NTNU

Assessment of Safety against Free Drift (Loss of Position) of Semisubmersibles

Master Thesis

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Assessment of safety against free drift (loss of position) of semi-submersibles

(Vurdering av sikkerhet mot fri drift (tap av posisjon) for halvt nedsenkbare plattformer.)

A semi-submersible is kept in position by a number of mooring lines. The characteristic load, t_c, for design of mooring lines is in most cases the expected largest mooring line load in the 100-year weather condition. In order to ensure a sufficient capacity against line failure, the characteristic load t_c is multiplied by a safety factor, s. The breaking load of the mooring line, t_b, must fulfil: $t_b > t_c*s$. The choice of safety factor depends on whether it is a permanent installation or a temporary installation e.g. drilling rigs. The required value of the safety factor is also dependent on the consequences of failure.

In many cases semi-submersibles are moored reasonably close to fixed structures. A fixed is to be controlled both against ULS (safety against the most severe loads likely to occur during life time) and ALS (ensuring safety against very rare and unexpected load events).Regarding ALS, the loads are defined as loads corresponding to an annual probability of exceedance of 10^{-4}. Assuming we have a moored platform in close vicinity of a fixed platform. If the probability of loosing platform position is 10^{-4} or higher per year, the collision load may represent an accidental load case for the fixed platform. The platform is not likely to withstand such a load event and if fixed platform is manned, it is a non acceptable scenario. It is therefore important that the annual probability of loosing position is smaller than 10-4 for the moored platform – in particular if platform is moored close to a fixed structure.

Let us denote the 3-hour maximum (or possibly storm maximum) with T. Let us furthermore denote the long term distribution of T by $F_T(t)$. In this thesis the aim is to discuss the annual probability of line failure under various assumptions regarding the safety factor, i.e.:

$$p(\text{line failure}) = P(T_1 > t_c * s) = 1 - F_{T1}(t_c * s) = 1 - [F_T(t_c * s)]^N \quad (1)$$

where T_1 is the annual maximum line load and N is no. of 3-hour periods in a year if T is the 3-hour maximum line load.

The challenge is to establish the distribution function for T. This will typically require time domain simulations using SIMO or a similar computer code. A major part of the work will be to make time domain simulations with SIMO for a given platform and various weather conditions.

The first thing to do is to formulate a solution scheme which requires a manageable amount of simulations. As example platform we will use a semi-submersible for which model test data is available.

Below a possible division into reasonable sub tasks is suggested.

1. Review briefly the procedure for designing a mooring line. Emphasis is to be given to the choice of safety factor. Governing rules and regulations shall be referred to.

2. Discuss the qualitative difference between line failure and loss of position. If probability of line failure is p_f, indicate an upper and lower bound for the loss of platform position assuming position is lost when all lines in a corner is lost.

3. As a first approach, consider the model test data for the considered platform. Let us for this consideration assume that the mooring line loads in the basin is good estimate for the mooring line loads for the real platform. Estimate first of all the characteristic load for the most exposed line. Estimate thereafter 10^{-2} and 10^{-4} – annual probability line loads utilizing the ideas underlying the environmental contour line method. Calculate the annual failure probability for various safety factors based on the model test data. Indicate the statistical uncertainty (uncertainty due to limited no of observations from model test) associated with the results.

4. In the numerical study, we shall use the computer program SIMO. In order to verify that SIMO is performing for mooring line predictions, a possibility is to verify predicted motions of a given platform with available model test results. It is proposed that Veslefrikk is used for this purpose. (This is provided we can find an available SIMO model for Veslefrikk.) Effect of thruster must be modelled properly.

5. Use SIMO to do the same as was done based on model test data. Estimate the annual probability of loosing a line.

6. A line failure will not necessarily result in loss of position. A loss of position requires a loss of multiple mooring lines. One shall there assessment the safety against free drift by exposing the moored platform to a full q-probability storm. A first step is to establish a proper temporal profile for the q-probability storm, i.e. the time histories of significant wave height, spectral peak period and mean wind speed. The following values can be adopted for q: 10^{-2}, 10^{-3} and 10^{-4}.

7. The q – annual probability storm events shall be repeated a number of times. The loads in the various lines are to be monitored and if breaking load of a line is exceeded, the line is taken out of the further analysis. Using this approach to investigate the probability of loosing position in a q -annual probability storm.

8. Repeat 7 for an upper and lower value for the safety factors.

The candidate may of course another scheme as the preferred approach for solving the requested problem.

The work may show to be more extensive than anticipated. Some topics may therefore be left out after discussion with the supervisor without any negative influence on the grading.

The candidate should in his report give a personal contribution to the solution of the problem formulated in this text. All assumptions and conclusions must be supported by mathematical models and/or references to physical effects in a logical manner. The candidate should apply all available sources to find relevant literature and information on the actual problem.

The report should be well organised and give a clear presentation of the work and all conclusions. It is important that the text is well written and that tables and figures are used to support the verbal presentation. The report should be complete, but still as short as possible.

The final report must contain this text, an acknowledgement, summary, main body, conclusions, suggestions for further work, symbol list, references and appendices. All figures, tables and equations must be identified by numbers. References should be given by author and year in the text, and presented alphabetically in the reference list. The report must be submitted in two copies unless otherwise has been agreed with the supervisor.

The supervisor may require that the candidate should give a written plan that describes the progress of the work after having received this text. The plan may contain a table of content for the report and also assumed use of computer resources.

From the report it should be possible to identify the work carried out by the candidate and what has been found in the available literature. It is important to give references to the original source for theories and experimental results.

The report must be signed by the candidate, include this text, appear as a paperback, and - if needed - have a separate enclosure (binder, diskette or CD-ROM) with additional material.

Supervisor:	Prof. II Sverre Haver, Statoil ASA.

Preface

This report is my Master's Thesis of the two years' master program in marine technology of NTNU. It describes my thesis work on the mooring line tension problems based on the semi-submersible platform Veslefrikk B.

Here I want to express my appreciations to my supervisor Prof. Sverre K. Haver who has guided me so much for the thesis work and the report writing. Also great thanks to Knut Mo (Marintek) for the lectures of SIMO and Tone M. Vestbøstad (Statoil) for the help in the numerical model.

Abstract

For the assessment of safety against free drift (loss of position) of semi-submersibles, the mooring system of a semi-submersible is introduced, and the mooring line tension is looked into based on the laboratory model test and the numerical simulations of Veslefrikk B platform.

The work is mostly about the prediction of the mooring line tensions. Based on the model tests data, the characteristic mooring line tension is obtained, the breaking strength is the characteristic mooring line tension multiplied by safety factor. Then both 10^{-2} and 10^{-4} annual extreme mooring line tensions are estimated. By fitting the maximum 10^{-2} and 10^{-4} annual extreme mooring line tensions to a Gumbel distribution, the probability of any extreme mooring line tension can be obtained according to the Gumbel distribution. Thus the single mooring line failure probabilities for different given safety factors can be determined. In the time domain simulation program SIMO (MARINTEK), the mooring line tensions are simulated under the same environmental conditions as the model tests, and the same analysis procedure is carried out to the numerical simulations.

At last, the full long term analysis is carried out by the numerical simulations. Large numbers of sea states are simulated. For every sea state, there are 10 seeding tests, and the 3-hour extreme mooring line tensions are fitted to Gumbel. Then the response surfaces of Gumbel parameters are defined by the MATLAB 4 gird data method. The long term wave statics of the Veslefrikk field are given in the Veslefrikk Metocean Desgin Basis report [10]. After that, the long term probability for certain mooring line tensions can be calculated by integrating the conditional distribution of the 3-hour maximum mooring line tensions for the given wave characteristics times the joint distribution function of the significant wave characteristics in the critical area of Hs and Tp. The long term distribution of the extreme mooring line tensions is finally determined. And the 100-year and 10000-year extreme values are estimated.

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Chapter 1

Introduction

1.1 Background

For the floating structures, normally they are located nearby with each other for different functions such as drilling, production and accommodation. The mooring system is normally used to position the structures, while under the effects of severe environmental conditions. The failure of the mooring lines will cause the loss position of the structures which is unacceptable for the vicinity manned platforms. In this thesis, in order to assess the safety against the free drift of the floating structures, the Veslefrikk B platform is investigated with regarding to the mooring line tensions.

The Veslefrikk B semi-submersible is a platform located at the oil reservoir Veslefrikk field in situated 145km west of Bergen coast in the northern part of the North Sea. The model test of the platform was performed by MARINTEK in 2009, so the recorded mooring line tension data is available.

Figure 1.1 Veslefrikk B (Photo: Øyvind Hagen, Statoil)

1.2 Objectives

The objectives of the thesis include the following items:

Review some of the mooring line design theory, and the catenary equations are simply introduced.

Discuss the methods to simulating the mooring line tensions, model tests and numerical simulations.

The single mooring line failure probability is about to be investigated. This has been done for both the model tests and the numerical simulations. From the 3-hour mooring line tension histories of the 100-year sea states, the characteristic mooring line tension can be determined. The design breaking strength is the characteristic mooring line tension times the safety factors. After that, the 100-year and 10000-year extreme mooring line tensions are estimated and fitted into a Gumbel distribution, by interpolating the design breaking strength into the Gumbel distribution, the annual failure probability of a single mooring line can be determined.

Lastly, the long term analysis of the maximum 3-hour mooring line tensions will be performed based on the numerical simulations. After the long term distribution determined, the 100-year and 10000-year extreme mooring line tensions will be estimated.

Chapter 2

Mooring Line Design

2.1 Introduction of Mooring System

In the offshore industry, it is usually desirable to conduct the marine operations such as drilling operations from platforms which can stay at position during the operation. In shallow water, the drilling and production platforms are supported by some kind of framework structures such as Jackets or Jack-ups. While in deep water, for example depths larger than 300 meters, such supports become very expensive and complex due to the major portion of mass being supported at the upper end of a relatively slender structure. Therefore, in deep water, for the drilling purpose or some other marine operations, a number of floating structures are proposed such as semi-submersible, drilling vessel etc. The difficulty in drilling from these floating structures is maintaining the structure in a stable position under the influence of wave, wind and current etc. Thus, for this kind of offshore structures, fit-for-purpose mooring system is essential. As mooring system anchors the floating structure over a fixed point on the underwater bottom and minimizes the movement of the structure due to waves, wind and current etc. A variety of mooring systems for this purpose have been proposed and used either permanently secured to the sea bottom or dis-connectible from the floating structures in case that when the sea states are too harsh such as typhoon or hurricanes, the floating vessels can be disconnected for evacuation.

Functional requirements for the mooring system include [1]:
1. Offset limitations
2. Lifetime before replacement
3. Installability
4. Positioning ability

These requirements are determined by the function of the floater

The mooring system consists of certain numbers of freely hanging lines connecting the surface platform to anchors which are positioned at some distance from the platform on the seabed. The mooring lines are normally laid symmetrically in plane view, around the platform.

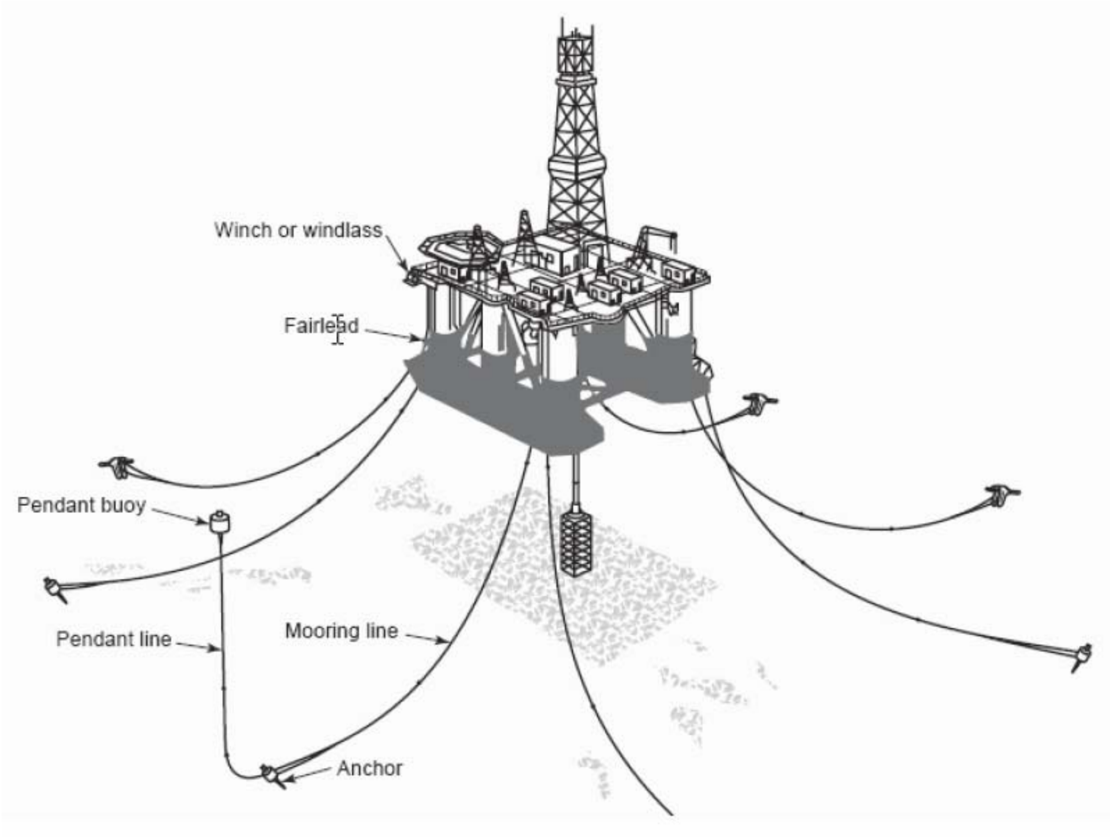

Fig 2.1 Mooring system for a semi-submersible platform [1]

The mooring system design is a compromise between avoiding excessive forces on the platform and making it stiff enough to avoid damages to the drilling or production risers, caused by the platform offsets.

In the past, the majority of mooring systems were passive. While more recently, mooring systems are used in conjunction with the dynamic positioning systems for station-keeping purpose. And DP systems help to reduce the loads in the mooring system by reducing the quasi-static offsets. [1]

2.2 Mooring Line Analysis

The floating vessels such as mono-hulls and semi-submersibles are traditionally moored with spread catenary lines system. In this section, the basic mechanics of a mooring line are demonstrated for understanding its characteristics with respect to the station-keeping performance.

A mooring line is simplified as a catenary line shown in Fig. 2.2, and one element of the line is given in Figure 2.3, which carries only tensions along the line but without considering the buoyancy effects. The characteristics of the mooring line tensions and the line pattern can be demonstrated by a serious of catenary equations [2]. The equations are based on the assumptions of that the bending stiffness effects of the mooring line are ignored as the bending stiffness is of minor important to the geometry of the mooring line. This is acceptable for a wire with relatively small curvature and gives a good approximation for a chain. Also, the dynamic effects are ignored at this stage.

