exceeded the capacity of the chain, chain broke off and left the anchor on the seabed which was found trapped underneath the pipeline.

Hydraulic simulation of operating conditions was carried out to evaluate the pressure inside the 26’’ pipeline and got the conclusion that the pipeline was partially flooded, not reaching the deepest part of pipeline nor Mazara del Vallo trench. Structural analysis was carried out to simulate hooking mechanism.

After that it has been decided that the 26’’ line had to be clearly repaired, because the damage did not allow the pipeline to be operated. Even though the 20’’ pipeline didn’t show any leak, by taking into account remaining uncertainties, the integrity of the structure wasn’t sure to sustain the operation loads during the future operation, which led to a decision of repair as well.

Actions were performed to repair the pipelines, starting from some preparation work, such as pipeline cut, de-commissioning & purging and installation of Pipe Recovery Tools.

The Above Water Tie-In (AWT) method was selected and used for the repairs by Saipem. The sequence of the repair was: (a) the connection of davit and anchor lines to pipeline clamps, (b) the pipeline lifting operations and (c) the pipeline cutting, alignment, welding, NDT and field joint coating, (d) the pipeline lowering. After recommissioning, the pipelines were back to use.

2.5 30” pipeline in Norwegian Sea

During a survey of the pipeline, it was identified being hooked by an anchor, which resulted in a lateral displacement of 10m correspondingly. The coating was damaged and a broken fluke was retrieved near the pipeline. This thesis utilized some data of this pipeline to explore the parameters which might have significant influences on the response of pipeline in FE analysis part. We used ‘PL-MODEL’ to represent this pipeline in the following contents.

2.6 Summary of known hooking incidents

A summary of the hooking incidents mentioned above is presented in Table 2-1:

Table 2-1 Summary of anchor hooking incidents

Project	CATS	Kvitebjørn	Huldra	Transmediterranean		PL-MODEL
Year of hooking	2008	2010	2008	2011		2012
OD (inch)	36	30	22	20	26	30
Wall thickness (mm)	28.4	19.2	15.1			26.8
D/T	32	40	37			28
Water depth (m)	32	209	121	70	70	146
Content	Gas	Gas	Gas	Gas	Gas	Gas
Anchor size (tonnes)	5	7-10	1	12	12	3
Lateral deflection (m)	5	54	6.4	43	30	10
Crack	No	Yes	No			
Dent	Yes	Yes	Yes			Yes
Repair	Curved grouted leak clamp	Pipe section replacement (Morgrip couplings)				

3. Anchor hooking issues related to risk assessment

Following a series of anchor hooking incidents mentioned in previous chapter, anchor hooking incidents can occur more frequently than previous expected. These experiences have pointed out that a hazard of anchor hooking can pose a significant threat to the integrity of pipeline. The severe consequences could be pollution in a wide range of sea, explosion, loss of life and capsized vessel. Even if there was no influence on environment or others, a damaged pipeline after anchor hooking incidents would call for a series of actions starting from inspection of damage, which could be a huge burden and loss for that operating company. DNV (2013b) identifies the load of dragging anchors as a typical accidental load and DNV (2010a) identifies possible scenarios of dragging anchors. However, guidance tends to be very basic and doesn't cover all aspects in risk assessments. There is a growing need for regulatory authorities to give guidance on protecting new-built pipelines in design phase and also protecting existing pipelines in their operation phase.

In this chapter, several parameters of significant contribution to risk assessments of hooking incidents were discussed.

3.1 Hazard and consequences

As for a subsea pipeline, there are various hazards related to 3rd party, like anchor hooking, dropped objects, trawling, dredging. In this part, the hazard of anchor hooking was discussed only.

Even though there is no universally agreed manner on the structural aspect of a hooking incident, ideas have been brought up in the risk assessment. Two causes are envisaged whereby a ship's anchor may be dragged across a pipeline (DNV, 2010a).

First scenario is a dragged anchor in the operation of anchor handling among rig and lay vessel operations. In this scenario, anchoring operations are carried out at prescribed areas and a dragged anchor could occur due to poor holding ground, or even breakage of anchor chain.

Second scenario is emergency anchoring of ships, like tankers, supply vessels and other commercial ships, in the shipping lane above the pipeline. These vessels may drop anchors in an emergency such as adverse environmental conditions and machinery failure, in the situation of which anchoring under appropriate procedures is necessary to avoid severe consequences such as collision.

In both scenarios hooking damages can be induced during deploying and retrieving anchors in the vicinity of a pipeline.

Consequences after anchor hooking incident could be as follows:

- Disturbances of the rock cover that exposes the pipeline
- Damages in coating or/and steel pipe due to direct impact. The coating could have damages like scratches and gouges. In some severe circumstances, like heavy anchors with big impact energy, it is possible to damage the steel pipe.
- Local buckling of pipe due to hooking force after initial impact. The hooking force is acting as a point load where anchor and pipe contact. There could be dents as results of concentrated load.
- Global buckling of pipe due to hooking force. There could be lateral buckling and upheaval buckling as responses of the pulling.
- The imperfection of the pipeline after hooking incident could affect its fatigue life under cyclic loads.
- In some extreme situations, the pipeline will rupture and contaminate the environment. The production is called off and the reputation of the operating company is of danger.
- If the released product is gas, it could be a risk to vessel, platform and crews on board (HSE, 2009).
- If severe consequence happens, e.g. pollution, it is essential to carry out an inspection or maintenance on the pipeline after a hooking incident happens, which is an extra consumption of man-hours.
- As for the 3rd party, anchor or chain might break off during the pulling. The capacity of mooring system is weaken. In extreme circumstances, the vessel could capsize.

3.2 Geometrical and other considerations related to frequency

The hooking frequency of planned anchoring is mainly defined through anchor handling and geometrical considerations (Hvam et al., 1990).

The hooking frequency of emergency anchoring operations within shipping lanes above the route of pipeline is based on Hvam et al. (1990):

- Ship traffic data across the concerned area
- Failure rates like machinery failure rates
- Procedures under emergency conditions, e.g. defined by international conventions
- Natural hazards like performance of soil, adverse environmental conditions
- Geometrical considerations together with pipeline location

Ship traffic data is available on Automatic Identification System (AIS). Data of vessel movements over a time period could be taken into consideration for quantifying the risk. Based on the data of incidents we have on hand, in contrast with regions of high prevalence of ship traffic, anchor hooking incidents didn't show a high frequency in these congested shipping lanes. It doesn't mean that a statistical analysis of ship traffic is of no importance, on the other hand, it implies striking potential risks underlying the facts. What's more, it should arouse attentions of the industry on designing the route of new pipeline and protecting existing pipeline proactively.

Failure rates are obtained from historical data. It describes the level of demands for emergency anchoring. After the situation could be categorized as an emergency, proper conventional procedures are carried out to minimize the consequences. Human errors during the anchoring operation become a reason for hooking incident.

The other aspects related to risk assessment are also related to structural analysis as inputs in FE model (see Figure 3-1).

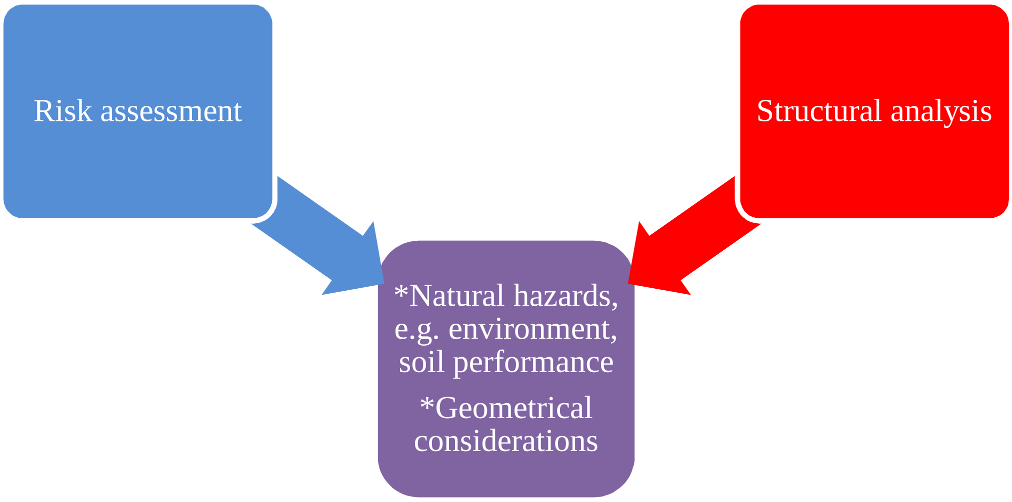


Figure 3-1 Common aspects shared between risk assessment and structural analysis

Pipeline is possible to float out of trenches in liquefied soft soil, which increases the possibility of being hooked by anchors. When an anchor is dragged on the seabed, the softer the soil is, the deeper the anchor will penetrate. Also adverse environment conditions affect the holding power of anchors. As a result, vessel could be drifting with a dragged anchor. Natural hazards could be used as inputs in FE analysis simulating the wave, current, soil performance.

As for geometrical considerations, even if an anchor is dragged, there is still a chance not to hook a specific pipeline. Multiple sizes of anchor and chain affect the possibility of hooking incidents directly. What's more, in order to get a convincible result of a structural analysis, the range of possible sizes should be narrowed down to give a good estimation of the hooking load. We explored this aspect in the following chapter.

3.2.1 Size of anchor

Most vessels travelling on the North Sea are equipped with stockless anchors (see Figure 3-2). There are several types of stockless anchor, but Spek and Hall (see Figure 3-3) are the most universally adopted. These anchors are easy of handling and simply hauled up until they rest with the shanks inside the hawsepipes and the flukes against the hull (or inside a recess in the hull) (Anonymous, 2014).

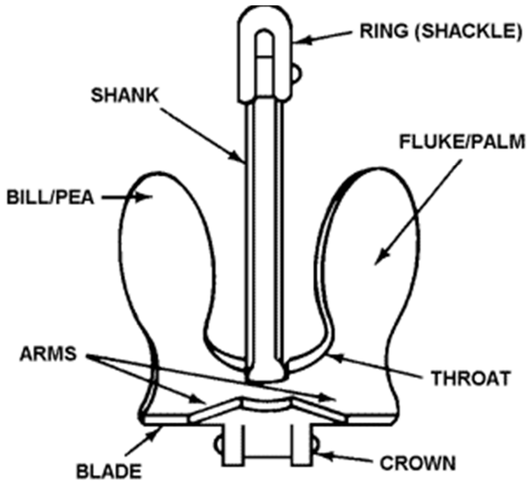


Figure 3-2 Stockless anchor illustration (Rahaman, 2014)

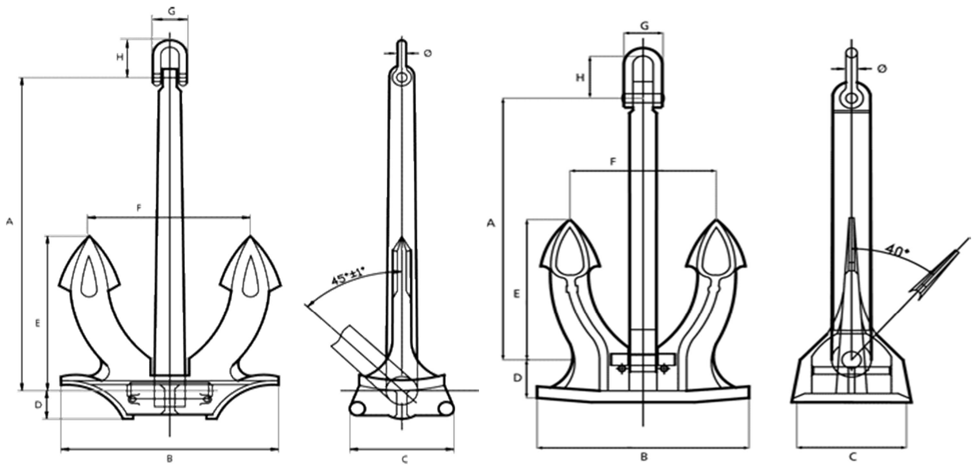


Figure 3-3 Hall schematic (left) and Spek schematic (right)

Figure 3-4 shows that not every size of anchor can hook a pipe. The size of anchor should be large enough to lead to an anchor hooking issue. The detailed dimensions of anchors are listed in Table 9-1 and Table 9-2 in Appendix 9.1.

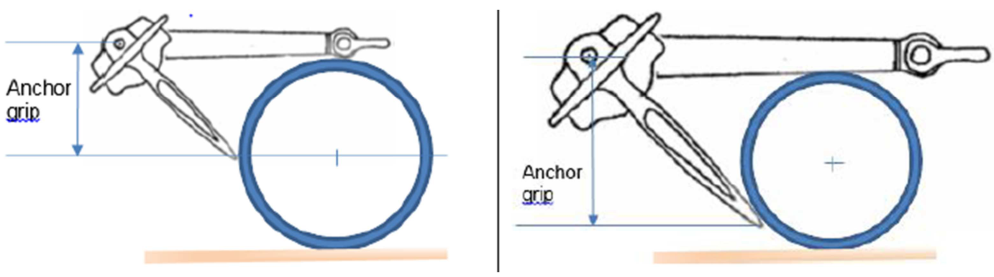


Figure 3-4 Anchor size vs. pipeline dimension

From the geometry of the anchor (see Figure 3-5), it can be seen that a specific anchor determines a range of pipelines it can hook. Thus we can calculate the maximum diameter of the pipeline for a specific anchor:

$$D_{max} = \frac{2 * L * (1 - \cos\alpha)}{\sin\alpha} \quad (3.1)$$

Where,

D_{max} is the maximum diameter a specific anchor could hook

L is the length of fluke

α is the angle between shank and fluke

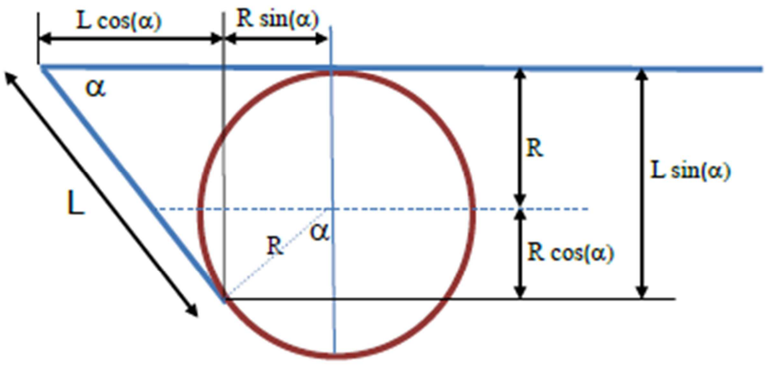


Figure 3-5 Schematic plan of anchor size vs. pipeline dimension (Vervik, 2011)

Since the fluke and shank has widths which will decrease the value of D_{max} to a certain degree, by taking into account this, $D_{max\ modified}$ is then calculated.

We can see the results of maximum dimension of pipeline that each Spek anchor could hook in Table 3-1. It can be seen from this table, as for a Spek anchor, minimum size of anchor that can be hooked onto a 30'' pipeline (e.g. dimension of Kvitebjørn & PL-MODEL) is of **3060kg** with a 247.50m chain length. The bigger dimension of a pipeline is, the more limited choices of anchor can hook.

Table 3-1 Max. diameter of pipeline that each Spek anchor could hook(α=40°)

Anchor weight	Fluke length L	Chain length	D_{max}	$D_{max\ modified}$	$D_{max\ modified}$
(kg)	(mm)	(m)	(mm)	(mm)	(inch)
3060.00	1200.00	247.50	873.53	770.67	30.34
5250.00	1450.00	288.75	1055.51	931.23	36.66
8300.00	1700.00	316.25	1237.50	1091.78	42.98
13500.00	1910.00	357.50	1390.37	1226.65	48.29
20000.00	2190.00	385.00	1594.19	1406.48	55.37
29000.00	2494.00	385.00	1815.48	1602.05	63.07

We can see the results of maximum dimension of pipeline that each Hall anchor could hook in Table 3-2. It can be seen from this table, for Hall anchor, minimum size of anchor that can be hooked onto a 30'' pipeline (e.g. dimension of Kvitebjørn & PL-MODEL) is of **1740kg** with a 146.67m chain length, which is a far smaller size of anchor compared to the Spek anchor that can hook the same size pipeline. This is because the fluke angle of Hall anchor is bigger than Spek anchor, which leads to the result.

Table 3-2 Max. diameter of pipeline that each Hall anchor could hook (α=45°)

Anchor weight	Fluke length L	Chain length	D_{max}	$D_{max\ modified}$	$D_{max\ modified}$
(kg)	(mm)	(m)	(mm)	(mm)	(inch)
1740.00	1068.00	146.67	884.76	785.05	30.91
3000.00	1283.00	247.50*	1062.87	942.73	37.12
4500.00	1465.00	275.00	1213.65	1076.22	42.37
6900.00	1681.00	201.67	1392.59	1234.73	48.61
9900.00	1896.00	330.00	1570.70	1392.41	54.82
15400.00	2199.00	371.25	1821.71	1615.14	63.59

3.2.2 Drag distance of anchor

Vessels would deploy their anchor on purpose only if their anchors are capable of reaching the seabed. When handling anchor operation, in most instances, ships will reduce speed to near stationary and then drop anchor in order to get a high probability of successful anchoring. According to Hvam et al. (1990), there is:

- For ships with DWT < 10000 tonnes, towing velocity < 1.0~1.5 m/s
- For ships with DWT > 10000 tonnes, towing velocity < 0.2~0.5 m/s

After the anchor is cast and touches the soil, there is a dragging length on the seabed until the anchor achieves the some holding capacity to stop the ship. The ultimate penetration depth is associated with drag lengths in the range 5 to 10 times the penetration depth (DNV, 2012). Drag anchors may penetrate about 1 fluke length in sand, 3 to 5 fluke lengths in mud and up to 1/2 fluke length in hard soils (Hvam et al., 1990). Taking a 3060kg Spek anchor with 1.20m long fluke as an example (see Table 3-3):

Table 3-3 Penetration depth and drag length of a 3060kg anchor regarding different soils

Soil type	Penetration depth (m)	Drag length (m)
Sand	1.20	6.0~12.0
Mud	3.60~6.00	18.0~60.0
Hard soil	0.60	3.0~6.0

Table 3-3 exhibits a rough estimation of drag length. If there is a pipeline lying within this distance, it is possible for the anchor to hook this pipeline.

There are also recommendations on estimating drag length. For instance, in Quantitative Risk Assessment of Subsea Pipeline (Anonymous, 2006), it assumes the dragging work is equal to the change in kinetic energy of ship:

$$H_c \cdot L_{drag} \cdot g = \frac{1}{2} m_s {v_s}^2 \tag{3.2}$$

$$H_c = m_a \cdot E_a \tag{3.3}$$

Where,
H_c is the average holding capacity of anchor, dependent on anchor type, penetration depth of anchor, soil condition etc.
L_{drag} is the dragging length of anchor
g is the acceleration of gravity
m_s is the total mass of ship
v_s is the towing velocity of ship when casting anchor
m_a is the mass of anchor
E_a is the efficiency of anchor

What's more, Hvam et al. (1990) states the kinetic energy of ship transfers to not only the drag work of anchor but also the drag work of ship itself.

In summary, no matter which method is used for calculation the drag length of anchor, as long as the anchor operation is carried out on purpose (i.e. low towing velocity), the anchor would be dragged on seabed and penetrate into soil until holding the ship in position. If there is a pipeline lying within the drag length, there is a risk of hooking incidents.

3.2.3 Tow depth of anchor

If vessels accidently drop their anchors due to mechanical failure like failure of braking system, towing speed could be likely bigger than that in a normal anchoring operation. In this case, the depth that an anchor could reach is another factor to consider. Thus, even if an anchor is possible to hook a specific pipeline as for the aspect of size, if the pipeline is installed on a seabed deep enough, it is still not able for the anchor to hook this pipeline.

Length of chain:

We still take 30" pipeline as an example. As for the Spek anchor, the minimum size to be hooked is of 3060kg with a 247.50m chain length. If the pipeline is lying 400m below sea surface, this 3060kg anchor still cannot hook the pipeline because the chain isn't long enough to reach the seabed.

Towing velocity:

Furthermore, the towing velocity of an anchor is another parameter influencing the depth that the anchor could reach. If a ship is moored in anchorage, the configuration of the chain is called catenary shape. When the seabed fails to hold the anchor in position, the ship will be moving forward at a certain speed and be dragging the anchor. If the speed of ship is big enough, the anchor will be dragged off the seabed and finally be suspended in seawater.

Vervik (2011) has carried out a sensitive analysis to investigate the relationship between tow speed and chain's configuration using Riflex. Assuming infinite water depth and eliminating wave or current effects, the tow depth versus distance between anchor and fairlead is plotted in Figure 3-6.

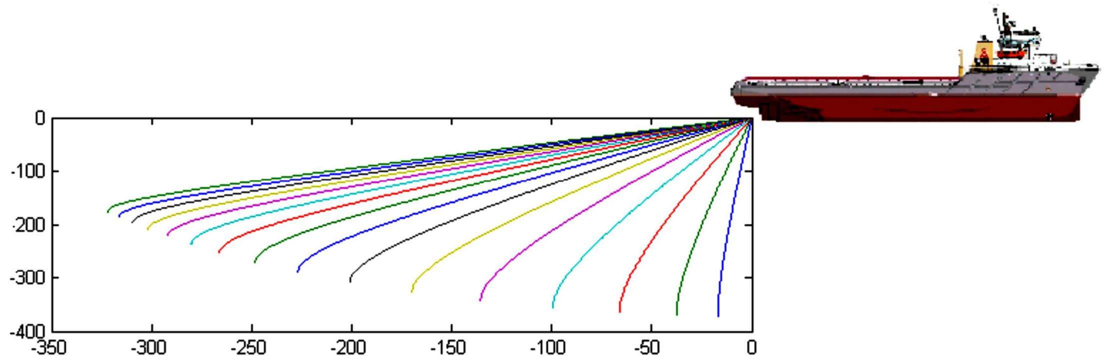


Figure 3-6 Tow depth vs. distance between anchor and fairlead related to velocities from 2 to 17 knots (Vervik, 2011)

As we could deduce from Figure 3-6, the chain could be approximately assumed to be straight, as a result of which, the reaction force from anchor will be along the axis of chain. Hence, there is equilibrium between the transverse component of gravity and drag force for the chain when anchor has got a stable velocity. Drag force per unit length becomes:

$$F = \frac{1}{2} * \rho_{water} * C_D * v^2 * D_{chain} \tag{3.4}$$

Where,

ρ_{water} is the density of seawater, 1027kg/m^3

C_D is the drag coefficient

v is the anchor velocity

D_{chain} is the diameter of chain (labeled as D in Figure 3-7)

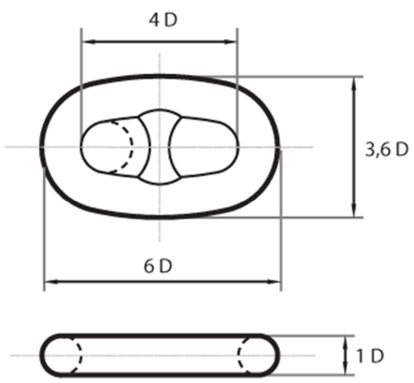


Figure 3-7 Sketch of stud chain

As for the transverse drag force along the chain, the total drag force is

$$F_{total} = L_c * F \tag{3.5}$$

$$F_{total} = m_c * g * \cos\beta \tag{3.6}$$

Where,
L_c is the length of chain
m_c is the total mass of chain, $m_c = L_c * \rho_{chain}$
ρ_{chain} is the density of chain per unit length
g is acceleration of gravity
β is the angle between horizontal direction and chain

The result of calculation is shown in Figure 3-8:

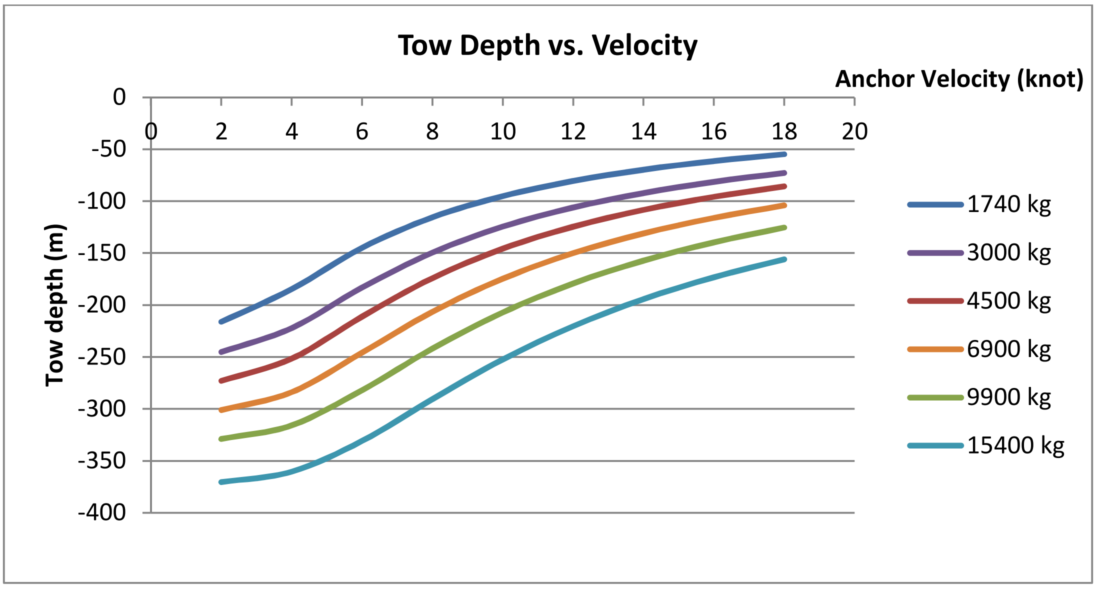


Figure 3-8 Tow depth vs. anchor velocity related to different sizes of anchor

Different weights of anchors exhibit the maximum depths they can reach corresponding their velocities. For instance, if a 3000kg anchor is moving at 6 knots, this anchor will reach maximum 175m below water surface. The relation between anchor velocity and tow depth doesn't matter with the type of anchor but the weight of anchor, chain length, chain density and chain diameter. If the velocity is bigger, the tow depth is shallower for specific size of anchor.

3.3 Prevention approaches and recommendations

Prevention of anchor damage mainly lies in physical protection of pipeline, communication with 3rd party and emergency arrangements (HSE, 2009).

As for physical protection measures, pipelines could be designed with thick coating decrease the initial impact damage. However, concrete coating offers limited protection due to its material property if the anchor is big and/or with big velocity. If the steel pipe has thicker wall, its strength increases, which might withstand the hooking load sufficiently. We can also trench the pipeline near anchorages and busy traffic lanes. This approach also has limited effect since anchors would penetrate into soil to some depth. Another similar approach is to place rock cover.

It is often regulated that anchorage is at a safe distance from pipelines. And there are exclusion zones prohibit 3rd party activities. It is also crucial to inform the 3rd party the route of pipeline. However, the vessels are possible to deploy their anchors in emergency situations. As for the part of pipeline near rig, it is routine for operation vessels such as supply vessels to carry out activities in vicinity of pipeline. Hence, it would be recommended to have protection structure for that part of pipeline.

HSE (2009) also suggests testing the emergency arrangements to review and revise until appropriate.

As most hooking incidents are unveiled during a routine survey, it is recommended that to monitor the hydrocarbon flow together with routine survey, which could be critical for further decision.

