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Abstract:

The focus of this master thesis is the estimation of annual probability of mooring line failure as a function of safety factors. It's a continuation of the work completed by the author in TMR4520 Marine Hydrodynamics, Specialization Project in the fall of 2010.
At first, the reader is given an introduction to which rules and regulations apply for the design of mooring lines for marine installations under Norwegian jurisdiction. Next, a discussion of how to estimate the annual probability of line failure is presented. At last, the annual probability of line failure is estimated by first using model test results and later by using results from the computer program SIMO. The annual probability of line failure will in both cases be investigated for the Midgard platform.

Keyword:

Annual probability of mooring line failure
Mooring lines safety factors

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Summary

In Chapter 2, the procedure for designing a mooring line under Norwegian jurisdiction is discussed. The procedure is given by the Norwegian Maritime Directorate through the **ANCHORING REGULATION 09** and **ISO 19901-7 (2005)**. The difference in the required safety factors and the environment return period between **ISO 19901-7 (2005)** Annex B and the **ANCHORING REGULATION 09** has been evaluated. The effect of this difference on the annual probability of mooring line failure is investigated Chapter 4.

In Chapter 3, two ways of estimating the annual probability of mooring line failure is discussed. One of them is the environmental line contour method. The method is used for the probability estimates performed in the following chapters of the report.

In Chapter 4, the annual probability of mooring line failure is estimated based on model test results for the Midgard platform model.

In Chapter 5, SIMO is used to analyze the line tensions of the Midgard platform. From the line tensions found by SIMO, the annual probability of mooring line failure is estimated for various safety factors. The results are compared with the results found in Chapter 4. The chapter also discusses the joint occurrence of environmental storm values.

In Chapter 6, the effect of water depth on the annual probability of mooring line failure is discussed by using SIMO.

Chapter 7 addresses problems raised while working on the previous chapters;

The determination of the sea state which produces the largest line tensions is further discussed after first raising the topic in Chapter 2.

The effect of changing the 90 % fractiles used in the environmental contour line method for deciding the annual probability of mooring line failure is investigated by using the model test results.

The effect of changing the wave heading on the annual probability estimates is investigated by using SIMO after not having enough model test results of the worst sea sate in Chapter 4.

The SIMO results found in Chapter 5 for 100 year environment are not a match to the results found in Chapter 4. The increase in values found by increasing the return period to 10 000 years is also not a match. The last discussion of chapter 7 is therefore the effect of the lack of matching increase.

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Abbreviations

ALS	Accidental Limit State
AR09	The Anchoring Regulation 09
ISO	International Organization for Standardization
MARINTEK	Norwegian Marine Technology Research Institute
MFP	Minimum Flow Project
N/A	Not applicable
NMD	Norwegian Maritime Directorate
ULS	Ultimate Limit State
WSP	Wind Speed

Symbols and notations

Hs	Significant wave height	m
Tp	Peak period	s
s	Safety factor	-
t_c	Characteristic line load/tension	N
t_b	Line breaking load/tension	N
n	Set value denoting a sea state's duration	h
P_f	Annual probability of line failure	-
S(f)	Spectral density at frequency f	m^2s^{-1}/Hz
f	Frequency	Hz
U	Wind speed	m/s
z	Water depth	m
q	probability	-
T_{3h}	3 hour maximum line load	kN
T_1	Annual maximum line load	kN
N	Number of 3 hour periods in a year (2920)	-
F_{T3h}	Long term distribution of T_{3h}	-
F_{T1}	Long term distribution of T_1	-
α	Gumbel parameter	-
β	Gumbel parameter	-

1. Introduction

1.1.Objective

The focus of this master thesis is the estimation of annual probability of mooring line failure as a function of safety factors. It's a continuation of the work completed by the author in TMR4520 Marine Hydrodynamics, Specialization Project in the fall of 2010.