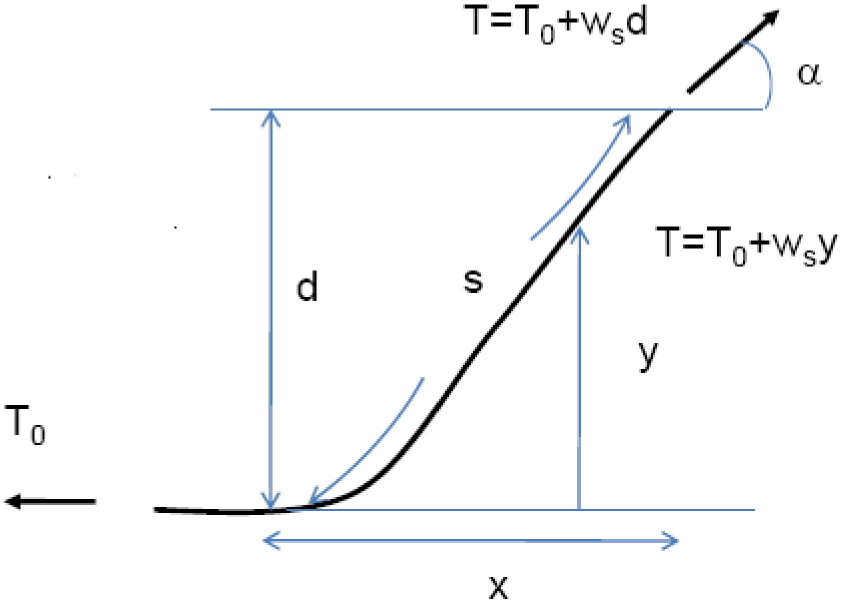

Figure 2.2 Global catenary geometry [2]

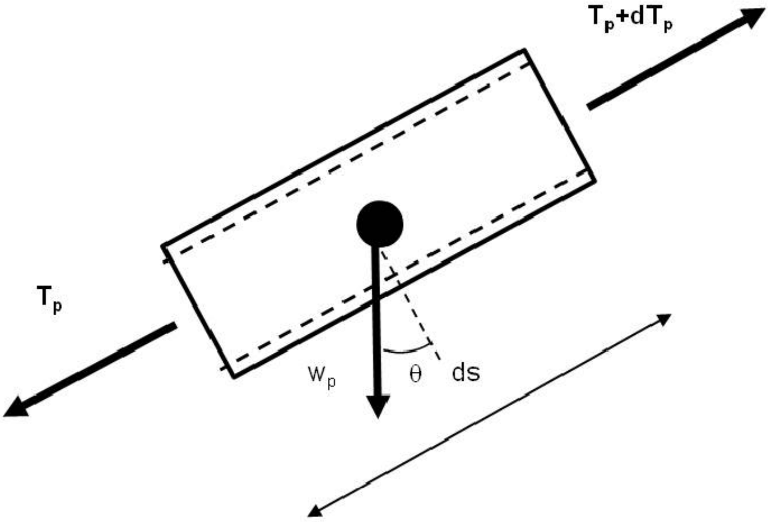

Figure 2.3 Infitesimal pipe element exluding buoyancy forces [2]

At the coordinate point y as illustrated in Fig. 2.2, the equilibrium yields:

$$dT_p = w_p \sin\theta ds = w_p dy \tag{2.1}$$

Further, by integration on both sides:

$$T_p = w_p y + T_{p0} \tag{2.2}$$

where T_{p0} is the pipe wall tension at the origin positioned at the seabed touch down point (TDP). Then by application of the effective tension concept [2] at the coordinate point y:

$$\begin{aligned}
T_{eff} &= T_{p0} + w_p y + p_e(y) \\
&= T_{p0} + w_p y + \rho_w g(d-y) \\
&= T_{p0} + \rho_w g d + (w_p - \rho_w g) y \\
&= T_{eff0} + w_s y
\end{aligned}$$

$$T = T_0 + w_s y \tag{2.3}$$

Where T and T_0 refer to the effective tension values.

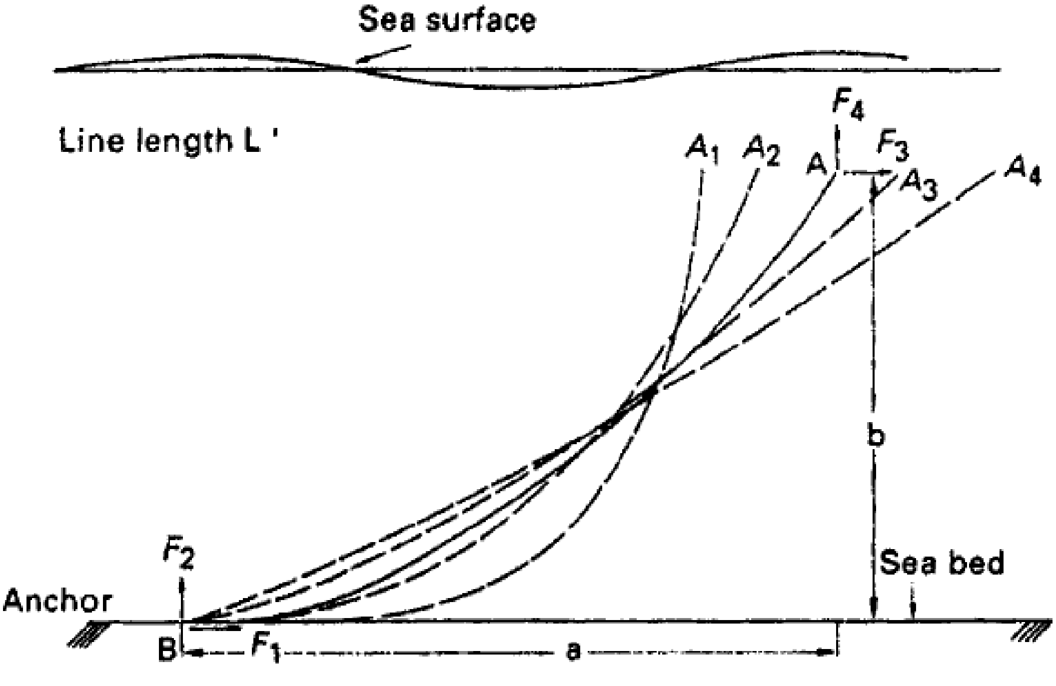

Figure 2.4 Catenary mooring line[1]

Fig. 2.4 shows a catenary mooring line from the connecting point A on a floating vessel to the touched down point B and to an anchor on the seabed. The line is partly laying at the sea bed in the vicinity of point B, and the horizontal dimension, a, is usually 5-20 times larger than the vertical dimension, b. As the horizontal drift motion of the floater, point A will shift in the range from A1 to A4, correspondingly, the suspended length varies with the shifting of the connecting point A, and so will the touched down point B. So, when the connecting point is at position A_1, the line length resting at the sea bed is longest and the line tension has the smallest component at the horizontal direction. When A moves to A_4, the line length lying at the sea bed is zero and the line has the maximum tension. And for a symmetrical mooring system, the two sets of symmetrical mooring lines provide a coupled horizontal restoring force to the vessel as the vessel offset from the initial point A.

2.3 Mooring Line Design

For the floating platforms, the mooring system shall be analyzed according to the design criteria formulated in terms of an ultimate limit state (ULS) and an accidental limit state (ALS). [3]

In an ultimate limit state, a mooring line should have the adequate strength to withstand the load effects under the extreme environmental actions. And in an accidental limit state, the mooring system should have the capacity to withstand the failure of one mooring line.

The design criterion is formulated as an equation in form of:

$$t_b > \alpha \bullet t_c \tag{2.4}$$

t_b is the breaking load of individual mooring line. t_c is the characteristic load for design of the mooring lines, in most cases, it's the expected largest load under the 100-year environmental conditions. α is the safety factor depending on the types of mooring line system, i.e. permanent installation or temporary installation.

For the floating facilities registered in Norwegian continental shelf, the safety factors of tension in mooring lines are given as in the following table.

Consequence class	1	2	3
Intact condition	1.50	2.00	2.20
One failure	1.20	1.35	1.50
One failure, transient	1.05	1.10	1.10
Tow failure	N/A	1.35	1.50
Tow failure, transient	N/A	1.10	1.10

Table 2.1 Safety factors of tension in mooring lines for mobile moorings [4]

While in many cases, the floating platforms are moored reasonably close to fixed structures. For the design criteria of fixed structures regarding ALS, the loads are defined as corresponding to an annual probability of exceedance of 10^{-4}. Assuming a moored platform in close vicinity of a fixed platform, if the probability of loosing platform position is 10^{-4} or higher per year, the collision load may represent an accidental load case for the fixed platform. The platform is not likely to withstand such a load event and if fixed platform is manned, it is a non acceptable scenario. It is therefore important that the annual probability of loosing position is smaller than 10^{-4} for the moored platform, in particular if platform is moored close to a fixed structure.

Denoting the 3-hour maximum (or possibly storm maximum) with T and the long term distribution of T with $F_T(t)$ In this thesis, the annual probability of line failure under various environmental conditions regarding the safety factors will be analyzed, i.e.:

$$p(\text{line failure}) = P(T_1 > t_c*\alpha) = 1 - F_{T1}(t_c*\alpha) = 1 - [F_T(t_c*\alpha)]^N \tag{2.2}$$

Where T_1 is the annual maximum line load and N is no. of 3-hour periods in a year if T is the 3-hour maximum line load.

Chapter 3

Methods of Simulating Mooring Line Tension

3.1 Model Test

Generally, there are several aims of model test [5]:

1. To achieve relevant design data to verify performance of actual concepts for ships and other marine structures.
2. Verification and calibration of theoretical methods and numerical codes
3. To obtain a better understanding of physical problems.
4. Can be done for establishing desire variables directly.

The model test of semisubmersible platform Veslefrikk B was carried out under both 10^{-2} and 10^{-4} annual probability weather conditions in the Ocean Basin Laboratory of MARINTEK in February 2009. It's assumed that the model test in the basin is a good estimation for the performance of the real platform in certain corresponding weather conditions.

3.1.1 Model Test Facilities

All the tests were carried out in the ocean basin of MARINTEK which has a surface area of 80m x50m and a depth adjustable from 0 to 8.7 m by means of a steel floor covering 48mx42m of the basin area. The layout and the dimension of the laboratory are shown in Fig 3.1.

The ocean basin is fitted with two sets of wave generators. Along the 50 m side there is a double-flap, hydraulically operated unit, capable of generating long-crested irregular as well as regular waves. Maximum wave height referring to regular waves is 0.9 m in the basin. And along the 80 m side there is a multi-flap unit, consisting of altogether 144 individually controlled flaps, for generating short crested as well as long crested waves. While for the model test of Veslefrikk B only the wave maker along the 50 m side was used.

The ocean basin has wave absorption beaches along both the short and the long sides, which can significantly reduce the wave reflections. Therefore, wave reflection is less than 5 per cent of the incoming waves. Due to the large basin area and the large length of the absorption beach, reflections from the model are normally negligible. A fan mounted near the model set-up position is used for generating a wind field at the test area. For the present model tests, the fans were positioned at 7.2 m in front of the model reference position. The wind velocity is measured by an anemometer at height corresponding to 22 m above the water plane at the reference position of the platform in the basin.

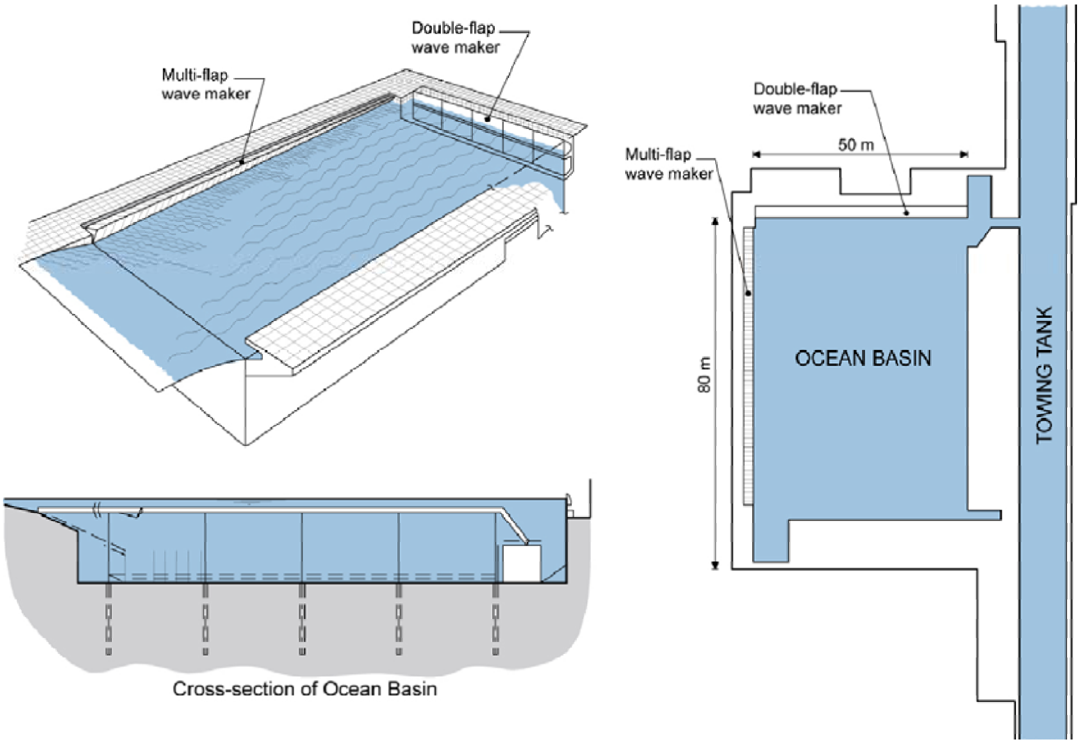

Figure 3.1 Ocean Basin of MARINTEK [6]

The irregular sea stations can be generated by the two sets of wave generators fitted along the two sides of the basin according to the Torsethaugen [6] wave spectrum illustrated by Eq 3.1 while for the case of this thesis, the irregular waves were generated only by the generator along the short side. During the tests, the model of Veslefrikk B platform was positioned in the middle of the basin with the mooring system.

$$S(\omega) = S_{swell}(\omega) + S_{windsea}(\omega) \tag{3.1}$$

3.1.2 The Veslefrikk B Model

This section is about the details of the Veslefrikk B model referred to the MARINTEK report. [6]

Model

The scale of the model is 1:50 with Veslefrikk B platform. The model was constructed according to linear scale and the principle of Froude's law which also has taken into account of the selected environmental conditions and thruster system, see Fig 3.2.

The model has two pontoons and 4 columns besides the two slender aft columns, and bracings in between just as the arrangement of the real platform Veslefrikk B. The geometry of the hull and the freeboard of the model were accurately modeled according to the initial state of the full-scale platform. The deck facilities and the topside structures were also modeled in order to obtain the representative wind forces on the model.