3.4 HAZID worksheet

Table 3-4 only presents a simplified HAZID worksheet on the hazard of anchor hooking as a summary of the discussions above:

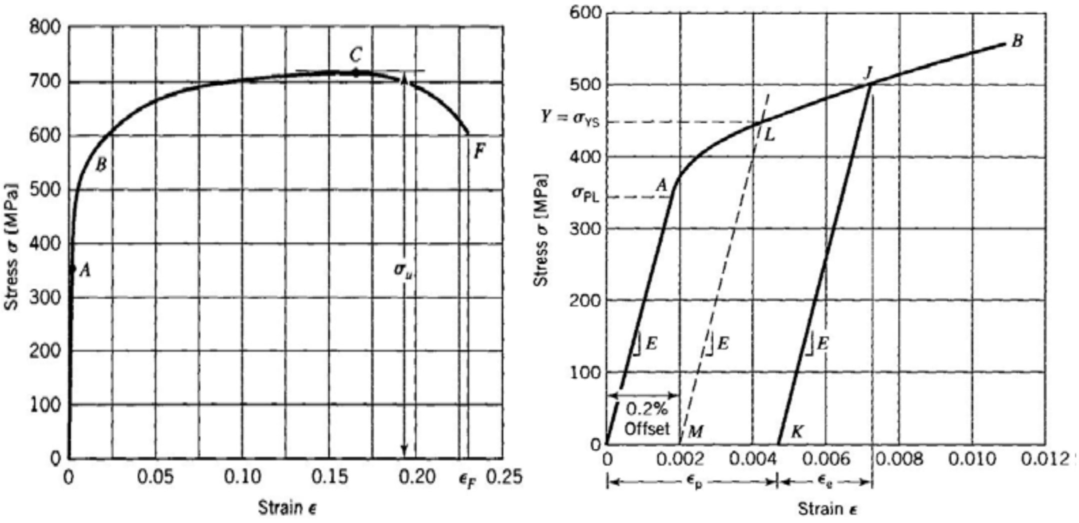
Table 3-4 HAZID worksheet of anchor hooking

Hazard of anchor hooking	
Causes	Planned anchoring
	Emergency anchoring
Consequences	Exposed buried pipeline
	Damage of coating
	Local buckling of steel pipe, decreasing fatigue life
	Global buckling of pipeline
	Hydrocarbon release and pollution
	Extra efforts on inspection and maintenance
	Loss of mooring capability for 3rd party vessel
	Risks for onboard crew
Safeguards	Rock cover
	Trenched pipeline
	Thick coating
	Protection near shore and rig
	Route away from anchorage
	Route away from populated ship traffic
	Informing 3rd party of route
Recommendations	Routine survey along pipeline
	Monitoring of hydrocarbon flow

4. Theory

4.1 Material properties

Here we will introduce the material properties (see Figure 4-1)



(a) **(b)**

Figure 4-1 Engineering stress and strain diagram for tension specimen of alloy steel (Boresi and Schmidt, 2003)

From O to A is the linear elastic part of the material, where $\sigma = E * \varepsilon$. If unloading within this region, the stain goes back to zero.

After point A, the curve is no longer linear. When taking a detail look at this part in (b), point L is called yield stress which is defined by the interaction point between the strain-stress curve and the dash line with the slope equaling E from the offset strain value point in strain axis. Usually, the offset value is arbitrary. However, a commonly agreed upon value of 0.2% is shown in Figure 4-1.

Point C is the ultimate tensile stress which indicates the maximum stress this material could achieve. After reaching the yield stress, this material maintains an ability to resist additional strain with an increase in stress before reaching point C, which is called strain hardening.

After point C, the stress no longer increases and the material breaks at point F. The maximum strain it can achieve is at point F. From point C to point F, it is called softening.

The Ramberg–Osgood equation is a method to describe the nonlinear relationship between stress and strain. The stress-strain curve has a smooth elastic-plastic transition and the total strain is sum of elastic and plastic parts (ASM-International, 2002).

$$\varepsilon = \frac{\sigma}{E}(1 + \alpha_{RO} \cdot (\frac{\sigma}{\sigma_0})^{n_{RO}-1} \tag{4.1}$$

$$\varepsilon_p = \varepsilon - \frac{\sigma}{E} \tag{4.2}$$

$$\varepsilon_E = e^{\varepsilon} - 1 \tag{4.3}$$

$$\sigma_E = \frac{\sigma}{1 + \varepsilon_E} \tag{4.4}$$

Where
ε is true strain
ε_p is true plastic strain
σ is true stress
σ_0 is true yield strength
E is Young's modulus
α_{RO}, n_{RO} are Ramberg-Osgood parameters
ε_E is engineering strain
σ_E is engineering stress

4.2 Mechanical model

Before an anchor hooking incident happens, the pipeline used for transporting product is long enough to allow for a study based on limited length of pipeline. The pipeline is installed on seabed but some parts of it are buried in rocks. When the pipeline is dragged by a moving anchor, it withstands the friction force from soil and rocks both in axial and lateral directions. Also hydrodynamic forces act on the pipeline when it is pulling sidewise. The sketch of the model is shown in Figure 4-2:

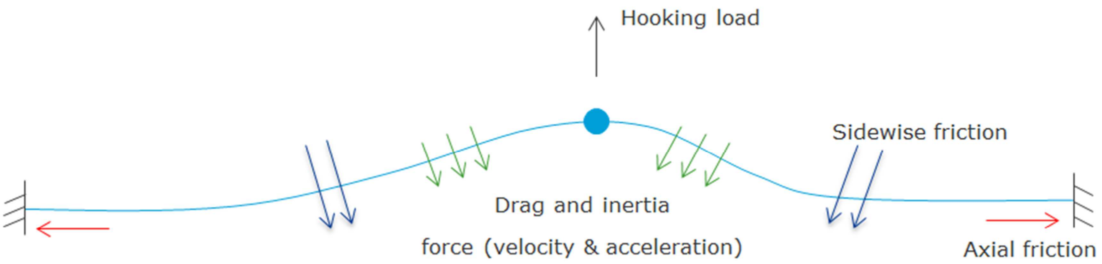


Figure 4-2 Sketch of force diagram

4.2.1 Process of pipeline's response

When a ship drags its anchor on the seabed, it has kinetic energy related to its velocity and weight. Usually, when anchor hits a pipeline, initial impact energy is absorbed by concrete coating without denting the steel pipe. If the moving anchor hooks the pipeline subsequently, the hooking load acting as a point load making the pipeline deform as a slender beam.

At first stage, the pipeline is subjected to global deformation. In elastic range of material, there is no permanent change. Then the hooking load starts to drag the pipeline sidewise, increasing with displacement.

As the hooking load becomes bigger, local buckling will be initiated. The global deflection continues, but local buckling is accumulated more and more. Membrane effect is triggered by large deflection, including a stiffening of the pipe to the additional loads (Hvam et al., 1990).

After the ultimate bending capacity is reached, the start of catastrophic capacity reduction occurs immediately since the pipeline is subjected to combined load (see dash line in Figure 4-3). In contrast, for pure bending, after the ultimate bending capacity is reached, there is a slow-down in the changes of cross section. Then the material will soften and collapse (see solid line in Figure 4-3).

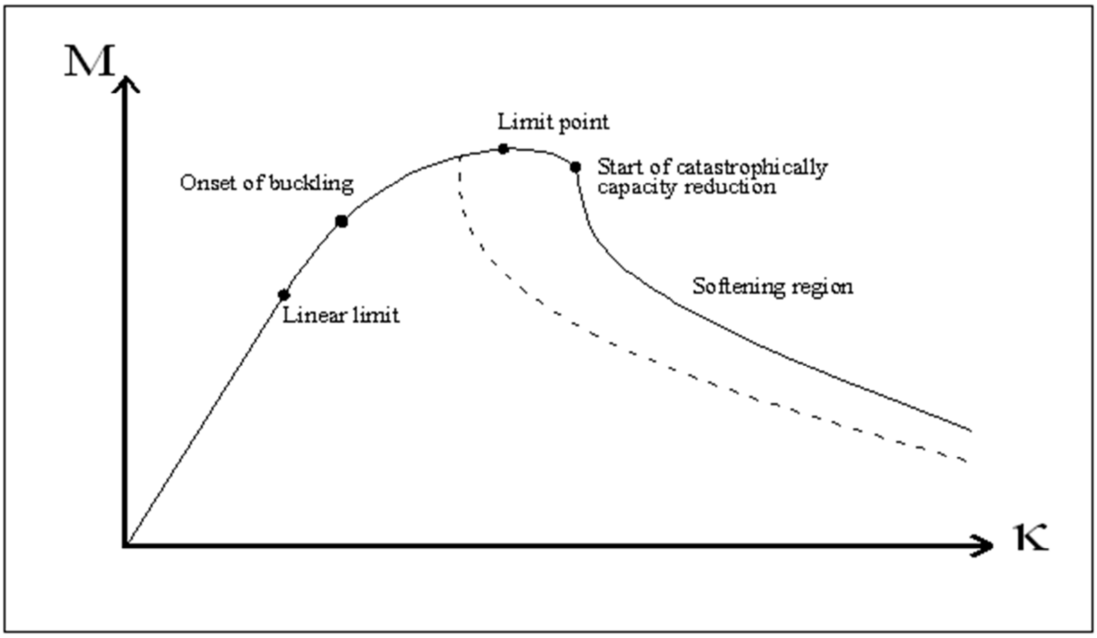


Figure 4-3 Bending moment vs. curvature (Hauch and Bai, 1999)

4.2.2 Functional loads

Loads arising from physical existence of the pipeline system and its intended use shall be classified as functional loads (DNV, 2013b). Several functional loads are discussed in the following.

Weight

The weight includes the weight of pipe, buoyancy, coating and content.

Pipe soil interaction

An interaction model between pipe and soil consists of seabed stiffness and friction factors.

The seabed stiffness is a function of several parameters, e.g. penetration distance into soil. For different types of soil, the nonlinear finite element model of penetration and stiffness is different as well. There are several models described in Bai (2001).

Based on DNV-RP-F109 (DNV, 2010b), the friction force from soil consists normally of two parts, a pure Coulomb friction term and a passive resistance term depending on the pipe's depth of penetration into the soil. Both Coulomb friction part and passive resistance part should be calculated based on nominal pipe weight. For pipes that not penetrating into the soil much, a pure Coulomb friction model is suitable enough. When the pipeline penetrates into soil deep, it will be taking more efforts to move the pipeline laterally compared to move it axially. According to Bai (2001), this is because the passive lateral resistance is produced when soil accumulates in pipe's lateral motion. Hence, an anisotropic friction model will satisfy this effect, which defines different friction coefficients in lateral and axial directions.

Current design practice like DNV-RP-F109 (DNV, 2010b) presents the behavior of the pipe soil interaction using 'F-Y' curve, which indicates the relationship between resistance F and lateral displacement Y. The curve is related to the type of the soil.

Temperature load and pressure load

During the whole life cycle of operation, the pipeline withstands several cycles of heat up and cooling down, thus the pressure and temperature change with time. If the end of pipeline isn't fixed, as the temperature goes up the pipeline will expand gradually, i.e. walking. If both ends are fixed, there will be buckles. Hence, loads due to temperature and pressure are also part of functional loads.

4.2.3 Environmental loads

Hydrodynamic forces are induced by relative motion between pipeline and surrounding water. Drag force and inertia force will act on a moving pipeline, more details referring to DNV-RP-H103 (DNV, 2011).

4.2.4 Accidental load-dragging anchor

Dragging anchor is categorized as an accidental load based on DNV-OS-F101 (DNV, 2013b). The load is a point load applied on pipeline which causes both global deflection and local deformation.

4.2.5 Boundary condition

If the pipeline is long enough, the boundary of pipeline could be taken as fixed when we want to analyze a certain part of the pipeline, i.e. the part of pipe between virtual anchors. The partially restrained pipe is not part of concern.

The pipeline is laid on the uneven seabed for the case we study. For some other cases, pipeline could also be trenched or covered by rocks. The vertical profile of the seabed is available by using geophysical survey tools like Swathe bathymetry, side scan sonar during the phase of route design.

4.3 Typical failure mode due to hooking – local buckling

A typical damage due to hooking load is local buckling of the cross-section as a result of excessive bending. Buckling mode confined to a short length of the pipeline causing gross changes of the cross section; collapse, localized wall wrinkling and kinking are examples thereof. If these criteria are exceeded then the pipeline will experience either collapse or rupture due to excessive yielding in the longitudinal direction, the latter being most relevant for small diameter pipelines (i.e. less than 6''- 8''). Large accumulated plastic strain may aggravate local buckling and shall be considered.

As for plastic bending moment (pure bending) and plastic axial force (pure tension or compression), there are expressions as:

$$M_P = f_y \cdot (D - t)^2 \cdot t \tag{4.5}$$

$$S_P = f_y \cdot \pi \cdot (D - t) \cdot t \tag{4.6}$$

Where,
M_P is plastic moment
S_P is plastic axial force
D is outer diameter of a pipe
t is wall thickness of a pipe
f_y is yield stress to be used in design

$$f_y = (\sigma_Y - f_{y.temp}) \cdot \alpha_u \tag{4.7}$$

σ_Y is yield stress
$f_{y.temp}$ is derating on yield stress due to temperature
α_u is material strength factor

If we consider the effect of combined loads on plastic bending moment, Hauch and Bai (1999) have developed an equation to predict the ultimate bending capacity of pipes, accounting for initial out of roundness, longitudinal force and internal/external overpressure. As a result of combined loads, the ultimate plastic bending capacity, M_c, is smaller than pure bending situation, M_P:

$$M_c = M_p \sqrt{1-\left(1-\alpha^2\right)\left(\frac{p}{p_l}\right)^2} \cos\left(\frac{\pi}{2} \frac{\frac{S}{|S_p|} - \alpha \frac{p}{|p_l|}}{\sqrt{1-\left(1-\alpha^2\right)\left(\frac{p}{p_l}\right)^2}}\right) \tag{4.8}$$

Where,
M_c is ultimate bending moment capacity
p is pressure acting on the pipe
p_l is ultimate pressure capacity
S is true longitudinal force acting on the pipe
α_s is a strength anisotropy factor depending on the ratio between the limit stress in the longitudinal and hoop direction respectively.

Also DNV GL suggests an equation as a judgment on acceptable bending moment, for more information, see Chapter 4.4.2.

4.4 Design criteria – local buckling

This section is based on DNV-OS-F101(DNV, 2013b).

The local buckling could be checked separately for:

- Displacement Controlled condition (DC condition).
- Load Controlled condition (LC condition)

A load-controlled condition is one in which the structural response is primarily governed by the imposed loads, while a displacement-controlled condition is one in which the structural response is primarily governed by imposed geometric displacements DNV-OS-F101 (DNV, 2013b).

4.4.1 Displacement controlled condition (Strain based criterion)

There are two strain based criterion for subsea pipelines categorized by internal overpressure domain or external overpressure domain. Since the pipeline we analyze is during its operation period, an internal overpressure will be described here as relevant.

Pipe members subjected to bending moment and axial force, internal over pressure shall be designed to satisfy the following criterion at all cross sections:

$$\varepsilon_{Sd} \le \varepsilon_{Rd} = \frac{\varepsilon_c}{\gamma_\varepsilon}, \qquad D/t \le 45, p_i \ge p_e \tag{4.9}$$

$$\varepsilon_c = 0.78 \cdot (\frac{t}{D} - 0.01) \cdot (1 + 5.75 \cdot \frac{p_{min} - p_e}{p_b}) \cdot {\alpha_h}^{-1.5} \cdot \alpha_{gw} \tag{4.10}$$

$$p_{min} = p_d \cdot \gamma_{inc} + \rho \cdot g \cdot (\Delta h) \tag{4.11}$$

$$p_b = \frac{2 \cdot t}{D - t} \cdot f_{cb} \cdot \frac{2}{\sqrt{3}} \tag{4.12}$$

$$f_{cb} = Min\left[f_y; \frac{f_u}{1.15}\right] \tag{4.13}$$

$$f_y = (\sigma_Y - f_{y.temp}) \cdot \alpha_u \tag{4.14}$$

$$f_u = (\sigma_U - f_{u.temp}) \cdot \alpha_u \tag{4.15}$$

Where,
ε_{Sd} is design compressive strain
ε_{Rd} is design resistance strain
γ_ε is strain resistance factor related to safety class, see Table 4-3
ε_c is strain capacity
p_{min} is minimum internal pressure that can be continuously sustained with the associated strain, in this case a local incidental pressure will be used as p_{min}
p_b is the burst pressure
p_e is the external pressure
$\alpha_h = (R_{t\,0.5}/R_m)_{max}$, is max. yield to tensile ratio, for steel X65 is 0.93
α_{gw} is girth weld factor, $\alpha_{gw} = 0.88$ based on Figure 4-4
p_d is design pressure at the pressure reference elevation
γ_{inc} is incidental to design pressure ratio, $\gamma_{inc} = 1.05$ (DNV, 2013b)
ρ is the content density
Δh is the difference of elevation between pressure reference point and local pressure point
$f_{y.temp}$ is derating on yield stress due to temperature
$f_{u.temp}$ is derating on tensile strength due to temperature
α_u is material strength factor, $\alpha_u = 0.96$ (DNV, 2013b)

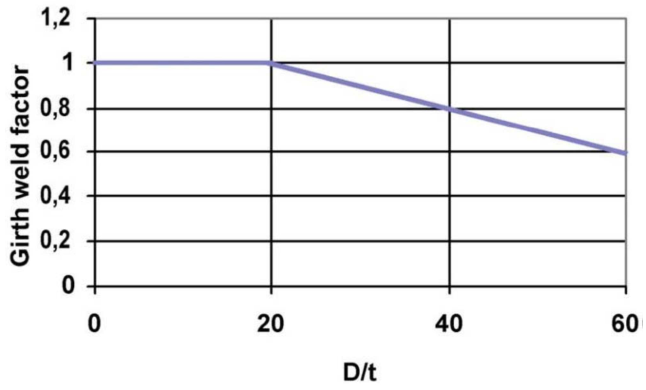


Figure 4-4 Proposed girth weld factors (DNV, 2013b)

The load effect can be expressed in the following format:

$$\varepsilon_{Sd} = \varepsilon_F \cdot \gamma_F \cdot \gamma_C + \varepsilon_E \cdot \gamma_E + \varepsilon_I \cdot \gamma_F \cdot \gamma_C + \varepsilon_A \cdot \gamma_A \cdot \gamma_C \qquad (4.16)$$

Table 4-1 shows the load effect factors regarding limit states:

Table 4-1 Load effect factor combinations (DNV, 2013b)

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 combine 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 presented i.e. when major part of pipeline is exposed to the same functional load. This will typically only apply to pipeline installation.

ALS is a ULS due to accidental loads which case we will use here, i.e. all factors set as 1 except for γ_C. Based on DNV-OS-F101 (DNV, 2013b), for $\gamma_C = 1.07$, pipeline is resting on uneven seabed, for a γ_C lower than 1 in expansion and global buckling design are to represent the degree of displacement control and uncertainties.

PL-MODEL has the basic data for calculation is shown in Table 4-2

Table 4-2 Basic data of PL-MODEL used for acceptable strain calculation

Basic data		
Outer radius of steel pipe	0.3718	[m]
Wall thickness of steel pipe	0.0268	[m]
Density of content	80.0	[kg/m^3]
Design pressure	2.55E+07	[Pa]
Operating pressure	8.00E+06	[Pa]
Reference elevation for pressure	-160.0	[m]
Water depth	-147.5	[m]

We could see the logic of calculation based on DNV-OS-F101 (DNV, 2013b) from Figure 4-5, where ε is the acceptable strain taking into consideration of the load factors which should be compared with the FE result. If ε is bigger than the result of FE analysis, then the FE result is acceptable.

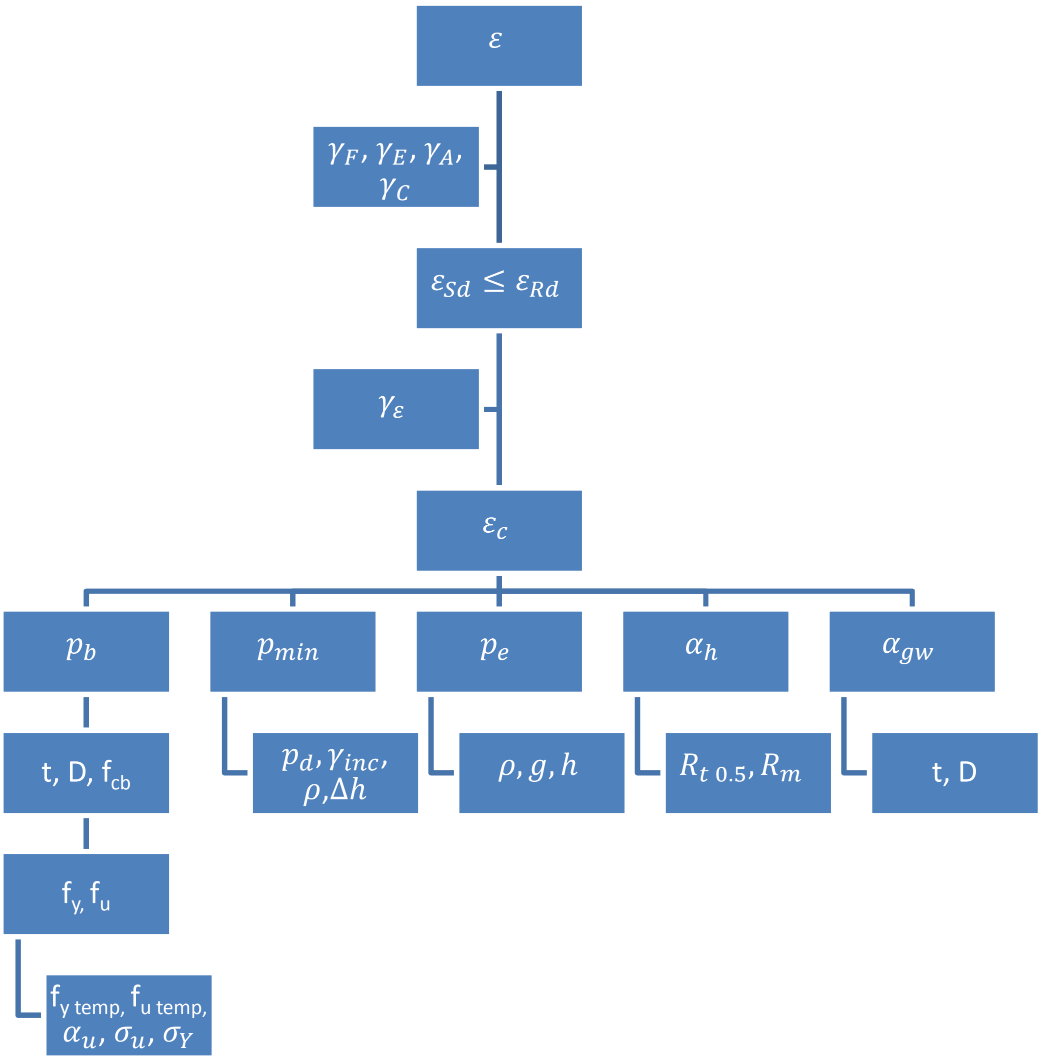


Figure 4-5 Flow diagram of strain calculation (from bottom to top)

A calculated result is shown in Table 4-3. The strain capacity is 3.99%. If considering the safety classes, the acceptable strains are smaller than this value.

Table 4-3 Calculated results of strain for PL-MODEL

Safety class	Low	Medium	High
Strain capacity		$\varepsilon_c = 3.99\%$	
$\boldsymbol{\gamma_\varepsilon}$	2.0	2.5	3.3
$\boldsymbol{\varepsilon_{Rd}}$	1.99%	1.59%	1.21%
$\boldsymbol{\varepsilon < \varepsilon_{Sd}/\gamma_c}$	Acceptable strain ε		
$\boldsymbol{\gamma_c = 1.07}$	1.86%	1.49%	1.13%
$\boldsymbol{\gamma_c = 0.82}$	2.43%	1.94%	1.48%

4.4.2 Load controlled condition (Bending moment capacity)

A load controlled condition is not required to be used as a failure criterion in the scope of this thesis. However, due to the relation between maximum bending moment and maximum strain (see Figure 4-6), there is higher allowable strength regarding the same safety level when we use a strain-based criterion. An LC criterion can always be applied in place of a displacement controlled design criterion. In this part, we discussed it to get more understanding about the failure criteria.

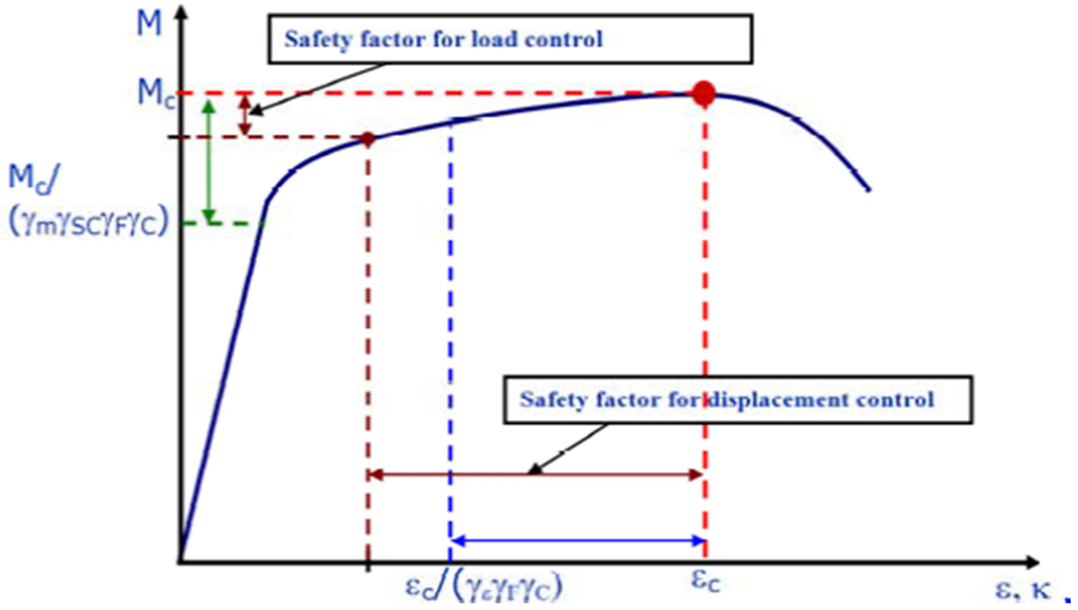


Figure 4-6 Bending moment vs. strain (Amdal et al., 2011)

$$\left\{\gamma_m \cdot \gamma_{sc} \cdot \frac{|M_{Sd}|}{\alpha_c \cdot M_P} + \left\{\frac{\gamma_m \cdot \gamma_{sc} \cdot S_{Sd}}{\alpha_c \cdot S_P}\right\}^2\right\}^2 + (\alpha_p \cdot \frac{p_i - p_e}{\alpha_c \cdot p_b})^2 \leq 1 \tag{4.17}$$

$$\alpha_p = \begin{cases} 1 - \beta, & \dfrac{p_i - p_e}{p_b} < \dfrac{2}{3} \\ 1 - 3 \cdot \beta \left(1 - \dfrac{p_i - p_e}{p_b}\right), & \dfrac{p_i - p_e}{p_b} \geq \dfrac{2}{3} \end{cases} \tag{4.18}$$

$$\beta = \frac{60 - D/t}{90} \tag{4.19}$$

Where,
M_{Sd} is the design moment
S_{Sd} is the design effective axial force
S_P and M_P denote the plastic capacities for a pipe
p_i is the internal pressure
p_e is the external pressure
p_b is the burst pressure
α_c is a flow stress parameter
α_p accounts for effect of D/t ratio

In an anchor hooking problem, the load is a point load. Based on the work of Vitali et al. (2003), local forces may reduce significantly bending moment capacity. This should be included by a modification of the plastic moment capacity as follows:

$$M_{P,point\ load} = M_P \cdot \alpha_{pm} \tag{4.20}$$

$$\alpha_{pm} = 1 - \frac{D/t}{130} \cdot \frac{R}{R_Y} \tag{4.21}$$

$$R_Y = 3.9 \cdot f_y \cdot t^2 \tag{4.22}$$

Where,
α_{pm} is plastic moment reduction factor accounting for point load
R is reaction force from point load

We can get plastic moments accounting for different point loads shown in Table 4-4. $M_{P,point\ load}$ decreases with increasing point load.

