Universitetet
i Stavanger

FACULTY OF SCIENCE AND TECHNOLOGY

MASTER'S THESIS

Study programme/specialisation: Mechanical and Structural Engineering and Material Science – Offshore Technology Engineering	Spring semester, 2017 Confidential
Author: Sigurd Vestbø Næss	Sigurd Vestbø Næss (signature of author)

Programme coordinator: Professor Ove Tobias Gudmestad

Supervisor(s): Knut Ove Steinhovden, Svein Larsen

Title of master's thesis:

Emergency Release of Mooring Lines in the Barents Sea

Credits (ECTS): 30

Keywords:

Disconnection of mooring lines

Catenary mooring lines

Ice management

Orcaflex

Number of pages: 104

+ supplemental material/other: 5 + Electronic attachment

Stavanger, 15.06.2017
date/year

Title page for Master's Thesis
Faculty of Science and Technology

(Page left intentionally blank)

Abstract

With increasing offshore activities in the Barents Sea, the need for risk reducing measures will increase as well. In the Arctic, the weather can change rapidly and is characterized by being difficult to forecast. As a final defense, a platform should be able to safely shut-down current operation, disconnect from its mooring lines and evacuate the site. The disconnection process will depend on the type of operation, whether exploration or production.

To analyze a disconnecting mooring line, the software program Orcaflex was used to analyze the disconnection process on a semi-submersible drilling rig, in time domain. The results are discussed with respect to safety and the possibility of reconnecting the mooring line. Discussion about relevant parameters for disconnection is also presented.

The upper parts of the mooring wire will in cases where the wire is taut, hit the pontoons of the rig. The maximum impact force calculated was approximately 200kN, which is assumed to be negligible with respect to damage to the rig itself, making damages to the wire a primary concern. Using a chain segment of 2 meter between the mooring wire and release tool will dampen the recoil to a more acceptable level, although there will be some movements of the release tool. Using more than 2-meter chain segments will induce shock-loads in the wire. Bending stress due to curling of the wire rope will not exceed the yield stress in individual wires.

Once the leeward mooring lines are disconnected, the rig should be manually move up against the wind or the wire rope should be paid out to approximately 300 meters to lessen the tension. At this release point, no significant curling will form on the wire rope, there will be no hull contact and no line clash provided 2-meter chain segment is used. G-forces must be accounted for in the design of the release tool, and the tool should passively protect weak components such as electronic components.

Acknowledgements

This thesis marks the end of my Master's degree in Offshore Technology Engineering at the University of Stavanger.

I would like to thank Knut Ove Steinhovden (CEO of Ejecto) and Svein Larsen for proposing the topic as well as providing practical guidance with respect to mooring. Knut Ove Steinhovden and Svein Larsen have worked in the mooring business for many years. An extra thank you to Svein Larsen for providing relevant information.

I would also like to thank Professor Ove Tobias Gudmestad for showing interest in the thesis and for providing feedback.

To my friends, and in particular; Preben Bøgwald and Svein Braseth for helping me with HydroD and Orcaflex, respectively. And for our discussions.

Finally thank you to my sister Sunniva for proof reading this thesis, and a thank you to Ove Haugen for providing practical information about platform management.

Sigurd Næss

University of Stavanger, 2017

Norway

Table of Contents

Abbreviations

ABS	American Bureau of Shipping
AT	Alert Time (HT-(T-time))
ATA	Automatic Thruster Assist
BOP	Blow Out Preventer
DNV-GL	Det Norske Veritas Germanischer Lloyd
DOF	Degree of Freedom
EDPHOT	Emergency Drill Pipe Hang-Off Tool
FPU	Floating production Unit
HT	Hazard Time
IM	Ice Management
IMP	Ice Management Plan
ISO	International Organization for Standardization
IWRC	Independent Wire Rope Core
LMRP	Lower Marine Riser Package
MOT	Move Off Time
NCS	Norwegian Continental Shelf
POD	Probability of Detection
SAR	Search and Rescue
ST	Secure Time
T-Time	Termination Time

1. Introduction

With increasing activities in the Barents Sea, new challenges will emerge. The Barents Sea introduces arctic elements, such as icebergs and polar lows (see Chapter 4.2). The arctic elements are characterized by being difficult to forecast with uncertainties in actions and effects. *Ice management* is a systematic approach to handle ice features (see Chapter 4.4) that can incorporate disconnection as a final defense of a vessel/rig in the event of an emergency. This is especially true for production platforms, which have the potential for large environmental damage and potential loss of life.

While this thesis will focus on the Arctic environment, the ability to safely disconnect is relevant for other waters and applications as well. For example, the South China Sea has seasonal typhoons and tropical storms. In the North Sea, on several occasions, barges have come loose during storms, leading to potential collisions with other installations, by having disconnection ability operation can be maintained for longer periods while the threat is being evaluated. Other applications that could potentially benefit from disconnection ability can include offshore fish farms and wind installations.

Safe disconnection ability is recognized by the industry as a need for arctic operations as stated in [1, p. 14], where industry participants were asked to rank ten different topics. The result can be seen in Figure 1-1, where disconnection/reconnection is ranked second.

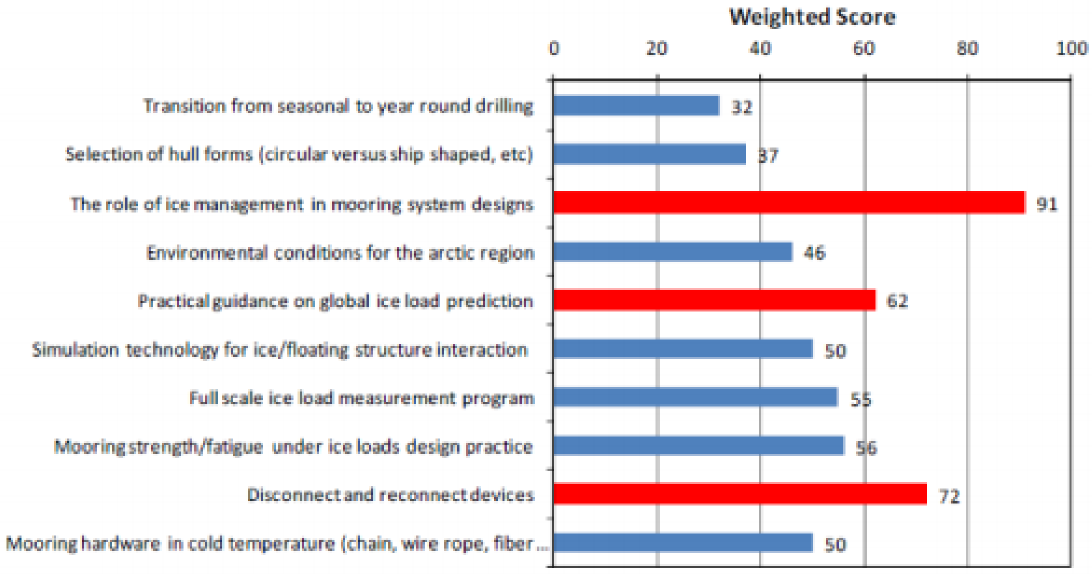


Figure 1-1: Results from ABS Arctic Mooring Workshop. Figure from [1, p. 14].

Current experience in arctic floating production is limited [1, p. 3], but drilling operations date back to the mid-1970s in the Beaufort Sea. The best source of information about moored vessels in pack ice conditions stem from the drill barge *Kulluk* which was moored in the Beaufort Sea. Throughout its life, the Kulluk collected in-ice performance data [1, p. 1]. The Kulluk was equipped with Remote Anchor Release system (RAR, see Chapter 3.3) that enabled disconnection, within 585 operating days the Kulluk disconnected 8 times [2, p. 13].

The most significant floating production operations in arctic waters are the Terra Nova project and White Rose project located off the coast of Newfoundland [1, pp. 3-4]. Both involve the use of FPSOs (Terra Nova FPSO and SeaRose FPSO respectively), with disconnectable spider buoys that hold mooring lines and risers. In the Norwegian part of the Barents Sea, production is limited to the Goliat platform. The offshore facilities scheme for the Shtokman field in the Russian part of the Barents Sea involves subsea production systems tied back to a ship shaped floating production unit (FPU) [1, p. 4]. An example of an FPU that has been suggested includes a disconnectable internal mooring turret, reconnecting the mooring systems can take up to three months therefore disconnecting the mooring system is expected to be a rare event [1, p. 5].

1.1 The Barents Sea

The Barents Sea lies to the north of Norway (Figure 1-2). It stretches from the Norwegian Sea in the west to Novaya Zemlya in the east, and all the way up to the archipelagos of Svalbard to the northwest.

Figure 1-2: The Barents Sea. Figure from [3]

Exploration in the Barents Sea started in 1980, and as of 2014 over 100 wells have been drilled with over 30 discoveries, most notably the Johan Castberg field and Goliat field [4]. With the 23rd Licensing round January 2015 [5, p. 3] several blocks in the eastern part of the Barents Sea was opened for further exploration.

Polar lows, fog and cold fronts characterize the Barents Sea. During summer fog will form as the warm air passes the cold water. Cold fronts will bring heavy precipitation, in winter this will come as snow, which will make visibility a challenge [5, p. 6]. Chapter 4 presents some of the weather phenomenona in greater detail.

1.2 Rig/Vessel in Arctic Environment

In cold climate, any vessel or rig must be winterized to sufficiently protect the vessel, equipment and personnel. The main concerns for winterization are the effect of ice accretion, cold temperature effects and the working climate [6, p. 3].

Ice accretion is the gradual accumulation of ice that can influence the stability of the vessel, unless proper de-icing measures are taken. [7] Table 2.2 specifies additional stability requirements, by considering the weight distribution along various surfaces e.g. decks, gangways and other horizontal surfaces. Equipment on deck is also subject to ice accretion and must be protected. [7] Chapter 2.1.1 recommends the use of passive protection i.e. enclosures etc. due to it being more reliable than active protection in the form of heating. Steps to secure personnel and equipment against falling ice (e.g. from a drilling rig) is of foremost importance.

Low temperature properties for materials must be known and considered during selection, for instance the mechanical properties in metals must withstand de-icing activities in addition to its intended purpose. E.g. must not degrade after repeated strikes from a wooden mallet or similar.

Relevant production units in the Barents Sea include a Sevan 1000 (used at the Goliat field), ship shaped FPSO with rotation ability, but choice of solution will be unique for each field. Relevant drilling units will typically be winterized H6, GM4000/GM4D or CatD. However, these drilling rigs are not necessarily optimal.

1.3 Mooring Systems

With exploration of oil and gas, the need for temporary fixed anchoring is needed. The purpose of a mooring is to maintain the position of a rig/vessel. If risers are involved the mooring system will have a maximum offset that the vessel is allowed to drift without compromising the integrity of the riser. Many different mooring systems exist such as: Catenary mooring, taut leg mooring and tension leg mooring. In this thesis, the catenary mooring will be explored with respect to disconnection. The catenary mooring can be used in shallow to deep water in a wire and chain configuration. The limiting factor is the weight of the line. Synthetic fibre rope has been developed for deep water mooring, where chain/wire would be too heavy.

In the Arctic, the low temperatures can affect the performance of some mooring equipment if exposed to the elements by undergoing a ductile-to-brittle transition. This can lead to brittle fractures if the system is subjected to an impact load, e.g. ice load [1, p. 12].

A relatively new method of mooring includes combining a traditional spread mooring system with thrusters. This is known as Automatic Thruster Assist (ATA) and works by using azimuth thrusters to counteract environmental forces, thus reducing the loads on the mooring lines. Satellites are used for positioning, with the thrusters reacting to changes in position. In the Arctic however, satellite coverage is not optimal with current systems. Available systems include the American “GPS”, the Russian “GLONASS” and the European “Galileo”. The latter system was made available in December 2016 with system completion in 2020 [8]. The GPS and GLONASS are both military in nature and due to geopolitical tensions may not be available to certain users. In general, current satellites do not cover the Arctic well enough, which can cause miscommunication between the ATA system and the satellites. Should this happen the ATA system can become a danger by unintentionally working with the environmental forces. This will lead to *drive-off* were the load in the mooring lines can become too great. Worst case scenario is if the resulting drive-off causes vertical offset (more than 8°) in the lower flex-joint of the riser. Due to this danger, the ATA system should consider using more reliable input to control the thrusters in the Arctic, or use a manned control unit.

1.3.1 Chain

Chain is the most commonly used type of mooring line with two distinct variants, studless and studlink see Figure 1-3.

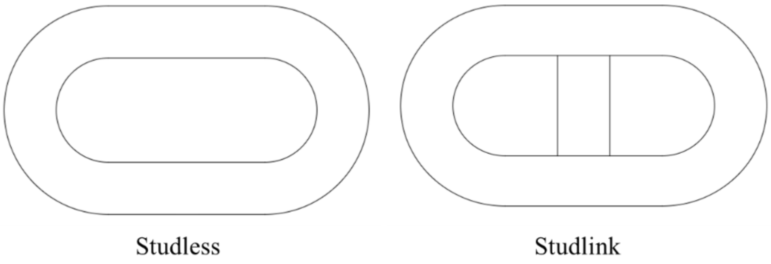


Figure 1-3: Studless vs. Studlink

Generally, studlink chains are used for operations of limited duration. Studlink chains are often reset during their lifetime, whereas studless chains are used on a more permanent basis [9, p. 12]. When combined with wire rope or synthetic rope the chain will be located at the bottom, connected to the anchor. The weight of the chain and friction with the seabed acts as the main component in station keeping. The bottom chain also reduces the vertical pull the anchor will experience. The biggest advantages gained by using chain are long life span and high strength [10, p. 198]. In arctic applications, if an all chain mooring line is used, the mooring line will have to deal with ice impact loading. How this will influence the integrity of the mooring chain is somewhat uncertain [1, p. 12], with some believing that studlinks are better suited to handle ice impacts [1, p. 12]. Per [11] mooring chains can be made with different steel grades with different yield stress and tensile strength, see Table 1-1.

Table 1-1:Excerpt from [11] Table E1 Minimum mechanical properties for chain cable materials

Steel grade	Yield stress [N/mm^2]	Tensile Strength [N/mm^2]
R3	410	690
R3S	490	770
R4	580	860
R4S	700	960
R5	760	1000

1.3.2 Wire Rope

Wire rope consists of multiple strands of steel wire. The main characteristic of wire rope is good strength-to-size ratio, but poor strength-to-weight ratio [10, p. 198]. Advantages over chain is a wire ropes redundancy, if one wire fails the entire system will still be intact. Three main classes of wire rope exist based on the cross section; spiral strand, six (or eight) strand and rotation resistant [12, p. 141]. In mooring application, typically a six-strand rope is used because this can pass over a sheave (e.g. fairlead). Figure 1-4 shows a cross section of a six-strand. Here *six-strand* refers to the number of strands spun helically around the core.

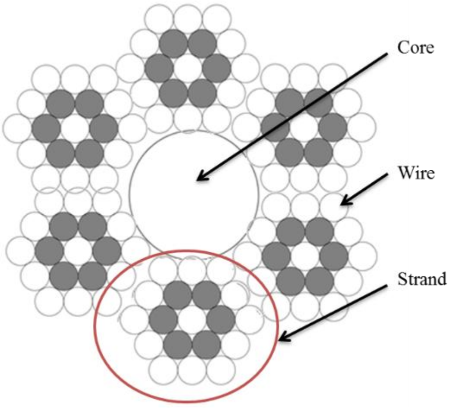


Figure 1-4: Wire rope composition

The core of the wire rope need not necessarily be metallic, wire ropes also comes with synthetic or natural fiber cores where weight consideration is needed. Apart from weight, a fiber core will have greater elasticity than a metallic core [13], and can store large amount of lubrication [14, p. 29]. A wire rope consisting of a metallic core is normally arranged as an “Independent Wire Rope Core” (IWRC) i.e. the core is formed as a wire rope, and offers greater strength, more resistant to crushing and heat than a wire rope with fibre core [13].

Experience with the use of wire rope in arctic waters is limited [1, p. 12], the Kulluk was moored by using shielded steel wire rope with no reported problems. In general, ice impact should not be allowed; to avoid mechanical abrasion.

Due to its complexity, a wire rope has many failure modes. If the wire rope is not properly lubricated it will be subjected to mechanical wear i.e. removal of material from the wire due to friction. Lubrication of the wire rope also protects against corrosion.

In mooring applications where a wire rope is spooled onto a drum, the fleet angle and pretension are important parameters. The fleet angle is defined as the angle formed between the flange of the drum and a sheave see Figure 1-5. A vessel can be used to apply pretension as the wire is spooled onto a drum.

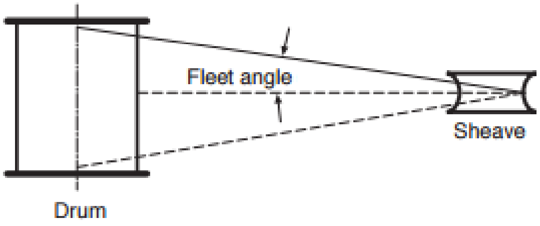


Figure 1-5: Fleet angle. Figure by Bridon [15, p. 37]

The fleet angle should generally lie between 0.5°-2.5° [15, p. 37], if the angle is smaller than 0.5° the wire can start to pile up at the flange. If this is not fixed, the wire rope will over time start to roll down creating a shock load in the rope and structure [15, p. 37]. The grooves of the wire must match the diameter of the wire rope. Oversized grooves lead to premature wire fractures due to insufficient support [15, p. 40], whereas undersized grooves will crush and deform the wire rope [15, p. 40].

Termination refers to the process of attaching a socket at the end(s) of a wire. In mooring applications, a CR-socket is often used, this locks the wire in place by using molten zinc or an epoxy resin. The strength of a termination is measured as *efficiency* based on the available minimum break load e.g. if the efficiency is 80% then 80% of the minimum break load will be available [16, p. 6].

Figure 1-6: CR-Socket. Figure from [17]

A wire rope is subjected to wear throughout its life, it will therefore have to be discarded when discard criteria are met. NS-ISO 4309:2010 [18] is the governing standard concerning discard of wire ropes, unless the wire manufacturers have their own discard criteria. In general, this standard deal primarily with number of wire breaks and changes in diameter and/or if deformation has occurred. With respect to release of mooring lines it is difficult to know for sure what kind of damage is likely to occur without any experimental data. However, based on the simulations presented in Chapter 7 external damage from hull contact and line clashing will be a concern. If twist has been induced in a wire rope during installation the resulting disconnect can lead to kinks in the wire rope (see Chapter 9.4).

A mooring wire will be subjected to fluctuating stresses induced by the motion of the vessel/rig. The inner wires are stressed more than the outer wires [14, p. 172], making visual inspection difficult. A wire rope should therefore be inspected by magnetic methods [14, p. 172].

When subjecting a wire rope to tension it will start to elongate. This elongation will increase the potential energy in the steel wire rope. The potential energy in a steel wire rope equals the area under the stress-strain curve (see Figure 1-7). At the moment of disconnect, this energy will become kinetic. This kinetic energy will accelerate the wire rope and any object connected to it e.g. release tool.

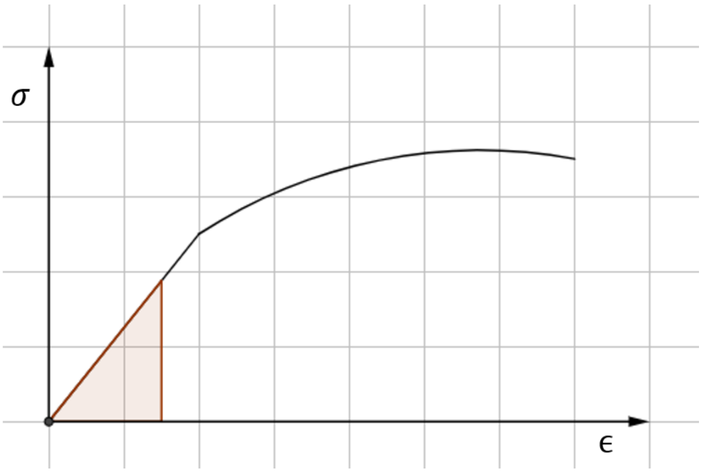


Figure 1-7: General stress-strain diagram

The shock experienced by the wire rope during disconnect, must be kept as low as possible to avoid damage to the wire rope, contrary to popular belief 99.5% of all birdcages, are not generated by shock-loads [19, p. 34]. Steps to lower the amount of potential energy for a wire rope could include adding less elastic parts (e.g. chain). Alternatively, by having a plastic layer between the steel core and outer strands, that act as shock absorber [20, p. 15]. How feasible the reducing methods are with respect to mooring must be determined in advance. In this thesis, chain segments between the tool and the wire rope will be explored.

1.3.3 Synthetic Fibre Rope

Fiber ropes are made of nylon, dacron, kevlar, polypropylene or polyethylene [10, p. 198]. Fiber ropes are almost neutrally buoyant making them good for deep-water mooring. A synthetic fiber rope consists of three parts, the core, sand barrier and cover [21, p. 134].

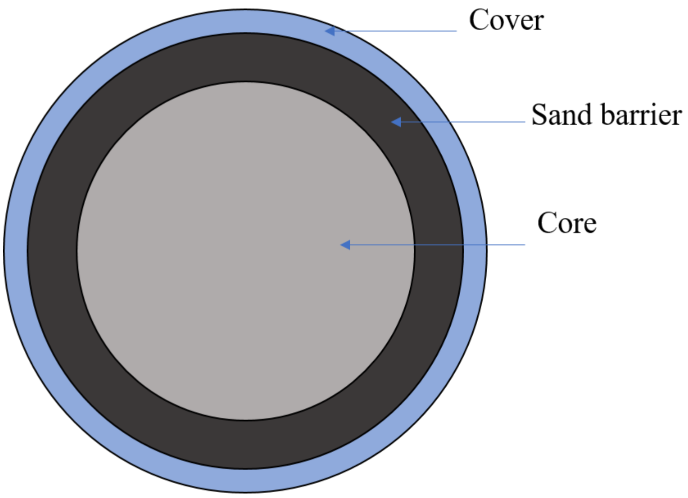


Figure 1-8: Synthetic fibre rope general cross section. Layers are not to scale.

If synthetic rope is considered for arctic applications, contact with the seabed and ice must be avoided. Synthetic rope can be difficult to control once a mooring system has been disconnected, for this reason synthetic rope was not considered in the Shtokman project [1, p. 5].

To control twist that can be induced in the mooring line, a swivel can be used in-between a steel wire rope and a fibre rope. A swivel will allow the ropes to twist without transferring the twist to the other rope.

Other considerations include damage by trawl wires and limiting amount of UV exposure during storage [10, p. 198].

2. Objectives and Thesis Structure

2.1 Objectives

The objective of this thesis is to explore and identify parameters for the continued development of an emergency release tool of catenary mooring lines. A model of a rig based on COSL Pioneer will be created and run in time domain in Orcaflex to understand the mechanical aspect of release. Several simulations will be performed, with varying loads and release points. The data provided by Orcaflex shall be presented and discussed.

The thesis will include a literature study on current knowledge and concepts. This part will include a description of the equipment involved i.e. wire, chain, release tools etc.

Limitations and parameters for a release tool and disconnection process should be highlighted and discussed. Proposed design criteria for a release tool will be presented.

2.2 Thesis Structure

The rest of the thesis is structured as follows. Chapter 3 presents some technologies that will enable the release of mooring lines. Chapter 4 describes some relevant background information about the weather effects in Barents Sea and what to expect. Chapter 5 presents the mathematical methods used in Orcaflex. Chapter 6 describes the process used to created and obtain relevant data for the rig model. The Orcaflex model is discussed in Chapter 7. In Chapter 8 difficulties encountered with the Orcaflex model is described. Chapter 9 presents and discusses the obtained results. Chapter 10 proposes a set of design criteria for a release tool. In Chapter 11 a discussion about the decision and what parameters govern a release of mooring lines, this chapter also presents a scenario that lead up to a disconnection. Chapter 12 summarize the Orcaflex results and a conclusion is made with respect to how a release should be done. Chapter 13 provides a list of recommendations for future work specifically to address the limitations in the Orcaflex simulations. Finally, lists of references, figures, tables and appendices are provided.

3. State of Art with Respect to Release Mechanisms

The following section presents three release tool concepts.

3.1 Ejecto

The MultiDog MCQ-9R (see Figure 3-1) is a new product that is in development by the company Ejecto. It is a quick release connector that is activated by acoustic signals sent from the surface using the HiPAP system. The technology behind the MCQ-9R is based on nine locking dogs that hold the tension. At release 3 out of 9 dogs will be sacrificed. The minimum break load is 900 metric tons that is distributed evenly among the locking dogs.

Figure 3-1: MultiDog MCQ-9R. Figure by Ejecto

Communication is achieved via three transponders that insure that at least one transponder is not in the shadow of the mooring line. Depth wise the MCQ-9R is pressure compensated with transponders that can operate up to 1000 meters.

The actual release is achieved when the acoustic signal sent from the onboard HiPAP system causes a valve to be opened, that releases a high-pressure fluid from an accumulator. This will shift the load from all locking dogs to the three sacrificial locking dogs. The material selection for the sacrificial dogs will be set according to mechanical properties.

With the separation of the connector, the fluid volume change will cause an under-pressure between the female and male parts that will damp some of the peak loads.

The MultiDog technology was initially designed as a tool for use in subsea lifting operations, up to 35ton. This tool was made available in 2001. The standards used in the development of the lifting tool, and later mooring connector can be seen in Figure 3-2. DNV was involved throughout the process. As of April 2017, the lifting tool is in the process of being recertified to 55 ton and will be CE-marked.

