Analysis of Riser Loads during BOP sailing.

Sigmund Anders Isaac Søgnesand

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for

Master Student Sigmund Anders Isaac Søgnesand

Analysis of Riser Loads during BOP sailing.

Analyse av belastninger på stigerør for undervanns flytting av BOP.

Running and retrieving the drilling riser column and subsea Blowout Preventer (BOP) is time consuming. The deeper the water depths, the more time is required for such operations. Hence, there is a potential to save a significant amount of time if the deployment and retrieval of the drilling riser column and subsea BOP is minimized.

When a Mobile Offshore Drilling Unit (MODU) is done at a well site, it usually retrieves the marine drilling riser column and subsea BOP. The MODU then moves to a new well location and runs the same drilling riser and subsea BOP. An alternative method has been explored in this thesis. This includes raising the subsea BOP some distance above the seabed, then transferring the BOP and marine drilling riser column to a new well location without having to pull all of the equipment to the drillfloor. While the platform is moving or 'sailing' from one well site to another, the riser with the BOP at the bottom will be hanging/suspended from the MODUs drillfloor.

During the BOP sailing activity there will be large hydrodynamic and inertial forces exerted on the suspended riser column and subsea BOP. In the present master thesis, the load effects as a function of significant wave height, current speed and sailing speed on different riser column lengths will be analyzed. The thesis will also discuss operations in detail, contains modeling and simulation results, sailing constraints, as well as risks and potential risk mitigation measures.

The candidate will be using the computer program RIFLEX in order to perform static and dynamic analysis of slender marine structures. There should also be a short and concise summary of the program and the theoretical background upon which it is based. Another computer program, called SIMO, will also be applied, which is a time domain simulation program for multi body systems

that allows non-linear analysis of this system for various sailing speeds, current speeds as well as wave conditions.

It is proposed that the work is performed according to the following plan:

1. Relevant literature in relation to analysis of riser and BOP response is to be reviewed. A summary of important publications is to be given. A description of the relevant subsea components and the sailing operation is also to be included.

2. The candidate is to get acquainted with the computer program SIMA/RIFLEX which is applied for static and dynamic response analysis of marine risers. An outline of this computer program and the corresponding theoretical basis is to be given.

3. A model for a specific riser and BOP configuration is to be created. This model is subsequently to be analyzed by application of SIMO/RIFLEX. Static and dynamic response analyses are performed for a set of particular wave- and current conditions. Parameter studies are subsequenty to be performed for this same system to the extent that time allows. Parameters that can be varied are e.g. riser column length, current- and wave-parameters as well as MODU sailing speed.

4. Relevant ultimate limit states for the riser pipe are to be investigated with respect to reserve margin. This applies to the combined effect of tension and bending moment. The influence of current, wave height and wave period on this reserve margin is to be investigated.

The work-scope may prove to be larger than initially anticipated. Subject to approval from the supervisor, topics may be deleted from the list above or reduced in extent.

In the thesis the candidate shall present his personal contribution to the resolution of problems within the scope of the thesis work. Theories and conclusions should be based on mathematical derivations and/or logic reasoning identifying the various steps in the deduction. The candidate should utilize the existing possibilities for obtaining relevant literature.

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

The thesis shall contain the following elements: A preface, list of contents, summary, main body of thesis, conclusions with recommendations for further work, list of symbols and acronyms, references and (optional) appendices. All figures, tables and equations shall be numerated.

The supervisor may require that the candidate, at an early stage of the work, presents a written plan for the completion of the work. The plan should include a budget for the use of computer and laboratory resources which will be charged to the department. Overruns shall be reported to the supervisor.

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 thesis shall be submitted in electronic form:

- Signed by the candidate

- The text defining the scope included

- Drawings and/or computer prints can be organised in a separate folder.

Supervisor: Professor Bernt J. Leira

Start: January 16th, 2015   Deadline: June 10th, 2015

Trondheim, January 16th, 2015

Bernt J. Leira

PREFACE

This thesis is the final work for completing a two-year master's degree program in Marine Subsea Engineering at the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway. The thesis was written during the last academic semester at NTNU and counts for 30 credits.

There are several people whom has helped and given me support throughout working on this thesis whom I would like to extend my sincere gratitude and thankfulness to. First of all, I would like to thank my supervisor Professor Bernt J. Leira at the Department of Marine Technology for his guidance and input.

I would also like to thank my parents, Sigmund Søgnesand and Paula Prlina Søgnesand, for their support throughout my entire academic career.

June 10th, 2015

Sigmund Anders Isaac Søgnesand

Trondheim, *June 2015*

ABSTRACT

Transferring a drilling rig and its subsea equipment from one location to another by conventional means tends to be time consuming. With low oil prices and increasing rig rates, operators are looking into making drilling rigs more efficient. This thesis will examine a method called BOP sailing, which may expedite the process of moving a drilling rig and its subsea equipment from one location to another. It will also make sure that the BOP sailing method is feasible from a safety and design point of view.

The BOP sailing operation is modelled and simulated in the riser analysis software RIFLEX for three riser column lengths:

- 311 m
- 800 m
- 1225 m

The riser joints for each of the riser column length have the same diameters and submerged weight per unit length. Weather conditions, current profiles and sailing speeds were defined prior to running the simulations. The results obtained from RIFLEX is then further analyzed by calculating a usage factor, η, based on the combined loading equation from the DNV-OS-F201 standard. This equation is used to perform riser analysis using tension and bending moments, and the value of the calculated usage factor may not exceed a critical value.

The usage factor is calculated at two locations on each of the riser columns for all of the weather conditions. One of the locations is located at the top of the riser column where the riser column is attached to the drilling vessel. The second location is where the maximum dynamic bending moment takes place.

Based on the simulation results, it is found that the value of η increases with an

- Increase in sailing speed
- Increase in wave height
- Increase in riser column length

However, the value of η did not exceed the limiting value in any of the simulations. One can therefore conclude that it is safe to sail with a suspended marine drilling riser and subsea BOP for all of the weather conditions and sailing speeds used in the RIFLEX simulations.

ABSTRAKT

Å flytte en borerigg fra en lokasjon til en annen ved bruk av konvensjonelle metoder kan ta mye tid. Med lave oljepriser og høye rigg rater ser operatører på forskjellige måter å gjøre boreplattformene mer effektive. Denne masteroppgaven undersøker en metode kalt BOP seiling, som kan forkorte tiden brukt på å flytte en boreplattform og dens undervanns utstyr (stigerør og BOP) fra en lokasjon til en annen. Masteroppgaven vurderer om det er mulig å gjennomføre en slik operasjon innenfor design- og sikkerhetsmessige aspekter.

BOP seiling er modellert og simulert i et stigerør analyse program kalt RIFLEX. Tre stigerørslengder er evaluert:

- 311 m
- 800 m
- 1225 m

Komponentene for de tre forskjellige stigerørskolonner har samme diameterne og vekt per lengde nedsunket i vann. Værforhold som vind og bølgehøyde, strømningsprofiler og seilehastigheter er parametere som inngår i simuleringene. Resultatene fra RIFLEX er analysert ved å beregne en bruksfaktor, η, basert på en kombinert last ligning fra DNV-OS-F201 standarden. Nevnte last ligning er anvendt i stigerørsanalyse ved å beregne strekk- og bøyemoment, og bruksfaktor som ikke kan ikke overskride en kritisk verdi.

Bruksfaktoren er beregnet ved to forskjellige lokasjoner på stigerørene for alle værforhold antatt i dette studiet. En lokasjon er på toppen av stigerøret hvor det er festet til boreplattformen. Den andre lokasjonen er hvor stigerøret utsettes for maks dynamisk bøye moment.

Basert på simuleringene, er det funnet ut at verdien av η øker med

- Økning i seilehastighet
- Økning i bølgehøyde
- Økning i stigerørslengde

Verdien av η overskrider ikke kritisk verdi i noen av simuleringene. Derfor kan man konkludere med av det er trygt å seile med hengende stigerør og BOP under alle værforhold og seilehastigheter som er evaluert i masteroppgaven.

ACRONYMS

ALS	Accidental Limit State
API	American Petroleum Institute
BOP	Blowout Preventer
DNV	Det Norske Veritas
FEA	Finite Element Analysis
FEM	Finite Element Method
FLS	Fatigue Limit State
HXT	Horizontal Christmas Tree
ISO	International Organization for Standardization
JONSWAP	JOint North Sea WAve Project
LMRP	Lower Marine Riser Package
MODU	Mobile Offshore Drilling Unit
NCS	Norwegian Continental Shelf
RAO	Response Amplitude Operator
SCM	Subsea Control Module
SLS	Serviceability Limit State
SMTS	Specified Minimum Tensile Strength
SMYS	Specified Minimum Yield Strength
ULS	Ultimate Limit State
VXT	Vertical Christmas Tree
WH	Wellhead
XT	Christmas Tree

SYMBOLS

H_s	Significant wave height
T_p	Wave period
σ_{vm}	Von Mises stress
σ_y	Yield Strength
ω	Angular frequency
ζ_a	Wave amplitude
g	Acceleration due to gravity
ϕ	Velocity potential
p	Pressure
k	Wave number
u	Displacement vector (x-direction)
$\dot{u}$	Velocity vector (x-direction)
$\ddot{u}$	Acceleration vector (x-direction)
ζ	Wave elevation
ρ	Density
h	Water depth
ϵ	Phase angle
$\dot{\eta}$	Velocity component of riser
$\ddot{\eta}$	Acceleration component of riser
C_M	Mass coefficient
C_D	Drag coefficient
A	Cross sectional area
r	Radius
η	Usage factor
M_d	Design bending moment
M_k	Plastic bending moment resistance
M_F	Bending moment from functional loads
M_E	Bending moment from environmental loads
M_A	Bending moment from accidental loads
T_{ed}	Design effective tension
T_k	Plastic axial force resistance

T_{eF}	Effective tension from functional loads
T_{eE}	Effective tension from environmental loads
T_{eA}	Effective tension from accidental loads
T_w	True wall tension
p_{ld}	Local internal design pressure
p_e	External pressure
p_b	Burst resistance pressure
ρ_i	Density of internal fluid
ρ_e	Density of external fluid
α_c	Flow stress parameter accounting for strain hardening
α_U	Material quality factor
q_h	Parameter to account for strain hardening and wall thinning
β	Parameter to account for strain hardening and wall thinning
γ_F	Load effect factor for functional loads
γ_E	Load effect factor for environmental loads
γ_A	Load factor for accidental loads
γ_m	Material resistance factor
γ_{sc}	Resistance factor dependent on safety class
f_u	Tensile strength to be used in design
f_y	Yield strength to be used in design
t_2	Pipe wall thickness
D	Nominal outside diameter
OP_{LIM}	Operational environmental limiting criteria
OP_{WF}	Forecasted (monitored) operation criteria
$\propto$	Factor accounting for uncertainty in weather forecast
t	Time variable
T_{POP}	Planned operation period
T_R	Operation reference period
T_C	Estimated contingency time

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1 INTRODUCTION

1.1   GENERAL BACKGROUND

In 1859 the first known oil well was drilled by "Colonel" Edwin Drake in northern Pennsylvania, USA [1]. This created interests in making further oil discoveries and was the starting point for further developments in the oil and gas industry.

Accumulations of hydrocarbons are found in porous rocks, usually sandstones or limestones, below the earth's surface. These accumulations are commonly referred to as reservoirs. The rock formations were originally desert sand dunes or seafloors for 100 to 200 million years ago. Organic materials were deposited on these surfaces and high pressures and high temperatures over longer periods of time transformed these organic materials into hydrocarbons [1].

In order for a reservoir to form, there has to be a "trap" of a non-porous medium or a layer that traps and lets the hydrocarbons accumulate. This prevents the hydrocarbons from migrating upwards. Common non-porous mediums are salt, shale, chalk or mud rocks [1].

The hydrocarbons that are trapped in the reservoirs are pressurized within the pores of the formation. When a well is drilled into a reservoir, the hydrostatic pressure in the reservoir pushes the hydrocarbons into the well and makes the well flow. Over time, the reservoir becomes depleted and the pressure in the reservoir decreases. The results of this is that the well produces less hydrocarbons [1].

When a reservoir has been proven to be cost efficient through seismic data and exploration wells, it is time to drill a well or multiple wells down into the reservoir. This is either done onshore/on land, or offshore. While drilling an offshore well, which is commonly referred to as a subsea well, a mobile offshore drilling unit (MODU) is often used. A simplified sketch of a MODU with its subsea equipment is seen in Figure 1.
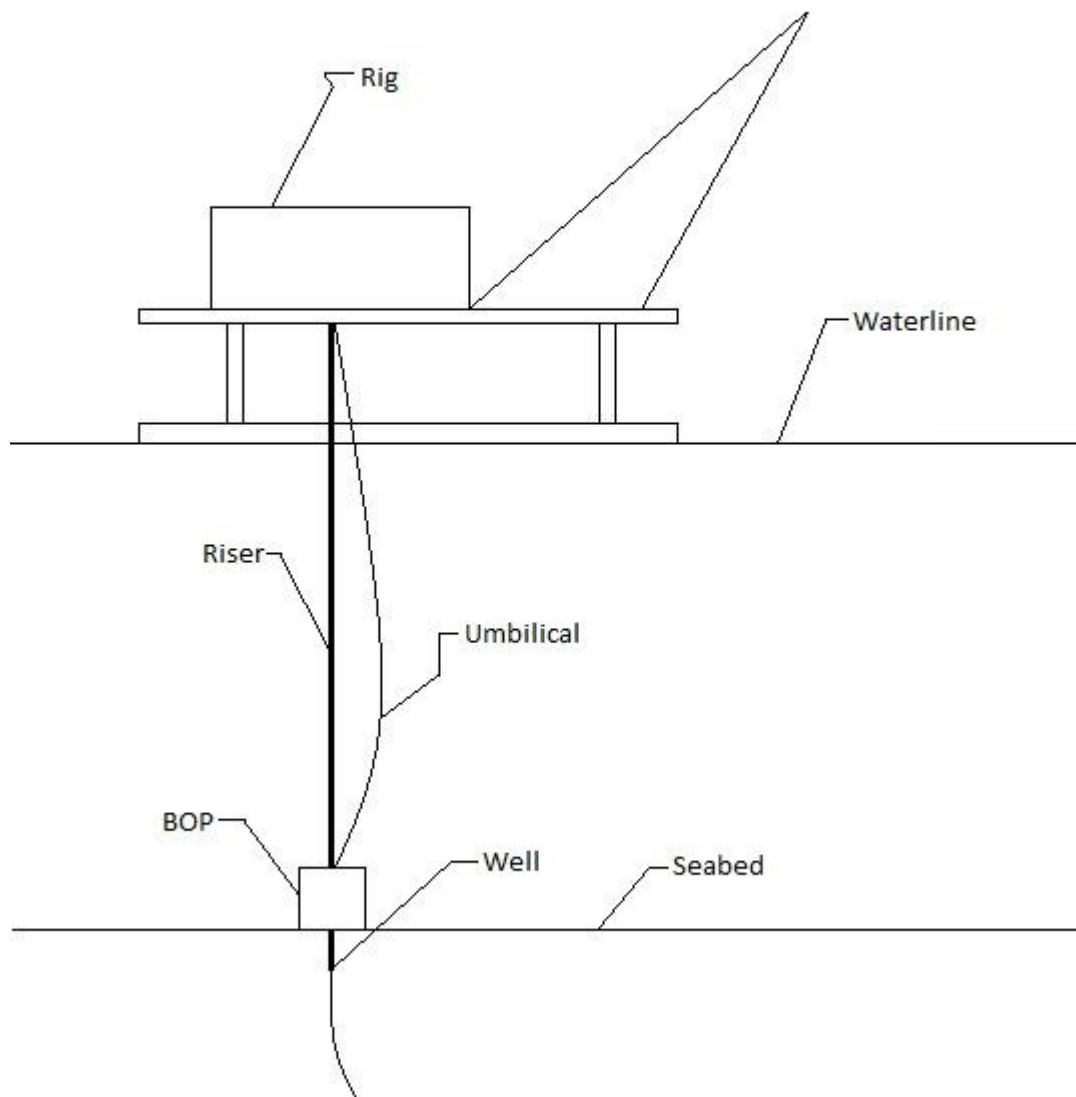
Figure 1: Typical subsea setup while drilling a subsea well using a MODU.

A more detailed description of the subsea components and their functions will be given later in the thesis. Prior to drilling a well, the MODU must deploy a large piece of equipment called a Blowout Preventer (BOP) stack down to the seabed. This piece of equipment is lowered down while hanging at the bottom of the riser column. The riser column is a series or pipe joints that are connected together one by one. When the BOP is on the seabed and is properly connected to the well, and the riser column connects the BOP stack with the MODU, drilling may start.

When the MODU is done drilling a well and is ready to depart, it must retrieve its BOP and drilling riser first. The BOP stack is raised off the seabed towards the MODU while the riser joints are disconnected one by one and laid down. When the BOP stack is on the drill floor and

properly secured, the MODU may proceed to sail to the new well site. This is the conventional method of running and retrieving the BOP stack and drilling riser at a well site.

1.2   PROBLEMS AND SOLUTIONS

Costs related to renting and operating drilling rigs are high. The day rate for high-spec drilling rigs on the Norwegian Continental Shelf was 147,500 USD per day in July, 2004 [2]. In September, 2008, the day rate had increased to 530,820 USD. This is an increase of 260 percent over a four year time period. In fact, hiring drilling rigs and costs of oil services are dominant drilling expenses [2]. Figure 2 shows the rental cost per day for some rigs on the Norwegian Continental Shelf.
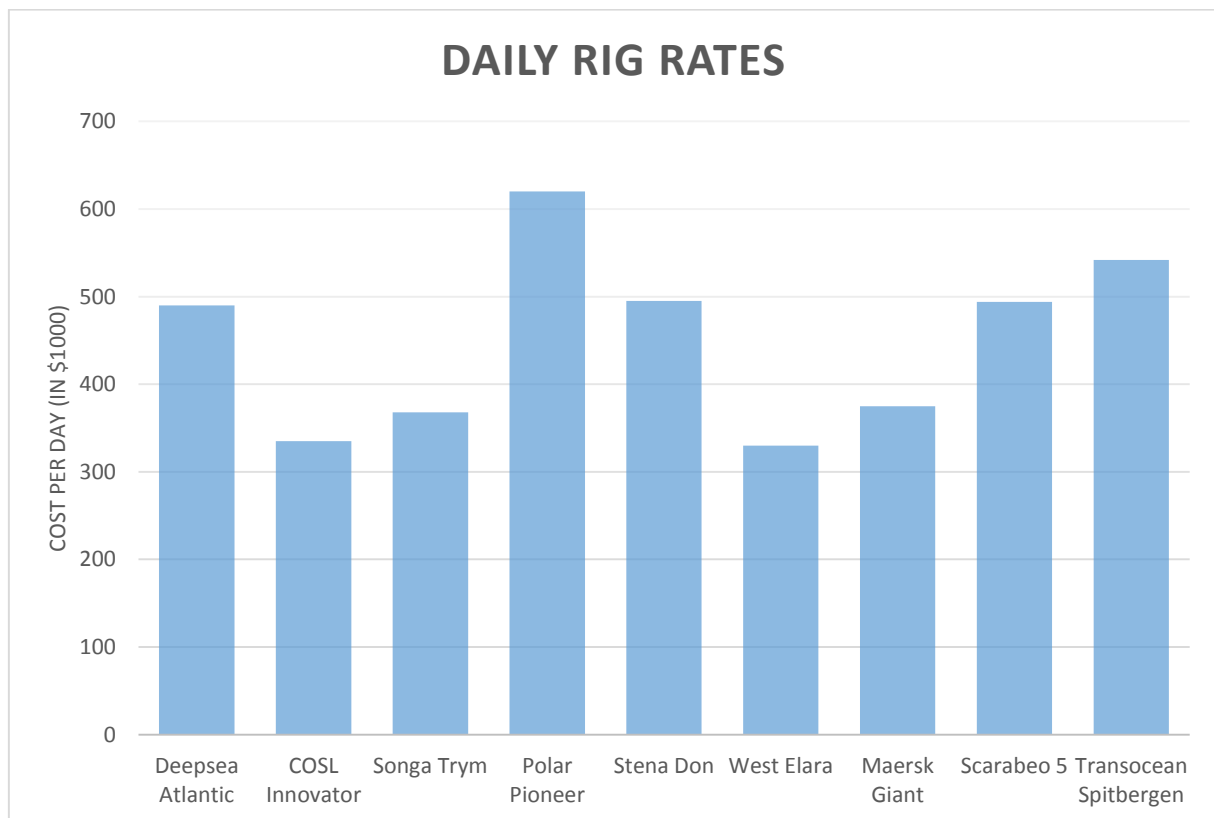
Figure 2: Daily rig rates for some rigs on the Norwegian Continental Shelf [3].

The high costs related to renting and operating drilling rigs has made operators focus more on effectivity. However, an interesting trend has been observed by Osmundsen et al. in the paper called *Drilling Productivity on the Norwegian Continental Shelf*. That is, with the increase in prices for renting and operating drilling rigs there has been a decrease in the drilling efficiency which can be measured in drilling meters per day. In fact, from 2004 to 2008 exploration drilling slowed down from an average of 144 to 67 meters per day [2].

Drilling meters per day and drilling meters per year are directly proportional to each other. Drilling one well fast and the next well slow will not solve the current problem of too low drilling rates. Therefore, operators must think long term and drill more wells per drilling rig per year. Operations where large amounts of time can be spent is running and retrieving the BOP and riser column. During these operations, the rig is not able to drill and the drilling meters per year declines the longer these operations takes.

In order to minimize the time spent moving the drilling rig and its subsea quipment from one well location to another, one can use the concepts of BOP jumping and BOP sailing. BOP jumping is when the BOP stack is lifted off of a well using the tensioners at the top of the riser column and moved over to a neighboring well without pulling the BOP stack to the drillfloor [4].

BOP sailing is when the BOP stack is lifted up from a well using the riser column. The riser column with the BOP stack at the bottom is then suspended or hung off from the drill floor. The platform can then proceed to sail to a new well location without having to retrieve and rerun the entire riser column and the BOP stack. The concept of BOP jumping/sailing is illustrated in Figure 3 below.
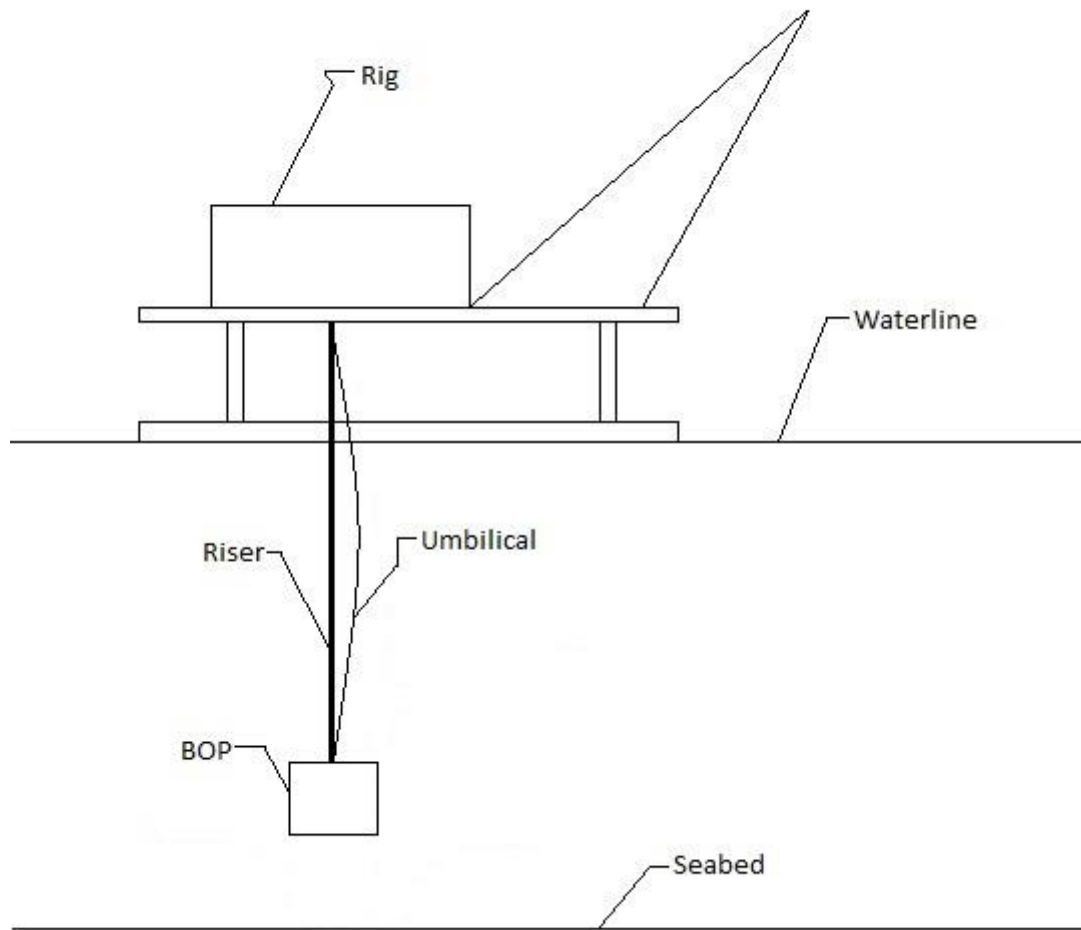
Figure 3: MODU sailing with suspended riser column and subsea BOP.

