NTNU
Norwegian University of
Science and Technology

A Discussion of Technical Challenges and Operational Limits for Towing Operations

Peter Wilhelm Stange Berg

Marine Technology
Submission date: June 2017
Supervisor: Kjell Larsen, IMT

Norwegian University of Science and Technology
Department of Marine Technology

NTNU Trondheim
Norges teknisk-naturvitenskapelige universitet
Institutt for marin teknikk

MASTER THESIS SPRING 2017
for

Stud. tech. Peter Wilhelm Stange Berg

Towing Operations – A Discussion of Technical Challenges and Operational Limits

Taueoperasjoner – en kvalitativ og kvantitativ vurdering av operasjonsgrenser og viktige tekniske aspekter

Background

Towing operations are the most common marine operation. It is defined as a transport of a self-floating object by one or several towing tugs. It includes towing of self-floating objects and large structures, objects on transportation barges, emergency towing (e.g. icebergs), towing of long, slender objects (pipes and bundles). These operations are associated with many incidents, mainly due to towline failure caused by lack of planning and risk understanding.

Important challenges for typical towing operations comprise
- Tow global behavior and load effects in towing lines (motions and environmental loads)
- Requirements to tugs and towing equipment
- Planning of operation in terms of limiting weather conditions, weather routing and safe havens.

Scope of Work

1) Review relevant literature and rules and regulations.
- Describe state-of-art concepts for towing. One selected towing operation shall be described in detail.
- Give an overview of the most important requirements given in present rules and regulations.
2) Towing is often planned as a weather restricted operation.
- Describe the concept of "alpha-factor" and use of safe havens in order to account for weather uncertainty for towing operations.
- A method to estimate operability and weather windows for weather restricted towing shall also be described.
3) Improve the simplified model of calculation of towline tension developed in the project work during autumn 2016. The model shall be used to estimate the characteristic tension response in the towing line and to establish operational limits for towing of a selected concept, e.g. towing of a drilling semisubmersible. A parameter variation of selected design parameters of vessel and towing equipment shall be performed. The parameters to be studied shall be discussed with the supervisor.
4) Operability shall be calculated based on given data for North Sea. Findings and results from task 2 and 3) shall be used. Weather data will be provided by the supervisor.
5) Conclusions and recommendations for further work

General information

The work shall be a continuation of the project work report "Safe Towing Operations – Important Technical Aspects and Challenges".

The work scope may change or prove to be larger than initially anticipated. Subject to approval from the supervisor, topics may be changed or reduced in extent.

In the project the candidate shall present his personal contribution to the resolution of problems within the scope of work.

Theories and conclusions should be based on mathematical derivations and/or logic reasoning identifying the various steps in the deduction.
The candidates should utilise the existing possibilities for obtaining relevant literature.

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

The report shall be written in English and edited as a research report including literature survey, description of relevant mathematical models together with numerical simulation results, discussion, conclusions and proposal for further work. List of symbols and acronyms, references and (optional) appendices shall also be included. All figures, tables and equations shall be numerated.

The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

The report shall be delivered electronically and shall also be submitted in two paper copies:
- Signed by the candidate
- The text defining the scope included

Ownership
NTNU has according to the present rules the ownership of the project results. Any use of the project results has to be approved by NTNU (or external partner when this applies). The department has the right to use the results as if the work was carried out by a NTNU employee, if nothing else has been agreed in advance.

Thesis supervisor:
Prof. II Kjell Larsen, NTNU/Statoil

Deadline: June 11, 2017
Trondheim, June, 2017

Kjell Larsen (date and signature): 08.06.2017

Peter Berg (date and signature): 08.06.2017

Preface

This master's thesis has been written by the author during the spring semester of 2017 of the 5^{th} and final year of a Master's Degree in Marine Technology at the Department of Marine Technology, Norwegian University of Science and Technology (NTNU). The thesis is about the topic *marine towing operations* and the work has been carried out at NTNU with a workload corresponding to 30 ECTS.

The thesis also builds on the work from the project thesis written in the fall semester of 2016 by the author.

Trondheim, 2017-06-09

Peter Wilhelm Stange Berg

Acknowledgment

I would like to express my sincere gratitude to Professor II Kjell Larsen, my supervisor during the semester. Weekly or more frequent meetings have been of great help making sure I have stayed on track throughout the semester. His deep knowledge regarding marine operations has been an eye-opener on this vast and very interesting field of marine engineering.

In addition I would like to thank Lars Bjerke and Trym Gade Lintoft at Ran Offshore for meeting with me at their offices discussing the challenges and procedures related to long distance tow operations.

P.W.S.B.

Summary

This thesis is written on the subject of marine towing operations. The purpose of the thesis is to identify and discuss technical challenges related to towing operations with respect to safety and operability. In addition, a simplified model used to estimate towline tension is created to establish operational limits when towing a semi-submersible drilling rig in the North Sea.

Towing operations are the most common marine operation today. They range from transportation of self-floating objects and large structures to subsurface tows of long pipes and bundles. The frequency and diversity of these operations brings several challenges as no operation is alike i.e. they are non-routine. As such, towing operations are accident prone. Statistics show that the transportation phase of marine operations make up for 26% of the registered accidents.

Almost all marine operations, towing operations included, are at the mercy of the weather. Uncertainties in weather forecast are accounted for via the α-factor which is dependent on location, planned operation time and operational limit. A method to estimate operability has been described and hindcast weather data is used to determine the operability at Heidrun in the North Sea. The results show that time needed to wait on weather is considerably lower for the summer months compared to the winter months.

Findings indicate that dynamics are important for the towline tension with large incoming waves, and should be well understood to avoid overload and failure. A base case has been developed and the operational limit, given by significant wave height, determined to be $OP_{WF} = 5,7m$. Results from operability calculations give a probability for weather window of 47% for the base case. Variation of operational parameters have shown potential in improving the operability. The most promising way of improving operability seems to be a combination of increasing the operational limit and decreasing the operational period. This has the potential of leading to massive cost savings for the marine operation as waiting on weather can be expensive.

Sammendrag

Denne avhandlingen omhandler marine taueoperasjoner. Formålet med avhandlingen er å identifisere og diskutere tekniske utfordringer relatert til taueoperasjoner med fokus på sikkerhet og operabilitet. En forenklet modell er i tillegg utviklet for å beregne strekket i tauelinen under slep. Modellen brukes og til å etablere operasjonsgrensene for en operasjon hvor en halvt nedsenkbar plattform taues av et fartøy i Nordsjøen.

I moderne offshore industri er taueoperasjoner den mest vanlige marine operasjonen. De varierer fra transport av flytende objekter og enorme konstruksjoner til tauing av lange rør og ledninger under havoverflaten. Hyppigheten og ulikheten mellom operasjonene fører med seg et brett utvalg av utfordringer siden ingen operasjon er like. Dette medfører at taueoperasjoner er utsatte for ulykker. Statistikk fra senere år viser at transportfasen i en marin operasjon utgjør 26% av registrerte ulykker.

I nærhet av alle marine operasjoner er avhengig av været og taueoperasjoner er intet unntak. Usikkerhet i værvarsel blir justert for ved bruk av en α-faktor. Denne reduksjonsfaktoren er avhengig av lokasjon, planlagt operasjonslengde og operasjonsgrense. En metode for å estimere operabiliteten for et område er beskrevet i kapittel 3 og værdata er brukt for å beregne operabiliteten ved Heidrun. Resultatene viser at nødvendig tid for å vente på et tilstrekkelig værvindu er betydelig lavere for månedene mai-august enn november-februar.

Resultater viser at dynamikken spiller en viktig rolle for strekket i linen ved større bølgehøyder og denne effekten må forståes godt for å unngå overbelastning og ulykker. Et eksempelstudie for en taueoperasjon er utført og operasjongrensen, bestemt ved signifikant bølgehøyde, er funnet til å være $OP_{WF} = 5,7m$. Resultater fra operabilitets beregninger gir at sannsynligheten for å treffe på et værvindu vil være 47% for eksempelstudiet. Variasjon av ulike operasjonelle parametere har vist potensial for å forbedre operabiliteten. En kombinasjon av å øke operasjonsgrensen og senke operasjonstiden viser å gi best effekt på operabiliteten. Økt operabilitet har potensial til å gi store kostbesbarelser for marine operasjoner.

Contents

List of Figures

List of Tables

Nomenclature

α	Alpha factor
ϕ	Velocity potential
ρ	Density of seawater
τ_c	Duration of calm
$c(\omega)$	Mean wave drift force coefficient
C_D	Drag coefficient
C_s	Slamming coefficient
c_{cu}	Drag coefficient current
c_{wi}	Drag coefficient wind
F_D	Viscous drag force
F_s	Slamming force
F_{cu}	Steady force due to current
F_{wd}	Wave drift force
F_{wi}	Wind force
g	Gravitational acceleration
H_s	Significant wave height

OP_{lim} Design criterion

OP_{WF} Operational criterion

T_C Contingency time

T_p Peak period

T_R Reference time

T_w Time waiting

T_{OP} Accumulated operational time

T_{POP} Planned operation time

V Tow velocity

V_{cu} Current velocity

V_{wi} Wind velocity

Chapter 1

Introduction

1.1 Background

As the oil and gas industry continuous to explore and push for deeper and more remote fields the importance of successful marine operations are essential. The most common marine operation today are towing operations ranging from transportation of small objects to moving huge and costly constructions like offshore platforms. In addition to the variation of the object being transported, the tow location and towed distance vary from operation to operation giving rise to the impression that no tow operation are alike and need to planned accordingly. In today's global market a module may be build in Asia and towed all the way to Norway resulting in operations that can last for months. This adds challenges as the operation must be designed to withstand extreme weather that can occur during specific seasons along the route. This will require precise planning and execution to provide the necessary safety during the entire tow.

A tow operation is as any other marine operation very dependable on weather. The risk from undesirable motions induced by waves, wind and current provides motivation for accurate weather information throughout the tow. More advanced weather forecast systems and knowledge about the ocean environment leads to safer and more efficient operations as the time needed to wait on weather decrease. This can potentially lead to massive cost savings and fewer accidents. As the drive to explore and look for hydrocarbons further north increase the harsh weather conditions at these areas will require excellent understanding of the marine environment and operational limits.

Towing operations are often associated with accidents and poor execution. Several accidents in recent years have led to loss of lives and can often be traced back to lack of procedures and towing in bad weather. The drive to perform cheaper and faster operations as well as pushing the operational limits requires that the safety of personnel, equipment and environment should always be the top priority to avoid incidents. As seen from figure 1.1 the transportation phase of an operation makes up for a quarter of the registered accidents. Transportation accidents is here regarded as accidents occurred during tow or other form of transportation. This carries motivation for further improvement of planning and evaluation procedures of tow operations where determining correct operational limits should be a priority. What is common to most towline breakages is the lack of knowledge about the static and dynamic behaviour of the towing line.

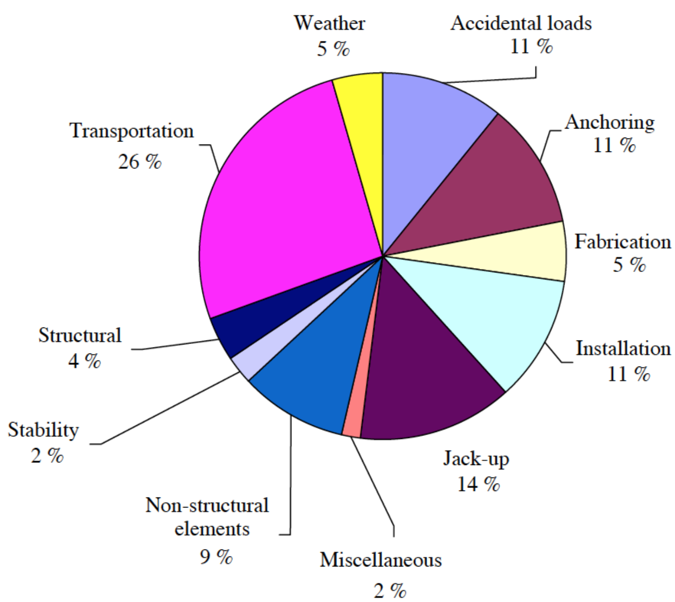


Figure 1.1: Statistics of accidents of marine operations. Lotsberg et al. (2004)

Problem Formulation

The thesis will assess the importance of safety and correct procedures during marine towing operations. Towing operations are involved in many accidents and some of these can be extremely severe. Challenges and correct planning is therefore in need of thorough investigation in order to locate where operations can go wrong and hence where they can improve. Previous accidents are valuable sources of information and need to be analyzed so that future operations can avoid similar mistakes. Operability will be evaluated based on hindcast data. As many accidents occur due to overload in the towline it is of interest to investigate how the tension varies with different parameters. Due to the complexity regarding the dynamics during operation, simplifications are to be expected when making the model.

Literature Survey

Much of the thesis is based on rules and regulations and lecture notes in the course *Marine Operations* lectured by Professor Kjell Larsen. The lecture notes covers several topics within marine operations and have been used as inspiration of what to investigate further. The rules and regulations have provided a more detailed description of important topics.

DNV GL (2015) has published an Offshore Standard on sea transport operations providing requirements, recommendations and guidance. Many topics are briefly mentioned and it is referred to DNV GL (2011a) for more specifics.

Nielsen (2007) provides a more detailed approach to marine operations. The book covers the most common marine operations from towing of structures to pipelaying as well as weather windows and general theory. Chapter 2 and 3 have been most relevant when writing the thesis.

1.2 Objectives

The overall goal of the thesis is to develop a simplified model to calculate the towline tension and establish operational limits for a selected concept. The model is to be used to evaluate how the tension varies with different operational parameters and how to improve the operability and safety of operation. The objectives are:

1. Describe state-of-art concepts for towing
2. Give a detailed description of a selected towing operation
3. Provide an overview of the requirements for towing operations given in present rules and regulations
4. Describe how the alpha-factor is used as a safety measure for marine operations
5. Establish a method to investigate the operability and availability for the North Sea
6. Use the towline tension model and operability calculations to evaluate and possibly improve a selected towing concept
7. Conclusions and recommendations for further work

1.3 Limitations

This master's thesis will focus mainly on the towing of floating structures which can be regarded as "classic" tows. Submerged tows and towing of slender structures like riser bundles and pipes will be covered in a descriptive manner but not investigated further. The scope is limited to the tow operation itself and not procedures of arrival at site or leaving starting point.

Due to the author's limited operational experience regarding towing operations of large structures, little first hand knowledge is provided throughout the thesis. Literature is used extensively and qualitative assessments have been made where deemed necessary.

Operability calculations have been made at a location in the North Sea. These are based on hindcast data and are only intended to give insight in how the operability vary during the year and how this will affect a marine towing operation. When evaluating a tow operation in the case study several simplifications and assumptions have been made in order to make a simplified model to calculate the tension in the towline. The model is used to study the tension and get some indication of how to plan and evaluate an operation early in the design process.

1.4 Structure of the Report

The rest of the thesis is organized as follows.

Chapter 2 describes and gives an introduction to modern towing operations. Typical configurations of towing vessels for offshore and inshore tows are described. The rigmove operation of Songa Trym is explained in more detail. The most important requirements related to towing operations are taken from relevant rules and regulations and presented.

Chapter 3 outlines theory relevant to towing operations and marine operations in general.

Chapter 4 describes how towing operations depend and rely on favorable weather. Weather windows are introduced and explained as well as the use of safe havens. A method to estimate operability is described and operability calculations are performed for Heidrun located at Haltenbanken.

Chapter 5 presents theory around the dynamics of towlines and presents a developed model for calculating the characteristic tension in the towline during operation. Calculations are performed for a base case and operability improvements are explored.

In Chapter 6, summary and conclusions are given. Recommendations for further work are also stated.

Chapter 2

Modern Towing Operations

A tow operation can be defined as a *"Non-routine operation of a limited duration related transport of object(s) and/or vessels in the marine environment during temporary phases...The tow operation shall be designed to bring the object from one defined safe condition to another safe condition."*Larsen (2016). Non-routine is important because no towing operation is exactly the same and hence each case has to be planned carefully in order to assure safety for personnel, equipment and environment. The second part of the citation above addresses safety more directly. DNV GL (2011a) defines a "Safe condition" as a *"condition where the object is considered exposed to normal risk (i.e similar risk as expected during in-place condition) for damage or loss"*. The need for careful planning is therefore important with respect to weather, equipment and operational procedures.

Today, most offshore development projects involve towing in one or several of its phases. This has added new challenges as larger constructions are required to be moved, often within a strict time frame. Examples of modern towing operations are:

- Rig move operations (towing of drilling rigs and flotels)
- Transport to or between sites of large floaters (semi-submersibles and FPSOs)
- Transport of objects on a separate barge

- Wet or submerged towing of long slender elements

This chapter will introduce and describe how towing operations are performed today and investigate how tugs are arranged during operation. Surface and subsurface tows will be covered as well including a more detailed description of the rigmove of Songa Trym. Important requirements related to towing operations are covered. Finally, an analysis of towing accidents is presented as a tool for learning.

2.1 State-of-art Concepts

2.1.1 Surface Tow of Large Structures

Classical surface tow of large volume structures will be the main scope of this thesis. It is stated by DNV GL (2015) that *"the towing equipment and tug(s) shall be arranged so that proper control over the towed object is ensured"*. These configurations will vary depending on the kind of operation and in which environment it is executed, for example inshore or offshore. Some classical configurations are shown in figure 2.1.

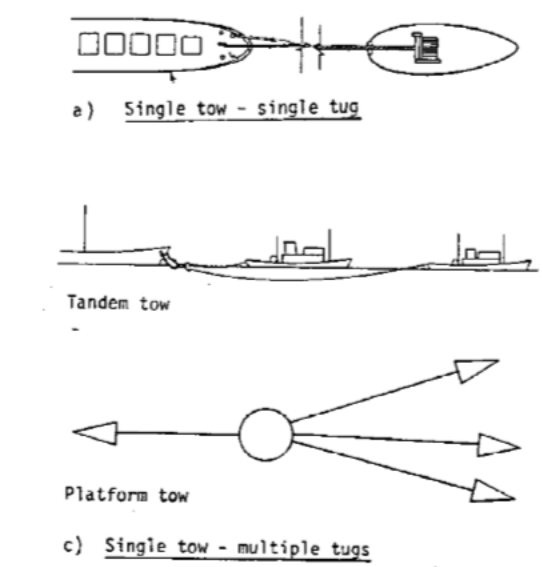


Figure 2.1: Classical towing configurations. Nielsen (2007)

For offshore operations the upper configuration is used for barges while the lower is used for platforms. The middle configuration called tandem tow is not applicable for open ocean towing operations but for restricted tows of limited duration like on rivers or sheltered inland waterways. Tow operations can be treated as a play between cost, speed, maneuverability and safety. All these factors need to be taken into account when planning and executing a tow operation.

Inshore Tow

For inshore/restricted tows maneuverability is key to provide a safe operation. To permit better control of the towed object the towline(s) may be shortened and multiple tugs may be used. A constant concern during inshore towing is that the towed object may overrun the leading tug(s) possibly resulting in major accidents. As seen from the Heidrun example in figure 2.2, three tugs are towed astern to counteract the tremendous inertia of the platform in case of an event that requires slowing down or coming to a complete stop. Being dragged astern, the tugs may have a tendency to be pulled down and swamped, so special stern sheets can be fitted to avoid this. The large inertia of the structure also makes it difficult to change direction during the operation. Additional tugs may be used on starboard and port side to enhance maneuverability (Gerwick Jr., 2007).

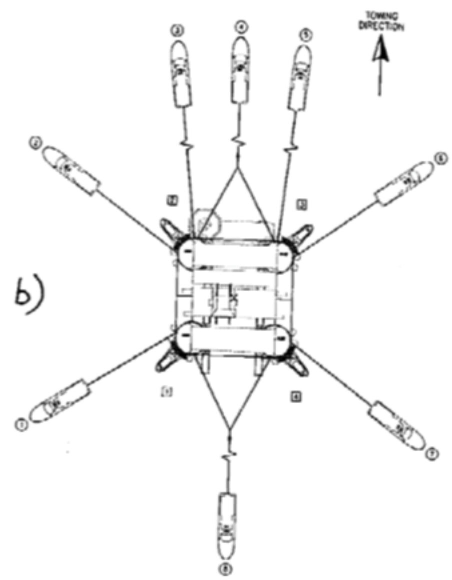


Figure 2.2: Inshore towing configuration of Heidrun platform. Nielsen (2007)

Offshore Tow

During offshore tows high speed is of importance to account for the long distances needed to be covered. The tugs will lengthen out their towlines to offset the wide range of loads in the lines due to the waves and swells (Nielsen, 2007). It can also be used a single lead boat ahead of the towed structure to verify route, confirm depths or pick its way through ice. This lead boat may also warn other ships ahead in order to prevent accidents. As seen from figure 2.3 almost all thrust available is applied in the same direction.

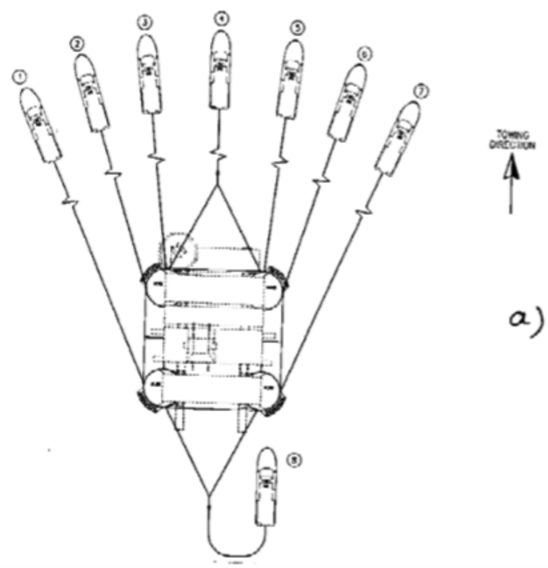


Figure 2.3: Offshore towing configuration of Heidrun platform. Nielsen (2007)

2.1.2 Subsurface Tow

To utilize fleet capacity and broaden acceptance criteria, submerged tow of objects is an alternative in modern towing operations. Transportation of modern subsea equipment will often require a large deck space and can limit the practical crane capacity on board. Several methods for subsurface towing exist today and three different configurations are:

- Submerged tow of objects attached to towed buoy (Pencil Buoy)
- Submerged tow of objects attached to vessel

- Surface or sub-surface tow of long slender elements

These methods will be described in more detail below. Wet towing operations can be very complex and contain numerous challenges. These challenges are both technical and operational and some examples to be considered could be (DNV GL, 2011b):

- Vessel motion characteristics
- Towing velocity
- The tow route (Varying current condition, limited space for manoeuvring)
- Wire properties
- Vortex induces vibrations (VIV)
- Clearance between object and tow vessel
- Lift effects on sub-surface towed structures

The Pencil Buoy Method

The Pencil Buoy Method is an Aker Marine Contractors (AMC) patented subsurface transportaion and installation method. The cargo is lifted through the splash zone inshore and towed to destination as a wet tow suspended from a spar-buoy as seen in figure 2.4 (Risoey et al., 2007). The buoy can be designed with a small water plane area relative to its displacement in order to reduce the vertical wave induced motion on the buoy. A tow velocity of 3-5 knots is normally used.

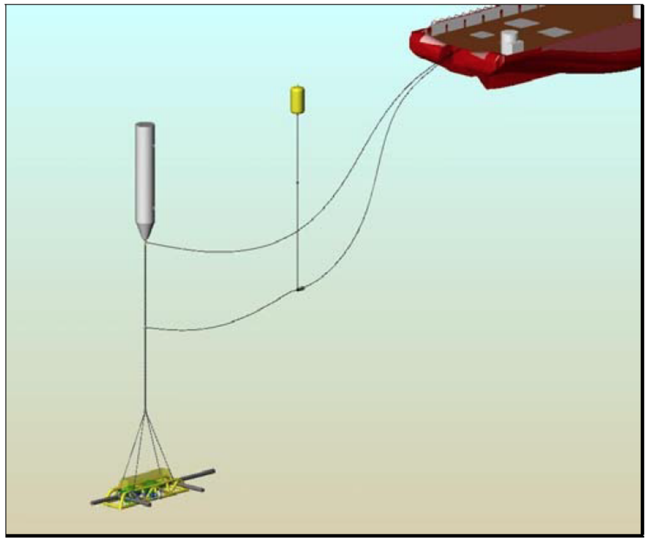


Figure 2.4: Pencil Buoy Method set-up. Risoey et al. (2007)

The structure to be installed is first transported from the fabrication site to the load-out site, in order to make the wet tow distance as short as possible. Consisting of three main steps, the first is to transfer the weight of the structure from a crane barge to a pencil buoy in calm inshore waters. The buoy is a steel structure with internal ring stiffeners and a diameter of typically 5 meters. In order to accommodate one-compartment damage, the buoy is subdivided into watertight compartments. The structure is lowered through the splash zone and its weight will be transferred to an installation vessel (IV). The different phases can be seen in figure 2.5.

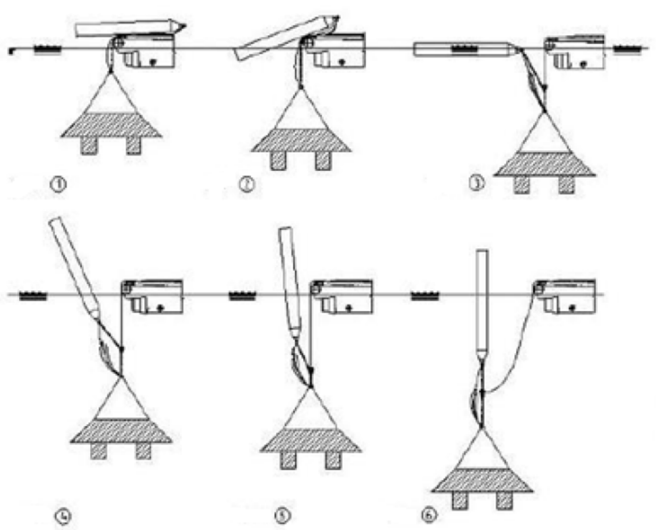


Figure 2.5: Launching of pencil buoy. Jacobsen (2010)

During tow the buoy is used to carry the submerged weight of the subsea structure as seen in figure 2.6. A towline with a length of 400 meter is used and a smaller buoy is connected to the towline in order to provide a normal angle of attack to the pencil buoy.

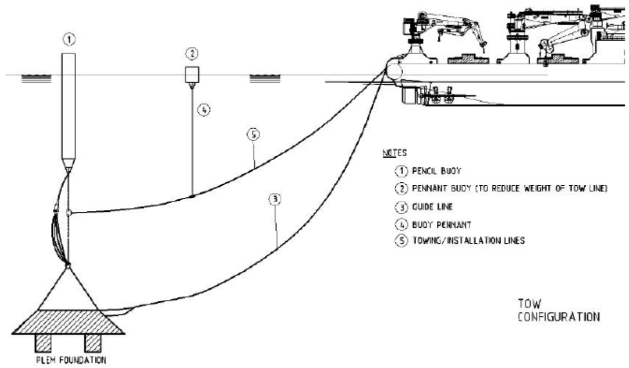


Figure 2.6: Towing of subsea structure using Pencil Buoy. Jacobsen (2010)

When reaching the installation site the towing wire is winched in and the the structure weight is transferred back from the Pencil Buoy and to the towing wire. The buoy is then disconnected. At this stage it is important to ensure that there is no contact between the installation vessel and the buoy. The IV will therefore move slowly forward during this load transfer. A passive heave compensator is used during the lowering of the structure to seabed.