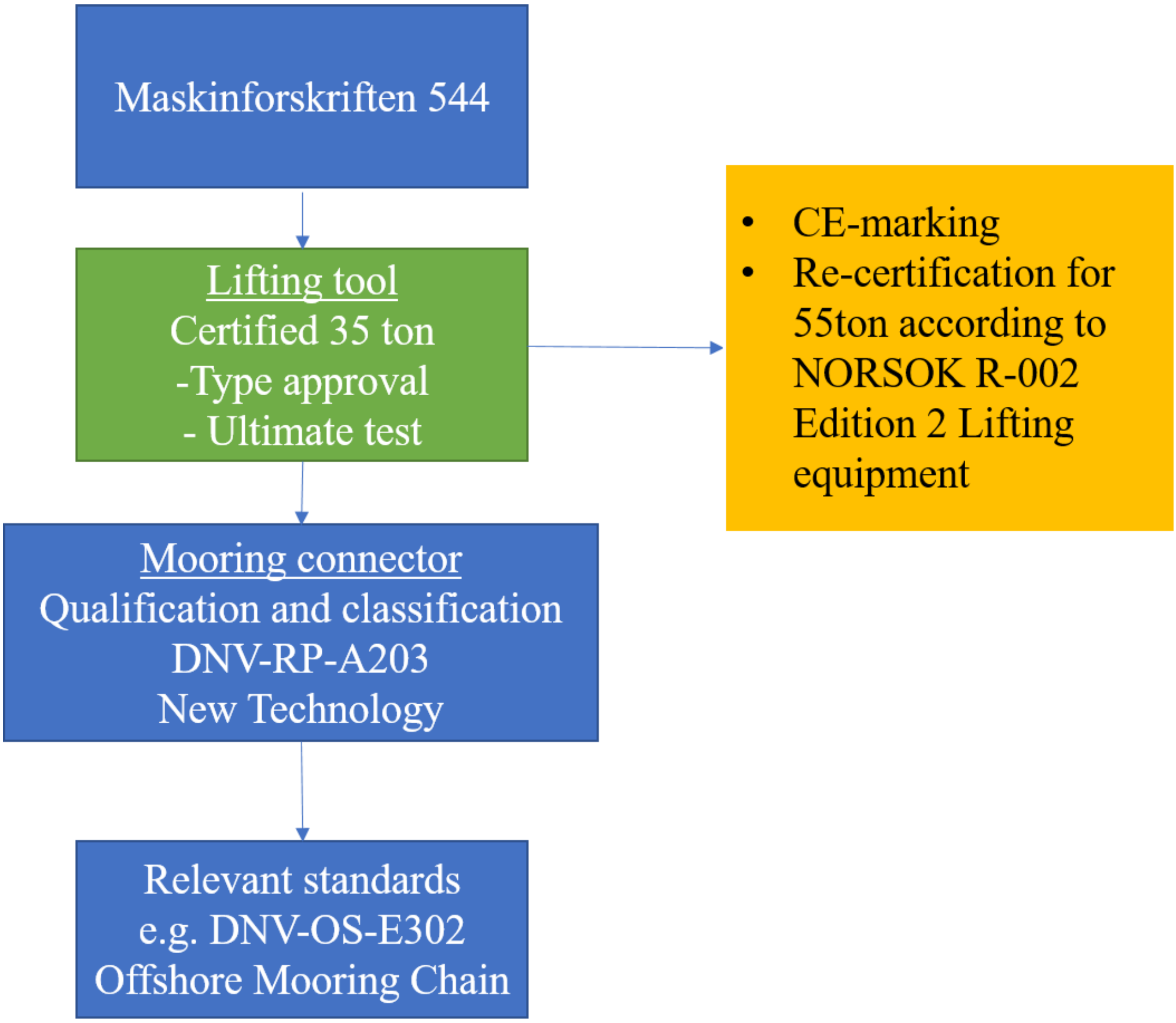


Figure 3-2: MultiDog standards flow chart

Figure 3-3 shows a cross section of the MCQ-9R. The general dimensions are ø520 x 1350 mm, and the design allows for the tool to be drawn over a stern roller for easy deployment. The connector will also include strain gauges so tension can be monitored in real time. Accumulator pressure and battery level can also be monitored periodically. The connector will have more than one accumulator in case one fail.

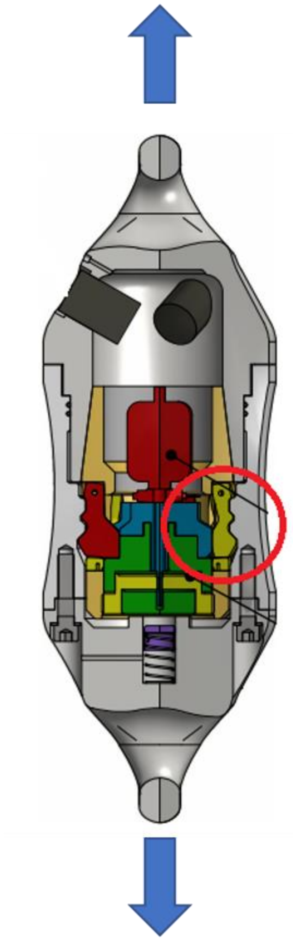


Figure 3-3: MultiDog MCQ-9R cross section, the locking system is highlighted. Figure by Ejecto

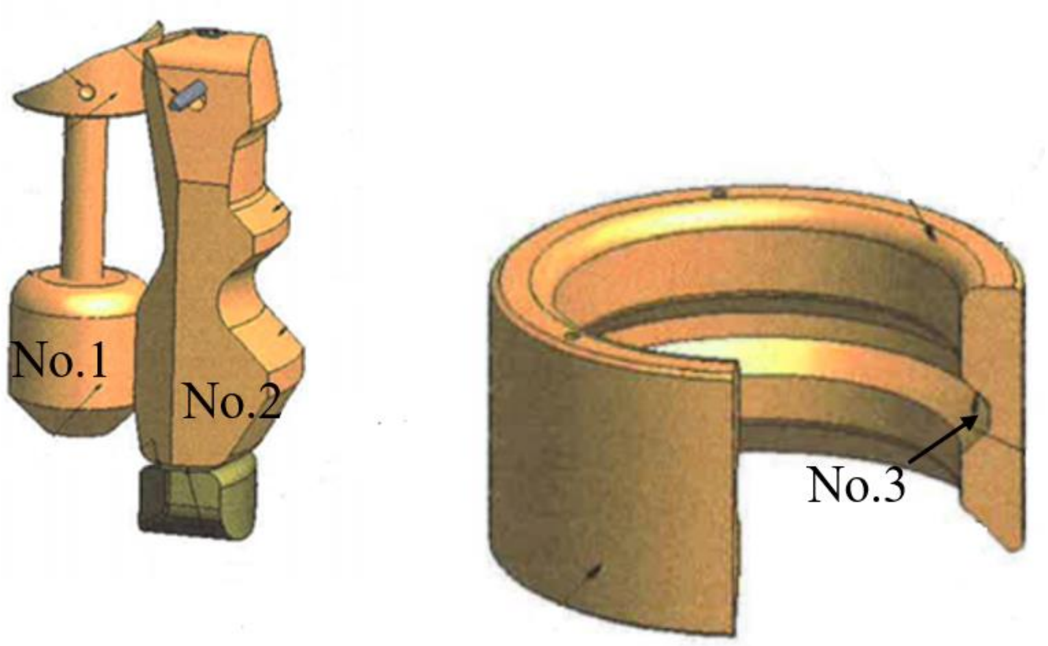


Figure 3-4: MultiDog locking system. Figure by Ejecto

The locking system in Figure 3-4 works when the piston (no. 1, Figure 3-4) is in contact with no. 2, the resulting friction and blocking will prevent the locking dog from swinging inwards. The locking dog will be locked in place by entering the grooves of the ring (no.3). The load in the connector is carried by compressing the locking dog (no. 2). When disconnecting, no.1 will be allowed to move upwards due to pressure from the accumulator. The locking dog (no. 2) can then swing inwards, by doing so the tips of the locking dog will be sheared off.

To avoid accidental release of the MCQ-9R, specific mooring line tension is required to achieve disconnect. If the line load is greater than the specified load, the pressure from the accumulator will be insufficient to move the piston (no. 1), thus preventing the locking dog to swing inwards. The specific line tension must be predetermined by the user of the system, so the correct accumulator pressure is selected.

Should the shearing process require more tension, the mooring winches can be used to pull and add more tension to the process.

The most apparent advantages the MultiDog possess is the ability to be drawn over stern rollers making the deployment faster and without the need for lifting operations. Secondly the use of the rigs onboard HiPAP system for communication and control, this will negate the need to deploy cables in potentially ice-covered waters. The inclusion of a damper will help to keep the integrity of the equipment intact.

The mooring connector development is scheduled to be completed in 2018.

Table 3-1: MultiDog summary

MBL [ton]	900
Length/diameter [m]	1.4/0.52
Line load at release [ton]	50
Pull over stern roller with load	Yes
Release damping effect	Yes
Line load tracking	Yes
Command unit	HiPAP

3.2 Balltec

RigLOK^{TM} (Figure 3-5) is a new concept from Balltec that was made available in 2017. This concept claims to offer the user the ability to release at full load in all operating conditions. This concept offers 2-way communication for status report before release. Communication is achieved via an external command unit. The RigLOK can be adapted for all types of drilling rigs and FPSO's [22]. The prototype is designed to accommodate 76/84 mm chain, but other interfaces and connections can be accommodated. The general dimensions are ø600x2200 mm [22]. The standard model can operate at maximum 1000-meter water depth with a minimum break load of 850 metric tons. The standard model has a service life of 5 years [23]. The RigLOK has been designed in accordance with DNV-OS-E301 and as of April 2017 Balltec is working on type approval with DNV GL.

The RigLOK does not include any damping with respect to the disconnection. The connector is designed so that damages to the male and female components are unlikely. However, some damage to the grooves of the female component is possible if disconnection takes place at high loads, i.e. at approximately 85% of the connector's rated MBL [22]. If damages occur, the grooves can be re-machined so that the component can be re-used [22]. The estimated separation time is approximately 15 seconds [22], and is accomplished hydraulically.

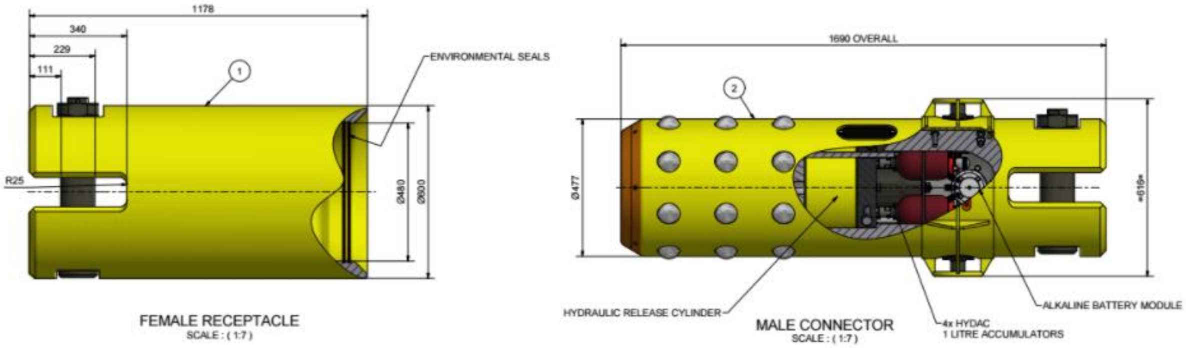


Figure 3-5: RigLOK Female and male components. Courtesy of Balltec

3.3 InterOcean Systems LLC

The Rig Anchor Release (RAR, Figure 3-6) is a tried and tested system, that is qualified according to both ABS (American Bureau of Shipping) and DNV. It has been in use for many years, in places like the Labrador Coast, the North Sea and the Beaufort Sea. The RAR is also designed for drilling operations and comes in three models, model 6500, model 6600 and RAR+. Table 3-2 displays a brief comparison between the models. The RAR was used in the mooring configuration of the Kulluk that included twelve wire ropes plus short segments of chain near the anchor [1, p. 2]. The RAR performed as expected for the Kulluk operation, with the reliability, security and performance deemed satisfactory [1, p. 11].

Figure 3-6: RAR. Figure taken from [24]

Table 3-2:RAR model comparison [25, p. 8], RAR+ [26].

	Model 6500	Model 6600	RAR+
Weight (air/water) [kg]	1805/1350	4100/3023	2676/2171
Dimensions (diameter x length) [cm]	61 x 230	76 x 324	73 x 279
MBL [tons]	680	1136	1000
Release Load [tons]	181.4	500	400
Operating Depth [m]	330	330	1000

The RAR uses a locking shoe configuration that locks the two ends together (see Figure 3-7). Disconnection is achieved when a coded acoustic signal is sent from an external command unit, causing pressure from an accumulator to push back a hydraulic cylinder, disengaging the locking shoes. The release is almost instantaneous and does not include damping [27].

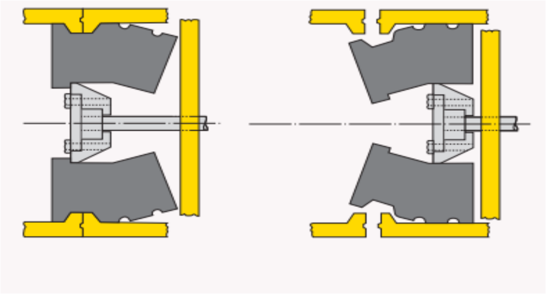


Figure 3-7: RAR locking mechanism. Figure taken from [25, p. 5]

The RAR+ was revealed at the 2017 Offshore Technology Conference. This next iteration comes with line monitoring ability (direct and indirect line tension) [26]. The minimum break load is stated to exceed that of 84mm R5 chain. A manual release system is also introduced in case the acoustic signal fails. The system bypasses the acoustic system by either winching the RAR+ to the fairlead (see Figure 3-8) where it will connect with a trigger sleeve and thereby disconnect. If this is not possible a nearby vessel can connect to the trigger sleeve by wire rope and lead the trigger sleeve along the mooring line.

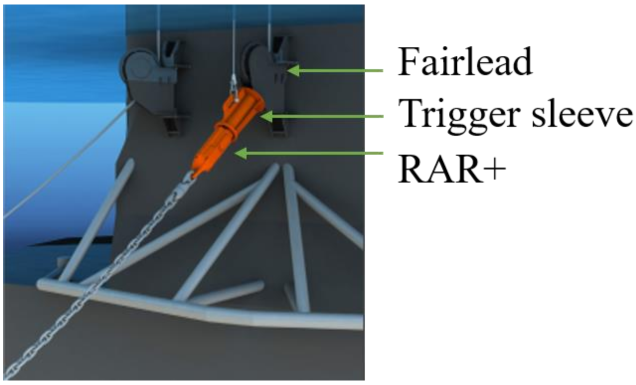


Figure 3-8: RAR+ mechanical release

3.4 Comparison of Release Tools and Limitations

Table 3-3: Comparison of release tool

Name	MultiDog	RigLOK	RAR 6500	RAR 6600	RAR+
MBL [ton]	900	850	680	1136	1000
Length/diameter [m]	1.4/0.52	1.8/0.6	3.24/0.76	2.3/0.6	2.79/0.73
Line load at release [ton]	50	Full	181.4	500	1000
Pull over stern roller with load	Yes	No	No	No	No
Release damping effect	Yes	No	No	No	No
Line load tracking	Yes	No	No	No	Yes
Command unit	HiPAP	*	*	*	*

* RigLOK and RAR (+) uses their own command units to transmit the signal to release. A command unit is a portable battery-powered unit with a transducer and cable that is lower into the sea.

The limitations are to some extent shared by all concepts except the RAR+ and involves the lack of secondary mechanical disconnect ability. MultiDog, RigLOK and RAR require external transducers if the primary signal fails. The RAR+ introduces a concept to mechanically disconnect the device as explained in Chapter 3.3. This system will require the rig to potentially offset in multiple directions to achieve disconnect, or by having nearby vessel(s) run the trigger sleeve(s). How practical this mechanical system will be in ice-covered waters remains to be seen. Nearby vessels will probably be used in ice management operations and the time required to winch in and potentially offset must be added to the Secure Time of the operation.

4. Background Information

4.1 Waves, Current and Wind in the Barents Sea

The Barents Sea is often thought of as being one of the harshest places on the Norwegian Continental Shelf (NCS). The truth is that wind, wave, and current conditions are similar to the North Sea [28, p. 2], making the magnitude of these parameters manageable. The environmental parameters presented in [29] are decided by global weather phenomena and are not considered to be more uncertain than the same parameters for e.g. the North Sea [30]. The uncertainties in the Barents Sea stem from the local weather phenomena such as polar lows [30]. The effects and what the Barents Sea might bring in the form of sea ice and ice bergs also contribute to uncertainties in operations. Difficulty in forecasting polar lows and combination of weather conditions can lead to conditions that require extraordinary measures to secure safe operations.

4.2 Polar Lows

Polar lows are a weather phenomenon that can occur in the Norwegian - and Barents Seas. They are smaller than tropical cyclones with a diameter of 200-600 kilometres see Figure 4-1. Polar lows form when air from the Pole or a cold landmass crosses the warmer water. The dry air will become increasingly saturated and heated by the ocean. Combined with thunder clouds a strong vertical wind flow will generate local low pressure at the surface. With strong enough winds, this low pressure can form a vortex and thus a polar low. Polar lows are seasonal in nature, and usually form from October to May, with the greatest concentration in December-March. Annually 12-15 occurrences are recorded on average for both seas [31].

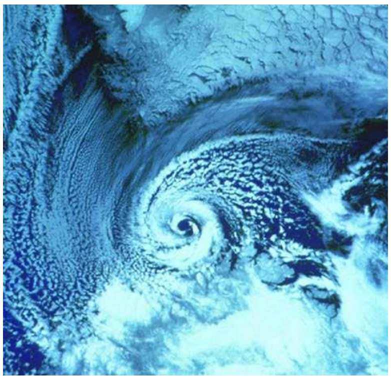


Figure 4-1: Polar low north of Finnmark [32]

Traditionally forecasting polar lows have been difficult with few observations and at times unstable conditions, these conditions increases the uncertainty level in the predictions [31]. Strike probability and projected path (see Figure 4-2) are supplied by the Norwegian Meteorological Institute and show the probability of a polar low striking an area within 42 hours.

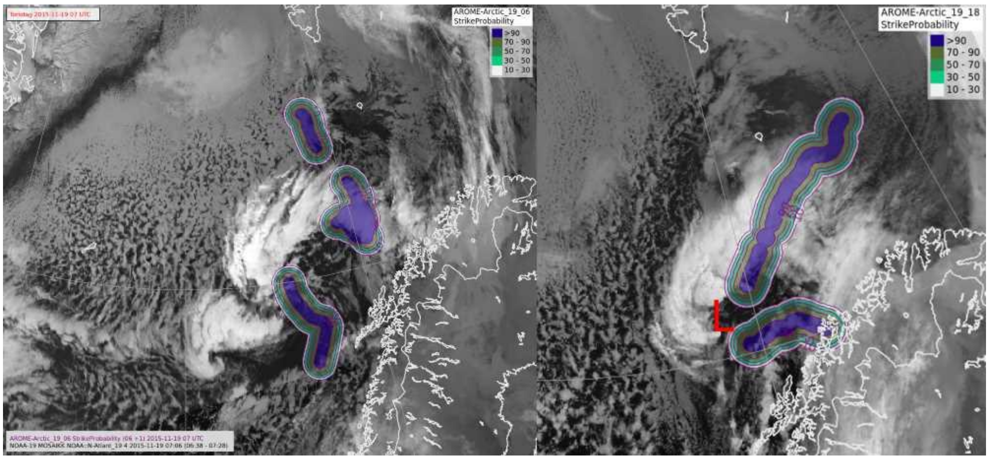


Figure 4-2: Projected path of a polar low. Figure from [31]. The blue area indicates strike probability >90.

Forecasts of polar lows are reported using four levels instead of numbered probabilities. The levels; High, Moderate, Low and Very Low are used [33]. Where a warning is issued at Moderate chance of a polar low forming. High probability is set when three out of three possible prerequisites of atmospheric conditions that is considered favourable for polar low formation are present, and the polar low is observed on satellite. Moderate probability is set when the three prerequisites are present, but before the polar low is observed via satellite. Low probability is set when two out of three prerequisites are present. Very Low probability is set when none of the prerequisites for polar low formation are present. Normally a polar low position is reported to be within an error of 50km, but error as large as 2-300km have occurred [33]. Events involving polar lows usually last for approximately one week, with several single polar lows. The average life of a polar low is 18 hours, with a typical life of 6 hours up to two days [33].

The greatest challenge with polar lows are rapid changes and secondary effects such as: increased snow/rain, visibility, wind etc. These parameters will affect logistical operations and especially lifting operations at sea [34, p. 29]. While in general the frequency of high wind and waves become less the further north and east one goes [35], the wind strength around a polar low can go from a breeze to storm in minutes, and with an increase in wave heights up to five meters in less than an hour [36]. Naturally if marine operations are performed when this happens the risk can become unacceptable. At present, infrastructure both offshore and onshore are limited with respect to HSE, and in the event of polar lows, visibility can drop to less the 100 meters making search and rescue difficult, if not impossible [31].

4.3 Sea Ice and Icebergs

Sea ice is formed at approximately -1.8℃ [34, p. 14], and is categorized into first-year ice and multi-year ice, where first-year ice has a thickness of 0.3-2 meter. Multi-year ice is ice that has made it through at least one melting season and has a typical thickness of 2-4 meter [34, p. 14]. The occurrence of sea ice in the Barents Sea is relatively well known, with satellite data going back to 1967, max prevalence occurs in March-April [34, p. 15].

Every day the Norwegian Metrological Institute’s Ice service develops ice maps for the Norwegian parts of the Arctic that shows ice concentrations (see Figure 4-3). Ice concentration is a dimensionless term that describes the amount of ice in a reference area. Ice concentration is presented as either a percentage, fraction from 0 to 1 or in tenths [37], e.g. if an ice concentration is reported to be 5/10, 50% of the reference area will be covered in ice.

Data are collected mainly from Synthetic Aperture Radar aboard the Radarsat-2 and Sentinel-1 satellites, which has a resolution of approximately 40-100 meters [34, p. 16].

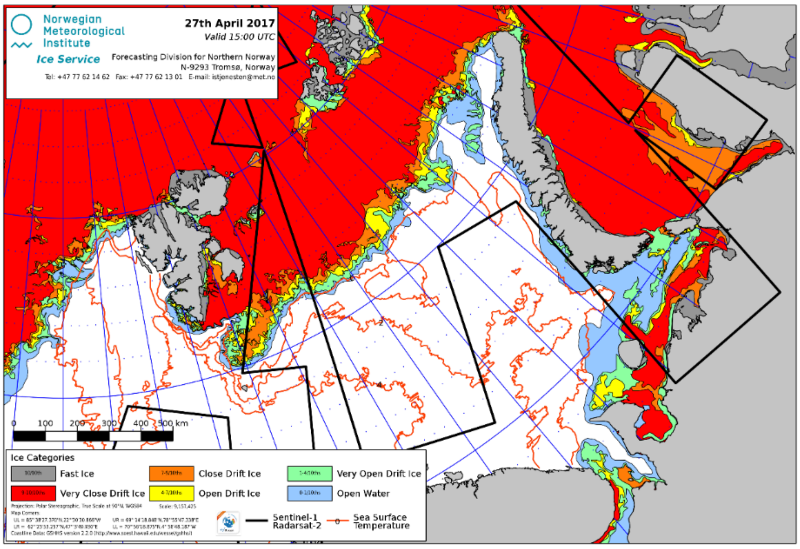


Figure 4-3: Ice map of the Barents Sea

Sea ice can pose significant risk to installations and activities at sea. The risk can be divided into *global load*, *local load* and *operational* [34, p. 16]. Global load is load large enough to influence the position of the installation and/or loss of stability/mooring lines. Local load is load that is sufficient to damage parts of the installation e.g. risers, cables, evacuation options etc. The operational aspect concerns what methods of evacuation, general safety measures and what level of ice management is required for the given location. Sea ice must be considered from the start when selecting design for offshore installations in arctic regions.

An iceberg by definition is "*ice that has broken off a glacier and is larger than 5 meters in diameter. The shape varies, but only 10 % is above the water line"* [34, p. 18]. In 1881, 1929 and 1939 icebergs were observed as far south as the coast of Finnmark. In recent years knowledge on occurrence of icebergs have been limited, with no evidence of their existence in the south-eastern Barents Sea [34, p. 18]. However, their existence cannot be excluded based on available data. By increasing the knowledge about size and likely drift for a given location, proper ice management and estimated down time (e.g. disconnect) will further increase the safety of personnel and installations. Figure 4-4 displays annual probability of occurrence of icebergs in the Barents Sea, the contour lines represent the probability (in per cent) for an iceberg to occur within 100km^2.

Figure 4-4: The red X marks the target location used in this thesis, and corresponds to approximately 10% probability. Excerpt from Chart 3.37 in [38].

A drifting iceberg is affected by all environmental actions. In general, current is the dominating factor for iceberg drift, with the possibility of wave drift dominating in open waters [2, p. 38]. Iceberg drift models exists, but the level of uncertainty in these models are great. This uncertainty is mainly due to uncertainties in input parameters [34, p. 19]

If an iceberg fragments into smaller pieces (0-5 meter in diameter) they will be called growlers, with the largest pieces called bergy bits [34, p. 23]. The presence of growlers in the open areas of the Barents Sea is uncertain, with few observations. The distribution between large and small growlers is also uncertain, but one expects that growlers are more common than icebergs [34, p. 23]. Detection of growlers and bergy bits are extremely difficult, given that they do not detect well via satellites. The risk associated with growlers and bergy bits are more localized damages to risers, cables and mooring lines [34, p. 23].