At first, the reader is given an introduction to which rules and regulations apply for the design of mooring lines for marine installations under Norwegian jurisdiction. Next, a discussion of how to estimate the annual probability of mooring line failure is presented. At last, the annual probability of line failure is estimated by first using model test results and later by using results from the computer program SIMO. The annual probability of line failure will in both cases be investigated for the Midgard platform presented below (see sub-chapter 1.3).

The description of the thesis is attached to this report (see Appendix A). To solve the problem raised in the topic of this report, the numbered tasks given in the thesis description will be answered.

1.2.Comments

Text printed in italic indicates that the information is a quotation. A reference number will be indicated where the quotation is taken from. A complete reference list can be found at page 73.

Text is printed in bold letters indicates the name of a book or a report.

1.3.Background

The Midgard field

According to Statoil, ref. (1), Saga Petroleum discovered the Midgard field in 1981. Today it is a part of the Åsgard field, situated on the Halten Bank in the Norwegian Sea about 200 kilometers off mid-Norway (see Figure 1).

Figure 1 Location of the Åsgard field, ref. (1)

Statoil pursued different options to find the optimal solution for producing gas at the Midgard field. One option was a semi-submersible platform named Midgard. There were model test performed with the platform. The test results will be used in this master thesis.

The platform has not been built in full scale.

The Midgard Platform Model

The Midgard platform is a semi-submersible platform with 6 risers and 14 mooring lines. It's designed to operate at 263 m water depth, ref. (2). The model of the platform is shown in Figure 2. The layout of the mooring lines and risers can be seen in Figure 3 and Figure 4.

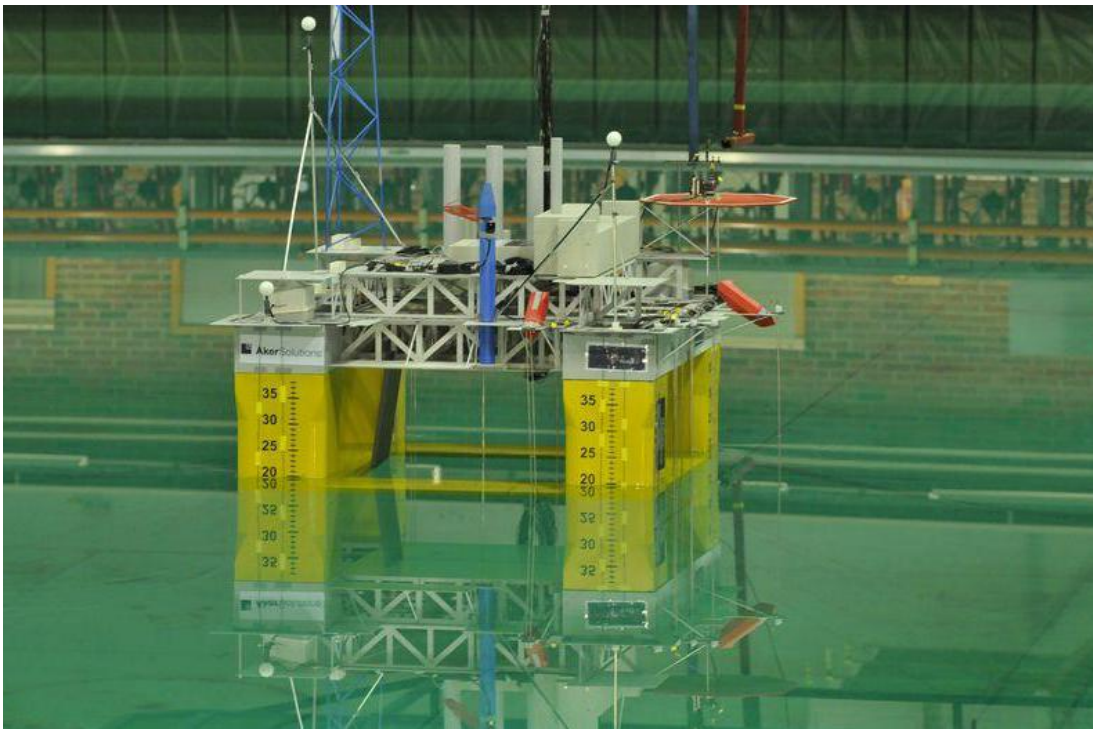

Figure 2 Midgard platform model, ref. (2)