Using the Pencil Buoy Method brings several advantages compared to traditional installation of subsea structures. Risks related to pendulum motions in air and slamming/uplift loads during lowering through splash zone are eliminated with the Pencil Buoy Method since the lift is done at inshore sheltered areas. This will also require less crane capacity and no need for an external offshore crane vessel. Since the structure is towed submerged in water and not on deck, the requirements for the installation vessel are easier to fulfill and availability in the market will be higher.

A challenge with this method is to retrieve the buoy safely without damaging it or the installation vessel. The limiting tow velocity is also of concern, limiting the distance it is feasible to use this towing concept. The cost saved by using the Pencil Buoy Method may be less than the combined cost of a time consuming tow and should be properly evaluated.

Still, this method has been used on several projects. The first projects used a buoy with 150 tonnes submerged weight capacity and later 250 tonnes buoys have been used (Risoey et al., 2007).

Objects Attached to Vessel

In 2007, Subsea 7 used its moonpool towing concept on four templates on the Tyrihans field. The tow and installation concept is designed to allow monohull construction vessel to pick up the template from its wet-store location, transit to the field with the template suspended through the vessel´s moonpool and install the templates at the location in a single vessel operation. The method consist of the following operations and can be seen in figure 2.7:

- Wet-store of template
- Pick up and hang-off
- Tow to field
- Transfer load to heavy lift winch system
- Landing of subsea template within the installation criteria

A crane barge lifts the template from a transportation barge and place it on the seabed. When the tow operation begins, the installation vessel positions itself above the template and a winch system is used for the pick-up from the wet-store location. The connection process is assisted by ROVs. This method for pick-up and installation improves the safety and working condition for the vessel crew as there is no handling of large templates on deck. During set down, the template is lowered to the seabed using the winch system which is not heave compensated, but a crane master is included for overload-protection during landing of the template.

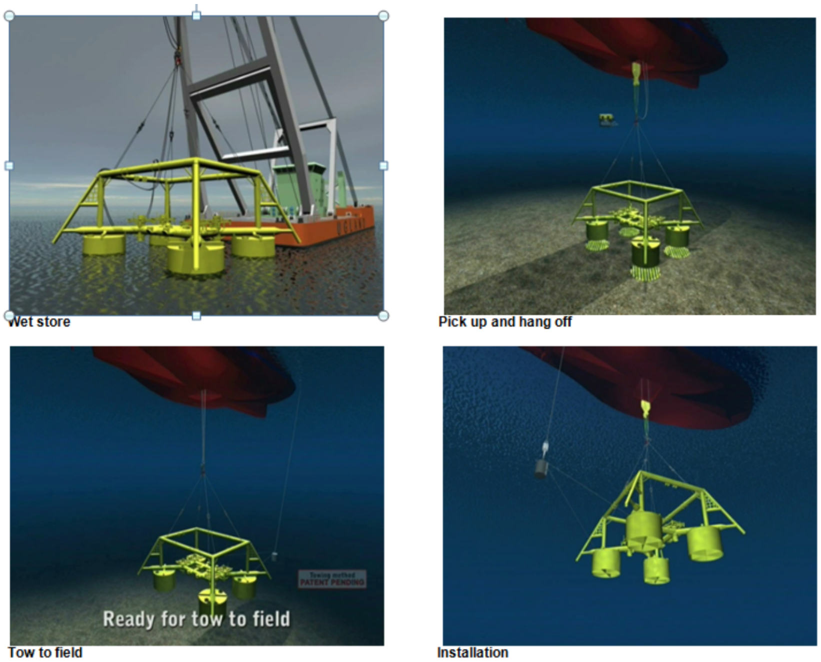


Figure 2.7: Stages of operation. Wet store, pick-up and hang-off, tow to field, installation. Jacobsen et al. (2014)

The winch system is shown in figure 2.8 and consists of a 300 tonnes winch with a 88 mm winch wire. The lifting wire runs from the winch, over a fairlead on the hang-off frame and down through the moonpool. The template is supported by four slings, all connected to a delta plate. The end of the lifting wire the runs back up to the Cranemaster which is connected to the hang-off tower.

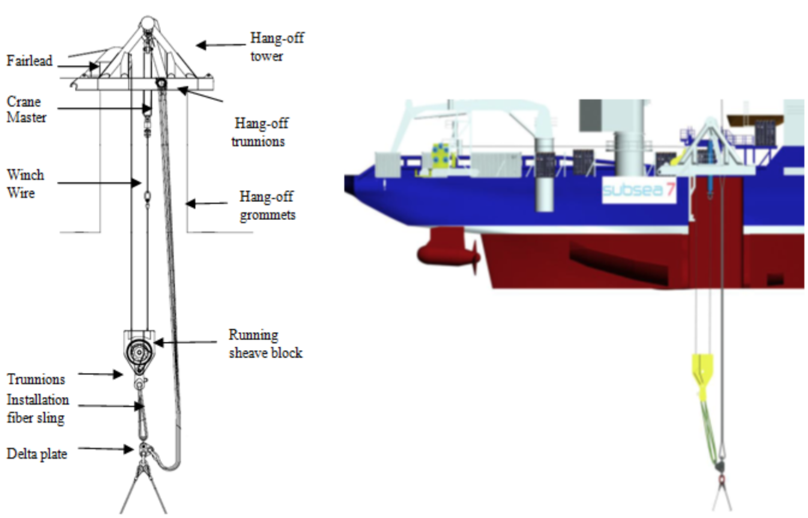


Figure 2.8: Winch System. Jacobsen et al. (2014)

Tow of Long Slender Objects

Towing can often offer an economic alternative to other methods of pipe-lay or pipeline installation, and may in some cases be the only alternative. There are several techniques for installing pipelines by towing and there are a wide range of applications for these methods. Four tow methods will be discussed here and they can be listed as follows:

- Bottom tow
- Off-bottom tow
- Controlled Depth Tow (CDT)
- Surface tow

Regardless of which method used, their main feature or restriction is the limited length of pipe that can be towed. Several slender objects may be towed together as a bundle. A pipeline bundle is a carrier pipe within which any combination of individual pipelines and umbilical components is carried (Subsea 7, 2012). The individual components terminate in "Towheads" within which manifolding may take place as seen in figure 2.9.

Figure 2.9: Towhead and schematic of cross section of bundle. Subsea 7 (2012)

No matter which method is selected there are great benefits in planning the method at an early stage. For a given location, selection of the installation method to be used should be based on a thorough evaluation of the alternative construction procedures. Each method has its advantages and limitations.

Bottom Tow

This technique has been used to tow pipelines or bundles very long distances, including installations in very deep water. As seen from figure 2.10, a pipeline is towed along the seabed connected to a tug by a cable. The pipeline may either be a single pipe or a bundle of pipes. A clear tow route is essential and a survey of the route is required to ensure that it is clear of debris, that the seabed soils are appropriate and that the bathymetry is suitable. Consideration will need to be given to the pipe coating and the abrasion which will occur during the tow. The length of pipeline which can be towed depend mainly on the submerged weight of the pipeline which can be reduced by using buoyancy elements (Ley et al., 2006).

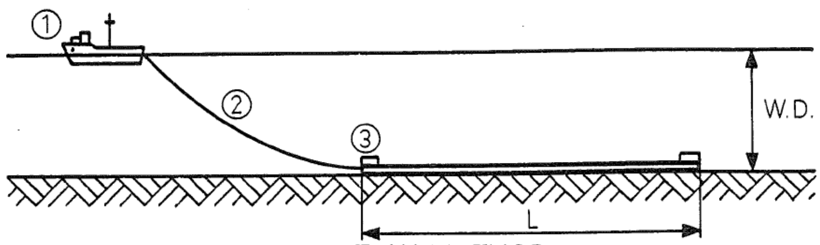


Figure 2.10: Bottom tow. Fernandez (1981)

Off-bottom Tow

The off-bottom tow technique may be considered as a variation of the bottom tow method. If the route allows it, bundles or pipelines can be towed long distances using this method. As for bottom tow, the route has to be surveyed and confirmed suitable. The difference is that the pipeline is elevated above the seabed and so abrasion and small obstructions present less of a problem, figure 2.11. Chains are introduced on the bottom of the pipe in order to achieve negative buoyancy and stability, see figure 2.12. Positive buoyancy or lift force may be provided by the pipeline itself, pontoons or floats attached to the pipeline. The use of trimming chains makes it possible to adjust the submerged weight to suit the design, which in turn will be specified to suit required stability requirements, and to keep pull forces within the capacity of the tug(s) (Ley et al., 2006).

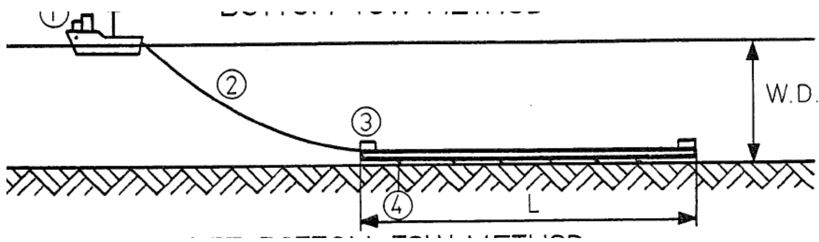


Figure 2.11: Off-bottom tow. Fernandez (1981)

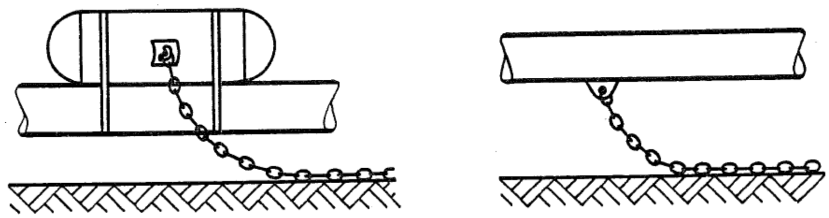


Figure 2.12: Section of pipeline. With float and chains and with chains only. Fernandez (1981)

Controlled Depth Tow

The Controlled Depth Tow (CDT) method is effectively a variant of the off-bottom tow and the layout can be seen in figure 2.13. This method is normally utilized for bundle installations but it has also been used for towing single and shorter pipelines where lay-barge methods might be uneconomical. From Ley et al. (2006) it is explained that a CDT bundle is designed and constructed such that its submerged weight, when launched and trimmed, and the hydrodynamic drag characteristics of its ballast and drag chains are such that the bundle will lift off the seabed at its critical tow speed. A combination of ballast and drag chains is used to counteract the buoyancy from the bundle carrier and in a static case keep the bundle in contact with the seabed. When the tow speed is lowered, the bundle will start to settle towards the seabed and the last part of the tow and installation is completed as a off-bottom tow. Long bundles up 7.5 km weighing several thousand tonnes can be towed hundreds of kilometers and installed in depths down to 150 m or deeper using the CDT method.

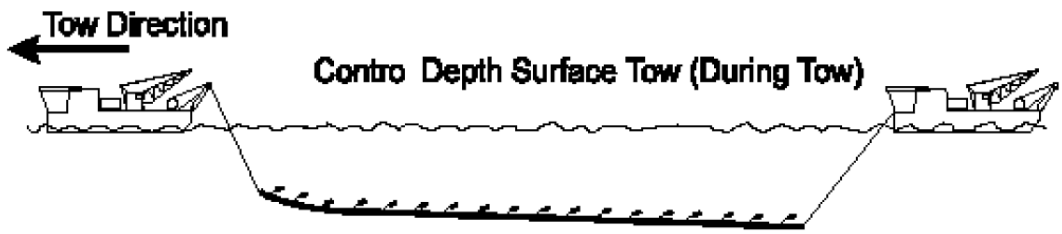


Figure 2.13: Controlled Depth Tow. DNV GL (2011b)

Surface Tow

According to Ley et al. (2006) a surface tow method known as the Flow-Lay has been developed primarily for single pipelines or flowlines but it can also be used for more complex bundles of pipelines and cables. The method is designed to reduce costs and to provide and economical alternative to conventional methods and allows pipelines to be fabricated on land, launched and towed to location in a single length. Unlike for the CDT method where the pipelines are installed in a sealed carrier pipe to provide buoyancy, for this method buoyancy is provided by fasting a plastic carrier pipe to the top of the pipeline. The plastic pipe is selected to give optimum buoyancy for tow and installation. Tow and trail tugs maintain tension in the pipeline during tow as seen in figure 2.14 which in turn decrease the effect of wave action and reducing stress effects (Group, 2016). Detailed analysis is carried out to determine the launch, tow and installation stresses under appropriate conditions for the project which also enables fatigue effects to be calculated (Group, 2016). This method eliminates the requirement for specialist vessels which significantly reduces project costs, duration and carbon emissions. The rate of pipe lay is controlled by the rate of flooding and this is in turn determined by the pipe-lay conditions and ability of the active tug to maintain the pipeline on the correct alignment.

Figure 2.14: Surface Tow. DNV GL (2011b)

The La Libertad project carried out in Ecuador in 2006 is an example of a pipeline installation using the surface tow technique. From Ley et al. (2006) the operation can be described in short. A 5.5 km long 20" concrete coated pipeline was required to be laid between an onshore refinery close to the beach and a new CALM buoy in the Bay of St. Elena. To mobilize a lay-barge to relatively remote location would have been expensive. It was however feasible to construct the entire 5.5 km long pipeline onshore at a site within 20 km of the refinery. From there it was launched and surface towed using locally available tugs. The pipeline was accurately laid by controlled flooding and the entire installation was completed within 3 days. A picture from the tow can be seen in figure 2.15.

Figure 2.15: Tow of 5.5 km 20" pipeline, La Libertad. Ley et al. (2006)

2.2 Emergency Iceberg Towing

As the offshore oil and gas industry explore the possibilities for developments in Arctic waters the risk of collisions with icebergs become probable. Icebergs may cause a threat to structures and operations in the Arctic regions and procedures to avoid collisions must be well established. According to Eik and Marchenko (2010) it has been documented that if icebergs are discovered and considered a threat they can be deflected around installations in approximately 75% of the events. If in need of deflection, the iceberg can either be pushed, towed or a combination of both. The most common way is the use of a single vessel with a single towline as seen in figure 2.16.

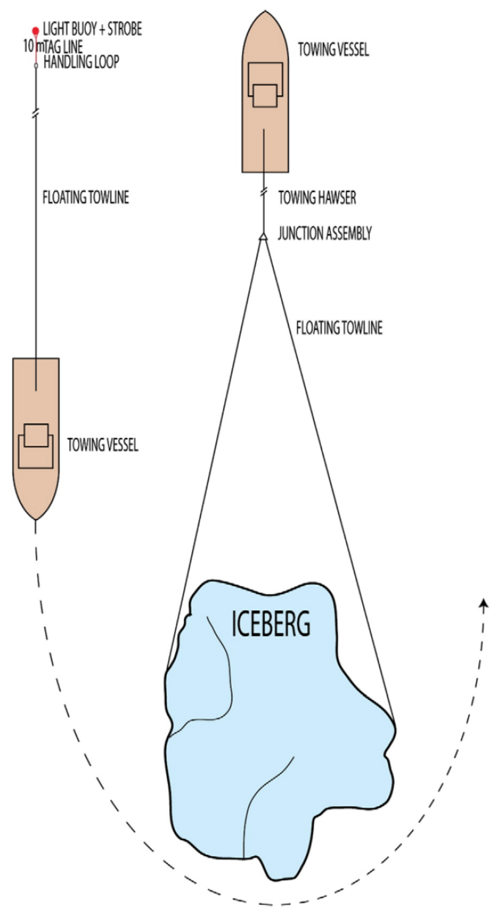


Figure 2.16: Deflection of iceberg using single vessel and towline. Eik and Marchenko (2010)

2.3 Rigmove Songa Trym

The following is a description of the move of the drilling rig Songa Trym from Tordis R1 to Sleipner D1 in 2015. The operation is studied in order to get a deeper understanding of how a large scale tow operation is performed. Songa Trym can be seen in figure 2.17 and rig specifications are tabulated in table 2.1. The guideline for the anchor handling and rig move operation is taken from Offshore (2015). The purpose of the guideline document is to ensure a safe operation for people, environment and values for the unmooring, transit and anchoring of the drilling unit. At Tordis R1 the rig was moored by 10 lines as seen in figure 2.18 but the process of unmooring the rig will not be covered extensively.

Figure 2.17: Platform Songa Trym. marinetraffic (2017)

Table 2.1: Songa Trym specifications. Offshore (2015) Offshore (2014)

Owner	Songa Offshore
Flag	Norwegian
Total length	108.2 m
Breadth molded	64.3 m
Main deck elevation	36.58 m
Operating draft	21.34 m
Ocean transit draft	8 m
Survival draft	18.2 m
Main power	4 x 2200 HP
Max water depth	1312 ft
Max drilling depth	25000 ft

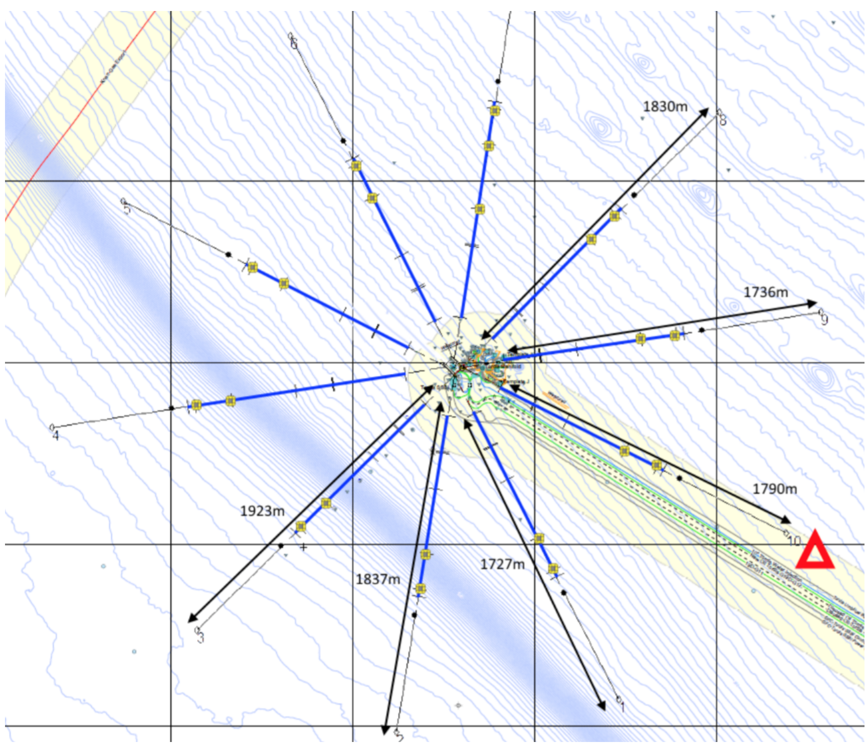


Figure 2.18: Mooring spread at Tordis R1. Offshore (2015)

2.3.1 Preparations

Before operation start a briefing should be held with the crew on the Anchor Handling Vessels (AHV) and all involved personnel on board the rig. A Safe Job Analysis (SJA) should also be carried out by the AHVs before the mooring operations starts. The rig must receive a copy of the SJA and planned work schedule for each personnel involved in the operation. During the anchor handling, an extra crew of 8 people is needed and the rig must be capable of operating two winches at the same as well as anchor handling for 24 hours a day. All equipment involved must be inspected prior to operation start. The operation is split into sub-operations and the respective time estimates are tabulated in table 2.2.

Table 2.2: Time estimates for moving Songa Trym. Offshore (2015)

Operations at Tordis R1	**Duration 4 AHVs**
De-ballast of rig to transit	5 hrs
Retrival of anchor lines	20 hrs
Transit to Sleipner D1	**Duration**
Transit 174 Nm at 6 knots	29 hrs
Operations at Sleipner D1	**Duration 4 AHVs**
Anchoring at Sleipner D1	20 hrs
Ballast rig to survival draft	5 hrs
Testing of mooring line integrity	4 hrs
Emergency release test	2 hrs

2.3.2 Transit

The total tow distance was approximately 174 Nm and the route can be seen in figure 2.19. Before start, the towing wire were kept available on the deck of the AHVs. Pennant wires were not used during tow. The tow configuration is displayed in figure 2.20, utilizing two AHVs. The option of using a tail vessel was possible if more control over the rig was deemed necessary. A sudden change in weather or an unexpected situation where the tow needed to slow down quick could require such a configuration.

During tow, an average speed of approximately 6 knots was estimated resulting in a transit time of 29 hours making the tow operation weather restricted. A weather forecast was provided every 6^{th} hour. If the operation ran into severe weather the rig would need to consider seeking sheltered water. This would be the captains decision.

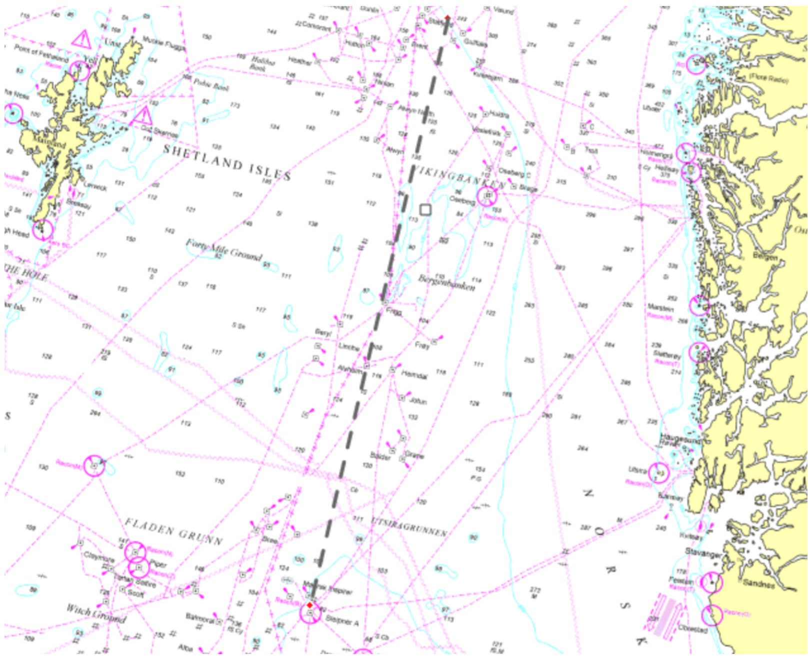


Figure 2.19: Transit route for Songa Trym from Tordis R1 to Sleipner D1. Offshore (2015)

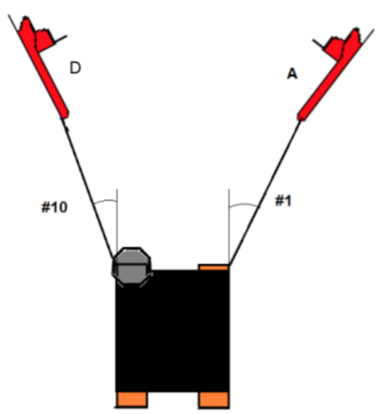


Figure 2.20: Towing configuration during transit from Tordis R1 to Sleipner D1. Offshore (2015)

During tow, the towline length required by the AHVs was longer than 1000 meters. Control of the catenary was important during tow in order to ensure that contact with sea bottom was avoided. The catenary should therefor be checked against the water depth throughout the transit. A minimum clearance between tow wire and seabed should be 50 meters. In order to uphold this criteria, the towline length was reduced when approaching the Sleipner field with a water depth of 84 meters.

2.4 Requirements for Towing Operations

Towing operations today vary greatly, but many share certain similarities in either location of operation, time span, objects being towed or all of the above just to mention some. Several standards and rules and regulations exist to ensure correct planning and execution of towing operations in modern industry in order to protect personnel, equipment and environment. These standards can be very specific so an overview of the most important requirements will be presented in this section. In Norway, frequently used standards are provided by DNVGL and the following will contain outtakes mostly from DNV GL (2011a), DNV GL (2011b) and DNV GL (2015).

2.4.1 Planning

A marine operation should be planned according to *fail safe* principles. What this means is that the handled object shall remain in a stable and controlled condition if a failure should occur (Nielsen, 2007). The overall objective is to ensure that the operation is performed within defined and recognized safety levels. The design acceptance criterion, i.e. the intention of the load-, safety- and material factors, is to ensure a probability for structural failure less than 1/10000 per operation (10^{-4} probability). This probability level defines a structural capacity reference. When considering the probability of operational and human errors as well, the total probability of failure may increase (Larsen, 2016). A towing operation is a costly and can be a dangerous affair, so it is desired to minimize cost while still maintaining the responsible safety level. Careful and thorough planning is therefor essential as well as understanding the marine environment and the dynamics of the system being towed. If possible, the tow operation or sub-operations should be classified as either restricted or unrestricted operations as this can have great impact on the safety and cost of operation. As such, the type of operation should be defined early in the planning process. This will be covered more extensively in chapter 4

Risk Management and Identification

During planning all possible contingency situations shall be identified early in the process and plans in order to prevent or handle these situation shall be outlined. These plans shall consider redundancy, extra personnel, emergency procedures or other relevant measures. To minimize risk during tow, design and planning shall as far as possible be based on well proven principles, techniques, systems and equipment. Towing in the marine environment has been around for many years and there are a lot of available data on typical hazards. Risk management shall be applied to the project, and the overall responsibility for risk management shall be clearly defined when planning a tow. The risk of each step of an operation shall be evaluated and the actions that are necessary to ensure a "tolerable risk level" needs to be specified. Risk is defined as the product of the consequence of a hazardous event and the probability for such event to occur:

$$Risk = Consequence \cdot Probability \tag{2.1}$$

It may be difficult in practice to define the probability levels for an operation directly. Therefore, robustness or vulnerability aspects such as complexity of the operations or weather sensitivity on one side may be evaluated against safety margins or redundancy on the other (Standard, 1997). Contingency situations can be identified or excluded based on risk identifying activities such as FMEA/FMECA, Hazard Identification Analysis (HAZID), system HAZOP or Design Review (DR). It is referred to Vinnem (2014) for theory on these risk identifying activities.

Weather Routeing and Forecasting

During and prior to a marine operation, weather forecasts shall be received at regular intervals. These forecasts shall be from recognised sources and shall be area/route specific. The weather forecast should be in writing and the confidence level(s) should be stated. If two forecasts from different sources does not agree, the most severe should be used for the operation. Three weather forecast levels are used and their definitions are as follows:

- **Level A**: Applies to major marine operations sensitive to weather. Typical operations may be: - mating operations, GBS tow out operations, jack-up rig moves or multi-barge towing.
- **Level B**: Applies to operations of significant importance with regard to value and consequences and sensitivity to environmental conditions. Typical operations may be: - float-out operations, sensitive barge towing and offshore lifting.
- **Level C**: Applies to conventional marine operations less sensitive to weather conditions, and carried out on a regular basis. Typical operations may be: - onshore/inshore lifting, load out operations and standard barge tow without wave restrictions.

Depending on the selected forecast level, a procedure complying with requirements in figure 2.21 should be established. The applicable limitations and the minimum required weather window for the operation shall be defined by the acceptance criteria for the weather forecast which shall be included in the marine operation manual. If a forecast of low confidence is used the weather situation shall be assessed according to a worst case scenario development. This also applies in areas with unstable weather.