4.4 Ice Management

According to Kenneth Eik ice management is defined as "*the sum of all activities where the object is to reduce or avoid actions from any kind of ice features*" [2, p. i]. To safely operate in arctic environments the design philosophy must incorporate actions from ice and address the various uncertainties in available environmental data [2, p. 1]. By implementing an effective ice management system that includes detection and towing, the risk can be reduced by nearly an order of magnitude. Reducing is possible by a further order of magnitude if an installation can safely disconnect and evacuate the site [39, pp. 17-18].

Ice management has been implemented for many years in arctic regions around the world. E.g. at the East Coast of Canada at the Grand Banks and at the West Coast of Greenland at Fyllas Banke.

Ice management can be divided into three situations; planning, strategic and tactical. In the planning situation, as much environmental data as possible should be collected. This data will lay the ground for selection of vessels, equipment, instrument and system verification and possibility of implementing new technologies [40, p. 25]. Strategic situations involve necessary preparations to effectively deal with ice. Preparations include but are not limited to deployment of equipment, vessel/aircraft mobilization, forecasting, satellite services etc. [40, pp. 25-26]. Tactical situations concern active measures directed towards incoming ice, such as ice management vessels and evacuation systems.

The first phase in ice management is "Ice intelligence". By collecting information about incoming ice, appropriate actions can be taken to mitigate dangerous situations. As mentioned in Chapter 4.3 the Norwegian Metrological Institute utilizes radars and satellites to detect ice. While these large installations can detect ice over a large area, their effort can be further improved by "local" radars/imagery on ships and aircrafts. Once ice has been detected, information about ice type, floe size, drift speed etc. will help in tracking the ice. The use of drone technology is increasing worldwide and has the potential to complement and improve existing methods [2, p. 24]. Limitations for the different detection methods vary, e.g. for satellites who can cover large areas, the resolution will not always be optimal [2, p. 13]. Satellites are therefor useful in a strategic sense, by being able to identify areas with potential risk and ensuring that the logistics are in place. Image sensors are dependent on the visibility.

If an iceberg is identified as a threat, steps to alter its trajectory can be taken. Sufficiently strong vessels must be on standby for this to be a possibility. Towing operations are a function of sea state and waterline length, therefore towing operations cannot be done in certain conditions [2, p. 104]. Experience from the Barents Sea includes the towing of an iceberg weighting approximately 200 000 tons that was surrounded by ice. The iceberg was broken free from the surrounding ice by using an icebreaker. The tugboat maintained a maximum speed of 1-3 knots and was unable to steer with the iceberg under heavy tension [2, p. 18].

Current installations (Goliat, Snøhvit, Johan Castberg) in the Barents Sea are outside the most likely ice-covered areas, or areas were drifting icebergs pose a threat as shown in [29] figure 7. With all the available sensors for detecting ice(berg), the Probability of Detection (POD) can never be 100% [2, p. 15]. By having an emergency disconnect system on the vessel/rig, the offshore installation manager of the vessel/rig will still have one final option, if the surveillance system does not detect an iceberg [2, p. 143], or the situation warrants evacuation from the site.

[40] defines some useful terms used in ice management. *Ice management plan* (IMP) is an operational plan for a specific operation and site [40, p. 12], however one must be able to adapt and/or add to this plan based on change in conditions or lessons learned [40, p. 17]. *Hazard Distance* (HD) and *Hazard Time* (HT) are, the distance from a facility to hazardous ice (or weather) and the time needed for the hazard to reach the facility [40, pp. 13-14]. For a disconnectable vessel *T-time* (Termination time) is defined as the time needed to end and secure current operations, and evacuate the site [40, p. 14].

As stated in Chapter 4.1 wind, wave and current do not pose significant threat on their own. In the Arctic however, due attention must be given to combinations of various conditions as uncertainties could multiply [5, p. 1]. This is supported by [40, p. 24] that lists various combined situations, called *unforecast events.* These events must be considered in the planning and execution phase of ice management [40, p. 37]. Examples of unforecast events range from: rapid ice drift changes, ice rivers, local/global current and weather changes and effects of polar lows etc. Mitigating measures include increased safety factor in T-time calculation, emergency disconnect and well-defined ice management plan. In the event of undetected ice/weather the offshore facility must have an *emergency T-time process* [40, p. 88], which is the absolute minimal time needed to shut down and evacuate the site. A side effect of emergency disconnect will often be damage to equipment and thus longer reconnection time.

An ice management plan shall include a description of ice zones, see Figure 4-5, around the offshore facility. If ice enters these zones predetermined actions will be taken [40, pp. 42-43]. Typical zones are:

1. Zone 1 – Ice alert
   Enough time to enable disconnect from well, mooring lines and the evacuation of personnel and/or facility.

2. Zone 2 – Reaction – Continue physical ice management
   This zone connects hazard time with T-time, because hazard time could potentially vary with time this zone varies in size continuously.

3. Zone 3 – Ice monitoring
   Zone 3 lies outside zone 2 and monitors all ice that is within sensor rang, as such this zone has no fixed width. At this stage, T-time will be calculated continuously.

T-time can be calculated as follows [40, p. 88]:

$$T_{time} = ST + MOT \tag{4-1}$$

Where:

ST = Secure time, time needed to secure the well and disconnect the Lower Marine Riser Package (LMRP) from the Blow Out Preventer (BOP) and secure and recover the riser.

MOT = Move off time, time needed to recover or release mooring lines and move off-site.

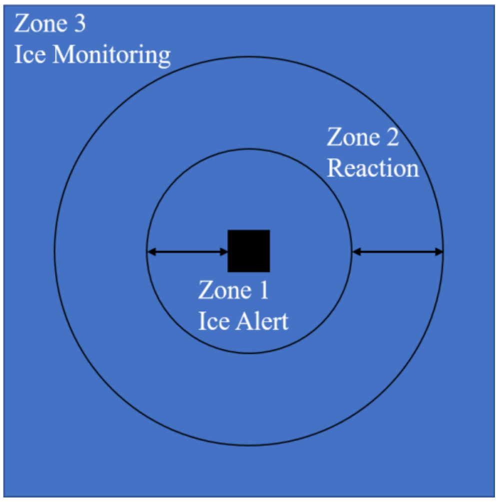


Figure 4-5: Ice zones, figure based on [40, p. 87]

The status of operation for an offshore facility is reported as a colour code, the colour defines the risk level [40, p. 15]. An example of the various colours and their meaning can be seen in Table 4-1.

The purpose of ice management is to ensure that T-time is shorter than hazard time. This is reported as *Alert time* (AT) which is given by:

$$AT = HT - T_{time} \tag{4-2}$$

Table 4-1: Alert colour code based on [41, p. 16] used by Shell in the Chukchi Sea, Alaska

Alert level	Description	Time calculation [hours]
Green	Normal operation – No hazardous ice in the area of operation.	AT > 24
Blue	Approaching ice – Risk assessment is initiated and secure time and move off time is validated.	24 >AT>12
Yellow	Securing the well is started - Logistical preparations with respect to potential evacuation are made.	12 > AT > 6
Red	Well is secured. Preparations to release mooring lines are made.	AT < 6
Black	Hazardous ice imminent. Platform must be moved in accordance with ice management plan.	

5. Orcaflex Background Theory: Mooring Lines

Orcaflex by Orcina is a software designed for the analysis of dynamic offshore systems. This chapter will present calculation methods done by Orcaflex. Orcaflex version 10.1 has been used during this thesis.

5.1 Coordinate System

Orcaflex uses a right-handed global coordinate system GXYZ (Figure 5-1) [42], where the Z-axis is positive upwards and G is the origin. Every object placed (vessel, lines, buoys etc.) has its own local coordinate system. Positive rotations are defined clockwise when looking in the direction of the axis of rotation.

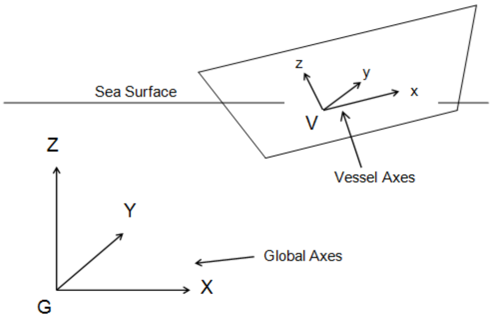


Figure 5-1: Coordinate systems used by Orcaflex Figure by Orcina.

5.2 Statics

By performing static analysis in Orcaflex one will be able to determine the equilibrium configuration of the system. Depending on the object the static analysis will search for the position of the object where the resultant force and moment acting on the object is zero. The resultant force and moment are called the “the out of balance load” in the Orcaflex documentation [43].

The equilibrium configuration is used as the initial condition for the dynamic analysis. The equilibrium is computed with respect to the weight, buoyancy, hydrodynamic drag etc.

The actual calculation is an iterative process where Orcaflex enables the user to set the accuracy and number of iterations. If convergence is not achieved before the max number of iterations the calculation is aborted. There are three stages in the calculation [43]:

1. Input data defines the initial positions of all objects.
2. Equilibrium configuration for each line is calculated.
3. The "out of balance load" is calculated for the initial position of the free body, based on this a new position is calculated. This process continues until the level of accuracy is achieved.

5.3 Dynamics

Orcaflex can analyze in both time domain and frequency domain, where time domain is nonlinear and frequency is linear. In this thesis, time domain analysis will be used.

To avoid sudden transients from the static state to full dynamic motion, a build-up stage is by default introduced. This build-up stage is displayed in the results as negative time, where the actual simulation starts at zero seconds i.e. stage one. If needed one can add more stages and set their individual durations. The purpose of stages it to control the model e.g. set a mooring line to release at the beginning of a certain stage.

5.3.1 Integration and Time Steps

In time domain Orcaflex can calculate using two different methods: implicit integration and explicit Euler integration [44]. The equation of motion is defined in Orcaflex as [45]:

$$M(p,a) + C(p,v) + K(p) = F(p,v,t) \tag{5-1}$$

Where:

$M(p,a)$ = System inertia load

$C(p,v)$ = System damping load

$k(p)$ = System stiffness load

$F(p,v,t)$ = External forces

p, v, a = Position, velocity, and acceleration vectors

t = Simulation time

For each time step both methods re-compute forces and moments for all lines and bodies.

5.3.2 Explicit Integration

The explicit scheme is semi-implicit Euler with constant time step. With this integration scheme the calculations are done at the beginning of the time-step. Forces included in the calculations are [46]:

- weight
- buoyancy
- hydrodynamic and aerodynamic drag
- hydrodynamic added mass
- tension and shear
- seabed reaction and friction
- contact forces with other objects (e.g. line clashing)
- forces applied by links and winches

The system wide equation of motion (5-1) is simplified for each free body and node:

$$M(p,a) = F(p,v,t) - C(p,v) - K(p) \tag{5-2}$$

This equation is solved with respect to the acceleration and integrated. Semi-implicit Euler integration is very simple:

$$v_{t+1} = v_t + dt \cdot a_t \tag{5-3}$$

$$p_{t+1} = p_t + dt \cdot v_{t+1} \tag{5-4}$$

Where:

v_t, p_t, a_t = Velocity, position, and acceleration at time t

$v_{t+1}, p_{t+1},$ = Velocity, position, and acceleration at time t+1

dt = Time-step

5.3.3 Implicit Integration

Orcaflex uses the Generalized-α integration scheme as described by Chung and Hulbert [47]. The system equation is computed at the end of each time-step, an iterative process is therefore needed because values of p, v and a are unknown. This process is a lot more computationally demanding, but the benefit is more stability for longer time-steps.

With respect to release of mooring lines (and risers), the tension in the line will drop quickly. If the time-step is set too large, mathematical “spiking” can occur. The explicit integration scheme can go unstable. Therefore, Orcaflex recommends using the implicit integration scheme, due to its inherent numerical damping [48].

5.3.4 Generalized-α Method

For a linear system, the equation of motion is [47]:

$$M\ddot{X} + C\dot{X} + KX = F \tag{5-5}$$

Where X is the displacement vector.

$$d_{n+1} = d_n + \Delta t v_n + \Delta t^2\left(\left(\frac{1}{2} - \beta\right)a_n + \beta a_{n+1}\right) \tag{5-6}$$

$$v_{n+1} = v_n + \Delta t((1-\gamma)a_n + \gamma a_{n+1}) \tag{5-7}$$

$$Ma_{n+1-\alpha_m} + Cv_{n+1-\alpha_f} + Kd_{n+1-\alpha_f} = F(t_{n+1-\alpha_f}) \tag{5-8}$$

Where:

$$d_{n+1-\alpha_f} = (1-\alpha_f)d_{n+1} + \alpha_f d_n \tag{5-9}$$

$$v_{n+1-\alpha_f} = (1-\alpha_f)v_{n+1} + \alpha_f v_n \tag{5-10}$$

$$a_{n+1-\alpha_m} = (1-\alpha_m)a_{n+1} + \alpha_m a_n \tag{5-11}$$

$$t_{n+1-\alpha_f} = (1-\alpha_f)t_{n+1} + \alpha_f t_n \tag{5-12}$$

$n \epsilon \{0,1,\dots,N-1\}$ where N is the number of time steps and Δt is the time step. The parameters α_f, α_m, β and γ are algorithmic parameters. d, v and a are the displacements, velocities, and accelerations, respectively, estimated at a given time step. The initial conditions are given by:

$$d_0 = X(0) \tag{5-13}$$

$$v_0 = \dot{X}(0) \tag{5-14}$$

$$a_0 = M^{-1}(F(0) - Cv(0) - Kd(0)) \tag{5-15}$$

5.4 Numerical Calculation of Mooring Lines in Orcaflex

Orcaflex uses a lumped-mass-model to model lines, where lines are defined as either mooring line (chain, wire or fibre rope) or pipes. The model consists of nodes connected by straight massless segments, where each node takes on the forces from half of the segments on either side. The nodes account for all properties such as mass, weight, buoyancy etc. whereas the segments account for the axial and torsional properties. Figure 5-2 shows the discretized model and Figure 5-3 displays the mathematical model of a mid-node.

The calculation of a mid-node is done in five stages [49]:

1. Tension forces
2. Bend moments
3. Shear forces
4. Torsion moments
5. Total load

Depending on the axial stiffness characteristic of the line, whether linear or nonlinear Orcaflex will calculate the effective tension as follows [50]:

Linear axial stiffness with torsional effects:

$$T_e = T_w + (P_o A_o - P_i A_i) \tag{5-16}$$

Where:

$$T_w = EA\epsilon - 2\nu(P_o A_o - P_i A_i) + K_{tt}\tau/L_0 + EAC(dl/dt)/L_0 \tag{5-17}$$

T_e = Effective tension

T_w = Wall tension

$P_{o,} P_i$ = Outer and inner pressure

A_o, A_i = Outer and inner cross-sectional area

ϵ = Total mean axial strain

ν = Poisson’s ratio

EA = Axial stiffness

C = Damping coefficient

dl/dt = Rate of change in length of segment

L_0 = Initial length of segment

K_{tt} = Tension/torque coupling

τ = Segment twist angle [rad]

As stated in Chapter 5.3.3, the implicit integration scheme has in-built numerical damping and because of this the damping term in equation (5-17) is only included for the explicit integration scheme.

The bending moment for linear isotropic bending stiffness is given by [51]:

$$M = EI|C| + D \cdot\ d|C|/dt \tag{5-18}$$

Where:

M = Bending moment

EI = Bending stiffness

C = Effective curvature vector

D = Damping coefficient

The effective curvature vector is the result of the angle between the axial direction of the line and the axial segment axis, divided by half the initial segment length.

$$C = \frac{\alpha}{1/2L_0} \tag{5-19}$$

The damping term only applies for explicit integration.

The shear force is a vector that is calculated based on the bending moment [52]:

$$V = z \times (M_2 - M_1)/L \tag{5-20}$$

Where:

V = Shear force vector

z = Axial direction of segment

M_1, M_2 = Moment vectors on either side of segment

L = Instantaneous length of the segment

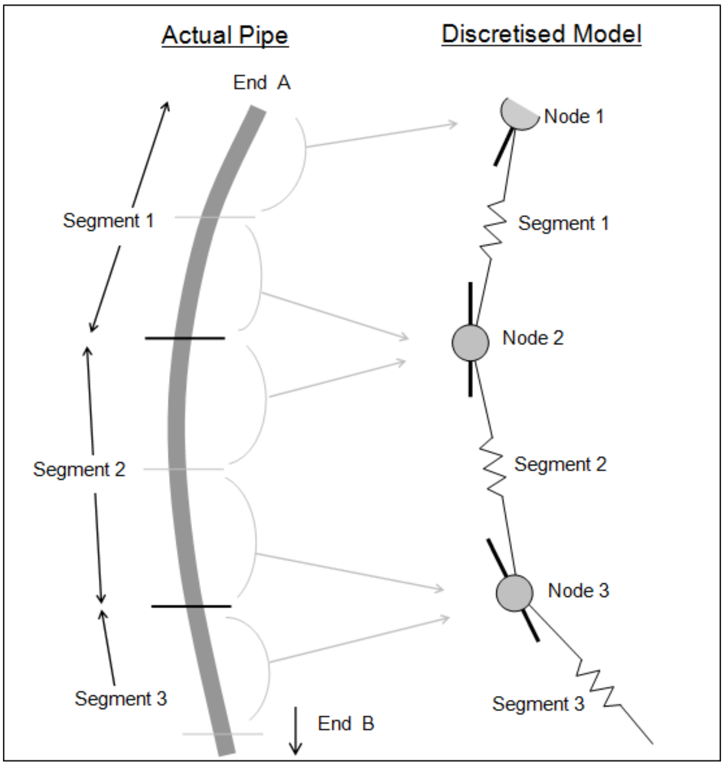


Figure 5-2: Finite element model used in Orcaflex. Figure by Orcina

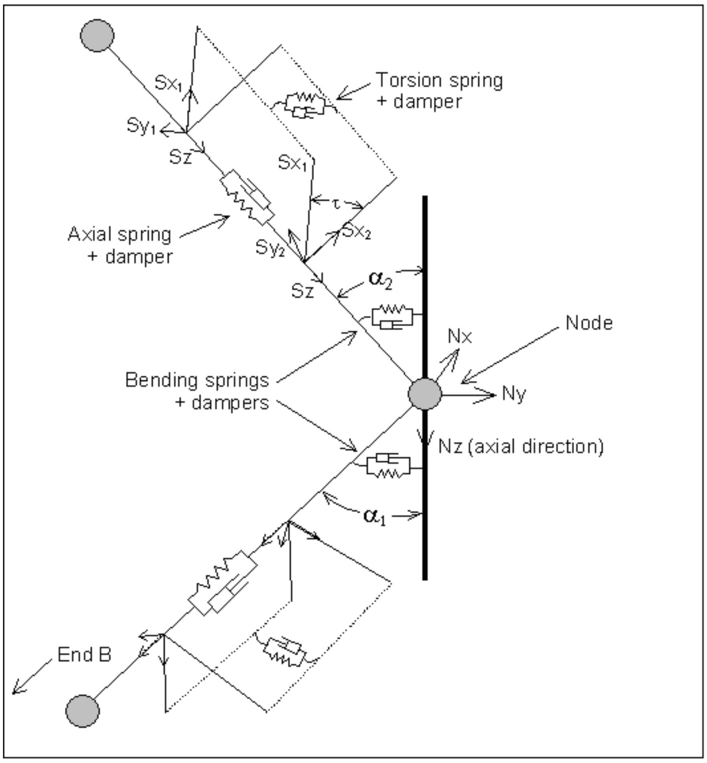


Figure 5-3: Spring-dampers model of line in Orcaflex. Figure by Orcina

The next stage in the calculation is the calculation of torsion moments. This is optional and must be enabled by the user of Orcaflex. The formula for torque with linear torsional stiffness is given by [53]:

$$Torque = \frac{K\tau}{L_0} + K_{tt}\epsilon + C(\frac{d\tau}{dt}) \tag{5-21}$$

Where:

K = Torsional stiffness

τ = Segment twist angle

L_0 = Initial length of segment

K_{tt} = Tension/torque coupling

ϵ = Total mean axial strain

C = Torsional damping coefficient

$d\tau/dt$ = Rate of twist [rad/s]

The damping term only applies for explicit integration. With these four stages completed, Orcaflex will combine all forces and moments with other non-structural loads such as weight, drag, added mass etc. and compute the total force and moment on the individual nodes.

5.5 Hydrodynamic Forces and Effects

Hydrodynamic drag is calculated using standard formulation of the Morison’s Equation, and is given in the three global directions as [54]:

$$F_x = \frac{1}{2} P\rho(D_n L)C_{dx}V_x|V_n| \tag{5-22}$$

$$F_y = \frac{1}{2} P\rho(D_n L)C_{dy}V_y|V_n| \tag{5-23}$$

$$F_z = \frac{1}{2} P\rho(\pi D_a L)C_{dz}V_z|V_z| \tag{5-24}$$

Where:

P = Proportion wet

ρ = Fluid density

C_{dx}, C_{dy}, C_{dz} = Drag coefficient in global directions

V_x, V_y, V_z = Fluid velocity in global directions

V_n = Fluid velocity normal to the line

$D_n L$ = Projected drag area in x and y directions

$\pi D_a L$ = Projected drag area in z direction

The drag coefficients can be set manually if they are properly documented, or the default values can be chosen. The default values used in Orcaflex are based on DNV-OS-E301 and can be found in Table 5-1 [55].

Table 5-1: Drag coefficients from DNV-OS-E301 Section 1 Subsection B700

	Transverse	Longitudinal
Studlink	2.6	1.4
Studless	2.4	1.15
Stranded rope	1.8	*
Spiral rope without plastic sheathing	1.6	*
Spiral rope with plastic sheathing	1.2	*
Fiber rope	1.6	*

The added mass effect and the Froude-Krylov force of a mooring line are considered in each direction as [54]:

$$F_{added\ mass} = C_m m_{fluid} a_{fluid} - C_a m_{fluid} a_{line} \tag{5-25}$$

Where:

C_a = Constant added mass coefficient

C_m = Inertia coefficient

m_{fluid} = Mass of fluid instantaneously displaced by the line

a_{line} = Acceleration of the line in a given direction

a_{fluid} = Acceleration of the fluid in a given direction

5.6 Compression

Compression in a straight section of a line under axial load, is described by classic Euler theory. “The Euler load” i.e. the maximum compressive load a section can support without transverse deflection is given by [56]:

$$F_{euler} = \frac{\pi^2 EI}{L^2} \tag{5-26}$$

Where EI is the bending stiffness and L the section length. For this to be computed correctly Orcaflex requires that enough sections are used to define a mooring line or pipe line. Should the Euler load be infringed one could try to simulate again with shorter sections. If the problem persists then the Orcaflex documentation stresses that, engineering judgment should be used to analyze the infringement and decide whether to ignore the result.

6. Modelling Tool for Semisubmersible Unit

To model a floating rig the following parameters are needed, hydrostatic stiffness, added mass, potential damping and RAOs. This chapter will explain the procedure used to obtain these parameters using the software program HydroD by DNV GL.

6.1 Making the Model

A rig design based on the general geometry of COSL Pioneer was chosen. Due to some missing data, certain details of the geometry had to be neglected. Figure 6-1 shows the model. The model was drawn in Autodesk Inventor and then exported in SAT format to GeniE, another program by DNV GL. The pontoons measure 104 meters from stern to bow by 13 meters wide. The columns are 13x13 meters and measure 16 meters tall. Total width is 64 meters.

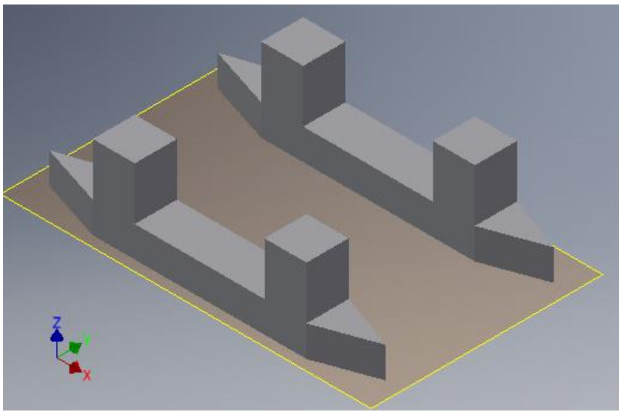


Figure 6-1: Model based on COSL Pioneer drawn in Inventor

The missing geometry effects include four slender tubes that goes between the columns. On the bow and stern side of the columns there is supposed to be half cylinders, and finally on the inside of the pontoons additional extrusions are present, see Figure 6-2.

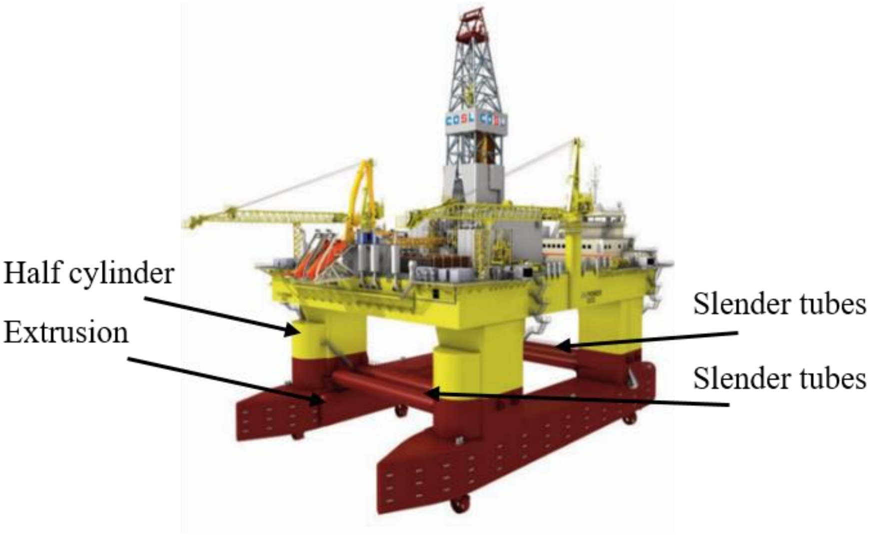


Figure 6-2: COSL Pioneer [57]

6.2 GeniE

The purpose of importing the SAT file from Inventor to GeniE is to generate a mesh of the model for further finite element analysis in HydroD. A total of three meshes where generated, this was done so a mesh convergence study could be performed.