The difference between BOP jumping and BOP sailing are the distances covered and equipment removed from the top of the riser column. Traditionally for a BOP jumping event, none of the equipment/parts at the top of riser column is removed or as little equipment as possible is removed. For a BOP sailing event the equipment at the top of the riser column and perhaps a few riser joints are removed [4].

BOP jumping and BOP sailing can be a huge time saver for operators on the NCS. A general rule of thumb is that the deeper the water depth, the longer it takes to run the BOP stack and the marine drilling riser column. So in deeper waters, the more time can be saved.

1.3 BOP SAILING CONSIDERATIONS

Sailing with a suspended riser column and BOP should in the long run help save time and hence make drilling rigs more efficient in terms of the number of wells drilled per year. However,

there are some scenarios were the BOP jumping/sailing activity may not be feasible and/or necessary. Some factors to include while planning such an operation are:

- Distances
- Water depth
- Weather conditions
- Subsea structures
- Seabed topography and wellhead elevations
- Riser column design and properties
- BOP design
- Future work

1.3.1 Distances

The BOP sailing activity should occur over limited distances. A scenario where sailing with a suspended riser and BOP is feasible is while travelling between neighboring well slots or well sites that are close to each other. However, travelling over long distances is not recommended as unforeseen obstacles and problems may arise.

1.3.2 Water Depth

Water depth is an important factor when choosing whether or not to sail with a suspended riser column and BOP stack. As mentioned earlier in the thesis, the deeper the water depths the longer it takes to run the BOP stack and drilling riser column. The equipment at the very top of the riser column is the most difficult to handle and takes the longest to assemble/disassemble [4]. Based on this, in shallow water depths, sailing with a suspended BOP stack and riser column may not save a considerable amount of time compared to retrieving the entire riser column and BOP stack.

1.3.3 Weather Conditions

Weather conditions have to be favorable for BOP sailing activities to occur. Weather parameters of importance are significant wave height and wave period, current speed and current direction as well as wind speed. Although most of the riser column is submerged and wind does not exert forces directly on the riser column, it may have an effect on the vessels motions which in turn can have an effect on the response of the riser column.

1.3.4 Subsea Structures

While performing a sailing activity, one should try to avoid crossing any subsea structures, especially pipelines and subsea templates. In the worst case scenario, the BOP could fall and damage one of these structures. This should be taken into account and a route that crosses the least amount of subsea structures should be chosen/considered.

If, however, there are no other alternatives and a subsea structure must be crossed during a sailing operation, one could call the operating platform and close off the template/pipeline while the MODU is crossing.

1.3.5 Seabed Topography and Wellhead Elevations

While planning a sailing a sailing activity, the seabed topography should be carefully mapped out. This is to prevent the bottom of the BOP touching the seabed and/or subsea structures which could cause damage to the equipment and rig crew.

1.3.6 Riser Column Design and Properties

The riser joints and their corresponding properties are important as they have to be able to withstand the submerged weight of the BOP stack and the weight of the drilling riser column. In addition to this, dynamic forces from the surrounding environment will be exerted to the system.

Drilling riser joints vary in design depending on its water depth rating, manufacturers, criteria from rig contractors etc. Hence, the riser joints may not be designed for a sailing activity. Inquiring the designers and manufacturers of whether or not the riser joints have the correct properties for a sailing activity is recommended.

1.3.7 BOP Design

When the rig is moving forward with a suspended riser column and BOP stack, there will be large hydrodynamic forces exerted to the system. This could cause damage to fragile parts on the BOP stack. Also, a BOP jump tool is often used for sailing activity, and is explained in depth later in the text. However, the pipe rams used to clamp around the BOP jump tool may not be designed to hold the weight of the submerged BOP stack and drilling riser column.

1.3.8 Future Work

Some jobs performed on wells do not require the BOP stack and the drilling riser column. Therefore, sailing with a suspended BOP stack and riser column should take place only if the previous job and the future job requires the BOP stack and drilling riser column.

1.4 GENERAL PROTOCOLS

Prior to and during a BOP jumping/sailing activity there are some protocols that shall be followed. These can be specified by either local authorities, company whom owns the rig, company whom is renting the rig, suppliers of equipment etc. The protocols in this text are suggestions made by the author and are not legally binding.

One of the protocols is to have updated weather reports. Weather parameters of importance that should be included in the weather forecasts are:

- Current velocity and direction
- Wind velocity and direction
- Significant wave height and wave period.

Drilling rigs are equipped with at least one ROV in order to check the status while running and using the subsea equipment. ROVs are equipped with a sonar, echo sounder, lights and cameras. Sonar is an abbreviation for SOund NAvigation Ranging [5] and can be used to scan the area in front and on the side of the ROV for any obstacles [6]. The sonar is a useful tool as it usually has a significantly longer range than the cameras. Hence, it is able to detect obstacles farther ahead than the cameras are able to.

ROVs are also equipped with echo sounders. The echo sounder can be used to measure the distance between the ROV and seabed [7]. An ROV or ROVs can be used concurrently during a BOP sailing operation and could be strategically placed in front of the BOP in order to verify that there are no upcoming obstacles and that there is an acceptable clearance between the bottom of the BOP and the seabed at all times. If any unforeseen obstacles are detected, the ROV(s) should be placed far enough ahead of the BOP so the drilling rig can decelerate and stop or change directions without damaging the riser and/or BOP.

Another protocol is to have the BOP double secured during a BOP sailing or BOP jumping activity. This has two effects:

1) Reduce the tension in the riser column
2) Acts as a backup if the riser column is to fail/yield

One way to keep the BOP double secured is using a BOP jumping tool, which is described in Section 2.1.2.

1.5 PREVIOUS WORK

Studies related to the topic of BOP jumping have been performed. One article in the magazine *Drilling Contractor* called *Study analyzes response of deepwater riser with suspended BOP.* The study analyzes marine drilling riser response with a suspended BOP in water depths up to 2000 meters [8].

In order to calculate the riser response, a finite element representation of the riser column was created. The calculations took into account the riser axial tension, environmental loads and pressure effects due to internal and external fluid pressure. In addition to this sea current, waves, vessel motions and vessel advancing speed were also taken into consideration. The critical region of the riser was identified to be at the top of the riser column, where the stresses are the highest.

The operational criteria for the study were based on API RP 16Q (1993). The operation could be executed if the maximum von Mises stress in the riser did not exceed the maximum allowable stress. The maximum allowable stress in the riser was defined as $\sigma_{vm} \leq \sigma_y$. That is, the von Mises stress in the riser could not exceed 1/3 of the material yield strength of the riser.

Graphs showing contour lines of the von Mises stress divided by the yield stress for various significant wave heights and wave periods were plotted for different riser column lengths. From the graphs, it was determined there was a safe operational limit for significant wave heights less than 3.5 meters for all the different riser column lengths.

A conclusion brought forth by the study determined that the waves and vessel motions are important but the sea current profile is essential as it generally defines the maximum stress in the riser [8].

In another article published *BOP-deployed move saves time, money* the drill ship Discoverer Spirit located in the Gulf of Mexico saved about a weeks' worth of time and possible millions of dollars by sailing with a suspended riser column and BOP from one well site to another [9]. The activity took place in water depths over 7000 feet, or roughly 2100 meters. The BOP was pulled up 400 feet above the seabed prior to starting the sailing activity. The vessel reached a max sailing speed of one knot while the rig crew rig paid close attention to the riser movements. The rig would usually reach a sailing speed of 9 knots. Despite the slow speed, the rig saved a considerable amount of time.

According to the article, sailing with a suspended riser column and BOP has been done on multiple occasions. For example the R&B Falcon used the same method in February, 2001. The Discoverer Spirit's sister vessel Discoverer Enterprise sailed with a suspended riser column and BOP in the Gulf of Mexico on multiple occasions and had its BOP submerged for the last 7 months in 2000 [9].

1.6 ORGANIZATION OF THESIS

Chapter 2 describes relevant subsea components and their respective functions.

Chapter 3 will look into relevant standards and requirements, specifically for marine drilling risers.

Chapter 4 will discuss the environmental forces of interest and the corresponding background theory.

Chapter 5 gives an overview of the programs SIMA and RIFLEX.

Chapter 6 gives an in depth explanation of the model in RIFLEX.

Chapter 7 summarizes and analyzes the results obtained from the simulations in RIFLEX.

Chapter 8 concludes the thesis.

Chapter 9 gives recommendations for further work related to the topic of BOP sailing.

Chapter 10 is an overview of all of the references used throughout the thesis.

2 RELEVANT SUBSEA COMPONENTS

2.1 BOP GENERAL

The blowout preventer or BOP was developed to drill for oil and gas [10]. Below the earth's surface are high pressure and high temperature oil and gas reservoirs which may be harmful to equipment and rig crew on the surface if an uncontrolled leak of formation fluids were to occur.

A blowout is when oil and/or gas from the formations that are being penetrated flow uncontrollably to the surface through the wellbore. The first barrier to prevent this from happening is drilling mud or drilling fluid. These are weighted so that their specific weights have a hydrostatic pressure at the bottom of the wellbore that is slightly higher than the static pressure of the deposits. Having a hydrostatic pressure slightly higher than the formation pressure will prevent the fluids within the formations to enter the wellbore. If the specific weight of the drilling mud is not high enough and formation fluids are allowed to enter the wellbore, the BOP stack will act as the second barrier and has the ability to completely close off the wellbore using different types of rams [10].

Currently, two different types of BOP stacks are used: 1) subsea BOP stacks and 2) onshore/surface BOP stacks. The BOP stacks are built up using two different types of rams: 1) ram preventers and 2) annular preventers [10].

The ram type preventers can either be blind shear rams or pipe rams. The blind shear ram is able to close off the wellbore by compressing and deforming the drill pipe or any other shareable tools in the wellbore from both sides until they shear and fail. This will completely seal off the wellbore and hence prevent any fluids from escaping to the surface either through the inside of the drill pipe or the outside of the drill pipe. The pipe ram on the other hand is similar to the blind shear ram, except that it has cut-outs in the middle which can form around the outside of the drill pipe which will prevent fluids from escaping up between the tool in the wellbore and the inside of the BOP [10]. An example of a pipe ram with the circular cut-outs in the middle is seen in Figure 4.

Figure 4: Pipe ram preventer with the circular cut-outs in the middle [10].

The annular preventer is a rubber donut that forms around the drill pipe, liner, or any tool that is in the wellbore [10]. It has the ability to seal off the area between the item in the wellbore and the inside of the BOP.

For a BOP stack, the different rams are usually stacked on top of each other, for redundancy purposes. That is if one ram fails to seal off the wellbore, there are backup options.

2.1.1   Subsea BOP

Subsea BOPs are utilized when a MODU or a drilling vessel performs well activities. Not all well activities, however, require the subsea BOP i.e. retrieving the christmas tree (XT). The subsea BOP stack is located on the seafloor on a subsea structure called a subsea template. Hence, the rams have to be hydraulically operated since they are located where humans are unable to physically reach them. The rams are controlled from the MODU and can be closed off at any time.

Subsea BOPs are large in terms of weight and size. In the 1980s, their wet weight ranged between 125 to 160 tonnes while their heights varied from 12 to 14 meters. The height and weight of a subsea BOP has increased in recent years due to more stringent safety standards. Nowadays, a typical subsea BOP has a wet weight ranging from 270 to 365 tonnes while its height ranges from 14 to 15.5 meters [11].

A typical schematic of a two-section subsea BOP is seen in Figure 5. The lower part is called the BOP stack and is circled in red, while the LMRP stack sits on top of the BOP stack and is circled in green.

200 Blowout Preventer Stack
202 Wellhead
204 Lower Stack Assembly
206 Upper Stack Assembly
     (Lower Marine Riser Package)
208 Wellhead Connector
210 Ram Blowout Preventers
212 Annular Blowout Preventer
214 Choke and Kill Valves
216 Hydraulic Accumulators
218 Annular Blowout Preventer
220 Choke and Kill Connectors
222 Riser Adapter (Flex Joint)
224 Control Pods
226 Collet Connector
228 Frame

Figure 5: Typical subsea BOP and LMRP stack [12].

2.1.2 BOP Jump Tool

The BOP jump tool is often used while transporting a hanging/submerged BOP from one well to another by means of sailing or jumping. A CAD (Computer Aided Design) drawing of the BOP jump tool provided by Transocean is seen in Figure 6 below.
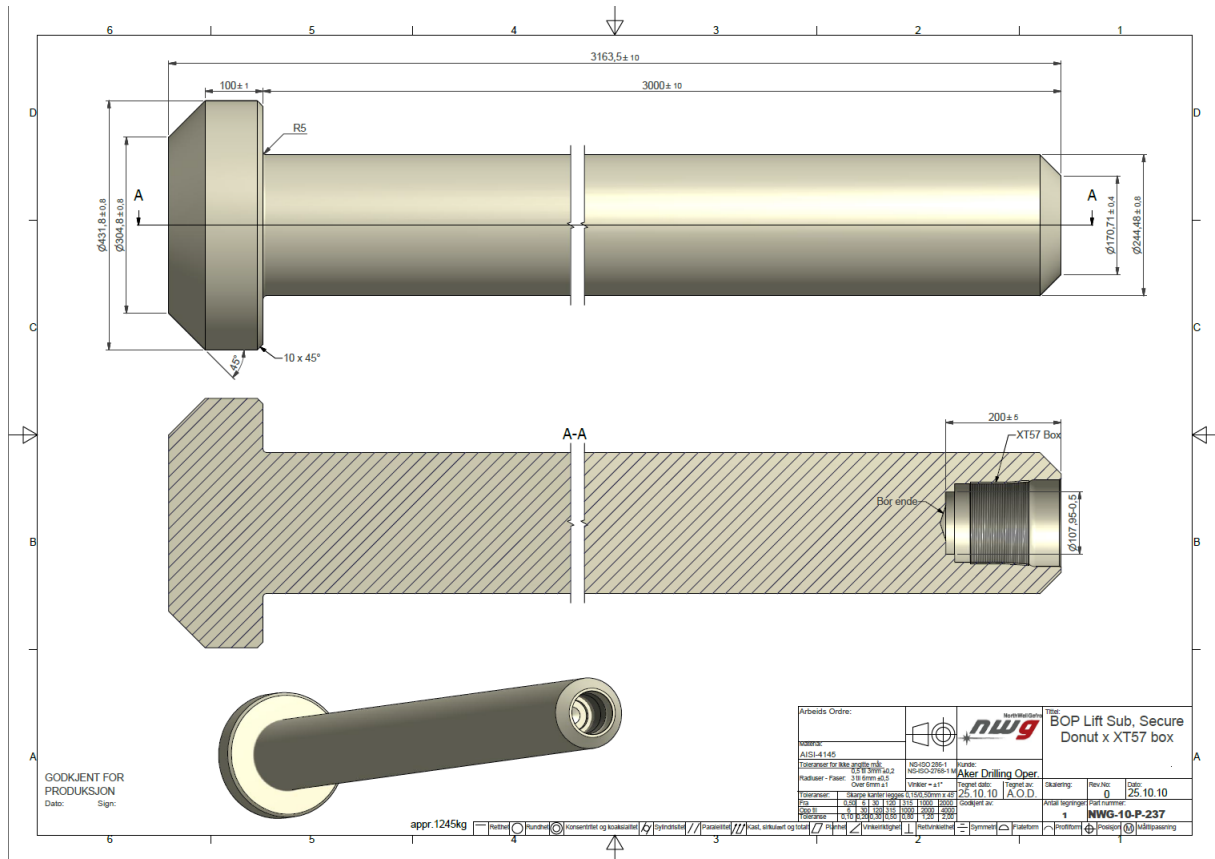
Figure 6: BOP jump tool provided used on Transocean Spitsbergen [13].

The BOP jump tool is formed as a circular T. The upper end of the BOP jump tool has a female connection, called "box" which allows for connection with the male connection end of a drill pipe called the "pin" [14].

The T-shape is meant to be located at the bottom of the string of drill pipes that is run down through the drilling riser and into the BOP. The depth of the bottom of the string is calculated/estimated so that one of the pipe rams can be closed and clamped right above the T-shape. The T-shape will prevent the pipe ram from slipping and possibly separating from the string of drill pipes.

Using the BOP jump tool can reduce the stresses in the riser column. This is done by pulling the string of drill pipes upwards, resulting in less stresses being present in the riser column.

Caution should be exercised by the rig personnel as the riser joints are designed to have a certain amount of tension. If the riser joints become compressed, riser buckling may occur.

The sequence for using the BOP jump tool is in the following order [15]:

- Run BOP jump tool on drill pipe
- Land BOP jump tool in BOP
- Engage BOP jump tool
  - This is done by closing a pipe ram around the drill pipe
- Lift, move and land BOP
- Disengage BOP jump tool by opening pipe ram
- Retrieve and lay down drill pipe and BOP jump tool

2.2 DRILLING RISERS

There are many different types of risers used in the offshore industry. Risers are predominantly used for [16]:

- Drilling
- Completion/workover
- Production/injection
- Export

The designs of the different types of risers vary greatly in terms of dimensions, materials etc. The risers of concern in this thesis are drilling risers. The primary functions of drilling risers is to [17]:

- Provide fluid communication between the wellbore and the MODU
- Support the choke, kill and auxiliary lines
- Guide tools into the wellbore
- Serve as a string for running and retrieving the BOP

There are two types of drilling risers: 1) high-pressure drilling risers and 2) low-pressure drilling risers [16]. For a MODU using a subsea BOP, a low-pressure drilling riser is conventionally used. The term low-pressure drilling riser is due to the fact that the riser is not designed to withstand full wellbore pressure. When the subsea BOP closes off the well, the riser is designed to withstand the pressure exerted by the hydrostatic mud column. High-pressure risers are used

with surface BOPs and needs to be able to sustain wellbore pressure when the BOP is closed off. Hence the name high-pressure drilling riser [16].

Riser joints are high strength, large diameter pipes with couplings at each end [17]. The marine drilling risers main tube typically has an outside diameter of 21 ¼ in or 539.8 mm. Typical steel grades used for the riser main tubes is API 5L X-52, X-65, and X-80 where the numbers represent the minimum yield strength of the material in ksi. Each riser joint is usually 50 to 75 feet long (approximately 15 to 23 meters) [17].

In addition to the main riser tube, there are also four peripheral lines that are clamped to the main tube [16]. A typical riser joint without buoyancy elements and four peripheral lines is seen in Figure 7.

Figure 7: Aluminum drilling-riser joint with peripheral lines [16].

The four lines that are clamped to the riser joints are called kill line, choke line, and auxiliary lines. The kill and choke lines are used to communicate with the wellbore when the rams in the BOP stack are closed. The auxiliary lines are mud boost lines, hydraulic supply lines and, if needed, an air supply line to control the buoyancy elements. The mud boost line is used to inject drilling fluid into the riser right above the BOP stack in order to increase the velocity of the returning fluids/drill cuttings. The hydraulic lines are multiple lines gathered in one larger diameter line and is used to carry hydraulic operating fluid to the subsea BOP control pod. In other words, it carries hydraulic oil that is used to control the different functions of the BOP stack. The air supply line supplies air for the air can buoyancy elements [16, 17]

Parts of the marine drilling riser column is often equipped with buoyancy elements which decreases the risers submerged weight and hence reduces the top tension in the riser [17]. The most common types of buoyancy elements are foam modules and air chambers or air cans. The design and the number of buoyancy elements depends on the water depth and other design criteria. Usually, there are multiple foam modules installed per riser joint with cut-outs for the different lines that go along the riser column. Air cans are usually installed where the risers are coupled together. Air is injected into the chambers through the air supply line and displaces seawater which results in an upward force [17].

2.2.1 Spider and Gimbal

While deploying the riser column, the riser joints are coupled to each other on the drill floor one-by-one then lowered down into the water. When a riser column is in the process of being retracted, the riser joints are decoupled from each other one-by-one prior to being laid down. In order to hold the riser column in place during coupling/decoupling, a device called a spider is installed on the drillfloor and its function is to support the weight of the suspended riser column and subsea BOP [18].

An example of a spider with hydraulic locking dogs as seen in Figure 8.
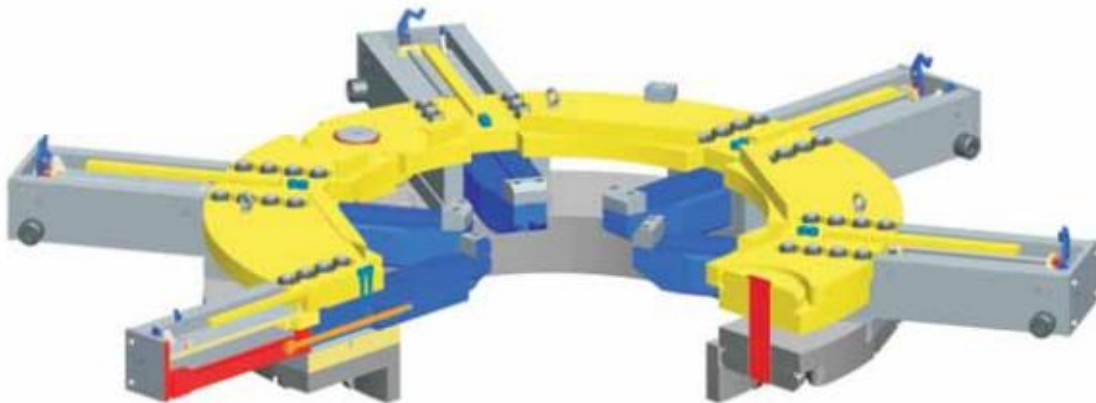
Figure 8:GE Vetco Gray MR-6E hydraulic spider [18].

The locking dogs are pushed in towards the outside of the riser joints and locks the riser joint to the drillfloor.

The gimbal is installed between the spider and the drillfloor and assists in maintaining a constant load on the riser and the spider as well as reducing the bending moments on the landing shoulders [17]. When any vessel or riser movements occurs, or any off-center loads are placed

on the spider, the gimbal absorbs these loads and distributes the loads evenly across the spider [19].

2.2.2   Tensioner System

The tensioner system is located at the top of the riser column and uses hydraulic rams with large volume, air-filled accumulators to help maintain a nearly constant force in the tensioner lines. The system, which usually comprises of multiple tensioner lines, applies a constant, vertical force on the riser in order to control the stresses and displacements in the riser while the drilling vessel is moving [17]. The tensioner system is usually a passive system, which means that it does not require an outside power source in order to function.

2.2.3   Telescopic Joint

The function of the telescopic joint is to account for vertical motions between the static riser column and the moving drilling vessel [17]. The telescopic joint consists of a tensioner ring, an outer barrel, which is located at the top of the riser column, and an inner barrel, which is attached to the drilling vessel. The tensioner ring is usually located at the top of the outer barrel, and provides connections where the tensioner lines are attached [17].

2.2.4   Flex/ball Joints

Flex and ball joints are usually located on top of the subsea BOP stack and at the topmost part of the riser column [17]. The function of the flex joint on top of the BOP stack is to allow deviations in the angle between the BOP stack and the riser. This helps reduce the bending moments in the riser and the wellhead, which the bottom of the BOP is attached to. In an ideal situation, the BOP and riser is completely vertical and the drilling vessel is located directly above the BOP stack. However, due to environmental forces acting on the drilling rig and marine drilling riser, the angle of the riser may deviate from a perfect vertical position. The flex joint at the top of the riser column allows for motions of the drilling rig [17].