Besides the external form of the model is identical with the real platform, the model mass, the centre gravity and the moments of inertia of the model were ballasted and adjusted by some solid weights to be correspondent with the real platform, so as the metacentric height for the survival condition.

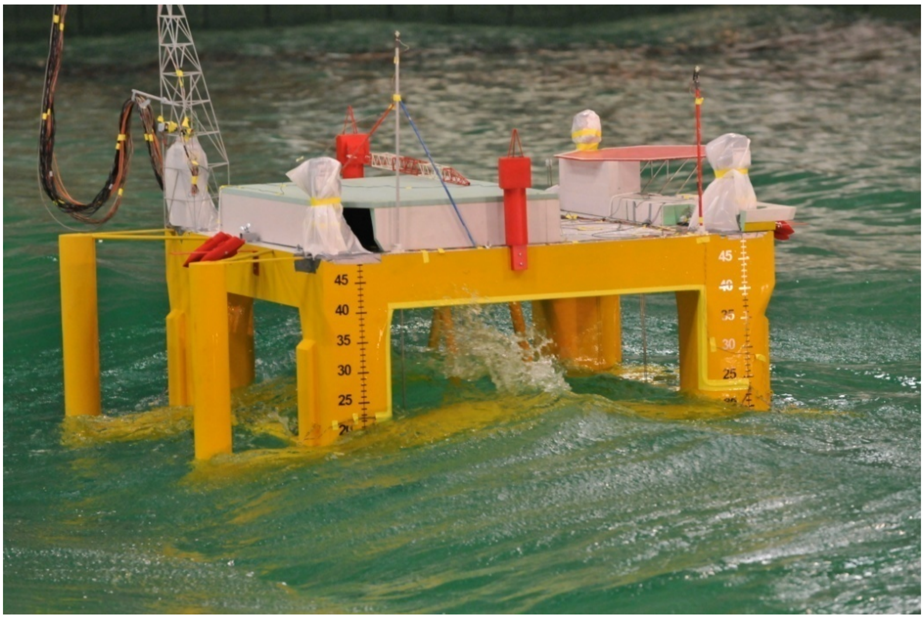

Figure 3.2 Model of the Veslefrikk B platform [6]

Mooring system

The mooring system was modeled using MIMOSA. The bottom chain segments of the lines were shortened to fit within the Ocean basin floor. Three environmental headings 0°, 45°, and 90° were specified for the model tests and the three horizontal projections of the mooring system are shown in Figure 3.3 to Figure 3.6 indicating the locations of the 12 lines. Comparisons between the full scale and 'shortened' mooring system as by calculating the restoring force curves from MIMOSA are shown in Figure 3.7. As can be seen from the curves, there is a good agreement between the two systems for the small platform offsets recorded during the wave tests. The mooring tensions were measured by the ring strain gauge transducers mounted on the model.

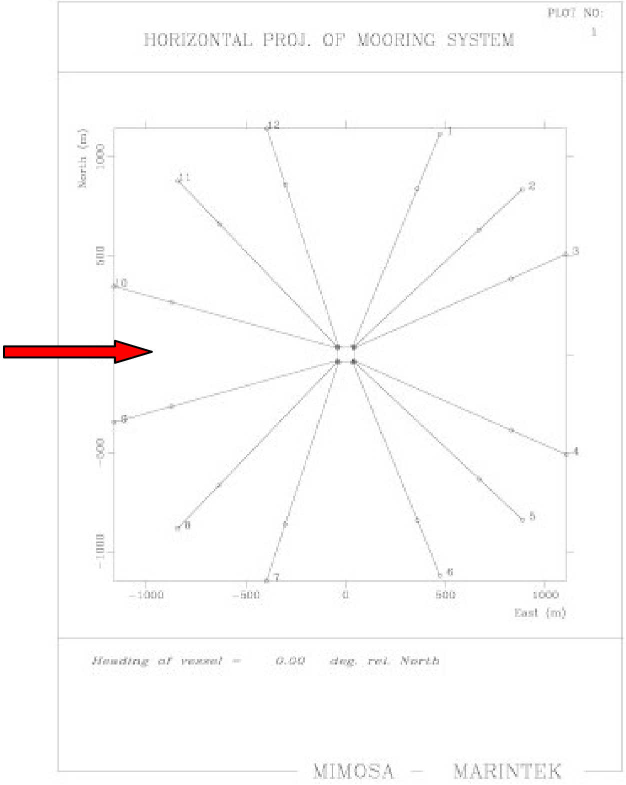

Figure 3.3: 0° heading[6] (wave direction as the red arrow)

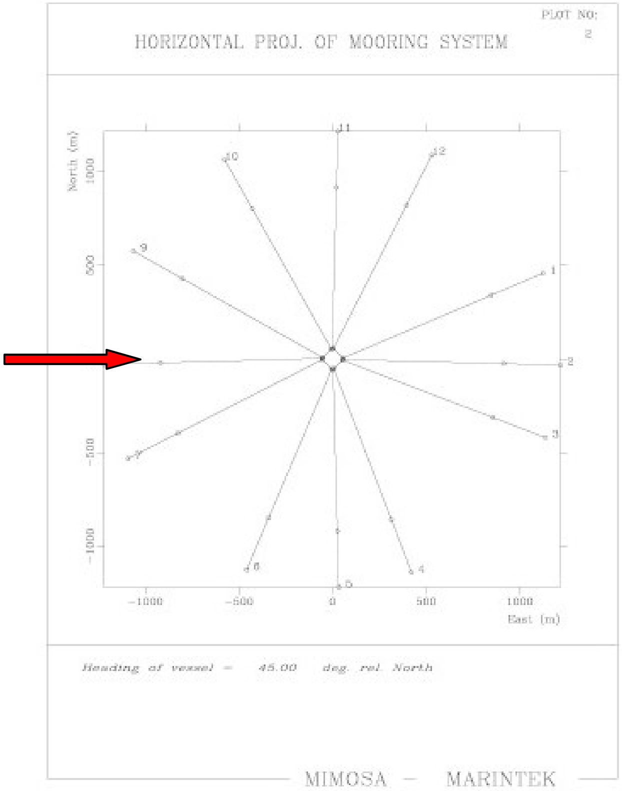

Figure 3.4: 45° heading[6] (wave direction as the red arrow)

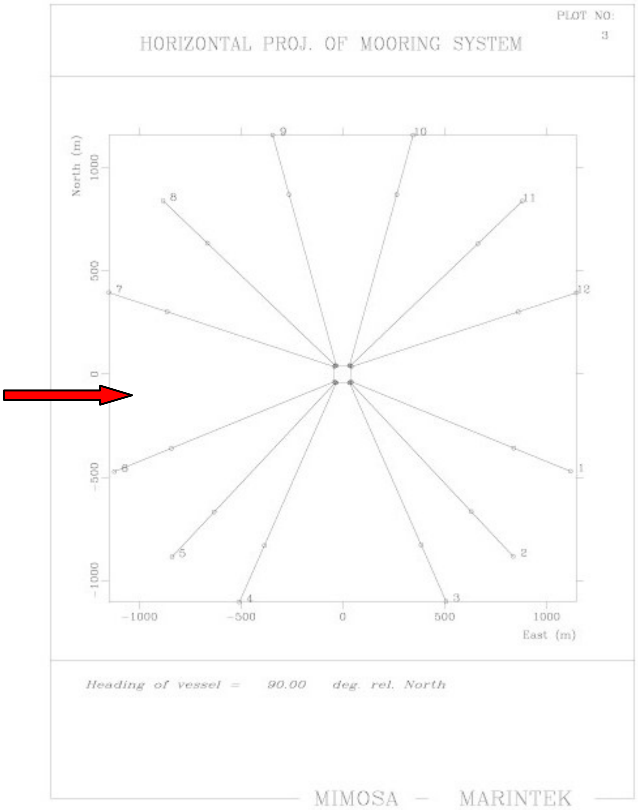

Figure 3.5: 90° heading[6] (wave direction as the red arrow)

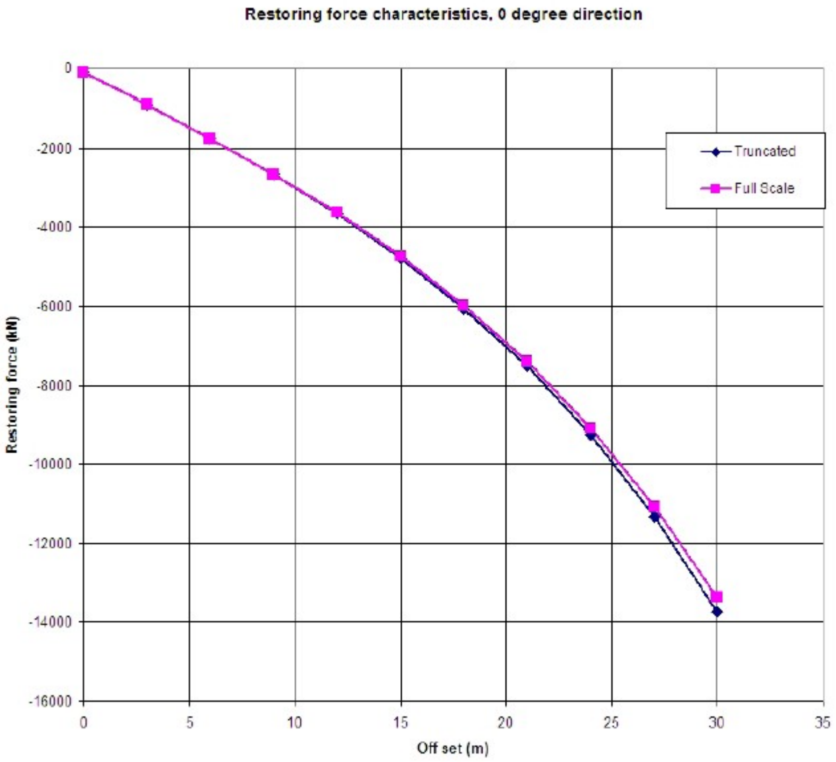

Figure 3.6: mooring restoring force curve of full scale and modeled systems [6]

Thrusters

The full-scale platform is equipped with 8 azimuth nozzle type thrusters, arranged in pairs, with 2 thrusters located near the bow and stern of each pontoon. For the model tests, each pair of thrusters was replaced by one equivalent azimuth thruster, thus applying 4 model thrusters. For the modeling, a primary goal was to obtain the correct level of damping effect on platform motions of the working thrusters. Stock model thrusters with diameter corresponding to 4.0 m were applied. The maximum open water capacity of the model thrusters corresponded to approximately 4000kN per thruster. The thrusters were calibrated before the tests in order to obtain the correct amount of thrust force to offset the wind force. The position of the model thrusters is under the centerline of each of the pontoons as shown in Figure 3.7. The direction of the thrusters was adjusted manually. The thrusters were manually rotated to different directions and fixed in position depending on the heading being tested.

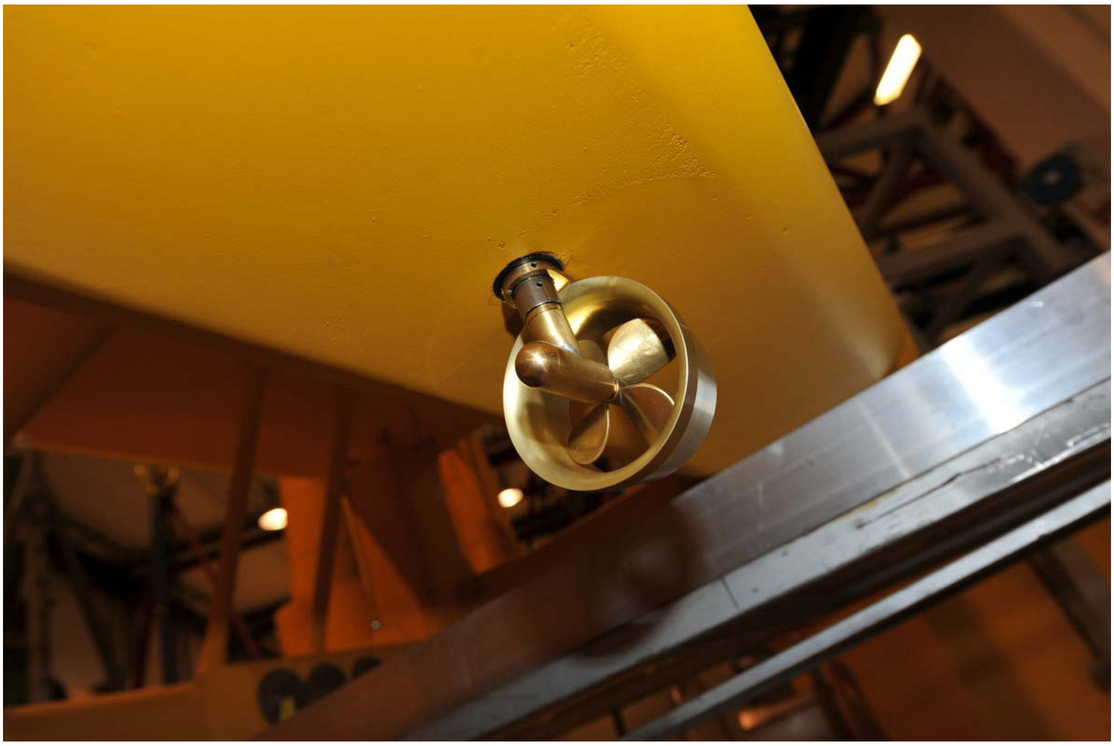

Figure 3.7 Model Thruster as mounted on the model.[6]

3.2 Numerical Simulation

For the numerical simulation, first the numerical model of Veslefrikk B platform was built in the SESAM (DNV) module GeniE. Then, loading the model into HydroD module WADAM, the frequency domain hydrostatic and hydrodynamic analysis can be carried out. After the WADAM running, the body data and the hydrodynamic parameters are written into an interface file which can be loaded into the time domain simulation module SIMO (MARINTEK). Finally, the time domain simulations for mooring line tension can be realized in the SIMO program.

3.2.1 SIMO Program

SIMO is a computer program for simulation of motions and station-keeping behavior of floating structures and suspended loads. The main features of the program includes [7]:

- Flexible modeling of multibody systems.
- Non-linear time domain simulation of wave-frequency as well as low-frequency forces.
- Environmental forces due to wind, waves and current.
- Passive and active control force.
- Interactive or batch simulation.

The program consists of five modules communicating with each other by a file system, which is shown below.

INPMOD	File system for communication between modules	Read and manipulate system description
STAMOD		Read system description, static analyses, define initial condition
DYNMOD		Dynamic analyses, generation of time series
OUTMOD		Post-processing of time series
S2XMOD		Export of time series
PLOMOD		Plotting

Figure 3.8 Modules of SIMO program

A complete dynamic analysis must run through the modules STAMOD and DYNMOD, while the post-processing or export of the results can be done alternatively by OUTMOD or S2XMOD.