6.2.1 Thickness

GeniE by default requires thickness properties of the plates. An arbitrary number was chosen, because the thickness properties will not influence the meshing process and as such is irrelevant.

6.2.2 Wet Surface

For HydroD to understand where water can touch the model, “wet surface” was applied to the model on the front of the plates. The entire hull was defined as wet surface, except the top of the columns, see Figure 6-3.

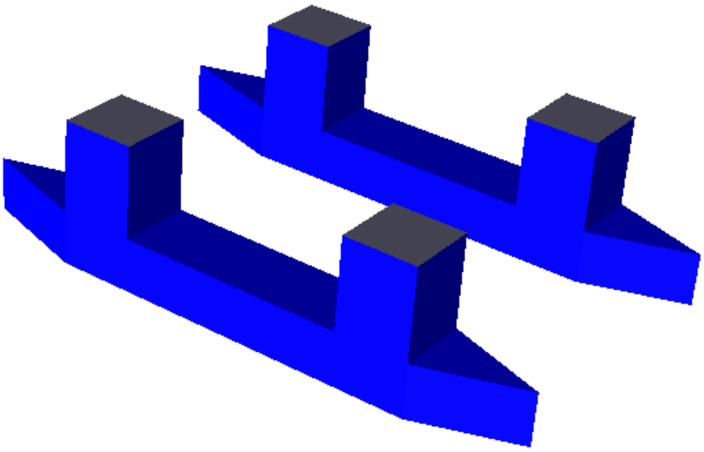
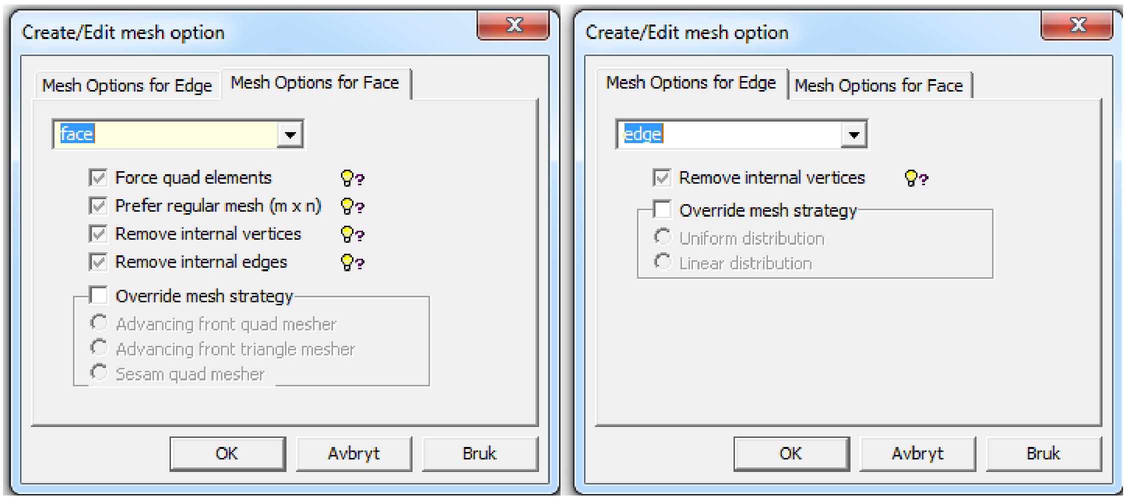


Figure 6-3: Wet surfaces (blue) in GeniE

6.2.3 Mesh Properties

The mesh properties are divided into two categories, mesh options and mesh density. Mesh options define the element preferences, such as force quad elements, prefer regular mesh etc. The default selections were kept and can be viewed in Figure 6-4.



Create/Edit mesh option

Mesh Options for Edge | Mesh Options for Face

face

☑ Force quad elements
☑ Prefer regular mesh (m x n)
☑ Remove internal vertices
☑ Remove internal edges
☐ Override mesh strategy
○ Advancing front quad mesher
○ Advancing front triangle mesher
○ Sesam quad mesher

OK | Avbryt | Bruk

Create/Edit mesh option

Mesh Options for Edge | Mesh Options for Face

edge

☑ Remove internal vertices
☐ Override mesh strategy
○ Uniform distribution
○ Linear distribution

OK | Avbryt | Bruk

Figure 6-4: Mesh options

Mesh density is defined as the element length in meters. Due to the relative simple geometry in the model, a uniform element length of two and three meters was used for two of the meshes, with the third mesh using different densities on the various plates. Table 6-1 presents the number of elements for the different meshes.

Table 6-1: Number of elements per mesh

	Number of elements	Element length
Mesh1	3230	3 meters
Mesh2	5248	2 meters
Mesh3	12468	Combined 1 and 2 meters

6.2.4 Load Cases

The final property before a mesh can be generated is the Dummy Hydro Pressure. This dummy load is applied to the wet surface and is used in HydroD. The mesh model is saved as a FEM file. The coverage area of the dummy load can be seen in Figure 6-5.

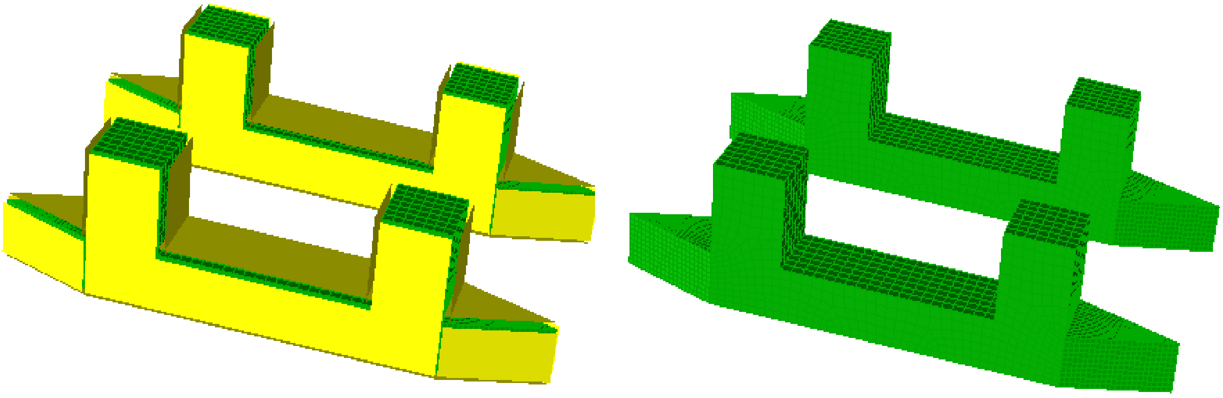


Figure 6-5: Mesh model with and without dummy load

6.3 Wadam

Wadam is the wave potential solver used in HydroD to compute the required data. The inbuilt Wizard consists of eleven steps with input data. These steps are presented below in chronological order

6.3.1 Model Choice

The first step is to select what type of model one wishes to analyse, this is based on the type of structure. Due to the absence of slender bodies on the model a “panel model” is selected with the following properties:

- Element model → Wadam recognize the FEM file from GeniE
- Frequency Domain
- Damping matrix → Outputs the damping matrix at the end of the simulation

6.3.2 Direction Set

The direction set was defined from 0°-180° with an interval of 15°. This was chosen because the rig is symmetric in the XZ-plane. The interval of 15° was chosen because Orcaflex uses interpolation between angles and recommends using less than 30° [58].

6.3.3 Frequency Set

The frequency set was defined from 0.05rad/s – 5rad/s, with and interval of 0.1rad/s. The frequency set covers a large spectrum so that added mass and damping matrices will be generated for many periods.

6.3.4 Location

This step defines air, water and gravity properties. All numbers are default except water depth. Gravity is 9.80665 m/s^2

Table 6-2: Location data

	Air	Water
Density	1.226 kg/m^3	1025 kg/m^3
Kinematic Viscosity	1.462e-005 m^2/s	1.19e-006 m^2/s
Depth	N/A	250 m

6.3.5 Frequency Domain Condition

This step allows the user to choose which direction and frequency set to enable if more than one set is defined.

6.3.6 Hydro Model

A floating column stabilized unit is defined and is centred in the origin by setting the floating point in the x-direction to 0 m.

6.3.7 Import Model

Import the FEM model from GeniE.

6.3.8 Loading Condition

Program default values are used.

6.3.9 Mass Model

This step allows the user to define the centre of gravity (COG), centre of buoyancy (COB), radius of gyration and product of inertia. If these values are unknown Wadam can calculate them based on the panel model. The calculation assumes that the mass is evenly distributed and that total mass equals buoyancy mass.

As stated in Chapter 6.1 some geometry was omitted, thus the mass model generated by Wadam will be considerably lighter than the actual COSL Pioneer. An overview of the mass properties generated in Wadam can be seen in Table 6-3

Table 6-3: Mass properties computed by Wadam

	Model	COSL Pioneer
Total mass [ton]	23730	26700-36400 [57]
COG [m]	[-1.26, 26.85, -4.87]	N/A
Radius of Gyration [m]	[27.28, 26.82, 37.33]	N/A
Product of inertia [m]	[-0.70, -0.96, -2.90]	N/A
COB [m]	[-1.33, 26.19, -7.35]	N/A

6.3.10 Damping Matrix

HydroD will calculate the damping matrix for each frequency.

6.3.11 Create Analysis

In the last step the input data defined earlier are chosen, this include the hydro model, loading condition and the environment condition. All other values are set to default except the characteristic length, which is set to 104 meters. Output from the analysis is stored in Wamit file and include:

- Displacement RAOs and load RAO
- Hydrostatic stiffness
- Potential Damping
- Added mass

6.4 Convergence Study

To determine if the mesh is sufficient, output from HydroD for all three meshes are compared.

6.4.1 Hydrostatic Stiffness

The hydrostatic stiffness is displayed as a 6x6 matrix for each degree of freedom, column 1 to 6 represent surge, sway, heave, roll, pitch and yaw respectively. The matrix displays the hydrostatic stiffness for the third mesh with over 12000 elements.

$$K_{Mesh3} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 6.80 \cdot 10^{6} & 1.78 \cdot 10^{8} & 5.57 \cdot 10^{6} & 0 \\ 0 & 0 & 1.78 \cdot 10^{8} & 8.77 \cdot 10^{9} & 1.51 \cdot 10^{8} & 1.80 \cdot 10^{7} \\ 0 & 0 & 5.75 \cdot 10^{6} & 1.51 \cdot 10^{8} & 4.30 \cdot 10^{9} & 1.54 \cdot 10^{8} \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

There was negligible difference between the matrices for the different meshes, which means that the values have indeed converged. The matrix was expected to display values for only heave, roll and pitch. The numbers generated for yaw is attributed to the offset in COG_{xy} COB_{xy} that can be seen in Table 6-3. Orcaflex will by default only import values from columns 3, 4, 5 and rows 3 ,4, 5, all other values are assumed to be zero and ignored. Apart from the deviation in column 6, the matrix is symmetrical as expected, and because of this, the matrix is assumed to be valid.

6.4.2 Damping and Added Mass

For each mesh, 51 matrices were generated for both added mass and damping, all matrices are 6x6. Overall convergence is achieved with only slight variations in the decimals. For some frequencies, greater deviations occur with values going from positive to negative and vice versa. This is probably due to local differences between the meshes. Preliminary tests yielded no error messages from Orcaflex, and combined with the focus on mooring lines no corrective measures were taken to correct the discrepancies in potential damping and added mass.

6.4.3 RAO

Displacement and load RAOs where generated in HydroD, convergence was checked for all DOFs at 0°, 45° and 90°. No significant deviations where noted between the meshes with respect to magnitude and shape of the curves. RAOs based on the actual COSL Pioneer was provided by Svein Larsen. Figure 6-6 displays an excerpt of the comparison between all meshes and COSL Pioneers RAOs. In conclusion, the RAOs are good enough for this thesis.

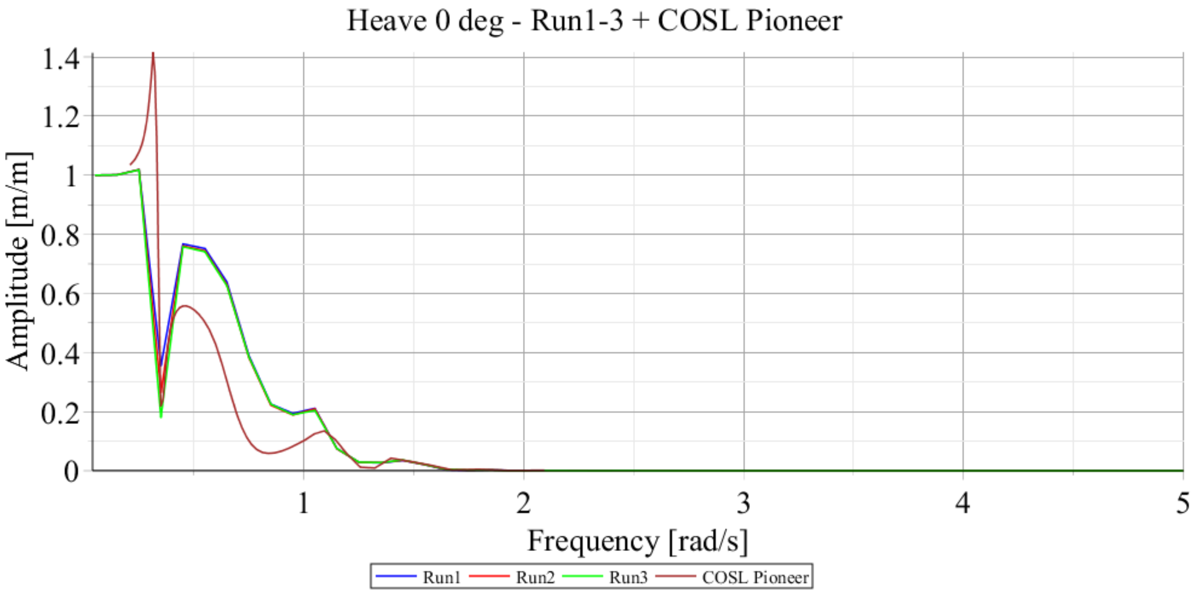


Figure 6-6: RAO comparison

6.5 Summary of the Rig Model

The final model imported into Orcaflex was the Mesh3 model, consisting of over 12000 elements. Overall most values converged reasonably well between the meshes, with some discrepancies in damping and added mass. The RAOs generated were compared to actual RAOs and found satisfactory for this thesis with respect to shape of curve and magnitude. Inconsistencies are attributed to local poor mesh. The weight of the rig is lighter than desired, as a result from lacking geometry. The model wound not be sufficient if vessel response were to be studied.

7. Orcaflex Model and Simulations

The purpose of the simulations are to establish the response and actions of the mooring line at release under various tensions and release points. The forces generated at release will be analyzed to see if they will influence the equipment (chain, wire, sockets etc.), or pose a threat to the rig.

7.1 Assumptions

The following assumptions are made for the Orcaflex model due to limitations in Orcaflex, lack of information or as a simplification:

1. Risers have been disconnected.
2. Vessel response will not be studied.
3. Constant material properties e.g. bending stiffness for wire.
4. Fairlead location is assumed to be underwater to prevent ice fouling.
5. Effect of current is minimal with respect to the response of the mooring line at release and has been omitted.
6. Release happens without energy loss in the release process.
7. No buoys on the synthetic fibre rope.

7.2 Environment

The environment has been selected based on environmental data from NORSOK N-003:2016: Actions and Effects [29] for 74N_34E. The location can be seen in Figure 7-1. The simulations are all done with a water depth of 250 meters.

Figure 7-1: Environmental location at the yellow thumbtack

7.2.1 Waves, Wave Calculation, Waves Preview

Professor Ove Tobias Gudmestad recommended a Torsethaugen wave spectrum for the location. From Figure A.2 in [29], a significant wave height of 14 meters, corresponding to annual exceedance probability of 10^{-2}, can be read from the contour lines. Figure A.3 in [29] gives a spectral peak period of 17 seconds. The wave train hits the rig at an angle of 45°.

7.2.2 Current and Wind

Current has been omitted from the simulations. The reason for omitting current is due to the sensitivity of the model. Preliminary simulations proved unstable and the running time was significant, by omitting the current the running time was reduced. The wind hits the rig at an angle of 45°.

Figure A.7 in [29] gives a 1-hour extreme wind speed of 31 m/s, corresponding to annual exceedance probability of 10^{-2}.

7.3 Mooring Line

The mooring configuration is based on a mooring analysis provided by Svein Larsen. The rig consists of 8 mooring lines in a wire rope, synthetic rope and chain configuration. Table 7-1 lists the components used in the mooring lines, and Figure 7-2 displays a bird's eye view of the whole rig and mooring system. Line 1 is set to release 5 seconds into the simulations, and all data is collected from this mooring line.

Table 7-1: Line components

Component	Type	Line length [m]
Chain	84mm R4 chain	1000
Wire rope	96mm Bridon DB2k	Varies with release point
Synthetic fiber rope	160mm polyester	1300

It should be noted that when using synthetic fiber rope, the rope will be prevented from touching the seabed. This is ensured by using buoys at key locations along the rope. No such buoys have been modeled here to keep the running time within reason.

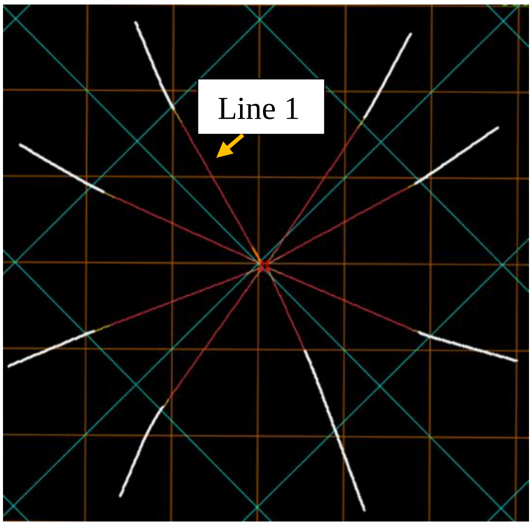


Figure 7-2: Mooring line overview, the white lines indicate the chain is in contact with the seabed.

The inbuilt wizard in Orcaflex, except for wire bending stiffness, generated material properties for the different components. Bending stiffness in wire rope is highly dependent on applied tension. Via e-mail correspondence with Bridon, the lower bound value for bending stiffness of a DB2k wire rope is $EI_{wire} = 985\ Nm^2$, this value is based on the summation of individual wire bending stiffness's.

Preliminary simulations including torsional effects proved to be very unstable and have been omitted from the simulations; it should however be noted that these simulations did indicate that the wire will twist in both directions (positive and negative torsion).

The rig/line connection was modeled as a fixed point in Orcaflex. This is strictly not correct, as the wire coming from the winch is passed through the fairlead and is technically free to move to some extent, see Figure 7-3. How this will affect the results will be discussed in Chapter 9.

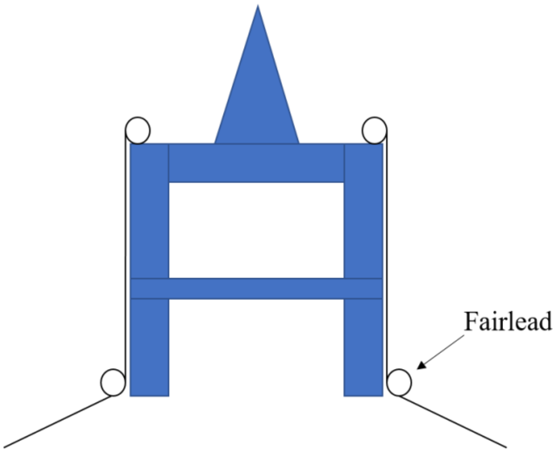


Figure 7-3: Fairlead location

A 6 degree of freedom buoy represents the release tool, geometry and mass are based on Ejecto's MultiDog MCQ-9R and measure ø0.5 x 1.3m and weighs 300 kg (in air). The buoy represents the "male" part, which is connected to the wire. The simulations do not simulate the release process in the tool itself.

7.4 Rig and Hull Contact

The rig properties were imported using the data collected from the HydroD analysis. For Orcaflex to understand the imported data certain conventions must be defined manually; waves are referred to by frequency (rad/s) and RAO phases are defined as leads. Wind load data, such as areas and load coefficients were taken from [59].

The default hull in Orcaflex does not register hull contact from mooring lines. To model this two *elastic solids shapes* were used. An elastic solid is a shape that represents a physical barrier to lines or buoys, and registers contact when nodes interact with the shape. The calculations behind hull contact, requires *normal stiffness* [60] which was assumed to be a high value due to possible ice strengthening ($K = 100{,}000\ kN/m/m^2$). To avoid interference from the node connected to the vessel (fairlead node) shape2 was place 10cm inside the hull. Figure 7-4 depicts the elastic solids used to model hull contact. Shape1 is here coloured in blue while Shape2 is coloured in brown.

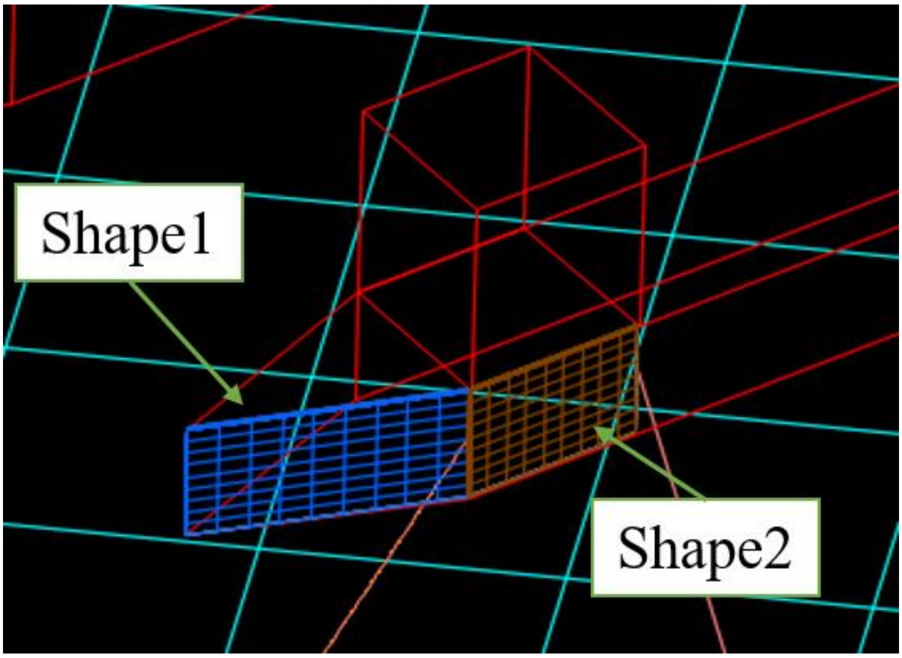


Figure 7-4: Hull contact shapes

7.5 Simulations

Several different simulations have been performed, Figure 7-6 shows a complete map of all simulations. Each batch consists of five simulations, one for each release point, except the “Offset case” that includes four simulations. The release point was selected to be tested at 150, 200, 250, 300 and 350 meters from the fairlead along the wire line. This represents the wire being paid out to the specified lengths. Release does not occur while the winch is in motion. In total 92 simulations have been performed.

Base case 1 was used to achieve full system static convergence and does not include weather effects. In Base case 2, wind and wave actions were included. This batch also served as a convergence test for the mooring line.

To check the wire response under extreme tensions, the base mooring configuration was changed by replacing the synthetic fibre rope with steel wire rope. The increased weight of the mooring lines increases the tension in the lines. This case is referred to as the “extreme case”.

“2m chain”, “5m chain” and “10m chain” are case names that refer to the length of chain placed between the wire rope and the release tool to act as damping, see Figure 7-5. Also included is a mass point of 130 kg that represents the CR-socket at the end of the wire. It should be noted that in simulations that include chain damping the wire rope length is compensated to keep the release point at the specified locations.

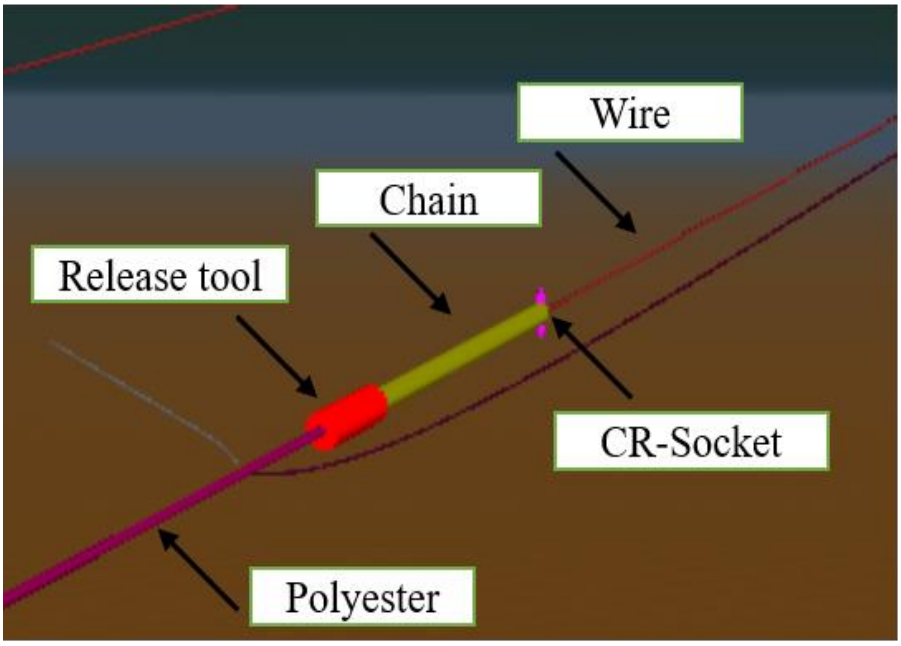


Figure 7-5: Connection detail

In the Offset case, release was done when the rig was offset from the centre. The release point is 50 meters from the fairlead along the wire rope, and includes simulations with and without chain damping.