2.3   OTHER RELEVANT SUBSEA COMPONENTS

Relevant subsea components is pointed out in Figure 9.
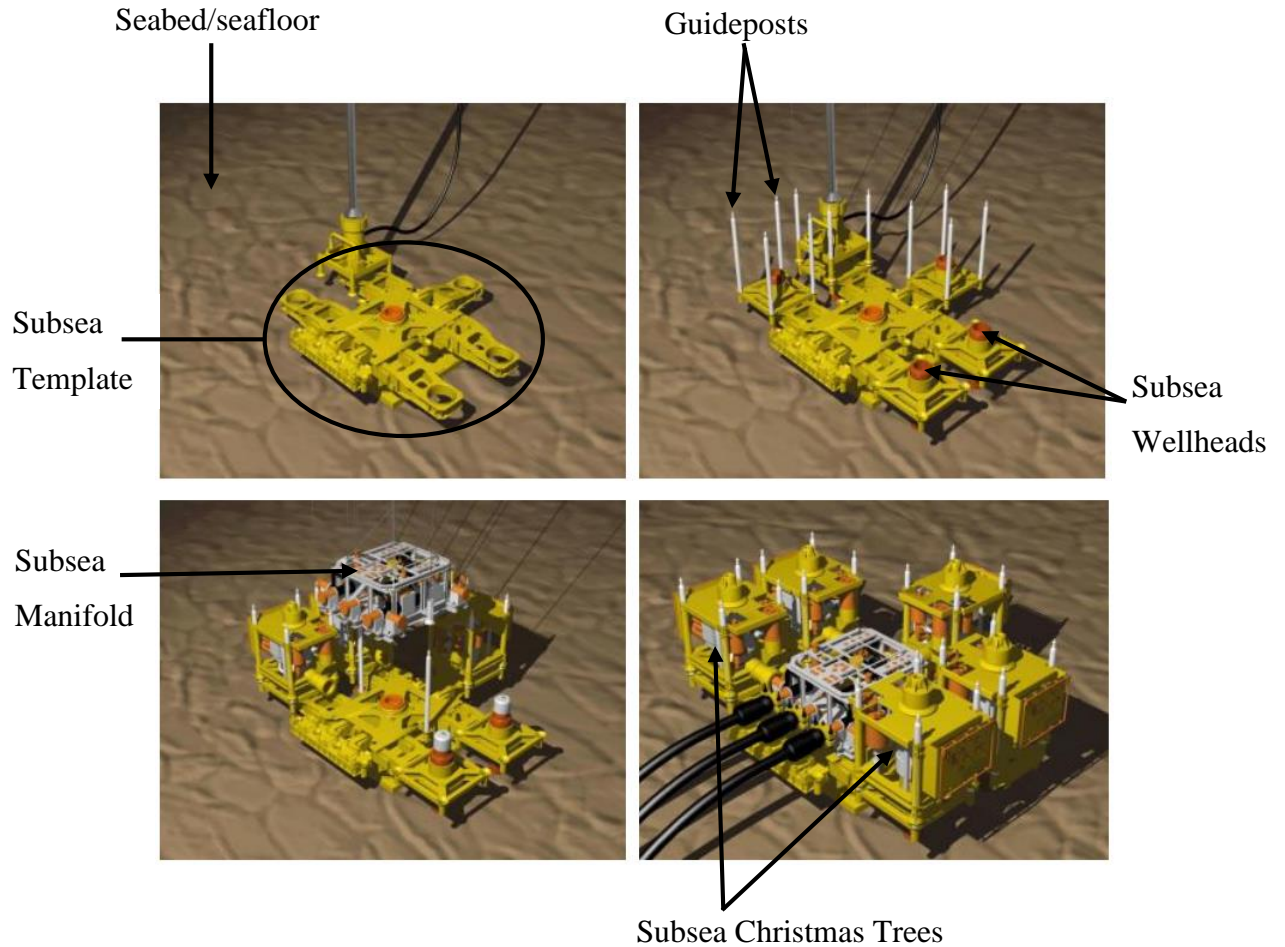
Figure 9: Subsea template manifold other subsea equipment [20].

The subsea components in Figure 9 and their functions are described in the following text.

2.3.1 Subsea Template

A subsea template is a structure installed on the seabed. For the NCS subsea developments, the subsea equipment is located within the subsea template structures [21]. The functions that the subsea template shall achieve is to

- Provide guide and hang-off for the conductor and wellhead in order to support drilling of the wells
- Support and provide a foundation structure to carry the weight of the manifold
- Support tie-in of umbilical and export- and/or injection-pipeline

The subsea template supports the wellhead, manifold and control system as well as the protection structure. The purpose of the protection structure is to protect the equipment installed on the subsea template from third part damages such as dropped objects, trawl equipment etc. [21].

The designs of subsea templates vary such that one well or multiple wells can be drilled and operated from the template. Each well has its own designated area called a slot. The template in Figure 9 is a 5 slot template which means that up to 5 wells can be operated from the template.

2.3.2   Subsea Wellhead (WH) System

The location of the subsea wellhead is at the top of the wellbore, on the subsea template, and is circular in geometry. The purpose of the wellhead system is to provide structural and pressure-containing interface for the drilling and production equipment [21].

On the inside of the wellhead are a series of grooves where the casings and production tubing are hung off (production tubing is hung off in the wellhead when vertical XTs are used). In order to maintain pressure integrity in the open space (annulus) between the casings, seal assemblies are used around the different grooves where the casings are hung off [21].

A typical 18 3/4 in wellhead with all of the casing strings and seal assemblies installed is seen in Figure 10.
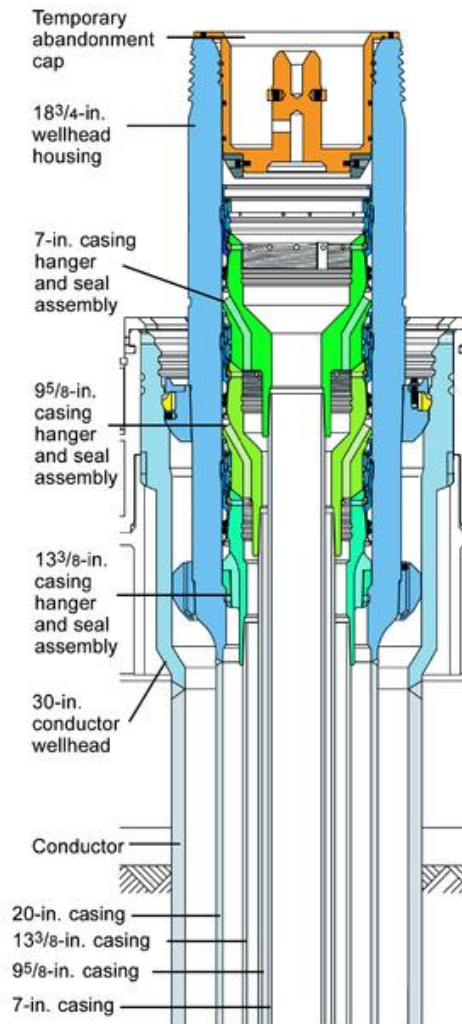
Figure 10: Subsea wellhead with casings and seal assemblies [22].

Note on the outside of the wellhead on the topmost part is a set of connectors, called H4 connectors, which allows for the subsea BOP or subsea XT to be installed.

2.3.3 Subsea Christmas Trees (XTs)

Subsea XTs are large pieces of equipment with a series of valves that is installed on the subsea template. The primary function of subsea XTs is to control and direct flow from the wellbore to the manifold [21].

Two types of subsea trees are currently used: 1) horizontal trees (HXT) and 2) vertical trees (VXT). The primary difference between the two types of XTs is where the production tubing is installed. For the horizontal system, the production tubing is installed in the XT while for the vertical system the production tubing is installed in the wellhead [21].

2.3.4 Bore Protector/Wear Bushing

Bore protectors and wear bushings are metal cylinders of various outside and inside diameters that are installed on the inside the wellhead to protect the grooves where the casings and seal assemblies are hung off from the equipment that is run in or pulled out of the well [22].

2.3.5 Guide Posts/Wires

Guide posts and guide wires are used to guide and align the equipment that is being lowered/raised from the drill rig onto or from the subsea template. Permanent guide posts are installed on the subsea template. Guide wires are attached to the top of the guide posts and extends up to the drilling rig [22].

2.3.6 Subsea Manifold

Conventionally on the NCS, the subsea manifold is located on the subsea template. The purpose of the subsea manifold is to [21]:

- Gather streams from multiple wells into the same flow line
- Monitor wellstreams
- Control XT valves and manifold valves

2.3.7 Multipurpose Tool

The multipurpose tool is used to run and retrieve the bore protectors and wear bushings. It may also be used to retrieve seal assemblies in the wellhead. An additional option is to attach a jetting sub to the tool. The function of the jet sub is to wash and remove any debris inside the wellbore i.e. within the wellhead and/or BOP [23].

2.3.8 Diverter System

The diverter system on a floating drilling rig is located right beneath the drill floor at the topmost part of the drilling riser column. It is used to redirect returning flow away from the rigs drillfloor [17].

2.4 SEQUENCE OF OPERATIONS

There is a general sequence of operations that is followed prior to, during and after a BOP sailing activity. The sequence of operations depends on many factors. This includes, but is not limited to, which and what activities have been performed and will be performed on the upcoming well, the equipment installed in and on the well, the history of the wells (any problems previously encountered), distance between wells, weather etc.

The following sequence of operations is a generalized sequence of operations that may differ between BOP sailing cases [15].

- Run in hole with multipurpose tool and jetting sub on drill pipe
- Wash and remove debris on the inside of wellhead and BOP
- Latch on and retrieve wear bushing/bore protector
    - If wear bushing or bore protector is installed
- Pull out of hole and lay down wear bushing/bore protector, multipurpose tool and jetting sub
- Run in hole with BOP jump tool on drill pipe
- Verify depth of BOP jump tool
    - Has to be inside of BOP - below pipe ram that is to be closed around drill pipe
- Engage BOP jump tool by closing pipe ram
- Remove equipment at top of riser column
    - Diverter
    - Tensioners
    - Upper flex joint
    - Telescopic joint
- Install riser spider
- Read and record bulls eye reading(s) prior to disconnecting BOP
- Disconnect BOP
- Land and lock riser to riser spider
- Verify distance between BOP and template using ROV
- Release and pull up guide wires
- Install corrosion/debris/dust cap on wellhead
- Sail with BOP and drilling riser to new well
- Open hatch at new well site
- Orient rig and BOP
- Verify distance between BOP and template using ROV
- Install guide wires
- Remove corrosion/debris/dust cap on wellhead
- Inspect wellhead using ROV
- Read and record bulls eyes readings prior to connecting BOP

- Install equipment at top of riser column
  - Diverter
  - Tensioners
  - Upper flex joint
  - Telescopic joint
- Land and connect BOP to wellhead
- Confirm latching/locking of BOP by performing over pull test
- Test BOP connector by closing shear ram and pressuring up below BOP against shallow set plug
- Open shear ram
- Open pipe ram
- Retrieve and lay down BOP jump tool

As mentioned, there may be deviations to the sequence of operations listed above. For example, a smaller vessel that is cheaper to rent can open and close the protective hatches on the templates as well as install and remove corrosion/dust/debris caps on the wellhead.

3   RELEVANT STANDARDS

The organizations DNV, ISO and API have separate standards for the offshore oil and gas industry. Relevant standards from each of the respective organizations will be studied in this section of the thesis. Of particular interest are standards pertaining to risers.

More specifically, the standards that will be looked into are:

- DNV-OS-F201
- ISO 13628-7
- DNV-OS-H101
- API-RP-16Q
- NORSOK D-010

The DNV-OS-F201 and API-RP-16Q standards will look into various methodologies to perform riser analyses. DNV-OS-F201 and ISO 13628-7 will be used to define the requirements related to the design of riser connectors. DNV-OS-H101 contains requirements related to performing marine operations. The NORSOK D-010 standard will look into testing of the subsea BOP.

3.1   DNV-OS-F201, DYNAMIC RISERS

The dynamic riser standard is a general standard applicable to all types of offshore risers. The standard gives criteria, requirements, and guidance on structural design as well as how to perform analysis of riser systems exposed to static and dynamic loading.

A summary of the different limit states applicable to offshore risers is seen in Figure 11.

Limit State Category	Limit State	Failure definition/ Comments
SLS	Clearance	No contact between e.g. riser-riser, riser-mooring line, riser-hull, surface tree-floater deck, subsea tree-seabed, surface jumper- floater deck.
	Excessive angular response	Large angular deflections that are beyond the specified operational limits, e.g. inclination of flex joint or ball joint.
	Excessive top displacement	Large relative top displacements between riser and floater that are beyond the specified operational limits for top tensioned risers, e.g. stroke of telescope joint, slick joint and tensioner, coiled tubing, surface equipment and drill floor. Note that systems can be designed for exceeding displacement limits if the structural integrity is maintained.
	Mechanical function	Mechanical function of a connector during make-up/break-out.
ULS	Bursting	Membrane rupture of the pipe wall due to internal overpressure only.
	Hoop buckling (collapse)	Gross plastic deformation (crushing) and/or buckling (collapse) of the pipe cross section caused by external overpressure only.
	Propagating buckling	Propagating hoop buckling initiated by hoop buckling.
	Gross plastic deformation and local buckling	Gross plastic deformation (rupture/crushing) of the pipe cross-section in combination with any local buckling of pipe wall (wrinkling) due to bending moment, axial force and internal overpressure.
	Gross plastic deformation, local buckling and hoop buckling	Gross plastic deformation and hoop buckling of the pipe cross section and/or local buckling of the pipe wall due to the combined effect of external overpressure, effective tension and bending moment.
	Unstable fracture and gross plastic deformation	Unstable crack growth or rest ligament rupture or cross section rupture of a cracked component.
	Liquid tightness	Leakage in the riser system including pipe and components.
	Global buckling	Overall column buckling (Euler buckling) due to axial compression (negative effective tension).
ALS	Same as ULS and SLS	Failure caused by accidental loads directly, or by normal loads after accidental events (damage conditions).
FLS	Fatigue failure	Excessive Miner fatigue damage or fatigue crack growth mainly due to environmental cyclic loading, directly or indirectly. Limiting size of fatigue cracks may be wall thickness (leakage) or critical crack size (unstable fracture/gross plastic deformation).

Figure 11: Summary of DNV's limit states [24].

3.1.1 Riser Yielding Assessment from DNV-OS-F201

The results from the simulations are analyzed using Microsoft Excel and equations from the DNV-OS-F201 Dynamic Risers standard.

3.1.1.1 Summary of Equations Used

The moment and force in the riser column are perhaps the two most important parameters that are provided by the RIFLEX simulations. Both of these parameters are included when using the combined loading equation, Equation (3-1), from the offshore DNV-OS-F201 standard [24].

$$
\eta = \{\gamma_{sc} \cdot \gamma_m\} \left\{ \frac{|M_d|}{M_k} \cdot \sqrt{1 - \left(\frac{p_{ld} - p_e}{p_b(t_2)}\right)^2} + \left(\frac{T_{ed}}{T_k}\right)^2 \right\}
$$
$$
+ \left(\frac{p_{ld} - p_e}{p_b(t_2)}\right)^2 \leq 1
$$

(3-1)

Where η is the usage factor, M_d is the design bending moment, M_k is the plastic bending moment resistance, T_{ed} is the design effective tension and T_k is the plastic axial force resistance, γ_m is the resistance factor that takes uncertainties in the material properties into account, γ_{sc} is a resistance factor dependent on the safety class or safety requirements of the

design and the consequences of failure, p_{ld} is the local internal design pressure, p_e is the local external pressure while $p_b(t_2)$ is the burst resistance.

The original formula from the DNV-OS-F201 standard includes the difference between the external and internal pressures in the riser. However, during a sailing operation the riser column is filled with sea water [4]. The sea water column within the riser is assumed to go from mean seal level to the bottom of the riser column, so the internal and external hydrostatic pressure is more or less the same. Therefore, the difference in external and internal pressure is negligible. This simplifies the equation above and subsequently the analysis of the riser. The new equation where the pressure differences are neglected simplifies to Equation (3-2).

$$\eta = \{\gamma_{sc} \cdot \gamma_m\} \left\{ \frac{|M_d|}{M_k} + \left(\frac{T_{ed}}{T_k} \right)^2 \right\} \leq 1 \qquad (3\text{-}2)$$

For the equation to be satisfied and to prevent yielding, gross plastic deformation or wrinkling due to combined loading, the left hand side of the equation must be less than or equal to one. That is, $\eta \leq 1$. The rest of the equations used from the DNV-OS-F201 standard are listed in Equations (3-3) - (3-11).

$$M_d = \gamma_F \cdot M_F + \gamma_E \cdot M_E + \gamma_A \cdot M_A \qquad (3\text{-}3)$$

$$M_k = f_y \cdot \alpha_c \cdot (D - t_2)^2 \cdot t_2 \qquad (3\text{-}4)$$

$$\alpha_c = (1 - \beta) + \beta \cdot \frac{f_u}{f_y} \qquad (3\text{-}5)$$

$$f_u = (SMTS - f_{u,temp}) \cdot \alpha_U \qquad (3\text{-}6)$$

$$\beta = \begin{cases} (0.4 + q_h) & for \dfrac{D}{t_2} < 15 \\[2mm] \dfrac{(0.4 + q_h)\left(60 - \dfrac{D}{t_2}\right)}{45} & for \ 15 < \dfrac{D}{t_2} < 60 \\[2mm] 0 & for \dfrac{D}{t_2} > 60 \end{cases} \qquad (3\text{-}7)$$

$$q_h = \begin{cases} \dfrac{(p_{ld} - p_e)}{p_b(t_2)} \dfrac{2}{\sqrt{3}} & for \ p_{ld} > p_e \\[2mm] 0 & else \end{cases} \qquad (3\text{-}8)$$

$$p_{ld} = p_d + \rho_i \cdot g \cdot h \qquad (3\text{-}9)$$

$$T_{ed} = \gamma_F \cdot T_{eF} + \gamma_E \cdot T_{eE} + \gamma_A \cdot T_{eA} \qquad (3\text{-}10)$$

$$T_k = f_y \cdot \alpha_c \cdot (D - t_2) \cdot t_2 \qquad (3\text{-}11)$$

A more detailed summary of the equations and the definition of each of the parameters listed in Equations (3-3) - (3-11) is found in Appendix A.

It should be noted that the plastic bending moment, M_k, and the plastic axial force, T_k, are both dependent on the temperature derating factor, f_y. According to DNV, when the operating temperature increases the effective yield stress and tensile strength of the material will decrease. Since the seawater in the North Sea is roughly equal to 2-4 °C, the decrease in the effective yield stress and tensile strength properties is neglected. In other words, the yield stress and tensile strength can be assumed to be equal to its values at room temperature multiplied by the material strength factor, α_U.

In order to calculate the plastic bending moment, the values for M_F, M_E and M_A which are the bending moments from functional loads, environmental loads, and accidental loads are needed. In addition to this, the tension values needed to calculate the axial force are T_{eF}, T_{eE}, T_{eA} which are defined as the effective tensions from functional loads, environmental loads and accidental loads, respectively. The riser analysis performed in this thesis is performed with ULS loading condition and therefore M_A and T_{eA} have already been accounted for [24].

3.1.1.2 Types of Loads

Functional loads are defined as loads that occur due to the physical existence of the system. Examples of functional loads are for a riser is [24]:

- Weight and buoyancy
- Weight of internal fluid
- Loads from drilling operations
- Thermal loads

Environmental loads are defined as loads imposed directly or indirectly to the system by the ocean environment. Examples of environmental loads are:

- Waves
- Currents
- Floater motions

Accidental loads are unforeseen loads exerted to the riser system, or when the riser is subjected to loads in abnormal conditions, incorrect operation or loads due to technical failures. Examples of accidental loads are [24]:

- Collisions

- Fires

- Failure of system

  o Loss of buoyancy elements

  o Heave compensator failure

  o Loss of DP (Dynamic Positioning) system

- Environmental events

  o Eartquake

  o Tsunami

  o Iceberg

3.1.1.3 Safety Factors

The safety factors γ_F, γ_E, and γ_A for each of the different load types are also needed. The values for the safety factors depends on the type of limit state used for the analysis. Different limit states have different safety factors. The safety factors in Table 1 are taken from DNV-OS-F201 and can be used for analyses corresponding to the different limit states.

Table 1: Load effect factors [24].

Limit state	F-load effect	E-load effect	A-load effect
	γ_F	γ_E	γ_A
ULS	1.1	1.3	NA
FLS	1.0	1.0	NA
SLS & ALS	1.0	1.0	1.0

There is no γ_A for the ultimate limit state and fatigue limit state due to the fact that accidental loads are already included in these load designs.

The safety class resistance factor, γ_{sc}, is dependent on how conservative the design is supposed to be and its values are listed in Table 2.

Table 2: Safety class resistance factors, γ_{sc} [24].

Low	Normal	High
1.04	1.14	1.26

Low, normal and high refers to how safe the design is with respect to the resistance factor. The material resistance factor, γ_m, is dependent on the limit state used for the analysis and values corresponding to each respective limit state are listed in Table 3.

Table 3: Material resistance factor, γ_m [24].

ULS & ALS	SLS & FLS
1.15	1.0

For the analysis of the suspended riser column, the ULS safety factors are used.

3.2 API-RP-16Q

American Petroleum Institute 16Q is the recommended practice for design, selection, operation and maintenance of marine drilling riser systems [17]. According to the standard, common steel grades used in risers are X-52, X-65 and X-80, where the numbers represents the minimum yield strength (in ksi) of the material.

The standard also mentions different riser handling systems and riser hang-off systems for emergency disconnect situations. It is a possibility that the same systems can be used while sailing with a suspended riser column and BOP. The diverter handling tool can be used to support the entire weight of the riser and BOP. The standard states that

"the disconnected riser may be hung off from the hook, the spider, the diverter housing…".

While choosing the hang-off system, the dynamic loads exerted to the riser should be considered to ensure that the hang-off system has sufficient strength and make sure there is no damage imposed on the riser nor the vessel.

The standard has defined operating guidelines for drilling, non-drilling and riser disconnect modes. The mode of concern for this thesis is the disconnected mode, in which the riser is disconnected from the template. For each of the respective modes there are two methods; method A which applies to most water depths and method B which is for deeper water depths. Due to the small water depths on the Norwegian Continental Shelf, method A is the most appropriate method.

The stress criteria for method A is $0.67\sigma_y$ where σ_y is the minimum wield strength of the material. The stresses in the riser are calculated using von Mises stress criterion which is given in Equation (3-12).

$$\sigma_{vm} = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]} \qquad (3\text{-}12)$$

Where σ_1, σ_2, and σ_3 are the axial bending stress, hoop stress and radial stress [17] as seen in Figure 12.
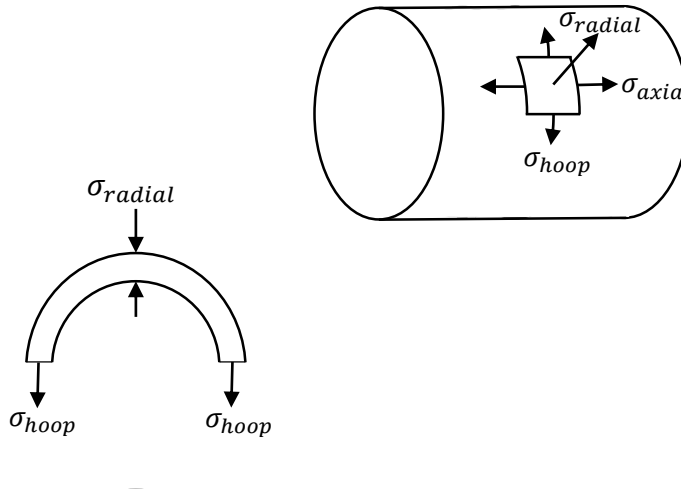
Figure 12: Axial, hoop and radial stresses

The axial stress goes along the cylinder length, the hoop stress is the tangential stress, and radial stress is due to internal and external pressures.

3.3 RISER CONNECTORS

While performing a riser analysis it is important to know whether any other components will fail prior to the main tube of the riser joint. Therefore, the design standards and requirements pertaining to riser connectors were looked further into. This was to determine whether the riser connectors would be a weak or strong link in the riser column.

3.4 DNV-OS-F201, DYNAMIC RISER

The DNV-OS-F201, Dynamic Risers standard covers the design requirements for riser connectors. In terms of functional requirements, the riser connectors should be able to be made up and broken apart on multiple occasions without having reliability issues [24]. In addition to this, the connectors shall not interfere or hinder normal operations that are taking place in and around the riser.

In terms of design qualifications, the connectors shall be able to withstand the loads exerted to them while they are being made up and broken down. They should be designed to be able to withstand a variety of loads, such as loads from thermal effects, internal and external pressure

effects, bending moments, cyclic loading, as well as other internal and external loads exerted to the riser. The connectors should at least be as strong as the riser main tube with respect to strength, fatigue, leakage and fire resistance. This implies that the connectors shall not be the weakest link in the riser column.

There shall be sealing elements between connections points of the riser joints. There are two types of seals; integral seals which are built into the connector and are non-replaceable, and non-integral seals which are separate sealing elements that are replaceable. The requirements for the seals is that they should be able to withstand the operating conditions they are exposed to. Sealing performance and sealing reliability are important factors while determining the appropriate sealing elements for the riser [24].

3.5 ISO 13628-7

In the connector section in the dynamic riser standard there is a reference made to ISO 13628-7 for further details on design, analysis and requirements. The ISO 13628 part 7 standard pertains to completion and workover riser systems [25]. According to this standard, a connector is defined as:

> "mechanical device used to connect adjacent components in the riser system to create a structural joint resisting applied loads and preventing leakage".

There are some fundamental design requirements that apply to the connectors such as the connectors should be able to withstand loads they are subjected to, meet a certain level of safety, provide sufficient structural resistance, leak-tight, and transfer loads smoothly between riser joints.

In terms of loads, the connectors should be able to withstand the same loads as the riser joints. The weakest part, or the part that can withstand the smallest loads, defines the maximum load that the riser column may be subjected to.

The suitability of the connectors for the specific application shall be based on analytical and experimental methods. The connectors should be designed to have a margin of safety with respect to all of the relevant failure modes. Make-up and break-out procedures are to be specified and followed carefully.

The seal requirements in the ISO standard is the basis for the seal requirements in the DNV standard. The integrity of the seal shall be intact while exposed to both internal and external

fluids and loading. The seals should have a certain amount of corrosion resistance and the material of the seals should be paired with the material of the surrounding parts in order to avoid galvanic corrosion [25].

3.6   DNV-OS-H101, MARINE OPERATIONS, GENERAL

There are two types of marine operations; 1) weather restricted and 2) weather unrestricted operations [26]. Weather restricted operations normally have a reference period, T_R, less than 96 hours and a planned operation period, T_{POP}, time less than 72 hours. Marine operations that take longer than 96 hours are normally classified as weather unrestricted operations.