Weather Forecast Level	*Meteorologist required on site?*	*Independent WF sources*	*Maximum WF interval*
A	Yes[1)]	2[2)]	12 hours[3)]
B	No[4)]	2[5)]	12 hours
C	No	1	12 hours

1) There should be a dedicated meteorologist, but it may be acceptable that he/she is not physically present at site. The meteorologist opinion regarding his preferable location should be duly considered. It is anyhow mandatory that the dedicated meteorologist has continuous access to weather information from the site and that he/she is familiar with any local phenomena that may influence the weather conditions. Note also that the meteorologist shall be on site in order to use alpha factors from Table 4-3 and Table 4-5.
2) It is assumed that the dedicated meteorologist (and other involved key personnel) will consider weather information/forecasts from several (all available) sources.
3) Based on sensitivity with regards to weather conditions smaller intervals may be required. However, see 305.
4) Meteorologist shall be conferred if the weather situation is unstable and/or close to the defined limit.
5) The most severe weather forecast to be used.

Figure 2.21: Weather forecast levels. DNV GL (2011a)

Monitoring

During a tow operation, monitoring of design parameters should be used extensively. The monitoring of environmental conditions could be both direct and based on responses caused by the environmental effects. A tow operation which is particularly sensitive to environmental conditions like waves, swell and current should use systematic monitoring of these conditions prior to and during the operation. Monitoring procedures for the tow operation shall be given in the tow manual, describing intervals, responsibilities, reporting and recording.

Restrictions on Route

As mentioned, since each tow operation are somewhat unique they should be assessed on their own by taking into account environmental conditions, length of areas of restricted manoeuvrability, capability of tugs and underwater topography. During operations where under-keel or side clearance is critical, a survey no older than 3 months should be available. If the on-board survey and bathymetry measurement systems have sufficiently high precision, the survey requirements can be relaxed. If possible, passage through areas of restricted manoeuvrability should take place during daytime.

Under-keel clearance during tow shall account for roll, pitch, heave, towline pull and errors in measurements and shall include a margin of no less than one metre or ten percent of the maximum draught. Some sections of the tow route may be tidally dependent. In these areas, locations where the tow can reside safely while waiting for favorable tidal conditions shall be identified. The minimum under-keel clearance must be upheld at these locations while waiting. Delays as a result from waiting on high tide must be included in the overall planning of the operation.

Some tows may require passage under bridges or power cables. The overhead clearance should be calculated allowing a margin of no less than 1 metre. The tidal level should be confirmed immediately before passage. Power cables also need a "spark gap" in addition to the physical clearance. This gap should be provided by the transmission company. Depending on the load being carried in the power cable, the catenary may change and the lowest position should be used.

2.4.2 Tow Force Calculations

Based on towing route and procedures, the minimum required towline pulling force, F_{TR}, shall be calculated. The calculations shall document the required towing force for; holding in open sea, manoeuvring in narrow waters and adequate speed. Calculations for F_{TR} shall include wind, wave-drift and current forces and all relevant combinations of these relative to the towed object.

For unrestricted towing the F_{TR} shall be calculated for the following conditions acting together:

- Sustained wind velocity, $V_w = 20 m/s$
- Head current velocity, $V_c = 0.5 m/s$
- Significant wave height, $H_s = 5 m$

2.4.3 Towing Configurations

Normal towing configurations are shown in figure 2.22.

Tugs		*Objects*		*Tow called (see notes)*
No.	*Position*	*No.*	*Position*	
1	NA	1	NA	Normal
2 or more	Parallel	1	NA	Parallel
2	Series	1	NA	Serial
3 or more	Series	1	NA	
1	NA	2	Parallel	Double
1	NA	3 or more	Parallel	
1	NA	2 or more	Series	Tandem

Figure 2.22: Towing configurations. DNV GL (2015)

The definition of each configuration are:

Normal tow: One tug towing one object.

Parallel tow: Two or more tugs in parallel. Each tug is connected by its own towline to the same towed object.

Double tow: Two towed objects each connected to the same tug with separate towlines. One of the towlines is of sufficient length to pass well below the first towed object.

Tandem tow: Two towed objects in series behind one tug.

Serial tow: Two tugs in series. The towed object is connected to the second tug and this tug is connected to the leading tug.

Based on risk assessment, other towing configurations than normal and parallel may be accepted considering the actual tow arrangement, towed objects, route and season.

In case of an emergency where the towline breaks, a backup towline should be kept ready on board the towing vessel. The towed object then needs a pickup arrangement in order to connect to the spare towing line. The entire emergency towing arrangement that is used must fulfill the design load requirements as presented in table 2.4. Most preferably, the emergency arrangement should be independent from the main towline and have connection points at the bow of the tow.

2.4.4 Towlines

Towlines may consist of several different materials and be of different thickness and length. What is common for all is that they need to fulfill certain basic functions. From Hensen (2003), the towline should function as the load carrying link between tug and ship. It should also cope with dynamic loads resulting from relative motion between ship and tug. The following towline requirements are important (Hensen, 2003):

- **Strength**. A towline should be of sufficient strength to cope with the forces that can be experienced during shiphandling operations.
- **Stretch**. Dynamic loads should be well compensated for by a towline in order to avoid excessive loads in the line and attachment points.
- **Weight/diameter**. The line should be manageable on board a tug as well as on board a ship. When no towing winch is used a towline should be flexible enough for easy and safe handling.
- **Life**. When in use a towline should suffer a minimum of wear, distortion and loss of strength, providing as long a life as possible.

For offshore towing operations the towlines should be steel wire ropes. Fibre ropes are acceptable to use for inshore and weather routed coastal tows. Synthetic rope is under continuous development and a lot of research is being carried out on this field. This will hopefully result in further improved performance of man-made fibre ropes in the future which may have a positive effect on cost and safety.

It is common to have the towline composed of several segments of different properties as seen in figure 2.23. The resulting stiffness of the line is important to the dynamic forces in the line. It is sometimes beneficial to use what is known as a "weak link" wire element. In case the towline should fail due to high impact loads it may be reconnected more easily because it fails at predetermined point on the line. Some line segments for different tows and areas are tabulated in table 2.3.

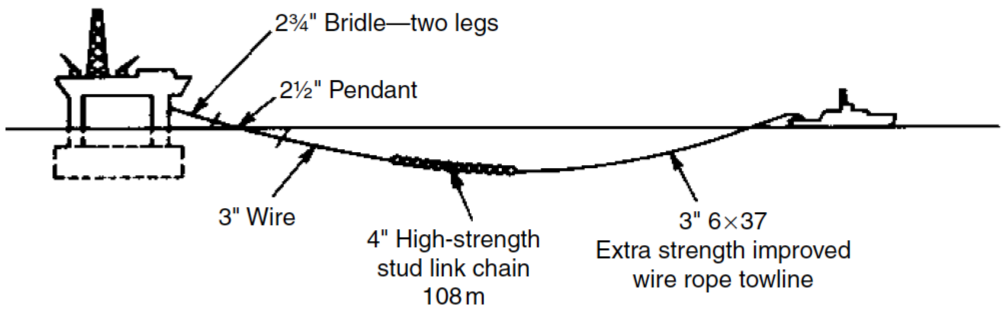


Figure 2.23: Towline configuration with different segments. Gerwick Jr. (2007)

Table 2.3: Examples of towline segments layouts. Nielsen (2007)

Tow (area)	Towline segment material	Diam. [mm]	Length [m]
Condeep (N.Sea)	wire	58.6	165
	nylon	121.3	55
	wire	58.6	1000
Barge (N.Sea)	wire bridle	42	20
	wire	40	30
	wire	42	1000
Ship (Pacific)	chain	51	20
	polyprop	81	400
	chain	51	10

Strength Requirements

The towline design load, F_{TD}, for all components in the main and emergency towing arrangement shall for unrestricted towing be at least as displayed in table 2.4. BP is the continuous static bollard pull of the vessel in tonnes.

Table 2.4: Towline design loads. DNV GL (2015)

F_{TD}	BP
$3.0BP$	$BP \leq 40$
$(220 - BP)BP/60$	$40 < BP < 100$
$2.0BP$	$BP \geq 100$

The minimum certified breaking strength, $MBL_{towline}$, shall be equal to or greater than the F_{TD}. If applicable, $MBL_{towline}$ shall be reduced due to the effect of bending and/or end connections.

Length Requirements

The required towline length varies depending on tow location. For unrestricted towing the deployable length should be no less than:

$$L_{towline} = 1800 \cdot BP/F_{TD} \quad \text{but minimum 650 meters} \tag{2.2}$$

where

$L_{towline}$ = minimum deployable tow line length [m]

BP = continuous static bollard pull of the vessel in tonnes

F_{TD} = towline design load in tonnes

For towing in benign areas the minimum deployable length shall not be less than:

$$L_{towline} = 1200 \cdot BP/F_{TD} \quad \text{but minimum 500 meters} \tag{2.3}$$

2.4.5 Towing Vessels

For planned towing operations, it is only permitted to use vessels intended for towing. This includes fulfilling the bollard pull requirement and having a trade certificate valid for the tow route. The towing vessel shall be equipped with a towing winch.

In case of towline failure and to be able to reconnect, spare equipment and arrangements shall be provided. Assisting tugs shall also be present in single tug tows at commencement and at arrival destination. Adequate contingency shall be provided during sailing in narrow areas and/or in areas with heavy traffic. Considering the tow route and season, the towing vessel shall carry adequate supply of fuel and other consumables. This should include potable water as well as lubricating oil and stores. For longer tows where refuelling is necessary this should be described in the towing manual.

2.5 Accidents

This section will introduce and discuss accidents during towing of large objects. The main focus will be on accidents which have occurred in Arctic waters where there is a rising level of marine and maritime activities. These waters are especially hostile with respect to cold temperatures in both water and air including rapid changes in weather. First, an overview will be given of recent accidents. Then, two severe accidents will be analyzed more thoroughly to get a deeper understanding of what can go wrong during a tow operation and what can be learned to provide safer operations in the future.

2.5.1 Overview

In the years 2011-2014, a total of 1566 service ships were involved in accidents in the EU member states. 21% of these accidents (334 cases) involved tugs performing either towing or pushing operations (EMSA, 2015). Several towing accidents result in fatalities and the incident cause is often lack of understanding operational procedures and the dynamics involved in such operations. The drive to perform cheaper and faster operations as well as pushing the operational limits requires that safety for personnel, environment and equipment should always be the top priority. Still, as seen in this chapter, towing operations are accident prone and impose danger to the people involved if not executed properly. Table 2.5 tabulates a few accidents which occurred between 2007 and 2011.

Table 2.5: Some towing accidents from year 2007-2011. GOV.UK (2016).

Vessel	Year	Location	Description	Fatalities
Retainer	2007	England	Most likely cause was that one tow rope became snagged on the forward section of the towed barge. When the snag cleared, it transmitted a wave along the tow rope which hit a crewman in the chest.	1
Englishman	2008	England	Tow wire protector used to avoid chafing. It was not fixed properly and slipped loose. While trying to reposition, the wire jumped, hitting a crewman in the head.	1
Flying Phantom	2007	Scotland	While acting as a bow tug for bulk carrier Red Jasmine the tug was girted and sank. There had been no established operational limits prior to the operation.	3
Westsund	2011	Baltic Sea	During towing of a barge one spud pile (barge leg) came loose and broke off. Hours later container ship Johanna collided with the spud pile which penetrated the the hull above the water line. Environmental wear and lack of inspection is believed to have caused the accident.	0

Three more cases are also worth mentioning. The first occurred in late December 2015 when the barge "Eide Barge" broke loose from its tow. After about 24 hours of drifting it was heading towards the oilfield "Vallhallfeltet" operated by BP. The barge had a small draft of only 1.5 m and three large superstructures which caught the wind well. With waves around four meters and wind gusts up to 35 knots the situation was quite severe and could have ended badly if a collision was to happen. Luckily the barge passed the field with a distance of just 2 nautical miles. Several attempts were made to secure the barge and it was even considered bombing it with the use of fighter jets (Aftenposten, 2016).

In December 2014 the towing line for the flotel "Safe Bristolia" broke due to bad weather during tow off the coast of Bergen. The two towing vessels "BB Troll" and "Odin Viking" struggled with reconnecting to the flotel due to the weather and pressing darkness. All non-essential personnel were evacuated by helicopter and the flotel dropped an anchor in order to reduce the drifting speed. Over the night the situation was under control (Tidende, 2014).

On the 8^{th} of August 2016 the 17000-tonne drilling rig "Transocean Winner" ran aground on the Western Isles of Scotland. The rig was under tow from Norway to Malta when it was hit by severe storms. Overnight the the towline snapped due to the heavy weather. After the accident it was questioned why there had only been one towline and what kind of emergency response vessels that were present (BBCNEWS, 2016). At the present time of this writing this thesis no official accident report has been published on the Transocean Winner accident.

2.5.2 Severe Accidents and what to Learn

In this section two accidents will be studied in more detail, the loss of Kolskaya and Kulluk during tow.

Kolskaya Accident

The following information in this section is the essentials taken from Berg et al. (2015). The jack-up rig "Kolskaya" was under tow by the icebreaker Magadan and AHST Neftegaz-55 on the 8^{th} December 2011. The rig was towed in the Okhotsk Sea after completing an exploratory well for Gazprom. During the tow the weather changed to gale force winds and 5-6 m high waves. The harsh weather forced the rig to send out a distress signal when a failure of some air tank inlets led to seawater flowing into the tanks. Heavy loads in the towline generated by the weather also led to damage in the line and the rig asked for immediate assistance. Around 0600 Moskow time Kolskaya capsized approximately 200 km off the Coast of Sakhalin Island, see figure 2.24. Among the 67 people on board, 53 died making it the worst accident in the Russian oil and gas sector history. Several questions were raised after the accident. Why were there so many people on board the rig during the operation and how was the tow approved when such weather could be expected?

Figure 2.24: Kolskayas planned route and location of accident

Lessons Learned

It was initially claimed by the rig owner that the towing operation had been in compliance with all safety standards. It was discovered early in the investigation that there had been violations of safety rules as well as failure to take weather windows into account when planning the operation. Finding a period of acceptable weather for this type of marine operation during the winter season can be very difficult. Postponing the tow until spring when the weather was more predictable should have been considered. When towing in such environmental conditions, all non-essential crew members should have been transferred to a separate vessel prior to the operation. The most important learning aspects to take away from the Kolskaya accident is the following:

- When towing in Arctic waters, planning and execution need to be done according to rules, regulations and area-specific operational procedures.
- Keep close surveillance of tow operations and have a clear line of communication between the tug and towed object. All changes from original plan shall be stated in good time.
- In case of operational challenges due to change in environmental conditions early warning is needed to avoid equipment overload/breakdown.
- Only necessary personnel should be on board when towing in rough conditions.

Kulluk Accident

The following information in this section is the essentials taken from Berg et al. (2015) and Guard (2014). In December 2012 the drilling rig Kulluk was towed from Unalaska to Seattle for winter maintenace. A coastal route was chosen to keep the distance to shore less than 200 nautical miles in case of an emergency. The total distance for the tow would be 1700 nm and was expected to last 24.6 days with an average speed of 3 knots or 18.5 days averaging 4 knots. The towing vessel was the offshore vessel Aiviq operated Edison Chouest Offshore and in spite of a metocean forecast of harsh weather the tow was scheduled to start on 21^{st} December. None of the deck officers on Aiviq had any experience with towing operations in Alaskan waters and it was voiced concern about this from the towing vessel captain to the towing master on the drill rig. The tow encountered a storm on the 27^{th} December resulting in large fluctuations in the towline tension for a period of more than six hours. The towline system was equipped with an alarm which was activated each time the wire tensile strength rose above 50% of the strength limit for the tow equipment. During the morning of the storm the alarm went of 38 times. A detailed time analysis of wire tensile strength and actions performed by the crew can be seen in figure 2.25.

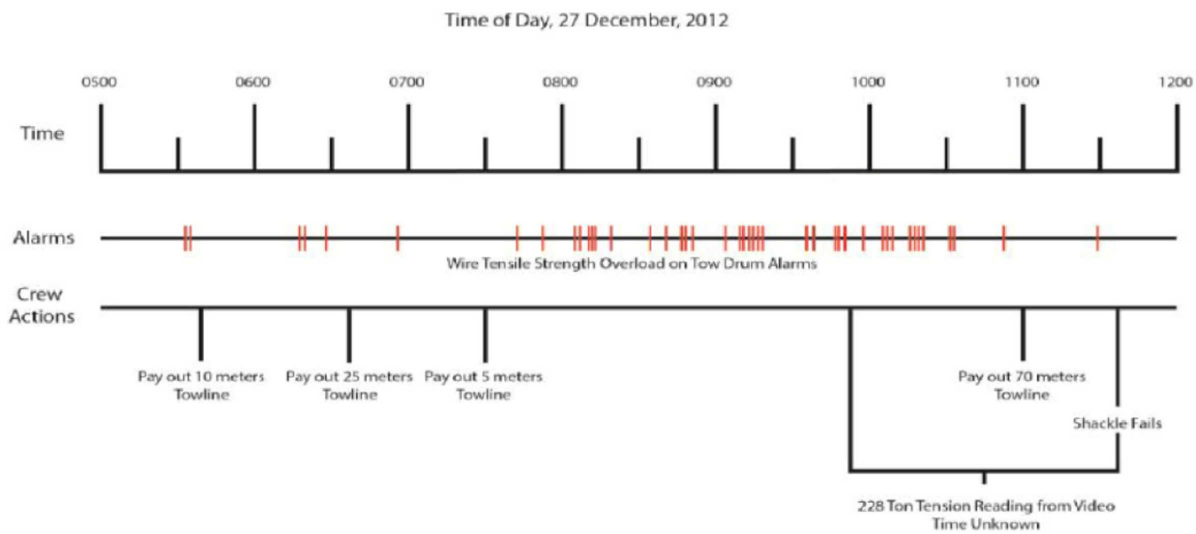


Figure 2.25: Analysis of wire tensile strength and crew actions. Berg et al. (2015)

From figure 2.25 one can see that the towline length was increased multiple times in order to try to lower the tension. Around 11.30 am, a shackle failed and the towline was lost. At this point the waves were too high to reset the towing gear with cranes. A temporary connection was established at a time, but this failed quite rapidly. Kulluk drifted out of control and grounded on the shore near Kodiak on 31^{st} December. The drilling rig endured some structural damage due to the grounding, but all 18 people on board were rescued.

The root cause of the accident is regarded as the poor risk management practices by Shell and Edison-Chouest. In addition to this was the lack of Arctic experience of the people responsible during the tow.

Lessons Learned

The lessons learned from the Kulluk accident are quite extensive. Guard (2014) listed eight safety recommendations in their accident report where the first three are related to activities regarding towing in the Arctic. The estimated towing time would have been approximately three weeks and given the uncertainty in extended forecast, the possibility of encountering bad weather should have been considered as a worst case scenario. From the investigation report, two important findings were:

- In the winter season, towing operations close to the coastline should be avoided.
- To prevent breaking loads in the towline tow-strain monitoring equipment should be closely watched.

Three ways to reduce towline tension are mentioned in Berg et al. (2015) where the second is regarded as the best in general:

1. Increase towline length
2. Reduce speed of towline vessel
3. Change heading for the towing operation

2.5.3 Discussion

Seen from these cases, harsh weather was the common factor in accident development. Weather forecasts are less reliable in Arctic waters and the need for extended weather windows are required when planning towing operations in these waters. The alpha factor is therefor especially important as discussed in section **??**. Area-specific knowledge among personnel combined with correct equipment will reduce the risk of losing control during tow.

Many accidents occur because maybe the most important part of equipment fails during tow, that is the towline. High loads in the line due to severe weather and waves results in breakage and dangerous situations arise when control is lost over the towed object. It is therefor very important to have a thorough understanding of the dynamics during tow and design the operation and towline against overload. The tug-master should know the durability of the equipment and not put the operation in unnecessary risk.

Chapter 3

Theory

This chapter will present and describe some theory relevant to marine operations. The theory is meant to give an overview and references should be consolidated to get a more in-depth knowledge.

3.1 Sea Environment

Towing operations will naturally be affected by environmental factors which will put boundaries on operational limits. The towed system will be subjected to forces rising from these environmental factors and the ones that are relevant for marine towing operations are mainly:

- Waves
- Current
- Wind

This section will present and discuss some theory related to these factors.

3.1.1 Waves

Linear Wave Potential Theory

First order waves are based on potential theory and the basic assumptions are (Faltinsen, 1999):

- The sea water is assumed incompressible
- The sea water is inviscid
- The fluid motion is irrotational

Using these assumptions, a velocity potential, ϕ, can be used to express the velocity vector of the fluid at any given time and space as seen in equation 3.1:

$$\mathbf{V} = \nabla\phi = \mathbf{i}\frac{\partial\phi}{\partial x} + \mathbf{j}\frac{\partial\phi}{\partial y} + \mathbf{k}\frac{\partial\phi}{\partial z} \tag{3.1}$$

where

V=Fluid velocity vector

ϕ=Velocity potential

i=Unit vector along x-axis

j=Unit vector along y-axis

k=Unit vector along z-axis

The velocity potential is convenient in the mathematical analysis of irrotational fluid motion. From the assumption that the water is incompressible, it follows that the velocity potential has to satisfy the Laplace equation:

$$\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2} = 0 \tag{3.2}$$

By using relevant boundary conditions it is possible to solve the Laplace governing equation for ϕ. (Faltinsen, 1999) have presented the kinematic boundary conditions and the dynamic free-surface condition used to derive the velocity potential for linear propagating waves. The dynamic free-surface condition is that the water pressure is equal to the constant atmospheric pressure, p_0, on the free surface (Faltinsen, 1999). Only one scalar function is needed to find the fluid pressure, p, and this is done by using Bernoulli's equation as in equation 3.3 (Faltinsen, 1999).

$$p + \rho g z + \rho \frac{\partial \phi}{\partial t} + \frac{\rho}{2} \mathbf{V} \cdot \mathbf{V} = C \tag{3.3}$$

where

C=Arbitrary function of time

ρ=Density of seawater

Wave Spectrum

Describing the sea surface is not an easy process. By applying the principles of linear theory it is possible to construct a wave spectrum. A wave spectrum gives the distribution of wave energy in a sea state and contains statistical information about the sea state. In most wave spectrum the significant wave height, H_s and the spectral period, T_p are common variables.

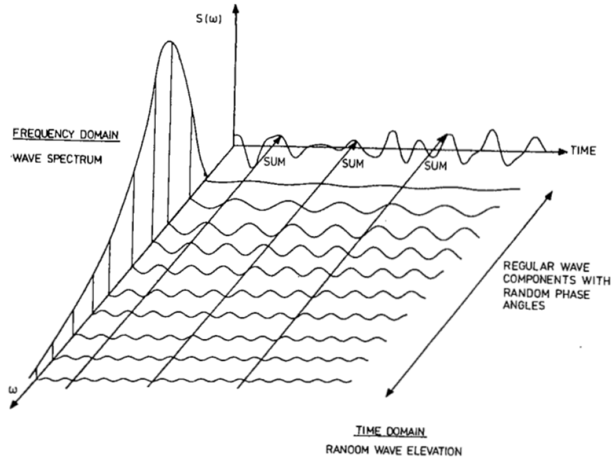


Figure 3.1: Irregular wave spectrum.(Faltinsen, 1999)

The JONSWAP (Joint North Sea Wave Project) is the result of a multinational measurement project in the south-east parts of the North Sea in 1968-1969. According to DNV GL (2011b) the spectrum is frequently applied for wind seas and extends the PM (Pierson-Moskowitz) to include fetch limited seas. The spectrum describe wind sea conditions that often occur for the most severe sea states. The JONSWAP spectrum is according to DNV GL (2011b) expected to be a reasonable model for $3.6 < T_p / \sqrt{H_s} < 5$. It is a five parameter spectrum and takes the form as equation 3.4, from Myrhaug (2007):

$$S(\omega) = \alpha \frac{g^2}{\omega^5} exp[-\beta(\frac{\omega_p}{\omega})^4]\gamma^{exp[-\frac{1}{2}(\frac{\omega-\omega_p}{\sigma\omega_p})^2]} \tag{3.4}$$

where

α = spectral parameter

ω_p = peak frequency, $\omega_p = 2\pi / T_p$

T_p = peak period

γ = peakedness parameter

β = form parameter, default value $\beta = 1.25$

σ = spectral parameter with deafault values

$\sigma_a = 0.07$ for $\omega < \omega_p$

$\sigma_b = 0.09$ for $\omega > \omega_p$

Significant wave height, H_s, is used to parametrize the spectrum (SIMO, 2013):

$$\alpha = (\frac{H_s \omega_p^2}{4g})^2 \frac{1}{0.065\gamma^{0.803} + 0.135} \tag{3.5}$$

where

$$\gamma = exp[3.484(1 - 0.1975\delta T_p^4 / H_s^2)] \tag{3.6}$$

$$\delta = 0.036 - 0.0056 T_p / \sqrt{H_s} \tag{3.7}$$

3.1.2 Current

During a tow operation it is important to consider the current. During submerged towing the current can cause drag and lift forces on the object being towed. From Faltinsen (1999) the surface current velocity U is divided into several components. The first component is denoted by U_t and is the tidal component. The tidal velocity component depends on the location and may be set up to $0.5ms^{-1}$. The second is the component generated by local wind, U_w. U_s is the component generated by Stokes drift and is valid for regular waves. Moreover, U_m is the component from major ocean circulation. U_{set-up} is the component due to set-up phenomena and storm surges. Last is the local density driven current caused by changes in density along the water column. All components add up to equation 5.3.

$$U = U_t + U_w + U_s + U_m + U_{set-up} + U_d \tag{3.8}$$

3.1.3 Wind

Depending on the location of the tow operation and the season the wind is important to consider. The following is largely based on Faltinsen (1999) and SIMO (2013).

The wind field is assumed to be propagating parallel to the horizontal plane (2D). When calculating the steady wind forces on marine structures the time average wind speeds over prescribed time periods are used. Due to wind gusts, fluctuating wind forces may also contribute and may in some cases excite resonant oscillations on structures. The wind profile used for the wind spectra is described by:

$$\overline{u}(z) = \overline{u_r}\frac{z}{z_r}^{\alpha} \tag{3.9}$$

where

z=height above the water surface

z_r=reference height, which is taken as 10 m

$\overline{u_r}$=average wind velocity at height z_r

α=height coefficient, which is taken as 0.11

3.2 Slamming

When the bottom of an object such as a ship or a barge hits the water with a high velocity, impulse loads with high pressure peaks occur (Faltinsen, 1999). This is what is often referred to as slamming which is a nonlinear phenomenon and an important aspect for marine operations. Towing operations where barges are used to transport costly equipment like subsea templates or parts for offshore wind turbines can be exposed to slamming. The slamming force, $F_s(t)$, for water entry in waves can be taken as (DNV GL, 2011b):

$$F_s(t) = \frac{1}{2}\rho C_s A_p(\dot{\zeta} - \dot{\eta})^2 \tag{3.10}$$

where

C_s=Slamming coefficient

A_p=Horizontal projected area of object

$\dot{\zeta}$=Vertical velocity of sea surface

$\dot{\eta}$=Vertical velocity of payload

As seen from equation 3.10 the relative velocity between the object entering the water and the sea surface must be accounted for. The slamming coefficient is defined by:

$$C_s = \frac{2}{\rho A_p}\frac{dA_{33}^{\infty}}{dh} \tag{3.11}$$

3.3 Metocean Statistics

Weather statistics are of importance when planning a marine operation. When observing the sea surface it is clear that the wave series consists of a number waves, appearing chaotic. This is what is referred to as irregular sea. The description of the sea is done statistically based on the theory of stochastic processes. When describing a sea state either short-term or long-term description is used.