All simulations except for Base case 1, was also used to model potential hull contact from the recoiling wire rope. Using the method described in Chapter 7.4.

Orcaflex allows the user to manually enable *line clash,* which registeres contact made between multiple lines or contact a single line makes with itself. This was done for all cases except Base case 1. To model line clash, line *clash stiffness* must be defined. This is a difficult parameter to estimate with any precision [61]. The clash stiffness was therefore assumed to be $K_{clash} = 1kN/m$ (the program default value).

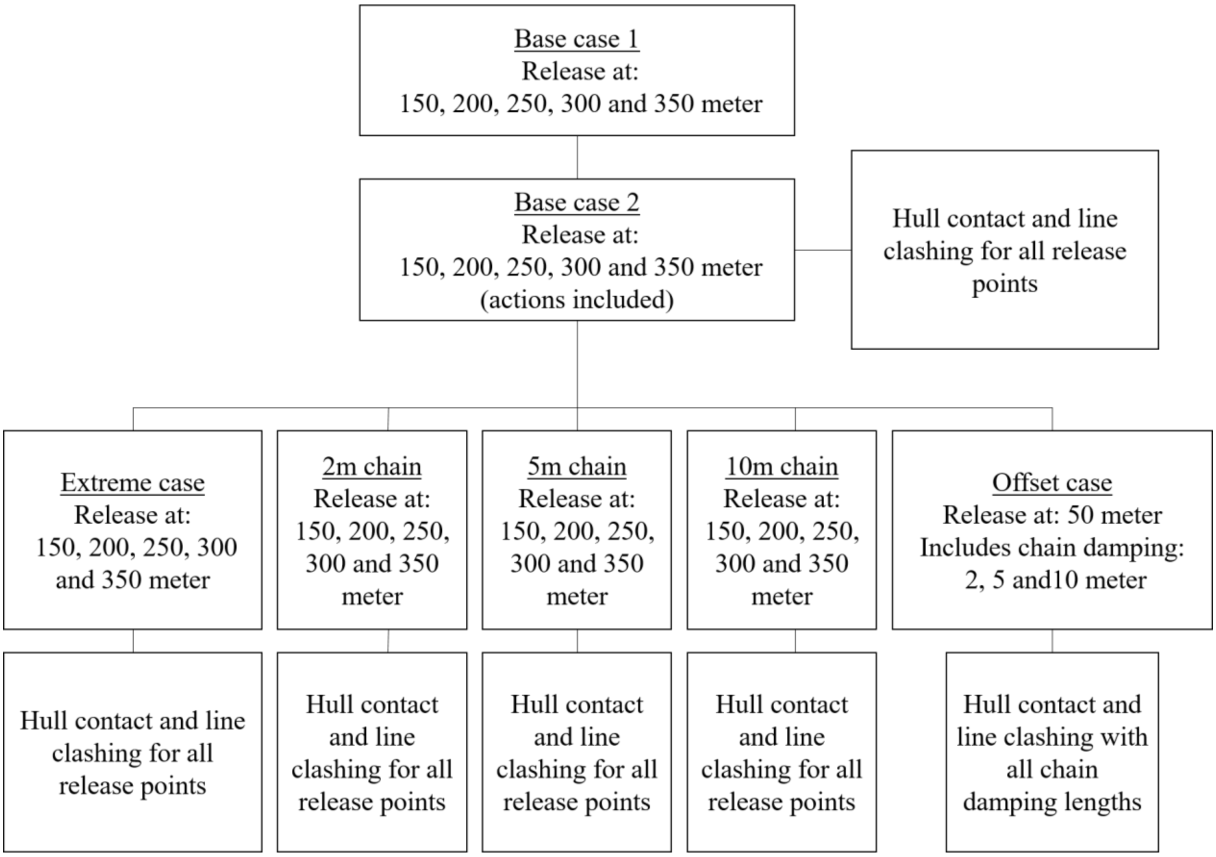


Figure 7-6: Simulation map

8. Computational Challenges and Warnings

8.1 Convergence Issues

Initially it proved hard to achieve static convergence for the model. By increasing the *min damping* parameter from 1.0 to 1.5 the step taken at each stage is reduced, making convergence easier.

8.2 Time-Step

Initially Orcaflex returned error messages concerning numerical instability at the time of disconnection, because of the rapid change in tension the simulations required a very small time-step to fix this issue. The time-step was set to $t = 0.001s$ which resulted in stable but relatively long simulation runs.

8.3 Length of Line Segments and Convergence

Initial length of line segments where set to 1 meter. Values for tension at t=0s, t=5s and t=5+s were compared to the same values for a line with line segments of 0.5 meter. Time equal to 5+ indicate the immediate response after release. The comparison can be seen in Table 8-1 and Table 8-2 with the actions occurring at the fairlead.

*Table 8-1: Values for line segments of 1 meter, * indicates no compression*

Release point	150m	200m	250m	300m	350m
Effective tension at t=0s [kN]	1449.37	816.64	305.4	139.45	107.00
Effective tension at t=5s [kN]	1394.54	751.80	218.90	48.80	93.00
Effective tension at t=5+s [kN]	-1580.37	-862.50	-211.37	*	*

*Table 8-2: Values for line segments of 0.5 meter, * indicates no compression.*

Release point	150m	200m	250m	300m	350m
Effective tension at t=0s [kN]	1449.37	814.64	303.54	139.00	108.00
Effective tension at t=5s [kN]	1398.67	746.68	218.58	48.60	93.70
Effective tension at t=5+s [kN]	-1569.36	-862.36	-210.00	*	*

No significant deviations can be seen, and it is assumed that this is true for all values found in the Orcaflex simulations. All subsequent simulations were done with 1 meter segment lengths, to minimize simulation time.

8.4 Warnings

By omitting torsional effects in the mooring line, Orcaflex displays a warning. This is because the release tool is modelled as a 6D buoy that can induce torsional moment in the line. This warning was ignored.

The load RAOs generated in HydroD does not cover the shortest periods (1.122s) found in some wave components in the sea state used in Orcaflex. Orcaflex solves this automatically by extrapolating. This can affect the results concerning vessel motion, which is not studied in this thesis and was therefore ignored.

9. Orcaflex Analysis Results and Discussion

When intentionally releasing a mooring line under tension, damages to the rig and equipment could potentially occur. The Orcaflex results and discussion will be twofold, one part will be discussing the results concerning HSE and potential damages to the rig. The other part will discuss the results concerning potential damage to the mooring line and release tool. When reconnecting, one must be sure that the structural integrity of the wire has not been compromised.

Areas of interest in the simulations are actions occurring at the fairlead and the release tool. The effects induced by the mechanism on the wire itself is very relevant when considering reconnection.

This thesis has focused on the top part of the mooring line after release. It should, however, be noted that if synthetic fibre rope (with buoys) is used, the release will cause the rope to flow with the current and probably start to curl and entangle. This not only makes the reconnection more difficult, it will also bring uncertainties by potentially inducing twist from the rope to the wire once connected. Steps should therefore be taken to avoid this, possibly by having chain or smaller secondary anchors that will keep that fibre rope in place after release.

9.1 Initial Findings

The tension registered before release for each case can be seen in Table 9-1.

Table 9-1: Pre-release tension [kN]

	50m	150m	200m	250m	300m	350m
Base case 1	N/A	815.71	276.18	136.78	117.07	101.84
Base case 2	N/A	1401.07	748.99	219.23	48.74	93.57
2m chain	N/A	1400.82	749.1	222.97	80.85	99.41
5m chain	N/A	1401.35	750.08	227.08	63.31	103.72
10m chain	N/A	1402.29	751.71	234.02	96.33	114.35
Extreme case	N/A	6203.87	1512.08	421.02	218.23	149.71
Offset case	1676.82	N/A	N/A	N/A	N/A	N/A

The discrepancy that can be seen in the blued-out cells in Table 9-1 are believed to be due to waves, because base case 1 (no actions included) has decreasing tension with increasing wire rope length as expected.

If disconnection happens at 300 meters the release tool will touch the seabed unless pulled to the surface in time. With release at 350 meter the release tool will touch the seabed. The design criteria for the release tool should specify if this can be permitted or not. E.g. from Figure 3-5 the RigLOK has two vulnerable transponders protruding from the male component that could be ruined if dragged along the seabed. Given the release tool velocities displayed in Appendix B, collisions will be unfortunate with respect to potential damages. Especially if collision occur close to the release time, when the transition is greatest.

The hydrodynamic loads are enough to prevent the wire rope from breaking the surface. This is a good indication that the disconnection process itself is safe for personnel. However, should release occur under high loads the resultant shock, could in worst case accelerate loose objects on deck unless mitigating measures are taken.

9.2 Effect of Acceleration on the Release Tool

The mooring lines are relatively taut for wires ranging from 50 to 250 meters. Significant curvature does not occur before 300-meter wire is paid out. A comparison of the catenary shapes for 150, 250 and 350-meter wire can be seen in Figure 9-1. The acceleration the release tool experiences at the various release points is interesting with respect to the electronic components (e.g. transponders) and other sensitive components. The components must be designed to withstand G-forces experienced. Figure 9-2 displays the immediate acceleration for the release tool for Base case 2. The release occurs at $t_r = 5s$.

For all release points, an increase in acceleration occurs until t_1 =5.1s (vertical lines in Figure 9-2). This suggests the inline acceleration is extremely brief. Disconnect at 150m dominates the graphs, this is assumed to be due to the taut nature of the wire; compared to the other wire rope lengths, the declination does not change significantly along the nodes on 150m wire rope.

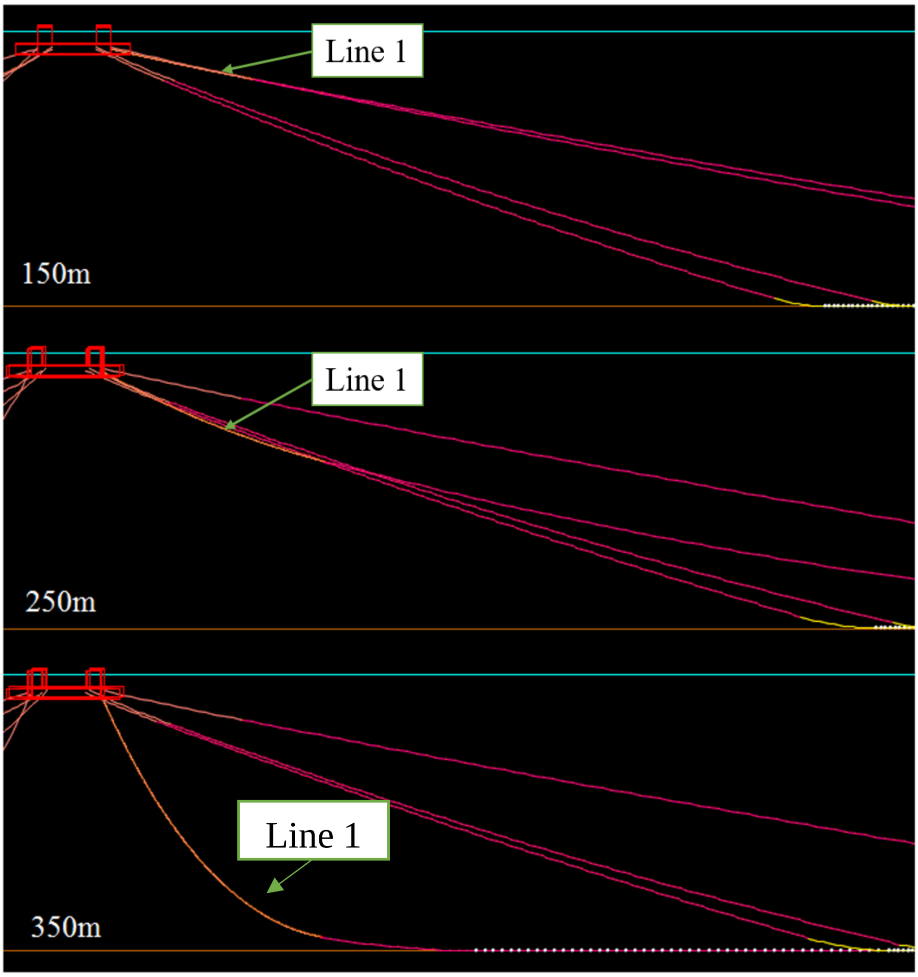


Figure 9-1: Catenary comparison

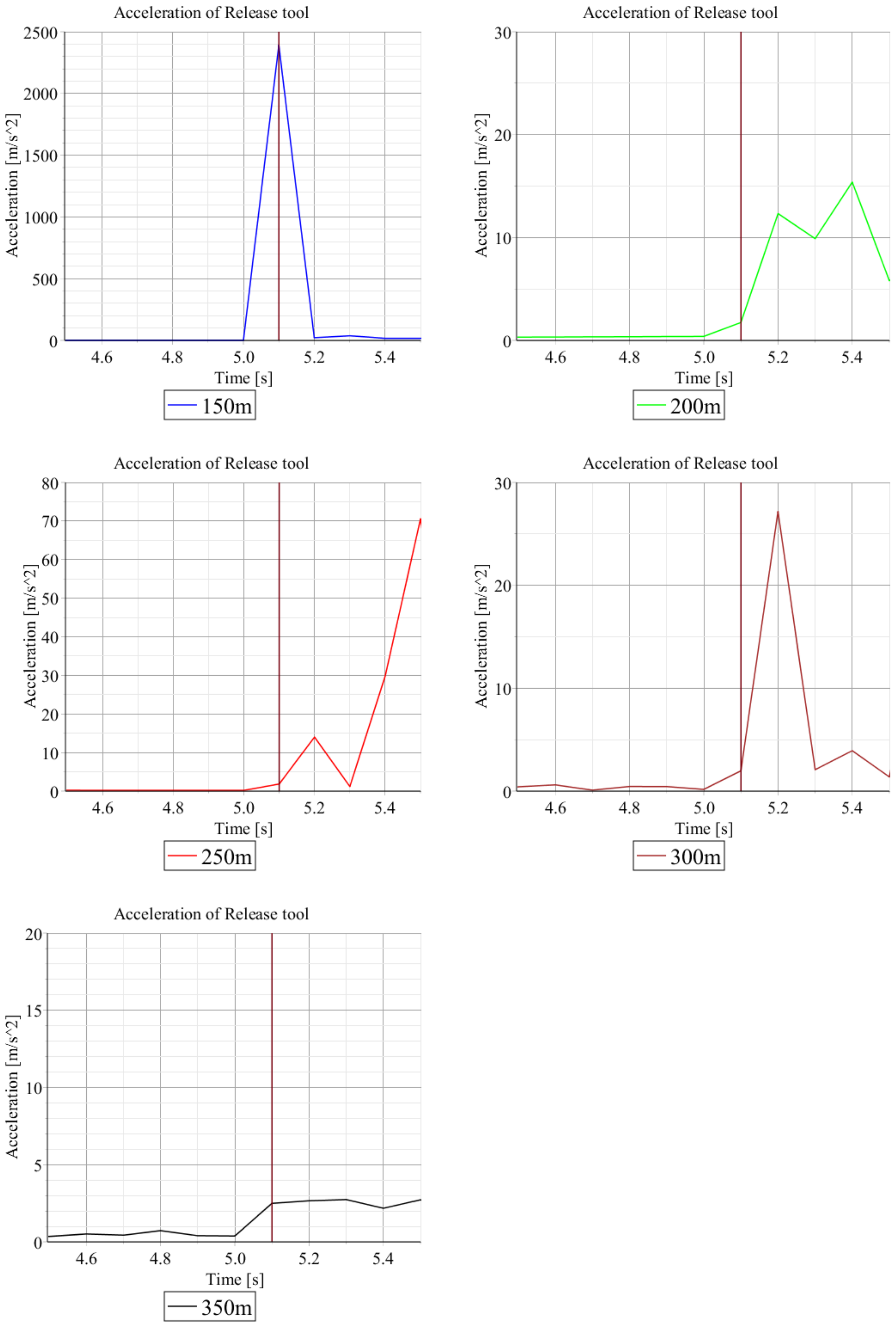


Figure 9-2: Acceleration of Release tool for all release points, Base case 2

After $t_1 = 5.1s$ the release tool will start to twist and turn, and it is believed that this accounts for any increase in accelerations after t_1.

Relevant electronic components include transponders such as Kongsbergs cNODE MiniS. Via communication with Ejecto’s contact person at Kongsberg Maritime it was confirmed that G-force tests are performed on relevant equipment, regrettably G-force tests were not provided in time to compare with the Orcaflex results. Given that the InterOcean Systems’ RAR uses similar technology, it is assumed that this issue is manageable.

The affect the acceleration might have on the mechanical functions of the release tool must be considered in the design. During the disconnection process the hydraulic forces must be sufficient to overcome potential G-forces that could counteract the disconnection process.

9.3 Tension at Fairlead (End A) and Hull Contact

The tension registered at the fairlead is presented for Base case 2, 2m chain, 5m chain and 10m chain and discussed. Of interest are potential damage to the rig, potential damage to the wire and how chain damping compares with Base case 2.

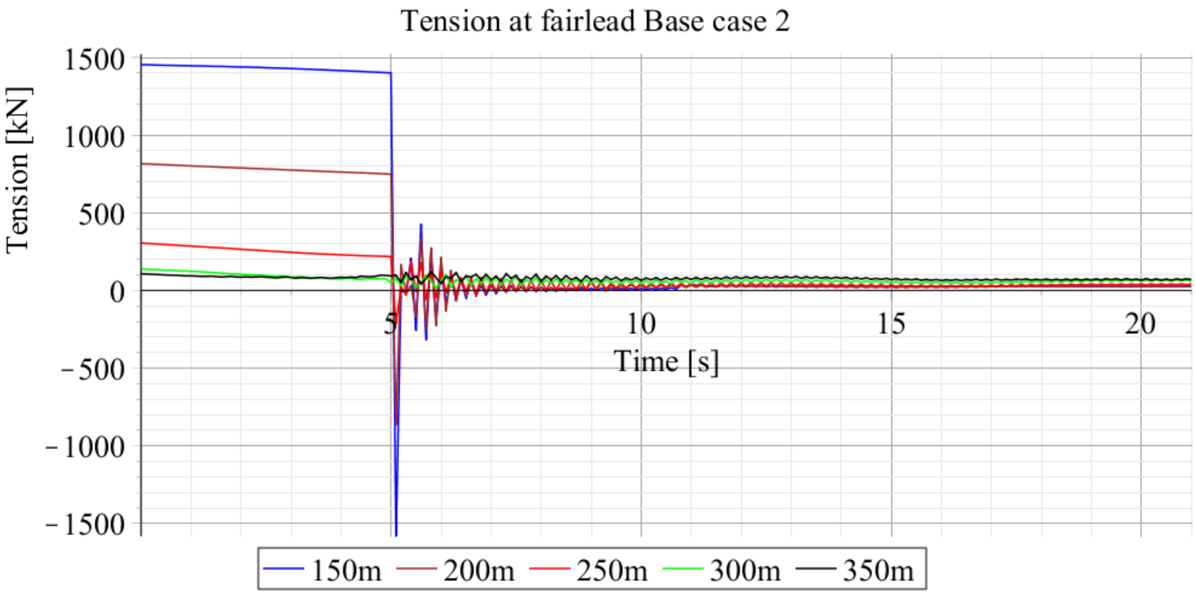


Figure 9-3: Tension at End A, Base case 2

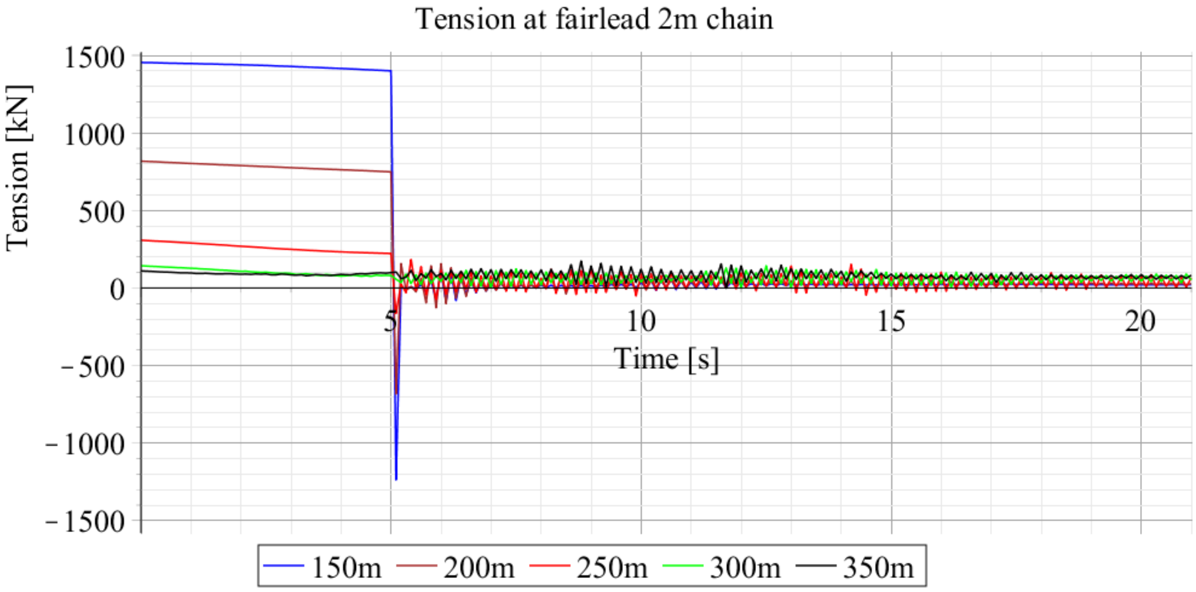


Figure 9-4: Tension at End A, 2m chain

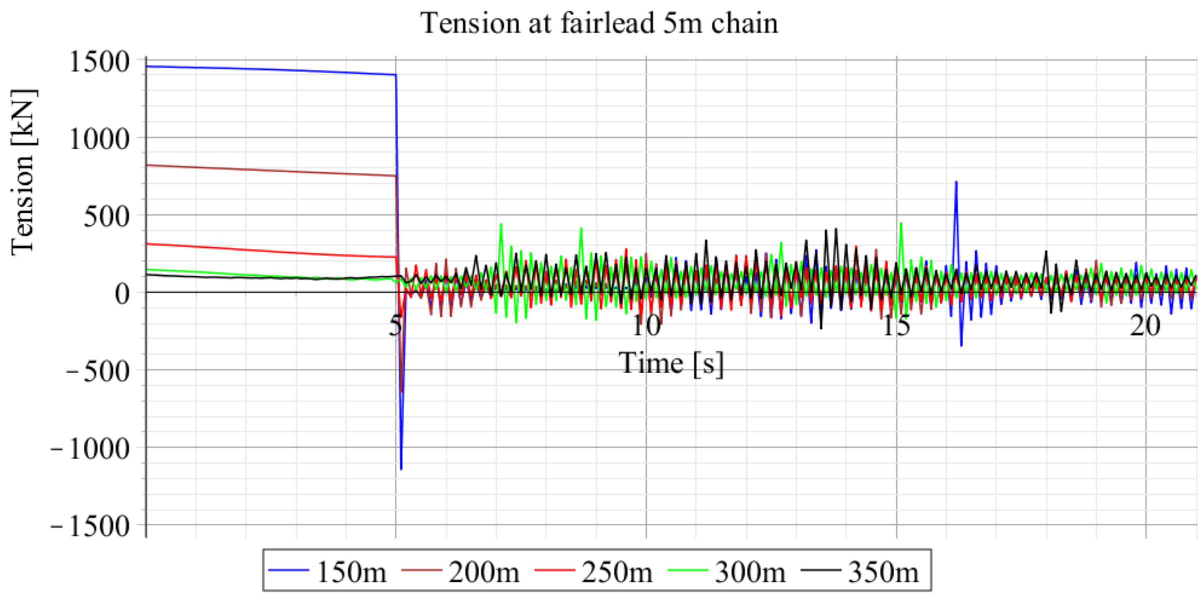


Figure 9-5: Tension at End A, 5m chain

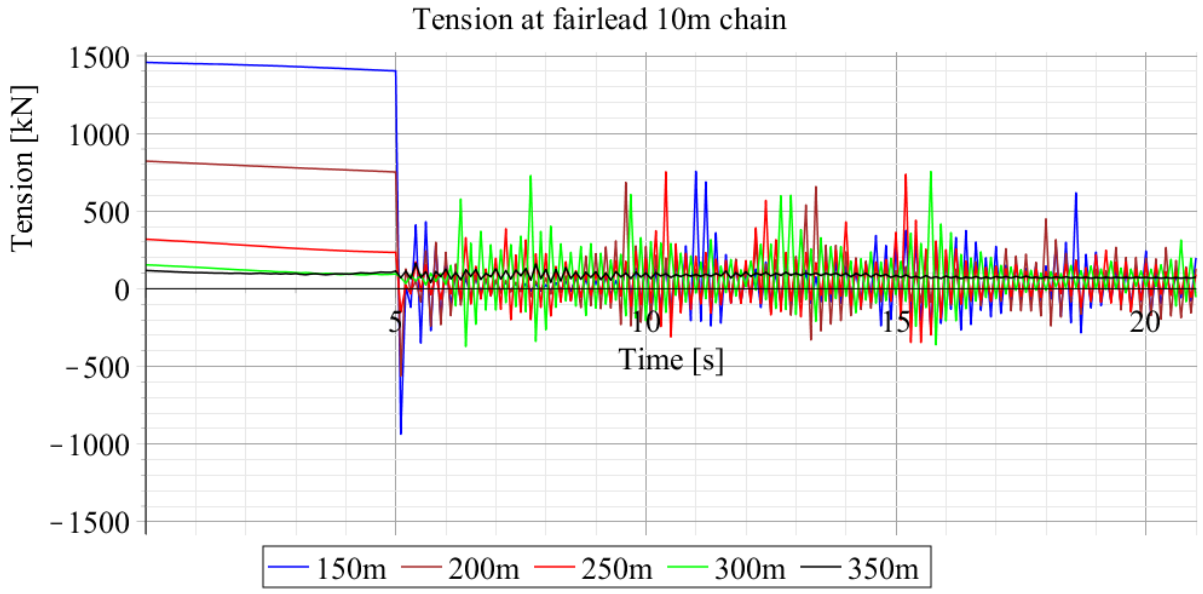


Figure 9-6: Tension at End A, 10m chain

When analysing the time history for all cases, compression is registered for all release points except for release at 300 and 350 meters. The magnitude of this compression is cause for concern. In Base case 2 the recoil from the release is nearly equal to the release load see Figure 9-3. I.e. for release at 150 meter the tension is approximately 1400kN with a recoil of -1580kN. Are these realistic numbers? As mentioned in Chapter 7.3 the fairlead is modelled as a fixed point, that will absorb some of the energy. While in theory a sudden release could result in a very short-duration compression of the same magnitude [48], it is impossible to know for sure based on a computer simulation. The compressive results obtained for all time histories are best viewed as qualitative. For this reason, the time histories in Figure 9-3 to Figure 9-6 yield no specific answers about possible damages to the rig/fairlead.