3.2.2 Numerical Model

The WADAM model of Veslefrikk B platform is shown in Figure 3.9 which is the panel model represents the underwater geometry.

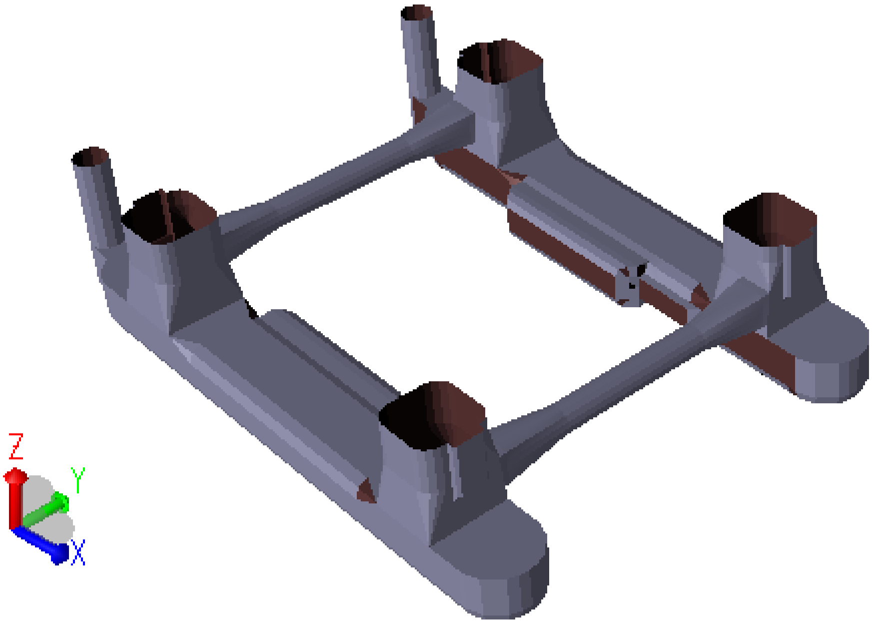

Figure 3.9 Panel model of Veslefrikk B platform

While as in the WADAM program, diffraction & radiation theory is adopted and viscous effects are neglected. It’s therefore important to establish the Morison model in order to account for the viscous damping that is of significance for some motion models. The Morrison model is shown in Figure 3.10.

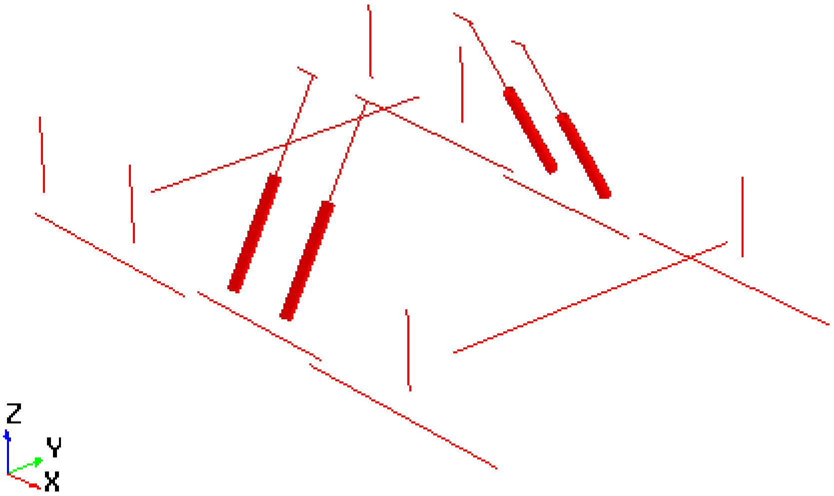

Figure 3.10 Morison model of Veslefrikk B platform

In addition to the panel model and Morison model, the mass model is also included in the WADAM model. The mass distribution of the platform is simulated in terms of the mass matrix in the mass model.

After carrying out the frequency domain analysis in WADAM program, the body information as well as the hydrostatic and hydrodynamic characteristics i.e. added mass, damping, transfer functions etc are presented in the interface file prepared for further analysis.

3.2.3 System File Introduction

Before proceeding to the STAMOD and DYNMOD to carry out the static and dynamic analysis, a system file is generated or modified in INPMOD, and this file includes all the body data specifications and the environment data specification which are needed in the following analysis. The body data specifications include the information of body mass, body locations and the motion properties i.e. added mass, damping and stiffness matrices for the six degrees of freedom, and the positioning system data, for the Veslefrikk B platform includes the mooring line system data and the thrusters data. The environmental data specification consists of wave specification and wind specification. The wave specification includes the spectrum type, significant wave height and spectral peak period, and the wind specification includes the wind gust spectrum type, the mean wind speed and some other parameters. [13]

Chapter 4

Mooring Line Tension Analysis from Model Test Data

The model test was carried out for Veslefrikk B platform in the Ocean Basin Laboratory and large amount of data was collected. Assume those data has a good estimation to the considered issues, which means the tested mooring line tensions has a good consistence with the mooring line tensions of the real platform. In this chapter, the modeled mooring line tensions in terms of 3-hour maximum for various environmental conditions will be processed and analyzed, the long term distribution of the 3-hour maximum value will be estimated and the failure probability of a single mooring line will be discussed.

4.1 Estimation of the Characteristic Mooring Line Tension

As mentioned in Section 2.3, the characteristic load for design of the mooring lines, in most cases, is the expected largest load under the 100-year environmental conditions. In the model tests of Veslefrikk B, the screening test of 100-year waves consist of four sets of 100-year irregular waves with three different heading directions, which are presented in the following table:

Sea State	Hs [m]	Tp [s]	Heading Directions [°]	No. of seeds
100-1	12.3	12.0	0，45 and 90	2
100-2	14.1	14.0	0，45 and 90	2
100-3	14.9	16.0	0，45 and 90	4
100-4	14.7	17.0	0，45 and 90	4

Table 4.1 100-year wave screening tests

The 3-hour maximum mooring line tension for every screening test can be found from the time series presented in MATLAB. For every test, there are 12 sets (one for each line) of 3-hour simulations. Then 12 maximum values will be given for every test, the largest one will be picked out for calculating the characteristic mooring line tension.

Take one simulation as an example, which is the 3-hour mooring line tension history under the 100-1 sea state with 0° heading, other environmental conditions are given as in the Marintek report.

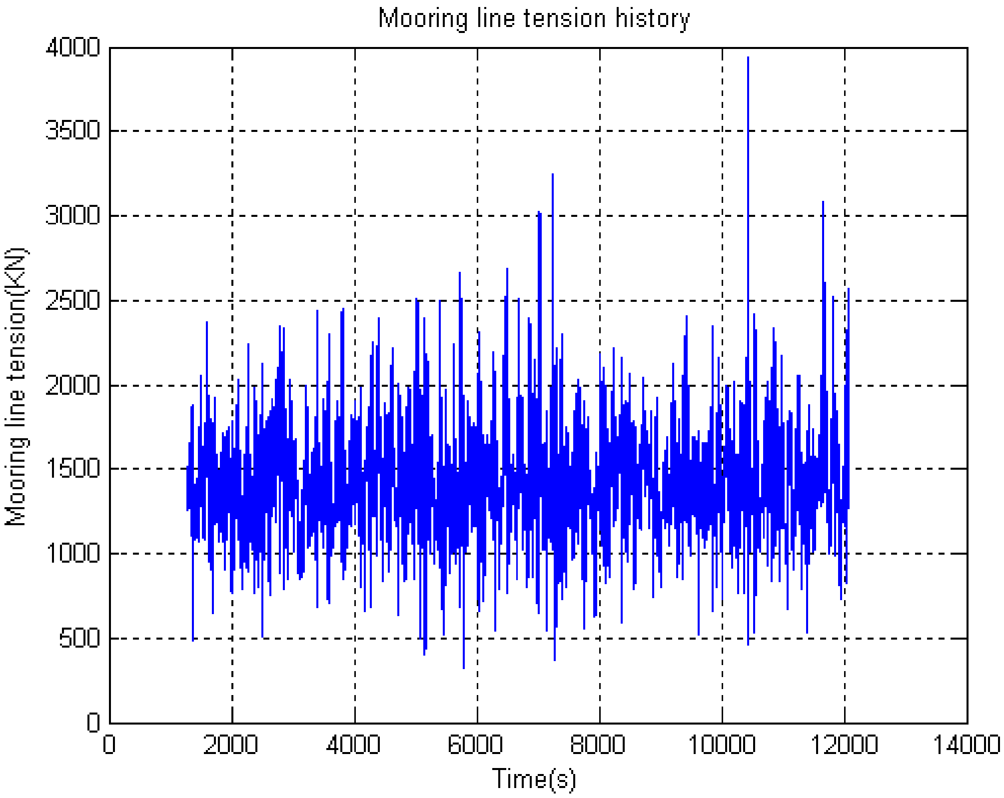

Figure 4.1 Example of 3-hour mooring line tension history

The maximum mooring line tension of a test can be checked from MATLAB, also the other 11 lines in the test. For every sea state with one heading direction, several seeding tests were carried out and the expected maximum will be estimated by the mean of the test results. Repeating the process for all the 100-year wave tests, the expected maximum value for every sea state are presented in Table 4.2, the mooring line number with maximum tension are also given.

It can be seen from the table that the largest expected maximum is observed from line 11 and 12 under the 100-3 (14,9m 16s) sea states with wave direction of 45° . Mean wind speed is 40 m/s, thruster force is 3920KN. The characteristic mooring line tension is 4229.5KN.

Test.no	Hs	Tp	Wave dir	Wind	Thruster force	Maximum mooring line tension/KN	Expected maxima/KN
2012	12.3	12	0	40	2770	3936(LINE01)	3429
2020	12.3	12	0	40	2770	2922(LINE01)	
2030	14.1	14	0	40	2770	3369(LINE01)	3623
2041	14.1	14	0	40	2770	3877(LINE12)	
2050	14.9	16	0	40	2770	3494(LINE12)	3686.5
2064	14.9	16	0	40	2770	3810(LINE01,12)	
2070	14.9	16	0	40	2770	3304(LINE01)	
2080	14.9	16	0	40	2770	4138(LINE01)	
2090	14.7	17	0	40	2770	3846(LINE01)	3867
2100	14.7	17	0	40	2770	4206(LINE01)	
2110	14.7	17	0	40	2770	4015(LINE12)	
2120	14.7	17	0	40	2770	3401(LINE01)	
2210	12.3	12	45	40	3920	3248(LINE11)	3103
2220	12.3	12	45	40	3920	2958(LINE11)	
2230	14.1	14	45	40	3920	3454(LINE11)	3629
2240	14.1	14	45	40	3920	3804(LINE11)	
2250	14.9	16	45	40	3920	4394(LINE12)	4229.5
2260	14.9	16	45	40	3920	4574(LINE11)	
2270	14.9	16	45	40	3920	3637(LINE11)	
2280	14.9	16	45	40	3920	4313(LINE11)	
2290	14.7	17	45	40	3920	4501(LINE11)	4207.75
2300	14.7	17	45	40	3920	4550(LINE11)	
2310	14.7	17	45	40	3920	4030(LINE11)	
2320	14.7	17	45	40	3920	3750(LINE11)	
2410	12.3	12	90	40	3170	4195(LINE09)	3505.5
2420	12.3	12	90	40	3170	2816(LINE09)	
2430	14.1	14	90	40	3170	3184(LINE09)	3531
2440	14.1	14	90	40	3170	3878(LINE09)	
2450	14.9	16	90	40	3170	3916(LINE09)	4038.75
2460	14.9	16	90	40	3170	4151(LINE09)	
2470	14.9	16	90	40	3170	3310(LINE09)	
2480	14.9	16	90	40	3170	4778(LINE09)	
2490	14.7	17	90	40	3170	4423(LINE09)	4004.25
2500	14.7	17	90	40	3170	4514(LINE09)	
2510	14.7	17	90	40	3170	3924(LINE09)	
2520	14.7	17	90	40	3170	3156(LINE09)	

Table 4.2 The expected largest values for all the 100-year sea states

4.2 Extreme Mooring Line Tension Prediction

Since the characteristic mooring line tension is obtained, the design breaking strength can be calculated according to Eq. (2.1). In order to avoid the ALS for the vicinity fixed platform, the annual mooring line failure probability should be smaller than 10^{-4} i.e. the breaking strength has smaller annual exceedance probability than 10^{-4}. In this section, the distribution functions for 100-year and 10000-year extreme mooring line tensions are established based on the model test results, afterwards, the annual probability distribution function of 3-hour extreme mooring line tensions are established by the estimated 100 and 10000-year extreme mooing line tensions.

The model test set up is based on the contour line method. By introducing the environmental contour line method, a limited number of costly model tests can properly predict the extreme mooring line tensions with certain exceeding probability by processing the time histories of the mooring line tensions obtained from the model tests. The main steps of contour line method are introduced below:

Screening Tests

In order to determine the sea states with worst performance for the considered issue, the so-called screening tests are carried out. The contour lines of the sea state characteristics i.e. Hs vs. Tp can be determined from the metocean data of certain fields i.e. Veslefrikk in this report. The contours corresponding to different annual exceeding probabilities are shown in Fig. 4.2.

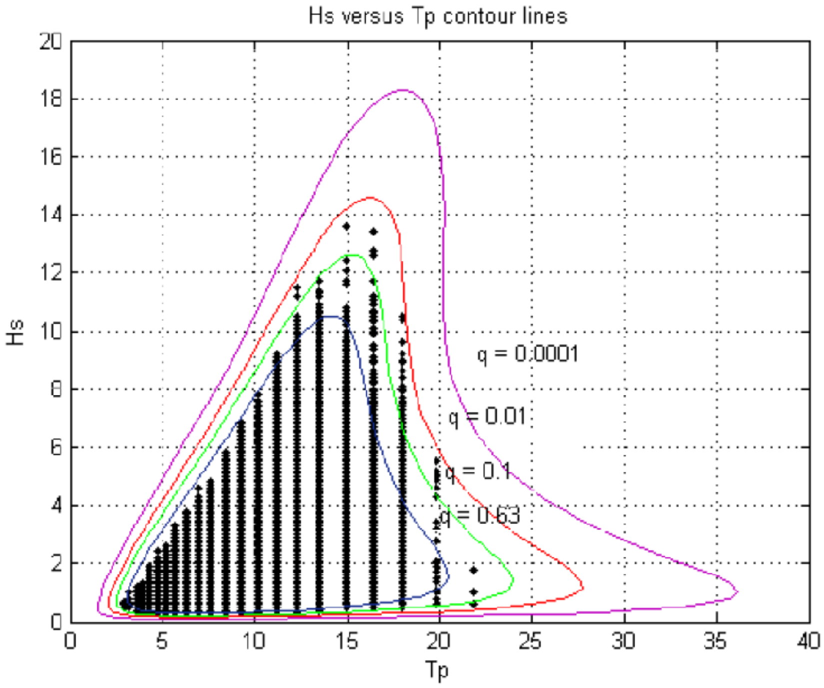

Fig. 4.2 Contour lines [8]

Certain numbers of sea states are selected from the contours as the testing sea states and from the testing results; one or two sea states will be adopted for further investigation. This selection is mainly determined from previous experience. For a semi-submersible, the experience from the previous model tests tell us that the worst sea states are almost always located at the left upper part of the contour lines. The results of the screening test will be compared with each other to determine the worst responses sea states. And both the maxima and the standard deviation of the results for every sea states will be used for the comparison because a compromise from both maxima and standard deviation will be more representative as the worst responses sea state.