The reference period is defined as the planned operation time plus a maximum estimated contingency plan, T_C. The planned operation time is a conservative estimate of how long the operation shall take. The contingency plan shall cover uncertainties in the operation as well as other situations that may require additional time to complete the operation.

A favorable weather forecast has to be issued prior to the start of a weather restricted operation. During the operation, weather forecasts are monitored continuously. Marine operations may still be classified as weather restricted although the duration is longer than 96 hours by continuously monitoring the current and forecasted weather and bringing the object into a safe condition.

Weather unrestricted operations are operations based on environmental conditions from long-term statistical data.

For weather restricted marine operations an operating limit, OP_{LIM}, and an alpha factor, $\propto$, must be defined. Operating limit criteria are weather conditions limiting a safe operation, usually wind and waves. The operational criteria, OP_{WF}, is defined as Equation (3-13).

$$OP_{WF} = \propto \times OP_{LIM} \qquad\qquad (3\text{-}13)$$

If the values of for example significant wave height exceeds OP_{WF}, the operation is not feasible. The alpha factor which is applicable to wind and significant wave height, is found in DNV's marine operations guidelines and is dependent on the duration of the planned operation period and the forecast level.

There are three different types of weather forecast levels which are referred to as level A, B, and C. Level A forecasts is applicable to major marine operations that are sensitive to environmental conditions. These types of operations requires a meteorologist on site, while

level B and level C forecasts do not require a meteorologist on site. Examples of a level A operation is mating operations, jack-up rig moves, offshore installation operations etc.

Level B forecasts are applicable to environmental sensitive operations that are important with respect to value and consequences. Examples are offshore lifting and subsea installations. Level C forecasts are applicable to typical marine operations that are less sensitive to weather and are carried out on a regular basis. Typical examples of a level C forecasts are onshore/inshore lifting and standard barge tow without wave restrictions. For all weather forecast levels, the maximum weather forecast interval is 12 hours. After 12 hours a new weather forecast has to be issued [26].

3.7 NORSOK D-010N

The NORSOK D-010N standard contains various criteria for testing of subsea BOP's on the NCS. Some of the criteria for BOP testing are [27]:

- BOP shall be tested to full pressure rating once every 6 months
    - Can be performed on the wellhead
- Pressure tests shall be performed every 14 days
- BOP function test shall be performed when BOP is on the seafloor
- BOP function test with kill- and choke lines shall be performed weekly
- Pressure test should be stable for 10 minutes during high pressure test and 5 minutes during low pressure test
- Prior to drilling, the BOP shall be tested to the maximum estimated pressure for the relevant section
- A complete overhaul and testing of BOP shall be performed every 5 years

The only point in the NORSOK standard that specifies how often the BOP has to be pulled to the surface is for the complete overhaul of the BOP which has to occur every 5 years. Besides this, the BOP can be submerged as long as the BOP function tests and pressure tests are satisfactory.

4 LOADS ON RISER AND BOP

The MODU, marine drilling riser and subsea BOP stack are subjected to various environmental forces during a BOP sailing activity.

The magnitude of the forces and their effects on the riser column may vary. These forces can cause an increase/decrease in the forces and bending moments within the riser column. Figure 13 shows the some important environmental forces related to a BOP sailing activity.
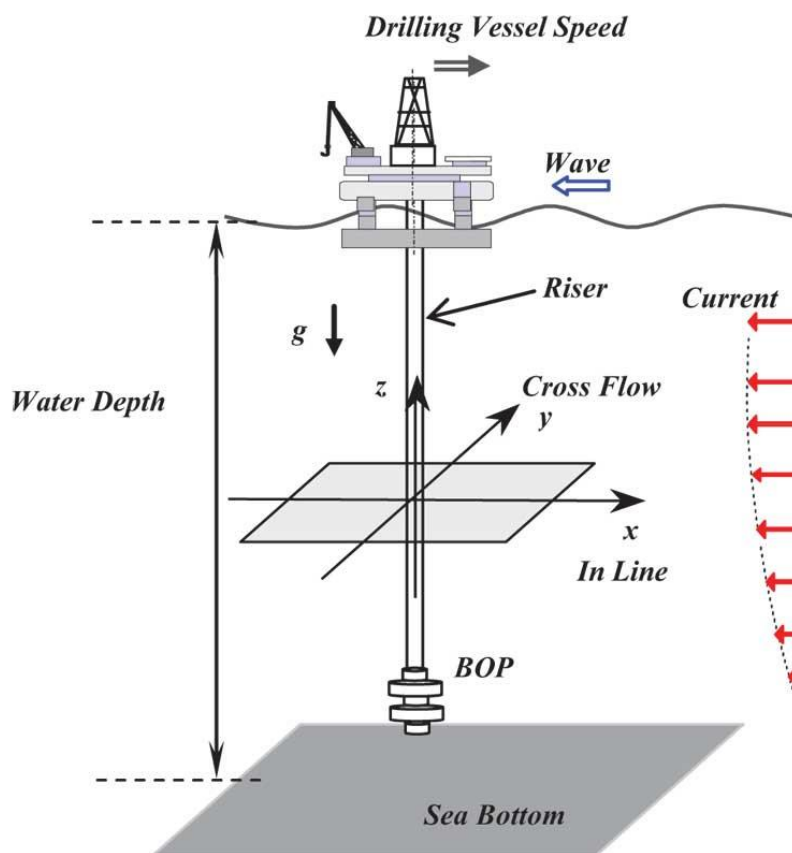
Figure 13: Illustration of a MODU sailing with a suspended riser and BOP with various environmental forces acting on the system [28].

The environmental forces of importance in this thesis is mainly due to:

- Current
- Significant wave height and wave period

These forces will be discussed more in depth in this part of the thesis.

4.1 CURRENTS

Ocean currents are bodies of moving water in the horizontal and/or vertical direction. The direction and speed of ocean currents depends on the following factors [29]:

- Tides
- Local wind
- Stokes drift
- Geographical location
- Storm surges
- Density jumps in the upper ocean

The current direction and speed may change significantly over the length of the riser column.

4.2 WAVES

Waves are of importance with regards to forces exerted to the MODU, drilling riser column and subsea BOP stack. In addition to this, the weather criteria for the sailing activity is largely based on the wave properties. Fundamental background information related to waves will therefore be summarized. All of the information related to wave theory is taken from [29]. This includes

- Basic assumptions for potential theory
- Boundary conditions
    - o Kinematic
    - o Dynamic free-surface
- Regular wave theory
- Irregular wave theory

4.2.1 Basic Assumptions for Potential Theory

For any given time, a velocity potential, ϕ, can be used to describe the fluid velocity vector as in Equation (4-1).

$$V = \nabla\phi = i\frac{\partial\phi}{\partial x} + j\frac{\partial\phi}{\partial y} + k\frac{\partial\phi}{\partial z} \qquad (4\text{-}1)$$

Where i, j, and k are unit vectors along the x-, y-, and z-axes, respectively. One assumption is that the fluid is irrotational. This is true when Equation (4-2) is zero everywhere within the fluid.

$$\omega = \nabla x V = 0 \tag{4-2}$$

The continuity equation describes seawaters incompressibility using Equation (4-3).

$$\nabla \cdot V = 0 \tag{4-3}$$

Which has to satisfy the LaPlace equation in Equation (4-4).

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = \nabla^2 \phi \tag{4-4}$$

4.3 BOUNDARY CONDITIONS

In the following section the boundary conditions for two scenarios are presented, kinematic boundary conditions and dynamic free-surface condition.

4.3.1 Kinematic Boundary Conditions

Kinematic boundary conditions ensures that the vertical velocity at the seabed is zero. For a body that is fixed this is satisfied using Equation (4-5) on the surfaces body.

$$\frac{\partial \phi}{\partial n} = 0 \tag{4-5}$$

Equation (4-5) represents impermeability, in other words no fluid enters or leaves the body surface. If the body is moving forward with a velocity, U, the equation can be written as Equation (4-6).

$$\frac{\partial \phi}{\partial n} = U \cdot n \tag{4-6}$$

Where U may vary, depending on location on the body surface. Using the substantial derivative DF/Dt as a function of $F(x, y, z, t)$ one is able to express the rate of change with time of the function F when a fluid particle is followed in space. Mathematically it is expressed as Equation (4-7).

$$\frac{DF}{Dt} = \frac{\partial F}{\partial t} + V \cdot \nabla F \tag{4-7}$$

Where V is the fluid velocity at the point (x, y, z) at time t. The free surface is also impermeable, so a particle at the free surface is assumed to stay at the free surface. Therefore, $DF/Dt = 0$. The following kinematic boundary condition can then be applied to the free-surface using Equation (4-8).

$$\frac{\partial \zeta}{\partial t} + \frac{\partial \phi}{\partial x}\frac{\partial \zeta}{\partial x} + \frac{\partial \phi}{\partial y}\frac{\partial \zeta}{\partial y} - \frac{\partial \phi}{\partial z} = 0 \tag{4-8}$$

On z=ζ(x, y, t). Second order terms can be neglected for small wave amplitudes. Then, the linear expression for kinematic free-surface simplifies to Equation (4-9).

$$\frac{\partial \zeta}{\partial t} = \frac{\partial \phi}{\partial z} \qquad (4\text{-}9)$$

4.3.2 Dynamic Free-surface Condition

In order to satisfy the dynamic free-surface condition, the water pressure at the free-surface is equal to atmospheric pressure, p_0. This condition can be expressed by the Bernoulli equation in Equation (4-10).

$$p + \rho g z + \rho \frac{\partial \phi}{\partial t} + \frac{\rho}{2} V \cdot V = C \qquad (4\text{-}10)$$

Where C is an arbitrary function of time. If we choose C to be p_o/ρ so that the equation holds with no fluid motion, then the Bernoulli equation is modified to Equation (4-11).

$$g\zeta + \frac{\partial \phi}{\partial t} + \frac{1}{2}\left(\left(\frac{\partial \phi}{\partial x}\right)^2 + \left(\frac{\partial \phi}{\partial y}\right)^2 + \left(\frac{\partial \phi}{\partial z}\right)^2\right) = 0 \qquad (4\text{-}11)$$

On z=ζ(x, y, t). Prior to solving the problem we do not know where the free-surface is. In this derivation, we assume that there is no forward speed and that the current is zero. In order to get a linear relation, the second order terms are neglected and the equation simplifies to Equation (4-12).

$$g\zeta + \frac{\partial \phi}{\partial t} = 0 \qquad (4\text{-}12)$$

On z=0. Combining this equation with the linear expression for the kinematic free-surface we get Equation (4-13).

$$\frac{\partial^2 \phi}{\partial t^2} + g \frac{\partial \phi}{\partial z} = 0 \qquad (4\text{-}13)$$

On z=0.

If the velocity potential ϕ is oscillating harmonically in time with circular frequency ω we can write the equation as Equation (4-14).

$$-\omega^2 \phi + g \frac{\partial \phi}{\partial z} = 0 \qquad (4\text{-}14)$$

On z=0.

4.3.3 Regular Waves

Regular wave theory assumes that there is a horizontal sea bottom and an infinitely large horizontal free-surface. In addition to this regular wave theory is based on potential flow theory, which means the fluid is considered irrotational, inviscid and incompressible.

For any given time within the fluid a velocity potential, ϕ, can be used to describe the fluids velocity vector $V(x, y, z, t) = (u, v, w)$ at a time t at a point $\boldsymbol{x} = (x, y, z)$ in a Cartesian coordinate system fixed in space. This can be expressed mathematically using Equation (4-15).

$$V = \nabla\phi = i\frac{\partial\phi}{\partial x} + j\frac{\partial\phi}{\partial y} + k\frac{\partial\phi}{\partial z} \qquad (4\text{-}15)$$

Where i, j, and k are unit vectors in the x-, y-, and z-axes. The fluid is considered irrotational when the vorticity vector in Equation (4-16) is zero everywhere in the fluid.

$$\omega = \nabla x V = 0 \qquad (4\text{-}16)$$

Also, the seawater is considered incompressible when $\nabla \cdot V = 0$ holds true.

The velocity potential for the fluid in finite water depth is expressed using Equation (4-17).

$$\phi = \frac{g\zeta_a}{\omega}\frac{\cosh k(z + h)}{\cosh kh}\cos(\omega t - kx) \qquad (4\text{-}17)$$

Where g is the acceleration due to gravity, ζ_a is the wave amplitude, ω is the waves angular frequency, k is the wave number, z is the vertical coordinate, h is the average water depth, t is a time variable, z is the position in the vertical plane is usually set to 0 at the water surface and x is the position along the x-axis.

The wave number k can be found using Equation (4-18).

$$k = \frac{g}{\omega^2}\tanh(kh) \qquad (4\text{-}18)$$

Where iteration is required to find k. The equations above applies for both shallow and infinitely deep water depths. However, certain simplifications can be made for deep water depths to make the equations easier to use during analysis. Simplifications for deep water depths can also be applied to the equation to find the wave number k so that an iteration procedure is no longer required.

The x-component, u, of the velocity potential is defined in Equation (4-19).

$$u = \omega\zeta_a\frac{\cosh k(z + h)}{\sinh kh}\sin(\omega t - kx) \qquad (4\text{-}19)$$

By differentiating the x-component of the velocity, the acceleration in the x-direction, $\dot{u}$, becomes Equation (4-20).

$$\dot{u} = \omega^2 \zeta_a \frac{\cosh k(z+h)}{\sinh kh} \cos(\omega t - kx) \tag{4-20}$$

Which can be similarly derived for the y-direction. For the z-direction the velocity potential, w, is defined in Equation (4-21).

$$w = \omega \zeta_a \frac{\sinh k(z+h)}{\sinh kh} \cos(\omega t - kx) \tag{4-22}$$

And differentiating the velocity in the z-direction once, the acceleration in the z-direction, $\dot{w}$, becomes Equation (4-23).

$$\dot{w} = -\omega^2 \zeta_a \frac{\sinh k(z+h)}{\sinh kh} \sin(\omega t - kx) \tag{4-24}$$

Where the wave elevation, ζ_a, is a sine wave that propagates in the positive x-direction and is defined in Equation (4-25).

$$\zeta = \zeta_a \sin(wt - kx) \tag{4-26}$$

The dynamic pressure exerted by the waves in a finite water depth can be described by Equation (4-27).

$$p_D = \rho g \zeta_a \frac{\cosh k(z+h)}{\cosh kh} \sin(\omega t - kx) \tag{4-28}$$

Where ρ is the density of seawater.

4.3.4 Irregular Sea

Irregular seas states are used for a large part of the analysis. The irregular waves are long crested and propagate in the same direction. This type of sea state can be described by regular sea states of different amplitudes, wavelengths and propagation directions.

The wave elevation for irregular seas can be described by Equation (4-29).

$$\zeta = \sum_{j=1}^{N} A_n \sin(w_n t - k_n x - \epsilon_n) \tag{4-30}$$

Where

N/n is the number of wave components

A_n = amplitude of the nth wave component

ω_n = angular frequency the nth wave component

k_n = wave number for the nth component

ϵ_n = random phase angle of the nth wave component, value between 0-2π

4.4 MORISON'S EQUATION

Morison's equation is often used to calculate wave induced loads on slender, circular structures [29]. The equation gives the horizontal force per unit length on a rigid circular cylinder and is expressed using Equation (4-31).

$$dF = \rho \frac{\pi D^2}{4} dz C_M \dot{u} + \frac{\rho}{2} C_D D dz |u| u \qquad (4\text{-}31)$$

Where D is the cylinder diameter, u and $\dot{u}$ is the horizontal velocity and acceleration of the fluid strip while C_M and C_D are the mass and drag coefficients.

Taking into the account the relative velocity between the cylinder and the fluid, Equation (4-31) can be modified to Equation (4-32).

$$\mathrm{d}F = \frac{1}{2} \rho C_\mathrm{D} D \mathrm{dz}(u - \dot{\eta})|u - \dot{\eta}| + \rho C_M \frac{\pi D^2}{4} \mathrm{dz} a_1$$
$$- \rho (C_M - 1) \frac{\pi D^2}{4} \mathrm{dz} \ddot{\eta} \qquad (4\text{-}32)$$

Where $\dot{\eta}$ and $\ddot{\eta}$ is the velocity and acceleration of the riser. The equations above are for a rigid cylinder [29].

4.5 EFFECTIVE TENSION

The effective tension is an important parameter with respect to riser analysis. The effective tension in the riser is defined in Equation (4-33).

$$T_e = T_W - p_i A_i + p_e A_e \qquad (4\text{-}33)$$

Where T_W is the true wall tension, p_i and p_e is the internal and external pressures, A_i and A_e is the internal and external cross sectional areas [30].

The effective tension of the riser column is the axial force in the riser column when taking into account the internal and external fluids in and around the riser. An example of a pipe with internal and external fluids with corresponding force systems can be seen in Figure 14.
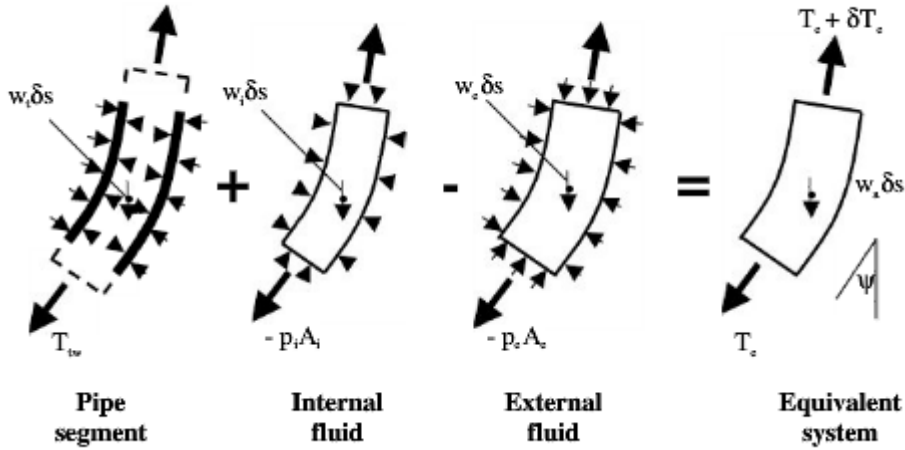
Figure 14: Pipe with internal and external fluids and equivalent force systems [30].

The weights per unit length of the tube, the internal fluid column, the displaced fluid column and the equivalent system is represented by w_t, w_i, w_e, and w_a.

5 SIMA/RIFLEX

The information in this chapter is found in the RIFLEX Theory Manual, SIMA User Guide and RIFLEX User Guide. The theory of the computer programs used to model and simulate the BOP sailing model is described more in depth

5.1 SIMA IN GENERAL

SIMA is used for modeling and analyzing objects within marine technology [31]. Prior to SIMA, a text file was used in order to create input to RIFLEX. Now SIMA enables the user to get a 3D graphical model of the objects being modelled and analyzed. This saves time as the user is able to visualize the model and get continuous feedback [31].

5.2 RIFLEX IN GENERAL

RIFLEX is a computer program used as a tool to analyze marine riser systems and other slender, flexible marine structures such as mooring lines, umbilicals, and pipelines [32]. These structures are characterized by small bending stiffness's, large deflections, nonlinear cross sectional properties, and have complex cross sectional structures.

RIFLEX is able to compute the static and dynamic characteristics of the structure and is based on nonlinear finite element formulation [32].

5.3 STRUCTURE OF RIFLEX

RIFLEX is consists of different modules that communicate via the file system, as seen in Figure 15.
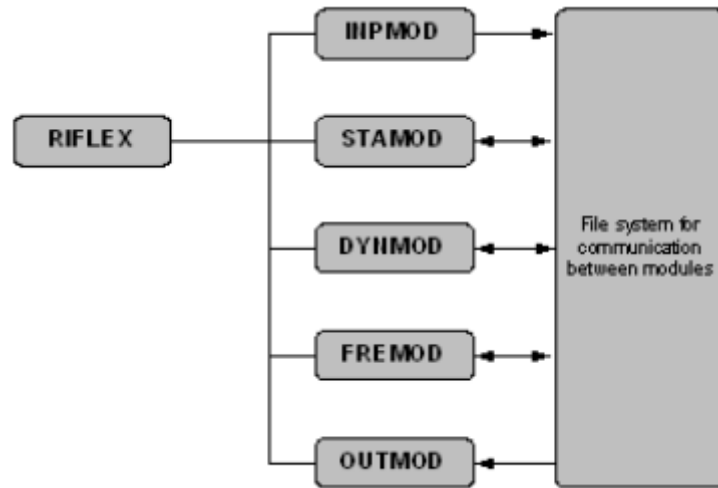
Figure 15: Strucutre of the RIFLEX program [32].

When RIFLEX is performing analyses, modules are working, communicating and sharing information with each other. In order for RIFLEX to perform a complete dynamic analysis, all of the modules have to be run [32].

5.3.1 INPMOD Module

The INPMOD module reads, interprets and organizes the input data into a system description file called SYSFIL. This includes data for the system and the environment. Multiple analyses can be performed without rerunning INPMOD [32].

5.3.2 STAMOD Module

The objective of the STAMOD module is to determine the initial configuration for dynamic analyses. The STAMOD module also performs static analyses. The SYSFIL file, which was organized and modified by the INPMOD module, describes the system that is to be simulated. The initial configuration for the dynamic analyses is written to the INIFIL file, which is to be used by the DYNMOD module [32].

5.3.3 DYNMOD Module

The main function of the DYNMOD module is to initialize dynamic simulations and perform time domain simulations of the system with the initial condition specified by the STAMOD module in the INIFIL file. Time domain simulations is used to solve the equation of motion. Different excitation forces may be applied to the system and its responses are determined. The DYNMOD module is also able to calculate the natural frequencies and modeshapes of the system [32].

5.3.4 FREMOD Module

The FREMOD is not part of the current RIFLEX version and will therefore not be described [32].

5.3.5 OUTMOD Module

The OUTMOD module is used for post-processing of the time series data. It generates a printout of the results generated from the INPMOD, STAMOD and DYNMOD modules. It then prepares a plot file called PLOFIL which can be used by the plot module, PLOMOD [32].

5.3.6 PLOMOD Module

The PLOMOD module uses the IFNP LO file to plot the results [32].

5.4 STATIC FINITE ELEMENT ANALYSIS

The purpose of the static analysis is to determine the nodal displacement vector so that the complete system is in static equilibrium [30]. Solving Equation (5-1) will give the equilibrium configuration.

$$\boldsymbol{R}^S(r) = \boldsymbol{R}^E(t) \qquad\qquad (5\text{-}1)$$

Where

r – is a vector for the nodal displacements that includes all degrees of freedom for the system. For a bar element this will include translations while for a beam element this will include translations and rotations. Both the translation and rotations are relative to the stress free configuration of the bar/beam element.

$\boldsymbol{R}^S(r)$ – Reaction force vector within the structure found by summing up all of the element contributions. Contact forces are internal reaction forces.

$\boldsymbol{R}^E(r)$ – Vector due to external forces. The vector accounts for specific forces such as rigid body forces for representation of buoys, clump weights etc. It also takes into account the distributed loading (i.e. weight, buoyancy and current forces) from all elements.

In general, the internal reaction forces and the external loads are non-linear functions of the nodal displacement vector. In order to find static equilibrium numerically, there will be an incremental loading procedure with an equilibrium iteration at each load step. This is also referred to as incremental-iterative procedure. This approach accumulates the external loads through a number of small load increments then uses the displacement vector [30].

5.5 INCREMENTAL EQUILIBRIUM ITERATIONS

The force imbalance vector at incremental load step k is introduced using Equation (5-2) [30].

$$R_k(r) = R_k^S(r) - R_k^E(r) \qquad (5\text{-}2)$$

The static equilibrium configuration at load step k is governed by zero imbalance force. The first step to find this is to calculate a start value based on the static equilibrium configuration computed at the previous load step using Equations (5-3) and (5-4).

$$\Delta r_k^o = - \left[\frac{\partial R_{k-1}}{\partial r} \right]^{-1} (R_{k-1}^S - R_k^E) \qquad (5\text{-}3)$$

$$r_k^0 = r_{k-1} - \Delta r_k^0 \qquad (5\text{-}4)$$

Where $\partial R / \partial r$ is the Jacobian matrix, Δr is the incremental displacement vector and subscripts k and $k-1$ denote load step k and $k-1$.

The iteration method used for static analysis is the Newton-Raphson iteration procedure. The expressions for correction of the displacement vector at iteration cycle j is expressed using Equations (5-5) and (5-6).

$$\Delta r_k^j = \left[\frac{\partial R_{k-1}}{\partial r} \right]^{-1} R_k^{j-1} \qquad (5\text{-}5)$$

$$r_k^j = r_k^{j-1} - \Delta r_k^j \qquad (5\text{-}6)$$

It is important to have a well-established and reliable convergence criteria while performing iterations so one knows when to stop the calculations. If ε is the predefined convergence criteria, the Equation (5-7) has to be satisfied before the iteration is terminated.

$$\frac{\left\| \Delta r_k^j \right\|}{\left\| r_k^j \right\|} < \varepsilon \qquad (5\text{-}7)$$

Where the incremental norm is calculated using Equation (5-8) [30].

$$\left\| \Delta r_k^j \right\| = \left\| r_k^j \right\| - \left\| r_k^{j-1} \right\| \qquad (5\text{-}8)$$

5.6 DYNAMIC TIME DOMAIN ANALYSIS

Dynamic analysis is important to find out the maximum and minimum values for tension and bending moments.