Table 4-4 Calculated plastic moment accounted for point load

R	976.5	1098.6	1220.7	1342.7	[kN]
$D/t = 28$ **(PL-MODEL)**					
S_P	29071.5				[kN]
M_P	5948.6				[kNm]
$M_{P,point\ load}$	4919.3	4790.6	4661.9	4533.3	[kNm]
$D/t = 23$					
S_P	31698.0				[kN]
M_P	7169.8				[kNm]
$M_{P,point\ load}$	6505.3	6422.2	6339.1	6256.1	[kNm]
$D/t = 40$					
S_P	18800.6				[kN]
M_P	4335.1				[kNm]
$M_{P,point\ load}$	2295.1	2040.1	1784.9	1530.1	[kNm]
***Values of D/t here have same outer diameter (D), different thicknesses (t) *The other properties are all the same as PL-MODEL *Chapter 5.3.2 studied these 3 cases with R=976.5kN**					

5. FE analysis

5.1 Introduction of FE method

FE method provides high-quality realistic simulation solutions with new capabilities allowing real-world physical behavior of products and materials to be explored. The FE method is the main tool used in industry to simulate pipeline response and it gives satisfactory results.

5.2 Basic Abaqus model

5.2.1 Main assumptions

We disregarded the imperfection during the construction of pipeline. The effect of concrete coating had on pipeline's stiffness and strain concentration at field joints were not accounted for in the model. We also assumed the cross section didn't change during the pull since we used beam elements in the pipeline model. The residual stress caused by installation method, like pipeline passing over a stinger in S-lay, was also not accounted for here.

In a real case, a fluke has thickness, which means pipeline might withstand a distributed load in a short length. However, when exploring parameter study in load model in Chapter 5.3, the load was assumed to be applied at a single point in this thesis instead of a short distributed load. The reason for this assumption was that the fluke thickness was far less than the pipeline's length in this model. Horizontal component of hooking was assumed bigger than vertical component referring to (DNV, 2010c).

When coming to velocity model in Chapter 5.4, it was assumed that the chain was straight at the instant of hooking. This assumption was because Vervik (2011) had investigated on the anchor tow depths with variant tow speed taking gravity, buoyancy, drag force and initial force into consideration. His result illustrated that the shape of chain was nearly straight except for a small length of chain where connecting anchor. Hence, there would be a relatively little time for the chain to be stretched until straight compared to the hooking time, especially for a high tow speed situation. Once an anchor hooks pipeline in a real incident, it is believed that tension in chain due to pipeline's resistance is far more crucial than other force components. Thus, a simplified chain model by only assigning material properties, dimension and density was used, which were of direct correlation with axial stiffness. What's more, there is short time for denting pipeline locally when anchor hits pipeline, which was not taken into consideration here as well.

5.2.2 Input data

In our case, a pipeline with length of 8000m was built as Table 5-1, with each element 2-meter (approximately) long. A total length of long pipeline was simulated in this model to minimize the boundary influence on the analysis. The element type of the pipeline was beam element. I-DEAS (2014) states ‘‘Compared to shell element, beam element is abstracted to 1D element by storing the 2D cross-section property while shell element is abstracted to 2D elements by storing the third dimension as a thickness’’. In a global analysis beam element is good to exhibit overall deflection of a pipeline. Since the cross section of the beam element doesn’t change during FE analysis, beam element doesn’t show local stress concentration where the load is applied. There is another disadvantage of the beam element. Stress could be displayed at different points on a cross section in a beam element, but it couldn’t display stress variation from inner surface to outer surface if we assume the cross section to be a hollow pipe. However, beam elements still give relatively good results for a global analysis.

Table 5-1 Abaqus input data-model data

Model		
Pipe nodes	1~4000	[-]
Length of pipe	8000	[m]
Position of the hooking point	4032	[m]

As is shown in Table 5-2, this pipeline contains two sections with different dimensions. The concrete coating would not only provide on-bottom stability but also affect the pipe stiffness, though only steel pipe was modeled here. Density had been adjusted due to the coating’s existence when calculating gravity force. As for buoyancy and dynamic calculation (initial force and drag force), dimension as the composition of steel and concrete was used in this model.

Table 5-2 Abaqus input data-dimension and material of pipeline

	Section 1	Section 2	
Location	0~4028	4028~8000	[m]
Outer radius of steel pipe	0.3718	0.3718	[m]
Wall thickness of steel pipe	0.0268	0.0268	[m]
Density of steel pipe	7850.0	7850.0	[kg/m^3]
Total coating thickness	0.0510	0.0610	[m]
Density of coating	2240.0	2261.0	[kg/m^3]
Steel material	X65	X65	[-]

In Abaqus, the cross section area doesn’t change for a beam element. Based on this fact, a nonlinear model was described using engineering stress vs. true strain, calculation based on Table 5-3 and Chapter 4.1. The result is shown in Figure 5-1.

Table 5-3 Abaqus input data-mechanical property of X65 at 20 °C

Material model	X65 at 20 °C	
Young's modules	2.07E+11	[N/m^2]
Poisson's ratio	0.30	[-]
Thermal Expansion coefficient	1.17E-05	[1/K]
SMYS	450	[MPa]
SMTS	530	[MPa]

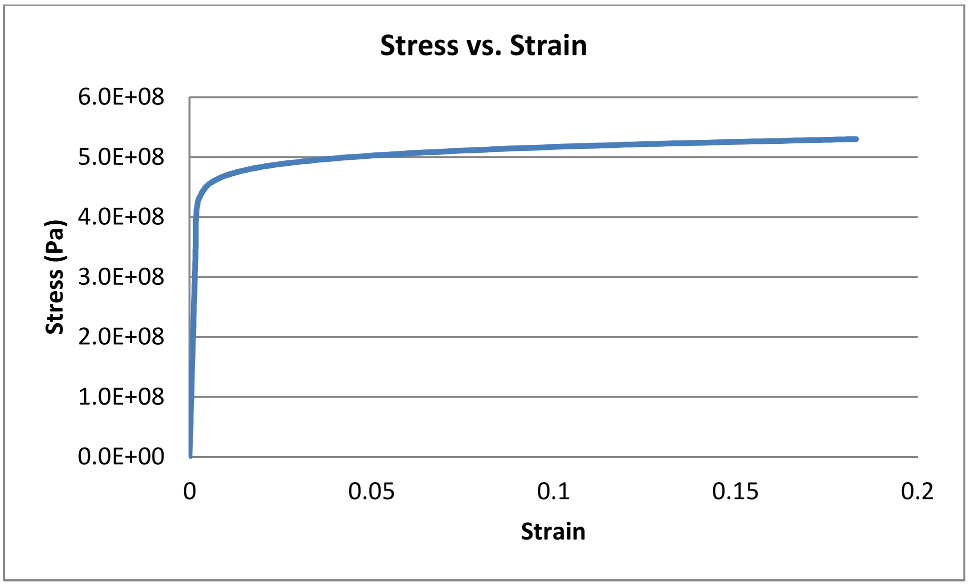


Figure 5-1 Stress-strain curve of X65

In this model, a friction model is shown in Table 5-4 according to a soil survey for this pipeline.

As noted by Bai and Bai (2014), if the soil berm is ignored, the lateral resistance could be assumed to remain constant with continuing lateral displacement. In a real situation when the pipeline is in motion, the soil around pipeline will accumulate, which supplies bigger resistance force. In this case, we neglected the soil berm's influence, and then the model exhibited the property using a constant friction coefficient. The friction coefficient was assumed to be (Abaqus Analysis User's Manual, 2012)

- Independent of the slip rate.
- Independent of the contact pressure.
- Independent of the temperature.

Since this pipeline is lying on a hard seabed, we used a small lateral friction coefficient here. And the vertical soil stiffness describes the soil's ability of resistance when pipeline has a trend of compressing the seabed.

Table 5-4 Abaqus input data-seabed property

Seabed properties		
Axial friction coefficient	0.45	[-]
Lateral friction coefficient	0.20	[-]
Vertical soil stiffness	1.50E+06	[N/m]

Temperature and pressure are directly influenced if the operator changes the flow rate or even shuts down exploitation process in some emergent situations. And during operation period, hydrocarbon displays different temperatures and pressures along the pipeline. In the upstream zone near wellhead, hydrocarbon has higher temperature and pressure than hydrocarbon in downstream zone because of heat loss and friction. As a result of temperature and inner pressure change, longitudinal strain alters as well.

In this case, inner pressure was assumed to be constant for this pipeline model since it is only a short part of the whole pipeline. Table 5-5 exhibits operational data of this pipeline. To be more accurate, it could add more steps to simulate the changes in pressure and in temperature like heating up and cooling down, but here this would pass. Lay tension was included in pipeline model as well. When pipeline is lying down from lay vessel, the end of pipeline is pre-tensioned to avoid collision between pipeline and stinger tip. In Chapter 5.3.6, we would study more about the effect of lay tension variation has on pipeline.

Table 5-5 Abaqus input data-operational data

Operational data		
Density of content	80.0	[kg/m^3]
Installation temperature	0.0	°C
Operating temperature	62.2	°C
Operating pressure	8.00E+06	[Pa]
Reference elevation for pressure	-160.0	[m]
Lay tension	3.50E+05	[N]

The input data regarding environment is presented in Table 5-6:

Table 5-6 Abaqus input data-environmental data

Environmental data		
Density of seawater	1027	[kg/m^3]
Drag coefficient	0.7	
Inertia coefficient	2.0	

5.2.3 Load sequence in static analysis

Table 5-7 describes the procedure of static analysis from the established model. Since the pipeline model was to analyze a pipeline situated on seabed, it had to include some sort of installation process to find the initial pipeline configuration for subsequent dynamic analysis.

Table 5-7 Load sequence in static analysis

Step	Description
1	Applying gravity and buoyancy to pipeline
2	Laying down of pipeline on seabed, including lay tension and axial friction coefficient
3~5	Modifying boundary conditions
6	Introducing content inside of pipeline
7	Including buckle
8	Including rock cover
9	Applying pressure & temperature
10	Including dynamics coefficients

During step 1, dry weight and buoyancy were applied to this pipeline with no content inside. Even though only steel pipe was modeled, density used for calculating gravity and outer diameter of pipe used for calculating buoyancy had been modified by taking into consideration of coating. Figure 5-2 depicts the pipeline above seabed before installation.

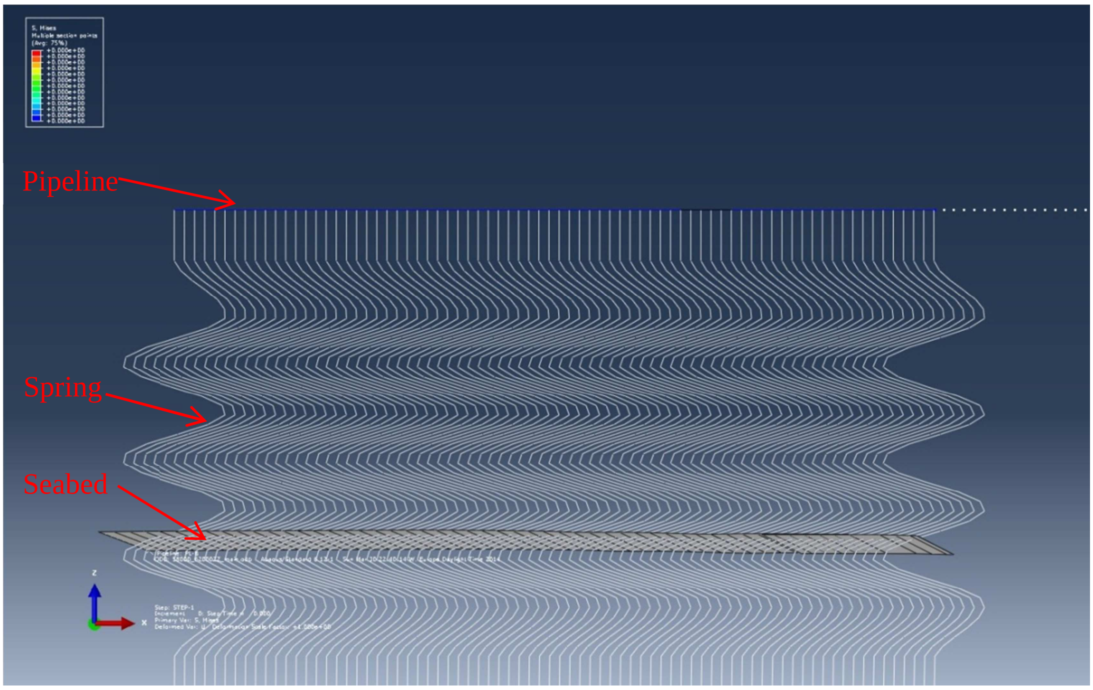


Figure 5-2 Abaqus model-Step 1 applying gravity and buoyancy

During step 2 (see Figure 5-3), lay tension was applied to one end of pipeline and pipeline was laid down on seabed by lowering springs. Then springs were removed from Abaqus model. And the pipeline was simplified to have no displacement in lateral direction, thus, only axial friction was applied in this step.

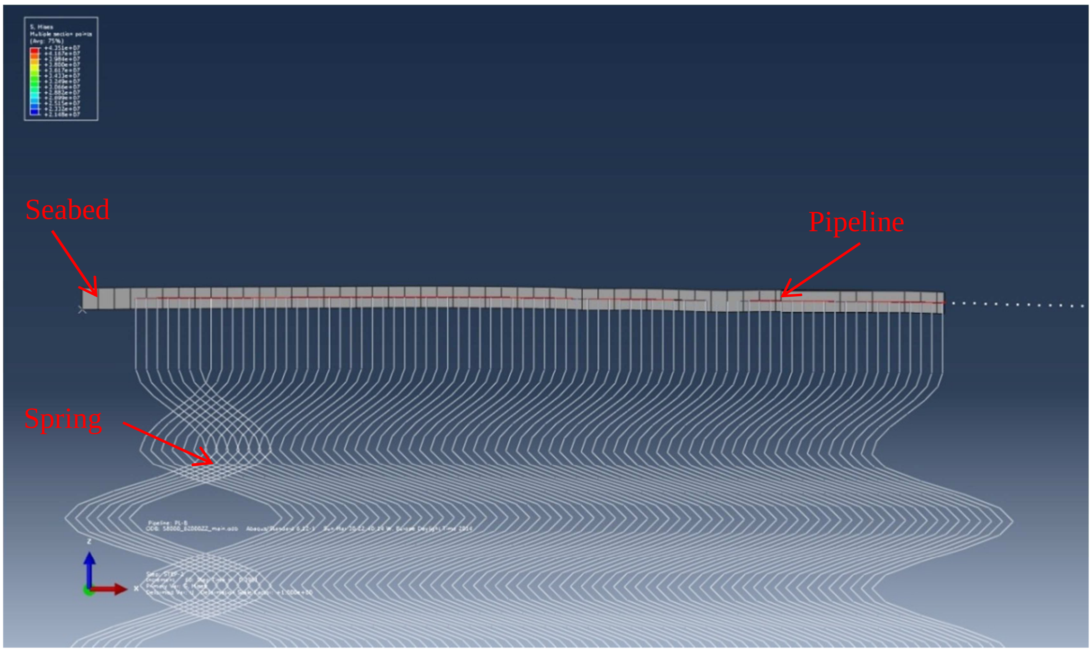


Figure 5-3 Abaqus model-Step 2 laying down of pipeline on seabed

During step 3~5, boundary conditions were modified like introducing axial and lateral friction coefficients, fixing pipeline ends.

According to previous survey, this pipeline had several buckles, which were modeled in step 7.

As is shown in Figure 5-4, rock cover using PSI34 element was added on pipeline.

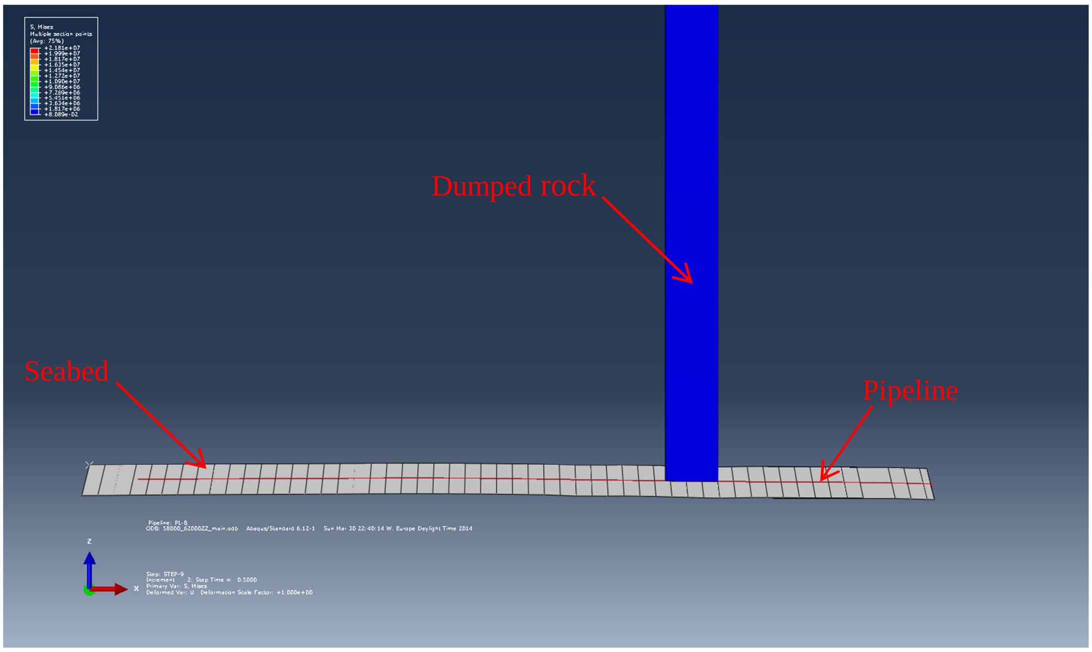


Figure 5-4 Abaqus model-Step 8 including rock cover

In step 10, drag coefficient and inertia coefficient were included in this model.

5.3 Parameter study of load model

5.3.1 Input of load model

In the sequence of static model, a dynamic model was run to activate a hooking load at Node 2016, which was based on a survey result showing a broken fluke was discovered near the middle of pipeline (see Table 5-8). In this part, a load history model was applied directly onto the pipeline where consistent with the position in a hooking incident.

Table 5-8 Subsequent steps of load model after static model (see Table 5-7)

Step	Description	Type of analysis
11	Activating hooking load at Node 2016	Dynamic

As shown in Table 5-9, load histories as input for dynamic analysis are listed. Horizontal force was estimated slightly bigger than vertical force if (DNV, 2010c) was taken as reference.

Table 5-9 Peak values of load as input for Case 01 ~22

Case	Horizontal force Fp	Vertical force Fz	Description
	[N]	[N]	
01	8.00E+05	5.60E+05	Monotonic T=5s
02	9.00E+05	6.30E+05	
03	1.00E+06	7.00E+05	
04	1.10E+06	7.70E+05	
05	8.00E+05	5.60E+05	Monotonic T=7s
06	9.00E+05	6.30E+05	
07	1.00E+06	7.00E+05	
08	1.10E+06	7.70E+05	
09	8.00E+05	5.60E+05	Cyclic T=5s
10	9.00E+05	6.30E+05	
11	1.00E+06	7.00E+05	
12	1.10E+06	7.70E+05	
13	8.00E+05	5.60E+05	Cyclic T=7s
14	9.00E+05	6.30E+05	
15	1.00E+06	7.00E+05	
16	1.10E+06	7.70E+05	
17	8.00E+05	5.60E+05	See Figure 5-12
18	8.00E+05	5.60E+05	
19	8.00E+05	5.60E+05	Monotonic T=7s
20	9.00E+05	6.30E+05	
21	1.00E+06	7.00E+05	
22	1.10E+06	7.70E+05	
*Case 01 ~18 are with pre-tension 3.5 E+05N. *Case 19 ~22 are with pre-tension 3.0 E+05N.			

5.3.2 D/t variation

We started with exploring the differences between different D/t values by using the monotonic load history in Case 01 as the hooking force (see Figure 5-5).

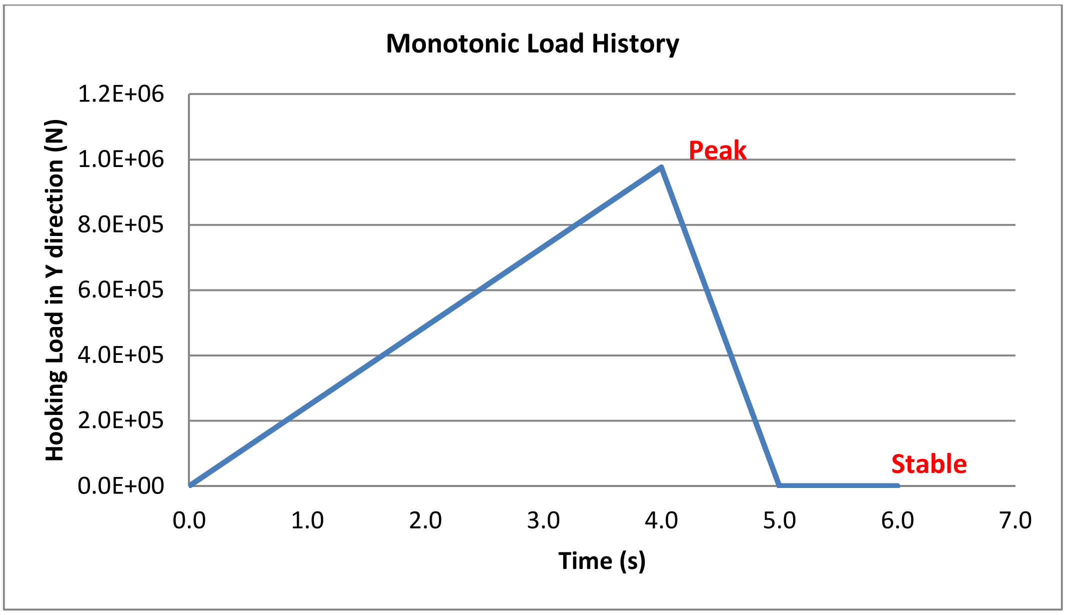


Figure 5-5 Monotonic load history used in D/t exploration

And we got the results of D/t =23, D/t =28 and D/t =40 (see Table 5-10 and Figure 5-6).

Table 5-10 Result regarding different D/t values

Case	Max. U2	Max. U3	Max. ESF1	Max. SF1	Max. M_{tot}	Max. ε	DC criterion	LC criterion
D/t	[m]	[m]	[MN]	[MN]	[MNm]	[-]	[-]	[-]
23	10.45	2.03	2.49	4.50	6.73	0.37 %	OK	NOT OK
28	11.67	3.65	2.13	4.25	6.00	0.62 %	OK	NOT OK
40	14.24	6.92	1.61	3.88	4.44	1.23 %	OK	NOT OK

We checked these cases using both DC criterion and LC criterion. Since local damage isn't included in DC criterion, the acceptable strain is estimated higher than it should be. On the other hand, by using LC criterion, even though smaller D/t still cannot meet the criterion, it has more satisfying result compared to larger D/t. This result coincides with the recommendations in HSE (2009), in which suggests to use extra steel during design to decrease the hooking damage.

In Figure 5-6, dash line represents the hooking point Node 2016. Figures with **'@Peak'** show the result of pipeline's lateral configuration and effective axial force when the hooking load reaches peak value. The figures with **'@Stable'** show the stable result of pipeline's lateral configuration and effective axial force after hooking load vanishes.

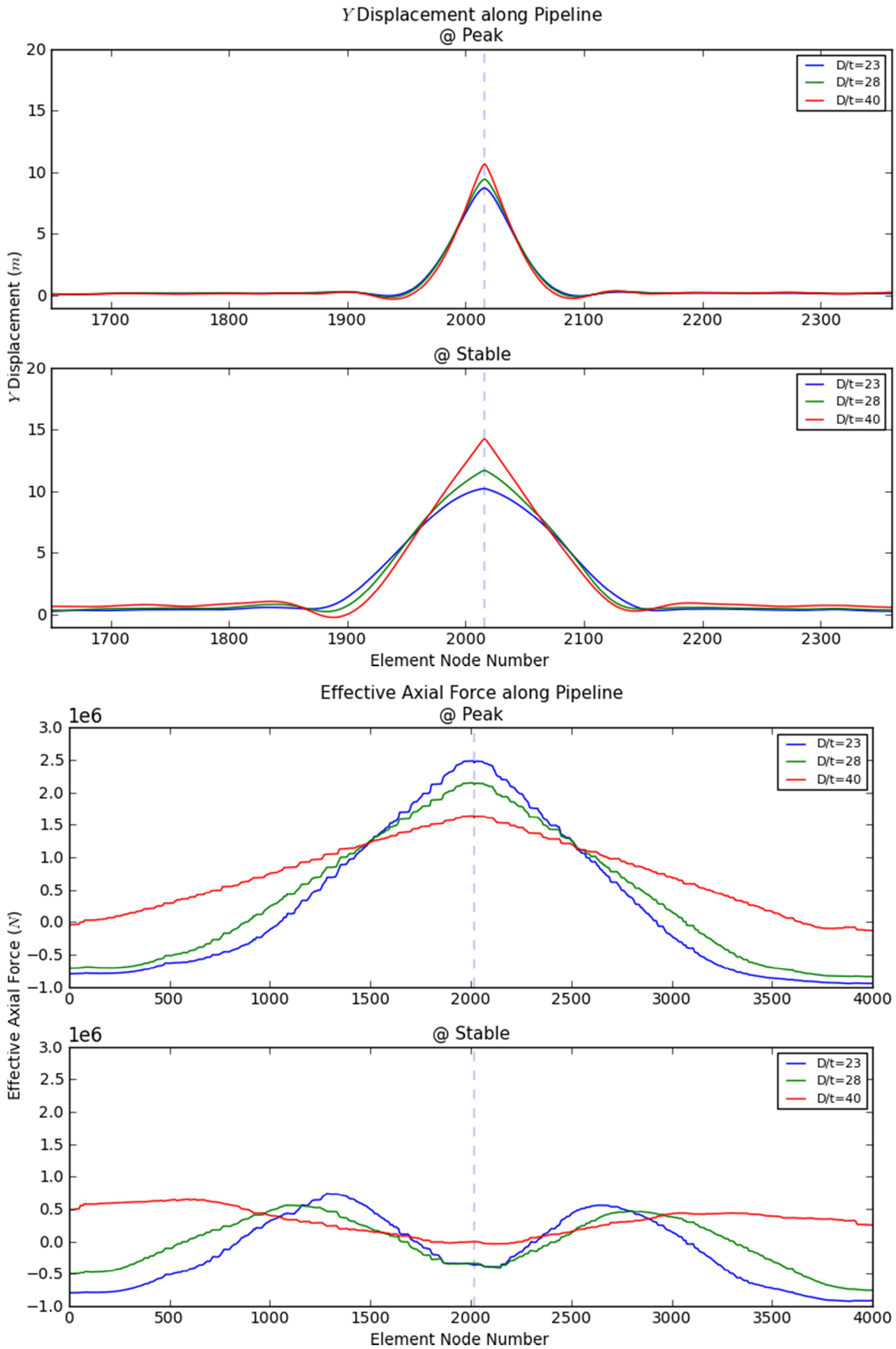


Figure 5-6 Results along pipeline regarding different D/t values

The result shows that after releasing the hooking load, the pipeline will still move a little bit further in Y direction, which leads to a bigger range of pipeline deforming until it’s stable. Thus we should bear in mind that the FE analysis should be given enough time to let pipeline system stabilize.