Seed Tests

After the screening tests, normally two sea states are chosen and for each of them, 20 seeds will be generated as the compromise of the accuracy and the cost. In addition, this will be done with different heading directions, i.e. 0°, 45° and 90°. After the seed tests of every sea state, a set of 20 independent 3-hour maximum mooring line tensions will be given. The maxima can be fitted to Gumbel distribution.

For every sea state with a given wave direction, there are several seeding tests as well as the 3-hour maximum values. For the extreme value problem, the Gumbel distribution can be selected as the distribution function and then the 100-year and 10000-year extreme mooring tension can be estimated by the 90% values.

Gumbel distribution:

$$F_{X_{3h}}(x) = \exp\{-\exp[\frac{-(x-h)}{\beta}]\} \quad ; \qquad -\infty<x<+\infty; h>0 \tag{4.1}$$

And the moment estimation method is used to determine the two parameters.

Mean value:
$$\mu_x = h + 0.57722\beta \tag{4.2}$$

Standard deviation:
$$\sigma_x = \frac{\pi}{\sqrt{6}}\beta \tag{4.3}$$

Take a set of 3-hour maximum mooring line tensions of a mooring line as a sample, the mean value and the standard deviation are calculated, then the Gumbel distribution can be determined. Finally, as the distribution function determined, the 90% value can be calculated.

For the model tests of Veslefrikk B platform, 4 100-year sea states were tested with three directions i.e. 0, 45 and 90 degrees. For every same condition, the test was only repeated once or three times., that means when fitting the maximum mooring line tensions into a Gumbel distribution, there are only two or four objects in the sample, so, the prediction is not very accuracy compared with the prediction from a sample with large number of objects.

Sea state	Hs	Tp	Wave dir.	No. of tests	μ	σ	h	β	90%maxima
100-1	12.3	12	0	2	3429	717.01	3106.30	559.04	4364.36883
100-2	14.1	14	0	2	3623	359.21	3461.335	280.07	4091.60687
100-3	14.9	16	0	4	3686.5	366.27	3521.65	285.58	4164.320136
100-4	14.7	17	0	4	3867	343.71	3712.30	267.99	4315.393848
100-1	12.3	12	45	2	3103	205.06	3010.71	159.88	3370.511796
100-2	14.1	14	45	2	3629	247.48	3517.61	192.96	3951.859064
100-3	14.9	16	45	4	4229.5	409.78	4045.07	319.50	4764.082858
100-4	14.7	17	45	4	4207.75	384.82	4034.55	300.04	4709.766836
100-1	12.3	12	90	2	3505.5	975.10	3066.65	760.28	4777.564711
100-2	14.1	14	90	2	3531	490.73	3310.14	382.62	4171.183401
100-3	14.9	16	90	4	4038.75	606.96	3765.58	473.25	4830.570196
100-4	14.7	17	90	4	4004.25	622.13	3724.25	485.07	4815.857835

Table 4.3 Estimation of 90% maximum mooring line tensions for 100-year waves/KN

As the no. of tests is either 2 or 4, which means the sample objects number is either 2 or 4, the fitted Gumbel distribution has large uncertainty and very inaccurate, thus should not give too much attention.

For 10000-years sea states, the screening tests consist of the sea states given in Table 4.4, while as the laboratory model test was performed mainly focusing on the air-gap and slamming, then, the worst sea states with regarding to the air-gap and slamming are picked to carry out the seeding tests. The mooring line tension estimations for 10000-year sea states are given in Table 4.5.

Sea state	Hs/m	Tp/s
10000-1	14.1	12
10000-2	16.3	14
10000-3	17.9	16
10000-4	18.3	18
10000-5	17.8	19

Table 4.4 10000-year sea states of screening tests

Sea state	LINE	μ	σ	h	β	90%maxima
0°,10000-2	LINE01	4850.1	637.6159	4563.137	497.147	5681.900257
	LINE12	4845.3	570.0675	4588.737	444.4798	5588.980204
45°,10000-2	LINE11	5516	297.1461	5382.267	231.6838	5903.641178
90°10000-2	LINE09	5110	537.8689	4867.929	419.3747	5811.675585
0°,10000-4	LINE01	5595.15	673.0087	5292.258	524.7428	6473.121951
	LINE12	5664.75	607.9893	5391.12	474.0473	6457.900935
90°10000-4	LINE09	6305.45	775.3021	5956.52	604.5006	7316.868481

Table 4.5 Estimation of 90% maximum mooring line tensions for 10000- year waves

4.3 Annual Failure Probability

After the characteristic mooring line tension determined and the estimation of the maximum 100-year and 10000-year mooring tension predicted, the annual failure probability can be calculated as demonstrated in Section 2.3. In the thesis, as for study purpose, more safety factors than those in the Table 2.1 will be calculated for the intact condition.

For every wave direction, the largest predicted mooring line tensions are selected respectively for 100-year wave condition and 10000-year wave condition, take 0 degree for instance, from Table 4.3 and Table. 4.5, the predicted maximum mooring tension are 4364.4KN and 6473.1KN respectively, and the annual probabilities are 10^{-2} and 10^{-4}. Fit the two sets of mooring line tensions and annual probabilities into a Gumbel distribution, the annual probability of any mooring line tension can be determined. The parameters of the Gumbel distributions are presented in the following table for the three wave directions.

Gumbel distribution:

$$F_{X_{3h}}(x) = \exp\{-\exp[\frac{-(x-h)}{\beta}]\} \;; \quad -\infty < x < +\infty ; h > 0 \tag{4.4}$$

Dir.	Sea sta.	90%maximum	Exceedance Probability	β	h
0°	100year	4364.4	10^{-2}	457.4047	2260.27
	10000year	6473.1	10^{-4}		
45°	100year	4764.1	10^{-2}	247.1725	3627.07
	10000year	5903.6	10^{-4}		
90°	100year	4830.6	10^{-2}	539.311	2349.689
	10000year	7316.9	10^{-4}		

Table 4.6 Parameters for Gumbel distributions of annual maximum mooring line tension.

The breaking strength of an individual mooring line is:

$$t_b = \alpha * t_c \tag{4.5}$$

In the Table 2.1, the safety factors α are 1.9, 1.8 and 1.5 for different conditions, while for the study purpose, the cases for the safety factors in Table 4.7 will be investigated.

Safety factor	Mooring line breaking strength/KN (Safety factor*Characteristic mooing line tension)
1.5	6344.25
1.6	6767.2
1.7	7190.15
1.8	7613.1
1.9	8036.05
2.0	8459
2.1	8881.95
2.2	9304.9

Table 4.7 Mooring line breaking strength

For those mooing line breaking strengths, the corresponding annual failure probabilities for individual mooring line are calculated and presented in Table 4.8 to Table 4.10.

$$\text{Annual failure probability} = 1 - \text{Annual probability of } t_b \tag{4.6}$$

0° wave direction		
Safety factor	Mooring line breaking strength t_b /KN	Annual failure probability
1.5	6344.25	0.000132536
1.6	6767.2	5.25738E-05
1.7	7190.15	2.08543E-05
1.8	7613.1	8.27214E-06
1.9	8036.05	3.28124E-06
2.0	8459	1.30154E-06
2.1	8881.95	5.16271E-07
2.2	9304.9	2.04785E-07

Table 4.8 Annual failure probability for 0° wave direction case

45° wave direction		
Safety factor	Mooring line breaking strength t_b /KN	Annual failure probability
1.5	6344.25	1.6818E-5
1.6	6767.2	3.03831E-6
1.7	7190.15	5.48894E-7
1.8	7613.1	9.91617E-8
1.9	8036.05	1.79143E-8
2.0	8459	3.23635E-9
2.1	8881.95	5.8467E-10
2.2	9304.9	1.05625E-10

Table 4.9 Annual failure probability for 45° wave direction case

90° wave direction		
Safety factor	Mooring line breaking strength t_b /KN	Annual failure probability
1.5	6344.25	0.000606935
1.6	6767.2	0.000277091
1.7	7190.15	0.000126492
1.8	7613.1	5.77413E-05
1.9	8036.05	2.63573E-05
2.0	8459	1.20313E-05
2.1	8881.95	5.4919E-06
2.2	9304.9	2.50687E-06

Table 4.10 Annual failure probability for 90° wave direction case

From the results, it can be found that there are several cases with annual failure probability exceeded 10^{-4} listed in Table 4.11 which are not accepted as demonstrated in Section 2.3.

Wave dir.	Safety factor	Mooring line breaking strength t_b /KN	Annual failure probability
0 degree	1.5	6344.25	0.000132536
90 degree	1.5	6344.25	0.000606935
	1.6	6767.2	0.000277091
	1.7	7190.15	0.000126492

Table 4.11 Cases with annual failure probability exceeded 10^{-4}

It can be noticed that the annual failure probabilities of 90° wave cases are the largest compared with the 0° wave cases and 45° wave cases for the corresponding safety factors, this is because for the 0 degree waves, the cross section of the pontoons face the coming wave and the area is small as well as the wave force, while for the 90 degree waves, the longitudinal side of the pontoon faces the coming wave and the area is much larger than the cross sections, so the wave force is larger and the mooring line tensions are larger too. On the other hand, as these sea states for seeding tests are selected with regarding to the air-gap and slamming problems, they are not necessarily the worst cases for the mooring line tensions, thus we can only conclude that the 45° waves are not the worst sea states for the mooring line tensions given the data we have.

Chapter 5

Mooring Line Tension Analysis from Numerical Simulation

As introduced in Chapter 3, in addition to the model tests in the laboratory, the numerical simulation is another method for the mooring line tension investigation. And in my work, as using the time domain simulation program SIMO, the mooring line tensions of Veslefrikk B numerical model were simulated in the same environmental conditions as in the laboratory model tests. And the results will be processed by the same procedure as what has been done for the laboratory model tests results in Chapter 4.

5.1 Estimation of the Characteristic Mooring Line Tension

As the definition of characteristic mooring line tension for design in Section 2.3, the maximum mooring line tensions in every simulation of 100-year waves are collected, which are listed in the Table A1 ~ Table A12 in Appendix A. The expected maximum mooring line tensions are given in Table 5.1.

Sea state	Hs	Tp	Wave dir.	Expected maximum mooring line tension/KN
100-1	12.3	12	0	4263.0693
100-2	14.1	14	0	4682.2421
100-3	14.9	16	0	4504.0102
100-4	14.7	17	0	4486.2769
100-1	12.3	12	45	4670.6705
100-2	14.1	14	45	5102.1628
100-3	14.9	16	45	5191.786
100-4	14.7	17	45	5015.1306
100-1	12.3	12	90	4464.2789
100-2	14.1	14	90	4977.484
100-3	14.9	16	90	4743.7298
100-4	14.7	17	90	4583.3546

Table 5.1 Expected maximum mooring line tensions

From the result, it can be seen that the largest expected maximum mooring tension is appeared in the simulation case of 100-3 wave with 45 degree wave direction, which has a good coincidence with the laboratory model tests. While the amplitude of the largest expected maximum mooring tension is 5191.8KN, compared with 4229.5KN from the model tests, it's 22.8% higher.

5.2 Extreme Mooring Line Tension Prediction

After all the maximum mooring line tensions are collected, the Gumbel distribution of the extreme mooring line tensions can be fitted as the same procedure of Section 4.2, the Gumbel parameters and the predicted maximum mooring line tensions of 100-year waves and 10000-year waves are presented in the Table 5.2 and Table 5.3 respectively.

Sea state	Hs	Tp	Wave dir.	μ	σ	h	β	90%maxima
100-1	12.3	12	0	4263.06	428.535	4070.20	334.127	4822.11413
100-2	14.1	14	0	4682.24	455.660	4477.16	355.277	5276.67303
100-3	14.9	16	0	4504.01	414.163	4317.61	322.921	5044.30614
100-4	14.7	17	0	4486.27	313.002	4345.40	244.047	4894.60395
100-1	12.3	12	45	4670.67	335.550	4519.65	261.627	5108.41255
100-2	14.1	14	45	5102.16	405.667	4919.58	316.297	5631.37556
100-3	14.9	16	45	5191.78	329.028	5043.70	256.542	5621.01934
100-4	14.7	17	45	5015.13	278.317	4889.87	217.003	5378.20900
100-1	12.3	12	90	4464.27	296.428	4330.86	231.124	4850.98401
100-2	14.1	14	90	4977.48	438.743	4780.02	342.086	5549.84517
100-3	14.9	16	90	4743.73	474.251	4530.29	369.772	5362.41316
100-4	14.7	17	90	4583.35	456.643	4377.83	356.043	5179.06754

Table 5.2 Gumbel parameters and predicted maximum mooring line tensions of 100-year wave cases

Sea state	LINE	μ	σ	h	β	90%maxima
0°,10000-2	LINE01	5367.137	707.2262	5048.845	551.422	6289.746998
	LINE12	5364.337	702.2768	5048.272	547.563	6280.490019
45°,10000-2	LINE11	5787.786	596.563	5519.299	465.1383	6566.030559
90°10000-2	LINE09	5621.903	698.8958	5307.36	544.9268	6533.645541
	LINE10	5604.12	711.0785	5284.095	554.4256	6531.756109
0°,10000-4	LINE01	5424.602	678.035	5119.448	528.6618	6309.130986
	LINE12	5430.819	666.7882	5130.726	519.8927	6300.675767
90°10000-4	LINE09	5624.885	631.8641	5340.51	492.6625	6449.181655
	LINE10	5618.523	600.43	5348.296	468.1534	6401.812829

Table 5.3 Gumbel parameters and predicted maximum mooring line tensions of 10000-year wave cases

Form the results given in the two tables above, the maximum predicted extreme mooring line tensions appear in the 45 degree wave case for both the 100-year wave and 10000-year wave.