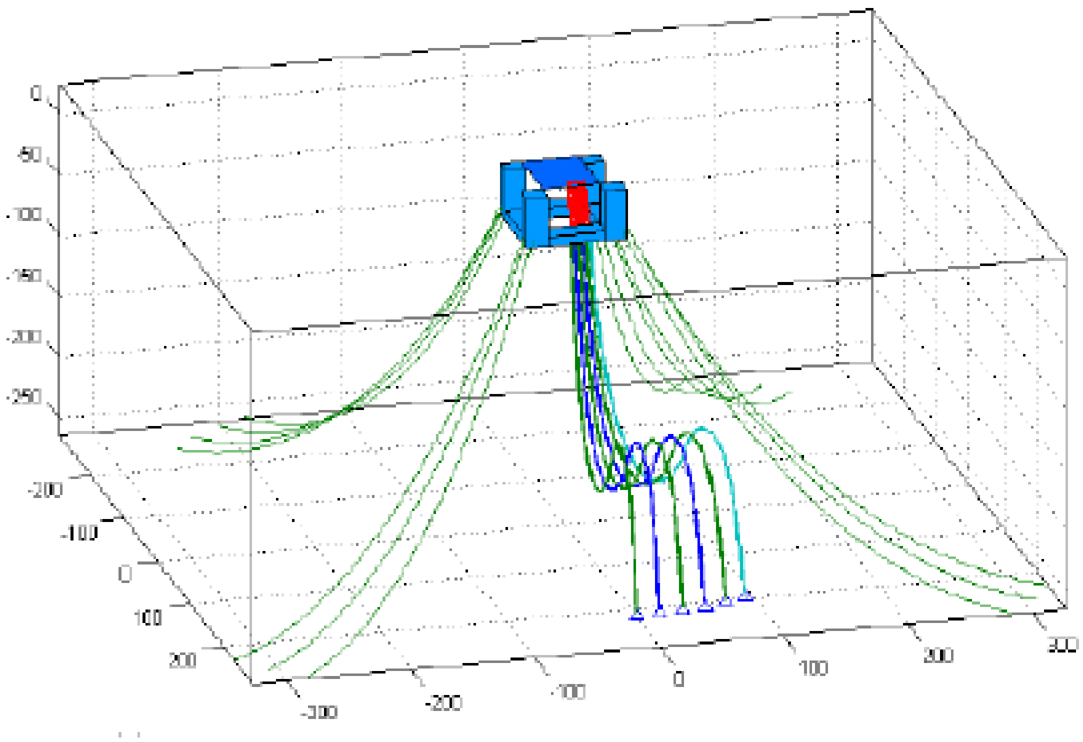

Figure 3 Mooring lines and risers, ref. (2)