To counter the potentially large recoil, damping has been included in the form of a length of chain between the wire and the release mechanism. By including the chain significant damping is achieved, this could be further increased if the release tool itself has damping e.g. as for MultiDog MCQ-9R. The chain damping also contributes some unpredictable behaviour as well as chaotic loads after release. This is especially evident in Figure 9-5 and Figure 9-6, where disconnect at 150, 200 and 250 meter results in large amplitudes after disconnection. These amplitudes are believed to be the result of dynamic amplification where the weight of the chain induces a snap-load in the wire rope as it falls to towards the seabed.

To further investigate the damage potential to the rig, line contact with the hull was modelled for the different cases. The Extreme case simulations yielded the greatest impact load when disconnected at 150 meters from fairlead see Figure 9-7.

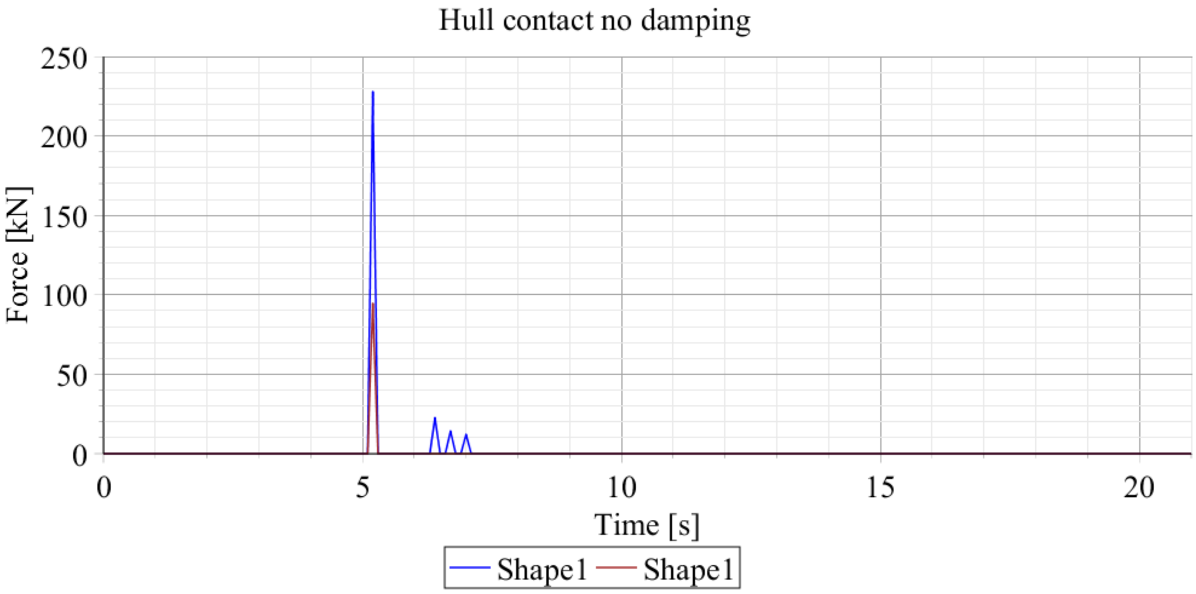


Figure 9-7: Hull contact for the Extreme case, release at 150m.

How an impact of approximately 225kN from a steel wire rope will affect the hull is assumed to within the tolerance of the hull, this assumption is based on the use of an ice class rig, and the flexible nature of a wire rope. Damage to the wire rope will be a greater concern.

Using the “Offset case”, with release at 50 meters along the wire rope, four simulations were performed. The simulations included the respective chain damping lengths and one without damping. The results from these simulations do indeed indicate that parts of the upper wire close to the fairlead contacts the hull, the results from hull contact with 2 meters and 5 meters chain damping can be seen in Figure 9-8, and is assumed to be of little consequence for the hull.

For the Offset case without chain damping, contact (approximately 9.5kN) is only made at the end of the simulation (from $t = 20.5\ s$), this suggests that the disconnection process is achieved without hull contact, and only occur when the wire sinks towards the seabed. With 10-meter chain damping no hull contact is registered in Orcaflex.

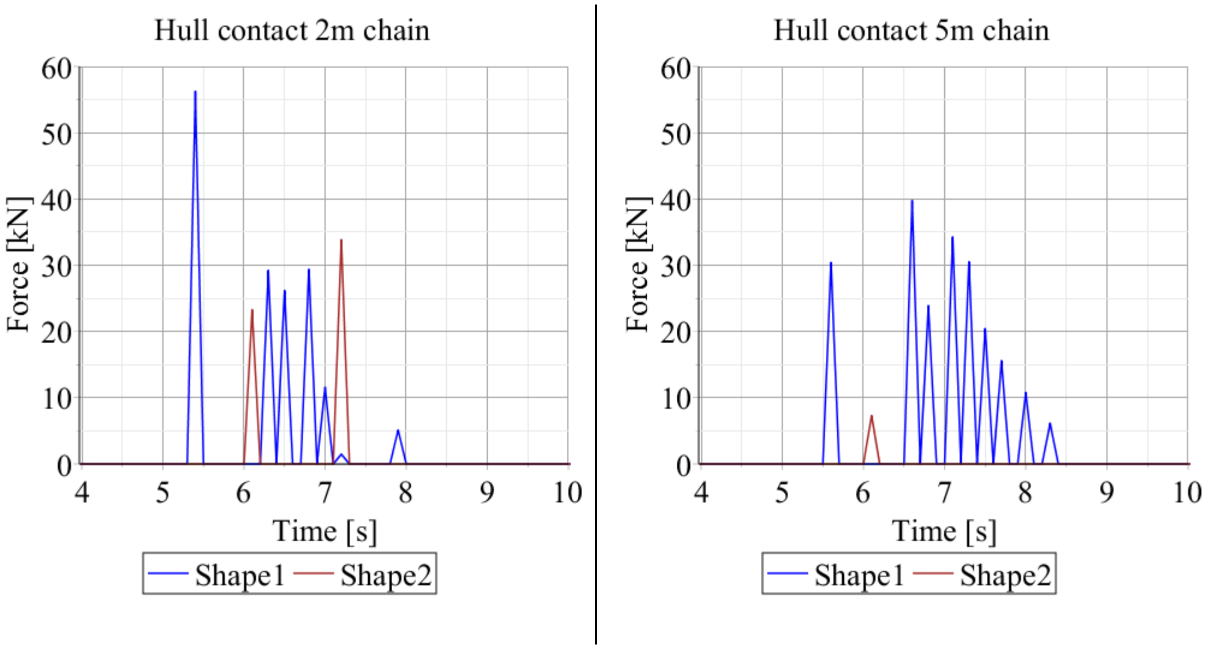


Figure 9-8: Hull contact offset case

Regardless of hull contact, proper inspection of the wire should be performed according to Chapter 5.4 in [18]. The remaining simulations yielded no significant contact forces with the hull. For simulations involving 2 and 5-meter chain, with release at 150 meter a slight contact of approximately 14-15kN was made.

By investigating past line failure reports involving wire rope, the damage potential can be further identified to some extent. The Norwegian Petroleum Safety Authority keeps record of line failures on the NCS. In their report about line failures for 2010-2014 [62] there was one incident in 2013 on the Island Innovator where wire rope failed at 15-20 meter from the fairlead causing damage to the port aft thruster and propeller [62, p. 14]. While no damage to the hull has been registered, the consequences of a damaged propeller might influence the post evacuation process.

During a planned disconnection, the lee side mooring lines will be disconnected first, the desired tension in the windward mooring lines will be achieved by moving the rig against the wind, and if needed paying out the wire. Once the rig is free to move, the thrusters will bring the rig to safety. However, if one or more thrusters have been damage during the disconnection process the rig might have insufficient thrust. Without the thrusters, it will be difficult to disconnect the mooring lines and expect a controlled outcome. Studies should be performed on rigs to identify the minimum length required to avoid the wire rope striking the thrusters under the hull. Another consideration is to identify the possibility of a wire rope being sucked into a thruster once disconnected.

9.4 Bending Stress in Wire Rope

Visual inspection of the simulations shows large curling in the wire rope immediately after the mooring line is disconnected see (Figure 9-9). Orcaflex is incapable of calculating stresses in a helix shaped wire rope. The bending moment due to the corresponding bending radius is calculated analytically.

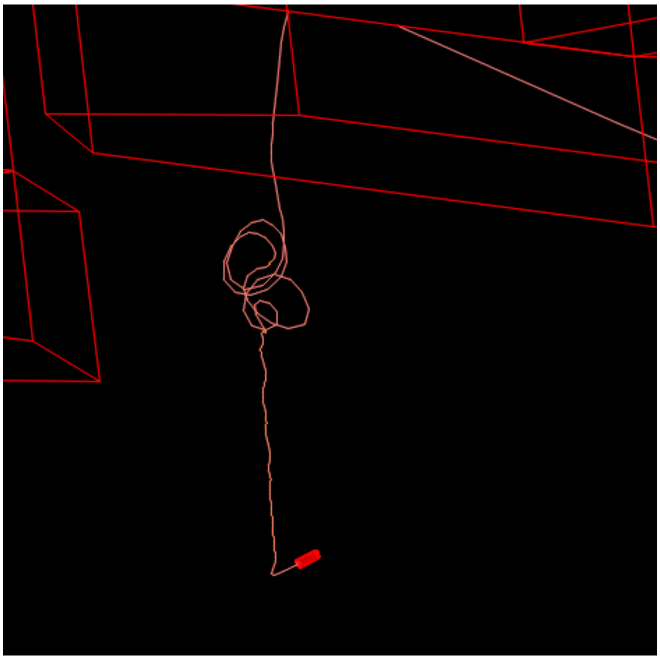


Figure 9-9: Wire rope curling after release

The bending moment that occurs in the wire varies slightly between the different simulations (see Appendix A). The extreme case (see Figure 9-10) yields the largest bending moment at 2.54 kNm. This bending moment corresponds to a bending radius of $R = 0.5m$ found in the Orcaflex results. The global bending stress of a single wire, in a wire rope described by Reuleaux yields [14, p. 179]:

$$\sigma_b = \frac{\delta}{D} E = 939.8 \frac{\mathrm{N}}{\mathrm{mm2}} \tag{9-1}$$

Where:

δ = Diameter of a wire (assuming 5mm)

D = Middle curvature diameter (2R)

E = Modulus of elasticity

This method calculates the stress by ignoring the helix form. This makes the Reuleaux stress an approximation that is both smaller and greater than the actual stress [14, p. 179], depending on the helix shape. In [14, p. 184] a comparison between Reuleaux Stress and more accurate methods indicate that an increase of 23% can occur for certain helix angles. Assuming this is true for the wire studied:

$$\sigma_{b,new} = 1.23 \cdot \sigma_b = 1155.9 \frac{\mathrm{N}}{\mathrm{mm2}} \tag{9-2}$$

Comparing equation (9-2) to the yield stress; based on minimum break load divided by cross sectional area found in [15, p. 10].

$$\sigma_y = 1668 \frac{N}{mm^2} > \sigma_{b,new} \tag{9-3}$$

The wires are unlikely to reach the yield stress, however additional stresses such as torsion stress (which has been ignored) and possible combination conditions have not been analysed. How these additional stresses will affect the health of the wire with respect to recoupling the mooring lines, must be answered through detailed FEM analysis or through experiments.

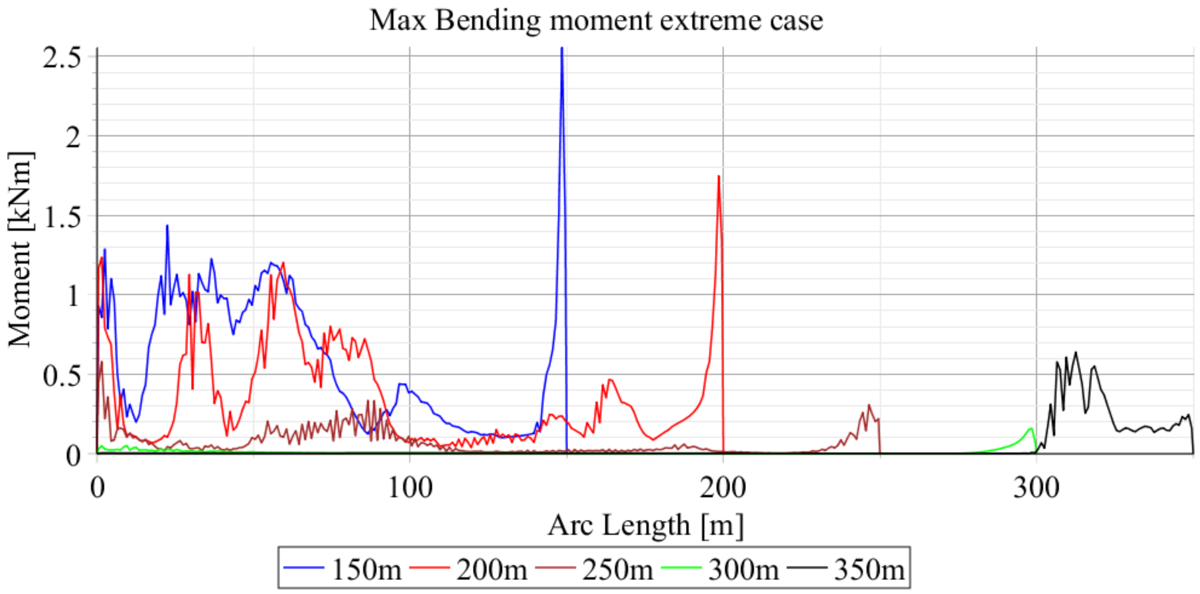


Figure 9-10: Bend moment Extreme case

From the bending stress graphs in appendix A the addition of chain damping causes increased fluctuations along the arc length. With release points at 150, 200 and 250 meters, peaks along the arc length will be points of interest during inspection of the wire rope. With release at 300 and 350 meter no significant peaks are detected, except for close to the end termination. If a wire rope is subjected to twist, the resulting disconnect can form kinks in the wire rope. If the kink is pulled tight, the rope could fail catastrophically. A kink can be seen in Figure 9-11, and is essentially a permanent bending. According to Chapter 6.6.8 in [18], kinks are a discard criteria.

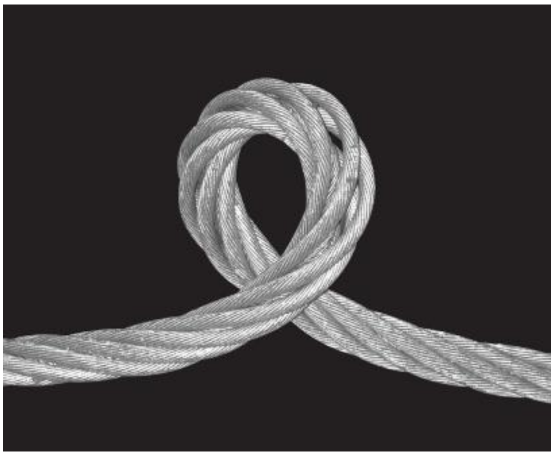


Figure 9-11: Kink. Figure from [19, p. 33].

9.5 Tension at End of Wire (End B) and Line Clashing

Critical inspection points for a wire rope can be found in Chapter 5.3.3 in [18], among them is any point in or close to a rope termination. Tension at the end of the wire is only registered in Orcaflex for simulations that includes chain damping. The immediate response after disconnecting can be seen in Table 9-2.

Damage to the resin lock is of interest. It is assumed that a steel CR-socket can withstand the max value found in Table 9-2. If the resin is poured correct and allowed to seat (move down the socket basket) it is virtually impossible to damage a socketed termination [63]. The movement of the resin cone is irreversible leading to permanent compression in the resin, the added benefit is no fluctuation in the stresses, thus no fatigue [63]. Making multiple disconnections possible with respect to the socket provided it passes inspection. This assessment was largely shared by WIRETECH as well; a Norwegian wire rope supplier, however in an ideal situation where a load is perfectly in line with the wire and socket, theoretically some form of damage can occur.

Table 9-2: Immediate tension after release. Negative tension indicate compression.

2 m chain	Length [m]	Tension [kN]
	150	-86.62
	200	-44.18
	250	-11.31
	300	-1.18
	350	1.14
5m chain	150	-72.65
	200	-37.20
	250	-9.65
	300	-1.20
	350	2.50

10m chain	150	-65.99
	200	-33.21
	250	-8.66
	300	-1.25
	350	-1.25

In all cases the wire rope will start to curl. To check if the line contacts itself or the relase tool, line clashing was checked for all cases. Due to the uncertainty in the clashing stiffness the clash force, impulse, penetation and energy will not be presented. Table 9-3 displays what line components registered line clashing. Table 9-3 does not specify the location of the line contact or how many clashes occurred.

It is evident from Table 9-3 that line clashing is of significant concern. Most of the clashes occur with the inclusion of chain damping, where the majority of clashes were the chain segments clashing with itself. The Orcaflex results did not specify contact between the release tool and chain/wire. This should however, not be ruled out, especially if the relase tool incorporates electronic componants which might be ruined if struck.

Generally, the clash locations for the wire rope where located in the wire/chain transition. In this area segments of the chain would clash with itself and the final meters of wire rope. Unless the wire rope is properly shielded this could lead to individual wires being damaged. Furthermore entanglement cannot be ruled out when using chain segments, but this was not explicitlly proven. This would be unfortuante with respect to potentially inducing twist in the wire rope or other effects. If studlink chains are used, individual studs could be knocked out of place. Spare studs or chain segments should therefore be available when reconnecting.

Table 9-3: List of lines clashing, x indicates line clash with line component

Release point	150m		200m		250m		300m		350m	
Line component	Wire		Wire		Wire		Wire		Wire	
Base case 2	N/A		N/A		N/A		N/A		N/A	
Extreme case	x		N/A		N/A		N/A		N/A	
Line component	Wire	Chain	Wire	Chain	Wire	Chain	Wire	Chain	Wire	Chain
2m chain	x	x	x	x	N/A		N/A		N/A	
5m chain	x	x	x	x	N/A	x	N/A	x	N/A	x
10m chain	x	x	x	x	x	x	x	x	N/A	x
Damping (chain)	No chain		2m		5m		10m			
Offset case	N/A		x	x	x	x	x	x		

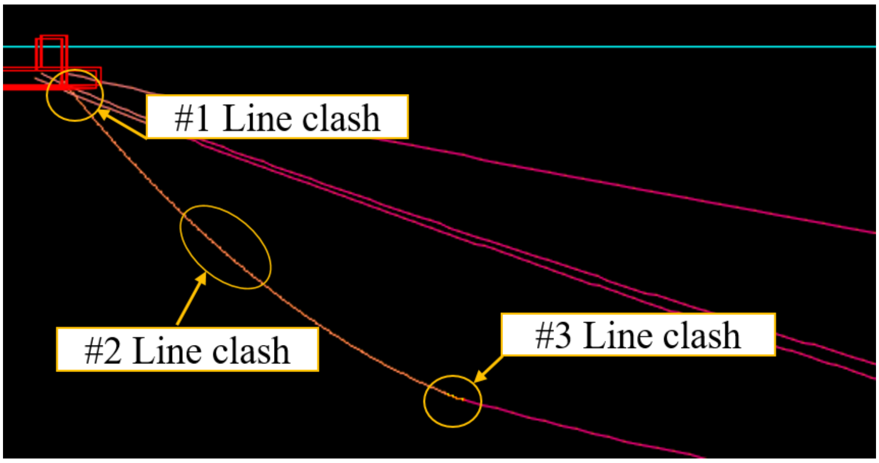


Figure 9-12: Line clash location

Figure 9-12 depicts a general picture of the clash locations (ignoring the catenary shape), here #1 and #2 are valid only for the extreme case and occurs when released at 150 meter Table 9-3 shows. #3 is valid for all cases except the extreme case.

10. Proposed Design Criteria for a Release Tool

It is assumed that the release tool is defined as *mooring accessories*, and is thereby covered to some extent by DNV-OS-E302 Offshore Mooring Chain.

Design Criteria

- The design shall secure safe operations on deck
- The release tool shall incorporate the ability to disconnect if primary signal fails
- Selection of material according to DNV-OS-E302 section A100 subsection 102[1]. Components shall be based on its ability to withstand the intended climate of operation, and forces during use
- The release tool shall be certified for a given minimum break load
- The geometry shall passively protect electronic components (e.g. transponder heads)
- The geometry of the release tool; including line interface, shall enable the ability to be handled without a crane or other lifting operations
- The release tool shall include the ability to remotely measure line load. E.g. using strain gauges
- Communication with the release tool shall be accomplished via the rig/vessel’s on-board systems
- The release tool must be pressure compensated
- The release tool must incorporate battery capacity for minimum 9 months
- The accumulator fluid type must comply with chemical spill regulations. Green chemicals must be used
- If permitted to touch the seabed, the design considerations must accommodate this

---

[1] See Table 1-1 in Chapter 1.3.1 for table of steel grades

11. Parameters for Disconnect and Reconnect

This chapter was written with input from Ove Haugen, Haugen is a retired offshore installation manager and the founder of OFFB (Operatørenes Forening For Beredskap) a second line Norwegian emergency response organisation.

Perhaps the most difficult aspect of disconnecting and evacuating a platform off-site, is the decision to initiate evacuation that must eventually be made. This decision is only as good as the available information at the time, and will in many cases be decided by probabilities, e.g. a polar low will form in 42 hours with a moderate probability, what to do? The primary concerns to consider when operating on an offshore installation are:

1. Life and health
2. The environment
3. Material values

Any decision must be made according to these priorities.

Before drilling or production operations can begin, a thorough risk assessment of the area must be performed to identify parameters that will define the criteria for safe operations, and selection of equipment. Prior to disconnecting the mooring lines, the well must be secured and the riser must be disconnected, a production unit will have several individual risers. This is a process that starts when a predefined alert level is reached, e.g. Alert Level Yellow per Table 4-1. A procedure for disconnecting the riser and mooring lines must be described in the operating manual. Due to the increased time needed to secure and disconnect several risers, column stabilized production platforms such as Visund and Kristin may not be feasible in the Barents Sea. As stated in the introduction, ship shaped FPSOs are currently used off the coast of Newfoundland. These FPSOs have weathervaning capability, and risers and mooring lines are connected to a disconnectable turret.

The nature of the threat will decide the necessary course of action, with respect to the methods used in securing the well and disconnecting the riser. In exploration, the main concern will be mostly material/monetary, as long as the drill bit has not entered the reservoir, while in production the possibility for large environmental pollution is present and more time is needed to properly shut-down and empty/disconnect the risers and secure the wells. Also, subsea infrastructure could impose restrictions for production units when disconnection of the mooring lines is considered.

The deciding parameters for successful disconnection will be to identify accurate Hazard Time (HT) regardless of hazard type, Secure Time (ST) and Move Off Time (MOT). These are parameters that can change over time due to shifts in weather conditions, therefore conservative estimates must be made to enable contingency plans. The accuracy with which HT can be estimated will depend on the hazard type and the corresponding methods of detection and/or forecast. In the Barents Sea due to fewer observations weather forecasts will be more uncertain than for example forecasts for the North Sea. Due to potential rapid changes in the Barents Sea, HT must be continuously updated so that correct alert level is set. Changes in conditions must be communicated to relevant personnel. If changes occur, ST could potentially have to be changed as well, using quicker methods for disconnecting the riser. To account for uncertainties in HT, safety factors can be used in calculating ST. The alert levels can also be used to account for some uncertainties, by allocating more time to intelligence gathering, typically when alert level blue is in effect. MOT calculation can be calculated for a quick-release using the concepts presented in Chapter 3, conventional mooring recovery or to run the wire rope off the drum. The choice of method will be decided by required MOT and reconnection considerations. Conventional mooring recovery will in most cases not be practical, while running off wire is a final resort in case of release tool failure. Running off wire will complicate the reconnection process and potentially compromise the integrity of the mooring lines.