In order to compare the 3-hour extreme mooring line tensions between the model test and numerical simulation, the 10000-year sea state Hs=16.3m, Tp=14s with 0 degree heading is taken as a sample. The sample distributions are given in the following tables and they are plotted in the Figure 5.1. It can be noticed that slop of the numerical simulated mooring line tensions are a bit smaller than the model test results, which means it has smaller β parameter compared with the model tests as the Gumbel scale is:

$$-\ln(-\ln(F)) = \frac{x-h}{\beta} \tag{5.1}$$

This is because the mooring line model in SIMO works as a nonlinear springs but neglects the drag force and inertia force. [14]

Seeding no.	Mooring line tension(LINE1)/KN	Sample distribution	Gumbel scale of sample distribution
1	3572	1/21	-1.113344
2	3949	2/21	-0.855
3	4187	3/21	-0.66573
4	4232	4/21	-0.50575
5	4362	5/21	-0.361224
6	4513	6/21	-0.225351
7	4522	7/21	-0.094048
8	4562	8/21	0.0355434
9	4732	9/21	0.165703
10	4826	10/21	0.2984905
11	4887	11/21	0.4359854
12	4930	12/21	0.5805048
13	5100	13/21	0.734859
14	5104	14/21	0.9027205
15	5109	15/21	1.0892396
16	5425	16/21	1.3021969
17	5562	17/21	1.5544333
18	5640	18/21	1.8698247
19	5724	19/21	2.3017509
20	6064	20/21	3.0202265

Table 5.4 Sample distributions of model test line tensions

Seeding no.	Mooring line tension(LINE1)/KN	Sample distribution(F)	Gumbel scale of sample distribution -ln(-ln(F))
1	5205.433	1/21	-1.113344
2	4199.155	2/21	-0.855
3	4217.324	3/21	-0.66573
4	4265.436	4/21	-0.50575
5	4787.848	5/21	-0.361224
6	5038.949	6/21	-0.225351
7	5064.937	7/21	-0.094048
8	5071.745	8/21	0.0355434
9	5198.592	9/21	0.165703
10	5365.477	10/21	0.2984905
11	5484.82	11/21	0.4359854
12	5556.347	12/21	0.5805048
13	5600.321	13/21	0.734859
14	5714.652	14/21	0.9027205
15	5719.17	15/21	1.0892396
16	5722.035	16/21	1.3021969
17	5864.278	17/21	1.5544333
18	5871.187	18/21	1.8698247
19	6244.143	19/21	2.3017509
20	7150.887	20/21	3.0202265

Table 5.5 Sample distributions of numerical simulated line tensions

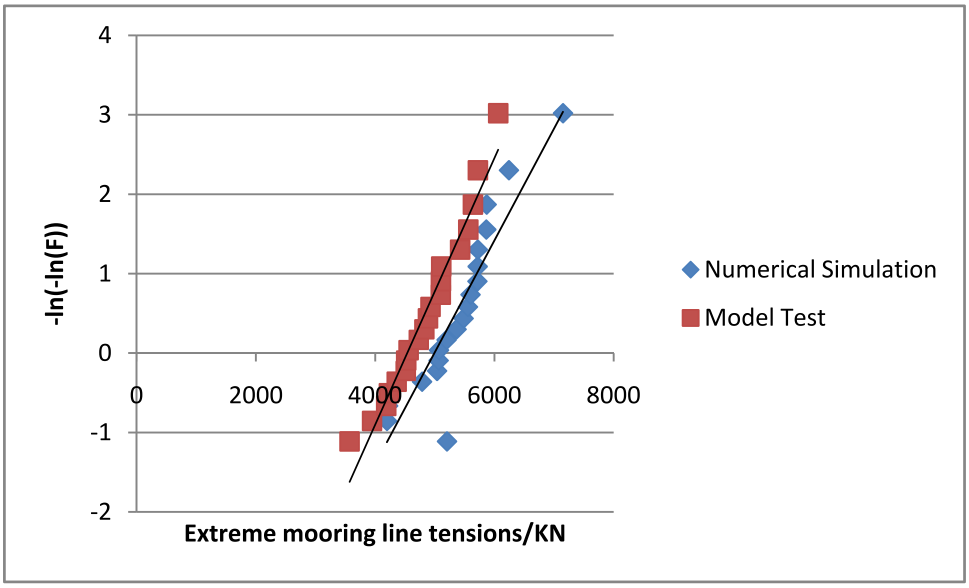

Figure 5.1 Comparison between model test and numerical simulated line tensions

5.3 Annual Failure Probability

The same analysis for the numerical prediction results were carried out with the same procedure as in the Section 4.3. The results are presented in the Table 5.6 ~ Table 5.10.

Dir.	Sea sta.	90%maximum	β	h
0°	100year	5276.6	223.9628	4246.338
	10000year	6309.1		
45°	100year	5631.4	202.727	4698.826
	10000year	6566.0		
90°	100year	5549.8	213.3991	4568.132
	10000year	6533.6		

Table 5.6 Parameters for Gumbel distributions of annual maximum mooring line tension.

Safety factor	Mooring line breaking strength/KN (Safety factor*Characteristic mooing line tension)
1.5	7787.679
1.6	8306.858
1.7	8826.036
1.8	9345.215
1.9	9864.393
2.0	10383.57
2.1	10902.75
2.2	11421.93

Table 5.7 Mooring line breaking strength

0° wave direction		
Safety factor	Mooring line breaking strength t_b /KN	Annual failure probability
1.5	7787.679	1.35786E-07
1.6	8306.858	1.33689E-08
1.7	8826.036	1.31625E-09
1.8	9345.215	1.29592E-10
1.9	9864.393	1.27591E-11
2.0	10383.57	1.25622E-12
2.1	10902.75	1.23679E-13
2.2	11421.93	1.22125E-14

Table 5.8 Annual failure probability for 0° wave direction case

45° wave direction		
Safety factor	Mooring line breaking strength tb /KN	Annual failure probability
1.5	7787.679	2.41471E-07
1.6	8306.858	1.86486E-08
1.7	8826.036	1.44023E-09
1.8	9345.215	1.11228E-10
1.9	9864.393	8.59013E-12
2.0	10383.57	6.63358E-13
2.1	10902.75	5.11813E-14
2.2	11421.93	3.9968E-15

Table 5.9 Annual failure probability for 45° wave direction case

90° wave direction		
Safety factor	Mooring line breaking strength tb /KN	Annual failure probability
1.5	7787.679	2.80421E-07
1.6	8306.858	2.46158E-08
1.7	8826.036	2.16083E-09
1.8	9345.215	1.89682E-10
1.9	9864.393	1.66507E-11
2.0	10383.57	1.46161E-12
2.1	10902.75	1.28342E-13
2.2	11421.93	1.12133E-14

Table 5.10 Annual failure probability for 90° wave direction case

From the analysis results of the numerical simulations, there is no anyone case that has the failure probability exceeding 10^{-4}, this is partly because of the conservative result of the characteristic mooring line tension for the numerical simulations.

Chapter 6

Long Term Analysis of the Extreme Mooring Line Tensions by Numerical Simulation

In the model tests, the contour line method was adopted in the extreme mooring line tension prediction for some certain exceedance probabilities. And for the design verification purpose, the long term distribution of the extreme mooring line tensions is established by carrying out a sufficient number of s-hour tome domain simulations for a sufficient number of different sea states. [9] In this chapter, the full long term analysis is carried out by numerical simulations, i.e. SIMO simulations.

6.1 Long Term Analysis of Extreme Mooring Line Tensions

For the extreme mooring line tensions, i.e. the 3-hour maximum values, the full long term distribution is established to verify the estimations corresponding to the contour line approach results. Denote the extreme mooring tension as X_{3h} in the following sections, the long term distribution of the extreme mooring line tensions is given as in Equation 6.1.

$$\begin{aligned} Q_{x_{3h}}(x) &= 1 - F_{X_{3h}}(x) \\ &= \iint\limits_{h,t} (1 - F_{X_{3h|H_sT_p}}(x|h,t) f_{H_sT_p}(h,t)) dtdh \end{aligned} \tag{6.1}$$

$F_{X_{3h|H_sT_p}}(x|h,t)$ is the conditional distribution of the 3-hour maximum mooring line tensions for the given wave characteristics. While $f_{H_sT_p}(h,t)$ is the joint distribution function of the significant wave heights and spectral peak periods, which describes the long term variation of the wave climate. After the long term distribution determined, the extreme mooring line tension corresponding to an annual exceedance probability of q can be estimated by:

$$1 - F_{x_{3h}}(x_q) = q/N \tag{6.2}$$

Where N is the number of 3-hour periods per year.

In this report, the analysis are based on the Veslefrikk B platform, and the metocean report [10] of the Veslefrikk field is available, which means the long term wave statistics are determined, as well as the joint distribution function of the significant wave heights and spectral peak periods. As indicated in Section 3.2 of Veslefrikk field Metocean Desgin Basis, the joint probability of the wave characteristics is described by the function in Equation 6.2. [10]

$$f_{H_sT_p}(h_s,t_p) = f_{H_s}(h_s)\bullet f_{T_p|H_s}(t_p|h_s) \tag{6.3}$$

In order to give a better fit to the data in the lower tail of the distribution, the long term distribution of the significant wave height is modeled as in Equation 6.3~6.4.

$$f_{H_s}(h_s) = \frac{1}{\sqrt{2\pi}\cdot\alpha\cdot h_s}\cdot\exp\left(-\frac{(\ln(h_s)-\theta)}{2\cdot\alpha^2}\right) \tag{6.4}$$

$$f_{H_s}(h_s) = \frac{\beta}{\rho}\left(\frac{h_s}{\rho}\right)^{\beta-1}\exp\left[-\left(\frac{h_s}{\rho}\right)^{\beta}\right] \tag{6.5}$$

And the conditional distribution of Hs and Tp is given as in Equation 6.6.

$$f_{T_p|H_s}(t_p|h_s) = \frac{1}{\sqrt{2\pi}\cdot\sigma\cdot t_p}\cdot\exp\left(-\frac{(\ln(t_p)-\mu)^2}{2\cdot\sigma^2}\right) \tag{6.6}$$

Where:

$$\mu = a_1 + a_2\cdot h_s^{a_3} \tag{6.7}$$

$$\sigma^2 = b_1 + b_2\cdot\exp(-b_3\cdot h_s) \tag{6.8}$$

The parameters in the equations determined in the Table 6.1 for the annual omni-directional distribution are used in the long term response analysis.

Parameter	**β**	**ρ**	**η**	**α**	**θ**	**a_1**	**a_2**	**a_3**	**b_1**	**b_2**	**b_3**
Value	1.387	2.353	4.064	0.565	0.733	1.850	0.227	0.533	0.005	0.119	0.380

Table 6.1 Parameters in the annual omni-directional joint distribution for Hs and Tp.

Since the long term wave statistics have been determined according to the Veslefrikk field Metocean Desgin Basis report, the only challenge left for the extreme mooring line tension long term distribution is the conditional distribution of the 3-hour maximum mooring line tensions for the given sea state characteristics.

6.2 Numerical Simulations for Long Term Analysis

As in the numerical method, sufficient number of 3-hour time domain simulations are carried out for large number of sea states, thus the long term distribution can be modeled with sufficient accuracy. For the mooring line tensions, the time domain simulations are carried out in the SIMO program which has introduced in the previous sections, and the sea states are chosen around the q-probability annual contour lines of the significant wave height Hs and spectral peak period Tp.

As in this report, 31 sets of sea states are tested in SIMO for the numerical model of Veslefrikk B platform. The wave heading direction is 0 degree for all the tests, and because of the symmetry of the platform, the mooring line tensions are similar in LINE01 an LINE12 and both of them are analyzed. The wind speeds are adjusted according to the different significant wave heights, the relation between the mean wind speed and the significant wave height is shown in Figure 6.1. The mean winds speeds for the tested sea states are given in Table 6.2.

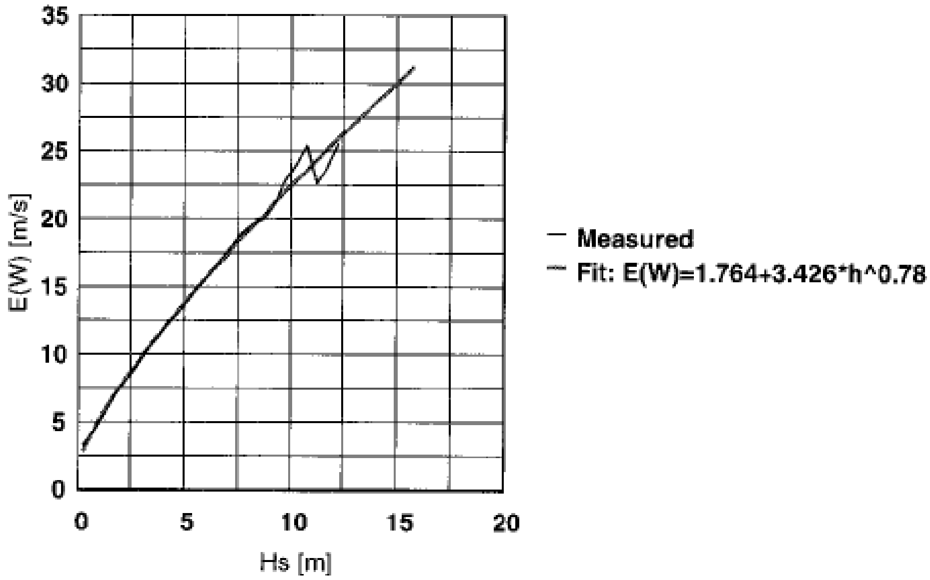

Figure 6.1 Conditional mean wind speed as a function of the significant wave height according to the measurement for Northern North sea and smooth parameterization [11].

Hs/m	Mean wind speed/(m/s)
8	19
12	26
14	29
16	32
18	34
20	37

Table 6.2 Mean wind speed for different significant wave height

As for every chosen sea states, 10 seeding 3-hour simulations are carried out and a Gumbel distribution can be fitted to the 10 maximum mooring line tensions form every seeding test, the process is described as in Section 4.2. The fitted Gumbel parameters with the corresponding sea states are listed in the Table 6.3 and 6.4 respectively for LINE01 and LINE12.