3.3.1 Short-term Statistics

From Faltinsen (1999), short-term statistics assumes that we can describe the sea as a stationary random process. Another way of saying this is that significant wave height, mean wave period, mean wind velocity and current are constant for a sea state. In practice the length of the sea state is limited to the range $1/2 - 10$ hours, often using 3 hours. Extreme wave statistics are estimated from the wave height distribution and aim to determine the largest expected wave in the evaluated time interval. By assuming that (Myrhaug, 2007):

- All wave heights are identically Rayleigh distributed.
- All wave heights are statistically independent.

the most probable largest wave height can be determined by equation 3.12. For a full description, see Myrhaug (2007).

$$H_M = H_{m0}\sqrt{\frac{lnN}{2}} \quad \text{for large N} \tag{3.12}$$

3.3.2 Long-term Statistics

In Long-term description of the sea the significant wave height and mean wave period will vary. Each stationary sea state is considered independent. The joint frequency of the significant wave height and the mean wave period need to be known in order to construct the long-term prediction. These values are presented in a scatter diagram. An example of such a scatter diagram is presented in figure 3.2.

H_s	SPECTRAL PEAK PERIOD																			SUM
	0-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	<20	
0-1	55	426	1105	1561	1545	1228	849	536	319	182	101	55	30	16	9	5	3	1	2	8028
1-2	4	136	992	2957	5061	6057	5704	4553	3234	2113	1300	765	436	243	133	72	39	21	23	33843
2-3	0	5	104	678	2048	3703	4709	4670	3869	2808	1846	1127	650	359	192	100	51	26	26	26971
3-4	0	0	4	61	370	1108	2038	2639	2640	2178	1552	989	578	315	163	81	39	18	15	14788
4-5	0	0	0	3	37	208	613	1121	1438	1410	1125	765	459	249	125	59	26	11	8	7657
5-6	0	0	0	0	2	25	131	373	664	823	771	580	366	201	99	44	19	7	4	4109
6-7	0	0	0	0	0	1	17	83	225	380	444	387	267	153	75	32	13	5	2	2084
7-8	0	0	0	0	0	0	1	11	53	132	207	221	175	108	55	23	9	3	1	999
8-9	0	0	0	0	0	0	0	1	8	33	75	105	101	70	38	16	6	2	1	456
9-10	0	0	0	0	0	0	0	0	1	6	20	40	49	41	25	11	4	1	0	198
10-11	0	0	0	0	0	0	0	0	0	1	4	12	20	21	15	8	3	1	0	85
11-12	0	0	0	0	0	0	0	0	0	0	1	3	7	9	8	5	2	1	0	36
12-13	0	0	0	0	0	0	0	0	0	0	0	0	2	3	4	3	1	0	0	13
13-14	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	4
14-15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
SUM	59	567	2205	5260	9063	12330	14062	13987	12451	10066	7446	5049	3140	1789	942	461	216	97	82	99272

Figure 3.2: Scatter diagram of significant wave height and spectral peak period.(Eik and Nygaard, 2004)

The scatter diagram can be used to find the cumulative probability distribution of wave heights, $P(h)$. This is the probability that the wave height does not exceed h. Using the scatter diagram for extreme value statistics can be useful. The probability level $Q = 1 - P(h)$ can be related by $Q = 1/N$ where N is the number of wave heights within a given period. By using this relation one is capable of finding the so called "100 year wave" which is typically used in offshore design. It is also possible to find the response variables for a ship, like the heave motion. By combining the joint probability of the significant wave height and mean wave period with the short-term distribution of amplitudes.

Furthermore the scatter diagram in figure 3.2 can be used in marine operation studies. Using the operational limiting criteria for an operation it is possible to find the percentage of time during a year when the operation can be performed. This operational criteria can be the significant wave height. However, the frequency table does not state anything about the duration of the sea states. As will be discussed in section 4.1.3, a marine operation is dependent on a weather window of sufficient time in order to be executed (Faltinsen, 1999).

3.4 System Response Analysis

Analysis of a towed or moored system can be performed by using a frequency domain method. This method works well for systems that are exposed to stationary random loads. From Veritas (2008), this is because the response spectrum, $S_R(\omega)$, can be determined directly from the transfer function and the wave spectrum as:

$$S_R(\omega) = |H(\omega)|^2 S(\omega) \tag{3.13}$$

where ω is wave frequency, $H(\omega)$ is the transfer function of the response in question and $S(\omega)$ is the wave spectrum. This requires linear equations of motion which will imply some inaccuracy in drag loads and time varying geometry.

3.5 Vortex Induced Vibrations

Vortex induced vibrations (VIV) is a structural response phenomenon that occurs due to the oscillating forces from alternate vortex shedding from a flow passing around a structure. The forces induced by vortex shedding has to be investigated since they can lead to resonant lock-in effects on structures. This section will describe vortex shedding and the resulting induced forces on a structure and how to calculate these.

Vortex Shedding

From Greco (2012) it is explained that when a flow is passing around a circular cylinder, the vorticity will be non-zero in the boundary layer because of the no slip condition. A fluid element will rotate if it is stuck to a surface but has a non-zero velocity at the top. Figure 3.3 shows the alternate shedding. For $Re > 40$, one vortex will grow bigger than the other and they will affect each other. The shedding pattern will depend heavily on Reynolds number and Keulegan-Carpenter number. It is the alternate vortex shedding that induce lift and drag forces on the cylinder.

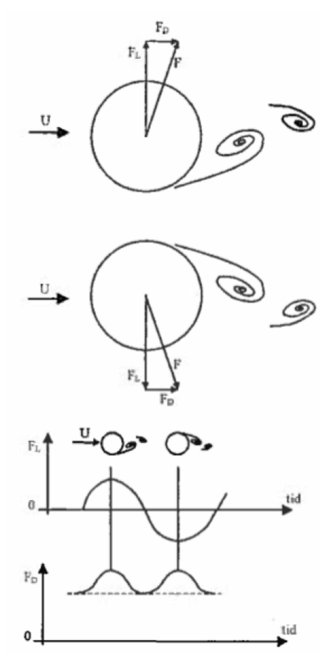


Figure 3.3: Alternating lift and drag forces due to alternating vortex shedding. Pettersen (2007)

If the lift- and drag forces become large it can lead to fatigue damage of the structure as well as large motions. It is therefore important to take this into consideration when planning a operation where this phenomenon could occur.

Shedding Frequency

The diameter of a cylinder D, the current velocity u, and vortex shedding frequency f_v, can be expressed dimensionless as in equation 3.14. This is the Strouhal number. The Strouhal number is equal to approximately 0.2 over a large area of the subcritical flow as seen in figure 3.4 for a circular cylinder.

$$S = \frac{f_v D}{u} \tag{3.14}$$

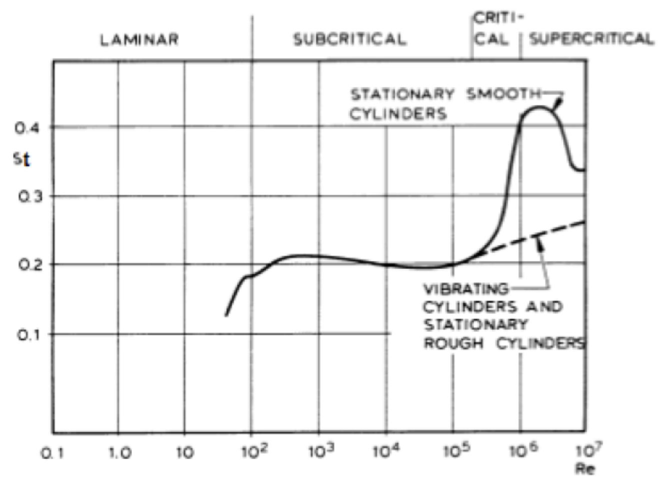


Figure 3.4: Coupling between Strouhals number and Reynolds number for a circular cylinder. Veritas (2000)

Drag Force

The vortex shedding causes an oscillatory drag force and it can be estimated as (Faltinsen, 1999):

$$F_D(t) = F_{d,mean} + A_D \cos(4\pi f_v t + \beta) \tag{3.15}$$

Here $F_{d,mean}$ is a mean value of the force that exists due to the mean frictioal term and pressure losses around the cylinder (Greco, 2012). The amplitude A_D is typically 20% of $F_{d,mean}$. From Faltinsen (1999) it is stated that the oscillation frequency of the oscillatory part of the drag force is twice the oscillation frequency of the vortex shedding frequency. β is the phase angle.

Lift Force

From Faltinsen (1999) the lift force can be approximated as:

$$F_L(t) = |f_L| cos(2\pi f_v t + \alpha) \tag{3.16}$$

Where $|f_L|$ is the lift force amplitude and α is the phase angle. As seen from figure 3.5 the lift force will oscillate around zero and the drag force will oscillate around an average value different from zero.

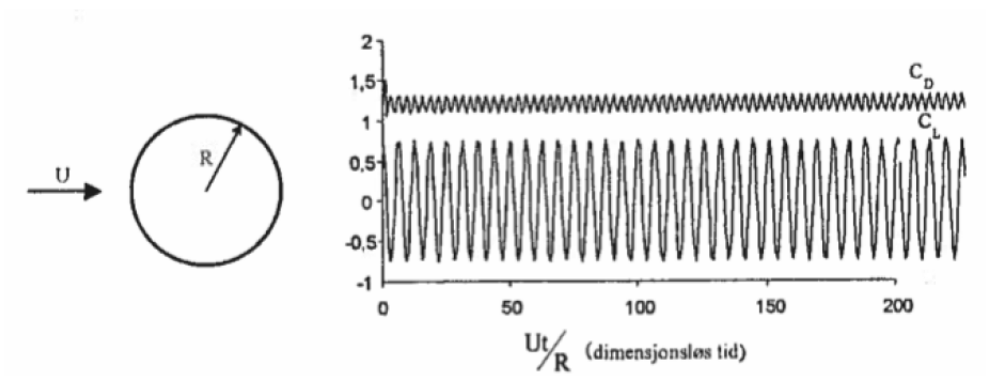


Figure 3.5: Oscillating drag and lift forces. Pettersen (2007)

Lock-In

The Strouhals number states a relation between the vortex shedding frequency, f_v and the flow velocity u. This is a linear relation as seen from figure 3.6. When the flow velocity is low and increasing, f_v will increase as well. However, at a certain flow velocity the vortex shedding frequency will coincide with the natural frequency of the cylinder and further increase in flow velocity will not change f_v. This is what is referred to as the lock-in phenomenon. The cylinder will oscillate and the excitation forces will increase. When the flow velocity reaches a certain level, f_v will again follow the same linear relation from equation 3.14. One should be aware of lock-in effects as large resonant motion behaviour may occur. Submerged tow of long and slender pipelines may be subject to this (Pettersen, 2007).

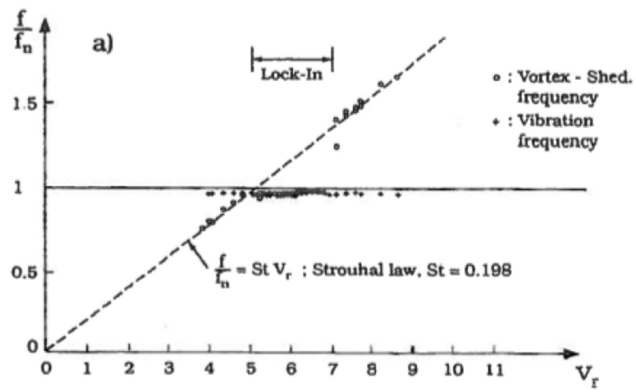


Figure 3.6: Lock-in. Pettersen (2007)

3.6 Towed System

3.6.1 Bollard Pull

Due to the variety of propulsion systems now in use, it is not advantageous to judge the power of a tug by the horsepower of its engine alone. It has therefore become necessary to a adopt a bollard pull test that can be universally accepted as a gauge of a vessel's ability to tow. Bollard pull is the amount of static pull the vessel can exert when tethered to a measuring device. The figure obtained is usually expressed in tonnes. A large stretch of water, unaffected by tides and of suitable depth is required for the test. The depth is of critical importance to avoid the phenomenon known as "ground effect". A depth of water not less than 20 meters is often typical (Gatson, 2002). In figure 3.7 a sketch of the test setup is shown, including the dynamometer used for measuring the thrust delivered by the propeller.

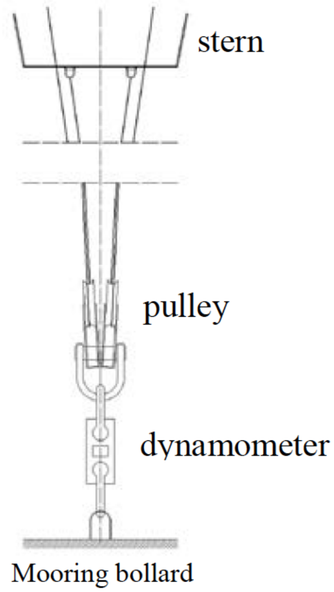


Figure 3.7: Bollard pull test setup. Notti et al. (2014)

A modern harbour tug will often produce a bollard pull of over 60 tonnes and a powerful tug supply vessel over 200 tonnes. Figure 3.8 shows some characteristic relations between installed power and bollard pull.

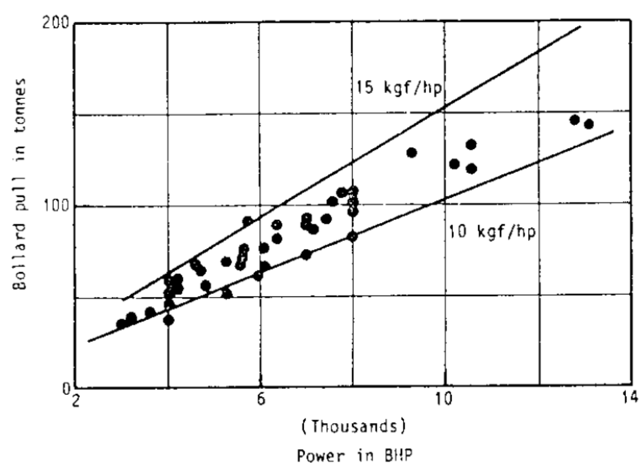


Figure 3.8: Bollard pull versus BHP for some supply vessels. Nielsen (2007)

3.6.2 Effect of Propeller Race

When towing with a very short towline, see section 2.1.1, the thrust of the propeller's wash may induce flow velocities at the towed structure which increases the towing resistance significantly. If the towed structure is small compared to the transverse dimensions of the propeller race the velocity in the propeller race may be considered as an increased towing velocity when calculating the towing resistance. It may be computed by using normal drag force considerations (Nielsen, 2007).

When the towed structure is large compared to the dimensions of the propeller race the approach above will not work for calculating resistance. To estimate the additional towing resistance momentum considerations may be used. If the propeller is assumed to be a circular disk of diameter D, the thrust of the propeller, F_p is equal to the axial flux of momentum through the propeller disk, dM_{0x}/dt:

$$\frac{dM_{0x}}{dt} = F_p = \rho \frac{\pi D^2}{4} U_0^2 \tag{3.17}$$

where the flow velocity through the disk is assumed to be homogeneous and is denoted U_0. It is assumed zero forward velocity of the tug. If a body is inserted in the propeller race the direction of the flow will be modified and a force will act on the body as a consequence, see figure 3.9.

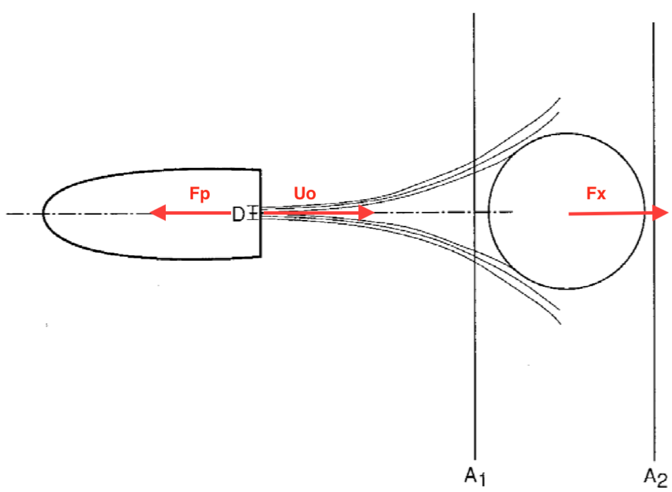


Figure 3.9: Deflection of the propeller race by a towed body. Nielsen (2007)

The difference in flux of momentum through the two infinite planes A_1 and A_2 represents the axial force on the body:

$$F_x = \frac{dM_{1x}}{dt} - \frac{dM_{2x}}{dt} = \rho \int_{A_1} U_x^2 dA - \rho \int_{A_2} U_x^2 dA \tag{3.18}$$

Two extreme cases arise. The first is that there is no change in momentum if $dM_{1x}/dt = dM_{2x}/dt$ and hence no net force on the body. However, there could be a small force contribution from friction due to viscous effects.

If the propeller race is completely reversed as seen in figure 3.10, $dM_{1x}/dt = 2F_p$ and $dM_{2x}/dt = 0$. This means that the force on the towed object is twice the propeller thrust and the total force on the tug and towed structure will be $F_p - 2F_p = -F_p$, hence the system will move backwards. This unwanted situation can arise during towing of large objects with short towlines (Nielsen, 2007).

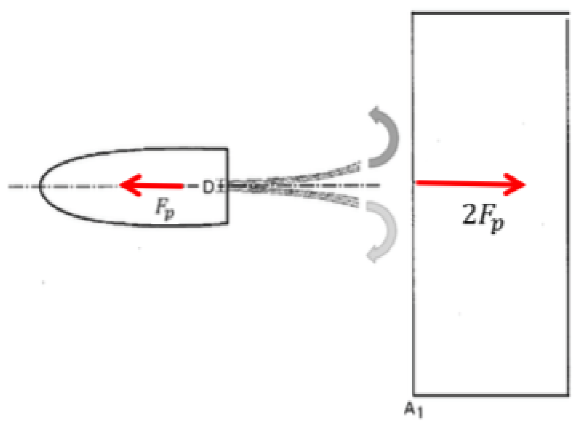


Figure 3.10: Propeller race completely reversed. Larsen (2016)

3.6.3 Reduction of Bollard Pull

From DNV GL (2015) it is stated that *"The effective BP shall be taken as the documented continuous static BP multiplied by relevant efficiency factors taking into account":*

- The effect of waves and other environmental loads on the tug itself

- Propeller race interaction
- More than one towing vessel

When towing with towlines longer than 30 m, a way to account for the additional force on the towed object due to propeller race is to introduce a factor to reduce the BP. The interaction factor α is proposed by DNV GL (2011b):

$$F_p^r = \alpha \cdot F_p \tag{3.19}$$

where

$$\alpha = [1 + 0.015 A_{exp}/L_{towline}]^{-\eta} \tag{3.20}$$

where
α = interaction efficiency factor
A_{exp} = projected cross-sectional area of towed object $[m^2]$
$L_{towline}$ = towline length $[m]$
η = 2.1 for typical barge shapes

The force on the structure decreases as the distance from the propeller increases as seen from equation 3.20 and figure 3.11. The reduction curve is for a barge with $B = 60m$ and $T = 20m$.

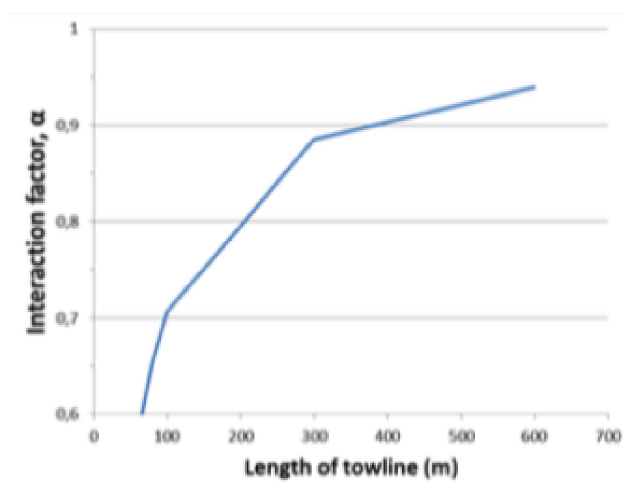


Figure 3.11: Reduction of available bollard pull due to propeller race for a barge with $B = 60m$ and $T = 20m$. Larsen (2016)

3.6.4 Bottom Clearance of Towline

In shallow waters the sag of the line must be limited to avoid bottom contact. Sliding contact between towline and sea bed may cause severe deterioration of towline strength. The length of the towline should be adjusted during normal operation at regular intervals to ensure that a sufficient clearance to the seabed is maintained throughout the operation. A typical static geometry of a towline is shown in figure 3.12.

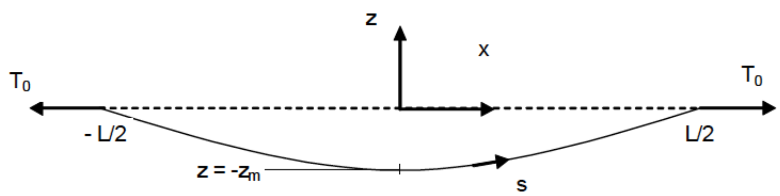


Figure 3.12: Geometry of towline. DNV GL (2011b)

When the towline tension is is much larger than the weight of the cable, $\frac{T_0}{W} >> 1$, the horizontal $x(s)$ and vertical $z(x)$ coordinates along the towline can be approximated like (DNV GL, 2011b);

$$x(s) = (1 + \frac{T_0}{EA})s - \frac{1}{6}(\frac{w}{T_0})^2 s^3 \tag{3.21}$$

$$z(s) = -z_m + \frac{1}{2}\frac{ws^2}{T_0}(1 + \frac{T_0}{EA}) \tag{3.22}$$

And

$$z_m = \frac{L}{8}(\frac{wL}{T_0})(1 + \frac{T_0}{EA}) \tag{3.23}$$

where

T_0 = towline tension [N]

L = length of towline [m]

w = submerged weight per unit length of towline [N/m]

W = total submerged weight of towline [N]

A = nominal cross-sectional area of towline $[m^2]$

E = modulus of elasticity of towline $[N/m^2]$

s = coordinate along the towline $(-L/2 < s < L/2)$

z_m = sag of towline

These formulas are approximations, but give good estimates. Usually $T_0/EA << 1$ so T_0/EA may be neglected. To provide sufficient bottom clearance;

$$z_m >> d \tag{3.24}$$

where d is the water depth.

3.6.5 Towing Winches

An active towing winch allows for adjustments to made to the towline length from the wheelhouse of the tug. No additional manpower is needed for adjusting the length during tow, which is a great advantage both for response and safety of crew. The winch may be equipped with a rendering winch which is a effective towline load reduction system. In case of high shock loads the winch will pay out in order to avoid snapping of towline. The winch will also automatically heave when the line tension is below a certain level. It can be adjusted with a tension control which allows for the winch to render more easily when working under difficult conditions like in heavy sea and wind (Hensen, 2003). In order for the winch to work efficiently in reducing extreme loads in the towline it requires a sufficient fast response. An illustration of the effect of a rendering winch is shown in figure 3.13. It is observed that the winch can reduce the maximum tension in the line considerably.

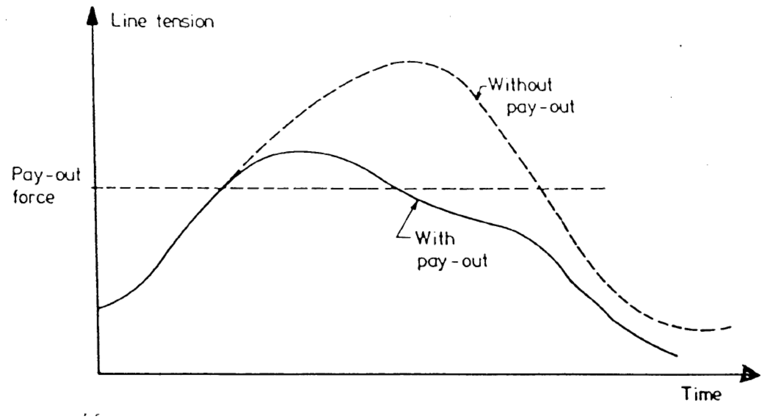


Figure 3.13: Illustration of the effect of a rendering winch during an extreme dynamic tension amplitude. Nielsen (2007)

3.6.6 Bridle

A bridle should be used to connect the towline to the towed object. Chains should be used in the way of chafing areas such as fairleads and deck edges. Locations where the bridle might bear on the towed object should be rounded of. In cases where the bridle consists of chain and wire, the length of the chain should extend beyond the towed object (DNV GL, 2015). The bridle will improve manoeuvrability and course stability of the towed structure as seen below from DNV GL (2011b).

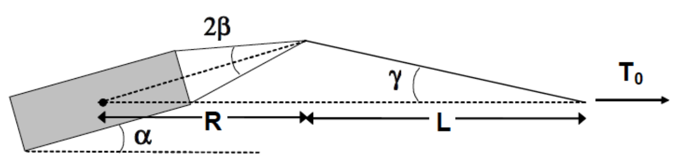


Figure 3.14: Layout of towline and bridle lines. DNV GL (2011b)

When the towed structure is rotated an angle α due to either change of course or environmental loads, the forces in each of the bridle lines will be different as seen from figure 3.14. Assuming each bridle line forms an angle β with the towing line, and the towing force is T_0, the distribution of forces in each bridle line for *small* rotation angles, is given by;

$$\frac{T_1}{T_0} = \frac{sin(\beta + \alpha + \gamma)}{sin 2\beta} \tag{3.25}$$

$$\frac{T_2}{T_0} = \frac{sin(\beta - \alpha - \gamma)}{sin 2\beta} \tag{3.26}$$

where

T_0 = towing force [N]

T_1 = force in port bridle [N]

T_2 = force in starboard bridle [N]

L = length of towline, measured from bridle [m]

R = distance from centre of gravity of towed structure to end of bridle lines [m]

α = angle of rotation of towed structure [rad]

β = angle between each of the bridle lines and the vessel centreline [rad]

$\gamma = \frac{R}{L}\alpha$ [rad]

The force in the starboard bridle line becomes zero when

$$\alpha = \frac{L\beta}{L + R} \tag{3.27}$$

For rotation angles greater than this value, one bridle line goes slack and only the other bridle line will take load. The moment of the towing force around the rotation centre of the towed structure is given as;

$$M_G = T_0 R(1 + \frac{R}{L})\alpha \tag{3.28}$$

and the rotational stiffness due to the towing force is given by;

$$C_{66} = T_0 R(1 + \frac{R}{L}) \tag{3.29}$$

Hence, the bridle contributes with a substantial increase in the rotational stiffness, improving the directional stability of the tow (DNV GL, 2011b).

Chapter 4

Operability

This chapter will describe and discuss the impact of metocean conditions on marine operations. Operability for towing operations is of importance as it is desired to perform the operation in a continuous manner without having to stop or halt due to unfavorable weather. Weather statistics will be used to assess the availability at Heidrun.

4.1 Weather Windows

From DNV GL (2011a) the duration of a tow operation is defined by an operation reference period given by equation 4.1.

$$T_R = T_{POP} + T_C \tag{4.1}$$

where

T_R = Operation reference period

T_{POP} = Planned operation period

T_C = Estimated maximum contingency time

T_{POP} should normally be based on a detailed, planned schedule for the operation. The contingency time shall be added to cover:

- General uncertainty in T_{POP}
- Possible contingency situations that will require additional time to complete the operation.

T_C may be set to 50% of the planned operation period, and should not be less than 6 hours. If uncertainties in T_{POP} are not assessed in detail the reference period should normally be taken as twice the planned operation period, $T_R = 2 \cdot T_{POP}$ (DNV GL, 2011a).