For a drilling rig, if the disconnection is required while the drill pipe is down-hole, there are three methods for disconnecting the riser from the BOP:

- Using Emergency drill pipe hang-off tool (EDPHOT)
  This method requires the drill pipe to be pulled out a distance equal the riser length plus two additional stands. Once this is done the hang-off tool will be installed and the drill pipe will be lowered so the tool is under the shear ram, the tool will be hung off on the pipe ram and disconnected from the drill pipe. The drill pipe will be pulled out and the shear ram will be closed. The riser will then be displaced for sea water, and the command to disconnect the Lower Marine Riser Package (LMRP) can be given.
  The disconnection time is dependent on the water depth (riser length), and the tripping speed. This method does not shear the drill pipe and requires the least amount of reconnection time (see Table 11-1).
- Hanging off the drill pipe

This method is used when there is no time for EDPHOT, and involves hanging the drill pipe off on the pipe ram in the BOP and shearing the pipe above the hang-off point. The cut pipe is then pulled to the surface and the blind shear ram is closed. This method is a lot faster than EDPHOT, but the resulting reconnection is more difficult with the possible need of milling and fishing.

- Shearing the drill pipe
  This final method simply cuts and drops the drill sting, and will be performed in extreme situations e.g. drive-off. The resulting reconnection time will depend on the level of milling and fishing, and in the worst case the well itself can sustain damage or be completely lost.

Table 11-1: Methods to disconnect riser. Based on philosophy written by Svein Larsen. Time estimated based on water depth of 300 meter.

Disconnection method	Disconnection time	Reconnection time
Emergency hang-off tool	3 hours	8 hours
Hanging off the drill pipe	90 seconds	24-48 hours
Shearing the drill pipe	60 seconds	Minimum 48 hours

Uncertainties in parameters must be considered with respect to probability and consequence. And realistic disconnection criteria for both riser and mooring lines must be set in advance to assist the offshore installation manager in decision making. Too strict criteria could lead to a late response or hesitation, resulting in situations where the use of more drastic measures need to be taken e.g. shearing the drill pipe. This will lead to longer reconnection time and greater monetary loss.

If release tools are used, the reconnection process must be quick and safe for personnel. Operations involving ROV and lifting will be necessary to “fish” for the on-bottom half of the mooring line and bring it up to a support vessel, and to perform necessary inspections. Reconnection on-deck can be tricky in the Arctic where temperatures, wind, lack of daylight etc. can affect the personnel’s ability to reliably re-assemble the connector. Therefore, spare connectors should be available to change the entire system. The connector will be connected at the interfaces by either a shackle or kenter shackle, that is easier to operate in challenging conditions. Used connectors will then be reconnected and reset according to standards, in a suitable environment. This will ensure that the mooring line is connected using a certified system. Reconnection time is also dependent on the weather conditions, and time can be lost due to waiting on weather or ice conditions.

11.1 Scenario: Drilling Operation in the Barents Sea

A scenario is presented that involves a drifting iceberg. The scenario will put a disconnection process in context, and communicate the time frame and order of events leading up to an evacuation off-site. An iceberg scenario was chosen because of its specific nature. Detailed monetary aspects are not considered.

11.1.1 Assumptions

The scenario takes place at 74N_34E (same place the Orcaflex model was imagined to be), at a water depth of 250 meter. Risk analysis has been performed and all mitigating measures taken to reduce the risk, this includes having a standby vessel on-site, helicopter on neighbouring rig, ability to disconnect and move off site. The alert levels presented in Table 4-1 are assumed to be valid. To save cost, ice management has been minimized, with the ability to disconnect seen as the best option to deal with drifting ice or hazardous features.

11.1.2 Accept Criteria

Prior to drilling operations, the company will have set several acceptance criteria for conducting safe operations. The decision to disconnect the riser and potentially the mooring lines must be made before the relevant acceptance criteria are exceeded to avoid dangerous situations and/or damage to equipment.

As an example, acceptance criteria should be set for (but not limited to):

- Rig motions
- Rig offset from centre (will influence the angle of the lower flex joint of the riser)
- Tension in riser system
- Tension in the highest loaded mooring line
- Alert level

Accept criteria will differ from type of operation (e.g. exploration vs. production), and the vessel type (e.g. ship shaped vs. column stabilized rig).

11.1.3 Scenario: Drifting Iceberg

The status of the rig and support is as follows:

- Drilling an exploration well.
- The rig is crewed by 152 people including ice advisor.
- A standby vessel is on-site.
- A neighbouring rig has a helicopter on standby 1 hour away.
- Strong current and wind from North to south. Other metocean parameters are favourable for drilling.
- Available sensors include radar and drone technology

According to Google Earth the target location is approximately 550km from Honningsvåg, Norway, assuming a ship sent from the main land with a speed of 10knots will use approximately 29 hours. Unless proper warning is issued, physical ice management will be limited to the standby vessel.

In this scenario, it is assumed that an iceberg has not been detected by satellites or aircraft. The iceberg is detected by an onboard radar at a distance of 35 km. At this point AT is estimated to be 24 hours (assuming 28 hour HT and 4-hour T-time), and the alert level is therefore set to blue. Once alert level blue is set, weather and ice forecasts are verified more frequently, risk assessment based on ice intelligence is initiated and ST (assuming 3 hours using EDPHOT) is established. The status of current operations and upcoming operations are verified and assessed with respect to possible changes in ST. The trajectory of the iceberg is calculated, using parameters such as wind, current and waves. The estimated trajectory will only be as good as input data.

Available sensors indicate that the standby vessel is not sufficiently strong to tow the iceberg away, and the vessel is therefore used to assist in monitoring the situation. A potential collision will exceed accept criteria for mooring tension and the riser.

Once AT reaches the 12-hour mark, the decision to go from blue to yellow alert level will escalate the mitigating measures taken by securing the well and riser. MOT is established based on a disconnection tool. The well and the drill pipe will be secured by using EDPHOT. The final order to disconnect the LMRP will be postponed, pending possible de-escalation of the situation. Yellow alert will increase the rig preparedness and the inclusion of second and third line emergency response organisations. These organizations will map all available resources in the area (vessels and aircraft) that can be called upon if the situation worsen, and assist the offshore installation manager in any way possible.

The probabilities involved in calculation of HT should influence the decision to change alert levels. For example, the decision to go from green to blue does not require a situation with a high probability because the act does not influence the operation of the rig. But to go from blue to yellow should require a more defined situation and higher probability, because this will affect the operation of the rig. As an example, an iceberg is on a collision course with an estimated probability of 50% of entering zone 1, Alert level Yellow will be set[2]. The consideration of the probabilities involved are done to avoid unnecessary down time. If the iceberg continues on course, the decision to disconnect and retrieve the LMRP is made prior to setting alert level red. Prior to alert level red, considerations regarding evacuation of personnel must be made. Due to good flying conditions, the neighbouring helicopter have been brought over, and is ready to start evacuation.

Once Alert level red is in effect, departure plans to a predefined site is made and confirmation on the status of well and riser is made. The decision to start evacuation of non-essential personnel is given once alert level red is in effect. This decision is taken based on the priority of the offshore installation manager, namely life and health[3]. To mitigate risk during the disconnection of the mooring lines, the drill floor will be secured with no loose objects. By using a release tool, the actual disconnection can be accomplished in minutes. With the leeward mooring lines disconnected first, at acceptable tension. The rig will then be able to move up against the wind to lessen the tension, or the wire ropes can be paid out. The order to release mooring lines are made based on the time required to move to the pre-defined site.

---

[2] Suggested by Ove Haugen
[3] Suggested by Ove Haugen

12. Summary and Conclusion

12.1 Mechanical Aspect of Disconnecting a Mooring Line

When considering emergency release of catenary mooring lines, several aspects must be considered. The Orcaflex analysis have yielded results concerning; acceleration of release tool, hull contact from recoiling wire rope and line clashing.

Several Orcaflex simulations have been run in time domain, with disconnection at various release points from 150 meters along the wire rope to 350 meters along the wire rope, with 50 meter increments. The cases studied include:

- “Base case 2”: Release of a steel wire rope.
- “Extreme case”: Changes the base mooring line configuration by replacing the synthetic fibre rope with steel wire rope. The added weight increases the tension.
- “2m chain”, “5m chain” and “10m chain”: are cases that include chain segments between the wire rope and release tool. The chain segments act as damping and is referred to as *chain damping.*
- “Offset case”: The rig is offset from the centre with the resulting release at 50 meters along the wire rope. Simulations also include the respective chain damping lengths.

The bending stress in a single wire in the wire rope was calculated analytically using minimum bending radius from the Orcaflex analysis, the calculation suggests that during disconnection the smallest banding radius will induce bending stress that is less than the yield stress.

If release occurs when the wire rope is taut, the resulting acceleration will induce G-forces that could influence components used in the release tool, such as electronic components or mechanical moving parts. This issue must be addressed in the design of a release tool.

The Orcaflex analysis proved that hydrodynamic drag alone, is enough to prevent the wire rope from breaking the water surface. This suggests that personnel will not be in any danger from the released wire rope. It is assumed that prior to releasing the mooring lines, the deck of the rig has been secured, and the risk of falling objects due to disconnection has been mitigated. In conclusion, the disconnection process is safe for personnel.

12.1.1 Hull Contact from Recoiling Wire Rope

It is evident from the analysis that hull contact from the upper parts of a released mooring line will in the cases; Base case 2 and the chain damping cases be relatively soft. Only in the event of the Extreme case and the Offset case did significant hull contact occur, approximately 220 kN and 55 kN, respectively. The potential damage to the hull itself is assumed to be negligible in these cases, making damage to the wire a primary concern with respect to reconnecting. Disconnecting while in the Extreme or Offset case should therefore be avoided. These results depend on the assumed value for *normal stiffness* used in Orcaflex. The assumption about normal stiffness can significantly change the values presented for hull contact in Chapter 9.3, and should therefore be interpreted as qualitative results.

Wire rope integrity must be ensured before reconnection. To avoid hull contact and thus potential damage to the wire rope, a release at any point from 150 meters to 350 meters is doable for Base case 2 and the chain damping cases, if only hull contact is considered.

By studying mooring line failure reports from 1990 – 2014, one incident occurred where wire failure damaged a thruster. Considerations should be made to ensure that this will not happen during disconnect, and that any loose wires are not sucked into the thrusts. It is assumed that this is most relevant for the Offset case, and release should therefore be avoided while offset.

12.1.2 Actions at Fairlead and Chain Damping

Actions at the fairlead remains uncertain due to the boundary condition in the Orcaflex analysis, with detailed engineering required to properly conclude. By paying out the wire, the tension will decrease and, the resulting recoil drops drastically. Recommended disconnection point will therefore be close to 300 meters along the line, to limit the actions at the fairlead. The disconnection point will be limited by the tools proximity to the seabed. The design criteria of the release tool and the mooring wire should specify if a release can occur on or close to the seabed.

Significant damping was achieved by using chain segments between the wire rope and the release tool. But as a side effect, chaotic displacements, unpredictable behaviour and loads ensued. In conclusion; the level of damping desired must be identified and the corresponding chain length selected. Too much chain can lead to unforeseeable effects in the wire rope, in worst case this could influence the reconnection process by damaging the wire rope or the release tool.

12.1.3 Line Clashing

Line clashing is Orcaflex terminology for when Orcaflex registers contact made between multiple lines, or contact a single line makes with itself.

Line clash will occur between the wire rope and chain segments in all cases, but not at every release point. The most frequent contact is when the chain segment contacts itself. This is because of the chaotic behaviour of the chain segments once released.

A wire rope without chain damping does not clash with itself, probably due to the bending stiffness of the wire rope, except for in the Extreme case where energy stored in the wire rope is enough to cause it to clash with itself. The extent of damage line clashing can cause is difficult to quantify, because of uncertainty in the *clash stiffness* parameter that Orcaflex requires. Contact with the release tool was not explicitly proven in the simulations, but should not be ruled out and steps should be taken to eliminate such clashes. Of particular concern are clashes to transponder heads and/or other softer components, passive protection must be implemented in the design of the release tool. The reconnection process should include a plan of how to deal with studlink chains where the studs have been “knocked out”.

12.1.4 Recommendations

Assuming enough time is available for a controlled release, the mooring line tension should be lessened by paying out to approximately 300 meters as seen in the simulations. At this release point the tension will be low, no significant curling and entanglement will form on the wire rope, no hull contact and no line clashes are expected. The simulations performed for this thesis assumed a release tool based on Ejecto’s specifications, and yielded clear indications that chain damping of more the 2 meters will cause unwanted effects such as line clashing and shock loads.

In practice, the lessening of tension can also be accomplished on the windward side by moving the rig against the wind. This should be done manually, to mitigate risk of potential drive-off.

12.2 Global Aspect

A successful disconnection and evacuation off-site for a drilling unit will require accurate predictions of Hazard Time (HT). This parameter will in large part influence the Secure Time (ST) parameter by controlling the method used in disconnection of the riser. The Move Off Time (MOT) parameter accounts for disconnection method of the mooring line and the time required to move to safe location.

Accurate predictions will not always be available in the Barents Sea due to local weather systems that are difficult to forecast, such as polar lows. The uncertainties in the forecasts will influence mathematical models, for example iceberg drift models and polar low tracking. To make the best possible decision, criteria for safe operation must be established so that operations can be terminated safely in time. Disconnection criteria for drilling/production units must be set to help decision makers, and not promote hesitation or late response.

Difference between exploration and production rigs are primarily environmental, seabed infrastructure and number of risers. During drilling operation where the reservoir has not yet been entered the consequences will be mostly related to material and monetary loss. For production units, large environmental pollution can occur, and increased time is needed to properly shut down and secure risers. The use of ship shaped production vessels with disconnectable turrets will probably be more feasible than column stabilized units with individual risers in ice infested waters.

Figure 12-1 displays a rough overview of the order of events leading up to disconnection of the mooring lines for a drilling rig. The corresponding colour alert levels are also displayed.

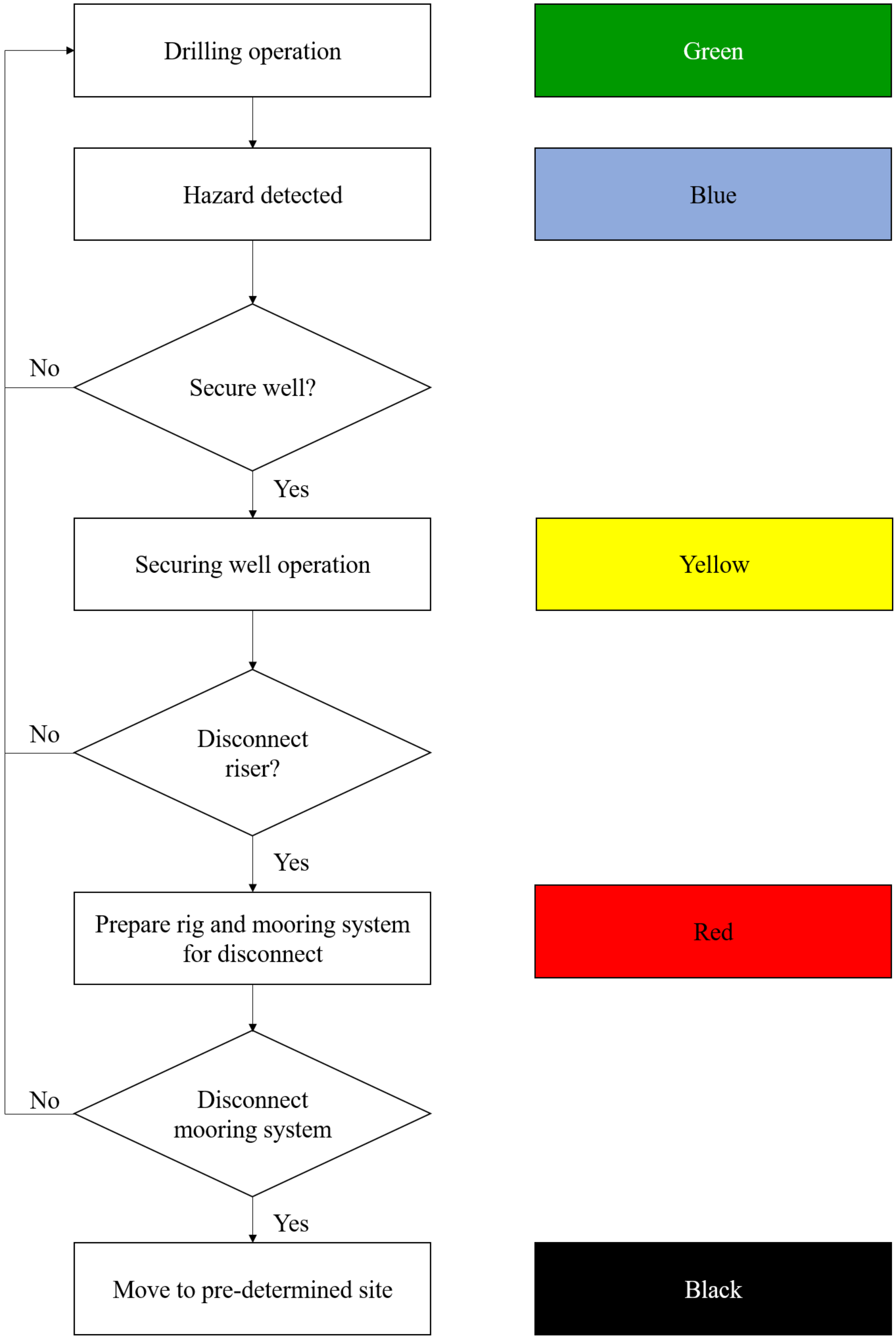


Figure 12-1: General disconnection procedure for drilling unit. If decision "no" is selected then it is assumed drilling operation will be resumed as soon as possible.

12.2.1 Limitations

Common for all release tool concepts presented in this thesis, is the use of an acoustic signal to activate the hydraulic process that leads to disconnection. In case of primary signal failure, the concepts will have to rely on the use of secondary signals to achieve disconnection. No mechanical backup is available for the MultiDog, RigLOK or RAR.

The exception is the newly introduced RAR +, which can use a preinstalled trigger sleeve at the fairlead, to mechanically separate the release tool. However, this trigger sleeve requires the mooring line to be winched in so the tool connects, or by having the trigger sleeve pulled by a support vessel along the wire rope. The feasibility of such a system in the Arctic must be carefully studied with respect to the time required for vessels to accomplish this task. In arctic waters support vessels may be away on ice management duties, and ice conditions could potentially complicate winching.

13. Recommendations for Future Work

During preparation of this thesis, several simplifications had to be made. To fully understand the process more work is needed.

- Detailed study of the fairlead

Further work on what to expected at the fairlead during disconnection will be of significant value, with respect to reconnecting the mooring line. This work should include wire health and effects on the fairlead itself. Is current design good enough?

- Optimized rig model and mooring lines

By optimizing the rig model, vessel response during disconnection can be studied. This should be done together with a mooring configuration that is designed for a given site.

- Torsional effects on steel wire rope

The effect of torsion on the wire rope should be studied with respect to wire health and reconnection.

- Reconnection operation

Detailed study of reconnection operations. Especially considering problems related to synthetic fibre ropes.

- Cost-benefit analysis of complete disconnection vs. ice management

Due to long distances and lack of infrastructure a cost-benefit analysis should be performed to see if disconnection ability can ensure safe operations with reduced use of ice management.

14. References

[1] Kwan, T., Bond, J., Yu, H. and Morandi, A., "Arctic Mooring Systems - The Past, Present, and Future," Offshore Technology Conference, Houston, 2014.

[2] Eik, K. J., Ice Management in Arctic Offshore Operations and Field Developments, Trondheim: PhD thesis NTNU, 2010.

[3] "Wikipedia.org," [Online]. Available: https://no.wikipedia.org/wiki/Barentshavet#/media/File:Barents_Sea_map.png [Accessed 9 January 2017].

[4] Norwegian Petroleum Directorate, 2 July 2013. [Online]. Available: http://www.npd.no/en/Publications/Resource-Reports/2013/Chapter-5/ [Accessed 24 April 2017].

[5] "Technology challenges for year-round oil and gas production at 74°N in the Barents Sea," DNV GL, Stavanger, 2015.

[6] Gudmestad, O. T., "Vessel Winterization for Cold Climate Operations," University of Stavanger, Stavanger, 2010.

[7] DNV-OS-A201: Winterization for Cold Climate Operations (Tentative), Høvik: Det Norsk Veritas AS, 2013.

[8] European Space Agency, [Online]. Available: http://www.esa.int/Our_Activities/Navigation/Galileo/What_is_Galileo [Accessed 20 May 2017].

[9] Vryhof Anchors, "Anchor Manual," [Online]. Available: http://insights.vryhof.com/download-the-vryhof-manual [Accessed 11 June 2017].

[10] Herbich, J. B. and Ansari, K. A., Developments in Offshore Engineering, Texas: Gulf Publishing Company, 1999.

[11] DNV-OS-E302: Offshore mooring chain, Høvik: Det Norske Veritas , 2008.

[12] Evans, J. J. and Ridge, I. M. L., "Chapter 7," in *Rope And Rope-like Structures*, WITpress, 2005, pp. 133-169.

[13] Ashley Sling INC. , [Online]. Available: http://www.ashleysling.com/wire-rope-3.htm [Accessed 13 April 2017].

[14] K. Feyer, Wire Ropes Tension, Endurance, Reliability Second Edition, Berlin: Springer-Verlag , 2015.

[15] Bridon, “Oil & Gas Catalogue,” [Online]. Available: http://www.bridon.com/x/downloads/oilandgas/Oil%20and%20Gas%20brochure.pdf [Accessed 21 April 2017].

[16] The Crosby Group , “Wire rope end teminations user's manual,” [Online]. Available: https://www.thecrosbygroup.com/wp-content/uploads/2014/01/9992320_Termination_Manual_With_Cover_LoRes.pdf [Accessed 14 May 2017].

[17] Erling Haug AS, [Online]. Available: http://www.haug.no/no/produkter/tilbehr-staltauwire/socket-og-wirepre/socket-cr-so4-gn__n64874
[Accessed 15 May 2017].

[18] NS - ISO: 4309:2010 Cranes Wire ropes Care and maintenance, inspection and discard, Standard Norge, 2010.

[19] Verreet, R. and Ridge, I., “Wire Rope Forensics,” [Online]. Available: http://www.ropetechnology.com/bro_engl/wire_rope_forensics_a4.pdf
[Accessed 11 May 2017].

[20] Verreet, R., “Steel Wire Ropes for Crances Problems and Solutions,” [Online]. Available:
http://www.ropetechnology.com/bro_engl/casar_steel_wire_ropes_letter.pdf
[Accessed 21 May 2017].

[21] Viking Moorings, “Marine Equipment Handbook,” 2010. [Online]. Available: http://docslide.net/documents/viking-mooring-handbook-2010.html
[Accessed 11 June 2017].

[22] Correspondence with Balltec.

[23] Balltec Engineered Solutions, [Online]. Available: http://www.balltec.com/index.php?option=com_mtree&task=att_download&link_id=12&cf_id=44
[Accessed 12 April 2017].

[24] InterOcean Systems, LLC, [Online]. Available: http://www.interoceansystems.com/rel_rar.htm
[Accessed 1 May 2017].

[25] InterOcean Systems, LLC , “Rig Anchor Release A remote selective, quick disconnect of mooring lines for drilling rigs.,” [Online]. Available: http://www.delmarus.com/uploads/RAR_Brochure.r3.pdf
[Accessed 13 June 2017].

[26] Delmar, "RAR Plus Next Generation Rig Anchor Release," [Online]. Available: http://www.delmarus.com/uploads/RARPlusBrochure.pdf
[Accessed 28 May 2017].

[27] Correspondence with InterOcean System.

[28] Barets Sea Exploration Collaboration, "Physical environment in the South-Eastern Barents Sea," 2016. [Online]. Available: https://www.norskoljeoggass.no/Global/BaSEC%20rapporter/Introduction%20for%20authorities%20-%20MetOcean%20and%20Ice_EN.pdf
[Accessed 25 April 2017].

[29] NORSOK N-003 Actions and Effects, Standard online AS, 2016.

[30] Correspondence with Magnar Reistad at Norwegian Meteorological Institute.

[31] "Barentswatch," 11 July 2014. [Online]. Available: https://www.barentswatch.no/en/articles/polar-lows-explained/
[Accessed 11 January 2017].

[32] "Wikipedia.org," [Online]. Available: https://commons.wikimedia.org/wiki/File:Polar_low.jpg
[Accessed 11 January 2017].

[33] Private correspondence with Gunnar Noer, State meteorologist and Developer for polar meteorology.

[34] Syversen, T., Dinessen, F., Paaske, B. J., Ekeberg, O-C., Hughes, N. and Kråkenes, T., "Kartlegging av is- og snøforekomst i barentshavet, inkludert risikovurderinger relatert til petroleumsaktivitet," SINTEF, Trondheim, 2015.

[35] Petroleum Safety Authority Norway, [Online]. Available: http://www.psa.no/video/fog-polar-lows-and-forecasting-in-the-barents-sea-article11719-1198.html
[Accessed 11 January 2017].

[36] Petroleum Safety Authority , [Online]. Available: http://www.psa.no/facts-the-far-north/weather-and-forecasting-article10446-1143.html
[Accessed 28 April 2017].

[37] National Snow & Data Center, [Online]. Available: https://nsidc.org/cryosphere/seaice/data/terminology.html
[Accessed 10 May 2017].

[38] Abramov, V., Atlas of Arctic Icebergs The greenland, Barents, Kara, Laptev, East-Siberian and Chukci Seas and the Arctic Basin, Backbone Publishing Company , 1996.