Effective axial force can be used to justify if the pipeline is long enough for FE analysis, which means the length of pipeline is of adequate length if the force in boundary zone doesn’t vary much. We could see that the final effective axial force in pipeline has sag at the hooking zone which indicates after load is released, the sections of pipeline near hooking point starts to stretch out (trend of moving sideways). The figure of Y displacement reveals the same conclusion. As a result of being fed into a buckle, effective axial force in hooking zone has a ‘slack’.

We can conclude that D/t values influence the final configuration of pipeline after a hooking incident. Even though the pipelines simulated in FE model are exposed to same load, a smaller D/t results to a smaller lateral displacement and a narrower buckle length. On the other hand, a larger D/t has smaller resistance to a hooking load, which is embodied in the effective axial force.

5.3.3 Load peak value variation

In the case of different sizes of anchor and corresponding anchor capacity, the hooking load varies in different situation, which means the bigger size is, the bigger pulling load will be until the anchor fluke breaks off. Actually we don’t have a clear clue of how the pulling force would be, monotonic, cyclic, or other styles. But based on a similar problem like trawling incident, some standard suggests using a monotonic load history in FE analysis, referring to (DNV, 2010c). However, according to several anchor hooking incidents, when comparing a survey result of pipeline’s final configuration, a monotonic load history usually leads to a narrow shape of pipeline moving sidewise. That’s why we included a cyclic load history here to give a better picture of this problem. What’s more, we would look into the details of load history style later in Chapter 5.3.4.

We analyzed the responses of the pipeline with different load peak values for monotonic and cyclic load history, respectively (see Figure 5-7 and Figure 5-8).

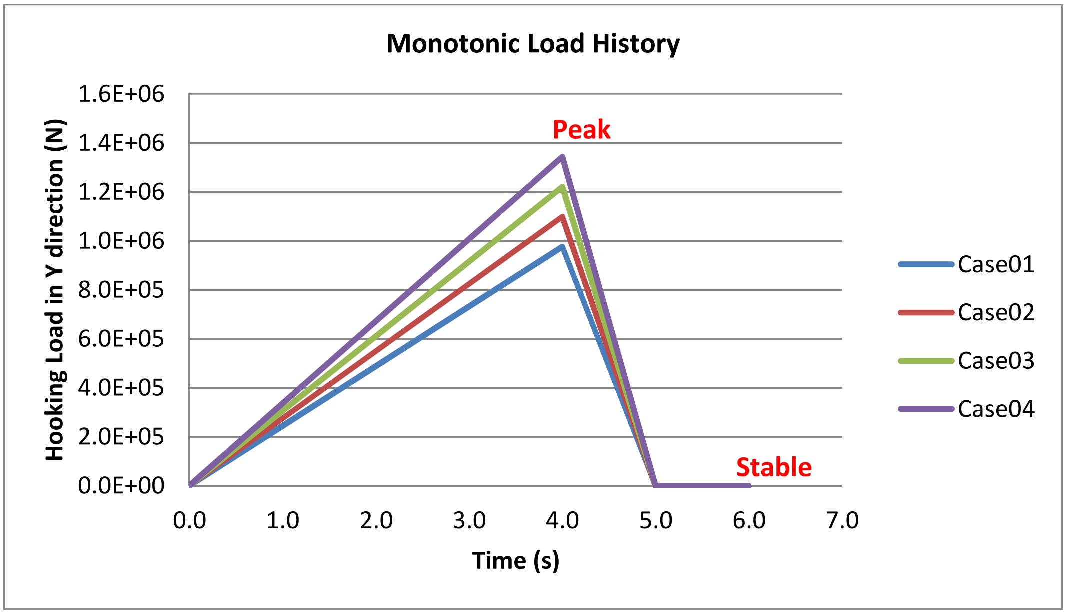


Figure 5-7 Monotonic load history with different peak values used in dynamic analysis (Case 01~04)

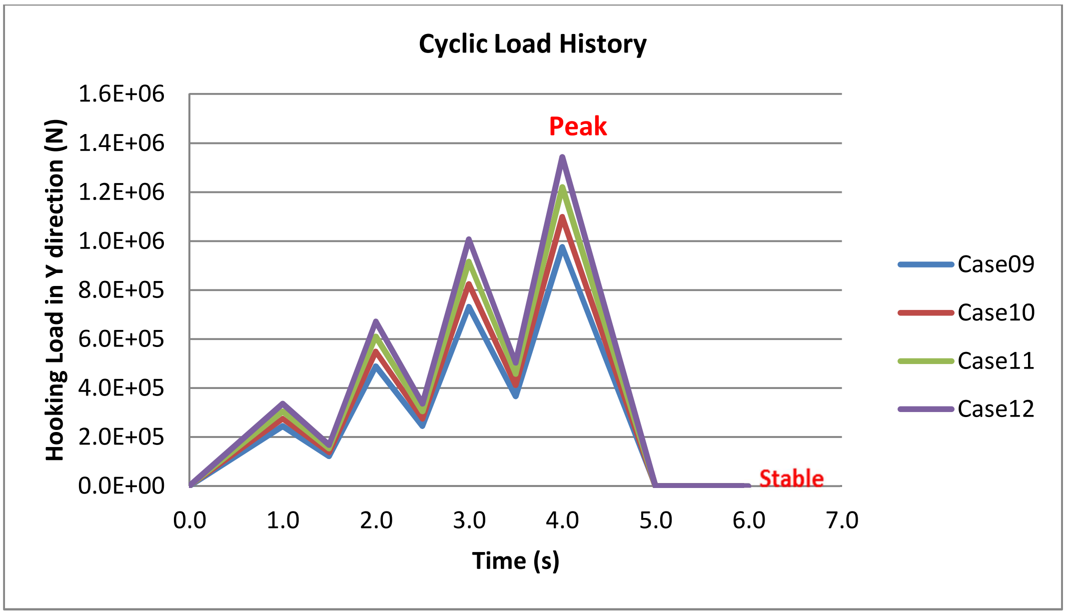
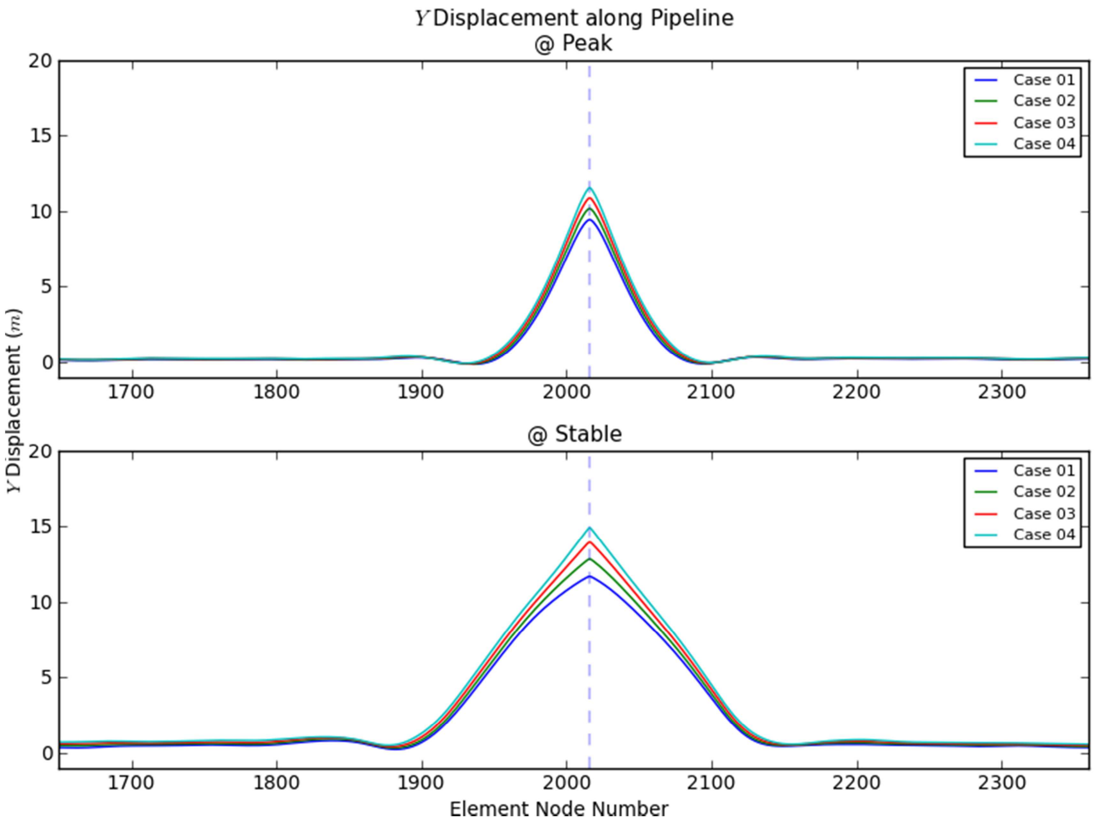


Figure 5-8 Cyclic load history with different peak values used in dynamic analysis (Case 09~12)

By comparing Case 01 ~ 04, we could get monotonic load results regarding different load peak values from small to big (see Figure 5-9).



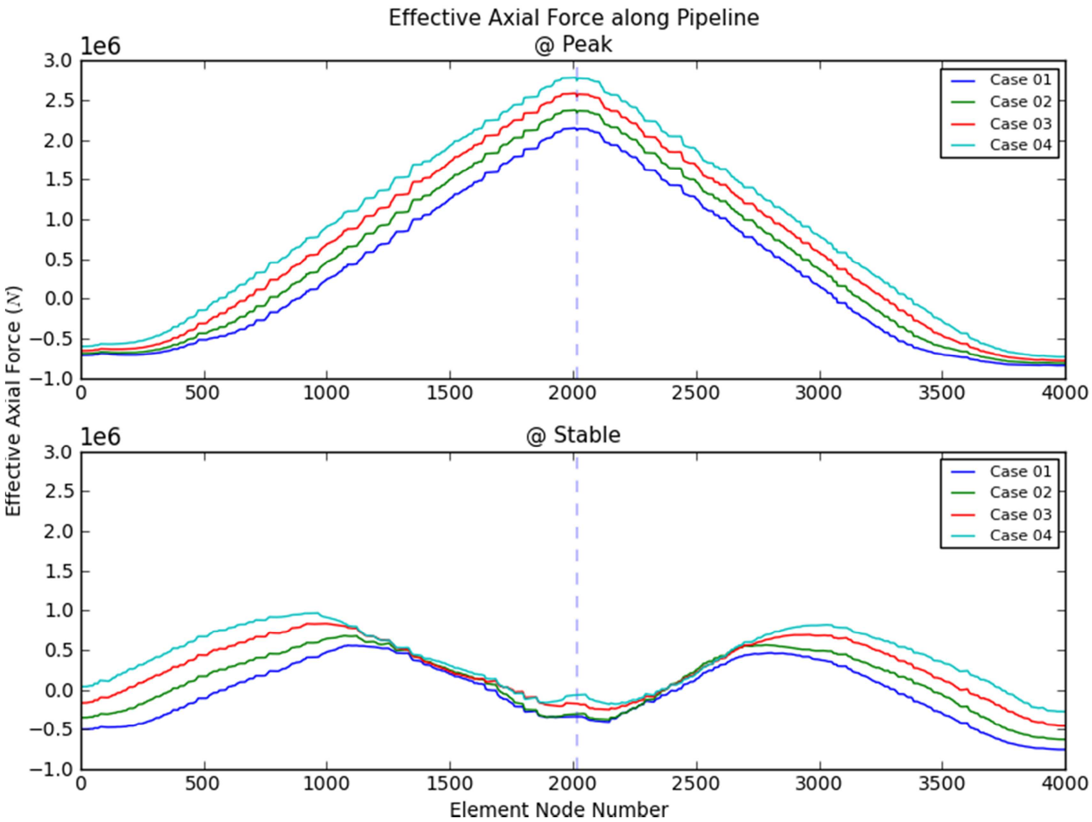
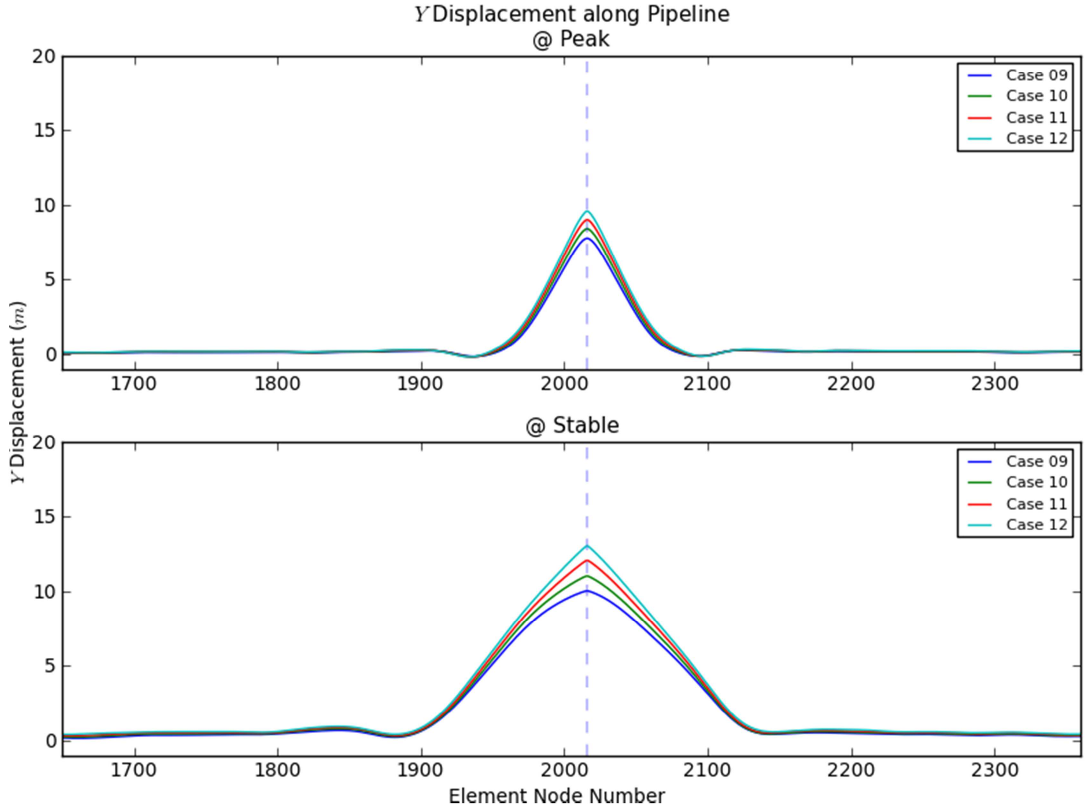


Figure 5-9 Results along pipeline regarding monotonic load history and different peak values (Case 01~04)

As we could see from Figure 5-9, the bigger load, the bigger influence on the pipeline both in axial force and displacement. We could find that the length of buckle is almost the same but with different amplitudes in Y direction, which means different inclinations for different hooking loads. If the hooking load is bigger, the lateral displacement is bigger. And we could notice that if the load is bigger, the influence goes to the boundary which means when we deal with big force or displacement we must build a long pipeline for FE analysis.

Comparing Case 09 ~ Case 12, we could get a cyclic load result regarding different load peak values from small to big (see Figure 5-10). Similar as monotonic load, cyclic load history presents same trend in displacement and effective axial force regarding different hooking loads.



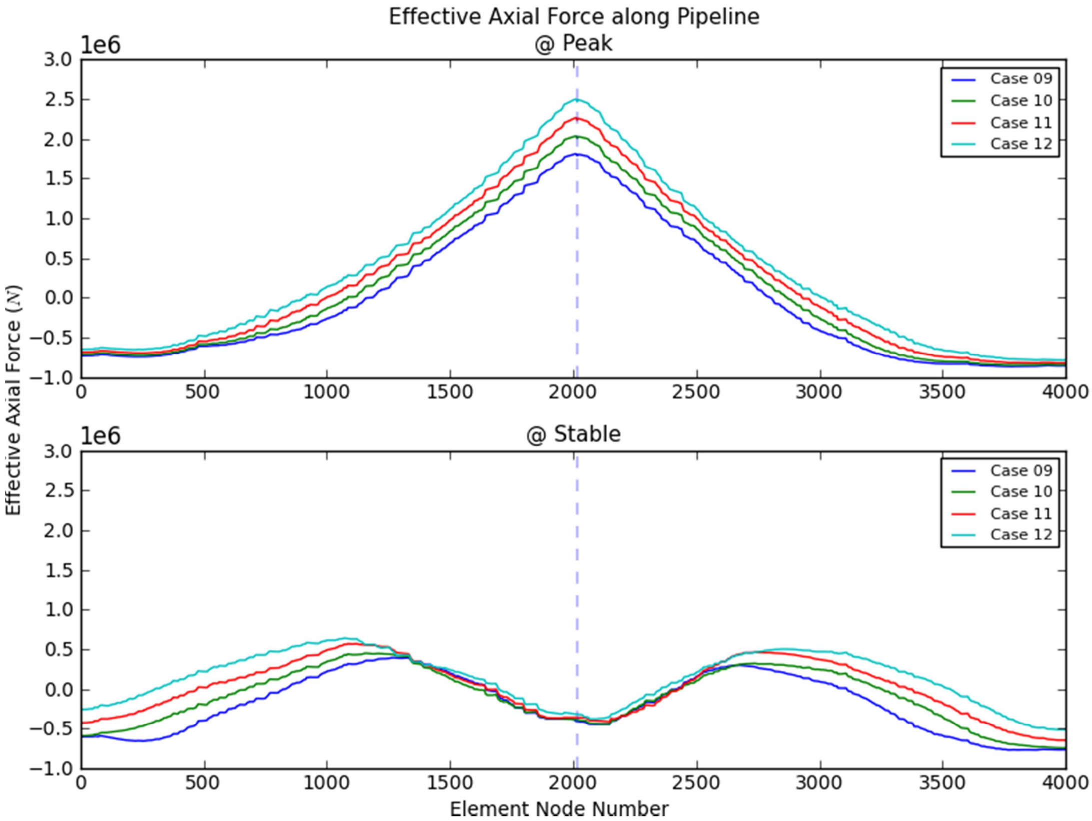
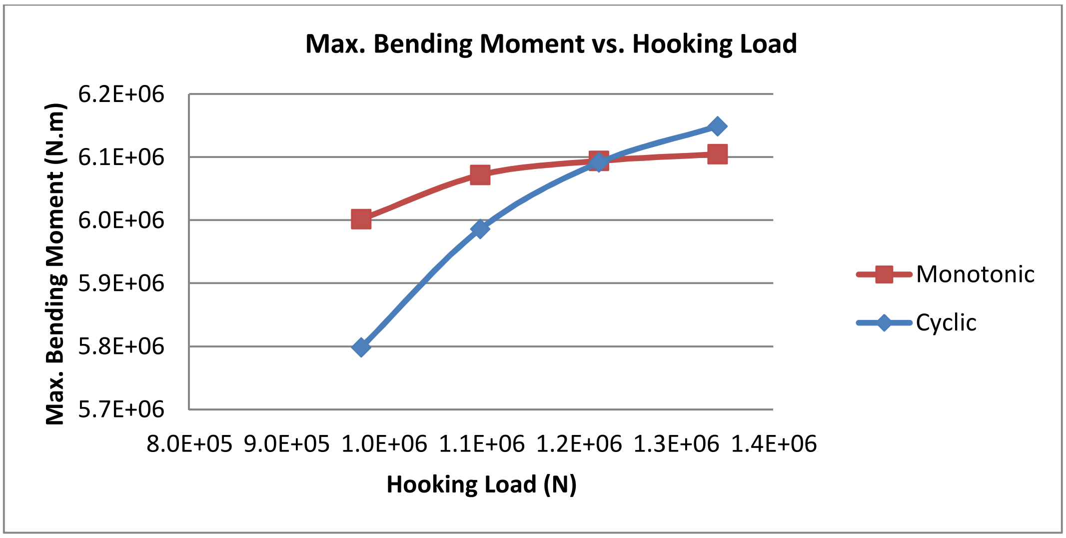


Figure 5-10 Results along pipeline regarding cyclic load history and different peak values (Case 09~12)

Since the maximum values appear at the hooking point (Node 2016) during the total analysis, here presents the results of maximum values like strain, total bending moment and displacement related to different load peak values (see Figure 5-11). Case 01~04 are represented by 'monotonic', while Case 09~12 are represented by 'cyclic' in the legend.



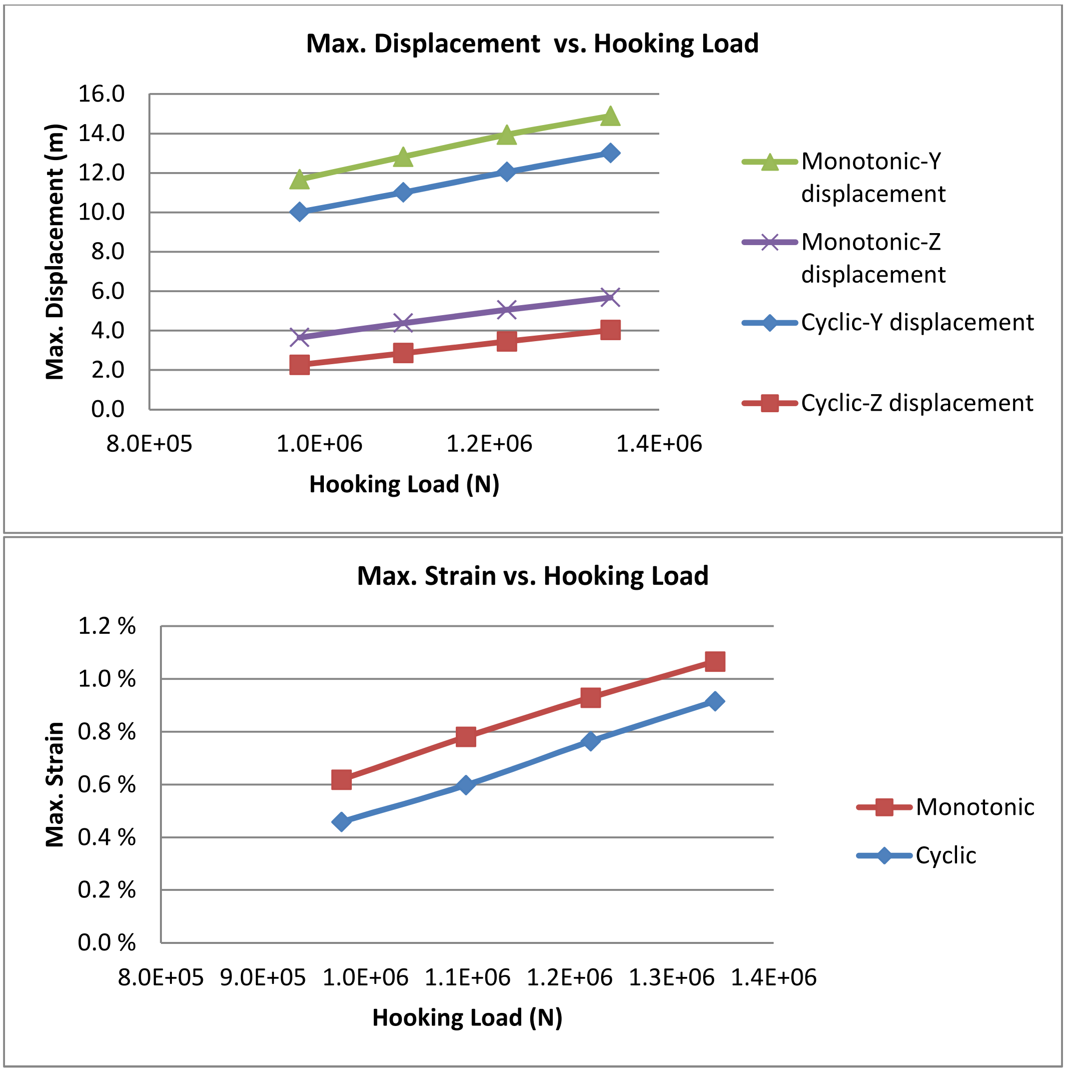


Figure 5-11 Results at hooking node (monotonic: Case 01~04 & cyclic: Case 09~12)

The result shows the bigger hooking load, the bigger values in strain, total bending moment and displacement. Comparing the maximum strain to the one calculated in Chapter 4.4.1, the maximum strain is far less then design. However, the bending moments are not acceptable based on the result in Chapter 4.4.2. The difference proves the discussion in Chapter 4.4.2, where LC condition has a more conservative criterion of failure.

5.3.4 Load history style variation

As what has been mentioned before, here we will look into the details of load history style (see Figure 5-12).