A tow operation is highly dependent on environmental conditions and should not be performed if the weather imposes danger to the operation. Generally, marine operations are separated into the following categories:

1. Weather restricted operations
2. Weather unrestricted operations

Weather restricted operations are marine operations with a reference period, T_R, less than 96 hours and a T_{POP} less than 72 hours. DNV GL (2011a) regards this as the maximum time period for which a weather forecast is sufficiently reliable. However, it is stated that in areas and/or seasons where the weather forecast may not be considered realistic, a shorter limiting T_R should be used. These types of operations are considered to start at the issuance of the latest weather forecast. An operation that can be halted and bring the handled object into a safe condition within the maximum allowable period for a weather restricted operation can be regarded as weather restricted even though its duration is to long to be defined as such initially. Continuous surveillance of actual and forecasted weather throughout the operation is then necessary. A tow operation is normally categorized as an weather restricted operation which means it can take place safely within the limits of a favourable weather forecast. Such periods are called weather windows and can be defined as:

"[...] the time span over which the stringent, multi-parametric conditions required by weather sensitive marine operations [...] are met".(Foo et al., 2014)

Figure 4.1 shows the required weather window and how the weather forecast influence the operation time.

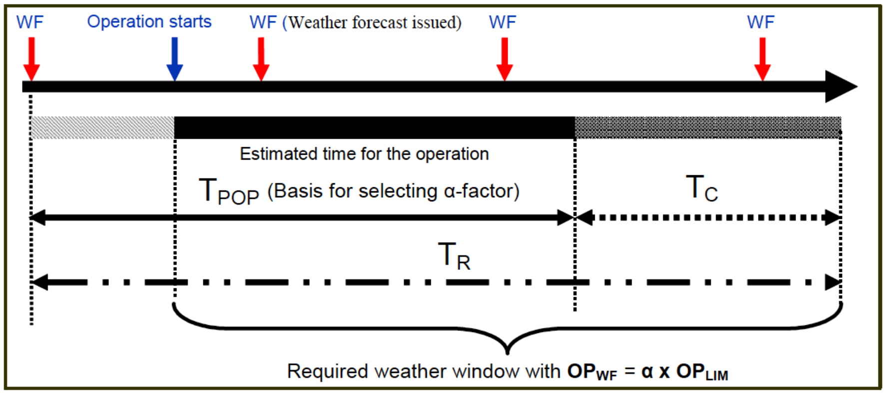


Figure 4.1: Operation periods. (DNV GL, 2011a)

Operations with a duration over 72 hours must be able to be carried out in any weather condition that can be encountered during the season. Such an operation is then classified as weather unrestricted. Statistical extremes for the area and season shall be considered in the design environmental criteria depending on the duration of the operation as tabulated in table 4.1. Operations of moderate duration can use seasonal variation for return periods.

Table 4.1: Acceptable return periods for unrestricted operations. DNV GL (2011a)

Duration of operation	**Return periods of metocean parameters**
Up to 3 days	Specific weather window to be defined
3 days to 1 week	1 year, seasonal
1 week to 1 month	10 year, seasonal
1 month to 1 year	100 year, seasonal
More than 1 year	100 year, all year

4.1.1 Uncertainty in Weather Forecast

When planning a weather restricted tow operation a operational environmental criteria is set, OP_{lim}. This design criterion is based on weather restrictions associated with the specific tow operation. It shall never be taken greater than the maximum environmental criteria, safe working conditions for personnel and/or equipment restrictions. When determining the required weather window there will always be some uncertainty related to the monitoring and forecasting of weather conditions. In order to account for this uncertainty DNV GL (2011a) introduces the α-factor (alpha-factor). The operational criterion then becomes the maximum weather condition for the execution of the tow operation and is defined as in equation 4.2.

$$OP_{WF} = \alpha \cdot OP_{lim} \tag{4.2}$$

The α-factor is important for safety and cost of the marine operation and should therefore be as reliable as possible. DNV GL (2011a) has tabulated the α-factor for several locations with respect to H_s, Design Wind Speed and T_{POP}. For waves, the α-factor is tabulated depending on weather forecast level and can have a higher value if a meteorologist is on site, monitoring of weather or two independent forecast sources are used. These measures will increase the certainty of the forecast which makes it less necessary to use a low α-factor to lower the operational criterion. In the North Sea and the Norwegian Sea the α-factor should be selected according to the tables in figure 4.2, 4.3 and 4.4 (DNV GL, 2011a). The tables can also be used as guidelines for other offshore areas. Some operations may be particular sensitive to certain wave periods and special considerations would need to be made in these cases. Uncertainty in the forecasted wave periods shall then be considered as well.

Table 4-1 α-factor for waves, base case							
Operational Period [h]	*Design Wave Height [m]*						
	$H_s = 1$	$1 < H_s < 2$	H_s =2= 2	$2 < H_s < 4$	$H_s = 4$	$4 < H_s < 6$	$H_s \geq 6$
$T_{POP} \leq 12$	0.65	Linear Interpolation	0.76	Linear Interpolation	0.79	Linear Interpolation	0.80
$T_{POP} \leq 24$	0.63		0.73		0.76		0.78
$T_{POP} \leq 36$	0.62		0.71		0.73		0.76
$T_{POP} \leq 48$	0.60		0.68		0.71		0.74
$T_{POP} \leq 72$	0.55		0.63		0.68		0.72

Figure 4.2: Values for α-factor for waves related to significant wave height, base case. (DNV GL, 2011a)

Table 4-3 α-factor for waves, Level A with meteorologist at site							
Operational Period [h]	*Design Wave Height [m]*						
	$H_s = 1$	$1 < H_s < 2$	$H_s = 2$	$2 < H_s < 4$	$H_s = 4$	$4 < H_s < 6$	$H_s \geq 6$
$T_{POP} \leq 12$	0.72	Linear Interpolation	0.84	Linear Interpolation	0.87	Linear Interpolation	0.88
$T_{POP} \leq 24$	0.69		0.80		0.84		0.86
$T_{POP} \leq 36$	0.68		0.78		0.80		0.84
$T_{POP} \leq 48$	0.66		0.75		0.78		0.81
$T_{POP} \leq 72$	0.61		0.69		0.75		0.79

Figure 4.3: Values for α-factor for waves related to significant wave height, level A forecast. (DNV GL, 2011a)

Table 4-2 α-factor for waves, Level B highest forecast							
Operational Period [h]	*Design Wave Height [m]*						
	$H_s = 1$	$1 < H_s < 2$	$H_s = 2$	$2 < H_s < 4$	$H_s = 4$	$4 < H_s < 6$	$H_s \geq 6$
$T_{POP} \leq 12$	0.68	Linear Interpolation	0.80	Linear Interpolation	0.83	Linear Interpolation	0.84
$T_{POP} \leq 24$	0.66		0.77		0.80		0.82
$T_{POP} \leq 36$	0.65		0.75		0.77		0.80
$T_{POP} \leq 48$	0.63		0.71		0.75		0.78
$T_{POP} \leq 72$	0.58		0.66		0.71		0.76

Figure 4.4: Values for α-factor for waves related to significant wave height, level B forecast. (DNV GL, 2011a)

As seen from from figure 4.5, α-factor decreases as T_{POP} increases and thus creating a stricter operational criterion for the planned tow operation from equation 4.2. In other words, the longer the planned operation period, the greater the difference between OP_{WF} and OP_{lim}. A thorough understanding of the operation in question and the challenges related to tow operations is therefore important.

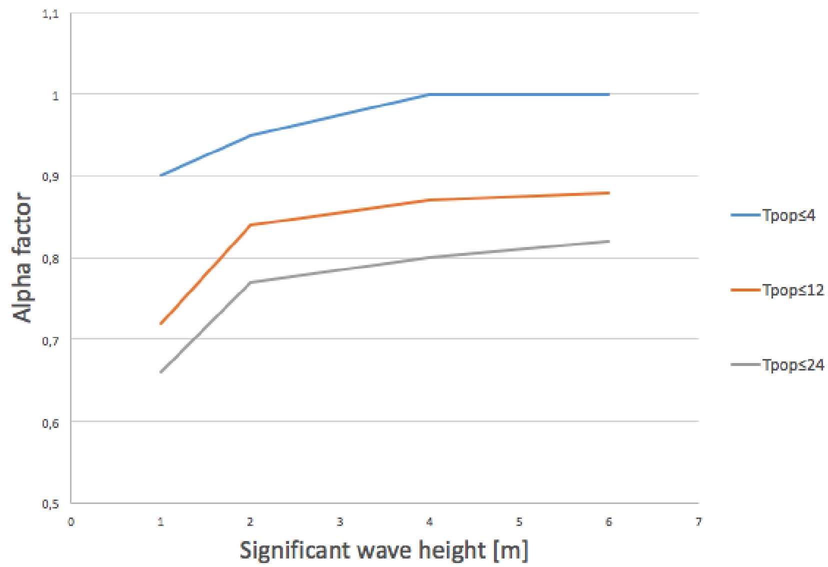


Figure 4.5: α-factor for waves, monitoring. (DNV GL, 2011a)

4.1.2 Safe Havens

DNV GL (2015) states that: *"Before departure, ports of shelter, or sheltered holding areas on or adjacent to the route, with available safe berths, mooring or holding areas, shall be agreed and all necessary permissions obtained."* If a marine operation has started and runs into unexpected weather and must halt it is called waiting on weather. A maintenance operation like pipeline repair or inspection of an offshore wind farm can be halted if the weather conditions makes it necessary. A tow operation can be regarded as a continuous operation where it is difficult to put the operation on hold when the tow is far offshore and runs into bad weather. It is therefore important to define safe havens along the planned route where the tow can reside in safe conditions. If this is not possible the tow operation should be classified as weather unrestricted. An operation can be planned as weather restricted even though the operation time is more than 72 hours. Continuous surveillance of weather forecast and planned safe havens along the route is then required. The accidental loads then needs to be designed for unrestricted weather conditions. An illustration of a tow operation with a planned operation time longer than 72 hours and safe havens can be seen in figure 4.6. This operation can be regarded as weather restricted if the tow can reach a safe state within 3 days at any time. Thorough planning of the tow route and safe havens is therefore of interest both for safety and cost.

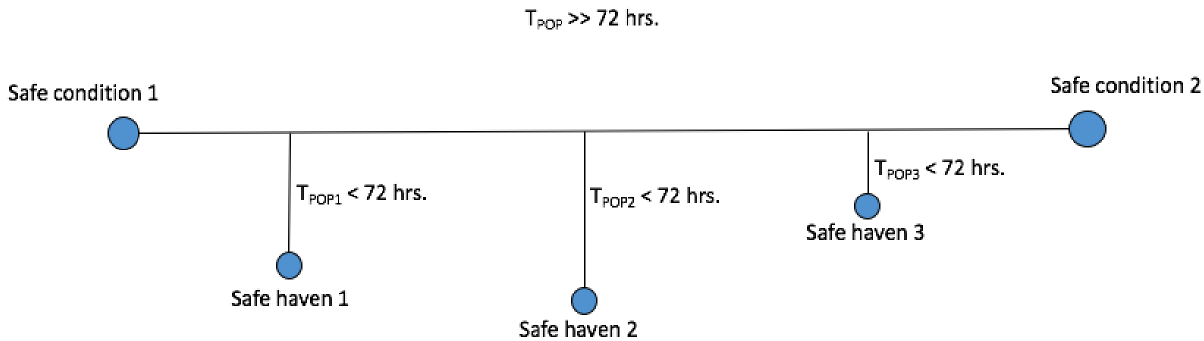


Figure 4.6: Illustration of safe havens for a tow operation with $T_{POP} >> 72hrs$.

4.1.3 Hindcast Data

As towing operations are most often classified as weather restricted it is very useful to be able to calculate the probability of experiencing acceptable weather conditions for a sufficient period of time. Since an operation is greatly affected by the motions initiated by waves, wind and current, it is very beneficial to have accurate weather information. This will lead to safer operations as well as more efficient ones reducing costs. In order to achieve a cost-effective operation it is important to plan thoroughly. The time period needed to perform the operation as well as what type of equipment that is available are of the first things to evaluate. The decisions for operation are normally based on weather forecast, but when planning budgets, schedules and contingencies it is important to have statistical information from historical observed weather data (Chen et al., 2008).

Weather windows can be visualized very easily by plotting the significant wave height, H_s, as a function of time. By marking the operational limit one can see when it safe to work and when it is not. Figure 4.7 is an example of such a plot.

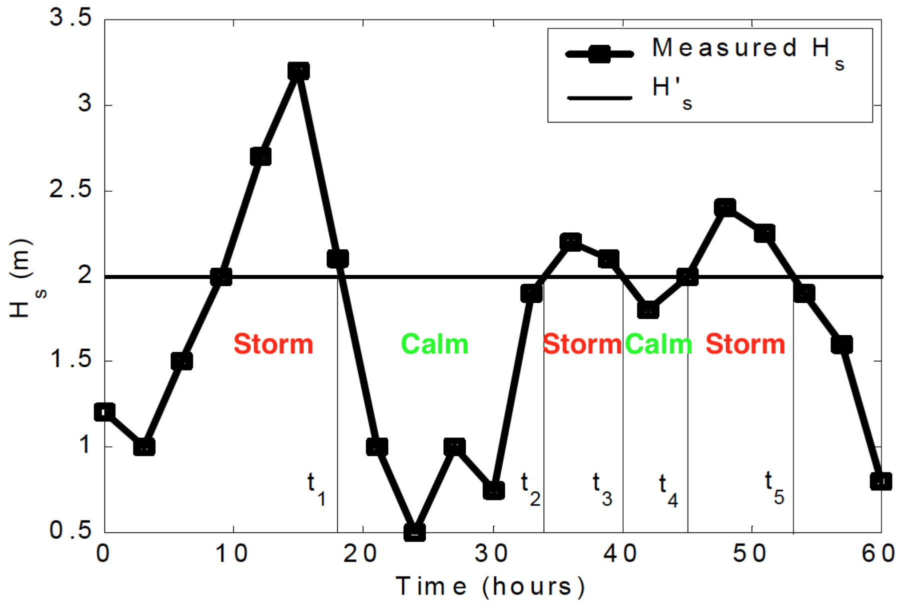


Figure 4.7: Example plot of weather windows with storms and calms. Nielsen (2007)

Storm condition as seen in in the plot is defined as a period when the wave height is above the threshold of the planned operation. A calm period is on the other hand when the wave height is below the operational limit and the operation can safely take place. For a operation to be conducted it is not enough to just have a period of calm, the duration of the calm must also be sufficiently long. That is, longer than T_R. This is the weather window. It is clear from figure 4.7 that if one can increase the operational limit by for example design, the average duration of calm periods increase and average time of storms decrease. However, there are more factors to consider than for example the forces induced by waves acting on components during tow. Crew safety and comfort may be threatened at a lower wave height than for equipment breaking strength. There exists a balance between what the operational limit can be and what it should be. Still, in order to maximize the time able to work, OP_{WF} must be as high as *possible*. Storms and clams are normally characterised based on significant wave height as mentioned above. However, forces and motion responses of vessels during tow may be more sensitive to wave period. Still, in practice, only wave height is normally considered when evaluating the feasibility of the operation (Nielsen, 2007).

Once the operational criterion has been set, it is important to find the probability of having such conditions so that it is possible to work. If the probability is found to be too small there may be necessary to relax the criterion in order avoid long unnecessary waiting. Based on hindcast data, the average duration of calms can be calculated for a specific area given an operating limit. The following is largely based on Larsen (2016). It is possible to use the observed/empirical data to find the cumulative probability distribution of a significant wave height denoted $P(H_s)$. From figure 4.7 H_s' is used to symbolize the operational limit, OP_{WF}. The accumulated duration of all calm periods during the total duration of the time series considered can be expressed as:

$$T_c = \overline{\tau}_c \cdot N_c \tag{4.3}$$

Where $\overline{\tau}_c$ is the average duration of calms and N_c is number of calm periods. From observations it is possible to determine $\overline{\tau}_c$. By plotting the cumulative distribution of wave heights $P(H_s)$ against the average length of calms it is found that the Weibull distribution gives an acceptable fit. This relationship can be seen in equation 4.4.

$$\overline{\tau}_c = A[-ln(P(H_s))]^{-\frac{1}{B}} \tag{4.4}$$

So, by knowing the cumulative probability distribution of H_s, the average length of calms can be estimated. In equation 4.4, A and B have region specific values. Observations from the North Sea gives $A = 20$ hours and $B = 1.3$. As mentioned above, a weather window is not only dependent on the operational limit, but also on the duration of this window. In other words it can be stated that *The probability of being able to work is equal to the probability that H_s is lower than OP_{WF} and that the calm period τ_c is longer than the operational reference period, T_R*. The probability of having a weather window is then:

$$P((H_s \leq OP_{WF}) \cap (\tau_c \geq T_R)) \tag{4.5}$$

Here, τ_c is the duration of the calm period and OP_{WF} is the operational criteria computed with equation 4.2. The cumulative probability of length of calms, τ_c, is described by a Weibull distribution:

$$P(\tau_c \geq t) = e^{-(\frac{t}{t_c})^{\beta}} \tag{4.6}$$

The parameters β and t_c are not known and need to be estimated. These values will vary depending on the geographical area and the level of significant wave height. t_c is determined from the mean value of the Weibull distribution and the cumulative distribution of H_s. This gives the relation:

$$\overline{\tau}_c(h) = t_c * \Gamma(1 + \frac{1}{\beta}) = A[-ln(P(H_s))]^{\frac{1}{B}} \tag{4.7}$$

Where $\Gamma()$ denotes the Gamma function. By solving equation 4.7 for t_c it is possible to plot cumulative probability of length of calms in equation 4.6. The probability of having a weather window for a given H_s and operation time can now be determined from equation 4.5. The total operational time T_{OP} in a given period T_{TOT} can then be expressed as:

$$T_{OP} = T_{TOT}((H_s \leq OP_{WF}) \cap (\tau_c \geq T_R)) \tag{4.8}$$

4.2 Polar Lows

In Arctic regions like the Barents sea the weather may change rapidly and strong storms may develop quickly. These are mesoscale weather events which means their horizontal length scale is less than 1000 km. Mesoscale vortices at high latitudes are most commonly known as "polar lows". What characterises polar lows are generally strong winds, showers and sometimes heavy snow. This can complicate a tow operation severely with implications like high sea, poor visibility and icing. Polar lows are difficult to forecast as they form quickly making it problematic to plan a marine operation in these areas. The fact that the storm moves is the reason for the generation of large waves. If reasonably stationary the wave height would be limited due to the short duration of the low. When moving, large waves develop where wind speed has the same direction as the low itself. As mentioned, it is the sudden change in environmental conditions that propose a big threat to marine operations in the Arctic. It has been observed cases where the wave height has increased from 3m to 6m in a matter of hours (Rasmussen and Turner, 2003).

4.3 Operation Time

Time is always an issue related to a tow operation in order make sure required weather conditions are present. There is also the important aspect of being able to deliver on time with respect to contracts and cost driven factors such as vessel day rates etc. All of this is important to consider during the planning process. A large platform of the Condeep type may have a displacement of $600000 tons$ in floating condition. When taking into account the added mass the total mass comes up to around $10^6 tons$. If three tugs are used each with a bollard pull of $2000kN$, the maximum acceleration which can be obtained is $0.006m/s^2$. This means that increasing the tow velocity from zero to $0.5m/s$ will take around 80 seconds (Nielsen, 2007). It is clear that an operation of this magnitude would require a large weather window for a long distance tow if it would be classified as weather restricted. Utilizing more tugs can be a way to reduce operation time and performing the operation during periods with reliable weather increases the probability of sufficient weather windows.

4.4 Operability Calculations

4.4.1 Heidrun

This section will study and perform statistical analysis of weather data at Heidrun using the theory described in section 4.1.3. The weather data were provided by the supervisor and covers the years 1957 - 2009. The data consists of measurements of wind speed, wind direction, significant wave height, peak period and wave direction taken every 3rd hour. The significant wave height will be the parameter of interest, as this is most often used when evaluating the feasibility of operation (Nielsen, 2007). As discussed previously the availability of an operation is not limited only to the wave height, but also the time period of a calm sea state, τ_{calm}. Finding the average length of calms during for example the months July, August and September can give a very useful indication of when it is best to perform the operation as compared to the winter months January and February.

Average Duration of Calms

The cumulative distribution of wave heights, $P(H_s)$, is found from the provided weather data. The all-year cumulative distribution of significant wave height for Heidrun from 1957-2009 is shown in figure 4.8. Figure 4.9 displays the plot of the average length of calms at Heidrun plotted against the cumulative probability of significant wave height. Average duration of calm periods for the entire year can the be found from equation 4.4, using the values $A = 20$ and $B = 1.3$, and are tabulated for different H_s in table 4.2. Figure 4.10 shows the plotted average duration of calms as a function of significant wave height. From this plot each H_s can represent a given operational limit and the related average calm period.

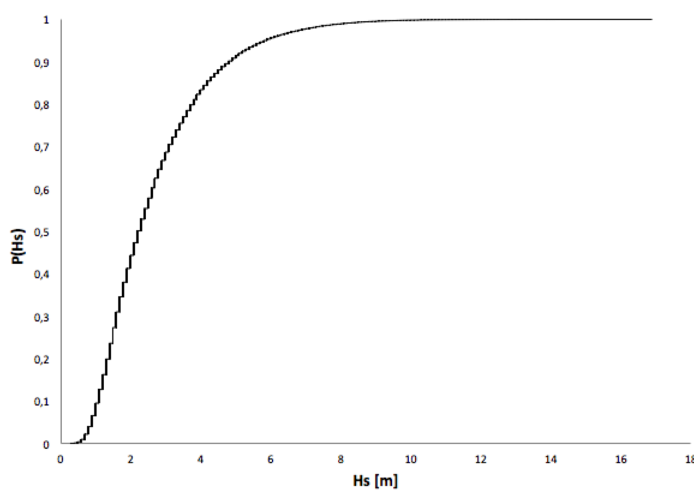


Figure 4.8: All-year cumulative distribution of significant wave height, H_s, for Heidrun. Years 1957-2009.

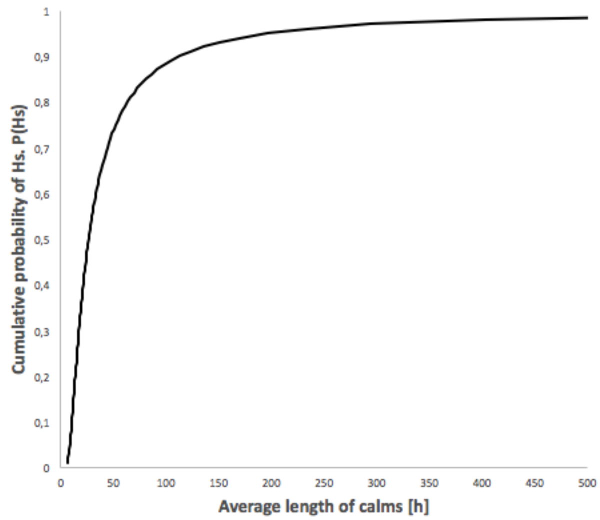


Figure 4.9: Average length of calms from observations for Heidrun plotted against the cumulative probability of significant wave height.

Table 4.2: Average duration of calms, $\overline{\tau}_c$, all-year for different H_s for Heidrun. Years 1957-2009.

H_s [m]	$\overline{\tau}_c$ [h]
1.0	10.16
1.5	16.25
2.0	22.8
2.5	31.9
3.0	41.65
3.5	56.2
4.0	69.42
4.5	91.25
5.0	123.2

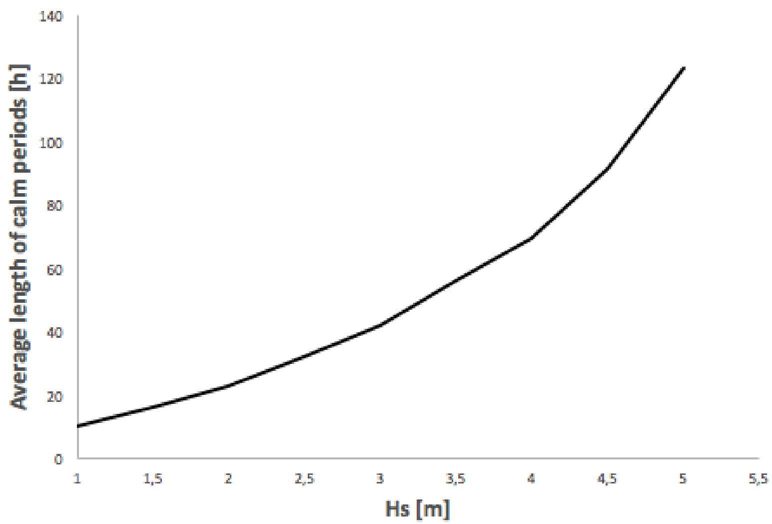


Figure 4.10: Average length of calms from all-year observations for Heidrun plotted against significant wave height, H_s. Years 1957-2009.

When planning a tow operation it may be convenient to know the operability for a specific period during the year. Weather data analysis of the summer and winter months are carried out in order to compare the differences in operability and get a deeper understanding of when it will be viable to execute a tow operation most efficiently and safely. Figure 4.11 shows the cumulative distribution of H_s for the months May-August and November-February. As can be expected the plot shows that the distribution of H_s is shifted towards larger values for the winter months. The rough sea state during winter in the Norwegian Sea can be challenging for marine operations as it can be seen form observed data that about 50% of registered H_s are above 3.8 meters during the months November-February.

Table 4.3 and 4.4 displays the average length of calms for May-August and November-February respectively. It is clear that the availability is much higher during the summer months as well as the probability of having a suitable weather window for the operation. When the average duration of calms are longer it is more likely to start an operation at the beginning of a favorable forecast. The difference between the two seasons is quite noticeable and is clearly visualized from the plot in figure 4.12. If a weather window of 50 hours is needed for an operation the operational limit would be around 1.8 m during the summer season as compared to around 4.5 m during the winter season.

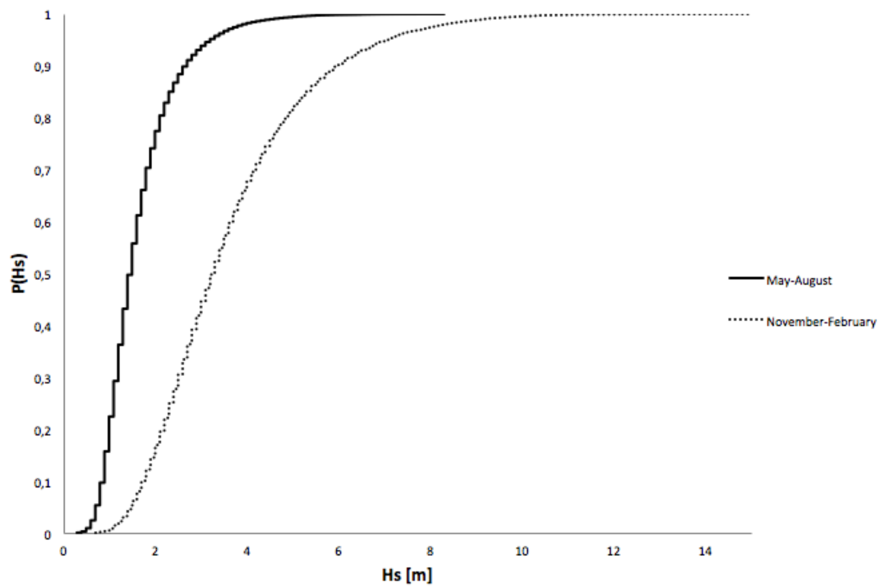


Figure 4.11: Cumulative distribution of significant wave height, H_s, for Heidrun. May-August and November-February. Years 1957-2009.