5.6.1 General

The dynamic equilibrium external force vector may be expressed using Equation (5-9) [30].

$$R^I(r,\ddot{r},t) + R^D(r,\dot{r},t) + R^S(r,t) = R^E(r,\dot{r},t) \qquad (5\text{-}9)$$

Where R^I is the inertial force vector, R^D is the damping force vector, R^S is the internal structural reaction force. Also $r, \dot{r}, \ddot{r}$ represents the structural displacement, velocity and acceleration vectors.

The external force vector accounts for weight and buoyancy, forced displacements due to motions of support vessel, drag and wave acceleration terms in Morison equation, as well as specified discrete nodal point forces.

The inertial force vector is represented by three components. The structural mass matrix, the mass matrix accounting for internal fluid flow and a displacement dependent hydrodynamic mass matrix accounting for the structural acceleration terms in the Morison's equation as added mass contributions in local directions.

The damping force is also expressed by three components. The internal structural damping matrix, the hydrodynamic damping matrix accounting for diffraction effects for partly submerged elements, and a matrix for dashpot dampers that may be displacement dependent.

For slender marine structures the most important nonlinear effects are due to geometric stiffness, nonlinear material properties, hydrodynamic loading due to Morison's equation, integration of loading to actual surface elevation, and contact problems (includes riser collision, vessel/riser contact etc.) [30].

6 MODEL IN RIFLEX

This part of the thesis presents how the suspended riser column and BOP stack is modelled. The model is created using the following procedure:

1. Obtain relevant riser and BOP data
2. Creating a suspended riser column and BOP model in SIMA/RIFLEX
3. Run simulations in SIMA/RIFLEX
4. Post processing the riser response provided by SIMA/RIFLEX

The following computer programs is used

- RIFLEX: Used for static and dynamic analyses of the suspended riser column and BOP stack.
- Microsoft Excel 2013: For calculating and post processing data returned from the simulation in RIFLEX.
- Microsoft Word 2013: To write and present data from RIFLEX and Microsoft Excel.

A total of three different riser columns are created and the lengths of each riser column is:

- 311 m
- 800 m
- 1225 m

Figure 16 shows the model of the drilling rig with the suspended riser and BOP stack from the side with the 311 m long riser column. The color scale to the left is not of importance with respect to this thesis. In the bottom, left hand corner is the coordinate system referred to in the text. Note that the x- and y-axis comprise the horizontal plane while the z-axis is the vertical axis.
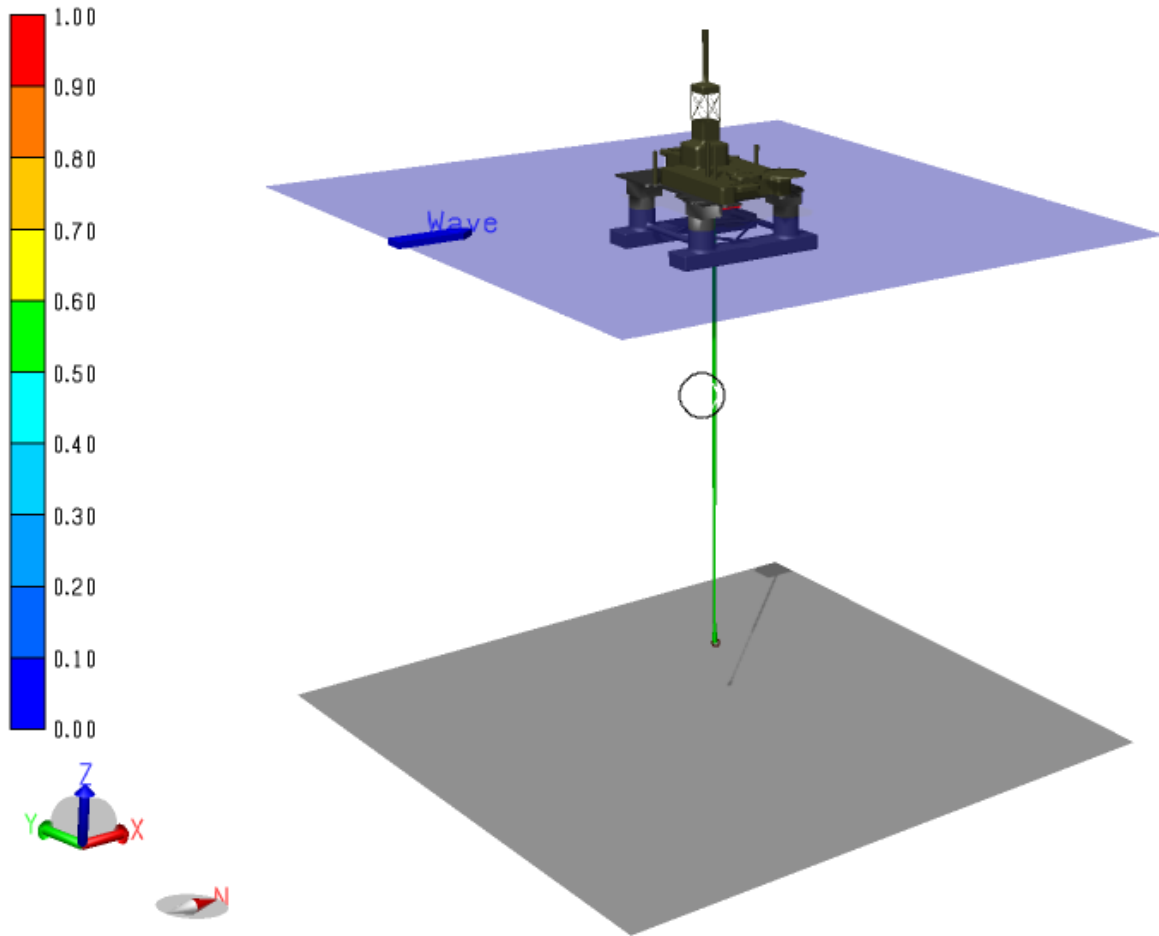
Figure 16: MODU with 311 m long riser column.

For the BOP sailing activity the slip joint, tensioner system, upper flex joint and other parts that make up the topmost part of the riser column are removed as mentioned in Section 1.2.

6.1 MODELLING AND ANALYSIS

In order to analyze the riser during a BOP sailing event, a physically correct model of a suspended riser column with a subsea BOP stack is created. The *Drilling riser* example in RIFLEX is used as a starting point for the BOP sailing model. However, the majority of the parameters defining this system is changed at some point.

Some considerations to take into account while creating the new and altered model include:

- Boundary conditions
- Number of elements
- Weather conditions
- Length of simulations

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- Riser properties

- BOP stack

- Vessel movements and advancing speed

6.1.1 Boundary Conditions

For BOP sailing operations, a spider is used to suspend the riser column from the drill floor. Hence, there are specific boundary conditions that is applied to the top of the riser column and the bottom of the BOP.

The attachment point at the top of the riser column has no freedom to translate in either direction, so the riser column with the BOP stack at the bottom is to be attached to the rig floor and follow the movements of the rig. In a real sailing operation using a hydraulic spider, there may be some limited translations in the horizontal plane due to the fact that there is a hydraulic piston operating each of the locking dogs. These pistons can be modelled as a non-linear spring that have the ability to deform to a certain extent before further deformation is not possible. However, no translations is assumed in the model.

Rotations at the attachment point between the riser column and the MODU are allowed in the model. In a real life situation using a hydraulic spider, rotations up to a certain angle is allowed. However, the angle of rotation and the resistance to rotate further is proportional to each other. That is, the higher the angle of rotation at the attachment point, the higher the resistance to rotate the riser further at the attachment point. This resistance will keep increasing until a limit is reached in terms of the rotation angle. Any rotation past this specific angle is not possible.

A summary of the boundary conditions at the attachment point between the rig and the riser column as well as the boundary conditions at the bottom of the BOP stack is listed in Table 4. Supernode 1 denotes the bottom of the BOP while supernode 2 denotes the attachment point between the rig and the riser column.

Table 4: Boundary conditions for each of the supernodes in RIFLEX.

Boundary condition	Supernode 1	Supernode 2
X	Free	Fixed
Y	Free	Fixed
Z	Free	Fixed
RX	Free	Free
RY	Free	Free
RZ	Free	Fixed

X, Y and Z denotes translations in the x-, y-, and z-axes while RX, RY RZ denotes rotations about the x-, y-, and z- axes, respectively. The x- and y-axes comprise the horizontal plane while the z-axis is the vertical axis.

6.1.2 Elements

SIMA/RIFLEX uses finite element method to calculate the forces and bending moments within structures. A rule of thumb for the finite element method is that with smaller element lengths, the more accurate the results. In other words, the more elements per unit length, the more accurate the results become. The reason is that the calculations are iterative, where the results calculated for the next element is dependent on the results obtained from the last element.

It is important to note that when increasing the number of elements, the computational time used to calculate the results for the simulations will increase. Therefore it was concluded that element lengths of roughly 1 m is sufficient based on an element convergence study conducted in Section 7.1.1.

6.1.3 Seed Numbers

The seed number has to be specified prior to performing the simulation. The seed number is an input parameter for the DYNMOD module and specifies the number of random phase angles that are created during the dynamic calculation. By varying the seed number, one will vary the number of generated time series for wind and waves [33].

6.1.3.1 PRNG to Create Seed Numbers

Random number generators (RNGs) are generators used to generate random numbers. The term pseudo means not real or a sham [34]. Based on this, pseudorandom number generators or PRNGs produce "fake" random numbers. The reason for its name is due to the fact that PRNGs use algorithms to generate "random" numbers [35].

Based on feedback from representatives in Marintek, it was concluded that Microsoft Excel is the best program to generate random numbers for the simulations. For each sea state, a total of 5 random numbers are generated and then exported to RIFLEX. These numbers are then used as inputs for the seed values in each of the respective runs for each sea state.

6.1.4 Weather Conditions

The loads exerted to the riser, BOP and LMRP are predominantly due to waves and currents.

6.1.4.1 Sea Spectrum

To describe the irregular sea state for the dynamic analysis in SIMA/RIFLEX, a 3-parameter JONSWAP spectrum is used. The significant wave height, H_s, and peak period, T_p, were parameters that are varied between runs. The gamma value of 3.3 is the default value in the original RIFLEX model and is not changed throughout the runs. A summary of the parameters for the irregular sea states used in the simulations is listed in Table 5.

Table 5: Parameters used for irregular sea analysis in RIFLEX simulations.

Parameter	Value
Direction	0.0
Spreading Code	Unidirectional
Spreading	0.0
Significant Wave Height	Variable
Peak Period	Variable
Gamma	3.3 (default value)

6.1.4.2 Determining Sea States

The significant wave heights, H_s, and the corresponding wave periods, T_p, is taken from a scatter diagram. These parameters are decided based on which significant wave height and wave period is most likely to occur. An excerpt of the scatter diagram used is seen in Table 6.

Table 6: Scatter diagram for Ekofisk data taken from 1980-1993 [36].

Significant Wave Height, H_s	Wave Period, T_p									
	<4	5	6	7	8	9	10	11	12	13
0.50	219	247	98	56	108	139	85	53	38	28
1.00	462	1444	1332	551	394	409	362	255	153	126
1.50	54	763	1991	1654	703	436	327	258	176	86
2.00	1	114	994	2015	1329	583	260	246	193	91
2.50	0	7	189	1122	1532	734	261	182	165	124
3.00	0	0	14	329	1082	958	309	137	139	96
3.50	0	0	0	59	533	983	382	140	87	72
4.00	0	0	0	10	133	660	418	144	65	36
4.50	0	0	0	0	28	313	417	149	41	25
5.00	0	0	0	0	2	113	271	190	40	19
5.50	0	0	0	0	0	23	154	136	49	23
6.00	0	0	0	0	0	4	61	109	52	26
6.50	0	0	0	0	0	0	20	58	35	14
7.00	0	0	0	0	0	0	6	23	35	14
7.50	0	0	0	0	0	0	2	21	16	13
8.00	0	0	0	0	0	0	0	4	8	9

8.50	0	0	0	0	0	0	0	2	8	3
9.00	0	0	0	0	0	0	0	0	2	5
9.50	0	0	0	0	0	0	0	0	1	5
10.00	0	0	0	0	0	0	0	0	0	0

For the simulations, three states were chosen based on the likelihood of occurrence. The sea states used in the simulations is listed in Table 7.

Table 7: Sea states used for the RIFLEX simulations.

Significant wave height, H_s [m]	Wave Period, T_p [sec]
1	5
2	7
3	8

Significant wave heights higher than three meters is not used for the simulations. The reason being that the likelihood of occurrence decreases by a large amount for significant wave heights higher than three meters, based on the scatter diagram in Table 6. Another reason is that BOP sailing activities are weather restricted and performing such an operation for significant wave heights higher than three meters seems unlikely from an engineering point of view.

6.1.4.3 Currents

The currents used for the simulations are realistic but at the same time considered a worst case scenario for each of the respective water depths. The reason for why the worst case scenario currents are used is due to the assumption that this will have larger contributions to the combined loading equation then for currents of smaller magnitudes.

The current profile used in the RIFLEX models for the three different riser columns is seen in Figure 17 - Figure 19.
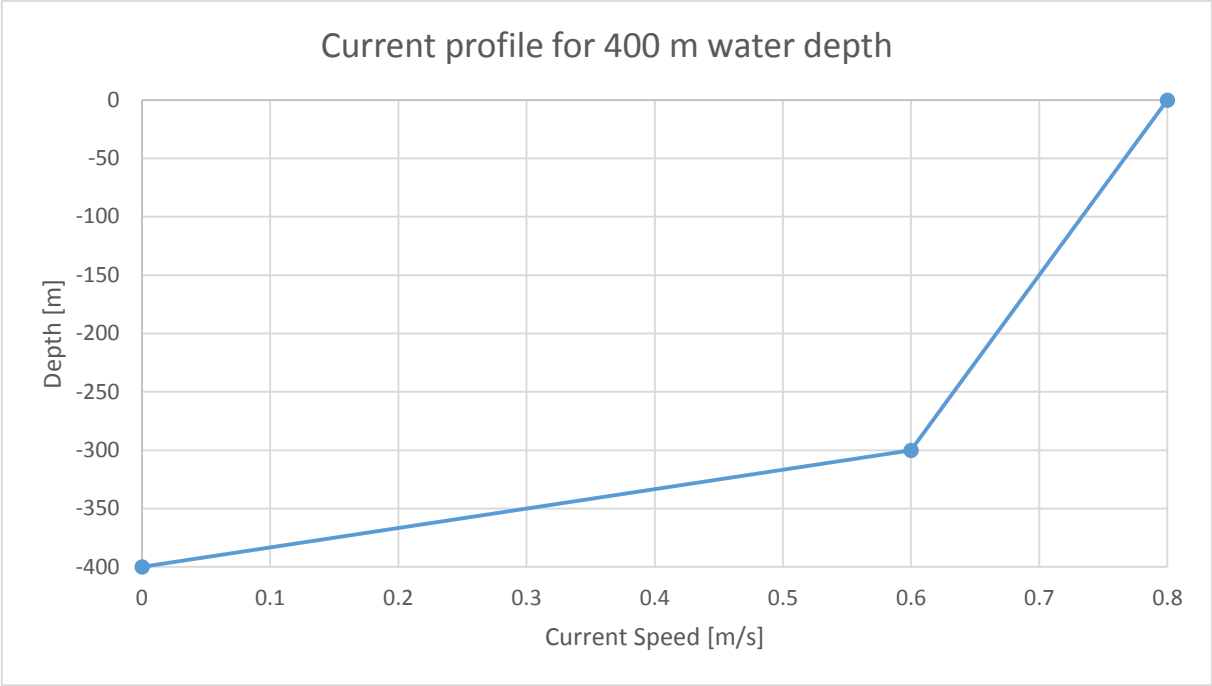
Figure 17: Current profile for 400 meter water depth [37].

The current velocity in Figure 17 has its maximum velocity at the surface and decreases linearly with water depth.
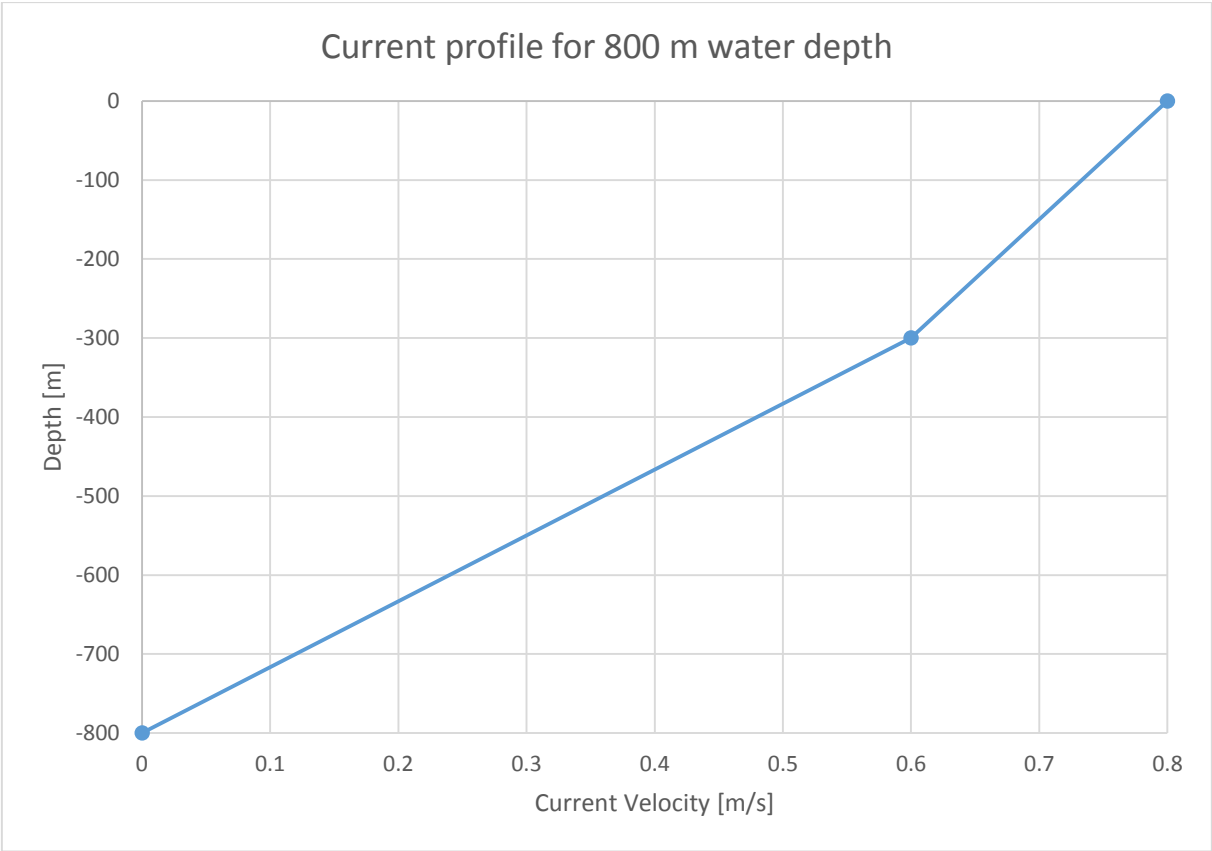
Figure 18: Current profile for 800 meter water depth [37].

The current profiles for the 400 m and 800 m water depth resemble each other. That is, the current decreases linearly from 0.8 m/s to 0.6 m/s from the surface to 300 m below mean sea level. From 300 m to the seabed, the current decreases from 0.6 m/s to 0 m/s.
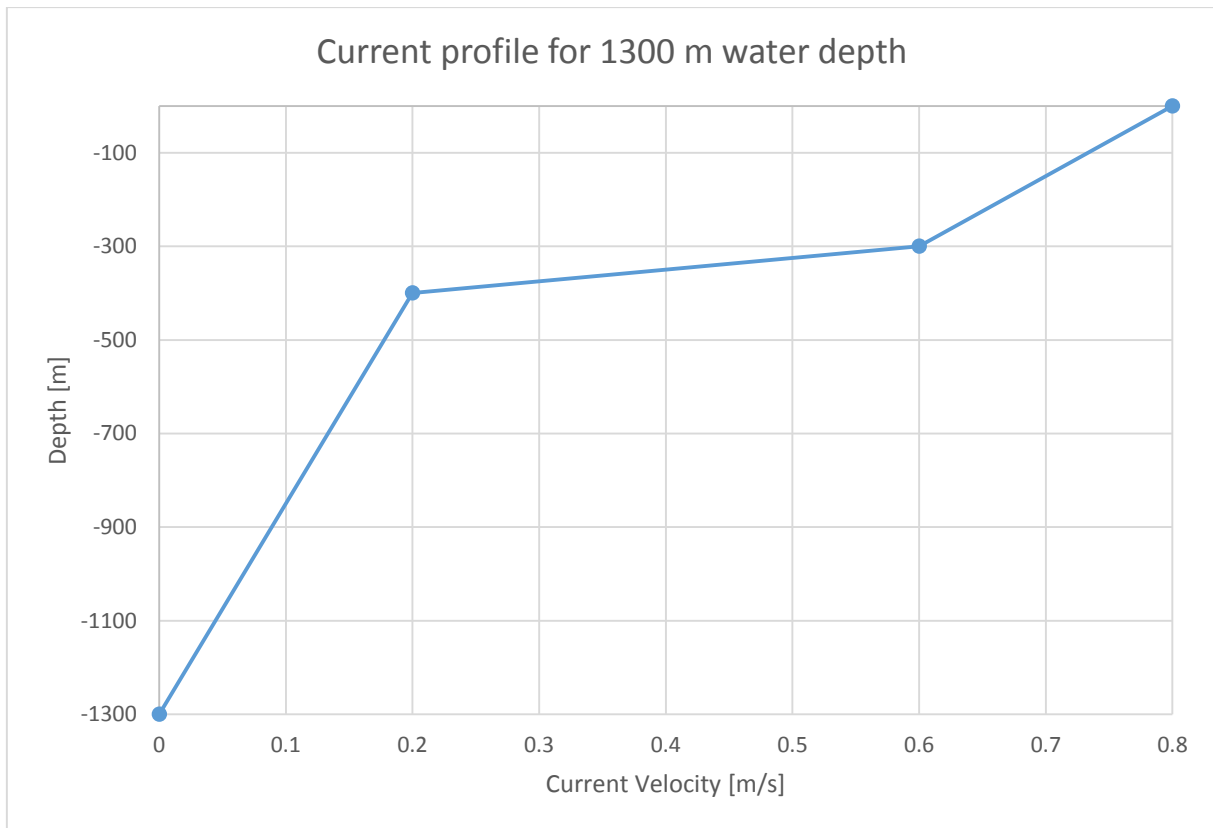
Figure 19: Current profile for 1300 meter water depth [38].

Notice that all of the current profiles have the same velocity at the surface. The velocity decreases linearly to 0.6 m/s at 300 m water depth. For the 1300 m water depth, the current decreases linearly from 0.6 m/s to 0.2 m/s between 300 m and 400 m water depth. From 400 m to 1300 m water depth, the current decreases from 0.2 m/s to 0 m/s.

The current profile 1300 m water depth is chosen based on the current profile from Aasta Hansteen field and the velocities for the different water depths are provided by Professor Carl Martin Larsen. The current profiles and corresponding velocities for the 400 m and 800 m water depths are current profiles that the author of the thesis and Professor Bernt J. Leira mutually agreed upon.

All of the current profiles are identical down to 300 m water depth so the results are comparable with each other. Note that RIFLEX can only model linear current profiles.

6.1.5 Length of Simulations

The length of the simulations for each run depends on the length of the riser column. For the 1225 m long riser column, a simulation length of 1000 sec is used while for the 311 m and 800 m long riser column, simulation lengths of 2000 sec is used. The reason for the long simulation lengths is that for irregular seas there are a number of waves with varying wave heights and wave periods. The maximum wave height and wave period may or may not occur during this time interval.

The simulations could be run for a longer period of time. However, due to limited computational power it is not feasible with respect to time, especially for the longer riser columns i.e. 800 m and 1225 m. The reason is due to the number of elements on the riser column. The element lengths for each of the three riser columns is set to one meter. Hence, with increasing riser column length is a corresponding increase in the number of elements which results in longer computational times.

The time step also effects the computational time for the dynamic simulations. The time step is the time interval between each calculation. That is, the time that is allowed to pass between the previous calculation and the upcoming calculation. The smaller the time step, the more calculations are performed during the dynamic simulation which results in a longer computational time. The time step for the simulations was set to 0.1 sec for the 800 m and 1225 m long riser column, while the time step was 0.05 seconds for the 311 m long riser column. The length of the time step used for the simulations is justified through a convergence study performed in Section 7.1.2. This type of study is performed prior to running the simulations and analyzing the data.

6.2 RISER COLUMNS

The riser column lengths used for the simulations is 311 m, 800 m and 1225 m.

A riser tally sheet and other information for a riser column used by the MODU Transocean Spitsbergen while drilling in roughly 1300 m water depth is the basis for the riser joint properties in this thesis. In the documents from Transocean, three different types of buoyancy joints is used, each with different submerged weights as well as water depth ratings. The water depth ratings are [39]:

- 7500 ft (2286 m
- 4500 ft (1372 m)

- 2000 ft (610 m)

While making up the three different riser columns, it was decided not to use the 7500 ft buoyancy joints for the 311 m and the 800 m long riser columns as the water depth is significantly less than the water depth rating.