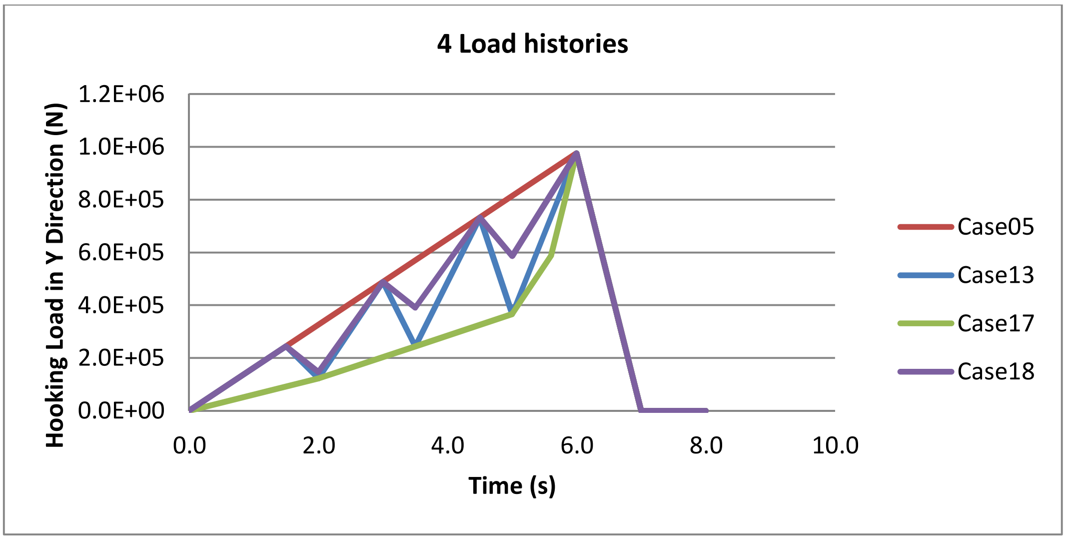
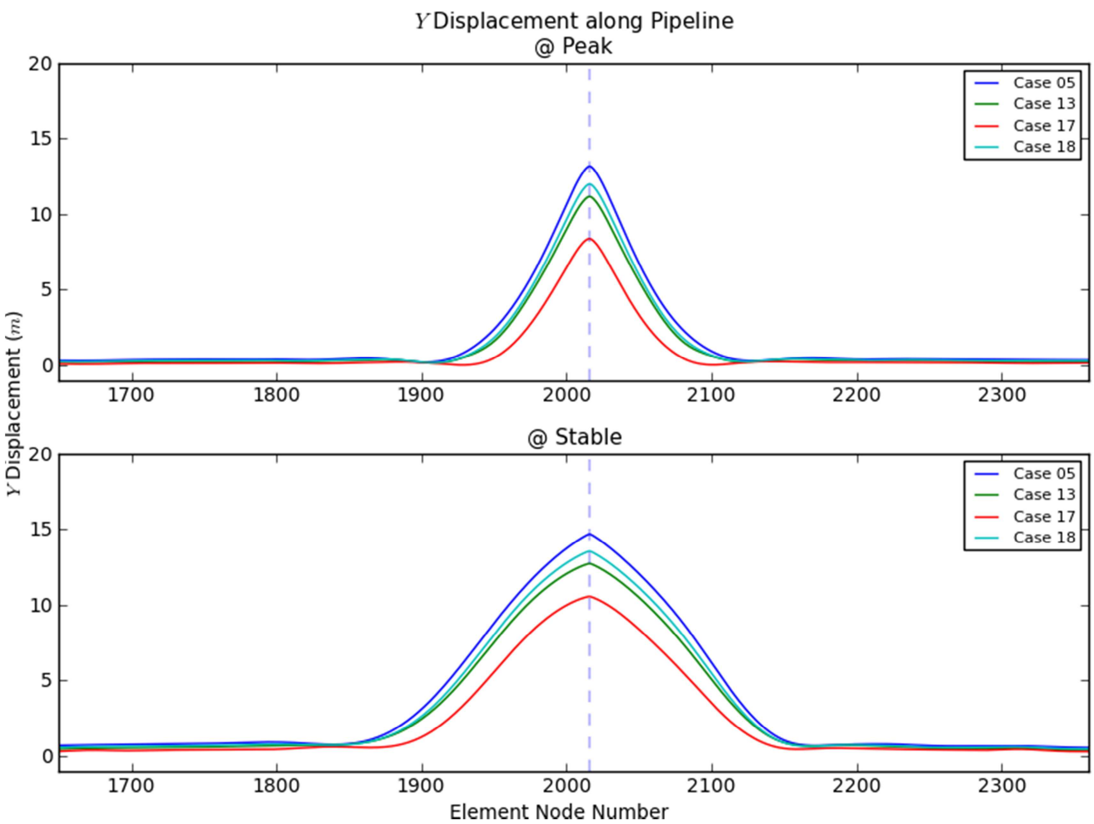


Figure 5-12 Different load history styles with same peak value used in dynamic analysis

Comparing Case 05, Case 13, Case 17 and Case 18, we could get the results regarding different load history styles with the same load value and time length (see Figure 5-13).



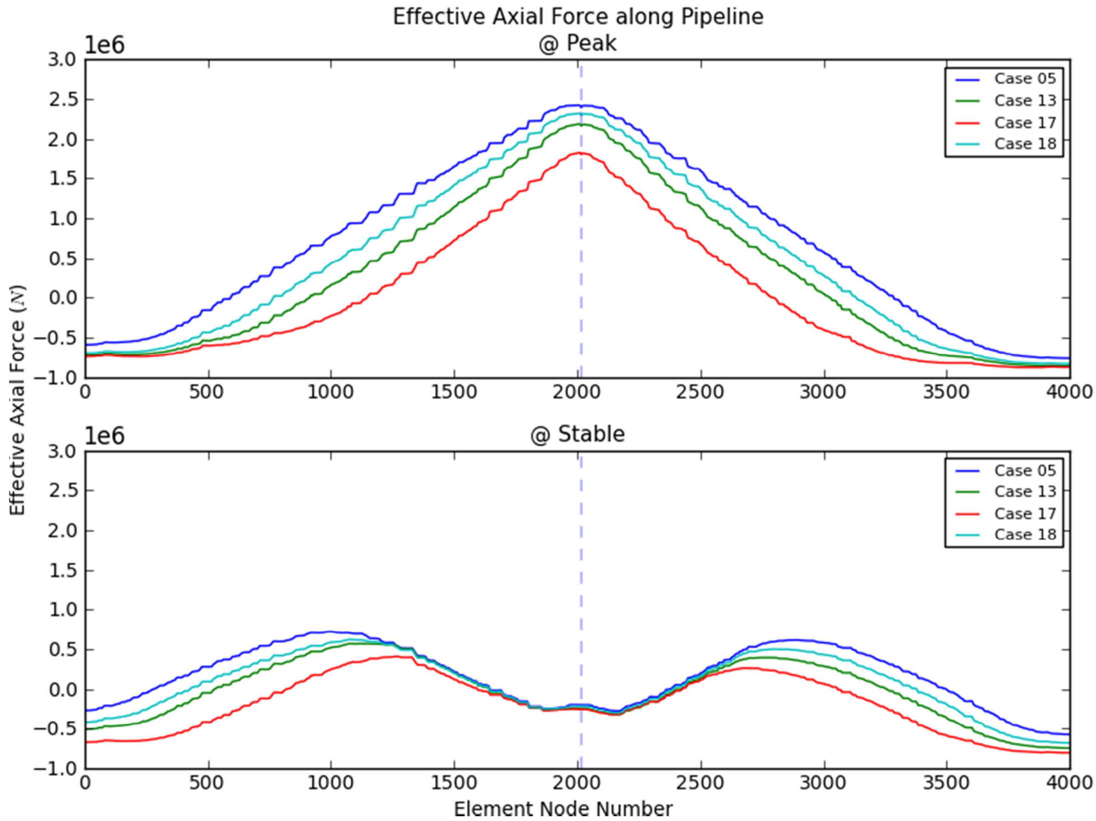


Figure 5-13 Results along pipeline regarding different load histories and same peak value (Case 05, 13, 17 and 18)

Figure 5-13 depicts that even if these 4 load histories have the same peak value and time length, there are big discrepancies. If we look at the Y displacement, we could find out both the max. Y displacement and buckle length changes with load history style. It might presume a correlation between impulse and response. The closer to monotonic load history, the bigger response will be. In this section, Case 05 is with biggest impulse, while Case 18 is the second, Case 13 is the third and Case 17 is smallest. The response corroborates the trend of impulse magnitude (see Table 5-11).

Table 5-11 Result at hooking node regarding different load history styles and same peak value

Case	Time	Max. U2	Max. U3	Max. ESF1	Max. SF1	Max. M_{tot}	Max. ε
	[s]	[m]	[m]	[MN]	[MN]	[MNm]	[-]
05	7	14.66	4.18	2.40	4.53	5.99	0.64 %
13	7	12.93	2.69	2.21	4.33	5.88	0.51 %
17	7	10.57	1.61	1.90	4.01	5.79	0.45 %
18	7	13.60	3.43	2.32	4.44	5.95	0.58 %

This section reveals that it is of great importance to study more about the load history especially for limited data of a hooking incident. However, we couldn’t determine which one is the exact style of load history in this part, which could be solved in the future by undertaking lab test and FE analysis taking chain and anchor into consideration.

5.3.5 Time variation

As a hooking incident happens, it is a time domain problem. Since the ship is traveling or drifting in a sea state, the velocity of the ship varies in cases. And the capacities of anchor fluke and chain also have effects on the hooking time. In this part, we would discuss how the time changes (see Figure 5-14 and Figure 5-15) will affect the pipeline's response.

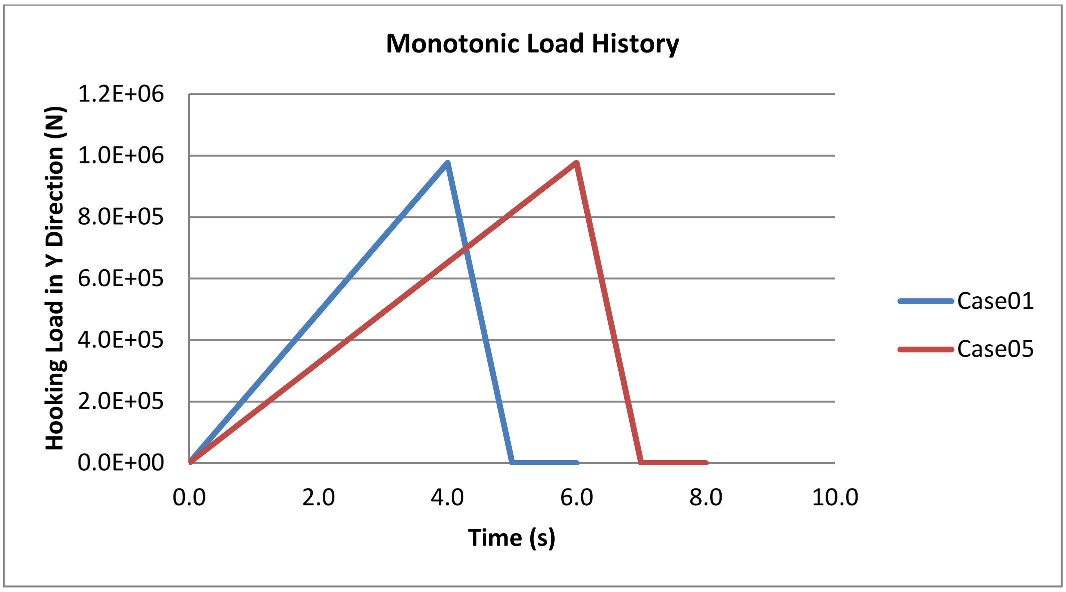


Figure 5-14 Monotonic load history regarding different time lengths used in dynamic analysis

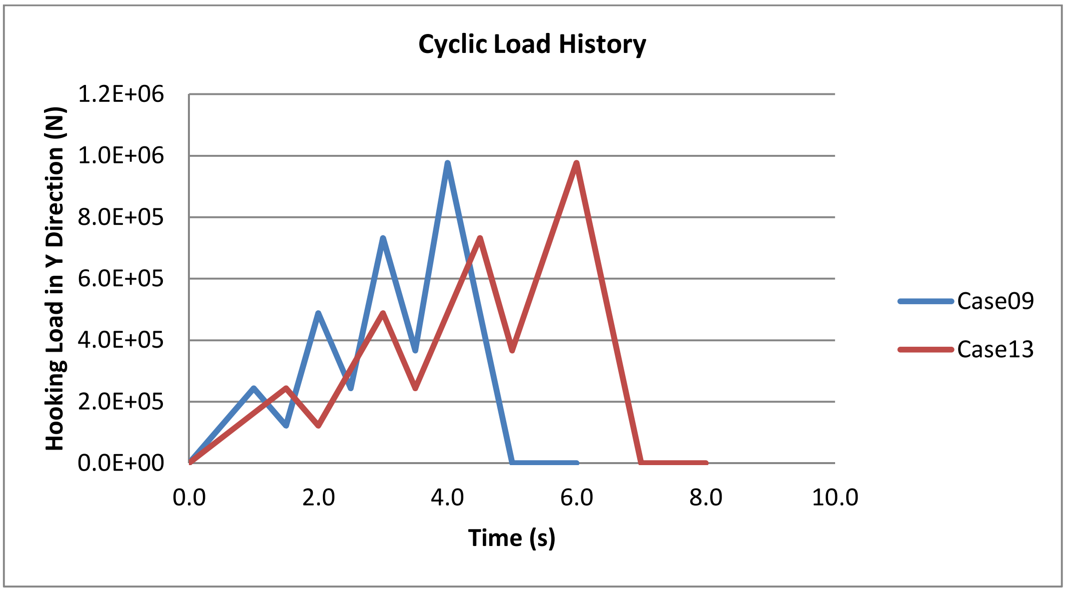


Figure 5-15 Cyclic load history regarding different time lengths used in dynamic analysis

Comparing Case 01 and Case 05 (Case 02 and Case 06, Case 03 and Case 07, Case 04 and Case 08 show similar results), we could get a monotonic load result regarding different time ranges (see Figure 5-16 and Figure 5-17).

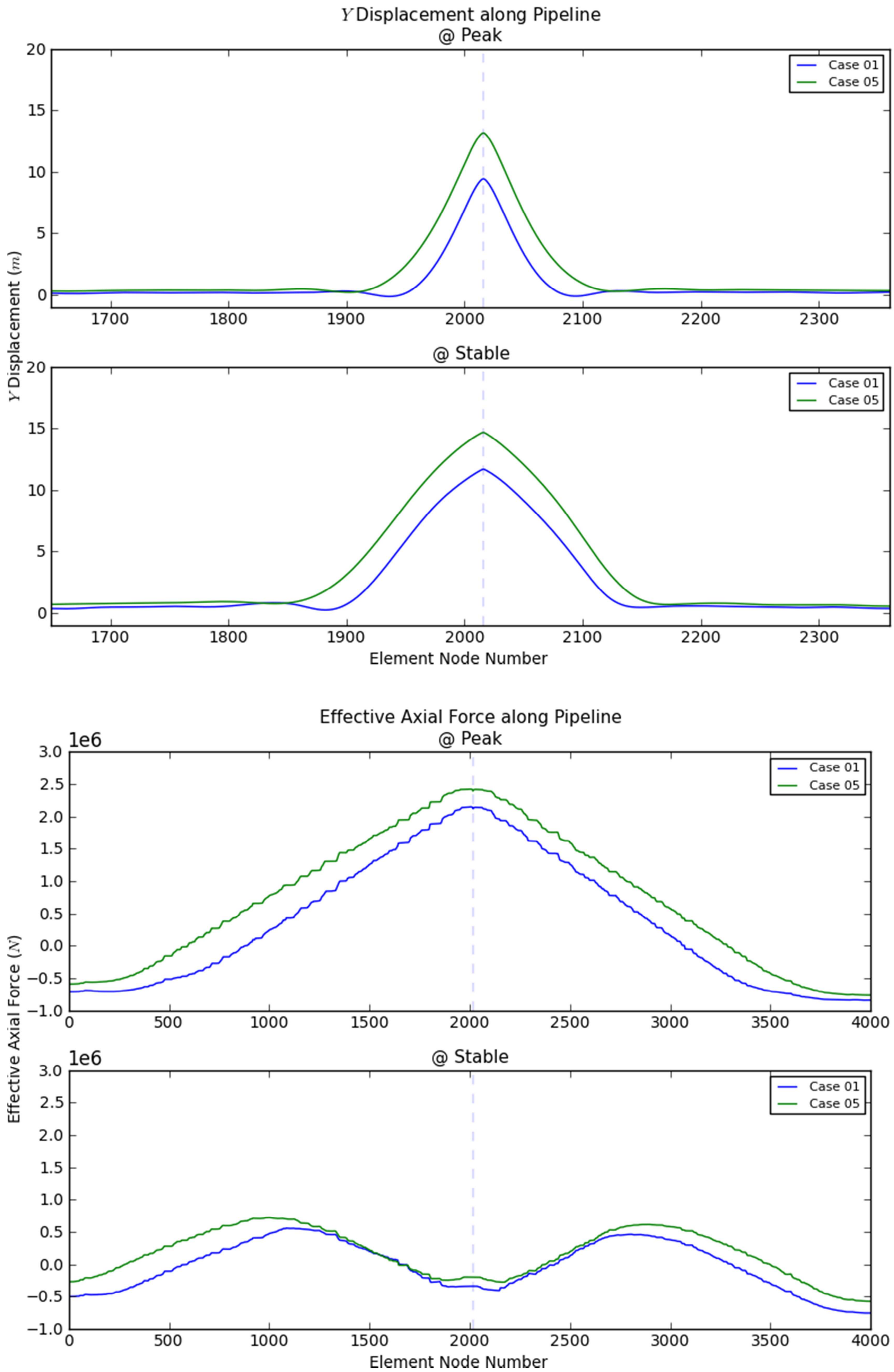
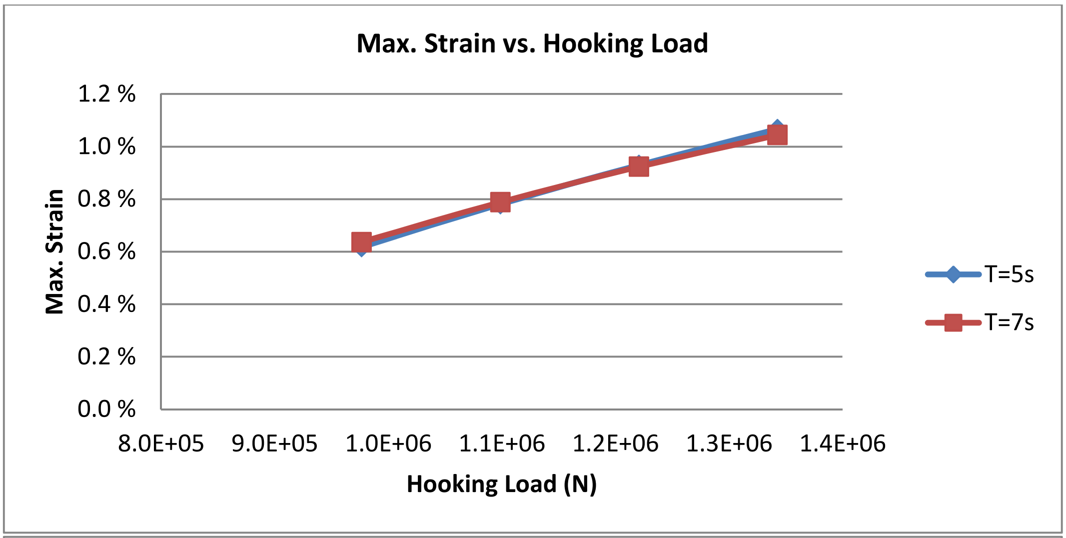
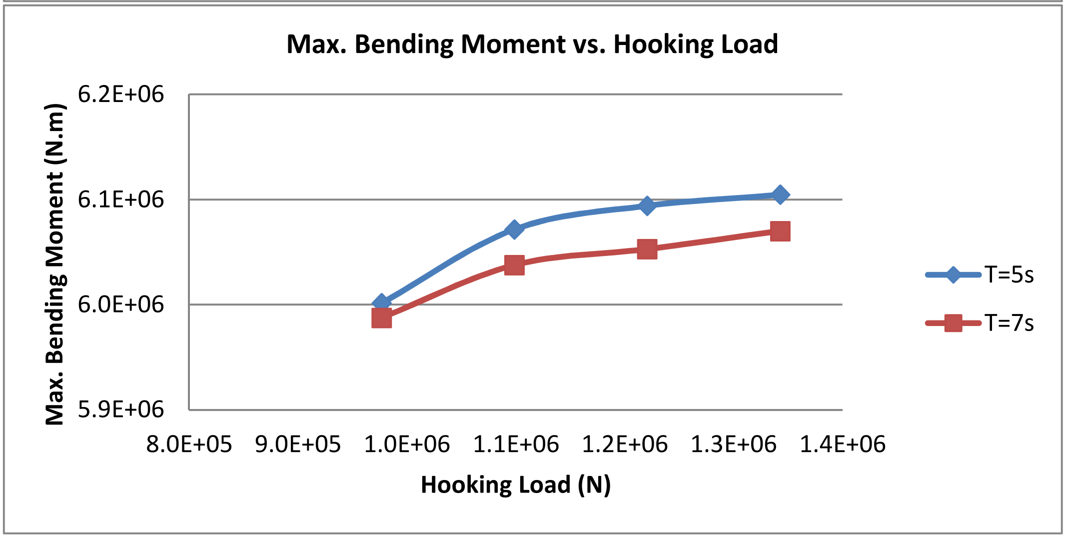


Figure 5-16 Results along pipeline regarding monotonic load history and different time lengths (Case 01, 05)

Figure 5-16 displays that with a longer hooking time in Case 05 than in Case 01, response of pipeline is bigger. But we should notice that the inclination of pipeline's configuration is almost the same for both cases, which could be a clue for changing hooking time to fit the survey result. For instance, if the survey result was with a Y displacement of 15m, we could then increase the hooking time in Case 01 to Case 05, which has a better match afterwards. However, even if the amplitude of the buckle matches the survey, there is a big chance with differences in the buckle length. Then we could come up with another decision based on the analysis in previous chapter by changing the peak value of load or even load style.

Figure 5-17 illustrates the result of monotonic load history regarding different time lengths. Case 01~04 are represented by 'T=5s', while Case 05~09 are represented by 'T=7s' in the legend.





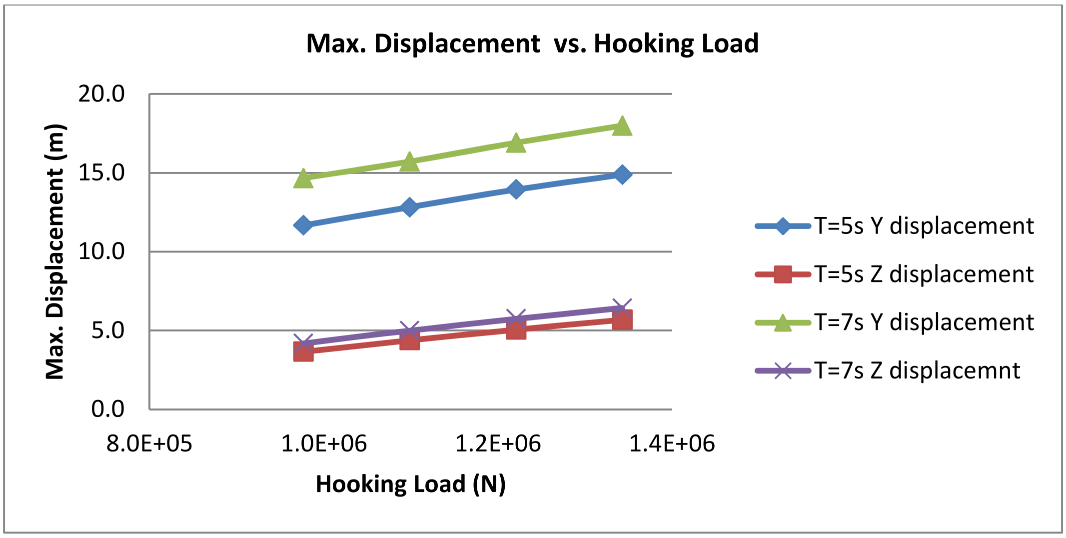


Figure 5-17 Result at hooking node regarding monotonic load history and different time lengths

Comparing Case 09 and Case 13 (Case 10 and Case 14, Case 11 and Case 15, Case 12 and Case 16 show similar result), we could get a cyclic load result regarding different time lengths (see Figure 9-3 and Figure 9-4 in Appendix 9.3). Similar as monotonic load, cyclic load history presents same trend in displacement, effective axial force and bending moment regarding different hooking loads.

5.3.6 Lay-tension variation

When the pipeline is being installed onto the seabed, the lay vessel provides a pretension in pipeline. The reason for this is that when the pipeline is deployed from the stinger, it is important to hold the pipeline in place and then slide it down gradually. What's more, tension in pipeline will free the tip end of the stinger, a buckle or a clash between the pipeline and stinger tip is then eliminated. During the operation phase, temperature and pressure of the content inside of pipeline is changing all the time. This fact will lead to an influence on the pipeline axial tension. Hence, a change of tension in pipeline was analyzed here for both static analysis and dynamic analysis.

Comparing Case 05 and Case 19 (Case 06 and Case 20, Case 07 and Case 21, Case 08 and Case 22 show similar result), we could get results regarding different lay-tensions (see Figure 5-18)

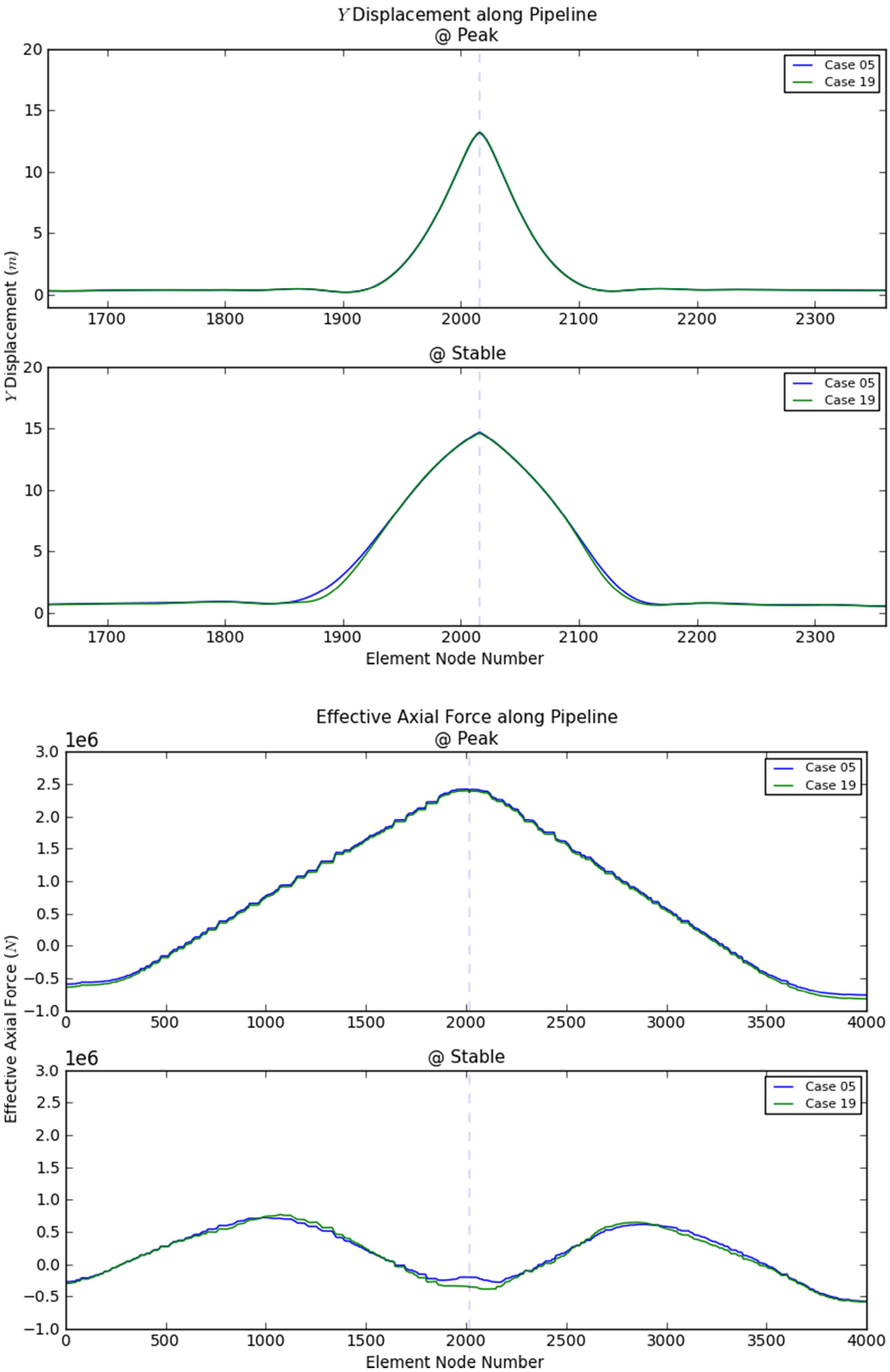


Figure 5-18 Results along pipeline regarding different lay-tensions (Case 05, 19)

As shown in Figure 5-18, there is no much difference Case 05 and Case 19. Hence, a difference of 50kN in lay-tension doesn’t influence much on the response of pipeline, which also indicates a change of inside pressure less than 0.13 MPa doesn't affect much.