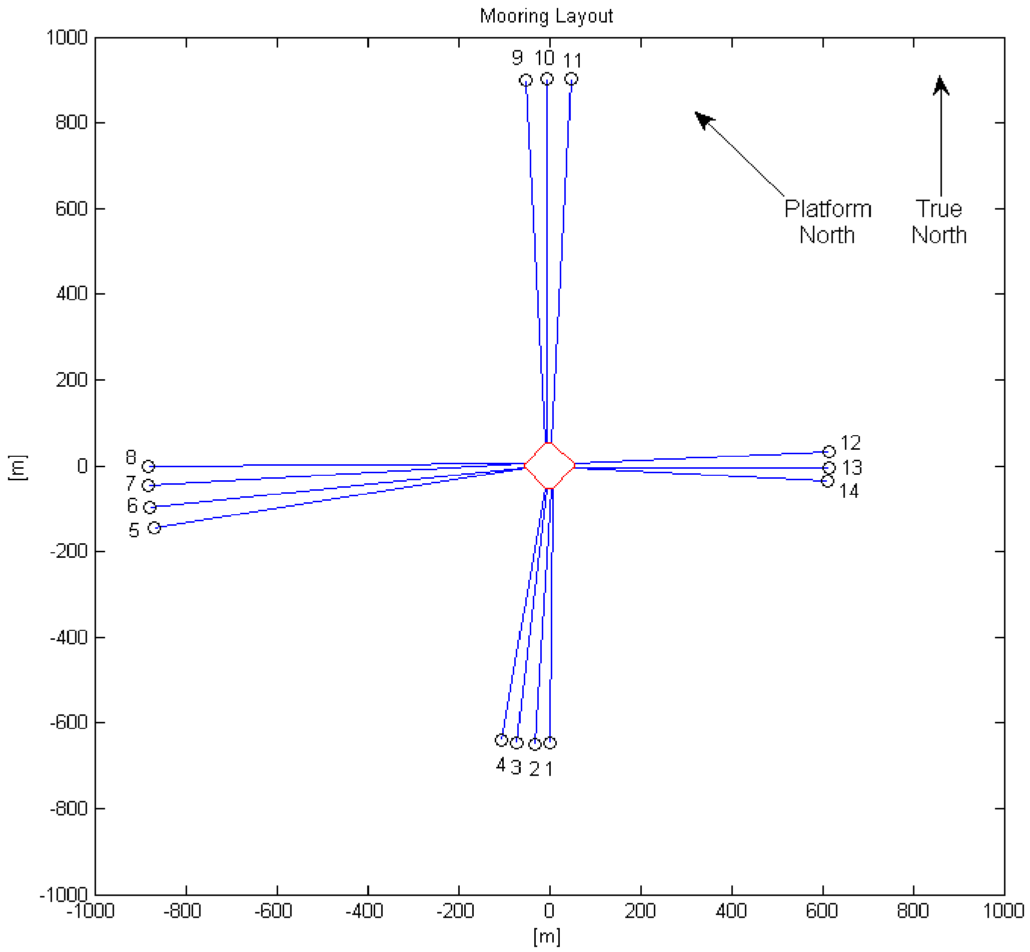

Figure 4 Mooring line layout, ref. (2)

2. Procedure for designing a mooring line

This chapter reviews the procedure for designing a mooring line for operation within the Norwegian jurisdiction, by assessing the governing rules, regulations and standards.

In general, when designing a mooring line, the characteristic load, t_c, multiplied by a safety factor, s, must be smaller than the line breaking load, t_b (see Equation 2.1).

$$t_c \cdot s \leq t_b$$

Equation 2.1

To ensure adequate safety for life and installations at sea, the design of offshore structures has to comply with governing regulations and standards. Hence, the characteristic load and safety factor for has to be in agreement with **Regulations 10 July 2009 concerning positioning and anchoring systems on mobile offshore units (Anchoring regulation 09),** ref. (3), given by the Norwegian Maritime Directorate (NMD), if the mooring line is designed for operation within Norwegian jurisdiction.

2.1.Regulations

The following text is quoted from NMD's webpage, ref. (4),:

The Norwegian Maritime Directorate is a government body sub-ordinated the Ministry of Trade and Industry and the Ministry of Environment. […] The directorate's main goals are to prevent accidents and to achieve a high level of safety for lives, health, vessels and the environment.

Chapter 3 of the Anchoring Regulation covers the anchoring analysis. §14 item 4 of the chapter states that calculations for the mooring line analysis shall be done in compliance with the procedure indicated by the standard provided by ISO in **ISO 19901-7 (2005)**.

2.2. ISO Standards

International Organization for Standardization (ISO) is the world's largest developer and publisher of international standards. […] ISO 19901-7 (2005) is the standard for station keeping systems for floating offshore structures and mobile offshore units, ref. *(5)*.