6.2.1 Riser properties

The data for the riser joints used by Transocean Spitsbergen is for 75 ft riser joints. In the simulations, 75 ft riser joints is used for the 800 m and 1225 m long riser columns. For the 311 m long riser column, 50 ft riser joints is used. However, the same properties applies to the 50 ft riser joints, i.e. submerged weight per unit length, cross sectional areas etc.

The three riser columns consists of different types of riser joints that have variations in their properties. For the simulations, drilling riser joints with 21 in (0.53 m) outside diameter and wall thickness of 0.875 in (0.022 m) is used [39]. This corresponds to an inside diameter of 19.25 in (0.48 m).

Table 8 is a summary of the riser joint dimensions and properties for the 311 m long riser column.

Table 8: Dimensions and properties for riser components used for the 311 m riser column in RIFLEX [39].

	Slick w/ Fins	7500 ft - Buoyancy	4500 ft - Buoyancy	2000 ft - Buoyancy	Spacer	XO sub	Units
OD	21	21	21	21	21	21	[in]
OD[1]	-	54	54	54	-	-	[in]
Wall thickness	0.875	0.875	0.875	0.875	0.875	0.875	[in]
ID	19.25	19.25	19.25	19.25	19.25	19.25	[in]
Mass per unit length in air	748.03	1234.43	1123.09	966.75	1358.26	638.58	[kg/m]
Mass per unit length in water	503.06	213.52	129.09	-70.77	142.48	555.55	[kg/m]
Length	15.24	15.24	15.24	15.24	3.048	22.86	[m]

[1] *The OD for the buoyancy joints excludes the buoyancy modules. The OD of the riser joints with the buoyancy modules is 1371.6 mm or 54 in, which is added to a normal slick riser joint.*

Table 9 is a summary of the riser joints dimensions and properties for the 800 m and 1225 m long riser columns.

Table 9: Dimensions for riser component used for 800 m and 1225 m riser columns in the RIFLEX analysis [39].

	Slick w/ Fins	7500 ft - Buoyancy	4500 ft - Buoyancy	2000 ft - Buoyancy	Spacer	XO sub	Units
OD	21	21	21	21	21	21	[in]
OD[1]	-	54	54	54	-	-	[in]
Wall thickness	0.875	0.875	0.875	0.875	0.875	0.875	[in]
ID	19.25	19.25	19.25	19.25	19.25	19.25	[in]
Mass per unit length in air	748.03	1234.43	1123.09	966.75	1358.26	638.58	[kg/m]
Mass per unit length in water	503.06	213.52	129.09	-70.77	142.48	555.55	[kg/m]
Length	22.86	22.86	22.86	22.86	3.048	22.86	[m]

[1] *The OD for the buoyancy joints excludes the buoyancy modules. The OD of the riser joints with the buoyancy modules is 1371.6 mm or 54 in, which is added to a normal slick riser joint.*

Slick riser joints with fins are regular riser joints equipped with fins to reduce the induced drag forces. The fins are not modelled in RIFLEX. Spacer joints are short, regular riser joints used to make the length of the riser column fit the distance between the drill floor and wellhead. For example, if there is a distance of roughly 10 m that is missing to make up the riser column, it is more appropriate to use three spacer joints that are 3.048 m in length then one riser joint that is 22.86 meters.

Based on Table 8 and Table 9 above, one can see that the mass per unit length in air of each of the riser joints varies by a large amount for each of the respective riser joints. The buoyancy joints have the largest mass per unit length in air as well as the largest external area. The large external area results in a larger volume of seawater being displaced and hence creates a smaller weight in water. The axial stiffness, bending stiffness, and torsional stiffness are identical for all the different types of riser joints.

6.2.2 Making up Riser Columns

This section will give an overview of the combination of riser joints that makeup each of three riser columns. While deciding how to make up the different riser columns, it is important to take into account that the top of the buoyancy section is below the mean sea level during the sailing operation. If the top of the buoyancy section extends above the mean sea level, there will be a large added mass exerted to the riser column due to the relatively large outer diameter

of the buoyancy modules. Another reason that the top of the buoyancy section shall be below the mean sea level is due to the fact that the weight of the buoyancy joints in air is significantly larger than regular riser joints. This may cause a large addition to the force at the top of the riser column.

A summary of the combination of riser joints used for the 311 m long riser column is seen in Table 10.

Table 10: Combination of riser joints used in 311.18 m long riser column.

Riser Joint	Unit Length [m]	Number of joints	Length of section [m]	Accumulated length [m]
Slick w/ fins	15.24	2	30.48	30.48
Buoyancy - 2000	15.24	4	76.2	106.68
Buoyancy – 4500	15.24	7	106.68	213.36
Slick w/fins	15.24	2	30.48	243.84
XO sub	22.86	1	22.86	266.7
Slick w/ fins	15.24	2	30.48	297.18
BOP stack	14	1	14	311.18

The order of the each of the respective riser joints corresponds to the order of the joints used for the RIFLEX simulations. At the very top of the riser column, where the attachment point is located to below the mean sea level, are slick riser joints. Further below the mean sea level are different types of buoyancy joints etc. The BOP stack is located at the bottom of the riser column. The distance between RKB and MSL is 17 meters, so the bottom of the BOP is located at 294.18 meters below mean sea level.

A summary of the combination of riser joints used for the 800 m long riser column is seen in Table 11.

Table 11: Combination of riser joints used in 800.38 m long riser column.

Riser Joint	Unit Length [m]	Number of joints	Length of Section [m]	Accumulated Length [m]
Spacer	3.048	3	9.144	9.144
Slick w/ fins	22.86	3	68.58	77.724
Buoyancy - 2000	22.86	7	160.02	237.744
Buoyancy – 4500	22.86	18	411.48	649.224

Slick w/fins	22.86	2	45.72	694.944
XO sub	22.86	1	22.86	717.804
Slick w/ fins	22.86	3	68.58	786.384
BOP stack	14	1	14	800.384

The bottom of the BOP stack for the 800 m long riser column is located 783.384 meters below the mean sea level.

The 1225 m long riser column used in the simulations resembles the riser column that Transocean Spitsbergen used while drilling in 1300 m water depth. A summary of the combination of riser joints used for the 1225 m long riser column is seen in Table 12.

<p align="center">Table 12: Combination of riser joints used in 1225.58 m long riser column</p>

Riser Joint	Unit Length [m]	Number of joints	Length of Section [m]	Accumulated Length [m]
Slick w/ fins	22.86	6	137.16	137.16
Buoyancy - 2000	22.86	8	182.88	320.04
Buoyancy - 4500	22.86	30	685.8	1005.84
Buoyancy - 7500	22.86	3	68.58	1074.42
Slick w/fins	22.86	2	45.72	1120.14
XO sub	22.86	1	22.86	1143.00
Slick w/ fins	22.86	3	68.58	1211.58
BOP stack	14	1	14	1225.58

For the 1225 m long riser column, the bottom of the BOP stack is 1208.28 meters below mean sea level.

6.2.3   Weight of Riser Joints

Based on the information provided by Transocean, the weight per unit length in water and in air of the riser joints are known. However, the input parameter for the riser joints weight in RIFLEX is in terms of mass per unit length in air. If the mass per unit length in air taken from the riser information is put directly into RIFLEX, the result will be an incorrect mass per unit length in water. Hence, some calculations are performed such that the mass per unit length in water would be the same as in the riser information sheet.

This can be done through the buoyancy relationship in Equation (6-1).

$$W_{water} = g\left(m - \frac{V\rho_{sw}}{l}\right) \qquad (6\text{-}1)$$

Where W_{water} is the weight per unit length in water, g is the acceleration due to gravity, m is the mass coefficient or mass per unit length of the riser joint in air, V is the volume of the riser joint, ρ_{sw} is the density of seawater and l is the length of the riser joint. Solving the equation for m will given the mass coefficient in air which is needed as an input in RIFLEX. The mass coefficient, m, is defined in Equation (6-2).

$$m = \frac{W_{water}}{g} + \frac{V\rho_{sw}}{l} \qquad (6\text{-}2)$$

Where $\frac{V}{l}$ is the cross sectional area of the specific riser joint and is defined as $A = \frac{V}{l} = \pi(r_o{}^2 - r_i{}^2)$. The outside radius of the riser joint is defined as r_o while the inside radius of the riser joint is defined as r_i. An illustration with the illustrating the external and internal areas of a hollow cylinder with a certain wall thickness taken from SIMA is seen in Figure 20.
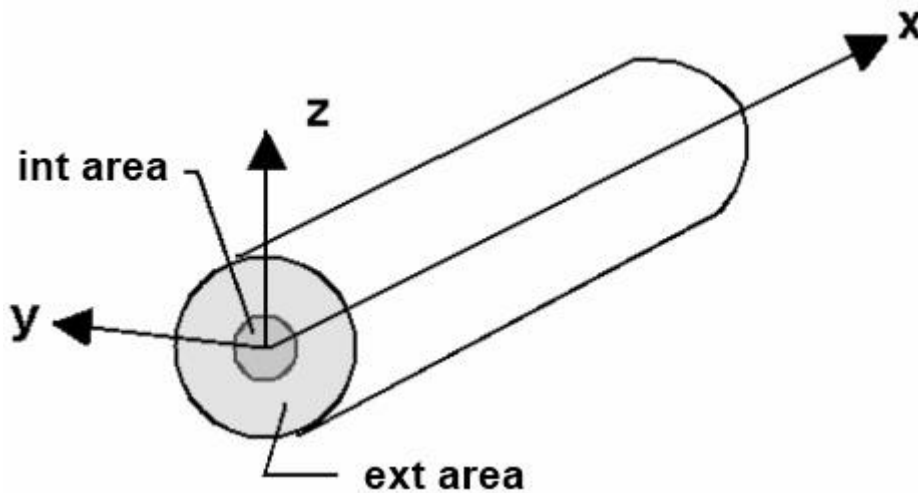
Figure 20: External and internal areas as defined in RIFLEX [40].

It should be noted that this procedure for finding the equivalent weight of the riser joints in air is only valid if the riser column is filled with seawater. If another medium is present, such as drilling mud or air, a more complex procedure for finding the equivalent weight of the riser joints is required.

6.2.4   Steel Grades

As mentioned in Section 3.2, the three most common steel grades used for riser joints are API 5L X52, X65 and X80. It is concluded that API 5L X52 is the most common type of steel grade

used on the NCS [41]. However, this is depends on operating temperature, operating pressure and the application that the material is used for. However, the riser joints used by the MODU Transocean Spitsbergen for a well drilled in roughly 1300 m water depth used the steel grade API 5L X80.

The material properties for the three API 5L steel grades is listed in Table 13.

Table 13: Properties for steel grades API 5L X52, X65, and X80.

	X-52	X-65	X-80	Units
Yield strength	52	65	80	ksi
Yield strength	358	448	551	MPa
Tensile strength	455	530	620	MPa

The higher the yield strength the more brittle the material becomes and vice versa [41]. In addition to this the transition temperature of the steels can be of importance for design considerations. The transition temperature is the temperature at which the steel goes from ductile behavior to brittle behavior. Below the transition temperature the steel becomes significantly more brittle then above the transition temperature [41].

The conclusion brought forth after a telephone interview and the riser information provided by Transocean is to perform calculations all three steel grades [41, 39].

6.3 BOP STACK

The lower part of the riser column consists of a two-section BOP which includes the lower BOP stack and the LMRP stack.

The properties and dimensions for the BOP and LMRP stacks in the original RIFLEX model were not realistic nor representative for a subsea BOP used on the NCS. It was concluded that a BOP of roughly 14 meters in height and a weight in air of at least 350 tonnes would be sufficient for the simulations. The updated BOP and LMRP properties and dimensions is listed in Table 14.

Table 14: Properties for BOP and LMRP stack for modified RIFLEX model.

	BOP stack	LMRP Stack	Units
Mass – In Air	19,191	33,039	[kg/m]
External Area	2.79200	2.79200	[m^2]
Internal Area	0.19792	0.19792	[m^2]
Height	7.00000	7.00000	[m]

This results in a BOP stack height of 14 meters and weight of 365 tonnes in air. These numbers are more representative for a BOP used on the NCS.

The entire BOP stack was modelled using beam elements. The axial stiffness, bending stiffness and torsional stiffness can be assumed to be infinitely high, which will result in small deformations of the BOP stack.

The BOP jumping tool is not included in the simulations. The reason is that it will have a relatively small influence on the dynamic behavior of the system.

6.4 SUPPORT VESSEL

The support vessels RAOs followed with the RIFLEX program. The RAO files describe the vessels movements in all six degrees of freedom and is vessel specific. The vessel movement in heave and surge is of particular interest in this thesis. Figure 21 shows the RAO in surge as a function of wave period.
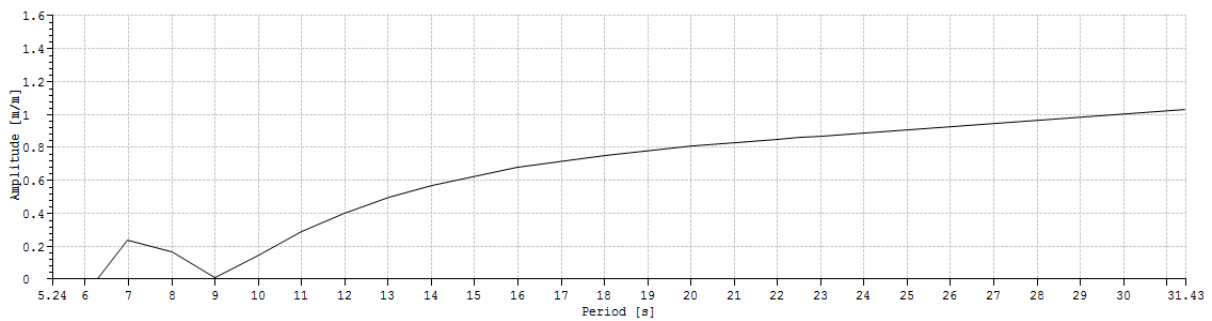

Figure 21: RAO in surge – Amplitude ratio [40].

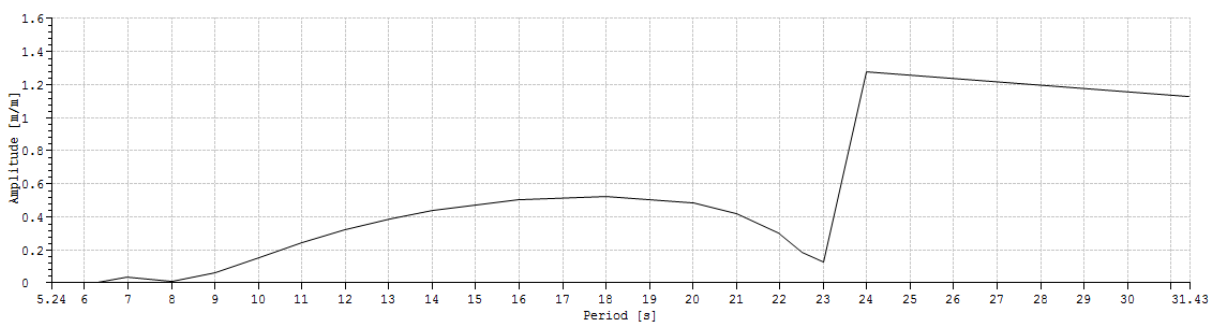Figure 22 shows the RAO in heave as a function of wave period.

Figure 22: RAO in heave – Amplitude ratio [40].

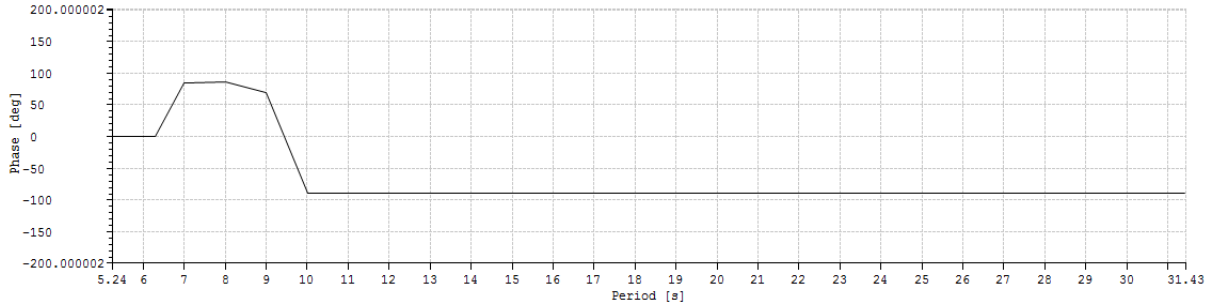Figure 23 shows the RAO in surge as a function of wave period.

Figure 23: RAO in surge – Phase angle [40].

Figure 24 shows the RAO in surge as a function of wave period.
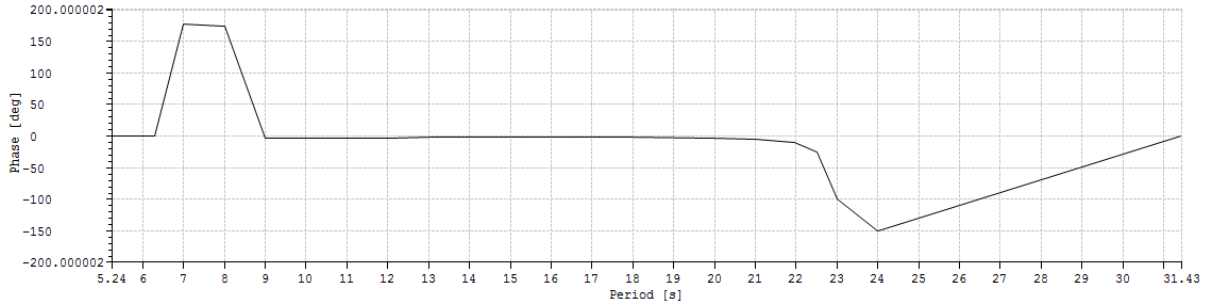
Figure 24: RAO in heave – Phase angle [40].

As aforementioned, RAOs are vessel specific. Some MODUs are extremely weather sensitive while other are less weather sensitive. The RAO of the MODU may have a significant effect the forces and bending moments present in the riser column.

6.4.1 Vessel Propagation

It is important to be able simulate a MODU moving forward with a suspended drilling riser column and subsea BOP so that the dynamic effects due to forward movements of the vessel is included in the analyses of the riser column. After meeting with professors, fellow students and representatives from Marintek, it is concluded that the easiest and perhaps the most accurate way to simulate a MODU sailing with a certain forward speed is to add the vessel speed to the current speed.

An example of adding the vessel speed to original current speed in 400 m water depth is seen in Table 15. In this example it is assumed that the vessel is moving with a speed of 1 m/s against the current. That is, if the current is moving in the +x direction in the horizontal plane, the vessel is moving in the –x direction.

Table 15: Example of current speeds in RIFLEX for 400 m water depth.

Depth [m]	Original current speed [m/s]	New current speed [m/s]
0	0.8	1.8
-300	0.6	1.6
-400	0.0	1.0

By adding the vessel speed to the current speed and assuming that the direction of the vessel and current is opposite to each other, one is able to simulate the worst case sailing scenario. The reason being that this will result in the largest relative velocity between the riser column and the surrounding water particles.

It should be noted that the effects of the thrusters on the riser column during the sailing activity is not modelled in the simulations.

6.5   VERIFICATION OF MODEL RESULTS

After completing the model of the MODU with the suspended riser column and subsea BOP, some simulations are run in order to check if the results agree with engineering intuition. Prior to analyzing the results, convergence studies related to the element length and time step are investigated and the results are summarized in Section 7.1.

At the attachment point, the riser column is allowed to rotate about the axes in the horizontal plane while no translation is allowed in either of the three directions. Based on this, it is expected that the highest tension in the riser column should occur at the top of the riser column where the riser is attached to the drilling vessel. The reason for this is because the attachment point holds the entire weight of the submerged and non-submerged parts of the riser column.

The tension per unit length is expected to increase by the largest amount over the BOP and LMRP stacks since these have a large submerged mass per unit length coefficient. On the contrary, the tension per unit length is expected to increase the least, or perhaps even decrease, over the buoyancy sections. This is due to the buoyancy riser joints which are designed to have a small submerged weight per unit length, and may in some instances have a negative submerged weights in order to minimize the tension at the top of the riser column.

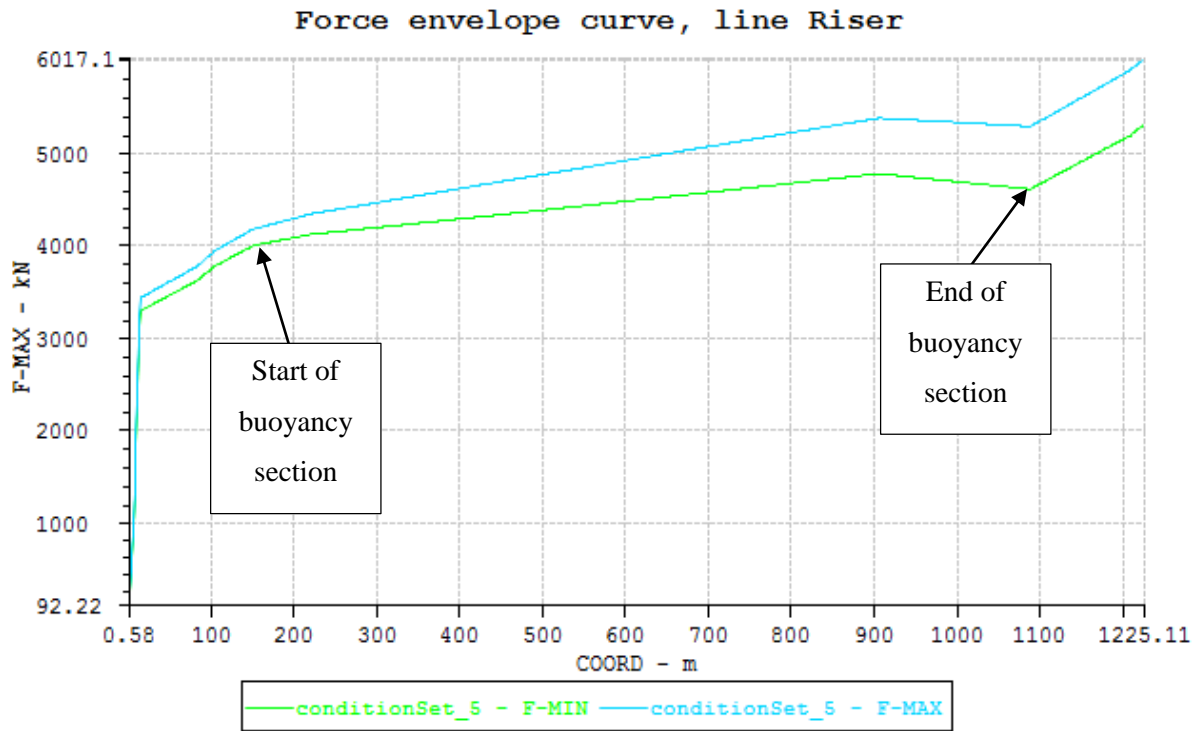Evidences of these trend lines is seen in Figure 25.

Figure 25: Force envelope curve for Hs=3 m and Tp=8 sec for the 1225 m long riser column without current and 0 m/s MODU speed.

The blue line in Figure 25 is the maximum dynamic force in the riser column as a function of depth, while the green line is the minimum dynamic force in the riser column. The left hand side of the graph, where both tensions are at a minimum, is the deepest point on the riser column or at the bottom of the BOP. The right hand side of the graph is highest point on the riser column, or at the attachment point between the riser column and the MODU.

The results from the simulations did agree with expectations. The minimum tension in the riser column is at the bottom of the BOP. The tension then increases drastically over the length of the BOP compared to the increase in tension per unit length over the rest of the riser column. The increase in tension per unit length was the least over the buoyancy sections. The start and end of the buoyancy sections is identified in Figure 25.

The BOP sailing simulations is also run in various sea states with different sailing and current speeds in order to observe the trend lines with respect to where the highest tension in the riser column occurs as well as how the maximum and minimum tensions varies as a function of these parameters. In each of the runs, the maximum tension is located at the attachment point between the riser column and the MODU.

The minimum tension experienced in the riser column at the attachment point decreased with increasing significant wave height and corresponding wave period, but remained positive in all

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sea states. It is important to check whether the force in the riser column reaches a negative value or not. If the riser joints become compressed, buckling may occur. Especially if the riser joints are not designed to withstand compressive loads. This, however, did not occur in any of the simulations.

6.6 INCREASING VESSEL SPEED AND CURRENT SPEED

The trend lines for the maximum dynamic bending moment over the length of the riser column is analyzed during the runs. Since the riser column at the attachment point is allowed to rotate about the axes on the horizontal plane it is expected that the largest bending moments occurs in the water zone, or on the buoyancy section.

The magnitude of the maximum dynamic bending moment exerted to the riser column is strongly dependent on the sailing and current speed. Based on the results, the maximum dynamic bending moment occurs either in the water zone or on the buoyancy section, depending on the sailing and current speed. Some of the simulations have the maximum dynamic bending moment in the water zone while some have the maximum dynamic bending moment at the buoyancy sections.