Test number	Hs/m	Tp/s	h	β
1	20	16	5516.849	598.7306
2	20	18	5163.164	396.4743
3	20	20	5500.239	772.1456
4	20	22	5606.236	483.1271
5	18	12	5781.017	934.0933
6	18	14	5085.897	752.4202
7	18	16	4572.236	448.7202
8	18	18	4404.014	302.0668
9	18	20	4435.84	597.5987
10	18	22	4672.174	307.0789
11	16	10	4672.174	307.0789
12	16	12	4699.191	742.775
13	16	14	4230.658	576.6575
14	16	16	3822.358	287.3525
15	16	20	3709.257	386.8661
16	16	24	4062.72	305.1706
17	14	12	3702.825	554.0781
18	14	14	3399.059	377.8972
19	14	16	3102.485	159.7338
20	14	20	3047.654	226.5179
21	14	24	3284.815	198.2722
22	12	9	4053.661	580.9755
23	12	11	3125.781	401.8474
24	12	13	2902.745	253.1376
25	12	15	2622.18	133.0534
26	12	18	2583.596	168.1841
27	12	22	2588.003	106.1176
28	8	7	2290.081	209.5302
29	8	11	2002.492	114.7683
30	8	16	1778.809	67.59024
31	8	21	1792.403	48.63634

Table 6.3 Fitted Gumbel parameters with the corresponding sea states of LINE01

Test number	Hs/m	Tp/s	h	β
1	20	16	5532.278	609.6699
2	20	18	5207.178	382.5988
3	20	20	5586.046	755.1018
4	20	22	5619.321	507.8037
5	18	12	5787.002	970.1927
6	18	14	5114.519	768.3053
7	18	16	4570.473	464.9039
8	18	18	4429.464	288.0534
9	18	20	4475.523	594.6363
10	18	22	4664.081	331.5212
11	16	10	4664.081	331.5212
12	16	12	4693.764	770.8647
13	16	14	4234.114	598.0458
14	16	16	3811.954	302.6307
15	16	20	3717.649	395.0786
16	16	24	4068.486	312.2896
17	14	12	3701.872	574.1874
18	14	14	3392.87	394.9099
19	14	16	3091.52	168.3747
20	14	20	3053.362	229.5009
21	14	24	3279.092	206.1241
22	12	9	4071.901	576.1314
23	12	11	3115.597	409.9951
24	12	13	2898.14	264.5475
25	12	15	2612.63	140.5887
26	12	18	2584.859	165.9005
27	12	22	2583.57	118.5178
28	8	7	2285.071	211.205
29	8	11	2002.837	111.1323
30	8	16	1773.47	66.90695
31	8	21	1790.216	48.6845

Table 6.4 Fitted Gumbel parameters with the corresponding sea states of LINE12

For the conditional distribution of the 3-hour maximum mooring line tensions for the given significant wave height and spectral peak period, it's described as Gumbel distribution given as:

$$F_{X_{3h}|H_sT_p}(x|h,t) = \exp\{-\exp[-\frac{(x-h)}{\beta}]\} \tag{6.9}$$

Where *h=h(Hs, Tp)* and *β=β(Hs, Tp)* are the Gumbel parameters. The response surfaces are established by the parameters *h=h(Hs, Tp)* and *β=β(Hs, Tp)*, and the MATLAB 4 grid data method denoted as "v4" is used to define the surfaces, the algorithm of the method is based on the theory in Sandwell[12]. Because the chosen sea states are distributed in the area of Hs range of 8~22m and Tp range of 1 ~ 30s, and the worst sea states are mostly laid in this area, so the response surfaces are only defined in the Hs range of 8~22m and Tp range of 0~30s. Take the data of LIN01 as the example, the response surfaces generated from MATLAB is shown in Fig. 6.2.

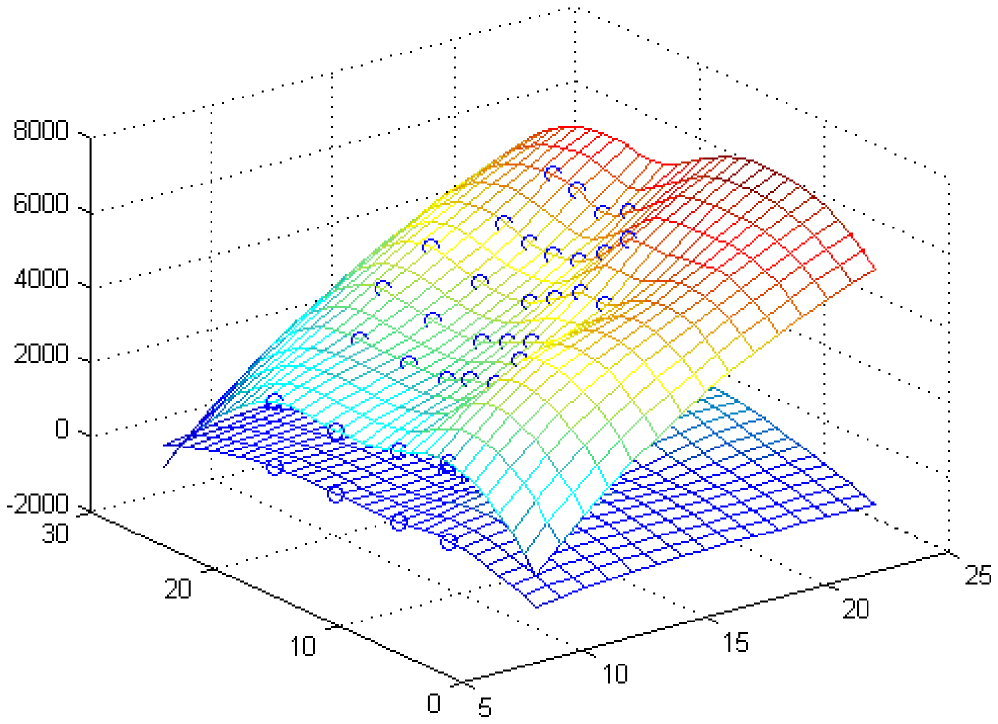

Figure 6.2 Fitted response surfaces for Gumbel parameters h and β (h - upper surface, β – lower surface)

6.3 Long Term Analysis

After both the long term wave statistics and the short term distribution of the extreme mooring line tensions for given wave characteristics are determined, the long term distribution of the extreme mooring line tensions can be established as in Eq.(6.1) and the q-probability extreme mooring line tension can be estimated. Then as in Eq. (6.2), the long term distribution function of the 3-hour extreme mooring line tension is given as:

$$\begin{aligned} Q_{3h}(x) &= 1 - F_{X_{3h}}(x) \\ &= \iint\limits_{h,t} (1 - F_{X_{3h}|H_sT_p}(x|h,t)) f_{H_sT_p}(h,t)dtdh \end{aligned} \tag{6.10}$$

The significant wave height ranges from 8 to 22m and the spectral peak period ranges from 0 to 30, while for the significant wave height lower than 8m, if the target 3-hour extreme mooring line tension is larger than some certain value, denote as X_0, (assume that the critical extreme mooring line tensions i.e. the 100-year extreme value and 10000-year extreme value are far larger than that), the short term distribution of extreme mooring line tensions for the given wave characteristics is very approaching to one.

$$\begin{aligned} Q_{3h}(x) &= 1 - F_{X_{3h}}(x) \\ &= \iint\limits_{h,t} (1 - F_{X_{3h}|H_sT_p}(x|h,t)) f_{H_sT_p}(h,t)dtdh \\ &= \int_0^8\int_0^\infty (1 - F_{X_{3h}|H_sT_p}(x|h,t)) f_{H_sT_p}(h,t)dtdh + \int_8^\infty\int_0^\infty (1 - F_{X_{3h}|H_sT_p}(x|h,t)) f_{H_sT_p}(h,t)dtdh \end{aligned}$$

As for $x_{3h} > X_0$, $F_{X_{3h}|H_sT_p}(x|h,t) \to 1$, the integral is conducted in the area with most critical sea states i.e. Hs in (8-22)m and Tp in (0-33)s, so:

$$\begin{aligned} Q_{3h}(x) &= 1 - F_{X_{3h}}(x) \\ &= \int_8^{22}\int_0^{30} (1 - F_{X_{3h}|H_sT_p}(x|h,t)) f_{H_sT_p}(h,t)dtdh \\ &= \int_8^{22}\int_0^{30} (1 - \exp\{-\exp[-\frac{x - h(H_s,T_p)}{\alpha(H_s,T_p)}]\}) \cdot f_{H_s}(h) \cdot f_{T_p|H_s}(t_p|h_s)dtdh \end{aligned} \tag{6.11}$$

The calculations are carried out in MATLAB, introduce all the parameters and response surfaces from previous sections into Eq. (6.11), and some certain extreme mooring line tensions are selected to calculate the corresponding exceedance probabilities and the results are presented in Table 6.5.

Point no.	X_{3h}	$Q_{3h}(x)$
1	3000	8.6512e-006
2	4000	2.2637e-007
3	5000	1.3519e-008
4	6000	1.4604e-009
5	7000	2.3392e-010
6	8000	5.0729e-011
7	9000	1.7716e-011
8	10000	1.1078e-011

Table 6.5 Long term exceedance probabilities of given extremes

The MATLAB codes for the response surfaces fitting and the long term distribution calculation are given in Appendix B.

From the previous procedure, the exceedance probability of certain extreme mooring line tension can be calculated directly. In order to obtain the extreme mooring line tension for the given exceedance probability, the points in Table 6.5 are fitted into a linear function equation. As the tremendously small amplitudes of the long term exceedance probabilities given in Table 6.5, the logarithms of these values i.e. $-\log_{10} Q_{3h}(X_i)$ take place the original values, which are given in Table 6.6.

Point no.	$X_{3h}/1000$	$-\mathrm{Log}_{10}Q_{3h}(x)$
1	3	5.062924
2	4	6.645181
3	5	7.869055
4	6	8.835528
5	7	9.630933
6	8	10.29474
7	9	10.75163
8	10	10.95554

Table 6.6 Logarithms of exceedance probabilities for given extremes

Given the points in Table 6.6, they are plotted in Figure 6.3, x coordinates correspond to $X_{3h}/1000$ and y coordinates correspond to $-\mathrm{Log}_{10}Q_{3h}(x)$. The long term probability of any 3-hour extreme mooring line tension can be obtained by interpolating the value in the plot.

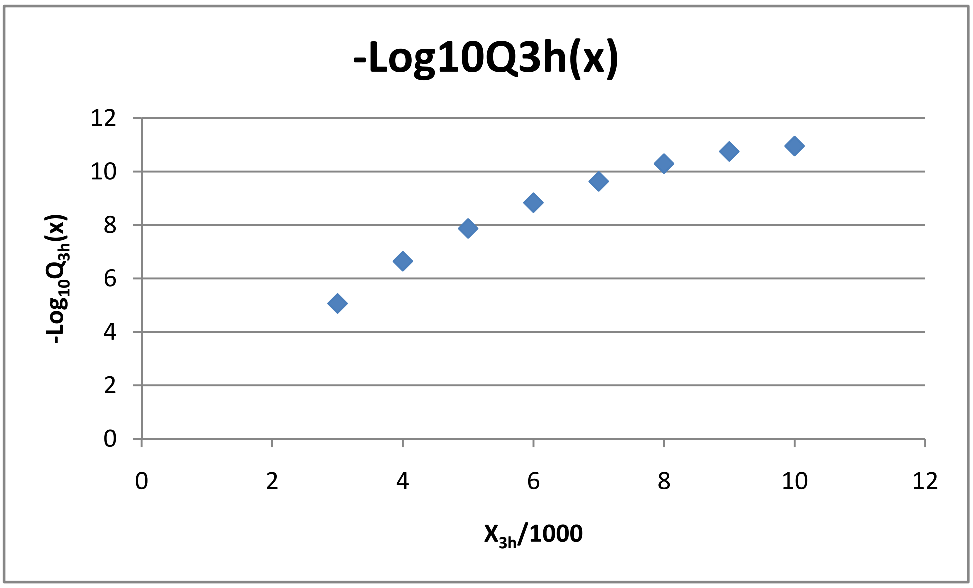

Figure 6.3 Long term distribution of 3-hour extreme mooring line tension

Therefore, for the 100-year 3-hour extreme mooring line tension X_{10}^{-2}, the exceedance probability is given as:

$$Q_{3h}(x_{10^{-2}}) = \frac{1}{N_{100}} = \frac{1}{100 \times 365 \times 8} = \frac{1}{292000} = 3.42e-6$$

$$-\log_{10} Q_{3h}(x_{10^{-2}}) = -\log_{10}(3.42e-6) = 5.47$$

Interpolate it into the plot between point 1 and point 2:

$$x = \frac{x_{10^{-2}}}{1000} = 3.258$$

Given that:

$$x_{10^{-2}} = 3.258 \times 1000 = 3258KN$$

Where N_{100} is the number of 3-hour periods in 100 years.

Correspondingly, the exceedance probability of the 10000-year 3-hour extreme mooring line tension can be obtained and interpolate both of them into the curve in

Figure 6.3, the corresponding 3-hour extreme mooring line tensions are obtained, the results are presented in Table 6.7.

Return period	Exceedance probability	3-hour extreme mooring line tension/KN
100 years	3.42e-6	3258
10000 years	3.42e-8	4678

Table 6.7 100-year and 10000-year results

According to the comparison between of the model test mooring line tensions and the numerical simulated values in Section 5.2, to modify the numerical simulations, the β Parameter is increase with 30%. The same procedure is repeated for the new β parameter.

Point no.	$X_{3h}/1000$	$-Log_{10}Q_{3h}(x)$
1	3	4.862076
2	4	6.303338
3	5	7.442048
4	6	8.367371
5	7	9.133282
6	8	9.78178
7	9	10.31742
8	10	10.70078

Table 6.8 Logarithms of exceedance probabilities for given extremes with 1.3β

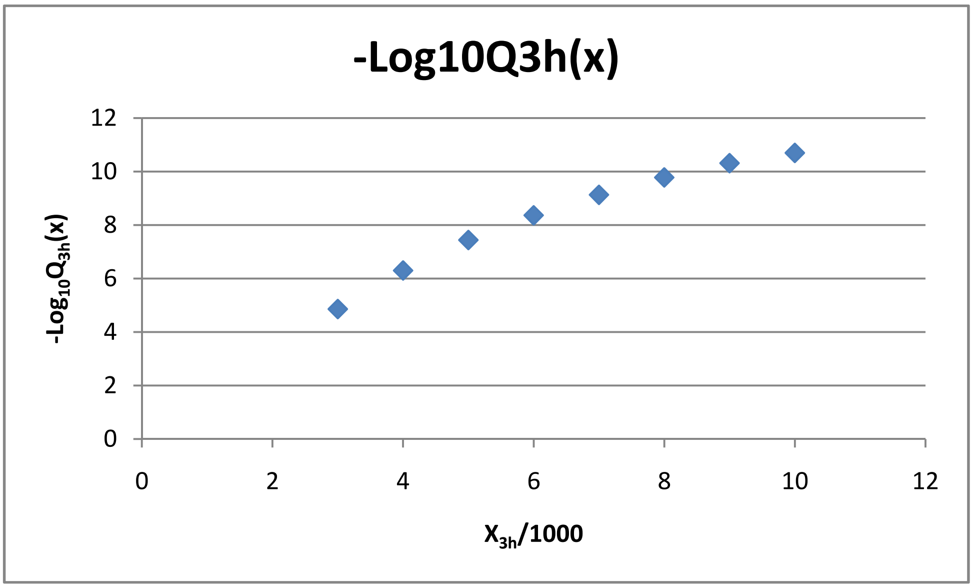

Figure 6.4 Long term distribution of 3-hour extreme mooring line tension with1.3β

Interpolate the 100-year and 10000-year long term probabilities into the plot, the 100-year and 10000-year 3-hour extreme mooring line tensions are obtained in Table 6.9.

Return period	Exceedance probability	3-hour extreme mooring line tension/KN
100 years	3.42e-6	3423
10000 years	3.42e-8	5032

Table 6.9 100-year and 10000-year results with modified β parameter

As in the previous chapters, the 90% maximum value is used to estimate the extreme value for the given Gumbel distributions. In order to investigate the accuracy of the 90% maxima as estimation, the long term estimations i.e. the 100-year and 10000-year long term extreme mooring line tensions are matched back to the Gumbel distributions of the worst sea states. The process is demonstrated below.