Table 4.3: Average duration of calms,$\overline{\tau}_c$, May-August for different H_s for Heidrun. 1957-2009.

H_s [m]	$\overline{\tau}_c$ [h]
1.0	14.19
1.5	29.72
2.0	56.2
2.5	97.47
3.0	150.74
3.5	234.76
4.0	403.51

Table 4.4: Average duration of calms, $\overline{\tau}_c$, November-February for different H_s for Heidrun. 1957-2009.

H_s [m]	$\overline{\tau}_c$ [h]
1.5	9.01
2.0	12.54
2.5	23.28
3.0	23.28
3.5	29.72
4.0	40.46
4.5	52.2
5.0	66.33
5.5	85.82
6.0	113.12
6.5	135.5
7.0	170.43
7.5	234.6
8.0	294.14

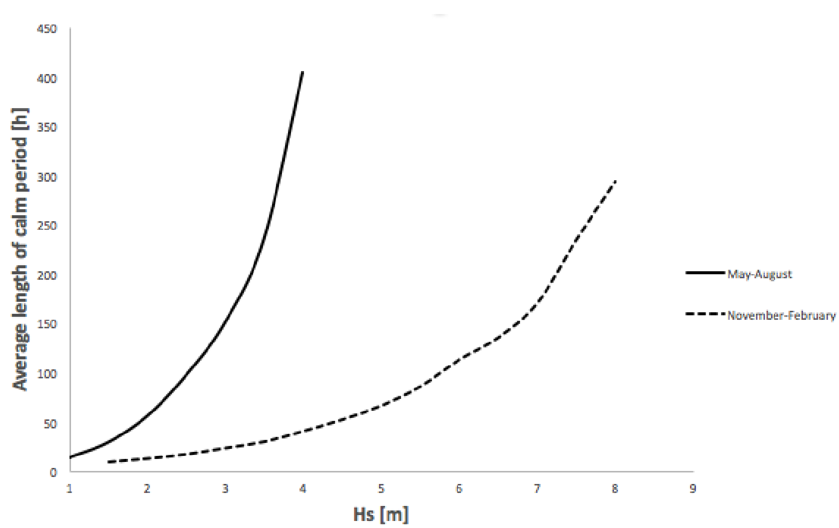


Figure 4.12: Average duration of calms for May-August and November-February observations for Heidrun plotted against significant wave height, H_s. Years 1957-2009.

Probability of Working

The probability of having an acceptable weather window is calculated for different H_S and weather window length requirement. The parameter t_c is calculated as described in section 4.1.3 and $\beta = 0.8$ is used with basis from Nielsen (2007). Results for the months May-August and November-February are tabulated in table 4.5 and 4.6 respectively. These results show that relaxing the operational limits in form of higher allowable H_S can significantly increase the probability of having an acceptable weather window. An increase in probability is also seen by reducing the required duration of weather window by shortening the operation time. In general, the summer months can be regarded as a more favorable part of the year for executing an operation as the probability of having an acceptable window is higher for the same operational conditions that is limiting significant wave height and duration of operation.

Table 4.5: Probability of having an acceptable weather window at Heidrun. May-August

	Duration [h]			
H_S [m]	10	24	48	72
1	9%	4%	1%	0%
2	55%	41%	27%	19%
3	82%	72%	60%	50%
4	93%	87%	80%	74%

Table 4.6: Probability of having an acceptable weather window at Heidrun. November-February

	Duration [h]			
H_S [m]	10	24	48	72
2	6%	2%	1%	0%
3	25%	14%	6%	3%
4	47%	32%	19%	12%
4.5	56%	41%	27%	18%
5.5	71%	58%	43%	33%
6	77%	65%	52%	42%
7	84%	75%	63%	54%

Chapter 5

Towline Tension Model

The purpose of this chapter is to develop a model to estimate the towline tension during the tow of a large offshore platform. Theory related to towline stiffness and dynamic response are presented in the development of the model. By calculating the tension in the line the goal is to establish operational limits in order to ensure a safe and cost effective operation. A case study is performed by performing calculations in Excel on the tow of semi-submersible drilling rig Deepsea Bergen (DSB) owned by Oddfjell Drilling. A parameter variation of selected parameters of equipment and environmental conditions is performed in order to study the tension and try to improve operability.

5.1 Motivation for Model

During a tow operation the breaking of towing lines can have severe consequences for personnel, equipment and environment. One problem that can cause breaking of the line can be overloading by exceeding the design breaking load of the towline. The use of proper safety factors, shock absorbers and correct evaluation of operational limits can reduce the occurrence of such situations. From Nielsen (2007) it is argued from statistical analysis of towline breakage that the most frequent reason for failure is in the synthetic fibre at the stern of the tug. A thorough understanding of the static and dynamic behaviour of the towed system is needed in order to plan the operation safely and establish reasonable operational limits. As the offshore industry continuously moves into areas of deeper waters as well as colder and more demanding locations like the Barents sea, longer and more complicated tow operations are needed which brings with it additional challenges.

A fast, simplified and reliable model for calculating towline tension can be useful in the design phase of an operation. By establishing the operational limitations in form of significant wave height the operability of operation can be found as well as the probability of being able to work. From Larsen and Sandvik (1990) it is argued that a model which incorporates the effect of dynamic behaviour can be helpful on several areas:

- The model can be used to check whether a quasi-static calculation gives reasonably accurate tension level.
- The effect of the parameters determining the dynamic behaviour can be clearly illustrated. This can help the designer choose the right system configuration.
- A model with acceptable accuracy can be used directly to determine the extreme line tension and fatigue load effects. This can eliminate the need for extensive time consuming analysis.

5.2 Model Setup and Assumptions

A sketch of the towed model with acting forces is shown in figure 5.1. In the analysis the semi-submersible or the the towed object is assumed to be at rest or at constant low velocity. This assumption is said to be reasonable when considering the large difference in mass between the rig and tug. During tow the ship stern is set to move in the horizontal direction alone (surge), denoted x_a in the model. With incoming waves as the tug and object sails forward this assumption will not be completely accurate. In addition to the surge motion, heave and pitch motion will affect the dynamic tension in the line as illustrated in figure 5.2. However, for simplicity only surge motion is considered in the model when calculating the dynamic towline tension. Low frequency motions are assumed. The environmental forces acting to the rig and tug from waves, wind and current are set to come directly on to the front of the towed system.

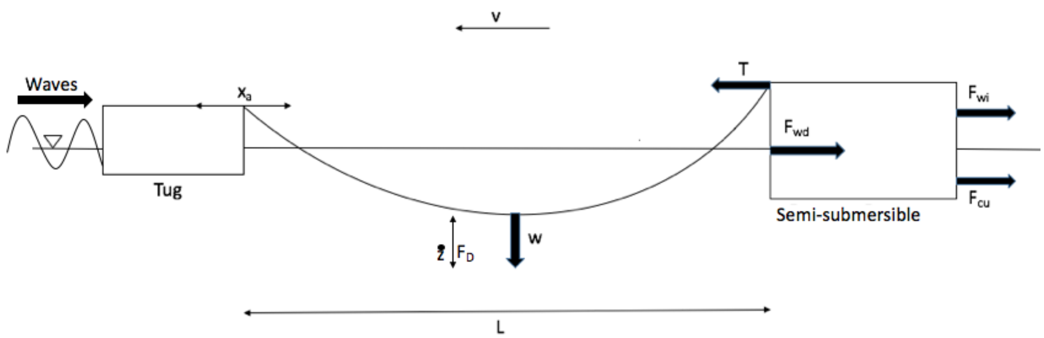


Figure 5.1: Dynamic model of towed system with acting forces when towing a semi-submersible.

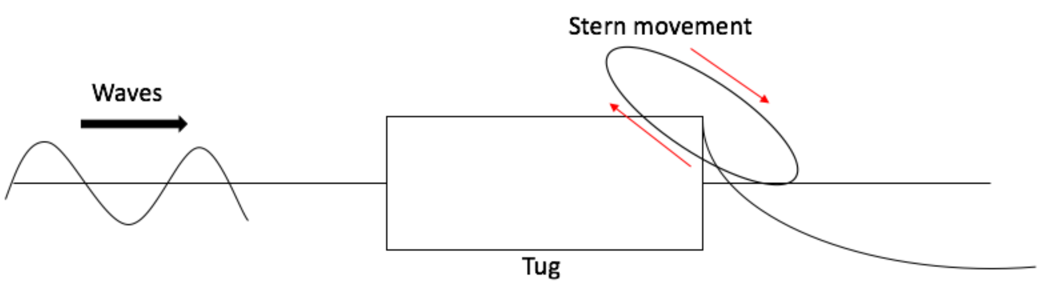


Figure 5.2: Illustration of tug stern movement with incoming waves during tow.

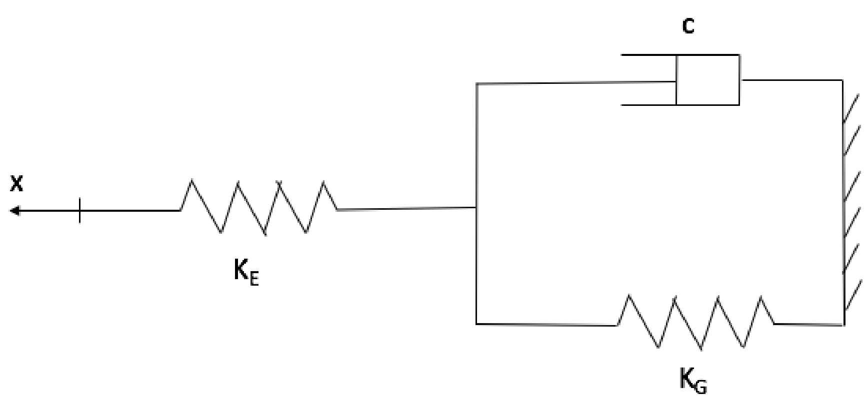


Figure 5.3: Model of towline as two springs in series and a damper.

The towing line is modeled as two springs in series and a damper as seen in figure 5.3 and it is assumed that the whole line is submerged in water during tow. The elastic stiffness, K_E is due to the elastic elongation of the towline and the geometric stiffness, K_G is due to the change of geometry and hence towline stiffness. The damper in parallel with the geometric stiffness is inserted to represent the viscous forces on the towing line when the line moves vertically in the water. The stiffness is important because:

1. It controls the low-frequency motions of the tow (surge, sway and yaw)
2. It controls the dynamic tension in the towing line

Only the drag forces normal to the line are considered. Tangential drag forces are not evaluated. The towline is modeled to be of the same material and have constant properties along its entire length. As the tug moves in surge the geometry of the towline will change and the sag of the line is assumed to be small, $|z_m| << L$.

5.2.1 Mean Towline Tension

Figure 5.1 is used as basis when determining the expression for the mean towline tension, $\bar{T}$. The mean tension is the sum of the mean resistance of the towed rig and the mean drag force of the tow cable. In this model it is assumed that a good approximation for $\bar{T}$ is given as:

$$\bar{T} = F_R = F_{wd} + F_{wi} + F_{cu} \tag{5.1}$$

where
F_{wd} = wave drift force
F_{wi} = wind force
F_{cu} = current force

In order to be able to calculate the mean tension some data is required about the towed semi-submersible, the operational conditions and environmental parameters. By knowing the drag coefficients for wind and current for the rig as well as the towing velocity, wind and current forces on the rig during tow can be calculated as:

$$F_{wi} = c_{wi} V_w^2 \tag{5.2}$$

$$F_{cu} = c_{cu} V_c^2 \tag{5.3}$$

where

c_{wi} = drag coefficient wind

c_{cu} = drag coefficient current

V = towing velocity

$V_c = V_{cu} + V$

V_{cu} = current velocity

$V_w = V_{wi} + V$

V_{wi} = wind velocity

The wave drift force is calculated as shown in equation 5.4. Theory on the JONSWAP spectrum can be found in section 3.1.1.

$$F_{wd} = 2\int_{\infty} S(\omega)c(\omega)d\omega \tag{5.4}$$

where

$S(\omega)$ = JONSWAP spectrum

$c(\omega)$ = mean wave drift force coefficients of semi-submersible

The integration of $S(\omega)c(\omega)$ is done by using the trapezoidal rule Excel. The function is broken into trapezoids, as seen in figure 5.4, and each area is calculated as:

$$Area = (t_2 - t_1)[\frac{f(t_1) + f(t_2)}{2}] \tag{5.5}$$

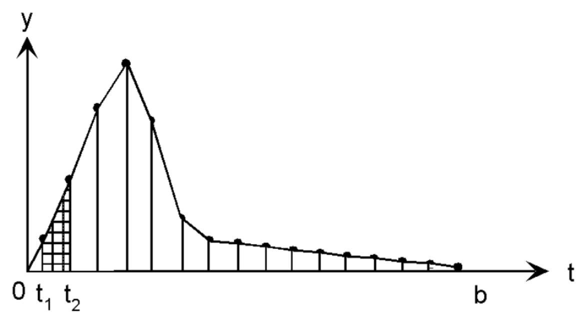


Figure 5.4: Illustration of the trapezoidal rule

5.2.2 Dynamic Towline Tension

The following expressions for the elastic and geometric contributions to the stiffness is used (Nielsen, 2007):

$$k_E = \frac{EA}{L} \tag{5.6}$$

$$k_G = \frac{12\bar{T}^3}{(wL)^2 L} \tag{5.7}$$

where

EA = axial elastic stiffness

L = towline length

w = submerged towline weight per unit length

$\bar{T}$ = mean towline tension

The total stiffness is then given by equation 5.8. An illustration of the total stiffnes in the line can be seen in figure 5.5.

$$\frac{1}{k_{tot}} = \frac{1}{k_E} + \frac{1}{k_G} \tag{5.8}$$

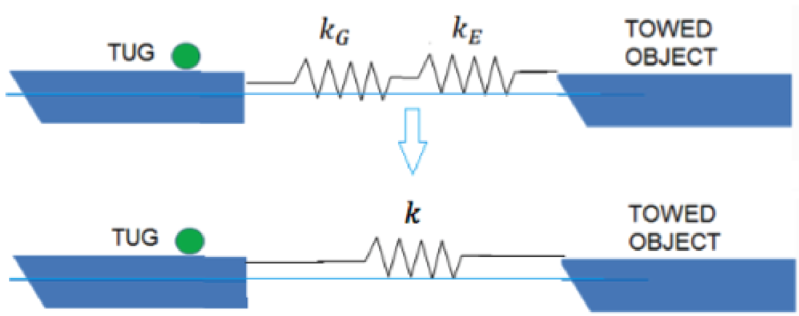


Figure 5.5: Total horizontal stiffness of towline. Larsen (2016)

By using Hooke's law for a linear spring, the dynamic tension in the towline can be calculated with equation 5.9.

$$T_d = k_{tot} x_a \tag{5.9}$$

where

x_a = horizontal movement of tug stern

There will also be a contribution to the dynamic tension from the drag force on the towline as it moves vertically in the water and it is calculated as in equation 5.10. See Nielsen (2007) for full derivation of expression.

$$T_D = \frac{11}{1920} \rho C_D d \frac{wL}{\bar{T}} \frac{k_{tot}^2 L^3}{\bar{T}^2} \dot{x}|\dot{x}| = K\dot{x}|\dot{x}| \tag{5.10}$$

where

T_D = tension due to drag forces

ρ = density of seawater

C_D = towline drag coefficient

d = towline diameter

w = submerged towline weight per unit length

$\dot{x}$ = horizontal velocity of tug stern

Equation 5.10 is not linear and need to be linearized. It is referred to Faltinsen (1999) for full theory on the linearisation process and the result is presented below.

$$T_D^{lin} = K_{lin}\dot{x} \tag{5.11}$$

$$error = T_D^{lin} - T_D = K_{lin}\dot{x} - K\dot{x}|\dot{x}| \tag{5.12}$$

$$K_{lin} = K\sqrt{\frac{8}{\pi}}\sigma_{\dot{x}} \tag{5.13}$$

$$T_D^{lin} = K\sqrt{\frac{8}{\pi}}\sigma_{\dot{x}}\dot{x} \tag{5.14}$$

Assuming a horizontal motion with $x = x_a \sin\omega t$ and $\dot{x} = x_a\omega\cos\omega t$. As described in section 3.4, the response velocity spectrum of the tug stern is found from $S_{\dot{x}}(\omega) = \omega^2 S_x(\omega)$ making it possible to determine $\sigma_{\dot{x}} = \sqrt{\int_0^\infty S_{\dot{x}} d\omega}$. It is noted that the quasistaic dynamic force given from $k_{tot}x_a$ and T_D^{lin} are out of phase and the total dynamic tension in the line is thus given by:

$$T_{dyn}^{tot} = \sqrt{(T_D^{lin})^2 + (k_{tot}x_a)^2} \tag{5.15}$$

It is the maximum dynamic tension along with the mean tension which is of interest in order to be able to determine which type of towline that is required and to establish operational limits. By finding the RAO for the dynamic tension and stern movement, equation 5.16, the maximum dynamic tension can be found as in equation 5.19

$$\frac{T_{dyn}^{tot}}{x_a} = \sqrt{(K\sqrt{\frac{8}{\pi}}\sigma_{\dot{x}}\omega)^2 + (k_{tot})^2} \tag{5.16}$$

$$S_{T_{dyn}^{tot}}(\omega) = |\frac{T_{dyn}^{tot}}{x_a}|^2 S_x(\omega) \tag{5.17}$$

$$\sigma_{T^{tot}_{dyn}} = \sqrt{\int_0^\infty S_{T^{tot}_{dyn}}(\omega)d\omega} \tag{5.18}$$

$$T^{tot}_{dyn,max} = \sigma_{T^{tot}_{dyn}}\sqrt{2lnN} \tag{5.19}$$

Where N = Operational length/T_p. During tow, the towline is stretched under water and its geometry will change. This will lead to transverse forces on the line due to viscous drag. When the drag force increase as the frequency of oscillations increase, the line is restricted from performing transverse oscillations and the geometric elasticity becomes locked. This is called "drag locking" and will cause the apparent stiffness of the line to increase.

Figure 5.6 shows how the towline tension RAO between surge motion and towline tension increase as the frequency of top end motion increases. At low frequencies the dynamic force shown by the C curve is approximately quasi-static. The damping term or drag force on the line which is dependent on velocity contributes very little as the transverse motion of the line is very slow at low frequencies. The value of A varies with the mean and low frequency tension in the line. As the frequency increase the drag resistance increase as well. At high frequencies the dynamic drag force can be approximated by considering the elastic stiffness term only, i.e. pure elastic illustrated by the value of B.

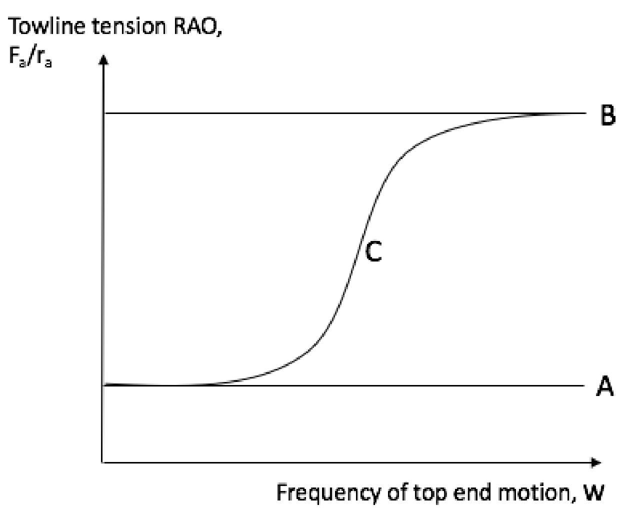


Figure 5.6: Illustration of linearized RAO between surge motion, r_a, and towline tension F.

5.2.3 Total Maximum Towline Tension

The total towline tension can now be found from equation 5.1 and 5.19 and is expressed in equation 5.20.

$$T_{tot}^{max} = \bar{T} + T_{dyn,max}^{tot} \tag{5.20}$$

5.3 Case Study

As the model for calculating towline tension have been developed, a case study of a selected tow can be completed. The object being towed will be the Semi-submersible drilling rig Deepsea Bergen which is pictured in figure 5.7 as it is being towed by Normand Ranger. The goal of the case is to present a way to calculate the tension in the towline based on given environmental conditions and to establish operational limits which will be used to evaluate the operability of operation. The model can be regarded as a simplified way to calculate towline tension in order to get a good understanding of how to dimension equipment in a safe and cost effective manner. Input data for the problem will be presented in tables as well as properties for the rig itself.

The tow operation is to take place in the North Sea, more specifically at Heidrun in November. It will be a rig move operation and the guidelines and requirements set by DNVGL, discussed in section 2.4, will be followed in order to make the case as representative of the real world as possible. The distance is to be towed is 220km and the planned operation period is set to take 24 hours with a planned tow speed of $V = 2,5 m/s$ making it a weather restricted operation.

Figure 5.7: Semi-submersible drilling rig Deepsea Bergen under to by Normand Ranger.

Presented in table 5.1 are the drag coefficients fro DSB needed to perform the initial force calculations on the rig during tow. Mean wave drift force coefficients, $c(w)$, are frequency dependant and are presented in appendix B. Data regarding DSB was provided by the supervisor.

Table 5.1: Deepsea Bergen data.

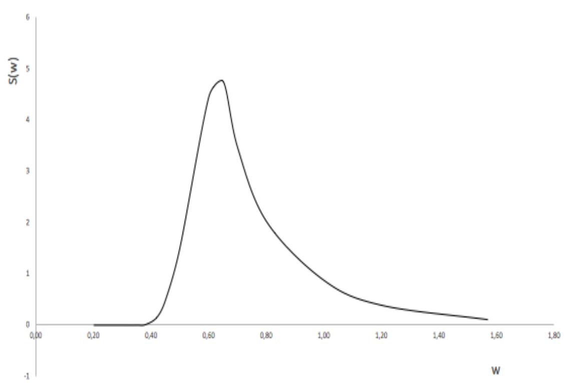
Drag coefficient wind	c_{wi}	1,5	$kN/(m/s)^2$
Drag coefficient current	c_{cu}	375	$kN/(m/s)^2$

A base case is created and a set of operational parameters are set with respect to the guidelines from DNV GL (2015) described in section 2.4.2. The parameters are tabulated below in table 5.4. The peak frequency is found from $w_p = 2\pi/T_p$ which gives $w_p = 0,6283 rad/s$.

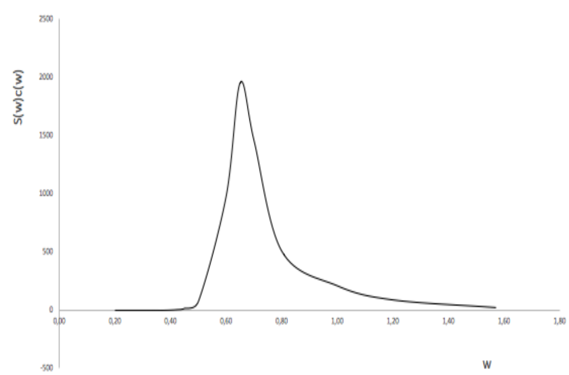
Table 5.2: Base case parameters.

Tow speed	V	2,5	m/s
Wind speed	V_{wi}	20	m/s
Current speed	V_c	0,5	m/s
Significant wave height	H_s	5	m
Peak period	T_p	10	s

Calculating the forces from current and wind acting on the rig is done with equation 5.2 and 5.3 and the results are tabulated in table 5.3. In order to be able to determine the wave drift force from equation 5.4 the JONSWAP spectrum must be created. The spectrum is shown in figure 5.8a.



(a) JONSWAP spectrum for given sea state.



(b) Plot of $S(\omega)c(\omega)$.

Figure 5.8: Plotted JONSWAP spectrum and $S(\omega)c(\omega)$ for base case.

Total mean towline tension is found with equation 5.1 and is presented in table 5.3. It is noted that the current drag force is significantly larger than the wind drag force.

Table 5.3: Calculated mean towline tension for base case.

Wind drag force	F_{wi}	794	kN
Current drag force	F_{cu}	3375	kN
Wave drift force	F_{wd}	866	kN
Mean towline tension	$\bar{T}$	5035	kN

In order to be able to calculate the dynamic towline tension the stiffness of the line is needed. First, a towline selection need to be made in order to have the necessary properties. The selection is based on the relationship $F_{TD} = 2BP$ set by DNV GL (2015) as described in section 2.4.4. In agreement with supervisor, a simplification is made to determine the continuous static bollard pull of the towing vessel. The static tension in the towline is calculated to be $5035kN$ which is equal to resistance of the towed drilling rig. It is assumed that the tug resistance is equal to 20% of the rig resistance which is regarded as a fair assumption considering their design from a hydrodynamic point of view. Thus, the required bollard pull is found to be, $5035kN \cdot 1.20 = 6042kN$. The minimum required breaking strength of the towline for the given operation will then need to be, $F_{TD} = 2 \cdot 604kN = 12084kN$. The chosen towline is steel chain with material properties found in Ramnaas (2016). A complete proof and break load sheet can be found in appendix B.2. Given the minimum required breaking load, a chain with a diameter of $132mm$ and a break load of $12294kN$ is chosen. The chain is stud-less and the quality used is the Oil Rig Quality (ORQ) since this is most frequently used in tow operations. The length is set from the minimum requirement from DNV GL (2015). Table 5.4 presents the towline properties for the base case. The weight in water is calculated as $w = 0,87 \cdot w_a \cdot g$. The drag coefficient is taken from Veritas (2008).

Table 5.4: Chain properties for base case.

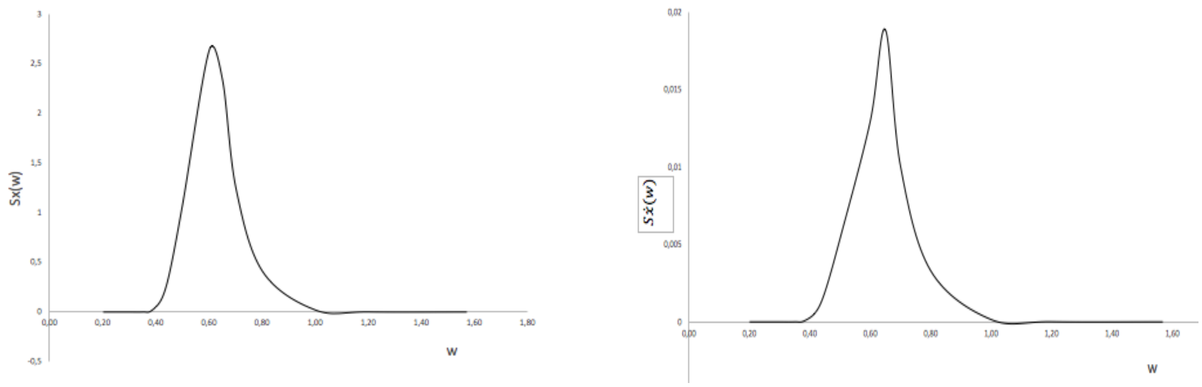
Modulus of elasticity	E	$1,25E+08$	kN/m^2
Towline length	L	650	m
weight in air	w_a	348	kg/m
Weight in water	w	2,97	kN/m
Diameter	D	0,132	m
Cross area	A	0,01368	m^2
Break load	F_{break}	12294	kN
Drag coefficient	C_D	2,4	[-]

It is now possible to perform stiffness calculations on the towline by applying equations 5.6, 5.7 and 5.8. The results are tabulated in table 5.5.