Figure 26 shows a moment envelope curve from RIFLEX illustrating the bending moments about the different axes as a function of riser column depth for the 1225 m long riser column.

Figure 26: Bending moment envelope curve for Hs= 3 m and Tp=3 sec for the 1225 m long riser column with no current and 0 m/s sailing speed.

The green line represents the maximum total bending moment and is the line of interest as it takes the bending moments about all the of the three axes into account. The left hand side of the plot in Figure 26 is at the bottom of the BOP stack while the right hand side is the attachment point between the MODU and the riser column. For this run, the maximum dynamic bending moment at the topmost part of the riser column occurs roughly 25 meters below the attachment point. The largest dynamic bending moment takes place on the BOP and is not of concern as this piece of equipment is robust and has a high resistance to deformations due to bending moments. The large bending moment at the topmost part of the riser column occurs a few meters below the water/wetted zone, where the riser comes in contact with the water.

Figure 27 shows a moment envelope curve from RIFLEX illustrating the bending moments about the different axes as a function riser column depth for the 1225 m long riser column.
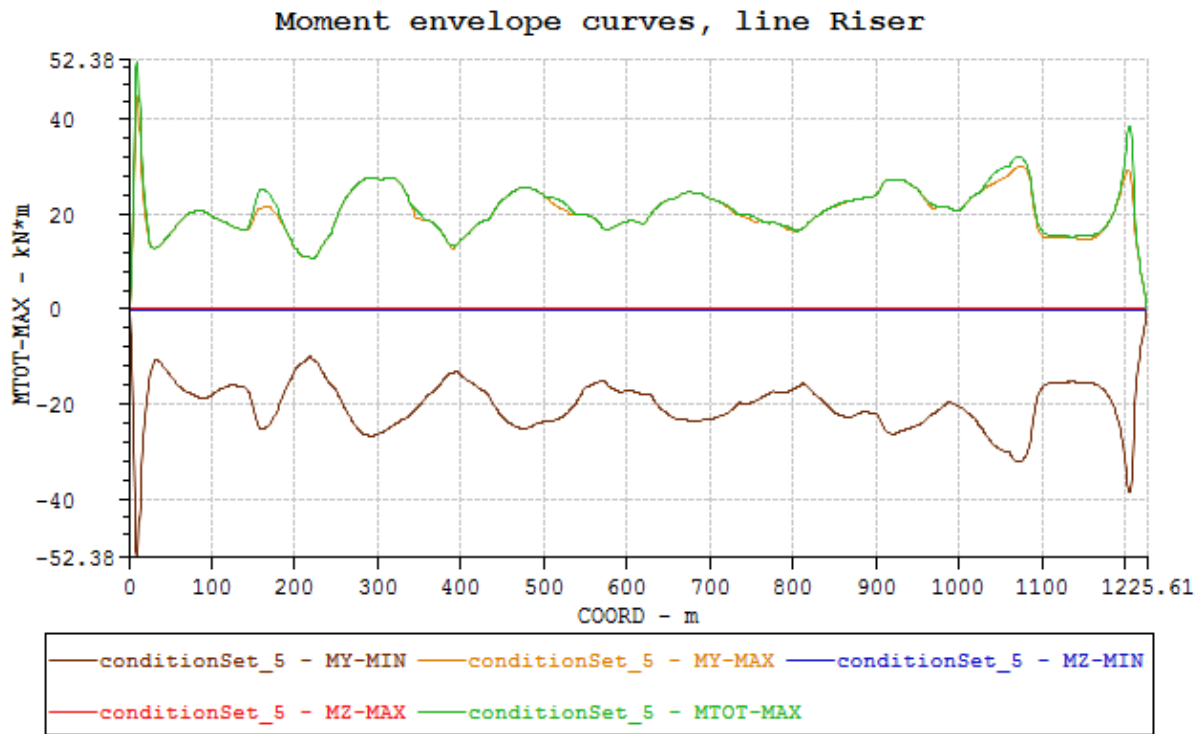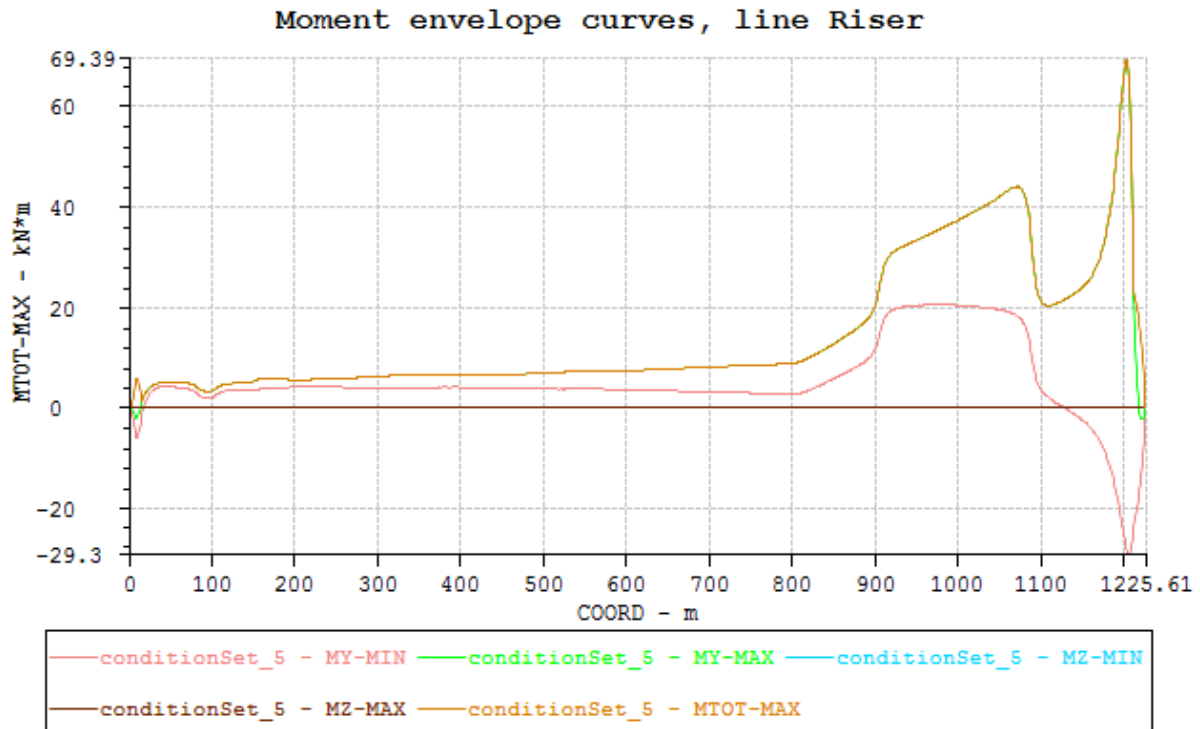
Figure 27: Bending moment envelope curve for Hs= 3 m and Tp=8 sec for the 1225 m long riser column with regular current profile and 0.5 m/s sailing speed.

Notice that when a current profile and sailing speed is applied to the riser column, the location and magnitude of the maximum dynamic bending moment is clearly in the vicinity of the water zone.

In general, with increasing significant wave height, sailing speed and current speed there is an increase in the maximum dynamic bending moment exerted to the riser column.

6.7   VERIFICATION OF MODEL RESULTS USING STANDARD DEVIATION AND MEAN

One method to verify if the simulation gives consistent results for the different runs for each sea state is using the standard deviation, σ, and mean, μ. This method was proposed by Professor Bernt Leira during a consultation meeting on the 8th of April, 2015.

First, the mean values for the maximum tension and bending moments are calculated. The mean is the same as the average of all the values for a specific sea state and is defined in Equation (6-3).

$$\mu = \sum_{i=1}^{N} \frac{x_i}{N} \tag{6-3}$$

Where N is the number of runs and x_i is the result from run i.

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The standard deviation for the maximum tension and bending moments are calculated using Equation (6-4).

$$\sigma = \sqrt{\sum_{i=1}^{N} \frac{(x_i - \mu)}{N - 1}} \tag{6-4}$$

The standard deviation is then divided by the mean values in order to see the amount that the results deviates relative to the average or mean value. A rule of thumb is that this value should be equal to or less than 10 percent or 0.1.

Table 16 shows results for various runs in SIMA/RIFLEX and are included to show that the simulations provides consistent results. The results are taken from different envelope curves. The direction of propagation of the vessel and currents are opposite to each other. The current profile is the current profile for 400 m water depth defined in Section 6.1.4.3. The values for the tension and bending moments in Table 16 are taken at the location where the dynamic bending moment has its maximum value.

Table 16: Consistency of dynamic results for the 311 m riser column in RIFLEX.

Significant Wave Height, H_s	1	2	3	[m]
Wave Period, T_P	5	7	8	
Vessel speed, U	1	1	1	[m/s]
$\mu_{max\,force}$	3916.00	3963.20	3997.6	[kN]
$\sigma_{max\,force}$	0.71	6.83	18.61	[kN]
$\dfrac{\sigma_{max\,force}}{\mu_{max\,force}}$	1.80e-4	1.7e-3	4.66e-3	[-]
$\mu_{max\,BM}$	93.84	131.30	176.84	[kN m]
$\sigma_{max\,force}$	.58	3.60	10.97	[kN m]
$\dfrac{\sigma_{max\,BM}}{\mu_{max\,BM}}$	6.20e-3	2.74e-2	6.20e-2	[-]

Based on the calculations above, the models provides results that are consistent within the defined criteria although the variations in bending moment are close to the 10 percent rule. Some readings may off by a few decimals, due to human error. This, however, should have negligible effects on the results listed above.

7   RESULTS AND DISCUSSION

This section of the thesis will present and discuss the results, observations and general trend lines from the simulations. The results are found in an Excel file called *MSc.results* in the electronic attachment.

A procedure is established that determines the loads in the simulations:

1. Run simulation without any waves, current or forward speed.
2. Run simulation with waves
3. Run simulation with waves and currents
4. Run simulation with currents, waves, and forward speed

This procedure gives an insight to which parameters will have the largest effect on the response of the riser column. Another reason to run the simulations in this sequence is due to the parameters required for the DNV calculations. Prior to subjecting the riser column to any environmental loads, the functional loads must be determined, which are found by running the simulations without any current, waves or forward speed.

When a current is applied, there are two critical spots on the riser column:

1) the top of the riser column at the attachment point between the riser column and the MODU
2) where the maximum moment occurrs on the riser column

For each run, these two locations are identified and the tension and moment values are read off for each of the respective spots. Note there is no moment at the attachment point between the riser column and the MODU since the riser column is allowed to rotate at this point. The maximum dynamic bending moment on the riser column tends to occur either on the buoyancy section or in the water/wetted zone. The location of the maximum bending moment has a tendency to move downwards with increasing sailing speed.

While calculating the usage factor from the combined loading equation, it is important to use the wall thickness of the pipe portion of the riser joints and exclude the buoyancy modules thickness. It can therefore be assumed that the forces and bending moments are absorbed by the pipe wall itself and not the buoyancy modules. That is, the buoyancy elements to not contribute the structural integrity of the riser column.

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7.1 CONVERGENCE STUDIES

The element length and the time step used for the simulations is justified in this section through convergence studies. The purpose of a convergence study is to ensure that the results do not change, or the change is negligible, for decreasing element length and/or time step.

In order to perform these two studies, there is no forward speed of the vessel. There is a regular current profile for 400 m water depth. The seed number is the same for all of the runs and the only variable is the element length and the time step. Table 17 is a summary of the parameters that are kept constant throughout both of the convergence studies.

Table 17: Fixed parameters used for the convergence studies.

Parameter	Value	Units
Significant wave height, H_s	1	[m]
Wave period, T_p	5	[sec]
Seed number	38918	[-]

For both convergence studies, the maximum dynamic force at the top of the riser is investigated. First, a relatively large element length or time step, depending on which convergence study is being investigated, is run and the corresponding forces of interest are recorded. The element length or time step is then decreased and it is expected that the forces over the length of the riser column will change. After several iteration steps, the maximum dynamic force at the top of the riser should start converging towards a certain value. Decreasing the element length or time step any further will then result in small changes in the maximum dynamic force at the top of the riser.

Another important reason for the convergence studies is to minimize the computational time for each run. If, for example, halving the element length or time step will result in a negligible difference in the results but increase the computational time exponentially, it is not considered feasible or necessary to do so.

7.1.1 Element Length

For the convergence study of the element length, the time step is set 0.1 sec while the element length is changed between the runs. With decreasing element lengths, there will be an increase in the number of elements present over the length of the riser column.

The force at the top of the riser column as a function of element length is plotted in Figure 28.
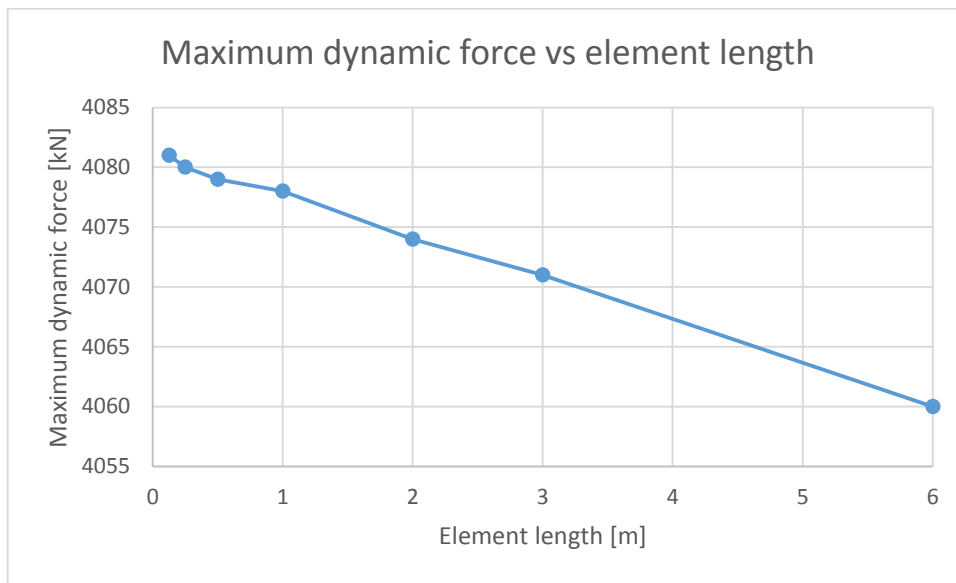
Figure 28: Maximum dynamic force at the top of the 311 m long riser column as a function of element length.

As seen in Figure 28, there is a significant change in the maximum dynamic force at the top of the riser between 6 m and 2 m element length. At 1 m element length, the maximum dynamic force at the top of the riser is 4078 kN while for an element length of 0.125 m, the maximum dynamic force at the top of the riser is 4081 kN. This corresponds to 0.0734 percent change in the force relative to the maximum dynamic force using an element length of 1 m. The increase in computational time, however, increases drastically. Therefore, due to the small changes in the results and the exponential increase in the computational time, using an element length of 1 m is justified.

7.1.2 Time Step

For the convergence study of the time step, the element length on the riser column is constant at 1 m while the time step in the dynamic calculation parameters is varied. With decreasing time step will be a corresponding increase in the number of calculations performed for the dynamic calculation analysis.

The force at the top of the riser column as a function of time step is plotted in Figure 29.
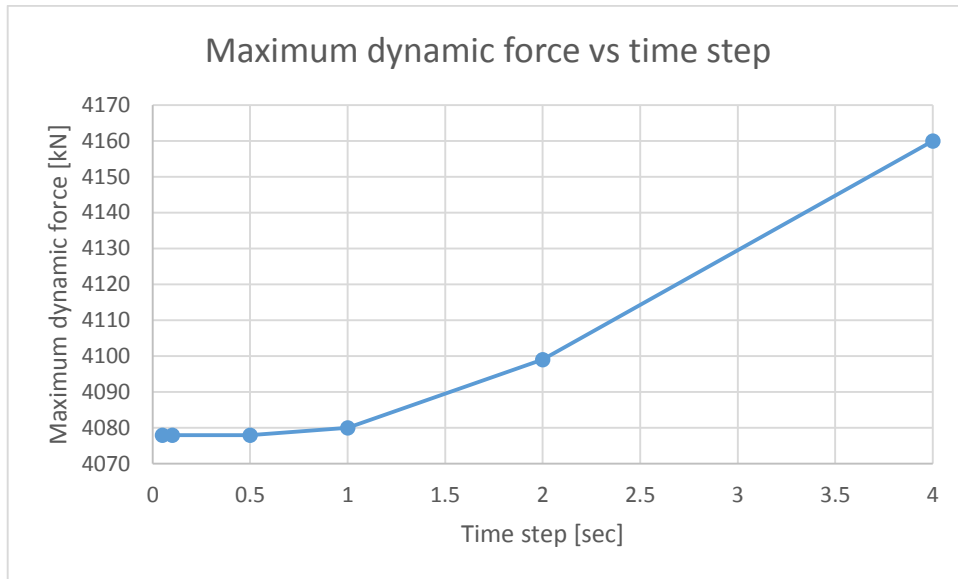
Figure 29: Maximum dynamic force at the top of the 311 m long riser column as a function of time step.

Based on Figure 29, there is a large change in the maximum dynamic force at the top of the riser column to between time steps 4 sec and 0.5 sec. For time steps smaller or equal to 0.5 sec, the maximum dynamic force stays constant at 4078 kN. Hence, a time step of 0.1 sec for the simulations is justified.

7.2 STATIC FORCES IN RISER COLUMNS

The static forces for the three riser column lengths varies due to the difference riser column lengths as well the difference in the riser column make up. The static forces for each of the three riser columns without any currents applied to them is seen in Figure 30.

Figure 30: The static forces for each of the three riser columns without any waves, currents or forward speed.

The bottom of the BOP is to the left, at 0 m depth. There is a large increase in the effective tension during the first 14 meters due to the large submerged weight per unit length from the BOP and LMRP stacks. The BOP and LMRP have the same dimensions and properties for all three of the riser columns and therefore the effective tension increases by the same amount for the first 14 meters.
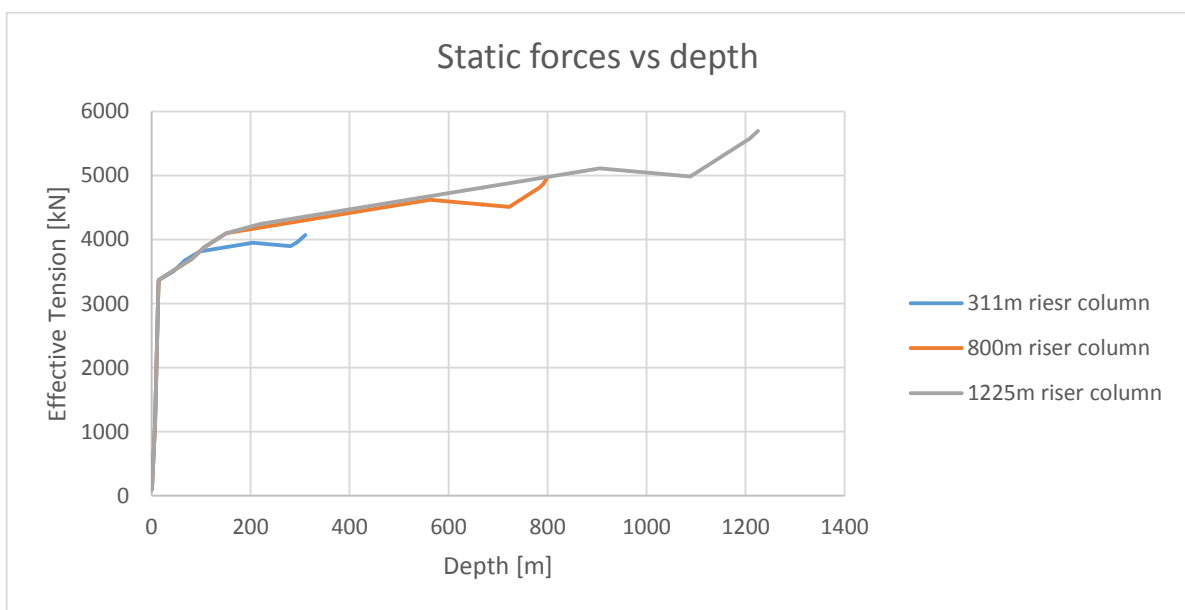
Above the BOP and LMRP stacks are slick riser joints and the XO sub. This contributes to a smaller increase in the effective tension per unit length than the contributions from the BOP and LMRP stacks due to a smaller submerged weight per unit length. The buoyancy joints are above the slick joints and XO sub. The relatively small submerged weight per unit length of the buoyancy joints compared to the slick riser joints, XO sub, the BOP and the LMRP stack contribute to a smaller increase in the effective tension per unit length. In fact, for each of the riser columns there is a decrease in the effective tension towards the top of the riser column. The reason for this is due to a type of buoyancy joint that is used, which has a negative submerged weight per unit length. The topmost part of each of the riser columns have slick riser joints and spacer joints which will contribute to a slightly larger increase in the effective tension per unit length compared to the buoyancy joints.

7.3   RISER YIELDING ASSESSMENT

The assessment of the riser column is carried out using Microsoft Excel 2013 and equations from the DNV-OS-F201 Dynamic Risers standard.

Prior to the starting the simulations and further analysis of the data, a critical value for η is to be defined. As mentioned earlier in the thesis when the usage factor is equal 1, it is assumed that the riser will deform and/or damage to the riser will occur. No safety factors other than the safety factors introduced in the DNV calculations are used in the analyses.

Combined loading calculations is performed for each of the three steel grades, API 5L X-52, X-65 and X-80. The results for the X-52 steel grade is presented since it is the steel grade with the poorest properties with respect to yield strength and ultimate tensile strength. Similar calculations are performed for each of the respective riser lengths.

7.3.1   1225 m Long Riser Column

The results for the 1225 m long riser column are presented since it has the largest values of η for all the riser column lengths. This is due to a combination of large forces in the riser column and bending moments exerted to the riser column.

The results are plotted in 2 dimensional plots with the sailing speed on the horizontal axis and the usage factor, η, on the vertical axis. Each of the three lines corresponds to a sea state chosen from the scatter diagram. When the vessel speed is 0 m/s, there is still a current present.

The usage factor as a function of the MODU sailing speed at the location where the maximum dynamic bending moment occurs for the 1225 m long riser column is plotted in Figure 31.
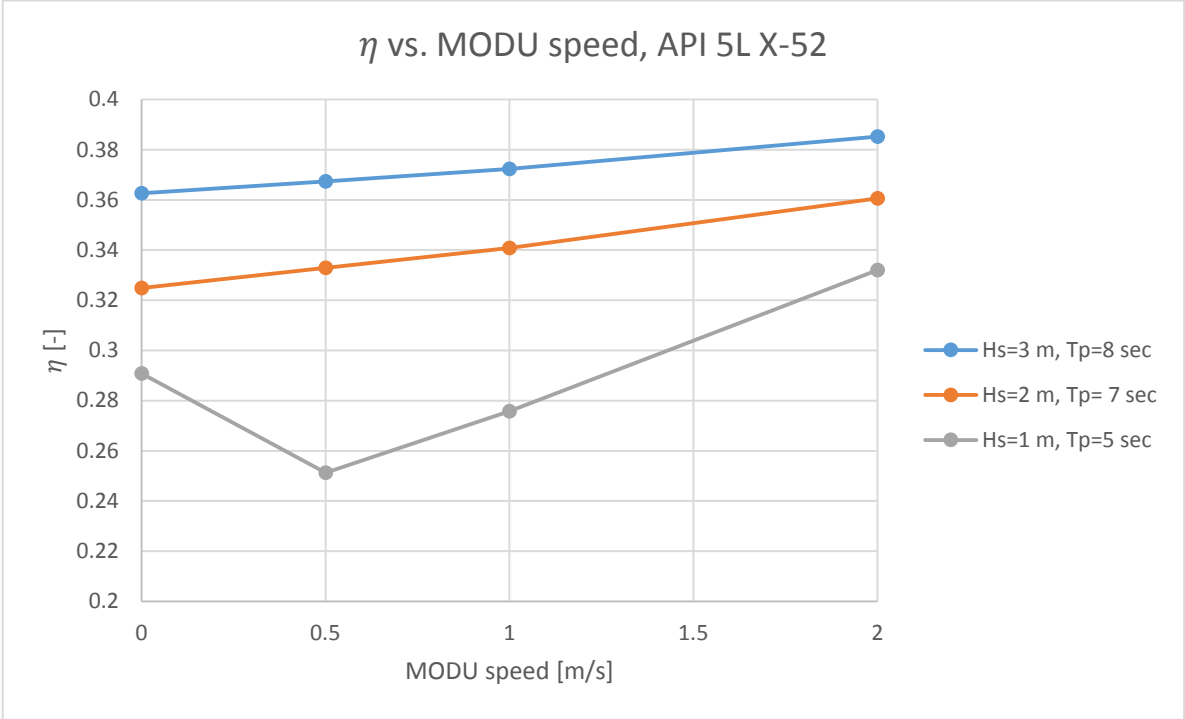
Figure 31: η vs. sailing speed where the maximum dynamic bending moment occurs on the 1225 m long riser column.