The function of a station keeping system is to restrict the horizontal excursion of a floating structure within prescribed limits. The limiting criteria for excursion and orientation are generally established either by the owner of the floating structure or by direct derivation from design requirements. The effects of external actions on the floating structure such as line tensions, structure offsets and anchor forces shall be evaluated for all relevant design situations, and shall be compared with the system and component resistances, to ensure the existence of reserve strengths against mooring line breakage, offset exceedance, anchor slippage or other undesirable occurrences, ref. (6).

2.3.Mooring line analysis

ISO 19901-7 (2005), ref. (6), Annex A.8.8, gives a step by step procedure for designing a spread mooring system. The procedure is given below.

A.8.8.1 Frequency-domain analysis for spread mooring systems

a) *Determine the environmental conditions such as wind and current velocities, significant wave heights and representative wave periods, their relative directions, storm duration and wind and wave spectra for the limit state of interest.*

b) *Determine the mooring pattern, the characteristics of the mooring line segments to be deployed, and the initial pre-tension.*

c) *Determine the mean environmental actions acting on the hull.*

d) *Determine the structure's mean offset due to the mean environmental actions using a static mooring analysis approach, including elastic line stretch and friction.*

e) *Determine the structure's low-frequency motions. Since calculation of low-frequency motion requires knowledge of mooring stiffness, use the mooring stiffness at the mean offset determined in d).*

f) *Determine the significant and maximum wave-frequency structure motions using an appropriate motion analysis tool.*

g) *Determine the extreme values of the structure's offset,* $S_{extreme}$*, and the corresponding suspended line length, quasi-static tension, and anchor load using the static mooring analysis tool.*

h) *If only a quasi-static solution is required, skip this step; otherwise determine the maximum expected line tension and maximum expected anchor force using a frequency-domain or time-domain dynamic mooring line analysis tool see 8.4, 8.5.2 and 8.7.*

i) *Compare the maximum structure offset and suspended line length form step g) and extreme line tension values and anchor force from step g) or step h) with the design criteria in Clause 10. If the criteria are not met, modify the mooring design and repeat the analysis.*

Item a) and h) will be further discussed in the following sub-chapters.

Note that in addition to the mooring line analysis procedure described above, a fatigue analysis is also required. This will not be further commented in this report.

2.3.1. Environmental condition, a)

The information presented in this sub-chapter originates from **ISO 19901-7 (2005),** ref. (6), if not otherwise stated.

The environmental design situation consists of a set of actions induced by waves, wind, current and ice (if any) on the floating structure, on the risers and on the mooring system, as applicable, and is characterized by a given return period for one or more environmental variables or for a contour of environmental variables. According to **THE ANCHORING REGULATION 09**, ref. (3), § 14, the return period for the weather conditions shall, for all mooring analysis, be 100 years, as described in **ISO 19901-7 (2005)**, ref. (6), Annex A.6.4.2.2.

The combination of environmental phenomena, such as wind, waves, current and tide, is site-specific. The wave height versus wave period and wave direction relationships for the design situations shall be accurately determined from oceanographic data for the area of operation. The same applies for wind speed and wind direction, and for current speed and current direction.

2.3.1.1. Combination of environmental actions

ISO 19901-7 (2005), ref. (6), Annex A.6.4.2.2 gives the following description for combination of the environmental actions:

Permanent mooring systems should be designed for the combination of wind, wave and current conditions that are likely to induce extreme values of action effects. In practice, this is often approximated by the use of multiple sets of design situations. For example, in the case of a 100 year return period, three types of design situations are often investigated:

- *The 100 year return period waves with associated wind and current;*
- *The 100 year return period wind with associated waves and current;*
- *The 100 year return period current with associated wind and waves.*

The directional combination of wind, wave and current that results in the most severe effects should be used to verify the design of the permanent installation being considered, consistent with the site's environmental conditions.