Table 5.5: Stiffness calculation for base case.

Elastic stiffness	k_E	5263	kN/m
Geometric stiffness	k_G	632	kN/m
Total stiffness	k_{tot}	564	kN/m

In order to find the dynamic towline tension the stern movement of the tug due to incoming waves need to be identified. The response spectrum, S_x is computed directly using the RAO for the tug and the wave spectrum and is presented in figure 5.9a. The tug RAO can be found in appendix B. The response velocity spectrum is computed using the relation $S_{\dot{x}}(\omega) = \omega^2 S_x(\omega)$ and is presented in figure 5.9b. The RAO for the dynamic tension and stern movement is computed and plotted for different frequencies and is displayed in figure 5.10. As discussed in section 5.2.2 it is observed that the RAO between surge motion and tension goes towards the value of the total stiffness in the towline for low frequencies. As the frequency of top end motion increase, the drag resistance will increase accordingly until the towline will be pure elastic with a stiffness equal to that of the calculated elastic stiffness. The plot in figure 5.10 proves to be a good and interesting way of checking that the dynamics in the model behaves according to the theory.



(a) Response spectrum $S_x(\omega)$ for base case. (b) Response velocity spectrum $S_{\dot{x}}(\omega)$ for base case.

Figure 5.9: Plotted response spectrum $S_x(\omega)$ and response velocity spectrum $S_{\dot{x}}(\omega)$ for base case.

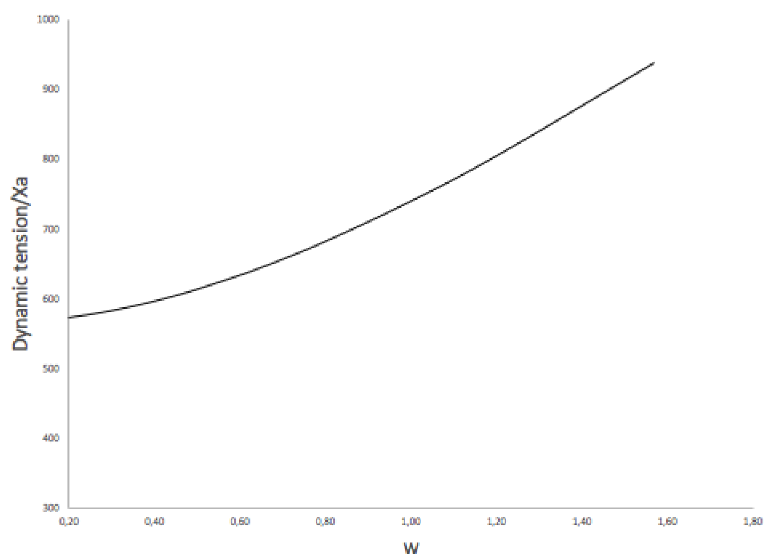


Figure 5.10: RAO between surge motion, x_a, and total dynamic tension, T_{dyn}^{tot} for base case.

The total maximum tension in the towline can now be computed for different wave heights and is shown in the plot in figure 5.11. Figure 5.11 shows that the maximum tension start to rise considerably at wave heights from around $4m$ and higher. This is to be expected as the dynamic loads in the line are small when the incoming waves induce small surge motions at the stern.

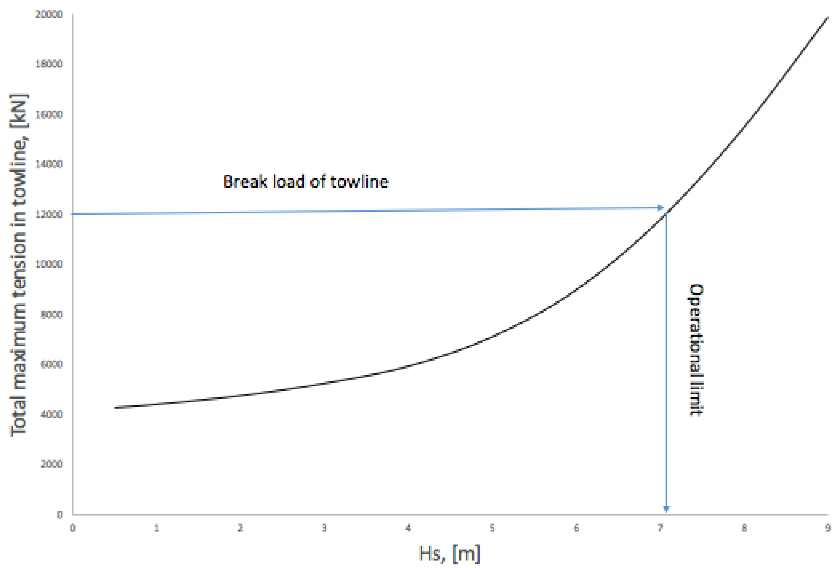


Figure 5.11: Total maximum tension in towline for different H_s for base case with marked operational limit.

The operational limit, OP_{lim}, in terms of limiting significant wave height can now be determined for the towing of Deepsea Bergen. The break load of the selected chain is $12294 kN$ which corresponds to an operational limit of $H_s = 7m$ as seen in figure 5.11 where the towline break load is marked along with the corresponding significant wave height. It is to be noted that this operational limit is solely based on the structural integrity of the towline and not on any other factors like strength at connection points or other on-board equipment.

A tow operation such as one in this base case rely on accurate weather forecasts to ensure a safe operation for personnel involved and costly equipment. In order to account for any uncertainties in weather forecast, the α-factor should be implemented as discussed in section 4.1.1. As seen from equation 4.2 the α-factor determines the operational limit that the tow operation must comply with. DNV GL (2011a) requires that a tow operation of this sort have a weather forecast level B. A level B forecast apply to operations that are environmentally sensitive with significant importance in regard to value and consequence. Based on the planned operation period of 24 hours and the limiting significant wave height, the corresponding α-factor can be determined from figure 4.4 and OP_{WF} calculated. Table 5.6 provides an overview of the operational limits considering the general uncertainty in weather forecast.

There will also be some uncertainty connected to T_{POP} and this will be accounted for through a contingency time. The contingency time, T_C is added to T_{POP} to cover situations that require additional time to complete the tow operation and should generally not be less than 6 hours (DNV GL, 2011a). Since T_{POP} is not assessed in detail it is decided to follow the procedure described in section 4.1 and set $T_C = T_{POP}$. This will lead to a reference period twice the planned operation period. DNV GL (2011a) states that it is possible to set T_C equal to 50% of T_{POP} for towing operations where redundant tug(s) are used along with a properly assessed towing speed. This possibility will be discussed later in section 5.4.

Utilizing the results from the operability calculations at Heidrun in section 4.4 the operation can now be evaluated in terms of operability. As the tow operation takes place in November, results from the winter months are used. The reference period, T_R, and the operational limit, OP_{WF}, are used when determining the probability of having an acceptable weather window for the base case. The result for the base case is presented in table 5.6. It can be seen from these results that the operability will be much higher during the summer months and it would be favourable to plan the operation in this time period if possible. The probability of weather window should be understood as the probability of being able to work given a random time in the period of interest. The greater the probability the less is the time needed to wait for favorable weather.

Table 5.6: Operational limit for base case tow operation of Deepsea Bergen.

Planned operation period	T_{POP}	24	h
Contingency time	T_C	24	h
Reference period	T_R	48	h
Operational design limit	OP_{lim}	7	m
Alpha factor	α	0,82	-
Operational limit	OP_{WF}	5,7	m
Probability of weather window	P_{op}	47	%

5.4 Investigation of Towline Tension

In order to get a further understanding of how the towline tension vary, this section will investigate changes with varying operational parameters. The first parameter of interest is one that can easily be changed from operation to operation or even during tow which is the length of the towline. Figure 5.12 shows how the tension increase with rising significant wave height for towline lengths in the span 650m to 1100m. It can be seen that for $0,5m < H_s < 3m$ the length of the line has little influence on the total tension as the waves increase. The tension remains close to the mean tension and the dynamic loads remain small as the wave induced motions at the stern of the tug are small. As the incoming waves increase above 3m the total tension start to rise more significantly and the difference in towline length becomes more noticeable. There is a calculated difference of $5600kN$ from the max tension when towing with 650m line compared to using a line of 1100m under the same conditions. The towline stiffness is dependent on the length of the line. A steel chain have a high axial stiffness, EA, and the geometric stiffness will therefor have the largest contribution to the total stiffness as seen from equation 5.8. As seen from equation 5.7 the geometric stiffness is dependent of the inverse of L^3. This will result in a lower stiffness for longer lines and thus a lower dynamic load as seen form the plot.

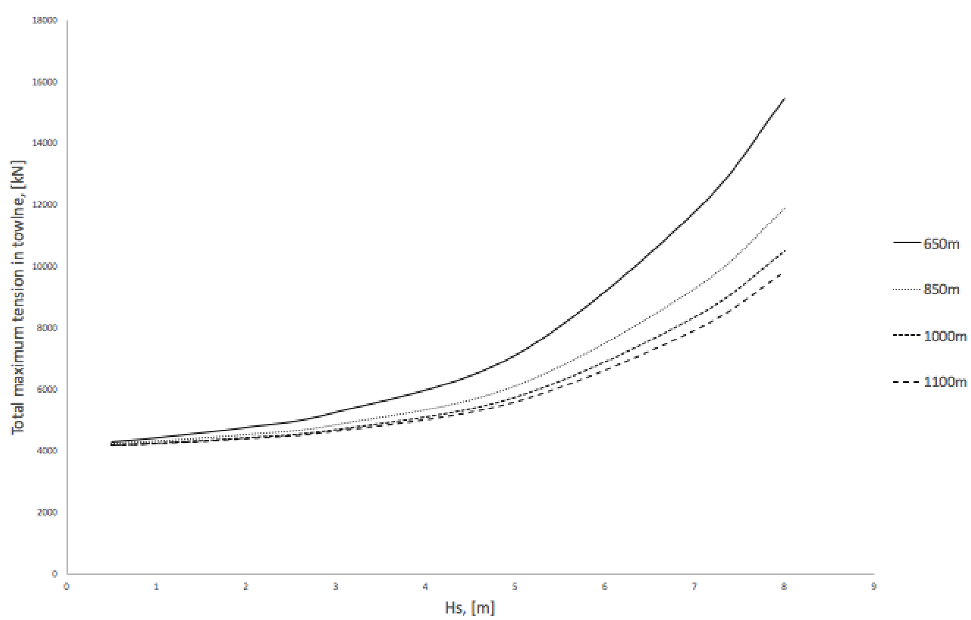


Figure 5.12: Maximum towline tension for different towline lengths. Base case parameters.

The correlation between dynamic and static tension can be visualized by the use of a histogram plot as seen in figure 5.13. The static tension increases considerably less than the dynamic tension as the significant wave height increase. The tow speed and other parameters remain constant. With low incoming waves the static tension makes up for almost all the tension in the line. As the waves increase the dynamic tension is seen to make up more and more of the total tension. From these results it is clear that a good understanding of the dynamic behaviour of the towed system is important in order make sure that overload in the tow line does not occur. Thorough planning of the operation beforehand combined with accurate weather forecast and operational limits are important to ensure safety and limit contingency situations.

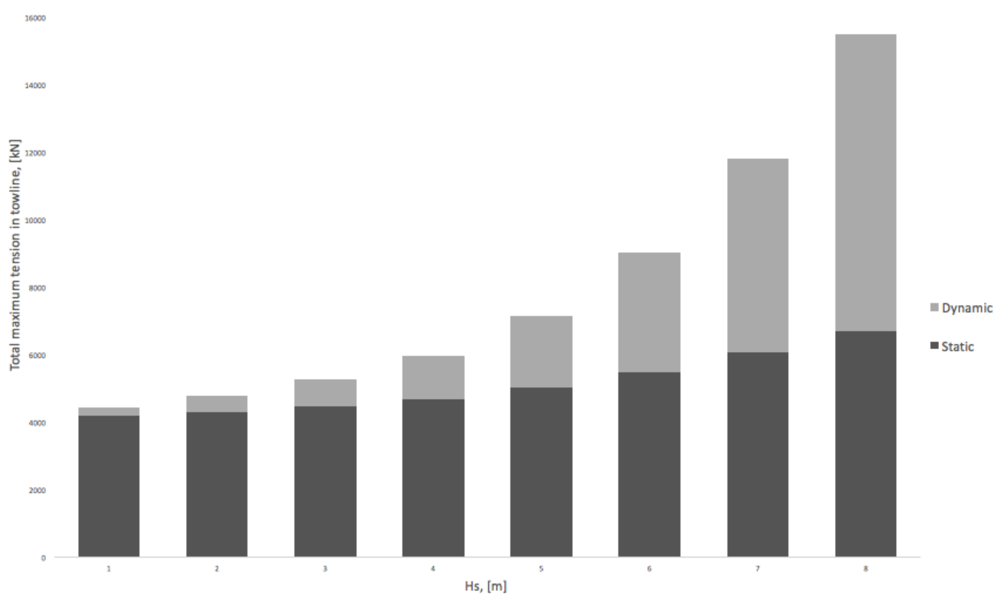


Figure 5.13: Static and dynamic tension in towline. Base case parameters.

The effect of tow velocity on tension is also studied. It can be seen from figure 5.14 that the velocity affects the tension quite a lot. As shown in section 5.3 the static tension is dependent on the tow velocity squared. With low tow velocity the tension does not change much with higher wave heights at the beginning where as the velocity increase the tension curve becomes steeper and steeper. At low significant wave heights where the dynamic loads are small the shift in tension curve can be described with the increase in static tension as the rig is towed faster through water.

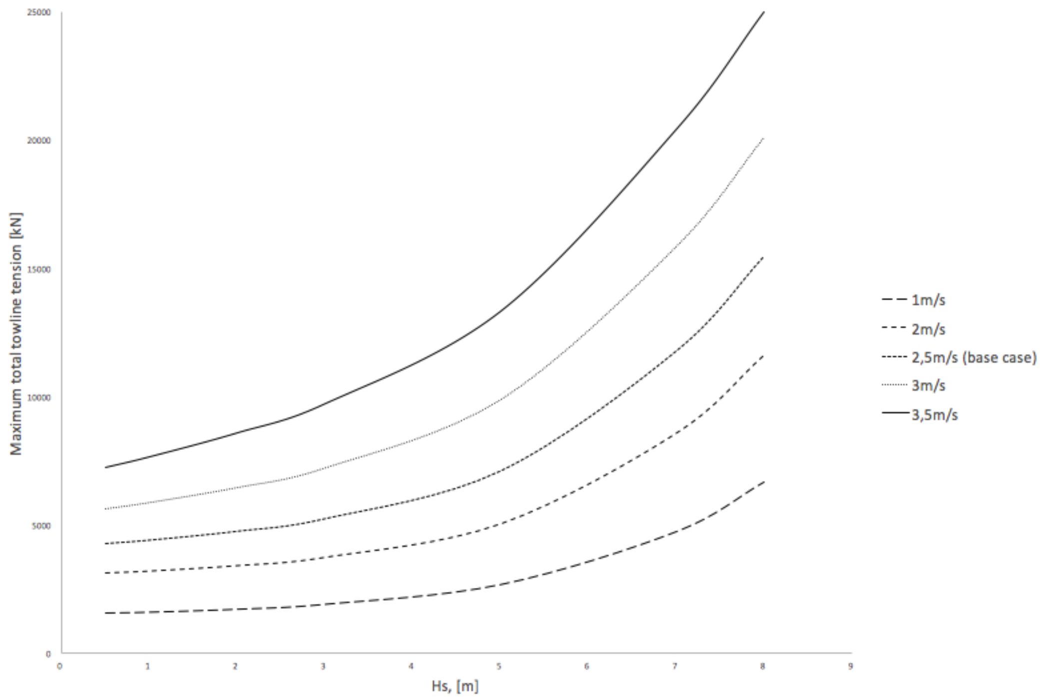


Figure 5.14: Maximum towline tension for various tow velocities. Base case parameters.

So far the chosen towline material have been steel chain, but other materials are also available. Since it is required by DNVGL to use steel wire or chain for offshore tow operations it was natural to use chain for the base case calculations above. However, it is of interest to examine the difference in tension when using a polyester towline which can be done during tows inshore. Polyester offers higher elongation and is more suitable for shock load absorption compared to steel chain or steel wire ropes and is more flexible and easier to handle for crew on board the rig and tug. The material properties of polyester rope are found in BRIDON (2013) and the complete proof and break load sheet is found in appendix B. Table 5.7 displays the properties used for the base case calculations. To make the tow operation more similar to an inshore tow some of the operational parameters are changed from the previous base case. The tow velocity is lowered to $1,5 m/s$ and the wind speed to $10 m/s$.

Some assumptions have also been made with respect to the properties of the polyester towline. It can be troublesome to determine the axial elastic stiffness, EA, for a towline made out of polyester. In agreement with supervisor, EA have been sett equal to $25F_{break}$ in order to simply the calculations. The maximum tension for polyester is computed and presented in figure 5.15

along with a steel chain under the same conditions. It is clear that as the incoming waves gets higher the stern motion and the dynamic tension increase. Due to the lower stiffness in the polyester line compared to the chain, the dynamic tension will be significantly less for $H_s > 5m$ as seen from the tension plot.

Table 5.7: Polyester towline properties for base case

Modulus of elasticity	EA	150775	kN
Towline length	L	500	m
Weight in water	w	0,06	kN/m
Diameter	D	0,184	m
Cross area	A	0,0266	m^2
Break load	F_{break}	6031	kN
Drag coefficient	C_D	1,6	[-]

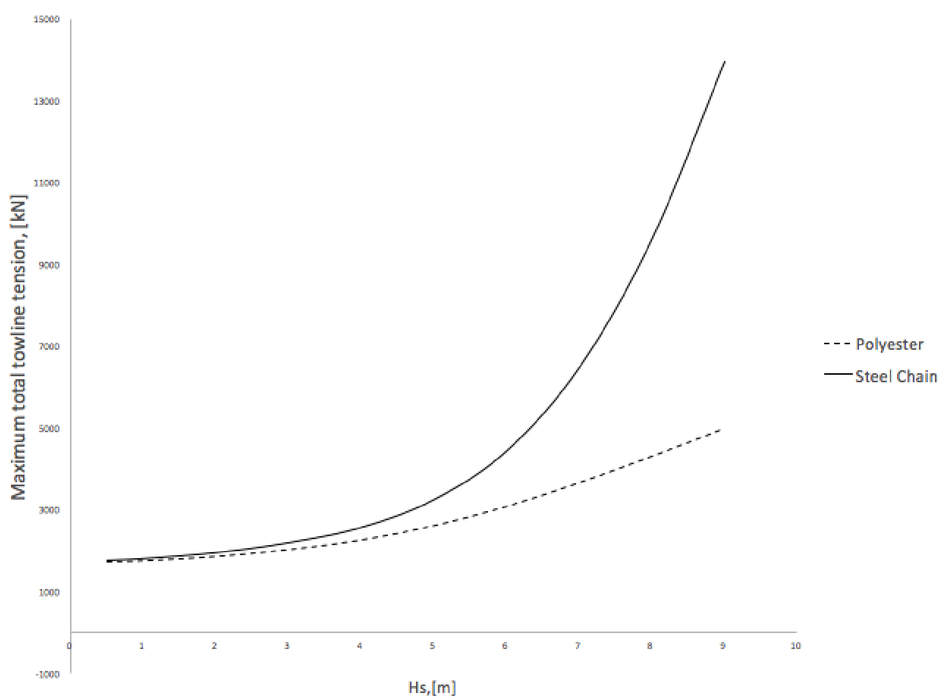


Figure 5.15: Maximum towline tension for steel chain and polyester rope.

5.5 Relevance of Findings

The model has been used to calculate the maximum tension in the towline during tow operation for a base case trying to replicate a real operation as well as possible. The operational limit in term of significant wave height has been established and different parameter variations have been studied. A marine operation must evaluate and account for safety, cost, rules and regulations, equipment and weather including much more. It will at this point be interesting to see if the operability results can be improved in some manner in light of the previous calculations and discoveries. This section will look at factors that influence the operability and discuss possible measures to achieve the mentioned improvements for the tow of the semi-submersible.

5.5.1 Operability Improvements

So, what controls the operability? As discussed previously, weather criteria is normally of major importance for marine operations. If very strict limitations are set on the operation it may result in costly waiting on weather. If the limitations are too optimistic, dangerous situations may occur. The reference period and limiting significant wave height will dictate the probability of working as illustrated by figure 5.16.

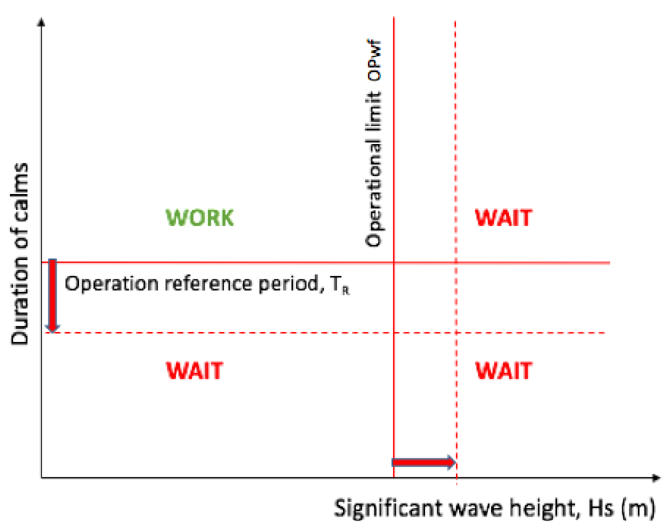


Figure 5.16: Improving operation window.

It can be seen that in order to increase the operational window T_R should be decreased and OP_{WF} increased. It then carries motivation to see what can be done to achieve these effects. The effect of lowering the reference time is clearly illustrated in section 4.4 where the probability of working is calculated for selected seasons. The reference time is as discussed defined as:

$$T_R = T_{POP} + T_C \tag{5.21}$$

T_R is dependent on both the planned operation period and contingency time. So to reduce T_R, T_{POP} or T_C must be reduced, or both. The planned operation period should be based on a detailed schedule for the operation and will often stem from experience with similar operations. One of the factors that will affect T_{POP} is the towing speed. The distance needed to be covered should be known prior to start and if the operation is under strict time limitations the speed can be set accordingly. The planned operation period can be reduced by increasing the mean towing speed. This will result in a higher mean and dynamic tension in the line as seen from figure 5.14. Reducing the operation time does not only benefit the operability. Time is closely linked to the cost of marine operations as possible downtime and vessels day rates can run into large sums.

T_C is based on the general uncertainty in T_{POP} as well as possible contingency situations. As a result of this a more well defined T_{POP} can lead to lower contingency time which again will reduce the reference period as seen from equation 5.21. A possible way to lower the contingency time can according to DNV GL (2011a) be to use redundant tug(s). It is then accepted to set $T_C = 0,5T_{POP}$ instead of the same value as T_{POP} as practiced in the base case. For an operation such as the one in the base case it seems very conservative to have an reference time double the planned operation period. Normally, the operation should be planned well enough with knowledge about previous operations to establish a more detailed T_{POP}. Trying to minimize T_C can be done through simulations beforehand where the goal would be to locate eventual problematic events and take necessary precautions. A goal should be to try and get close to the minimum requirement of 6 hours for shorter operations.

As the α-factor decrease the operational limit compared to the design limit decrease as well. As seen in the base case it is of interest to have the α-factor as high as possible. The reason for implementing this reduction factor is due to the general uncertainty in weather forecast and monitoring. If this uncertainty can be reduced this would greatly benefit the operability as the operational limit can be set closer to the design limit, increasing the probability of having a weather window. This would require innovative solutions where maybe the most promising seems to be real time forecasting of wave heights. Edgar et al. (2000) outlines how statistical forecasting of the sea-state is vital for marine operations and how it may be used as an indicator of conditions for when certain operations may be impossible to undertake. Further it is stated that predicting the actual instantaneous sea surface shape carries the possibility of changing this by using a process called Deterministic Sea-Wave Prediction by the use of buoys placed in a set of locations. Naaijen and Huijsmans (2008) describes the use of a linear short term wave and ship motion prediction model for long crested waves. The theory is described to be accurate but will require further improvement in technology. In the base case for towing "Deepsea Bergen" the α-factor were chosen based on T_{POP}, OP_{lim}, location and forecast level. If a more reliable forecast level is chosen, for example level A even though this is not required, the α-factor can be set higher. This would require the operation to have a meteorologist on site.

It is clear that the operational factors discussed above are connected in some manner. Looking at figure 5.16 and equation 5.21 the dependency becomes clear. If T_{POP} is reduced this will in turn affect and increase the α-factor. As the α-factor is increased, reflecting less uncertainty in weather forecast, the operational limit, OP_{WF}, is also increased resulting in a more flexible operation. OP_{WF} is also dependable on the design limit. The design limit is calculated as in the base case and a way to try an increase this could be to reduce the tension by increasing the length of the towline. Figure 5.12 show how the tension vary with length and that the limiting significant wave height potentially can be higher for a longer line. However, a longer line will have an increased weight putting restrictions on the towing vessel. The line will also be more difficult to handle as well as increased sag in the line. This would perhaps require a more thorough survey of the tow route with respect to water depth so that bottom contact is avoided. The use of a rendering towline winch will allow for easier handling of long lines and are able to adjust the length according to situation. Nielsen (2007) describes a rendering winch as an efficient tool for reducing the extreme loads in the towing line. The operational limit have been evaluated based only on the significant wave height. Other factors such as T_p could potentially make the design criteria more flexible in combination with H_s. An α-factor for T_p similar to the one used for waves should then be probably be investigated.

5.5.2 Implementing Improvements

Some of the improvements outlined in section 5.5.1 will be implemented to see if the operability can be enhanced in a reasonable way. Operational parameters such as towline length, towing speed and additional tugs will be investigated. The potential improvements will be evaluated based on operational limit and operability compared to the base case. Calculations will not be described as thoroughly as in the base case as the focus will be more on the results and what can be understood from these.

As seen from figure 5.12 the maximum tension in the line can be decreased by increasing the length of the line. This will result in lower dynamic loads since the stiffness in the line will be smaller. Increasing the length to $850m$ while keeping towing speed and chain properties unchanged results in a new $OP_{lim} = 8m$. This will in turn result in a improved $OP_{WF} = 6,5m$ when applying the α-factor. The probability of having a weather window will then increase from 47% in the base case to 57% with the increased towline length.

An increase in tow velocity compared to the base case will as discussed increase the mean tension in the line as well as the dynamic loads. The operation time will on the other hand be reduced which will potentially affect the operability. If it is desired to reduce the duration to $T_{POP} = 18h$ the mean tow speed must be set to approximately $3,4m/s$. The reduction in operation time will require a shorter weather window and T_C as well as the possibility for using a higher α-factor resulting in a higher OP_{WF}. The planned increase in mean velocity will require a redimension of the towline in order to fulfill the the break load requirement set by DNV GL (2015) as outlined in section 2.4.4. Using a towline with a diameter of $162mm$ and a break load of $17188kN$ the operational design limit is determined to be $OP_{lim} = 7,7m$. The reduction in planned operation period is not sufficient to select a higher α-factor as seen from figure 4.4 and the operational limit will then be $OP_{WF} = 6,3m$. However, T_C will take a lower value as T_{POP} is reduced due to the increasing velocity. Since no other changes are made to the operation besides the velocity, the relation $T_C = T_{POP}$ is still used resulting in $T_R = 36h$. With a new operational limit and reference period the probability of having a weather window is now calculated to be 60%.