5.3.7 Friction coefficient variation

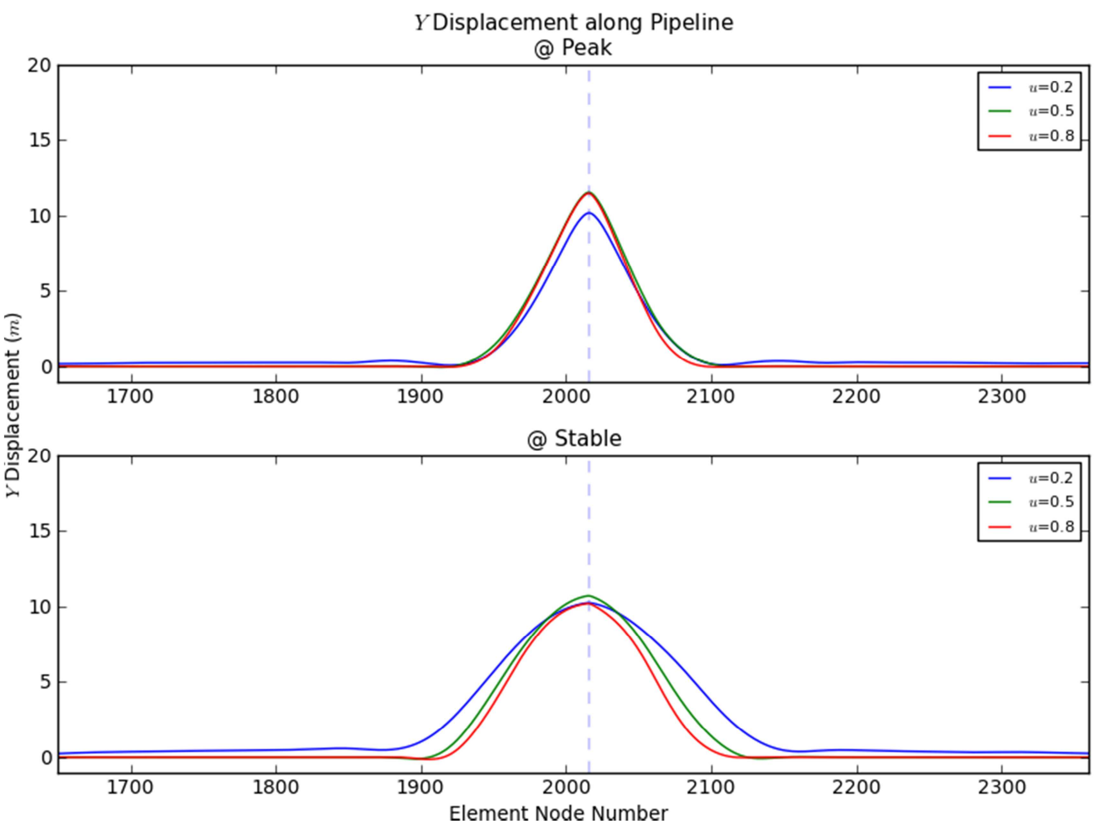
Since this pipeline is installed on a hard seabed, the lateral friction coefficient supplied by DNV GL is relatively small. As a result, we adjusted the lateral friction coefficient to simulate a soft seabed, then the responses were studied in this part. We investigated the cases with final lateral displacement as 10m (see Table 5-12).

Table 5-12 Result at hooking node regarding different lateral friction coefficients

Case	Max. U2	Max. U3	Max. ESF1	Max. SF1	Max. M_{tot}	Max. ε
μ	[m]	[m]	[MN]	[MN]	[MNm]	[-]
0.2	10.45	2.53	1.85	3.97	5.36	0.32 %
0.5	11.67	3.06	2.17	4.39	5.63	0.41 %
0.8	14.24	3.14	2.39	4.51	5.74	0.45 %

We could find that in the case of large lateral friction coefficient, the pipeline moves towards its original position more than cases of small lateral friction coefficient after chain and pipeline disconnects.

Figure 5-19 also demonstrates differentiates between cases.



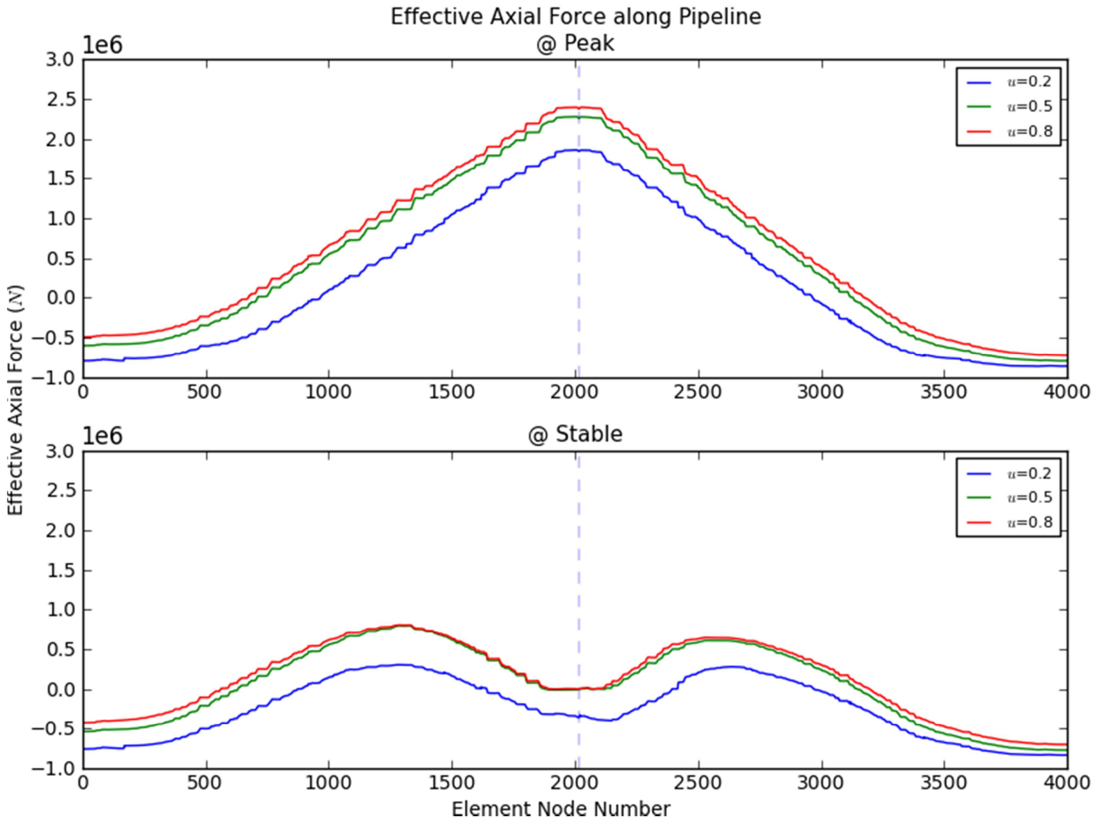


Figure 5-19 Results along pipeline of 10m displacement regarding different lateral friction coefficients

Figure 5-19 exhibits that the bigger friction coefficient is, the narrower length of the buckle would be. The reason for this response is that large friction absorbs more hooking load during the lateral displacement and large passive resistance prevents the pipeline from moving sidewise.

5.4 Parameter study of velocity model

Based on the experience from previous anchor hooking incidents, monotonic load history resulted in relatively narrow buckles after FE analysis, while cyclic load history had wider ones. PL-MODEL has a survey result after a hooking incident. Works have been done by DNV GL finding that a cyclic load history gets the result matching the survey better than monotonic load. However, a cyclic load history was generated manually. In order to find a method matching the survey, in this chapter we studied a chain model together with a pipeline.

Since an anchor hooking incident associates with anchor size and chain size, in this part we connected a chain to pipeline in this model giving velocity on the top of chain instead of applying load directly. According to the survey, it shows evidences that an anchor weighing approximately 3 tonnes hooks the PL-MODEL pipeline. For each anchor weight, there're limited numbers of chain dimension matched according to Table 9-3 in Appendix 9.2. Table 5-13 exhibits the chain's properties regarding a

3-tonne anchor, which would be used in a 'velocity model'. The diameter used in velocity model is a nominal dimension which leads to the same axial stiffness as a real 44mm chain. According to Table 9-4 in Appendix 9.2, there are different strengths for different grades of chain. Here the chain's material was assumed same as pipeline's, see Appendix 9.4.

Table 5-13 Abaqus input data-dimension and material of chain

Operational data		
Density of chain	14567.3	[kg/m^3]
Radius of chain	0.031	[m]
Length of chain	247.5	[m]
Young's modules	2.07E+11	[N/m^2]
Poisson's ratio	0.30	[-]

During the analysis, the top of chain will be given a certain velocity (see steps in Table 5-14).

Table 5-14 Subsequent steps of velocity model after static model (see Table 5-7)

Step	Description	Type of analysis
11	Including chain	Static
12	Activating velocity on the chain top	Dynamic

As we have a survey result of PL-MODEL after hooking incident, which has a displacement of 10m and 3.5m in Y direction, we stop the analysis until getting 10m and 3.5m displacement respectively when the pipeline is stable. Then we could compare the results between survey and FE analysis. Figure 5-20 depicts the model with chain before pulling. Figure 5-21 depicts the pipeline being pulled by chain. And Figure 5-22 shows the final shape of the pipeline after hooking incident.

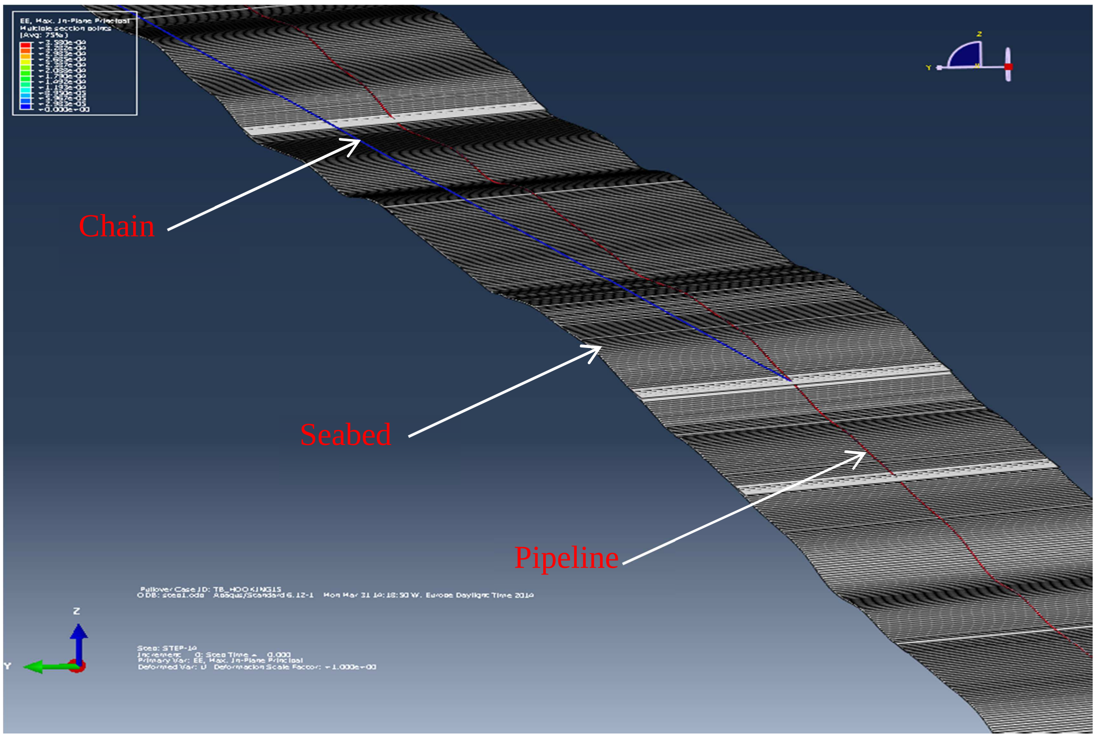


Figure 5-20 Abaqus model with chain before analysis starts

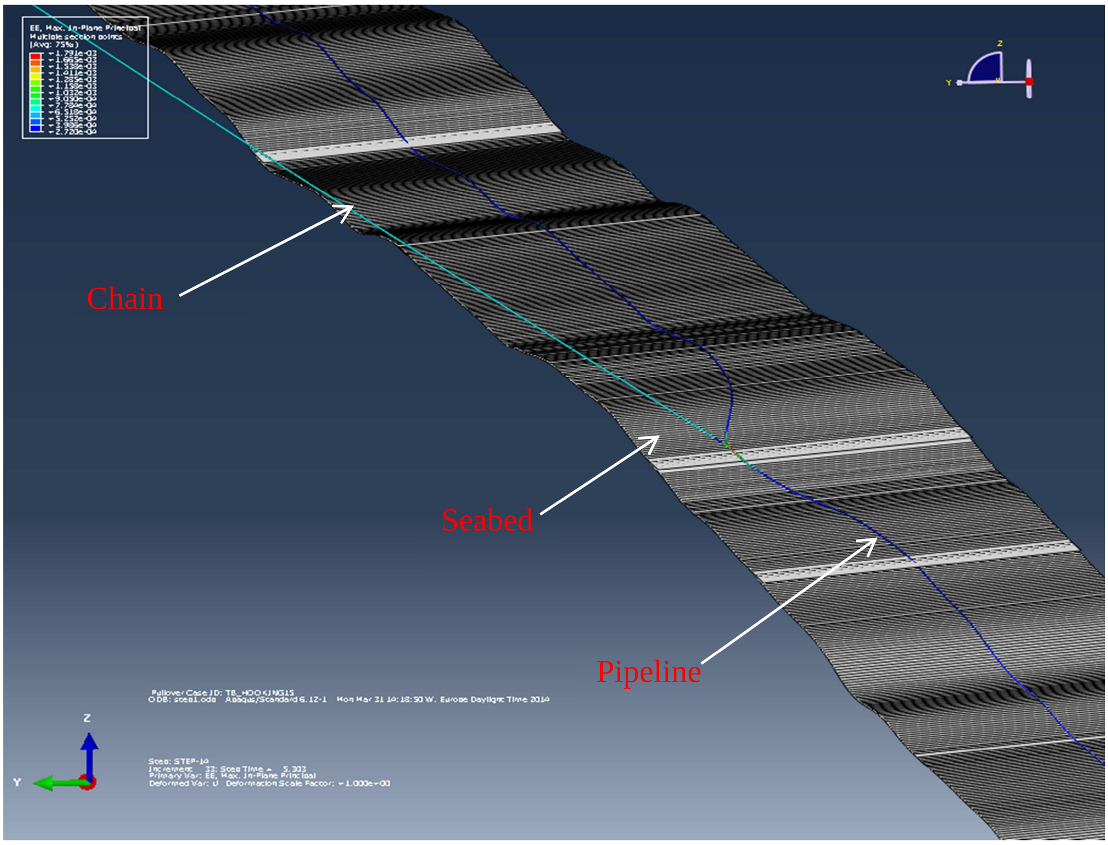


Figure 5-21 Pipeline pulled by chain during analysis

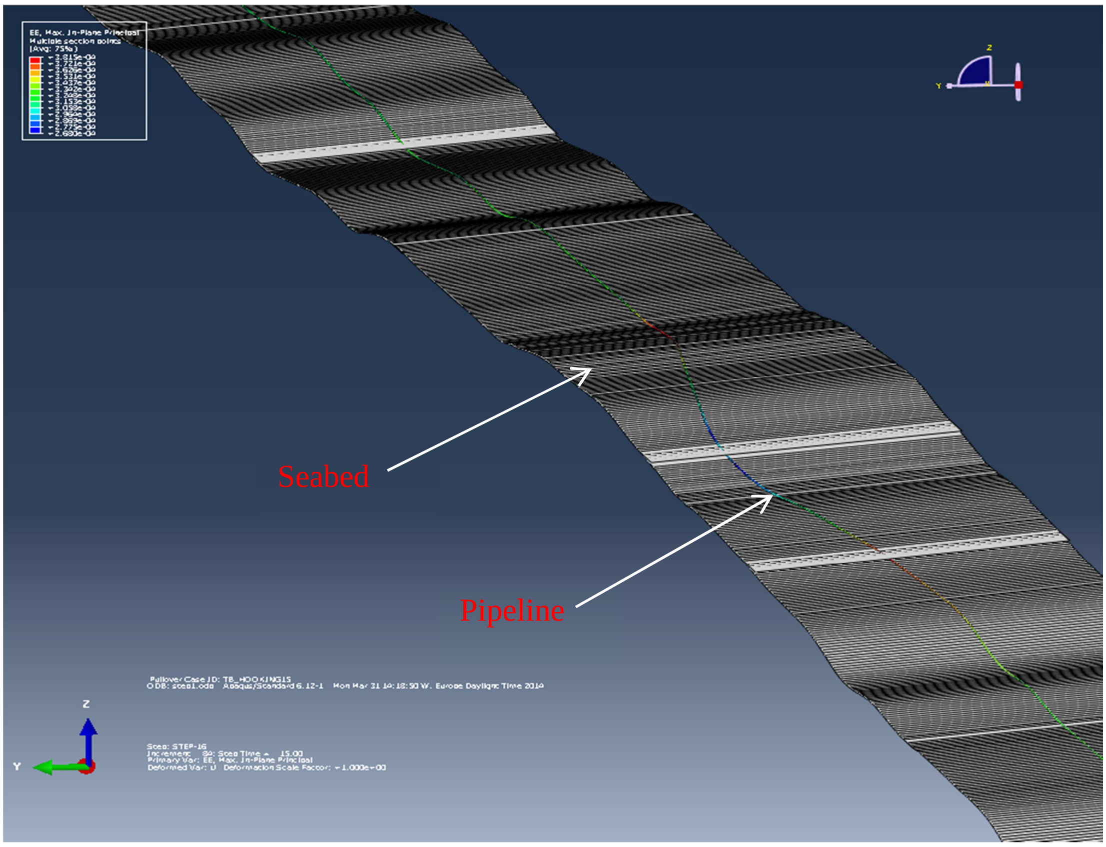


Figure 5-22 Pipeline lying on seabed after releasing chain

5.4.1 Velocity variation

In this velocity model, different velocities were applied on top of chain in the sea surface. Figure 5-23 depicts the load history in the chain. It indicates some fluctuations at the very beginning, and then the force keeps increasing. Since the pipeline is lying still on seabed at first, it is reasonable to have resistance (friction and inertia force) against being pulled. But once the pipeline is partly free from seabed the force decreases subsequently. As longer and longer of pipeline is lifted up, hooking force in the chain elevates gradually until reaching breaking-off magnitude.

Based on the real condition of this pipeline, we remove chain from Abaqus model to get 10m displacement in Y direction (see load history in Figure 5-23). As Figure 5-23 manifested, the load applied on pipeline is far less than 1540kN which is the magnitude of breaking load as a 44mm diameter chain. However, the breaking force could be lower in a dynamic situation.

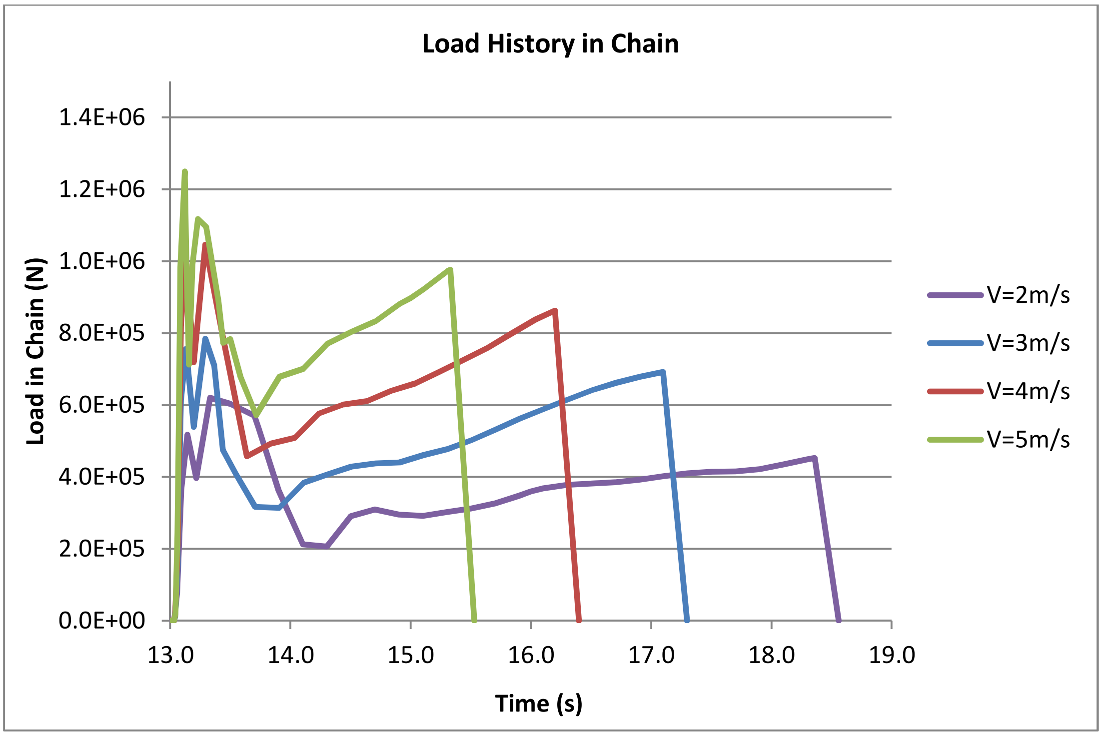


Figure 5-23 Load history in the chain axis in dynamic analysis to get U2=10m

Figure 5-23 illustrates the load history in the axis of chain corresponding to various velocities but these cases all reach a 10m lateral displacement finally. Figure 5-23 reveals that chains moving with big velocities achieve the breaking load faster than those moving with small velocities. For instance, it only takes the chain 4 seconds to disconnect when it moves at 3m/s. On the contrary, a chain takes more time to disconnect when it moves at 2m/s. As a result, a low velocity case causes bigger response of pipeline, to which more attentions should be paid.

As we have discussed in Chapter 3.1, a planned anchoring operation is usually with low velocity, while an emergency anchoring is likely with high velocity. Hence, we need to concern more on the planned anchoring operations such as appropriate handling procedure.

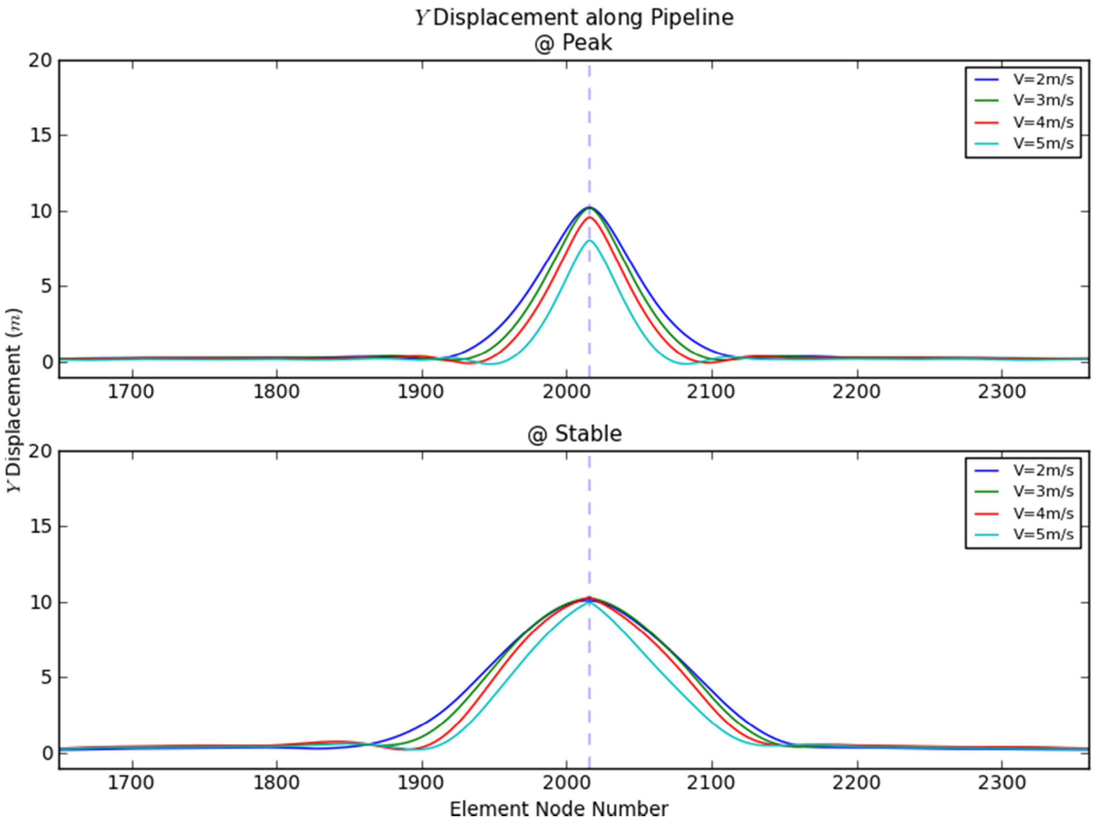
Table 5-15 exhibits the results of velocity model related to various velocities, which have 10m lateral displacements.

Table 5-15 Result regarding different velocities (U2= 10m)

Case	Max. U2	Max. U3	Max. ESF1	Max. SF1	Max. M_{tot}	Max. ε	DC criterion	LC criterion
[m/s]	[m]	[m]	[MN]	[MN]	[MNm]	[-]	[-]	[-]
V=2	10.42	0.47	1.47	3.58	4.02	0.18%	OK	OK
V=3	10.53	2.53	1.85	3.97	5.36	0.32 %	OK	NOT OK
V=4	10.27	4.00	2.01	4.13	5.85	0.51 %	OK	NOT OK
V=5	9.97	4.44	2.08	4.20	5.99	0.64%	OK	NOT OK

Even though case V=2m/s satisfies the criteria, this case is more like a pull-over since the hooking load hasn't achieved the breaking-off load of the anchor.

We could also see the results of getting a 10m lateral displacement finally related to different velocities in Figure 5-24.