As can be seen from the quotation above, the ISO standard doesn't provide exact information regarding how the associated loads should be combined. As a consequence the conservative approach from **THE NORSOK STANDARD N-003 ACTIONS AND ACTION EFFECTS**, ref. (7), presented in Table 1, is utilized. The table concerns the two limit states; Ultimate Limit State (ULS) and Accidental Limit State (ALS), which each consider five combination alternatives.

Limit state	Wind	Waves	Current	Ice	Snow	Earthquake	Sea level [a]
Ultimate Limit State	10^{-2}	10^{-2}	10^{-1}	-	-	-	10^{-2}
	10^{-1}	10^{-1}	10^{-2}	-	-	-	10^{-2}
	10^{-1}	10^{-1}	10^{-1}	10^{-2}	-	-	m
	-	-	-	-	10^{-2}	-	m
	-	-	-	-	-	10^{-2}	m
Accidental Limit State	10^{-4}	10^{-2}	10^{-1}	-	-	-	m*
	10^{-2}	10^{-4}	10^{-1}	-	-	-	m*
	10^{-1}	10^{-1}	10^{-4}	-	-	-	m*
	-	-	-	10^{-4}	-	-	m
	-	-	-	-	-	10^{-4}	m

[a] m - mean water level
m* - mean water level, including the effect of possible storm surge
Seismic response analysis should be carried out for the most critical water level.

Table 1 Combination of environmental actions with annual probability of exceedance, N-003 (7)

2.3.1.2. Environmental conditions at the Midgard field

The aim of this sub-chapter is to determine the environmental conditions for designing a mooring line at the Midgard platform by determining the requests from **ISO 19901-7 (2205)** A.8.8.1 a) (described in sub-chapter 2.3) and utilizing the information presented in sub-chapter 2.3.1.1.

ÅSGARD MFP METOCEAN DESIGN BASIS, ref. (8), is used to investigate the environmental design conditions at the Midgard field (a part of the Åsgard field at the Halten Bank). The facts presented below originate from the Metocean report, if not otherwise specified.

The duration of the sea states described here is taken to be 3 hours. The wave spectrum to be considered is that which gives the largest result of Torsethaugen and Jonswap. In this way, the most severe occurrence is always utilized.

The wind spectrum to be considered is specified by Equation 2.2.

$$S(f) = \frac{320 \cdot \left(\frac{U_0}{10}\right)^2 \cdot \left(\frac{z}{10}\right)^{0,45}}{\left(1 + \tilde{f}^{\,n}\right)^{\frac{5}{3n}}}$$

where

$$n = 0,468$$

$$\tilde{f} = 172 \cdot f \cdot \left(\frac{z}{10}\right)^{\frac{2}{3}} \cdot \left(\frac{U_0}{10}\right)^{-0,75}$$

where

$S(f)[m^2 s^{-1} / Hz]$	Spectral density at frequency f (Hz)
z[m]	Height above sea level
U_0[m/s]	1-hour mean wind speed 10 m above sea level

Equation 2.2 ref. (7)

Table 2 show the extremes of 1-hour average wind speed at the Halten Bank area. The strongest wind is estimated to be 36 m/s from the directional sector 240° for 10^{-2} annual probability of exceedance and 32 m/s from the same direction for 10^{-1} annual probability of exceedance. The wind direction is the direction from which the wind is blowing.

Direction	Sector prob.	Weibull parameters			Annual probability of exceedance		
		Shape	Scale	Location	0.63	10^{-1}	10^{-2}
	%	-	m/s	m/s	m/s	m/s	m/s
0°	7.88	1.941	8.65	0.00	23	27	30
30°	8.37	2.000	8.33	0.00	21	25	28
60°	8.35	2.100	8.20	0.00	20	23	26
90°	7.39	2.170	8.33	0.00	20	23	25
120°	6.70	2.028	8.86	0.00	22	26	29
150°	6.39	2.014	9.30	0.00	23	27	31
180°	7.02	2.000	10.26	0.00	26	30	34
210°	11.48	2.150	11.27	0.00	28	32	35
240°	12.28	2.100	11.21	0.00	28	32	36
270°	9.56	2.022	10.47	0.00	27	31	35
300°	7.17	1.921	9.64	0.00	25	30	34
330°	7.42	1.930	9.09	0.00	24	28	32
0° - 360°	**100.00**	**1.978**	**9.59**	**0.00**	**29**	**33**	**36**