The use of a redundant tug may also prove to be beneficial for the operability. Two tugs will allow for a lower contingency time, that is $T_C = 0,5T_{POP}$. Applying this to the base case results in a reference period of $T_R = 36h$. With the new reference period the improved operability is calculated to be 53%.

Using a level A weather forecast may eliminate some uncertainty and hence improve operability. A forecast procedure complying with the one shown in figure 2.21 should then be established. This would include a meteorologist dedicated to the operation and two independent weather sources used. The α-factor is found in figure 4.3 and set to 0,86 compared to the value of 0,82 used in the base case. The operational limit will then become $OP_{WF} = 6m$ resulting in a operability of 52%.

A combination of the improvements may result in even more promising results. If the towline length is set to $850m$ combined with a redundant tug and level A weather forecast the improved operability is determined to be 68%.

5.6 Discussion of Results

This chapter have used theory and assumptions to create a model used to calculate the maximum towline tension during the transport of a semi-submersible drilling rig. The discoveries and results found will be discussed in this section.

The assumptions made regarding the model and the model setup are discussed in section 5.2 and are important in order to understand the capability and limitations of the model. The damper was added to represent the viscous drag forces on the line as it moves vertically in water.

The tangential drag forces are not considered and would have caused a higher dynamic load in the line which could have led to the need for a different towline. The availability of operation would probably have been affected as well if no other changes had been done to the parameters.

It is assumed that the towline is oscillating in calm water and this would not be a completely accurate representation. During tow the line is subjected to wave particle velocities as well. This should be accounted for with a relative velocity in the expression for the drag forces.

A clear dependency is shown between the dynamic loads, mean tension and significant wave height. With incoming waves with a significant wave height below $3m$ the dynamic loads contributes little compared to the mean tension. With increasing waves the dynamics becomes more and more significant. For a significant wave height of $8m$ the dynamic tension is 56% of the total towline tension when towing with a velocity of $2,5m/s$. When the incoming waves are reduced to a height of $2m$ the dynamic tension is just 15% of the total maximum tension in the line. The model shows the importance of understanding the dynamics during operation.

It is observed from the tension model that the dynamic tension is dependent on the third power of the mean static tension. This implies that the dynamic tension is more important for lines under high tension rather than for slack lines. This effect is important to understand when towing with high velocity so that a failure in the towline does not occur as a result of overload.

The improvements discussed in section 5.5.2 have shown potential in making the base case more available. From the evaluated changes the increase in velocity resulted in the highest change in operability, from 47% to 60%. An increase in velocity resulted in a shorter planned operation period which in turn gave a smaller contingency time. Both affect the operability. If the planned operation period would have been shortened even more as a result of an higher increase in velocity, the α-factor might have been affected as well, taking on a higher value. This would also result in a higher operability as less degree of uncertainty would be connected to a potential weather forecast. However, the increase in velocity gave a higher mean tension in the towline which required the towline to be redimensioned compared to the base case. This was done to meet the requirements set by DNV GL (2015). The new towline had a higher break load which resulted in a higher operational design limit. If the velocity is increased without making changes to the towline the operational design limit would be lower compared to the base case due to the higher tension as seen from figure 5.14.

Utilizing a redundant tug proved to give a lower contingency time which again improved the operability to 53%. It was possible to lower the contingency time in this case due to the safety backup another tug provides. However, the cost of this should be evaluated during the planning stage. A redundant vessel will add costs in terms of vessel day rate, fuel and crew just to mention some. Due to the downturn in the offshore and gas industry at present time the demand for anchor-handling tug supply (AHTS) vessels have greatly declined. The day rates for AHTS vessels have hence decreased and are low compared to a few years ago. According to Journal (2016) the ATHS North Pomor was fixed for as little as $\$1960$ a day in 2016 as compared to $\$27900$ just a few years back. The potential savings gained from the increase in operability and less time needed to wait on weather should be compared to the cost of the redundant tug and the cost effectiveness may be evaluated.

Changing the operation forecast level from B to A also showed some potential with respect to the availability of operation. The improvement was a result of the increased α-factor due less uncertainty in the weather forecast since a meteorologist will be dedicated to the operation leading to a somewhat less strict operational limit. The cost of this change must also be evaluated during the planning stage of operation.

It appears that increasing OP_{WF} has a more significant impact on the operability than decreasing T_R. The improvements have been assessed individually and in combination to try and reach the highest availability possible. Increasing towline length combined with a level A forecast and a redundant tug will affect both the operational limit and the reference period resulting in the highest availability.

Chapter 6

Summary and Recommendations for Further Work

6.1 Summary and Conclusions

This thesis has investigated towing operations with the main focus on surface tows of large structures. State-of-the art concepts for towing are described and the configurations of tugs used during inshore and offshore tows studied. It is found that speed and maneuverability are key elements to consider when towing in either open or constricted areas respectively.

By studying accidents from the past ten years it is clear that most accidents can be traced back to poor operational management and planning. Major tow operations have not used proper risk evaluation and neglected operational limits, assessment of weather windows and the use of α-factor in order to account for uncertainty in weather forecast. It is concluded that many accidents have occurred because of towline failure due to overload as a result of poor understanding about the static and dynamic behaviour of the towing line. This has resulted in loss of lives and costly equipment.

A thorough understanding of the marine environment and forces associated with marine towing operations is necessary in order to plan and execute safe and cost effective operations. This thesis shows relevant theory related to identifying parameters that dictate the dynamic response of a towed system. These dynamics are important when designing the operation and to establish operational limits.

A method to estimate operability and weather windows from hindcast data is described and operability for Heidrun in the North Sea is investigated. The results indicate time needed to wait on weather is considerably lower for the summer months compared to the winter months. The probability of weather window, also referred to as operability, should be understood as the probability of being able to work given a random time in the period of interest. The greater the probability, the less is the time needed to wait for favorable weather.

A model is developed to estimate the characteristic tension response in the towing line and to establish operational limits for the towing of a semi-submersible drilling rig. A base case is created and the operational design limit, given by significant wave height, is found to be $OP_{lim} = 7m$ resulting i a operational limit of $OP_{WF} = 5,7m$ when accounting for uncertainties in weather forecast. The probability of having a weather window in the operation period is determined to be $P_{op} = 47\%$. Results show that the dynamic tension is more significant for larger wave heights. Moreover, based on the results presented in the thesis these conclusions can be drawn from the base case calculations:

- Increasing the towline length reduces the maximum tension and improves operability.
- Increasing the tow velocity improves operability if the towline is redimensioned according to regulations. This proved to be the single improvement to give the highest operability.
- The use of a redundant tug will lower the contingency time and hence improve operability.
- Some uncertainty in weather forecast can be eliminated by upgrading to a Level A weather forecast for tow operations offshore. This will in turn improve operability.
- Results show that OP_{WF} has the most significant impact on operability. A combination of increasing OP_{WF} and decreasing T_R will achieve the greatest improvement of operability.

6.2 Recommendations for Further Work

Due to the limited scope of the thesis, several areas regarding towing operations should be investigated furhter in order to study the operability and safety during operation.

First and foremost a time domain simulation of the selected tow concept should be established. This will allow for a further investigation of the towline tension. Snap loads in the line and possible solutions to reduce these should be evaluated to minimize the risk of towline failure. The use of a active pay-out winch should be implemented in the model for this purpose and the effects analyzed. Modeling the winch as a spring-mass-damper system would then be recommended. Additional methods to reduce peak loads should be investigated as well.

Simulations of weather windows should be conducted to get a better understanding of the operability. Using Monte Carlo simulations where an operation is performed at a random point in time should then be considered. Hindcast data would then be used as a weather forecast and the operability could be better understood compared to realistic conditions. A more detailed analysis of cost and waiting on weather could then be performed and the operation evaluated in more depth.

Operational improvements like multi-segments towlines and their effect on the line tension have should be analyzed. Finite element analysis similar to those used for mooring lines would be needed in order to handle this. Multi-segment lines are often used in modern operations and can help absorb shock loads. Other tow configurations than the single object single tug should also be evaluated. This could include multiple tugs towing one object or one tug towing several objects like in a tandem tow. The use of buoys connected to the towline could help prevent steep inclination of the line for certain tows and this may be included in the simulation. The effect on line tension by the use of a buoy may also prove to be beneficial.

In depth study of accident scenarios and emergency towing should be studied further. Emergency towing arrangement and procedures surrounding this have the potential of saving lives and equipment and carries strong motivation for further work.

Appendix A

Acronyms

AHC Active Heave Compensation

AHV Anchor Handling Vessel

AHTS Anchor Handling Tug Supply

CDT Controlled Depth Tow

DSB DeepSea Bergen

DNV Det Norske Veritas

JONSWAP Joint North Sea Wave Project

RAO Response Amplitude Operator

ROV Remotely Operated Vehicle

SJA Safe Job Analysis

SIMA Simulation Workbench for Marine Applications

SIMO Simulation of Marine Operations

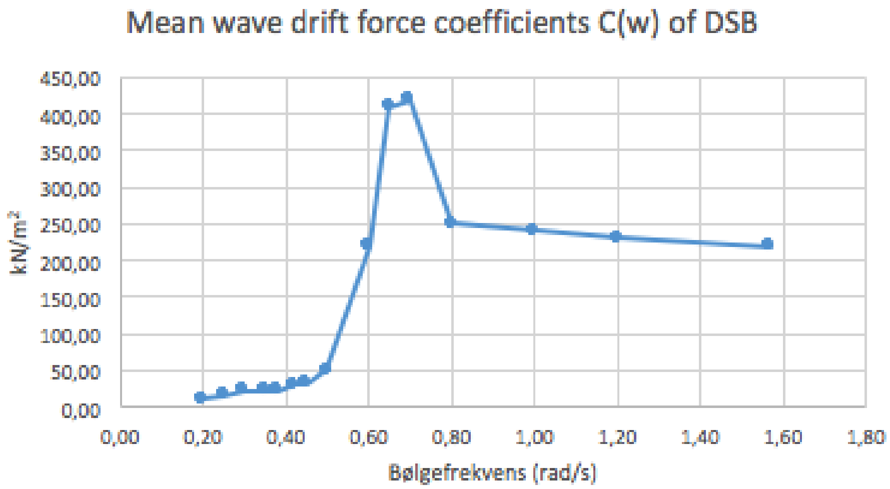
VIV Vortex Induced Vibrations

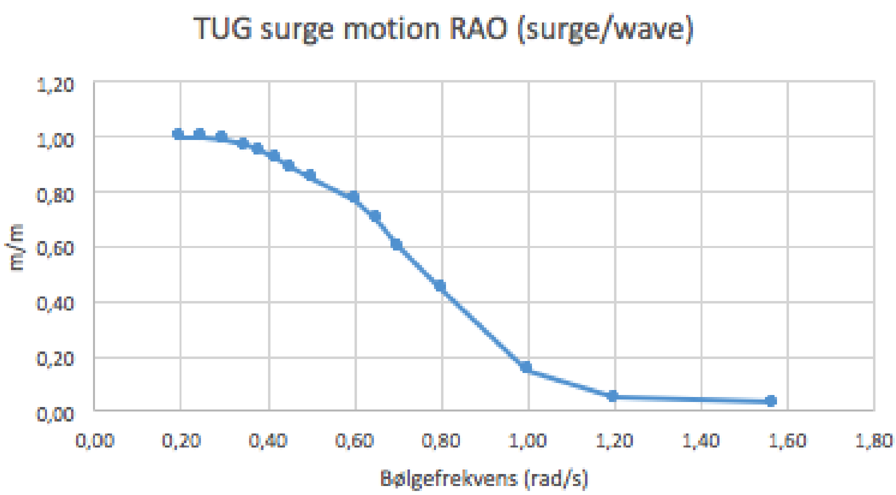
Appendix B

Case DSB Data

B.1 Input RAO and Wave Drift, $c(\omega)$

Bølgefrekvens (rad/s)	Bølgeperiode (sec)	Wave drift force (kN/m^2)	Jag (surge) motion RAO (m/m)
0,20	31,42	10,00	1,00
0,25	25,13	15,00	1,00
0,30	20,94	22,00	0,99
0,35	17,95	22,00	0,97
0,38	16,53	22,00	0,95
0,42	14,96	30,00	0,92
0,45	13,96	32,00	0,89
0,50	12,57	50,00	0,85
0,60	10,47	220,00	0,77
0,65	9,67	410,00	0,70
0,70	8,98	420,00	0,60
0,80	7,85	250,00	0,45
1,00	6,28	240,00	0,15
1,20	5,24	230,00	0,05
1,57	4,00	220,00	0,03


Mean wave drift force coefficients C(w) of DSB
450,00
400,00
350,00
300,00
250,00
200,00
150,00
100,00
50,00
0,00
kN/m²
0,00
0,20
0,40
0,60
0,80
1,00
1,20
1,40
1,60
1,80
Bølgefrekvens (rad/s)


TUG surge motion RAO (surge/wave)
1,20
1,00
0,80
0,60
0,40
0,20
0,00
m/m
0,00
0,20
0,40
0,60
0,80
1,00
1,20
1,40
1,60
1,80
Bølgefrekvens (rad/s)

B.2 Chain Properties

Test Load	Break Load						Proof Load										Weight	
Grade	ORQ	R3	R3S	R4	R4S	R5	ORQ	R3	R3S Stud	R3S Stud-less	R4 Stud	R4 Stud-less	R4S Stud	R4S Stud-less	R5 Stud	R5 Stud-less		
C-factor	0,0211	0,0223	0,0249	0,0274	0,0304	0,032	0,014	0,0156	0,018	0,0174	0,0216	0,0192	0,024	0,0213	0,0251	0,0223	Stud	Stud-less
mm																	kg/m	
76	4621	4884	5454	6001	6658	7009	3066	3417	3942	3811	4731	4205	5257	4665	5498	4884	126	116
78	4847	5123	5720	6295	6984	7351	3216	3584	4135	3997	4962	4411	5514	4893	5766	5123	133	122
81	5194	5490	6130	6745	7484	7877	3446	3840	4431	4283	5317	4726	5908	5243	6179	5490	144	131
84	5550	5866	6550	7208	7997	8418	3683	4104	4735	4577	5682	5051	6313	5603	6602	5866	155	141
87	5916	6252	6981	7682	8523	8971	3925	4374	5046	4878	6056	5383	6729	5972	7037	6252	166	151
90	6289	6647	7422	8167	9062	9539	4173	4650	5365	5187	6439	5723	7154	6349	7482	6647	177	162
92	6544	6916	7722	8497	9428	9924	4342	4838	5582	5396	6699	5954	7443	6606	7784	6916	185	169
95	6932	7326	8180	9001	9987	10512	4599	5125	5913	5716	7096	6307	7884	6997	8246	7326	198	181
97	7195	7604	8490	9343	10366	10911	4774	5319	6138	5933	7365	6547	8184	7263	8559	7604	206	188
100	7596	8028	8964	9864	10944	11520	5040	5616	6480	6264	7776	6912	8640	7668	9036	8028	219	200
102	7868	8315	9285	10217	11336	11932	5220	5817	6712	6488	8054	7159	8949	7942	9359	8315	228	208
105	8282	8753	9773	10754	11932	12560	5495	6123	7065	6829	8478	7536	9420	8360	9851	8753	241	221
107	8561	9048	10103	11118	12335	12984	5681	6330	7304	7060	8764	7790	9738	8643	10184	9048	251	229
111	9130	9650	10775	11856	13154	13847	6058	6750	7789	7529	9347	8308	10385	9217	10861	9650	270	246
114	9565	10109	11287	12420	13780	14506	6346	7071	8159	7887	9791	8703	10879	9655	11378	10109	285	260
117	10005	10574	11807	12993	14415	15174	6639	7397	8535	8251	10242	9104	11380	10100	11902	10574	300	274
120	10452	11047	12334	13573	15059	15852	6935	7728	8916	8619	10700	9511	11889	10551	12434	11047	315	288
122	10753	11365	12690	13964	15493	16308	7135	7950	9173	8868	11008	9785	12231	10855	12792	11365	326	298
124	11057	11686	13048	14358	15930	16768	7336	8175	9432	9118	11319	10061	12576	11161	13153	11686	337	308
127	11516	12171	13591	14955	16592	17466	7641	8515	9824	9497	11789	10479	13099	11626	13700	12171	353	323
130	11981	12663	14139	15559	17262	18171	7950	8858	10221	9880	12265	10903	13628	12095	14253	12663	370	338
132	12294	12993	14508	15965	17713	18645	8157	9089	10488	10138	12585	11187	13984	12411	14625	12993	382	348
137	13085	13829	15441	16992	18852	19844	8682	9674	11162	10790	13395	11906	14883	13209	15565	13829	411	375
142	13887	14677	16388	18033	20008	21061	9214	10267	11847	11452	14216	12637	15796	14019	16520	14677	442	403
147	14700	15536	17347	19089	21179	22294	9753	10868	12540	12122	15048	13376	16720	14839	17487	15536	473	432
152	15522	16405	18317	20156	22363	23540	10299	11476	13241	12800	15890	14124	17655	15669	18464	16405	506	462
157	16352	17282	19297	21234	23559	24799	10850	12089	13949	13484	16739	14879	18599	16507	19452	17282	540	493
162	17188	18166	20284	22320	24764	26068	11405	12708	14663	14174	17596	15641	19551	17351	20447	18166	575	525
167	18030	19056	21278	23414	25977	27345	11963	13330	15381	14869	18458	16407	20508	18201	21448	19056	611	558
172	18876	19950	22276	24513	27196	28628	12525	13956	16103	15566	19324	17177	21471	19055	22455	19950	648	592
177	19725	20847	23278	25615	28420	29915	13088	14584	16827	16267	20193	17949	22437	19912	23465	20847	686	627

B.3 Braidline Polyester Properties

Rope Diameter		Rope Circumference		Nominal Mass				Minimum breaking force (F min)		
				In Air		Submerged				
mm	in	mm	in	kg/m	lb/ft	kg/m	lb/ft	kN	Tonnes	Tons
16	5/8	50	2	0.19	0.28	0.05	0.07	61.9	6.31	6.95
18	3/4	57	2 1/4	0.23	0.33	0.06	0.08	77.5	7.90	8.71
21	7/8	66	2 5/8	0.39	0.58	0.10	0.15	106	10.8	11.9
24	1	75	3	0.50	0.74	0.13	0.19	148	15.1	16.6
28	1 1/8	88	3 1/2	0.68	1.01	0.17	0.26	163	16.6	18.3
32	1 5/16	101	4	0.89	1.32	0.22	0.33	244	24.9	27.4
36	1 1/2	113	4 1/2	1.12	1.67	0.28	0.42	286	29.2	32.2
40	1 5/8	126	5	1.22	1.82	0.31	0.46	346	35.3	38.9
44	1 3/4	138	5 1/2	1.47	2.19	0.37	0.55	397	40.5	44.6
48	2	151	6	1.76	2.62	0.45	0.66	489	49.9	55.0
52	2 1/8	163	6 1/2	2.05	3.05	0.52	0.77	551	56.2	61.9
56	2 1/4	176	7	2.38	3.54	0.60	0.90	628	64.0	70.5
60	2 1/2	188	7 1/2	2.74	4.08	0.69	1.03	756	77.1	85.0
64	2 5/8	201	8	3.12	4.64	0.79	1.18	828	84.4	93.0
72	3	226	9	3.95	5.88	1.00	1.49	1059	108	119
80	3 1/8	251	10	4.87	7.25	1.24	1.84	1304	133	147
88	3 1/2	276	11	5.91	8.79	1.50	2.23	1549	158	174
96	3 3/4	302	12	7.02	10.45	1.78	2.65	1785	182	201
104	4 1/8	327	13	8.25	12.28	2.09	3.11	2050	209	230
112	4 3/8	352	14	9.56	14.23	2.42	3.61	2354	240	264
120	4 3/4	377	15	11.00	16.37	2.79	4.15	2697	275	303
128	5	402	16	12.50	18.60	3.17	4.72	2932	299	329
136	5 3/8	427	17	14.10	20.98	3.58	5.32	3305	337	371
144	5 5/8	452	18	15.80	23.51	4.01	5.96	3717	379	418
152	6	478	19	17.60	26.19	4.46	6.64	4129	421	464
160	6 1/4	503	20	19.50	29.02	4.95	7.36	4580	467	515
168	6 5/8	528	21	21.50	31.99	5.45	8.11	5031	513	565
176	7	553	22	23.60	35.12	5.98	8.91	5521	563	620
184	7 1/4	578	23	25.80	38.39	6.54	9.74	6031	615	678
192	7 1/2	603	24	28.10	41.82	7.13	10.60	6570	670	738
216	8 1/2	679	27	35.60	52.98	9.03	13.43	8316	848	934
240	9 1/2	754	30	43.90	65.33	11.13	16.57	10268	1047	1154

Bibliography

Aftenposten (2016). Vurderte å bombe løpsk lekter offshore. http://www.aftenposten.no/norge/Vurderte-a-bombe-lopsk-lekter-offshore-15807b.html. Visited on 2016-10-01.

BBCNEWS (2016). Drilling rig blown ashore in stroms off western isles. http://www.bbc.com/news/uk-scotland-north-east-orkney-shetland-37007656. Visited on 2016-11-05.

Berg, T. E., Selvik, Ø., et al. (2015). Emergency towing operations in arctic waters. In *OTC Arctic Technology Conference*. Offshore Technology Conference.

BRIDON (2013). Oil and gas, wire and fibre rope solutions for the world's most demanding applications.

Chen, Y., Mukerji, P., et al. (2008). Weather window statistical analysis for offshore marine operations. In *The Eighteenth International Offshore and Polar Engineering Conference*. International Society of Offshore and Polar Engineers.

DNV GL (2011a). Marine operations, general, offshore standard dnv-os-h101.

DNV GL (2011b). Modelling and analysis of marine operations, recommended practice dnv-rp-h103.

DNV GL (2015). Sea transport operations, offshore standard dnv-rp-h202.

Edgar, D., Horwood, J., Thurley, R., and Belmont, M. (2000). The effects of parameters on the maximum prediction time possible in short term forecasting of the sea surface shape. *International shipbuilding progress*, 47(451):287–301.

Eik, K. and Marchenko, A. (2010). Model tests of iceberg towing. *Cold Regions Science and Technology*, 61(1):13–28.

Eik, K. J. and Nygaard, E. (2004). Heidrun Metocean Design Basis.

EMSA (2015). Annual overview of marine casualties and incidents 2015.

Faltinsen, O. (1999). *Sea Loads on Ships and Offshore Structures*, volume 1. Cambridge University Press.

Fernandez, M. (1981). Tow techniques for marine pipeline installation.

Foo, Y. P., Gan, K., Giudice, D., De Masi, G., et al. (2014). Analysis of windows of opportunity for weather-sensitive operations. *Oil and Gas Facilities*, 3(04):63–71.

Gatson, M. J. (2002). *The tug book*. Haynes Publishing, Sparkford, Nr Yeovil.

Gerwick Jr., B. C. (2007). *Construction of marine and offshore structures*. Taylor Francis Group, SF, CA, 3rd edition.

GOV.UK (2016). Marine accident investigation branch reports. https://www.gov.uk/maib-reports?date_of_occurrence%5Bfrom%5D=&date_of_occurrence%5Bto%5D=&keywords=tow&page=1. Visited on 2016-10-19.

Greco, M. (2012). Tmr 4215: sea loads lecture notes. *Trondheim, Norway: Dept. of Marine Technology, Norwegian University of Science and Technology*, pages 77–80.

Group, M. (2016). Innovation edge: Flow-lay system. http://www.murphygroup.co.uk/innovation/innovation-edge/marine/flow-lay-system/. Visited on 2017-03-20.

Guard, U. C. (2014). Report on investigation into the circumstances surrounding the multiple related marine casualities and grounding of the modu kulluk on december 31, 2012.

Hensen, H. (2003). *Tug use in port: a practical guide*. Nautical Institute.

Jacobsen, T. (2010). Subsurface towing of a subsea module.

Jacobsen, T., Naess, T.-B., et al. (2014). Installation of subsea structures using mid-size construction vessels in harsh environments. In *Offshore Technology Conference-Asia*. Offshore Technology Conference.

Journal, O. S. (2016). North sea: dire day rates and record layups. http://www.osjonline.com/news/view,north-sea-dire-day-rates-and-record-layups_45043.htm. Visited on 2017-25-05.

Larsen, K. (2016). Lecture notes in tmr4225 marine operations.

Larsen, K. and Sandvik, P. C. (1990). EFFICIENT METHODS FOR THE CALCULATION OF DYNAMIC MOORING LINE TENSION.

Ley, T., Reynolds, D., et al. (2006). Pulling and towing of pipelines and bundles. In *Offshore Technology Conference*. Offshore Technology Conference.

Lotsberg, I., Olufsen, O., Solland, G., Dalane, J. I., and Haver, S. (2004). Risk assessment of loss of structural integrity of a floating production platform due to gross errors. *Marine structures*, 17(7):551–573.

marinetraffic (2017). Songa trym. http://www.marinetraffic.com/no/ais/details/ships/shipid:304197/mmsi:257091000/imo:8752271/vessel:SONGA_TRYM. Visited on 2017-03-05.

Myrhaug, D. (2007). Marin dynamikk–uregelmessig sjø. *Department of Marine Technology, NTNU*.

Naaijen, P. and Huijsmans, R. (2008). Real time wave forecasting for real time ship motion predictions. In *ASME 2008 27th International Conference on Offshore Mechanics and Arctic Engineering*, pages 607–614. American Society of Mechanical Engineers.

Nielsen, F. G. (2007). *Lecture notes : Marine operasjoner*. Kompendium (Norges teknisk-naturvitenskapelige universitet. Institutt for marin teknikk). Marinteknisk senter, Institutt for marin hydrodynamikk, NTNU, Trondheim.

Notti, E., De Carlo, F., and Sala, A. (2014). Evalutaion of trawling thrust by means of a bollard pull test. ResearchGate.

Offshore, S. (2014). Songa Trym, Rig and Equipment Overview.

Offshore, S. (2015). SOW for Rigmove Songa Trym Tordis to Sleipner.

Pettersen, B. (2007). Marin teknikk 3: hydrodynamikk. *Dept. of Marin Techn. NTNU, Trondheim, Norway*.

Ramnaas (2016). Top quality mooring products for harsh offshore conditions.

Rasmussen, E. A. and Turner, J. (2003). *Polar Lows: Mesoscale Weather Systems in the Polar Regions*. Cambridge University Press.

Risoey, T., Mork, H., Johnsgard, H., Gramnaes, J., et al. (2007). The pencil buoy method-a subsurface transportation and installation method. In *Offshore Technology Conference*. Offshore Technology Conference.

SIMO, project, t. (2013). Simo, theory manual version 4.0 rev.3.

Standard, N. (1997). Marine operations. *J-003, Rev*, 2.

Subsea 7 (2012). Bundle pipeline systems shell fram development.

Tidende, B. (2014). Nytt slep festet i drivende boligrigg. http://www.bt.no/nyheter/innenriks/Nytt-slep-festet-i-drivende-boligrigg-266297b.html. Visited on 2016-10-03.

Veritas, D. N. (2008). Offshore standard dnv-os-e301: Position mooring.

Veritas, N. (2000). *Environmental conditions and environmental loads*. Det Norske Veritas.

Vinnem, J.-E. (2014). *Offshore Risk Assessment vol 1*. Springer.