[39] AMEC Earth and Environmental, McKenna, R. F., "Grand Banks Iceberg Managment,". [Online]. Available:
http://nparc.cisti-icist.nrc-cnrc.gc.ca/eng/view/fulltext/?id=754dda8b-6c1c-4712-bdc8-a8844324ccaa
[Accessed 13 June 2017]

[40] ISO/TC 67/SC 8/WG 4 Ice Management IOGP Draft ISO/CD 35104, Petroleum and natural gas industries -- Arctic operations -- Ice management, 2016.

[41] Shell Offshore inc. , “Driling Ice Management Plan Chukchi Sea, Alaska,” [Online]. Available:
https://www.boem.gov/Appendix-G-Drilling-Ice-Management-Plan/
[Accessed 1 June 2017].

[42] Orcina Ltd., “Theory/Coordinate Systems,” [Online]. Available:
https://www.orcina.com/SoftwareProducts/OrcaFlex/Documentation/Help/
[Accessed 25 April 2017].

[43] Orcina Ltd., “Theory/Static Aalysis/Static Analysis,” [Online]. Available:
https://www.orcina.com/SoftwareProducts/OrcaFlex/Documentation/Help/
[Accessed 25 April 2017].

[44] Orcina Ltd., “Theory/Dynamic Analysis/Time Domain Dynamic Analysis,” [Online]. Available
https://www.orcina.com/SoftwareProducts/OrcaFlex/Documentation/Help/
[Accessed 25 April 2017].

[45] Orcina Ltd., “Theory/Dynamic Analysis/Time Domain Solution,” [Online]. Available:
https://www.orcina.com/SoftwareProducts/OrcaFlex/Documentation/Help/
[Accessed 25 April 2017].

[46] Orcina Ltd., “Theory/Dynamic Analysis/Dynamic Analysis: Time Domain Solution,” [Online]. Available:
https://www.orcina.com/SoftwareProducts/OrcaFlex/Documentation/Help/
[Accessed 2017 April 2017].

[47] Chung, J. and Hulbert, G. M., “A Time Integration Algorithm for Structural Dynamics With Improved Numerical Dissipation: The Generalized-α method,” *Journal of Applied Mechanics*, pp. 371-375, 1 June 1993.

[48] Corresponence with Orcina Software Support.

[49] Orcina Ltd., “Theory/Line Theory/Line Theory: Calculation Stages,” [Online]. Available:
https://www.orcina.com/SoftwareProducts/OrcaFlex/Documentation/Help/
[Accessed 25 april 2017].

[50] Orcina Ltd., “Theory/Line Theory/Line Theory: Calculation stage 1 Tension Forces,” [Online]. Available:
https://www.orcina.com/SoftwareProducts/OrcaFlex/Documentation/Help/
[Accessed 25 April 2017].

[51] Orcina Ltd., “Theory/Line Theory/Line Theory: Calculation stage 2 Bend Moments,” [Online]. Available:
https://www.orcina.com/SoftwareProducts/OrcaFlex/Documentation/Help/
[Accessed 25 April 2017].

[52] Orcina Ltd., “Theory/Line Theory/Line Theory: Calculation Stage 3 Shear Forces,” [Online]. Available:
https://www.orcina.com/SoftwareProducts/OrcaFlex/Documentation/Help/
[Accessed 25 April 2017].

[53] Orcina Ltd., “Theory/Line Theory/Line Theory: Calculation Stage 4 Torsion Moments,” [Online]. Available:
https://www.orcina.com/SoftwareProducts/OrcaFlex/Documentation/Help/
[Accessed 25 April 2017].

[54] Orcina Ltd., “Theory/Line Theory/Line Theory: Hydrodynamic and Aerodynamic Loads,” [Online]. Available:
https://www.orcina.com/SoftwareProducts/OrcaFlex/Documentation/Help/
[Accessed 25 April 2017].

[55] Orcina Ltd., “Modelling, Data and Results/Lines/Chain/Drag,” [Online]. Available:
https://www.orcina.com/SoftwareProducts/OrcaFlex/Documentation/Help/
[Accessed 25 April 2017].

[56] Orcina Ltd., “Theory/Line Theory/Treatment of Compression,” [Online]. Available:
https://www.orcina.com/SoftwareProducts/OrcaFlex/Documentation/Help/
[Accessed 25 April 2017].

[57] COSL, “RIGS,” [Online]. Available:
http://www.cosl.no/coslpioneer
[Accessed 27 February 2017].

[58] Orcina Ltd., “Modelling, Data and Results/Vessels/Vessel types/RAOs,” [Online]. Available:
https://www.orcina.com/SoftwareProducts/OrcaFlex/Documentation/Help/
[Accessed 10 May 2017].

[59] Browne, V. C., “Assessment of Low-Frequency Roll Motions on the Semisubmersible Drilling Rig COSL Pioneer,” NTNU Master's Thesis, Trondheim, 2013.

[60] Orcina Ltd., “Theory/Shapes/Shapes,” [Online]. Available:
https://www.orcina.com/SoftwareProducts/OrcaFlex/Documentation/Help/
[Accessed 1 May 2017].

[61] Orcina Ltd. , “Theory/Line Theory/Clashing,” [Online]. Available: https://www.orcina.com/SoftwareProducts/OrcaFlex/Documentation/Help/ [Accessed 9 may 2017].

[62] Kvitrud, A., “Anchor line failures- Norwegian Continetal Shelf - 2010-2014,” The Norwegian Petroleum Safety Authority, Stavanger, 2014.

[63] Correspondence with Wirelock Technical, at Millfield Wirelock.

15. List of Figures

16. List of Tables

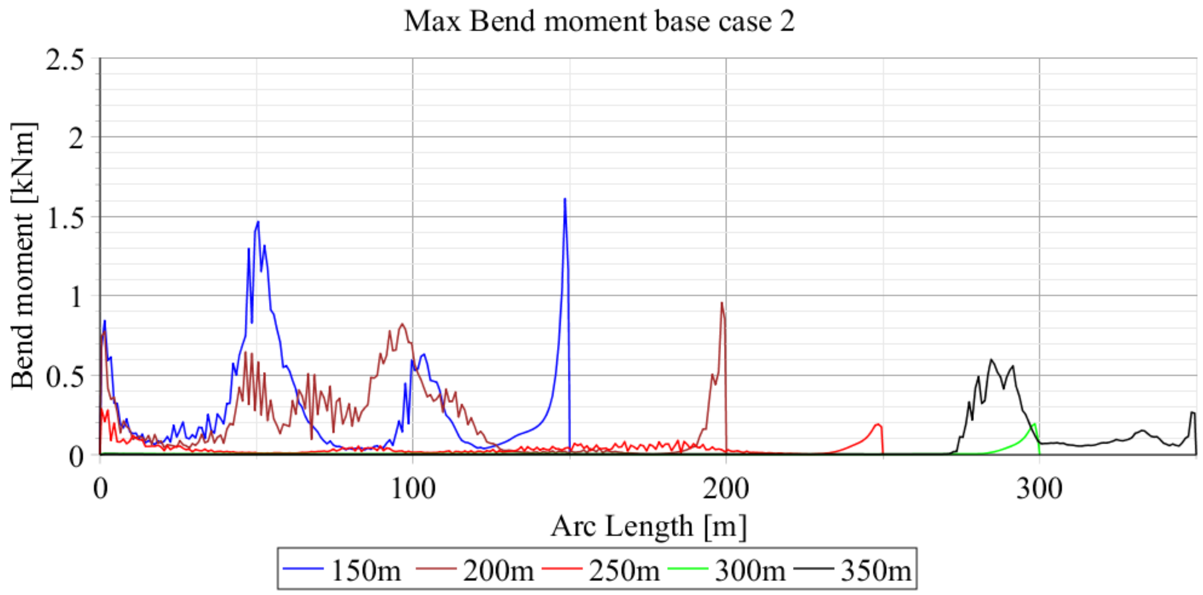
17. List of Appendices

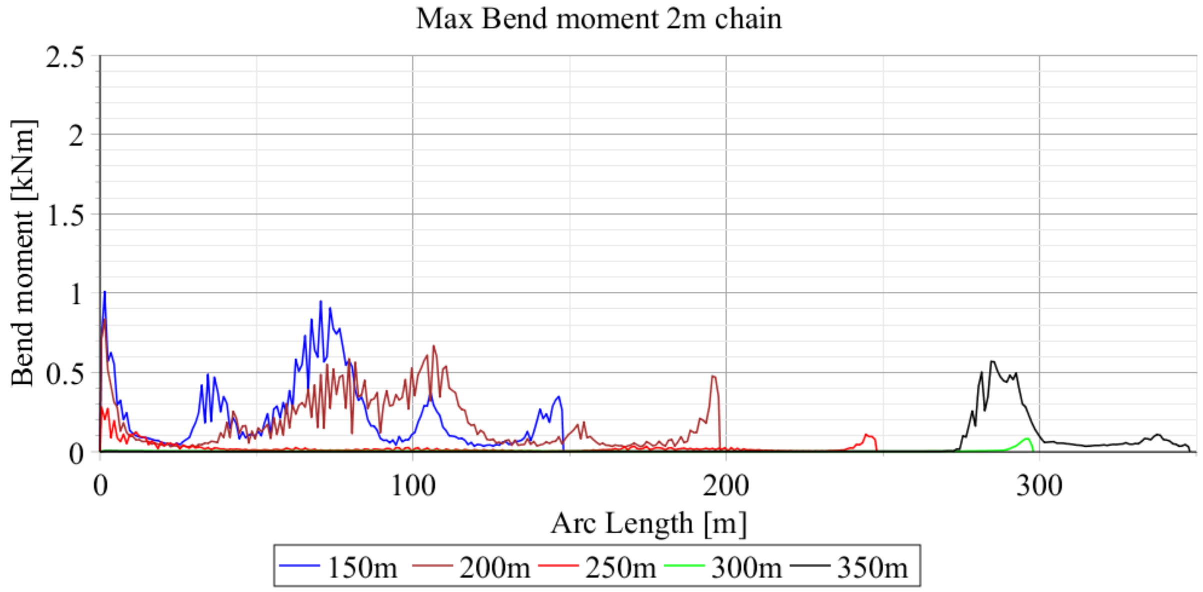
Appendix	Description	Format	Pages	Comment
A	Bending moment graphs	N/A	1-2	
B	Velocity graphs of the release tool	N/A	3-4	
C	Description of electronic attachment	N/A	5	
D	Orcaflex simulations	.SIM	N/A	See 1. below
E	Mesh properties comparison	.xlsx	N/A	Comparison of RAOs, added mass, damping and hydro static stiffness r
F	WADAM output	N/A	N/A	

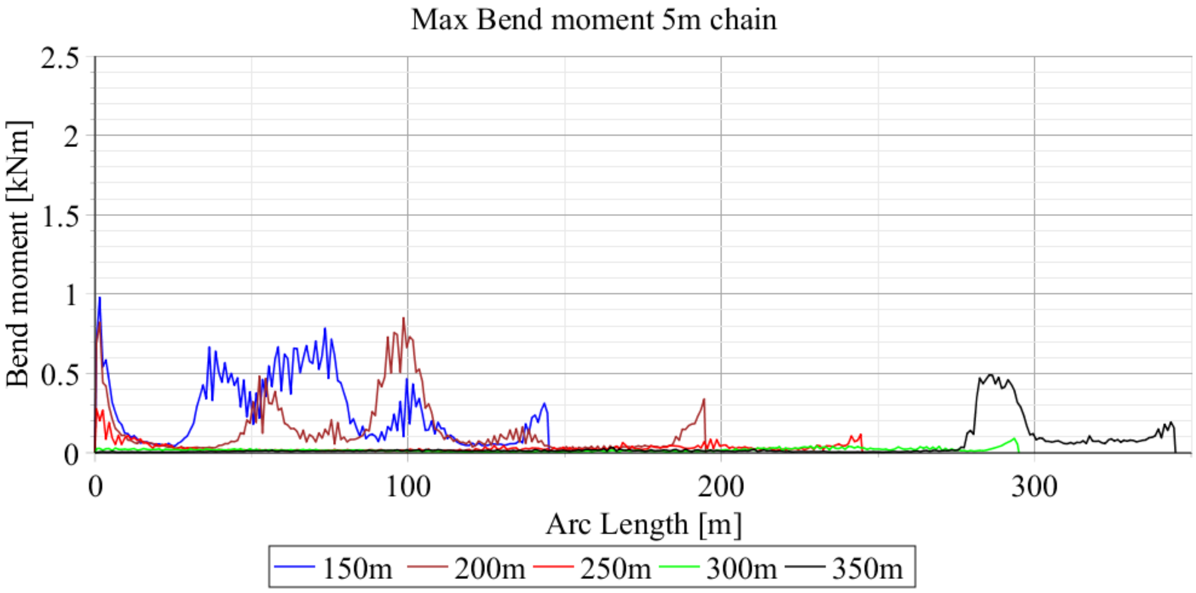
1. Requires an Orcaflex license, or alternatively a free demo that allows viewing of .SIM files is available at: https://www.orcina.com/SoftwareProducts/OrcaFlex/Demo/

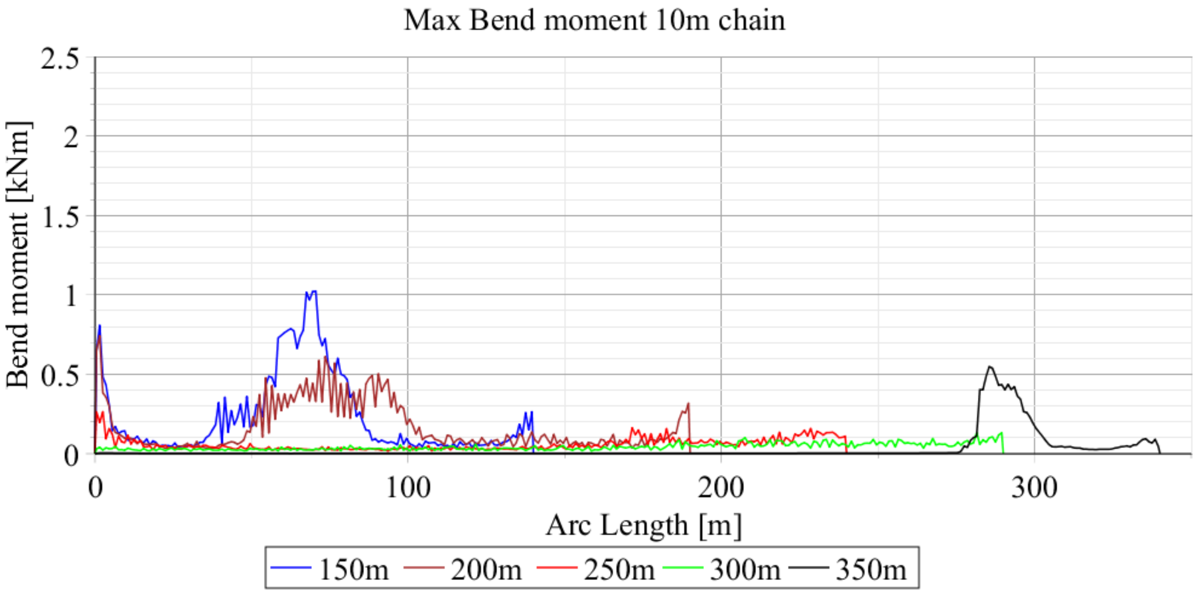
Appendix A

Bending moment along arc length



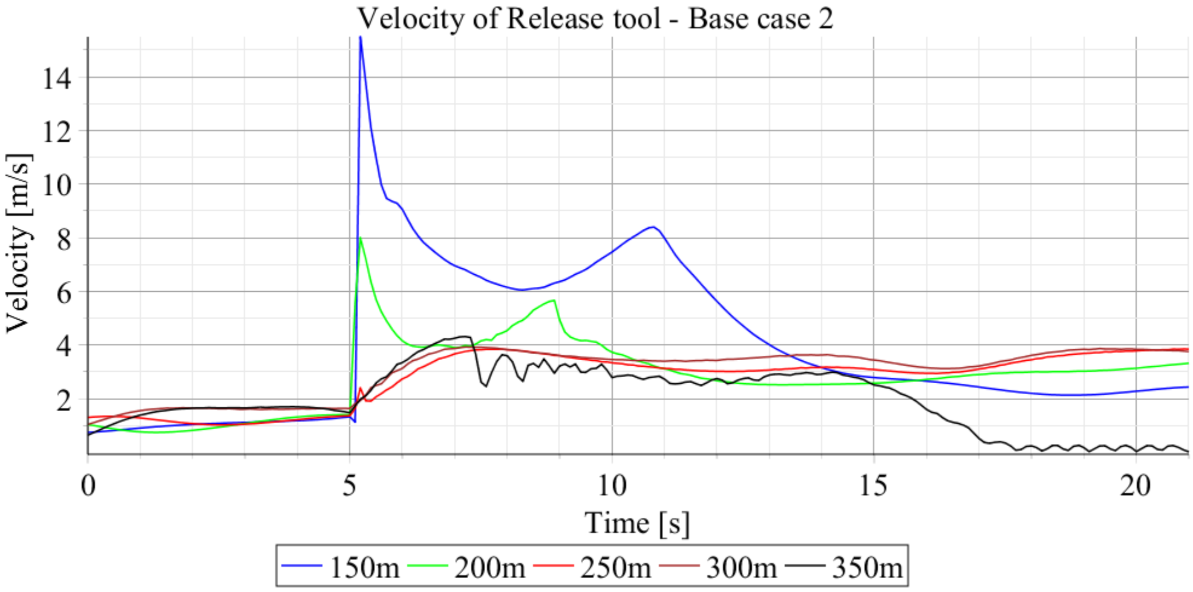


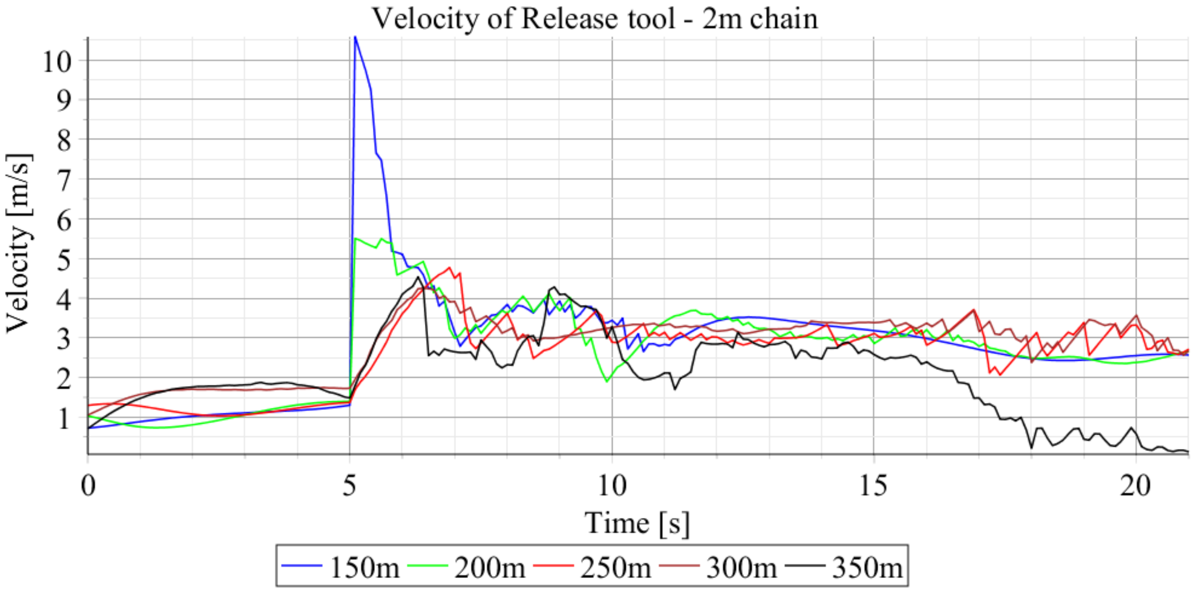

Max Bend moment 5m chain
Bend moment [kNm]
2.5
2
1.5
1
0.5
0
0
100
200
300
Arc Length [m]
150m
200m
250m
300m
350m

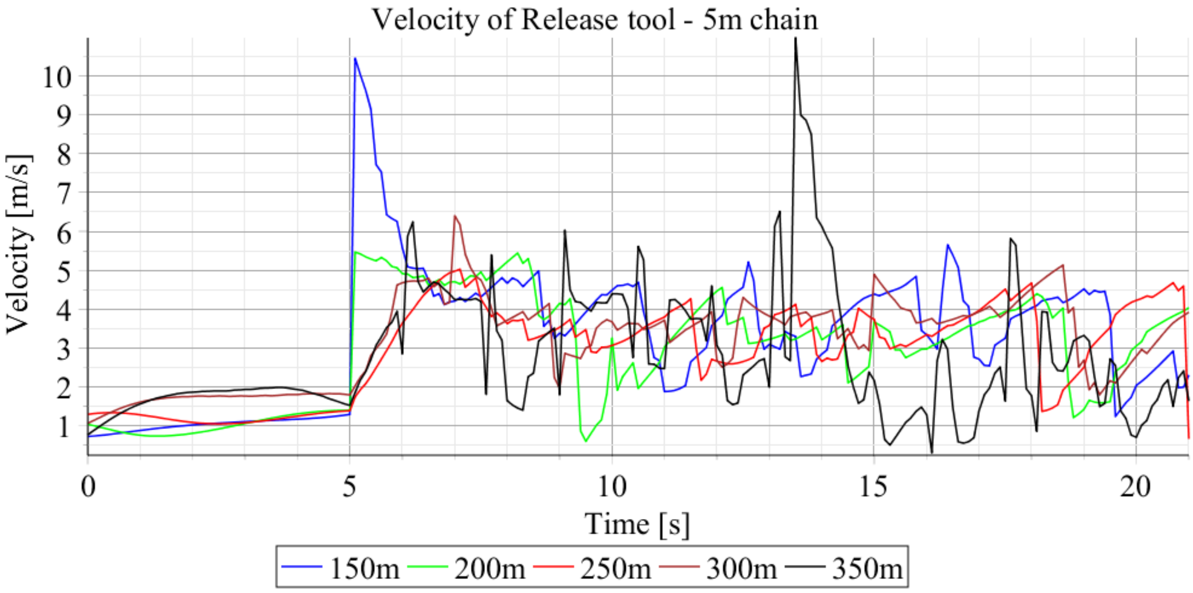

Max Bend moment 10m chain
Bend moment [kNm]
2.5
2
1.5
1
0.5
0
0
100
200
300
Arc Length [m]
150m
200m
250m
300m
350m

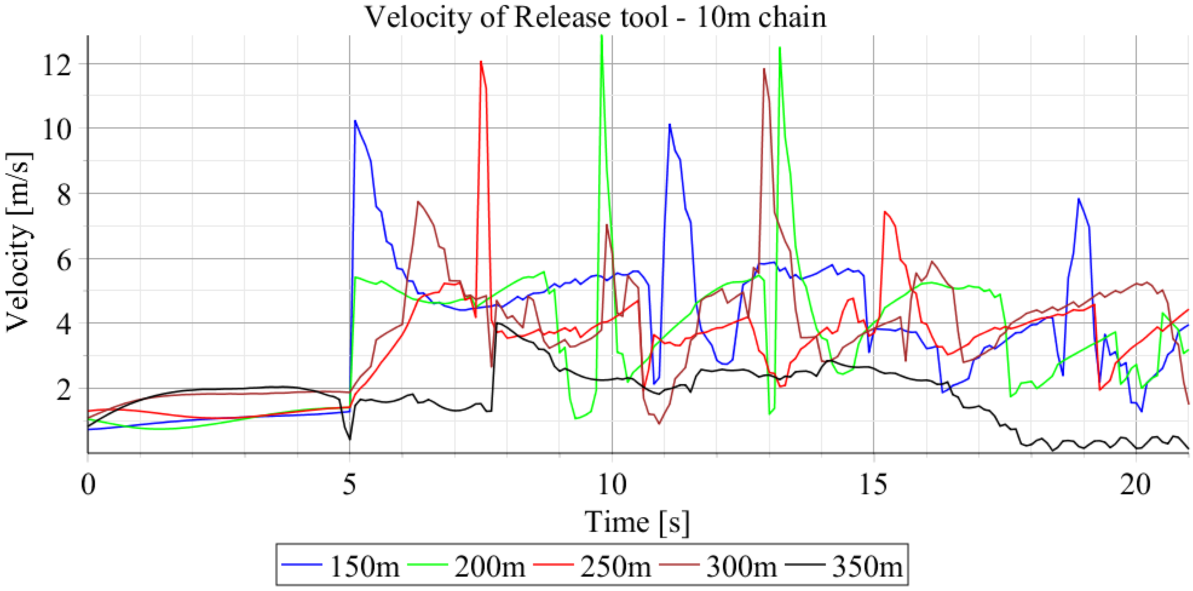
Appendix B

Release tool velocities






Velocity of Release tool - 5m chain
Velocity [m/s]
1
2
3
4
5
6
7
8
9
10
0
5
10
15
20
Time [s]
150m
200m
250m
300m
350m


Velocity of Release tool - 10m chain
Velocity [m/s]
2
4
6
8
10
12
0
5
10
15
20
Time [s]
150m
200m
250m
300m
350m

Appendix C

Description of electronic attachment

The electronic attachment includes the following:

- Orcaflex simulations as described in the simulation map (Figure 7-6).
- Excel sheet of comparison of added mass, potential damping and hydrostatic stiffness made between the three different meshes made in GeniE.
- Excel sheet of comparison of RAOs made between the different meshes in GeniE. Frequency range is the same for the COSL RAOs provided by Svein Larsen.
- WADAM results from HydroD for all three meshes.