Based on Figure 31, the general trend line for the locations where the maximum dynamic bending moment occurs is that the value of the usage factor increases with increasing MODU sailing speed. The reason for the decrease in the usage factor for increasing rig speed when H_s=1 m and T_p= 5 sec is because the maximum bending moment takes place farther below mean sea level with increasing rig speed. This means that the effective tension where the maximum bending moment occurs is or can be significantly lower which may result in a smaller usage factor value.

The usage factor as a function of the MODU sailing speed at the attachment point between the 1225 m long riser column and the MODU is plotted in Figure 32.
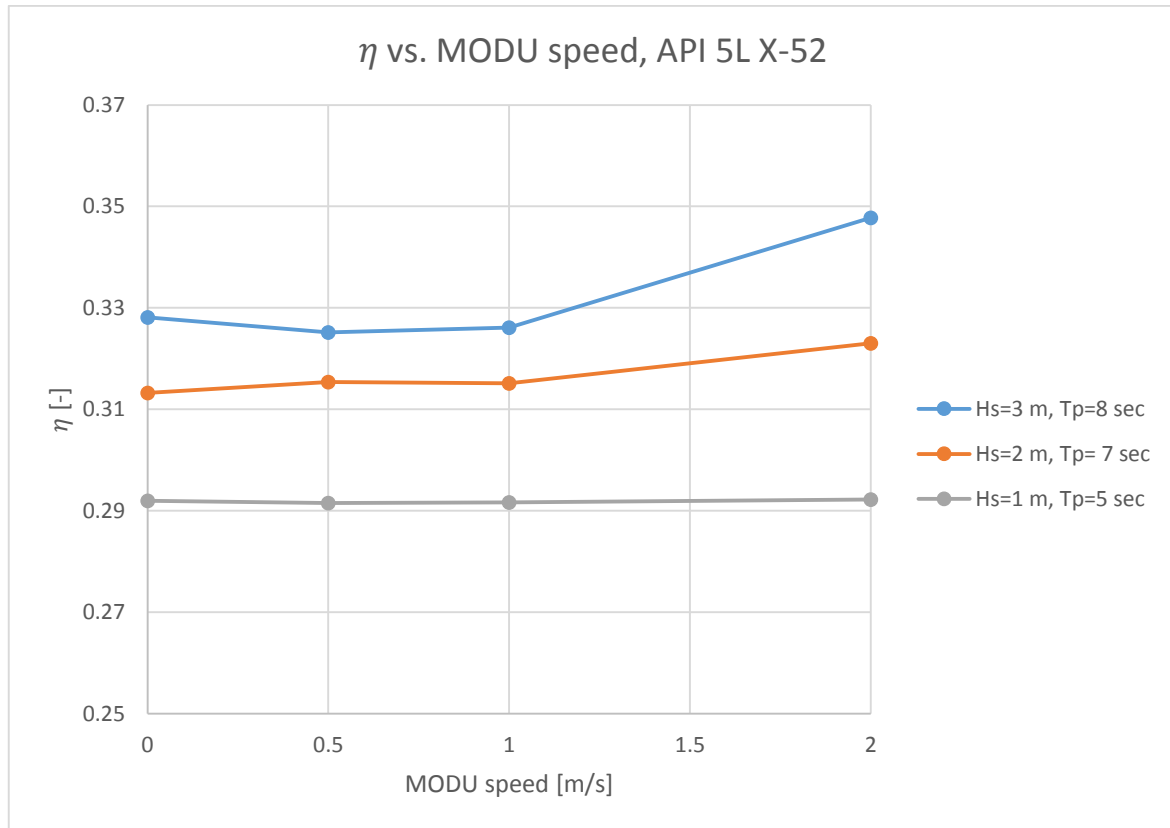
Figure 32: η vs. sailing speed at the attachment point between the riser and MODU for the 1225 m long riser column.

There are small variations in the usage factor with increasing MODU speed. In addition to this, the usage factor is significantly lower than the limiting value of 1 both at the location where the maximum bending moment occurs and at the attachment point between the riser column and the MODU.

The calculated usage values from the combined loading equation for the X-65 and X-80 steel grades for the 1225 m long riser column are significantly lower than for the X-52 steel grade. Hence, the plots for these steel grades are not included since the usage factor values are as small as they are.

It should be noted that Figure 31 and Figure 32 above do not necessarily follow a linear trend line. A best fitted line can be applied to the data points to estimate the trend line for the utilization factor.

7.4   COMPARING BENDING MOMENTS

The maximum bending moments are recorded under the conditions

- Only waves present
- Waves and current present with 0 m/s sailing speed

- • Waves and current present with varying sailing speeds

This is done in order to evaluate the riser joints at the location where the maximum bending moments occurs and to observe the effects of currents and increasing sailing speed.

When only waves are present, and, when there are waves and current present with 0 m/s sailing speed, the maximum dynamic bending moment occurs the highest on the riser column. That is, right around the water or wetted zone. The length or distance on the riser column from the attachment point between the riser column and RKB where the maximum dynamic bending moment occurs for the 1225 m long riser column when H_s=2 m and T_p=7 sec is presented in Table 18.

Table 18: Depth of maximum dynamic bending moment from the attachment point when Hs=2 m and Tp=7 sec for the 1225 m long riser column.

Sailing speed [m/s]	Depth [m]
Only waves (no current)	21.63
0.0	21.63
0.5	23.23
1.0	159.90
2.0	166.53

Waves are present for all of the sailing speeds. When there is 0 m/s sailing speed there is still waves and current present. The buoyancy section for the 1225 m long riser column is roughly 137 m below the drillfloor. As the sailing speed increases from 0.5 m/s to 1 m/s, the location of where the maximum dynamic bending moment occurs shifts from the water zone or wetted zone on the riser column to the buoyancy section of the riser column. The length or distance on the riser column from the attachment point between the riser column and RKB where the maximum dynamic bending moment occurs for the 800 m long riser column when H_s=2 m and T_p=7 sec is presented in Table 19.

Table 19: Depth of maximum dynamic bending moment from the attachment point when Hs=2 m and Tp=7 sec for the 800 m long riser column.

Sailing speed [m/s]	Depth [m]
Only waves (no current)	20.97
0.0	21.17
0.5	95.45
1.0	98.25
2.0	106.46

The buoyancy section for the 800 m long riser column starts roughly 77 m below the attachment point between the riser column and RKB. As the sailing speed increases from 0 m/s to 0.5 m/s, the location of the maximum bending moment shifts from the water zone or wetted zone on the riser column to the buoyancy section of the riser column.

For the 311 m long riser column in irregular seas with H_s=2 m and T_p=7 sec, the maximum bending moment takes place on the buoyancy section in all of the respective runs, including when there are only waves present and no current.

One interesting observation is that the magnitude of the maximum dynamic bending moment subjected to the riser column has a tendency to increase with decreasing riser column length. The maximum bending moment subjected to each of the three riser column lengths for H_s=2 m and T_p=7 sec with regular current profile and 2 m/s sailing speed is listed in Table 20.

Table 20: Maximum dynamic bending moments for Hs=2 m and Tp=7 sec with regular current profiles and 2 m/s sailing speed

Length of riser column [m]	Maximum bending moment [kN m]
311	242.68
800	167.60
1225	141.98

Based on the results in Table 20 and results for other wave heights and sailing speeds, the trend line is that the shorter the riser column the larger the maximum dynamic bending moment exerted to the riser column.

The relationship between the riser column length and the magnitude of the maximum dynamic bending moment may be subject for further analysis and discussion. However, this trend line was obvious after the simulations were completed and the results recorded, and is therefore mentioned in the text.

7.5 WORST CASE SCENARIO

From the predefined weather conditions there is a worst case scenario run for each of the riser column lengths. This is when

- H_s=3 m and T_p=8 sec
- Regular current profile
- Direction of vessel propagation and current are opposite of each other

As mentioned earlier, the maximum dynamic bending moment exerted to the riser column is larger for the shorter riser columns then for the longer riser columns. This statement holds true for the worst case scenario runs as well. In fact, the magnitude of the maximum bending moment in the shortest riser column is twice of the maximum bending moment in the longest riser column.

For all three riser columns, the maximum dynamic force in the riser column at the attachment point between the MODU and the riser column increased with increasing sailing speed and increasing significant wave height, and reached its maximum in the worst case scenario run. Based on this, an assumption made is that the general trend line will continue and sailing in higher significant wave heights and sailing speeds will increase the maximum dynamic force at the top of the riser column.

The contributions from the bending moment to the combined loading equation is also dominant in these runs. This is an effect that will be discussed more in depth in a following section, however, for the 311 m long riser column the maximum dynamic bending moment contributes nearly 62 percent to the usage factor calculated from the combined loading equation. This is the highest contribution to the usage factor from the maximum dynamic bending moment for any of the predefined sailing speeds and weather conditions. If the significant wave heights and sailing speed increases further, there could be damage to the buoyancy elements and/or riser pipe joints due to deformations caused by the maximum dynamic bending moment.

7.6   CONTRIBUTIONS FROM BENDING MOMENT AND TENSION

The percent that the bending moment contributes to the usage factor in the combined loading equation is presented in this section.

At the top of the riser there is no bending moments present so the only contribution on the combined loading equation is from the tension in the riser column. Hence, there is no need to present the percent contribution from the bending moment at this location. If the boundary conditions at the attachment point where such that the riser is unable to rotate, it is expected that the bending moment would have a major contribution to the combined loading equation.

At the location where the maximum bending moment occurs, there are contributions due to bending moment and tension. The percentage of each respective contribution is summarized in Table 21 - Table 23 for the three riser column lengths as a function of sailing speed when H_s=2 m and T_p=7 sec.

Table 21: Percent contribution at location where maximum bending moment occurs for Hs=2 m and Tp= 7 sec for 311 m long riser column.

Sailing speed [m/s]	% from bending moment	% from tension
0.0	26.15	73.85
0.5	32.78	67.22
1.0	42.26	57.74
2.0	57.40	42.60

Table 22: Percent contribution at location where maximum bending moment occurs for Hs=2 m and Tp= 7 sec for 800 m long riser column.

Sailing speed [m/s]	% from bending moment	% from tension
0.0	12.15	87.85
0.5	16.87	83.13
1.0	25.58	74.42
2.0	40.14	59.86

Table 23: Percent contribution at location where maximum bending moment occurs for Hs=2 m and Tp= 7 sec for 1225 m long riser column.

Sailing speed [m/s]	% from bending moment	% from tension
0.0	8.2	91.8
0.5	10.05	89.95
1.0	18.39	81.61
2.0	30.92	69.08

It should be noted when the MODU speed is 0 m/s, there is still a current present. When there is no current or forward speed, there will be no bending moments exerted to the riser column and hence the bending moment will have no effect on the combined loading equation.

Based on Table 21 - Table 23, the higher the speed of the MODU the higher the contribution of the bending moment to the combined loading equation. Also, the shorter the length of the riser column the larger effect the bending moment has on the combined loading equation. One possible explanation for this is because the effective tension in the riser column is significantly smaller and, thus, the bending moment will have a more profound effect on the combined loading equation. Another explanation is based on the observation made in a Section 7.4, that is, with decreasing riser column length there is a corresponding increase in the maximum dynamic bending moment exerted to the riser.

As mentioned in Section 7.4, with increasing sailing speed the location of the maximum bending moment tends to occur at deeper water depths. With increasing water depths, there is

corresponding decrease in the effective tension in the riser column. Based on this observation, a small increase in the bending moment will have a larger effect on the combined loading equation. If the maximum bending moment occurred at the same location on the riser column, the percent contribution to the combined loading equation due to the maximum bending moment would decrease slightly in Table 21 - Table 23. However, the same trend line would take place. That is, with increasing rig speeds there is a higher contribution from the bending moment to the combined loading equation.

7.7 SUMMARY

Three riser column lengths are used for the simulations:

- 311 meters
- 800 meters
- 1225 meters

Each of the riser columns are run with all the significant wave heights and corresponding wave periods listed in Table 24.

Table 24: Significant wave height and corresponding wave period used for the RIFLEX simulations.

H_s [m]	T_p [sec]
1	5
2	7
3	8

Each of the riser column lengths had its own current profiles and with sailing speeds:

- 0.0 m/s
- 0.5 m/s
- 1.0 m/s
- 2.0 m/s

The results are then recorded and subsequent riser analyses is performed.

Based on the observations, parameters important for evaluating BOP sailing are:

- Rig sensitivity to weather
- Rig type
- Riser properties

- Riser dimensions

- Length of riser column

- Sailing distance

- Thruster-riser interaction

- Risk and HSE evaluation

- Crossing of subsea structures and installations

Each of the respective points should be considered carefully prior to starting a BOP sailing event.

8 CONCLUSION

This thesis examines an alternative method of moving a drilling rig from one well location to another with a suspended marine drilling riser and subsea BOP. The loads on the riser column during the BOP sailing event have been analyzed for different rig speeds and weather parameters.

Interesting observations and trend lines have been observed. However, it can be concluded that it is safe to sail with a suspended riser column and BOP for the three different riser column lengths in all of the weather conditions and sailing speeds listed above for the specific RAO transfer function used for the analyses. In fact, based on the results the MODU could sail in harsher weather conditions and faster sailing speeds, which can be studied further in another study. From a safety point of view, this is reassuring as costly and large pieces of equipment are involved. It is undesirable to be dangerously close to the critical usage factor value, which did not occur in any of the runs.

The most important parameters while sailing with a suspended marine drilling riser and subsea BOP are:

1) Sailing speed
2) Current speed
3) Sailing direction
4) Current direction
5) Significant wave height and wave period

Where the order of importance based on the results are listed accordingly.

In order to decide weather criteria's for BOP sailing events, rig and riser specific data is necessary in order to perform the required simulations and analyses.

9   RECOMMENDATIONS FOR FURTHER WORK

This thesis is the first to explore the concept of BOP sailing and there is a great deal of further work that may be explored in the future for BOP sailing and BOP jumping.

The forces and moments present in the riser column vary with the MODU used due to the difference in RAO transfer functions. Simulations with BOP sailing and/or BOP jumping for specific vessels are interesting studies, especially for a MODU that plans to used BOP sailing and/or BOP jumping frequently.

Riser joints are provided by different service companies and the properties may vary as a function of the service company and design considerations. Simulations and further analyses of riser joints with differing properties is also a possibility to study further.

Another possible study that can be conducted is an extreme value study during irregular seas using the Gumbel or Rayleigh distribution. This is an option which can be performed in the RIFLEX post processor.

The BOPs used on the NCS vary in height and weight, which may influence the forces and bending moments present in the riser column. Studies related to different BOP sizes is an option.

3D plots featuring significant wave height, wave period and current speed for specific MODUs or riser columns is another interesting study. The mapping in the 3D plot can have various colors depending on whether it is considered safe to sail under the specific weather conditions or not.

Studies related to fatigue and damage assessment of the riser joints and other relevant components during a sailing operation can also be studied more extensively.

10 REFERENCES

[1]. Devold, H. (2013). *Oil and gas handbook – An introduction to oil and gas production, transport, refiing and petrochemical industry*. Oslo, Norway: ABB Oil and Gas.

[2]. Osmundsen, P., Roll, K. H., Tveterås, R. *Drilling Productivity on the Norwegian Continental Shelf.* Stavanger, Norway: University of Stavanger.

[3]. Offshore.no. (2015). *Riggdata.* Retrieved on April 13th, 2015, from: http://www.offshore.no/Prosjekter/riggdata.aspx.

[4]. Statoil ASA employee. (2015). Interview on April 30th, 2015.

[5]. Encyclopædia Britannica. (2015). *Sonar (from "sound navigation ranging").* Retrieved on May 9th, 2015, from; http://global.britannica.com/EBchecked/topic/554214/sonar.

[6]. Kongsberg Mesotech Ltd. (2015). *Underwater Vehicle Instrumentation*. Vancouver, Canada: Kongsberg Maritime.

[7]. Kongsberg Mesotech Ltd. (2015). *Echo sounders*. Vancouver, Canada: Kongsberg Maritime.

[8]. Sevillano, L. C., Mendes, J. R. P., Miura, K., & Morooka, C. K. (2013). *Drilling riser analysis during installation of a wellhead equipment.* Nantes, France: ASME 32nd International Conference on Ocean, Offshore and Artic Engineering.

[9]. Offshore Magazine. (2002). *BOP-deployed move saves time, money.* Tulsa, OK: PennWell Corporation.

[10]. Lyons, W. C., Guo, B., Graham, R. L., Hawley, G. D. (2009). *Air and Gas Drilling Manual – Applications for Oil and Gas Recovery Wells and Geothermal Fluids Recovery Wells* (3rd ed.). Elsevier Inc: Burlington, MA. 48-52.

[10]. Schlumberger Oilfield Glossary. (2015). *Pipe ram*. Houston, Texas: Schlumberger Limited. Retrieved on May 26th, 2015, from; http://www.glossary.oilfield.slb.com/en/Terms/p/pipe_ram.aspx

[11]. Sangesland, S. (2008). *Drilling and completion of subsea wells.* TPG 4200, NTNU; Trondheim, Norway.

[12]. Whitby, M. F., Mangan, J. T. (2007). *U.S. Patent No. 7,300,033.* U.S. Patent and Trademark Office: Washington, DC.

[13]. Transocean Spitsbergen. (2010). *BOP jump tool.* Vernier, Switzerland: Transocean Ltd.

[14]. DrillingFormulas. (2013). *Basic Understanding about Drill Pipe*. Retrieved on May 26th, 2015, from; http://www.drillingformulas.com/basic-understanding-about-drill-pipe/.

[15]. Transocean Spitsbergen. (2010). *Detailed operational procedure – Jump BOP.* Vernier, Switzerland: Transocean Ltd.

[16]. Sparks, C. P. (2007). *Fundamentals of Marine Riser Mechanics: Basic Principles and Simplified Analysis* (1st ed.). PennWell Corporation: Tulsa, OK.

[17]. API. (2010). *API RP16Q – American Petroleum Institute Recommended Practice for Design, Selection, Operation and Maintenance of Marine Drilling Riser Systems* (1st ed.). : Washington, DC: American Petroleum Institute. 5-14.

[18]. VetcoGray Inc. (2008). *Capital drilling equipment.* Houston, Texas: General Electric. 3, 18.

[19]. Jones, H. W. (1976). *U.S. Patent No. 3,984,990.* Washington, DC: U.S. Patent and Trademark Office.

[20]. DNV GL. (2014). *Introduction to Subsea Production Systems.* Høvik, Norway: DNV GL Oil and & Gas. Retrieved on April 19th, 2014, from: http://www.uio.no/studier/emner/matnat/math/MEK4450/h14/undervisningsmateriale/module-2/mek4450-dnvgl-05-templates-and-manifolds.pdf.

[21]. DNV. (2014). *Subsea Facilities – Technology Developments, Incidents and Future Trends.* Høvik, Norway: DNV GL Oil and & Gas.

[22]. Petrowiki. (2014). *Subsea wellhead systems.* Society of Petroleum Engineers. Retrieved on April 10th, 2015, from: http://petrowiki.org/Subsea_wellhead_systems.

[23]. Petrowiki. (2014). *Multipurpose tool and accessories.* Society of Petroleum Engineers. Retrieved on April 10th, 2015, from: http://petrowiki.org/Subsea_wellhead_systems#Multipurpose_tool_and_accessories.

[24]. DNV. (2010). *Offshore Standard DNV-OS-F201, Dynamic Risers.* Høvik, Norway: DNV GL Oil and & Gas. 1-33, 42-43.

[25]. ISO. (2005). *Konstruksjon og drift av produskjonssystemer under vann Del 7: Kompletterings- og arbeidsstigerør med tilhørende systemer (ISO 13628-7:2005).* Lysaker, Norway: Standard Norge. 107-110.

[26]. DNV. (2010). *Offshore Standard DNV-OS-H101, Marine Operations, General.* Høvik, Norway: DNV GL Oil and & Gas. 12, 28-35.

[27]. NTS. (1998). *NORSOK standard D-010N - Boring og brønnoperasjoner* (Rev. 2). Oslo, Norway: Norsk Teknologisenter. 26.

[28]. Drilling Contractor. (2014). *Study analyzes response of deepwater riser with suspended BOP*. Houston, TX: Drilling Contractor.

[29]. Faltinsen, O. M. (1990). *Sea loads on ships and offshore structures*. Cambridge, UK: Cambridge University Press. 13-33, 37, 223-225.

[30]. Ormberg, H., Passano, E. (2014). *RIFLEX Theory Manual* (V4.2v0). Marintek: Trondheim, Norway. 41-43, 53, 74-75.

[31]. Marintek. (2014). *SIMA User Guide*. Marintek: Trondheim, Norway.

[32]. Marintek. (2014). *RIFLEX User Guide*. Marintek: Trondheim, Norway.

[33]. Marintek. (2014). *SIMO User Guide*. Marintek: Trondheim, Norway.

[34]. Dictionary.com. (2015). *Pseudo.* Retrieved on June 5th, 2015, from: http://dictionary.reference.com/browse/pseudo.

[35]. Whatis.com. (2011). *Pseudo-random number generator.* Retrieved on June 5th, 2015, from: http://whatis.techtarget.com/definition/pseudo-random-number-generator-PRNG.

[36]. Myrhaug, D. (2007). *Marin dynamikk – uregelmessig sjø*. TMR 4180, NTNU: Trondheim, Norway. 63.

[37]. Leira, B. J. (2015). Consultation meeting.

[38]. Larsen, C. M. (2015). Meeting.

[39]. Transocean Spitsbergen. (2010). *TSB Roald Rygg.* Vernier, Switzerland: Transocean Ltd.

[40]. RIFLEX model. (2015). Modelled by Sigmund Anders Isaac Søgnesand.

[41]. Sele, J. (2015). Telephone conversation on April 22nd, 2015.

Appendix A: DNV-OS-F201, Dynamic Risers Equations

The formula for the design bending moment is given by Equation (A-1).

$$M_d = \gamma_F \cdot M_F + \gamma_E \cdot M_E + \gamma_A \cdot M_A \qquad \text{(A-1)}$$

Where M_F, M_E and M_A are the bending moments from functional loads, environmental loads, and accidental loads and γ_F, γ_E, and γ_A are the corresponding safety factors for each of the different load types.

The plastic bending moment resistance is given by Equation (A-2).

$$M_k = f_y \cdot \alpha_c \cdot (D - t_2)^2 \cdot t_2 \qquad \text{(A-2)}$$

Where f_y is the characteristic yield strength of the material, α_c account for strain hardening and wall thinning of the material, D is the nominal outside diameter and t_2 is the wall thickness of the riser joint.

f_y is defined in Table 5-5 in the DNV Dynamic Risers standard and is given by Equation (A-3).

$$f_y = (SMYS - f_{y,temp}) \cdot \alpha_U \qquad \text{(A-3)}$$

Where SMYS is the minimum yield strength of the material and is normally specified at room temperature, $f_{y,temp}$ is the yield stresses temperature derating factor (as temperatures increases the yield stress usually decreases which the derating factor takes into account), and α_U is the material strength factor and under normal conditions equal to 0.96.

As mentioned earlier, α_c is a parameter that accounts for strain hardening and wall thinning which is given by Equation (A-4).

$$\alpha_c = (1 - \beta) + \beta \cdot \frac{f_u}{f_y} \qquad \text{(A-4)}$$

Where f_u represents the characteristic tensile strength of the material that is to be used in the design and is given by Equation (A-5).

$$f_u = (SMTS - f_{u,temp}) \cdot \alpha_U \qquad \text{(A-5)}$$

Where SMTS is the minimum tensile strength which is usually given at room temperature and $f_{u,temp}$ is the temperature derating factor for the materials tensile strength. β and q_h are parameters that account for strain hardening and wall thinnning and are defined in Equations (A-6) and (A-7).

$$\beta = \begin{cases} (0.4 + q_h) & for\ \dfrac{D}{t_2} < 15 \\[2mm] \dfrac{(0.4 + q_h)\left(60 - \dfrac{D}{t_2}\right)}{45} & for\ 15 < \dfrac{D}{t_2} < 60 \\[2mm] 0 & for\ \dfrac{D}{t_2} > 60 \end{cases} \qquad \text{(A-6)}$$

$$q_h = \begin{cases} \dfrac{(p_{ld} - p_{e)}}{p_b(t_2)} \dfrac{2}{\sqrt{3}} & for\ p_{ld} > p_e \\[2mm] 0 & else \end{cases} \qquad \text{(A-7)}$$

Where p_{ld} is the local internal design pressure, p_e is the external pressure and p_b is the burst resistance of the riser pipe.

The local internal design pressure, p_{ld}, is given by Equation (A-8).

$$p_{ld} = p_d + \rho_i \cdot g \cdot h \qquad \text{(A-8)}$$

Where p_d is the pressure at the top of the riser column, ρ_i is the density of the fluid inside of the riser column, g is the acceleration due to gravity and h is the vertical height from the top of the riser column to the point of interest.

The design effective tension, T_{ed}, is defined in Equation (A-9).

$$T_{ed} = \gamma_F \cdot T_{eF} + \gamma_E \cdot T_{eF} + \gamma_A \cdot T_{eA} \qquad \text{(A-9)}$$

Where T_{eF}, T_{eE}, T_{eA} are the effective tensions from functional loads, environmental loads and accidental loads.

The plastic axial force resistance, T_k, is given by Equation (A-10).

$$T_k = f_y \cdot \alpha_c \cdot (D - t_2) \cdot t_2 \qquad \text{(A-10)}$$