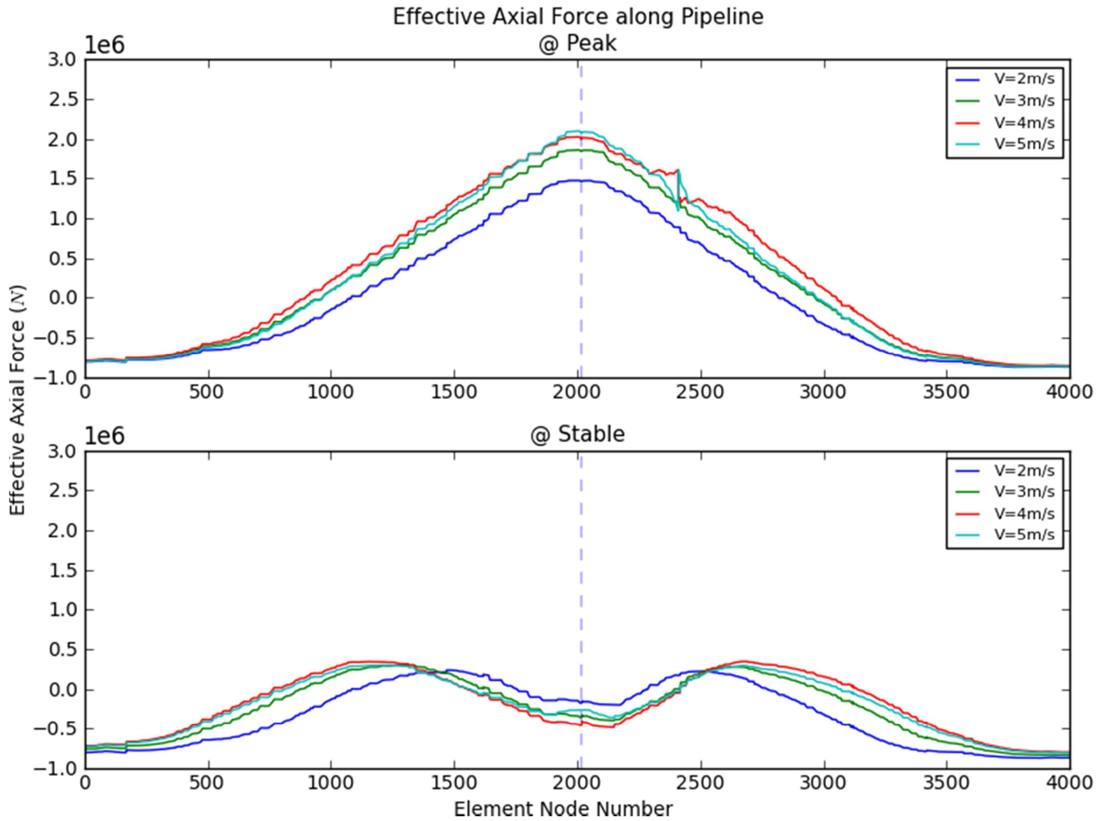


Figure 5-24 Results along pipeline regarding different velocities (U2=10m)

Figure 5-24 shows that the bigger velocity is, the narrower length of buckle we could get, if we have a 10m lateral displacement when the pipeline becomes stable. Together with the load history in Figure 5-23, we could imply that bigger velocity spends less time to reach 10m displacement and too little time to induce longer length of buckle, comparing with smaller velocity.

Figure 5-25 illustrates the FE result compared with real survey result when getting a 10m lateral displacement.

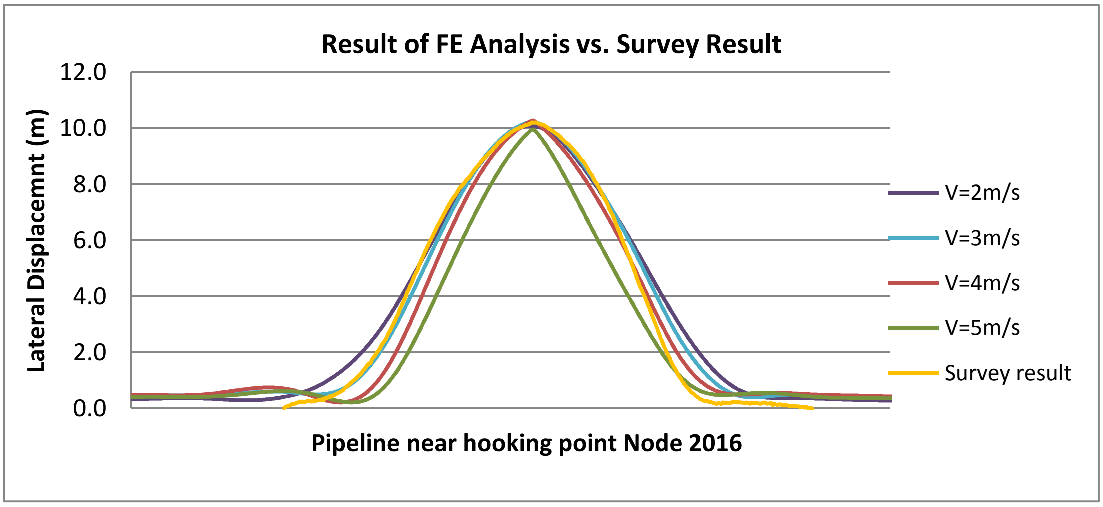
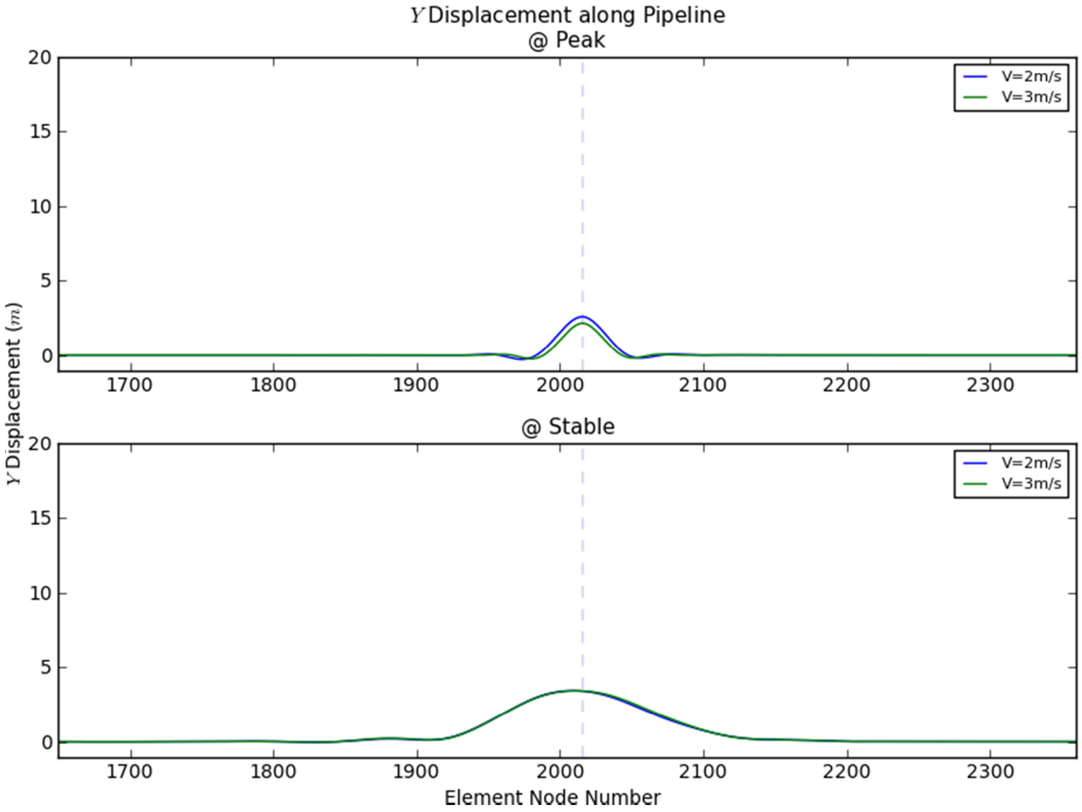


Figure 5-25 Result of FE analysis regarding different velocities vs. survey result (U2=10m)

We found out that V=3m/s and V=4m/s were the most close cases compared with survey among all the cases studied here (see Figure 5-25).

The pipeline was pulled for only several seconds, however, an obvious consequence was caused. What if we decrease the interference time? Does velocity still contribute to the final configuration significantly? Figure 5-26 shows the results of the case with 3.5m lateral displacement related to different velocities.



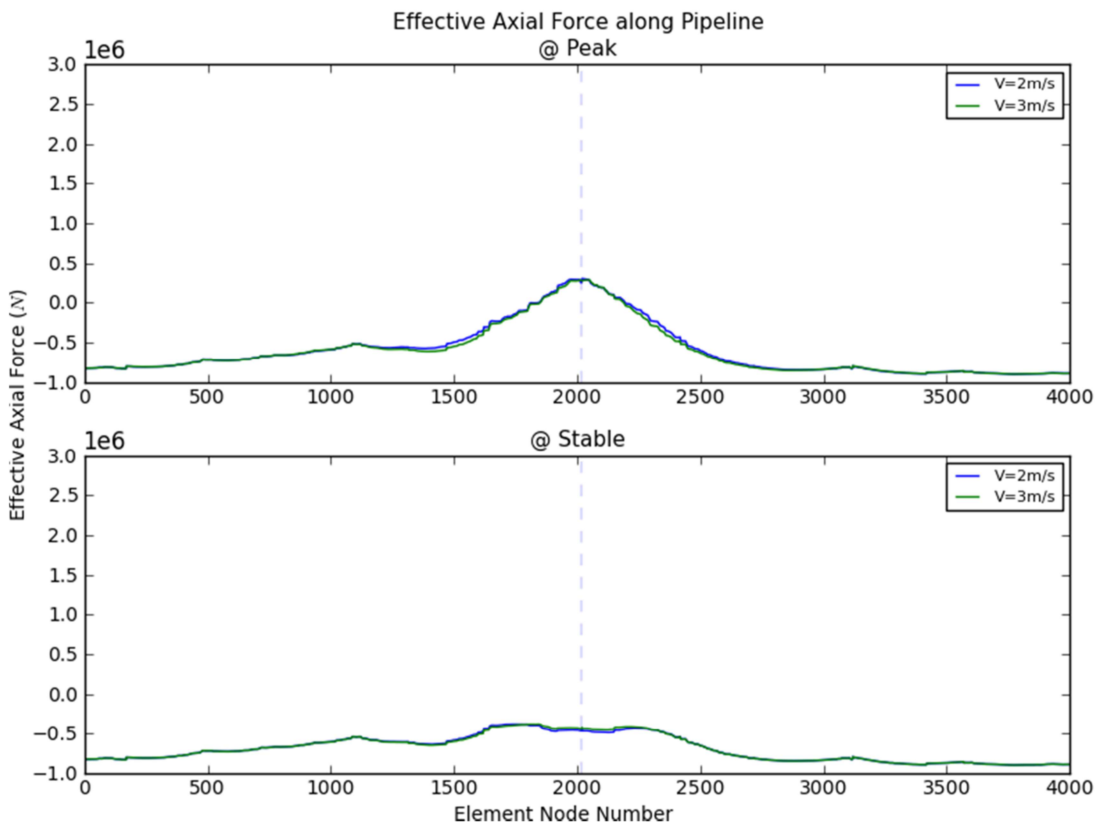


Figure 5-26 Results along pipeline regarding different velocities (U2= 3.5m)

Figure 5-26 illustrates the pipeline's responses related to different velocities. It demonstrates, for a smaller lateral displacement like 3.5m, the shape of buckle doesn't vary much with different velocities. We could guess here it is because that the hooking time is much too short to generate a difference. At the instance of releasing the chain, the shape of pipeline was nearly the same, which could supply same resistance together with the contribution of soil to let itself stop. After the chain was released, the pipeline moved further until stable.

5.5 Tabulated results of FE analysis

Table 5-16 gives out the results for all the executed cases in this chapter.

Table 5-16 Summary of all the results

Case	Time	Max. U2	Max. U3	Max. ESF1	Max. SF1	Max. M_{tot}	Max. ε
	[s]	[m]	[m]	[MN]	[MN]	[MNm]	[-]
01	5	11.67	3.65	2.13	4.25	6.00	0.62 %
02	5	12.82	4.38	2.35	4.47	6.07	0.78 %
03	5	13.94	5.05	2.56	4.68	6.09	0.93 %
04	5	14.89	5.68	2.76	4.88	6.10	1.07 %
05	7	14.66	4.18	2.41	4.53	5.99	0.64 %
06	7	15.72	4.99	2.64	4.76	6.04	0.79 %
07	7	16.91	5.74	2.87	4.99	6.05	0.92 %
08	7	18.00	6.42	3.09	5.21	6.07	1.04 %
09	5	10.02	2.26	1.94	4.05	5.80	0.46 %
10	5	11.01	2.85	2.17	4.29	5.99	0.60 %
11	5	12.05	3.45	2.38	4.50	6.09	0.76 %
12	5	13.01	4.02	2.60	4.72	6.15	0.92 %
13	7	12.93	2.69	2.21	4.33	5.88	0.51 %
14	7	13.99	3.39	2.48	4.60	6.03	0.69 %
15	7	15.01	4.06	2.73	4.85	6.10	0.85 %
16	7	16.08	4.70	2.96	5.08	6.13	0.97 %
17	7	10.57	1.61	1.90	4.01	5.79	0.45 %
18	7	13.60	3.43	2.32	4.44	5.95	0.58 %
19	7	14.68	4.21	2.38	4.50	5.99	0.64 %
20	7	15.88	5.02	2.62	4.74	6.04	0.80 %
21	7	17.07	5.77	2.84	4.96	6.05	0.93 %
22	7	18.17	6.46	3.07	5.19	6.07	1.05 %
μ =0.2		10.45	2.53	1.85	3.97	5.36	0.32 %
μ =0.5		11.67	3.06	2.17	4.39	5.63	0.41 %
μ =0.8		14.24	3.14	2.39	4.51	5.74	0.45 %
[m/s]		[m]	[m]	[MN]	[MN]	[MNm]	[-]
V=2		10.42	0.47	1.47	3.58	4.02	0.18%
V=3		10.53	2.53	1.85	3.97	5.36	0.32 %
V=4		10.27	4.00	2.01	4.13	5.85	0.51 %
V=5		9.97	4.44	2.08	4.20	5.99	0.64%

Since a beam model was used in this thesis, we could find out that the plastic bending moment is around 6 MNm (see in Figure 5-27). If a point load as 700 kN was accounted, the plastic bending moment reduced to approximately 5.2 MNm (see in Figure 5-27). After reaching the plastic bending moment, actually, bending moment wouldn't stay in plateau as the curve in Figure 5-27 but decrease rapidly like Figure 4-3. Since beam element only took bending moment and hooking force globally and Kristoffersen et al. (2013) suggested the deformation first goes locally, we need to explore more about the pipeline's response by using shell element in the future.

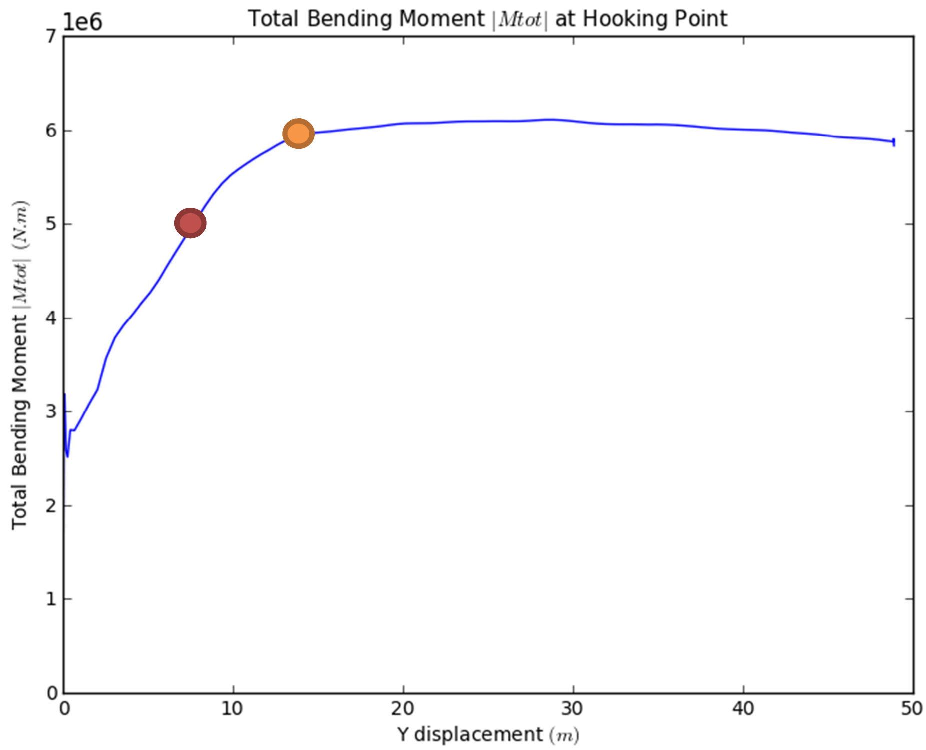


Figure 5-27 Bending moment vs. lateral displacement in beam model

The FE analysis described our concern about the pipeline after hooking incident. Even a small anchor could arouse the response of pipeline unacceptable based on the LC criterion in DNV-OS-F101. However, the results satisfied DC criterion.

6. Conclusions

In this thesis, two drag scenarios, planned anchoring and emergency anchoring, were discussed and possible consequences were summarized in this thesis. Considerations especially geometrical aspects were explored as a screening frame regarding the frequency of emergency anchoring. It was more possible for large anchors than small ones to hook a specific pipeline as a matter of geometrical fact. As for a 30’’ pipeline, the size of anchor which was probably to get stuck was at least 3 tonnes and 1.7 tonnes for a Spek anchor and a Hall anchor, respectively. What’s more, traffic data together with important information, like ship velocity and chain length, could be used as an evident to narrow down the range of possible anchors. For instance, as for water depth of 148m, a 3-tonne anchor wouldn’t touch seabed if it was towed faster than 8 knots. Hooking incidents were with higher prevalence if large anchors (with long chains) were in vicinity of pipeline compared to small ones (with short chains).

Large anchors usually have bigger magnitudes of hooking load than small ones. Based on the FE analysis, pipeline had larger response under the effect of large anchors. For instance, pipeline was demonstrated to be pulled laterally farther. Large hooking force released more ‘pre-compression’ than small anchor did. The configuration of pipeline was sensitive to the anchor sizes in maximum lateral deflection, not really in buckle length.

Load styles also influenced the response obviously even with same magnitude of load. This fact reveals the necessity of dealing with anchor hooking problem in another way to see if we could get a result close to a survey.

The hooking time was discovered as another parameter to affect the response of pipeline. If the load history had longer time length, the responses in bending moment, strain or deformation were observed to be bigger.

The differences caused by lay tension variation were mainly presented in strain, which is a matter of fact. A ‘tightly-compressed’ pipeline was apparently prone to larger damage than a ‘loosely- compressed’ pipeline. It indicated that if the load variation induced by temperature and pressure changes was in the order of 50kN (conservative estimation) or less during operation phase, the difference in pipeline’s response except for strain was negligible in a hooking incident.

As we explored on friction aspect, the result proved that if the pipeline was installed on a soft soil or buried with rocks, where the lateral friction coefficient was considered bigger than dense soil, the length of buckle was shorter. Pipelines on soft soil or buried with rocks moved back more than on dense seabed to get the same lateral displacement.

As the trend of configurations got in load models were not satisfying compared with the survey result, a so called ‘velocity model’ was brought up, where the pipeline was dragged through a moving chain. We found out that the breaking load was reached faster at large towing velocities in contrast to small ones, which also meant the pipeline deflected less in this situation. If the ship was moving at 3m/s, 4 seconds’ hooking incident had a lateral deflection as 10m. However, cases of high velocities tend to have bigger strains and bending moments at hooking point compared with cases of low velocities. It could be guessed if the hooking zone was modeled with shell elements, local deformations could be worse in high velocity cases. Significant risks during emergency anchoring (probably big velocities) are implied, rather than during planned anchoring operation (low velocities). In addition, the global result of a velocity model was found to match the survey well.

A 3-tonne anchor is relatively small in the portfolio of all anchor products. However, the results seemed impossible to satisfy the ALS LC criterion in DNV-OS-F101 even for small anchors. In other words, we couldn’t design out the anchor damages based on ALS LC criterion. Furthermore, pipelines would be more vulnerable faced with big anchors.

7. Recommendations for future work

It should be noted that this thesis was based on a real hooking incident happened to a 30’’ pipeline with a lateral deflection as 10m, where the damage was quite small if we referred to Kvitebjørn pipeline. In view of points mentioned in Chapter 6, some recommendations have been brought up in order to shed some light on dealing with anchor hooking incidents.

First, pipelines should be protected in some areas. For example, if the pipeline crosses anchorage, there should be a protection in any case. As for other areas, like traffic lanes and areas near platforms, appropriate protective approaches should be taken regarding risk assessment. Additionally, history has shown that pipelines usually don’t leak right after hooking incidents. Hence, in-time remedial approaches are of great importance. What’s more, parts of the pipeline that are exposed to significant dynamic loading should be inspected more often than other parts. Effective remedial approaches should be found regarding different extents of anchor damages.

We need to define the failure as loss of containment based on the criteria we have in DNV-OS-F101. Probability of leak should be explored more in ALS. Load effect factors should be established by a comprehensive investigation accounting for the loss of containment.

As for the Abaqus model, there were limitations of beam element such as the hooking force only caused the pipe participating in lateral deflection near the point of hooking. There weren’t any evidences about the local deformation in this thesis. Hence, shell element is recommended to be modeled near the hooking point, while beam element in other parts can take care of the global response. Membrane effect and local deformation could be then found regarding different lateral displacements. The sequence of damage manifesting globally or locally is of great importance to classify the damage based on local strain related to the lateral deflection.

In addition, a more detailed chain should be included in the model taking into account the forces on it and we need to pay more attention to the material properties if faced with a large anchor. What’s more, if we have more hooking incidents in the future, we need to explore various approaches to find the one matched the survey best to estimate the damage by using Abaqus.

We need to learn from the rather few cases of anchor hooking that have occurred to get a better understanding why these event happened. In addition, it is also important to be aware of the loads imposed and severity of damage.

8. Bibliography

1 2012. Abaqus Analysis User's Manual.

2 AFZAL, H. 2014. Industry Seminar on Anchor Threats for Pipelines. Norway.

3 AMDAL, L. W., R NEID, S. & ETTERDAL, B. Optimised Design of Pipelines Exposed to Trawl Pull-over. International Offshore and Polar Engineering Conference, 2011 Maui. International Society of Offshore and Polar Engineers, 5.

4 ANONYMOUS. 2006. Quantitative Risk Assessment of Subsea Pipeline. *EIA Report* [Online].Available: http://www.epd.gov.hk/eia/register/report/eiareport/eia_1252006/html/eiareport/Part2/Section13/Sec2_13_AnnexB.htm.

5 ANONYMOUS 2013. CATS – Technical Brochure.

6 ANONYMOUS. 2014. *Anchor* [Online]. Wikipedia. Available: http://en.wikipedia.org/wiki/Anchor.

7 ASM-INTERNATIONAL 2002. *Atlas of Stress-strain Curves*, ASM International.

8 BAI, Q. & BAI, Y. 2014. Subsea Pipeline Design, Analysis, and Installation, Elsevier Science.

9 BAI, Y. 2001. *Pipelines and Risers*, Elsevier Science.

10 BORESI, A. P. & SCHMIDT, R. J. 2003. *Advanced Mechanics of Materials*, Wiley India Pvt. Limited.

11 DNV 2008. DNV-OS-E302 Offshore Mooring Chain. Norway: DET NORSKE VERITAS.

12 DNV 2010a. DNV-RP-F107 Risk Assessment of Pipeline Protection. Norway: DET NORSKE VERITAS.

13 DNV 2010b. DNV-RP-F109 On-Bottom Stability Design of Submarine Pipelines. Norway: DET NORSKE VERITAS AS.

14 DNV 2010c. DNV-RP-F111 Interference betweem Trawl Gear and Pipelines. Norway: DET NORSKE VERITAS.

15 DNV 2011. DNV-RP-H103 Modelling and Analysis of Marine Operations. Norway: DET NORSKE VERITAS AS.

16 DNV 2012. DNV-RP-E301 Design and Installation of Fluke Anchors. Norway: DET NORSKE VERITAS AS.

17 DNV 2013a. DNV-OS-E301 Position Mooring. Norway: DET NORSKE

VERITAS AS.

18 DNV 2013b. DNV-OS-F101 Submarine Pipeline Systems. Norway: DET NORSKE VERITAS AS.

19 ESPINER, R., KAYE, D., GOODFELLOW, G. & HOPKINS, P. Inspection & Assessment of Damaged Subsea Pipelines: A Case Study. International Pipeline Conference, 2008 Calgary. International Pipeline Conference, 8.

20 GJERTVEIT, E., OPHEIM, B. S. & BERGE, J. O. The Kvitebjørn Gas Pipeline Repair. Offshore Technology Conference, 2010 Houston. Offshore Technology Conference, 9.

21 HAUCH, S. & BAI, Y. 1999. Bending Moment Capacity of Pipes. *Offshore Mechanical and Arctic Engineering***,** 12.

22 HSE 2009. Guidelines for Pipeline Operators on Pipeline Anchor Hazards. Aberdeen: Health & Safety Executive.

23 HVAM, C., BRUSCHI, R., TOMINEZ, M. & VITALI, L. Risk of Pipe Damage from Dragging Anchors. International Society of Offshore and Polar Engineers, 1990 Trondheim. International Society of Offshore and Polar Engineers, 11.

24 I-DEAS. 2014. Which Element Type Should I Use for Finite Element Simulation? Available: http://www.colorado.edu/MCEN/MEMSII/.

25 KARUNAKARAN, D. 2013. Pipelines and Risers. University of Stavanger.

26 KRISTOFFERSEN, M., B RVIK, T., LANGSETH, M., HOPPERSTAD, O. S., ILSTAD, H. & LEVOLD, E. Damage and Failure in An X65 Steel Pipeline Caused by Trawl Gear. Offshore and Arctic Engineering, 2013 Nantes. Offshore and Arctic Engineering, 10.

27 ORSOLATO, R., FABBRI, S. & CHERUBINI, P. Transmediterranean Pipelines Repair. Offshore Mediterranean Conference, 2011 Ravenna. 12.

28 PURI, G. 2011. Python Scripts for Abaqus: Learn by Example, Kan sasana Printer.

29 RAHAMAN, M. M. 2014. Anchoring: Windlass, Winch, Anchor and Chains. Available: http://www.scribd.com/doc/211076609/anchor.

30 SOTRA. 2014. *Sotra Anchor & Chain: Stockist of anchors, chains & shackles* [Online]. Available: http://www.sotra.net/.

31 SRISKANDARAJAH, T. & WILKINS, R. Assessment of Anchor Dragging on Gas Pipelines. International Offshore and Polar Engineering Conference, 2002 Kitakyushu. 8.

32 VERVIK, S. 2011. *Pipeline Accidental Load Analysis.* Norwegian University of Science and Technology.

33 VIGSNES, M., FERGESTAD, D. & OMLAND, Ø. 2008. Huldra Gas Export Anchor Hooking Pre-Assessment. DNV.

34 VITALI, L., TORSELLETTI, E., SPINAZZE, M., BRUSCHI, R. & BRUNETTO, L. Bending Capacity of Pipes Subject to Point Loads. International Conference on Offshore Mechanics and Arctic Engineering, 2003 Cancun. International Conference on Offshore Mechanics and Arctic Engineering.

9. Appendix

9.1 Anchor dimension

Table 9-1 and Figure 9-1 show the dimension of Hall.