The Gumbel parameters as function of Hs and Tp are determined, i.e. the response surface in Figure. 6.2, the 90% extreme mooring line tensions can be calculated for the screening test sea states which are listed in Table 6.10, which are also the sea states along the dangerous part of the contours.

Sea state	Hs/m	Tp/s
100-1	12.3	12
100-2	14.1	14
100-3	14.9	16
100-4	14.7	17
10000-1	14.1	12
10000-2	16.3	14
10000-3	17.9	16
10000-4	18.3	18
10000-5	17.8	19

Table 6.10 Sea states along the dangerous part of the 100 and 10000-year contours

From the response surfaces, the Gumbel parameters can be obtained and given in Table 6.11.

Sea state	h	β
100-1	2971	330
100-2	3399	378
100-3	3452	220
100-4	3363	186
10000-1	3703	554
10000-2	4231	577
10000-3	4572	449
10000-4	4404	302
10000-5	4393	465

Table 6.11 Gumbel parameters of the dangerous sea states

Estimate the 90% maximum mooring line tensions for these sea states respectively according to Gumbel distribution:

$$\exp(-\exp(-\frac{X_{90\%}-h}{\beta}))=90\%$$

$$X_{90\%}=h-\beta\cdot\ln(-\ln(90\%))$$

Thus the estimated 90% maximum mooring line tensions for the given sea states are presented in Table 6.12.

Sea state	90% maximum mooring line tension/KN
100-1	3713.621
100-2	4249.639
100-3	3947.081
100-4	3781.568
10000-1	4007.703
10000-2	4400.462
10000-3	5582.415
10000-4	5083.611
10000-5	5439.421

Table 6.12 90% maximum mooring line tensions for the dangerous sea states

From the results, it can be concluded that the worst sea states are 100-2 and 10000-3 for the 100-year and 10000-year sea states respectively.

Sea states	Hs/m	Tp/s	h	β
100-2	14.1	14	3399	378
10000-3	17.9	16	4572	449

Table 6.13 Worst sea states with regarding to the 90% maximum mooring line tension

Interpolate the estimated long term 100-year and 10000-year extreme line tensions in table 6.7 into the Gumbel distributions of the worst sea states, the Gumbel probabilities of these values can be obtained in Table 6.14.

Sea states	Long term 3-hour extreme mooring line tension/KN	Gumbel probabilities for the long term extremes
100-2	3258	23%
10000-3	4678	45%

Table 6.14 Percentile used to matching the long term estimations for 100-year and10000-year sea states

For the case with β parameter increased 30%, the percentiles are modified in Table 6.15. Here it need to clear that not only the long term extreme mooring line tension estimations are calculated by the modified β parameter, but also the worst sea states are determined according to the modified β parameter. The new percentiles are given in Table 6.15.

Sea states	Long term 3-hour extreme mooring line tension/KN	Gumbel probabilities for the long term extremes
100-2	3258	39%
10000-3	4678	70%

Table 6.15 Percentile used to matching the long term estimations for 100-year and10000-year sea states (Modified β parameter.)

Compare to the 90%, the given percentiles in Table 6.14 and Table 6.15 are far smaller that it, while this is partly because the inadequacy of 100-year data causes the accuracy of the calculation, but also can conclude that the 90% is a conservative percentile for the design process.

Chapter 7

Summary and Conclusion

The work of this Master Thesis has looked into the mooring line tensions of a semi-submersible, while the demonstration and calculation are based on the Veslefrikk B platform which has been tested in the MARINTEK ocean basin and simulated in the computer program SIMO respectively. The mooring line tension is simulated and analyzed with regarding to the model test and numerical simulations and the main work of the thesis is carrying out the stochastic analysis of the mooring line tensions. In this chapter, all the analysis has been done in the previous chapters will be summarized and conclusions will be given.

7.1 Annual Failure Probability of Mooring Line Tension

Firstly, the methods of mooring line tension simulations are introduced, in this thesis, include the model test and numerical simulation. For the model test method, the platform and the mooring system are built with scale of 1:50 with the real platform. The environmental conditions including the waves, wind are also simulated by the facilities in the MARINK ocean basin. The screening tests and seeding tests i.e. the 3-hour simulations were performed for both 100-year and 10000-year environmental conditions, mooring line tension data were collected. The characteristic mooring line tension was calculated based on the 100-year mooring line tensions, i.e. 4229.5KN. Design strength of the mooring line can be calculated by characteristic mooring line tension multiplied by safety factors in Table 2.1. Afterwards, the annual failure probabilities of regarding to 100-year and 10000-year sea states were determined, the results are given in Table 4.11 of Section 4.3. For the numerical simulations, i.e. the SIMO program simulated data, the same procedure was carried out and the results are presented in Section 5.3.

7.2 Long Term Analysis of Mooring Line Tension

The long term analysis is carried out by numerical simulations. In the SIMO program, mooring line tensions are simulated with large number of sea states in the critical area of Hs and Tp, i.e. in the 10^{-4} contour area. By processing the data, the Gumbel parameters as function of Hs and Tp were determined, i.e. the response surfaces in Figure 6.2. Combining with the long term wave statistics given in the metocean report

[10], long term probability for given mooring line tension can be calculated, which is shown in Table 6.5. Plotting these points with Gumbel scale in Figure 6.3, then the extreme mooring line tensions can be extrapolated from the plot for the given probabilities, the 100-year and 10000-year long term extreme mooring line tensions are determined in Table 6.7. While given the comparison results between model tests data and numerical simulated data in Section 5.2, β parameter is modified by increasing 30% and the same calculation is conducted, the results are given in Table 6.9. Lastly, the percentile used to estimate the extreme mooring line tension in Gumbel distribution is investigated, by matching the 100-year and 10000-year long term extreme line tensions back to the Gumbel distributions of the worst sea states, the new percentiles are determined and given in Table 6.14 and Table 6.15 respectively for original β parameter and modified β parameter.

Appendix A

The characteristic load t_c for the design of mooring lines (the expected largest mooring line load in the 100year weather condition), KN:

100-1, Hs=12.3, Tp=12, Wave dir.=0, Thruster force=2770KN:

Test no.	Maximum mooring line tension/KN
1	3928.4385(LINE01)
2	4302.5342(LINE12)
3	3888.3884(LINE12)
4	4182.833(LINE12)
5	4066.5916(LINE01)
6	4106.0552(LINE12)
7	4292.7017(LINE12)
8	5373.8047(LINE12)
9	4028.0171(LINE01)
10	4461.3286(LINE12)
Expected largest/KN	4263.0693

Table A1 Maximum mooring tensions and the expected value

100-2, Hs=14.1, Tp=14, Wave dir.=0, Thruster force=2770KN:

Test no.	Maximum mooring line tension/KN
1	4272.186(LINE01)
2	4878.7202(LINE12)
3	4224.9717(LINE12)
4	4350.2349(LINE01)
5	4726.02(LINE01)
6	4781.2578(LINE01)
7	4319.0894(LINE12)
8	5767.9746(LINE12)
9	4824.1201(LINE01)
10	4677.8467(LINE12)
Expected largest/KN	4682.2421

Table A2 Maximum mooring tensions and the expected value

100-3 Hs=14.9, Tp=16, Wave dir.=0, Thruster force=2770KN:

Test no.	Maximum mooring line tension/KN
1	3926.1895(LINE12)
2	4855.2554(LINE12)
3	4376.5923(LINE12)
4	4267.6841(LINE12)
5	4083.3169(LINE12)
6	4277.8169(LINE01)
7	4434.2344(LINE12)
8	5068.5166(LINE12)
9	4569.3638(LINE01)
10	5181.1318(LINE12)
Expected largest/KN	4504.0102

Table A3 Maximum mooring tensions and the expected value

100-4, Hs=14.7, Tp=17, Wave dir.=0, Thruster force=2770KN:

Test no.	Maximum mooring line tension/KN
1	4248.3594(LINE12)
2	4768.4292(LINE01)
3	4921.8149(LINE01)
4	4368.5273(LINE12)
5	3937.4966(LINE12)
6	4571.7666(LINE12)
7	4386.8257(LINE12)
8	4352.3555(LINE01)
9	4380.0298(LINE01)
10	4927.1641(LINE12)
Expected largest/KN	4486.2769

Table A4 Maximum mooring tensions and the expected value

100-1, Hs=12.3, Tp=12, Wave dir.=45, Thruster force=3920KN:

Test no.	Maximum mooring line tension/KN
1	4338.1621(LINE11)
2	5161.5938(LINE11)
3	4769.8794(LINE11)
4	4990.7422(LINE11)
5	4283.1079(LINE11)
6	4794.8965(LINE11)
7	4128.2485(LINE11)
8	4536.8672(LINE11)
9	4907.541(LINE11)
10	4795.6665(LINE11)
Expected largest/KN	4670.6705

Table A5 Maximum mooring tensions and the expected value

100-2, Hs=14.1, Tp=14, Wave dir.=45, Thruster force=3920KN:

Test no.	Maximum mooring line tension/KN
1	4642.0093(LINE11)
2	5153.0405(LINE11)
3	4768.3501(LINE11)
4	5097.9829(LINE11)
5	4806.3877(LINE11)
6	5168.8721(LINE11)
7	4600.7495(LINE11)
8	5570.4268(LINE11)
9	5402.9805(LINE11)
10	5810.8286(LINE11)
Expected largest/KN	5102.1628

Table A6 Maximum mooring tensions and the expected value

100-3, Hs=14.9, Tp=16, Wave dir.=45, Thruster force=3920KN:

Test no.	Maximum mooring line tension/KN
1	4701.8145(LINE11)
2	5354.2432(LINE11)
3	5293.4219(LINE11)
4	5345.5127(LINE11)
5	4664.8257(LINE11)
6	5507.271(LINE11)
7	4930.0781(LINE11)
8	5080.8828(LINE11)
9	5502.8916(LINE11)
10	5536.9185(LINE11)
Expected largest/KN	5191.786

Table A7 Maximum mooring tensions and the expected value

100-4, Hs=14.7, Tp=17, Wave dir.=45, Thruster force=3920KN:

Test no.	Maximum mooring line tension/KN
1	4753.3921(LINE11)
2	5408.1826(LINE11)
3	5454.5957(LINE11)
4	5308.3208(LINE11)
5	4828.9785(LINE11)
6	4986.1245(LINE11)
7	4685.8462(LINE11)
8	4852.6567(LINE11)
9	4857.8457(LINE11)
10	5015.3633(LINE11)
Expected largest/KN	5015.1306

Table A8 Maximum mooring tensions and the expected value

100-1, Hs=12.3, Tp=12, Wave dir.=90, Thruster force=3170KN:

Test no.	Maximum mooring line tension/KN
1	4130.353(LINE09)
2	4659.189(LINE10)
3	4668.1147(LINE09)
4	4821.8359(LINE10)
5	4291.9907(LINE10)
6	4608.1499(LINE09)
7	4639.8638(LINE10)
8	4698.981(LINE09)
9	3983.9487(LINE09)
10	4140.3623(LINE09)
Expected largest/KN	4464.2789

Table A9 Maximum mooring tensions and the expected value

100-2, Hs=14.1, Tp=14, Wave dir.=90, Thruster force=3170KN:

Test no.	Maximum mooring line tension/KN
1	4455.4321(LINE10)
2	5179.9819(LINE09)
3	5264.9243(LINE10)
4	5050.5225(LINE09)
5	4430.4038(LINE10)
6	5175.3857(LINE09)
7	5043.2534(LINE10)
8	5689.1802(LINE09)
9	4311.8442(LINE09)
10	5173.9116(LINE09)
Expected largest/KN	4977.484

Table A10 Maximum mooring tensions and the expected value

100-3, Hs=14.9, Tp=16, Wave dir.=90, Thruster force=3170KN:

Test no.	Maximum mooring line tension/KN
1	4370.8032(LINE09)
2	5205.1455(LINE09)
3	5494.1484(LINE10)
4	4211.5293(LINE10)
5	4418.0161(LINE09)
6	5385.353(LINE09)
7	4601.0796(LINE10)
8	4907.9849(LINE09)
9	4258.4092(LINE09)
10	4584.8291(LINE09)
Expected largest/KN	4743.7298

Table A11 Maximum mooring tensions and the expected value

100-4, Hs=14.7, Tp=17, Wave dir.=90, Thruster force=3170KN:

Test no.	Maximum mooring line tension/KN
1	4366.5962(LINE09)
2	4924.1104(LINE09)
3	5269.9111(LINE10)
4	4051.6477(LINE10)
5	4319.8359(LINE09)
6	5213.9321(LINE10)
7	4478.3579(LINE10)
8	4890.9629(LINE09)
9	4043.2747(LINE09)
10	4274.917(LINE09)
Expected largest/KN	4583.3546

Table A12 Maximum mooring tensions and the expected value

Appendix B

The MATLAB codes for the response surfaces fitting and the long term distribution calculation:

```
clc;
close all;
clear all;

Hs=[20 20 20 20 18 18 18 18 18 18 16 16 16 16 16 16 14 14 14 14 14 12 12
12 12 12 12 8 8 8 8];
Tp=[16 18 20 22 12 14 16 18 20 22 10 12 14 16 20 24 12 14 16 20 24 9 11
13 15 18 22 7 11 16 21];
h=[5516.849 5163.164    5500.239    5606.236    5781.017    5085.897
4572.236    4404.014    4435.84 4672.174    4672.174    4699.191
4230.658    3822.358    3709.257    4062.72 3702.825    3399.059
3102.485    3047.654    3284.815    4053.661    3125.781    2902.745
2622.18 2583.596    2588.003    2290.081    2002.492    1778.809
1792.403];
beta=[598.7306  396.4743    772.1456    483.1271    934.0933    752.4202
448.7202    302.0668    597.5987    307.0789    307.0789    742.775
576.6575    287.3525    386.8661    305.1706    554.0781    377.8972
159.7338    226.5179    198.2722    580.9755    401.8474    253.1376
133.0534    168.1841    106.1176    209.5302    114.7683    67.59024
48.63634];

t1=8:1:22;
t2=1:1:30;
[XI,YI] = meshgrid(t1,t2);
H = griddata(Hs,Tp,h,XI,YI,'v4');
mesh(XI,YI,H), hold on
plot3(Hs,Tp,h,'o'), hold on

[XII,YII] = meshgrid(t1,t2);
BETA = griddata(Hs,Tp,beta,XII,YII,'v4');
mesh(XII,YII,BETA), hold on
plot3(Hs,Tp,beta,'o'), hold off

Sum=0;

for i=1:30
```

```
    for j=1:15

Q(i,j)=(1-exp(-exp(-(10000-H(i,j))/BETA(i,j))))*(1.387/2.353)*((j+7)/
2.353)^0.387*exp(-((j+7)/2.353)^1.387)*(1/(0.565*(2*pi)^0.5*i))*exp(-
((log(i)-(1.85+0.227*(j+7)^0.533))^2/(2*(0.005+0.119*exp(-0.38*(j+7))
))));
        Sum=Sum+Q(i,j);
    end
end
```

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