Table 9-1 Dimension of anchor Hall (Sotra, 2014)

Weight	A	B	C	D	E	F	G	H	Ø
kgs	mm	mm	mm	mm	mm	mm	mm	mm	mm
1020	1645	1268	584	195	891	891	183	255	50
1290	1778	1374	630	211	965	965	216	280	62
1500	1869	1447	664	222	1015	1015	216	280	62
1740	1966	1517	698	234	1068	1068	238	310	68
2000	2058	1590	732	245	1120	1120	238	310	68
2280	2150	1657	763	255	1165	1165	260	340	74
2460	2207	1700	784	262	1194	1194	260	340	74
3000	2374	1832	841	282	1283	1283	284	360	82
3540	2490	1926	883	295	1349	1349	287	380	82
4000	2610	2008	924	309	1406	1406	310	385	90
4500	2712	2093	962	322	1465	1465	316	410	90
4890	2769	2135	984	329	1498	1498	346	415	100
5000	2790	2150	991	331	1510	1510	346	415	100
6000	2965	2284	1054	352	1605	1605	350	450	100
6900	3100	2393	1105	369	1681	1681	370	480	110
7800	3235	2493	1152	385	1752	1752	380	500	110
8775	3355	2585	1195	399	1816	1816	400	540	117
9072	3392	2615	1209	404	1837	1837	421	580	124
9900	3502	2699	1248	417	1896	1896	421	580	124
11100	3638	2803	1297	433	1970	1970	437	600	130
15400	4056	3126	1446	483	2199	2199	498	680	150
16100	4117	3173	1468	490	2232	2232	498	680	150

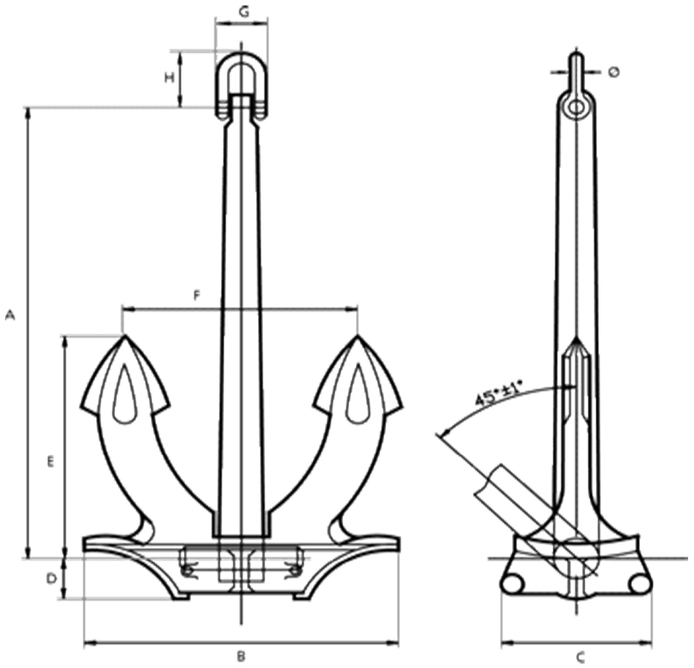


Figure 9-1 Schematic of anchor Hall

Table 9-2 and Figure 9-2 show the dimension of Spek.

Table 9-2 Dimension of Spek (Sotra, 2014)

Weight	A	B	C	D	E	F	G	H	Ø
kgs	mm	mm	mm	mm	mm	mm	mm	mm	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

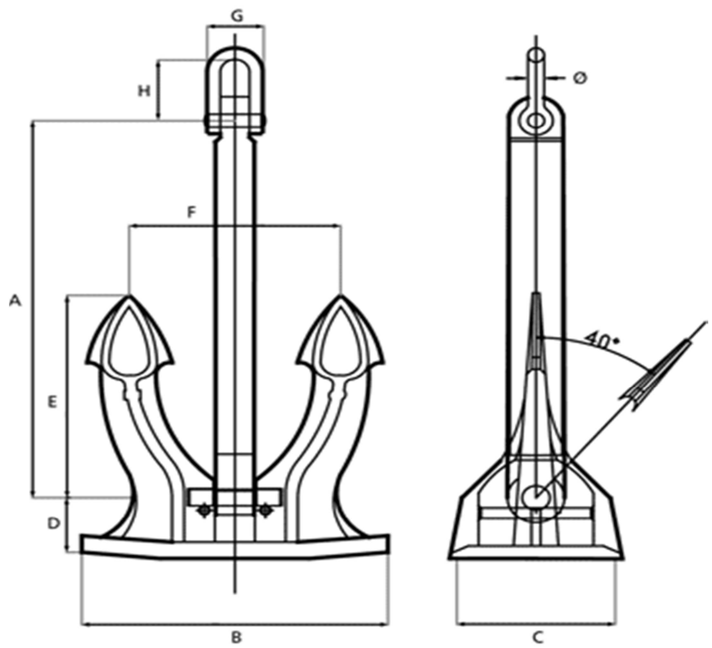


Figure 9-2 Schematic of anchor Spek

9.2 Chain dimension

Table 9-3 shows the dimension of chain related each size of anchor.

Table 9-3 Chain dimension related to anchor weight (DNV, 2013a)

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
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*
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 may 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.

3) If steel wire rope is used the length shall at least be 50% above the values given.

Table 9-4 shows the mechanical properties of chain.

Table 9-4 Mechanical properties for chain cable (DNV, 2008)

Steel grade	*Yield stress* R_e N/mm^2	*Tensile strength* R_m N/mm^2	*Elongation* A_5 %	*Reduction of area* Z %
R3	410	690	17	50 [2)]
R3S	490	770	15	50 [2)]
R4	580	860	12	50 [3)]
R4S	700	960	12	50 [3)]
R5	760	1000	12	50 [3)]

1) For grade R3 and R3S, testing may be carried out at either 0°C or -20°C.
2) For cast accessories, the minimum value shall be 40%.
3) For cast accessories, the minimum value shall be 35%.

9.3 FE analysis results

Figure 9-3 shows the result along pipeline regarding different time length by using cyclic load history.

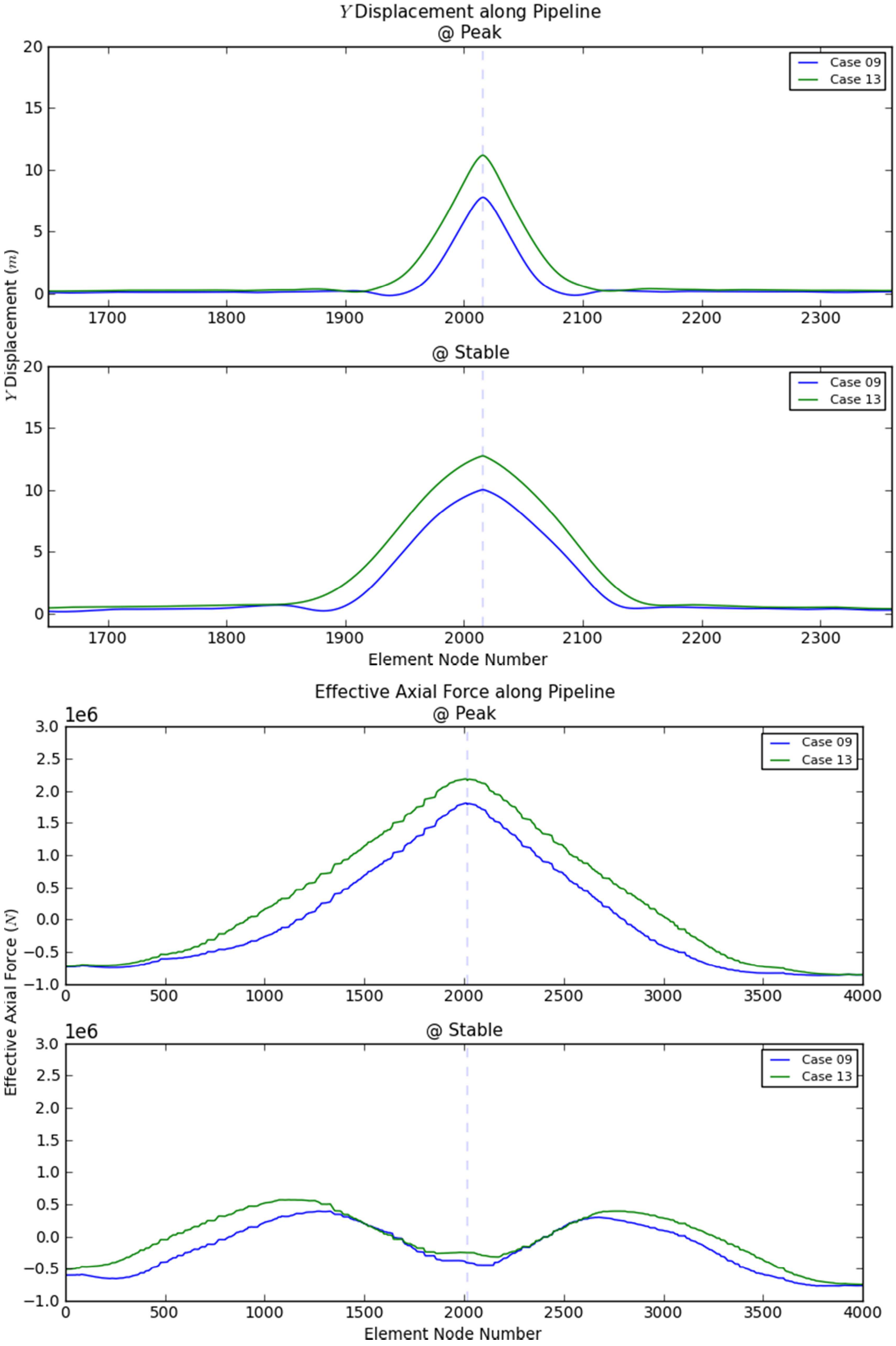


Figure 9-3 Results along pipeline regarding cyclic load history and different time lengths (Case 09, 13)

Figure 9-4 shows the result of hooking node regarding different time length by using cyclic load history.

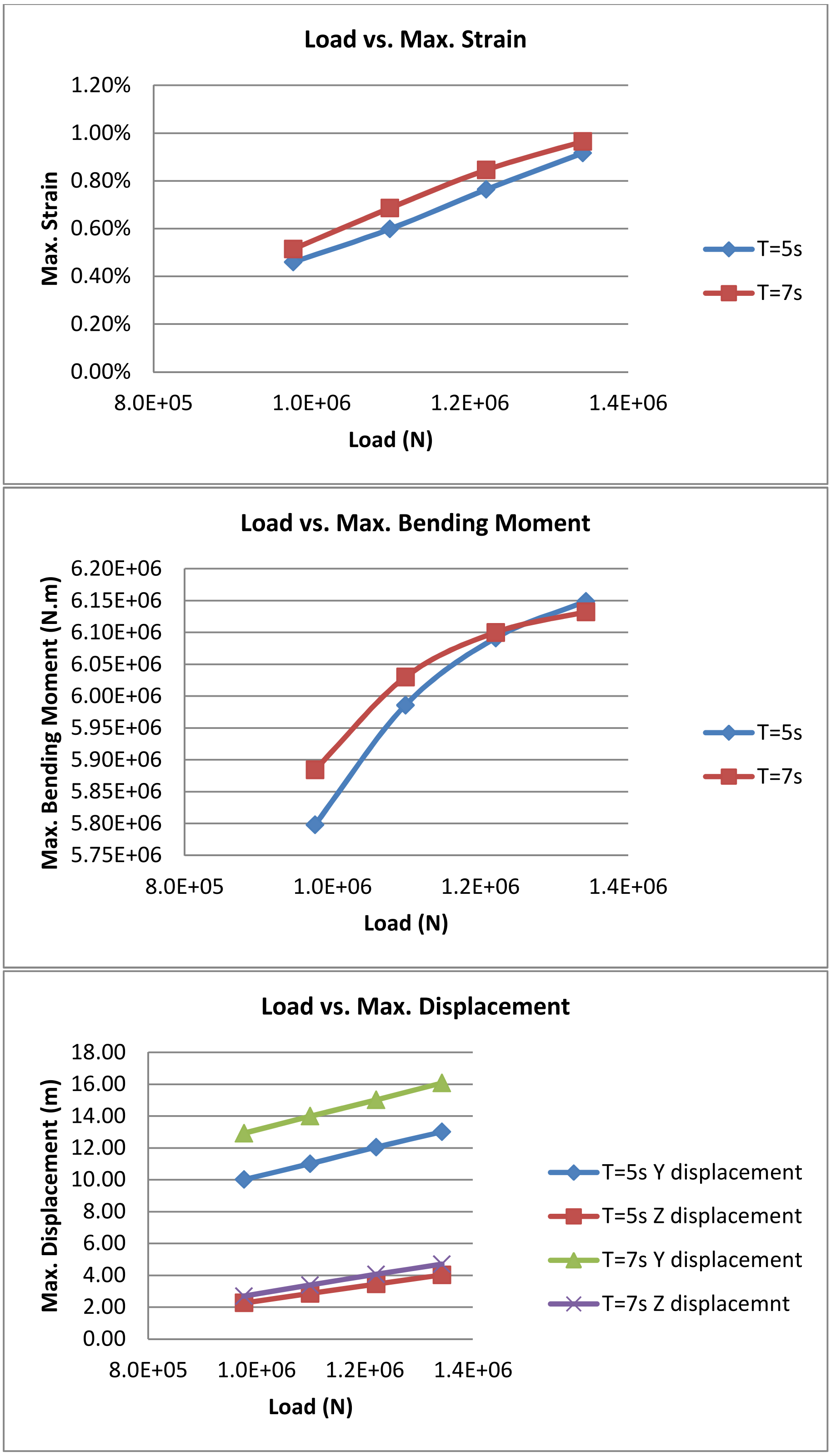


Figure 9-4 Result at hooking node regarding cyclic load history and different time lengths

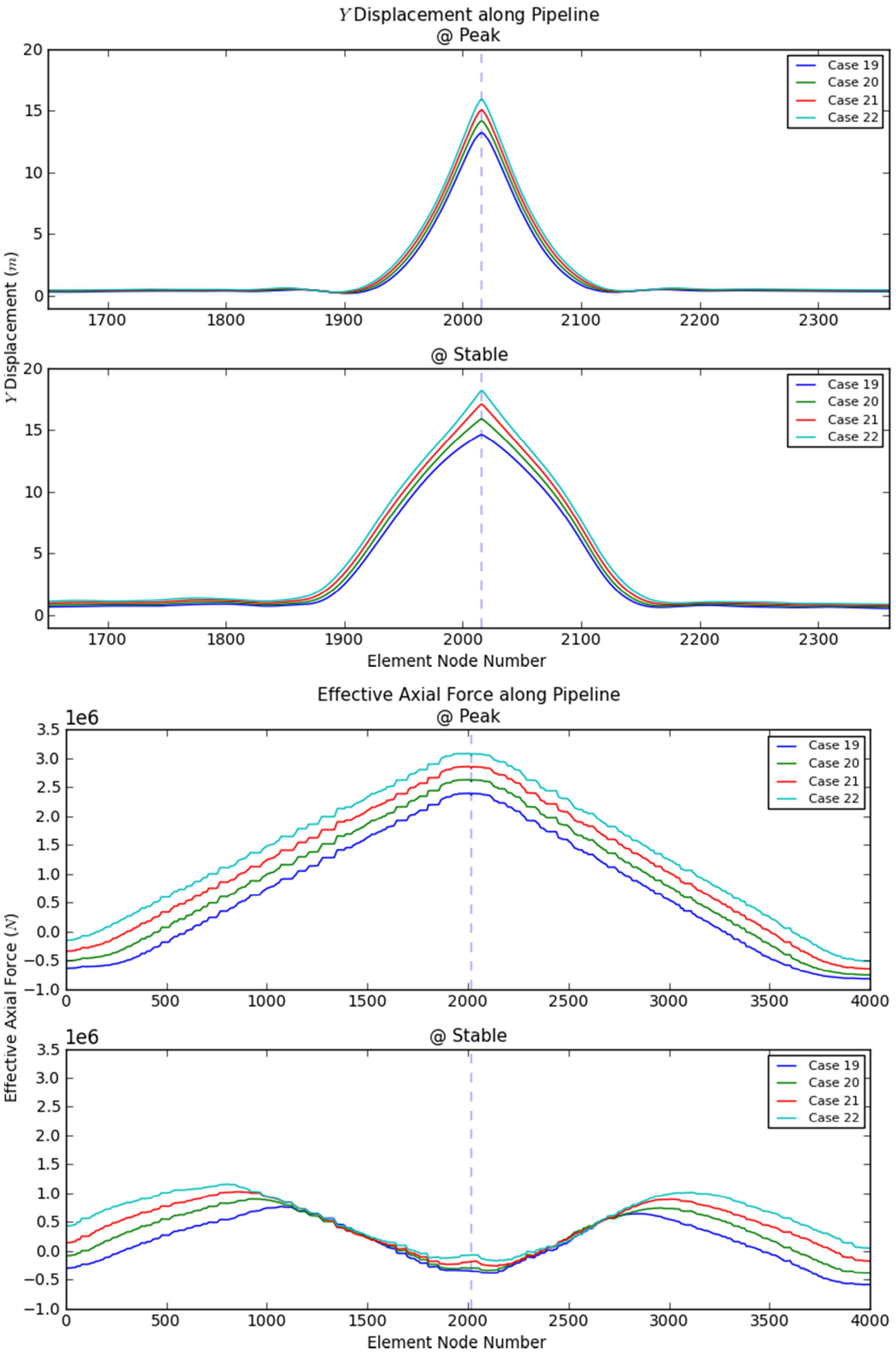


Figure 9-5 Results along pipeline regarding monotonic load history and lay-tension as 300kN (Case 19~ 22)

9.4 Explorations of chains in velocity model

During exploring the chain's properties, we investigated the properties based on a 44mm chain as follows:

- Density per unit volume
- Area of cross section (influencing axial stiffness)
- Material: elastic and elastic-plastic
- Element of chain: beam and truss

Table 9-5 shows the differences between cases, which is the objective of this section. All the chains explored here have same length. All the chains have same mass except for **e-p,b,b**.

Table 9-5 Comparison between cases

	e-p,b,b	**e-p,b,s**	**e,s,b**	**e-p,s,b**	**e,s,b(truss)**
e-p,b,b		Different densities		Different areas of chain's cross section	
e-p,b,s	Different densities				
e,s,b				Different materials	Different elements
e-p,s,b	Different areas of chain's cross section		Different materials		
e,s,b(truss)			Different elements		
	e-p,b,b: elastic-plastic material, bigger cross sectional area than 44mm chain, same density as 44mm chain, beam element e-p,b,s: elastic-plastic material, bigger cross sectional area than 44mm chain, smaller density than 44mm chain, beam element e,s,b: elastic material, same cross sectional area as 44mm chain, same density as 44mm chain, beam element e-p,s,b: elastic-plastic material, same cross sectional area as 44mm chain, same density as 44mm chain, beam element e,s,b(truss): elastic material, same cross sectional area as 44mm chain, same density as 44mm chain, truss element				

Figure 9-6 and Figure 9-7 show the axial force of chain regarding time in different cases extracted from Abaqus.

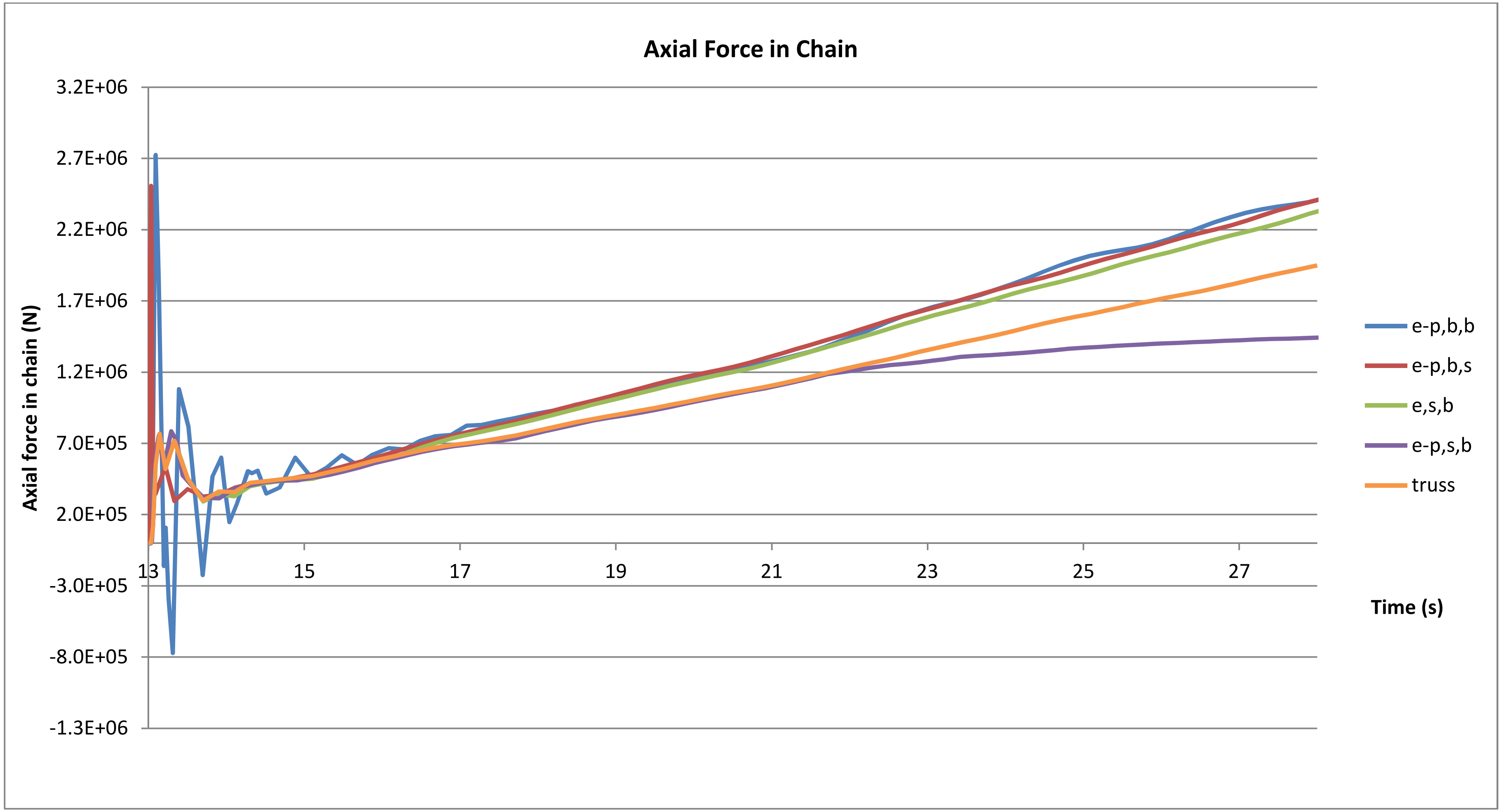


Figure 9-6 Load history in axis of chain in different cases in long time

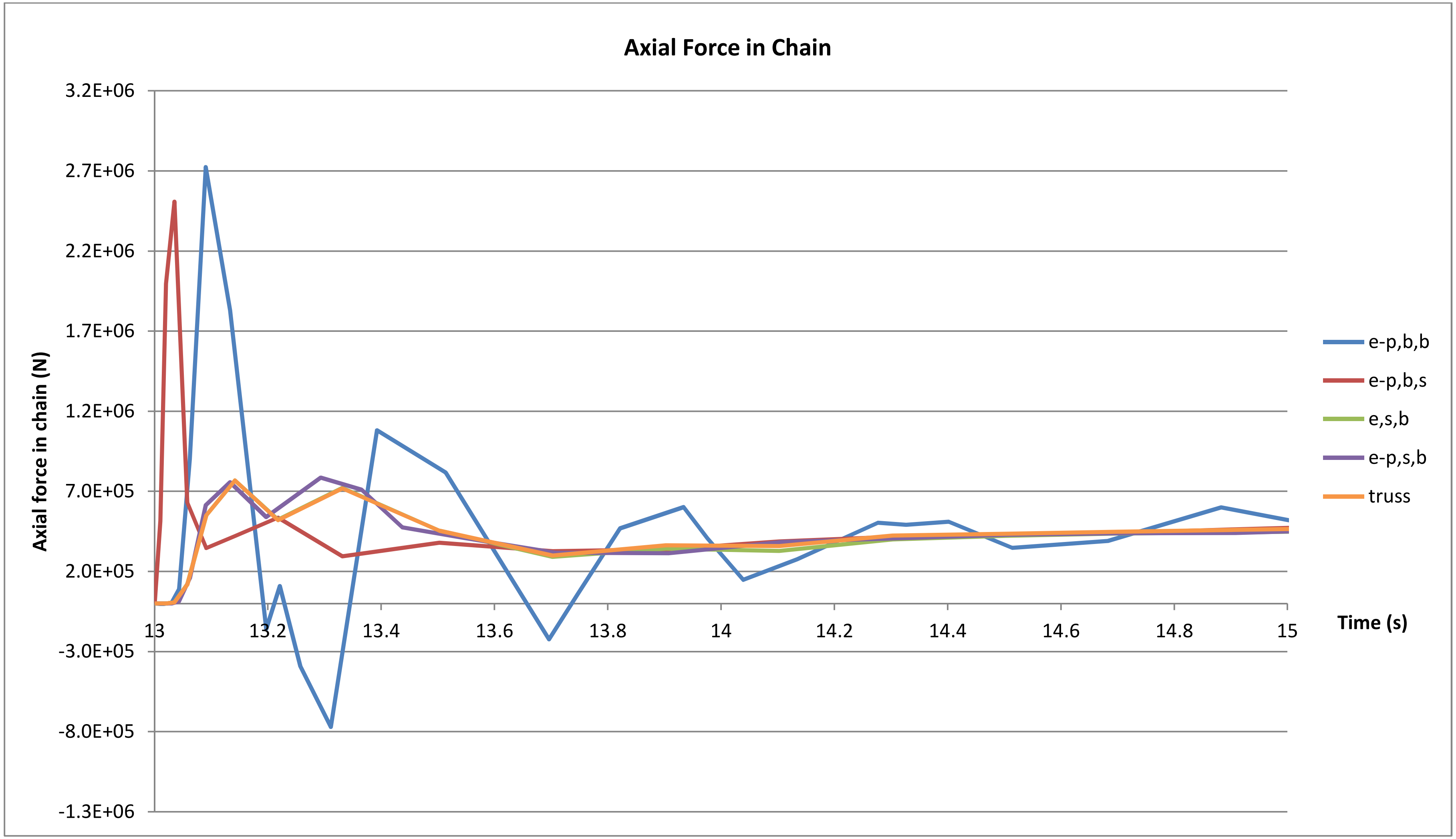


Figure 9-7 Zoomed load history in axis of chain in different cases in short time

Table 9-6 shows the result of comparison based on the axial load history in chain presented in Figure 9-6 and Figure 9-7.

Table 9-6 Result of comparison based on Figure 9-6 and Figure 9-7

		Result of				
		e-p,b,b	e-p,b,s	e,s,b	e-p,s,b	e,s,b(truss)
Compared with	e-p,b,b		Close peak value; fewer initial fluctuations; close load history beyond initial fluctuation		Lower peak value; fewer initial fluctuations; reaching a plateau faster	
	e-p,b,s	Close peak value; more initial fluctuations; close load history beyond initial fluctuation				
	e,s,b				Nearly the same load in the beginning; reaching a plateau due to plastic with time	Nearly the same load in the beginning; slightly smaller load as time increasing
	e-p,s,b	Higher peak value; more initial fluctuations; reaching a plateau more slowly		Nearly the same load in the beginning; keeping increasing due to elastic with time		
	e,s,b(truss)			Nearly the same load in the beginning; slightly bigger load as time increasing		
	e-p,b,b: elastic-plastic material, bigger cross sectional area than 44mm chain, same density as 44mm chain, beam element e-p,b,s: elastic-plastic material, bigger cross sectional area than 44mm chain, smaller density than 44mm chain, beam element e,s,b: elastic material, same cross sectional area as 44mm chain, same density as 44mm chain, beam element e-p,s,b: elastic-plastic material, same cross sectional area as 44mm chain, same density as 44mm chain, beam element e,s,b(truss): elastic material, same cross sectional area as 44mm chain, same density as 44mm chain, truss element					

e-p, s, b (elastic-plastic material, same cross sectional area as 44mm chain, density same as 44mm chain) is the type of chain we used in velocity model since the hooking time is relatively short. The load in the chain hasn’t reached the plateau yet. Hence, theirs is not much difference between cases as long as the chain as same dimension as 44mm chain.