Table 2 Extreme values for 1-hour average wind speed at the Halten Bank area, ref. (8)

Table 3 show the sector and omni-directional extremes for current speed at 5, 50, 100 and 175 m depth and 5 m above sea bottom at the Halten Bank area. The strongest current speed is estimated to be 100 cm/s for the 30° directional sector for 10^{-2} annual probability of exceedance and 87 cm/s from the same direction with 10^{-1} annual probability of exceedance. The current direction is the direction towards which the current is flowing.

Direction sector	Sector prob.	Weibull parameters			Annual probability of exceedance		
		Shape	Scale	Location	0.63	10^{-1}	10^{-2}
	%	-	cm/s	cm/s	cm/s	cm/s	cm/s
0°	11.86	1.240	9.99	2.48	60	72	83
30°	21.32	1.226	11.43	1.98	73	87	100
60°	19.76	1.340	13.61	1.23	73	86	98
90°	10.69	1.360	14.08	1.27	70	83	95
120°	5.17	1.258	12.28	1.58	65	79	93
150°	3.76	1.300	11.20	1.28	55	67	78
180°	2.58	1.751	13.77	-1.00	42	49	55
210°	2.64	1.672	13.32	-1.17	42	50	57
240°	2.48	1.476	12.26	-0.42	46	56	65
270°	4.28	1.460	11.75	0.49	48	57	66
300°	6.52	1.380	11.07	1.24	52	62	71
330°	8.93	1.330	10.48	1.88	54	64	74
0°-360°	**100.00**	**1.292**	**11.83**	**1.47**	**76**	**89**	**100**

Table 3 Extreme values for the sector and omni-directional distribution of current speed, ref. (8)

Table 4 show directional extreme significant wave heights and corresponding spectral peak periods at the Halten Bank area. The wave direction is the direction from which the waves are coming. Deciding on which sea state (wave height and wave period) is the worst at a given probability of exceedance cannot be done by only addressing Table 4. The highest wave height and wave period isn't necessarily the sea state that produces the largest line tensions. Further investigation (e.g. model tests) is required to determine the most severe sea state. Here, the highest Hs-value is regarded as the sea state producing the largest line tensions. For the annual probability of exceedance q=10^{-1} this will be Hs =13,8 m and Tp=17,3, while for q=10^{-2} it's Hs= 16,0 and Tp=18,7.

Direction sector	Sector probability	Annual probability (q) of exceedance					
		q = 0.63		$q = 10^{-1}$		$q = 10^{-2}$	
		H_S (m)	T_p (s)	H_S (m)	T_p (s)	H_S (m)	T_p (s)
0°	15.27	8.1	13.8	10.1	15.1	12.1	16.3
30°	6.82	6.5	12.8	8.3	14.0	10.0	15.0
60°	1.87	4.9	11.7	6.5	12.8	8.0	13.7
90°	2.09	4.7	11.6	5.8	12.4	6.7	12.9
120°	1.81	5.0	11.8	6.1	12.6	7.0	13.1
150°	1.03	5.3	12.0	6.9	13.1	8.3	13.9
180°	1.78	7.2	13.2	9.5	14.7	11.6	16.0
210°	10.96	9.3	14.5	11.5	15.9	13.5	17.1
240°	21.53	10.8	15.5	13.5	17.1	16.0	18.6
270°	13.16	9.8	14.9	12.4	16.5	14.9	18.0
300°	10.29	9.1	14.5	11.8	16.1	14.3	17.6
330°	13.38	8.7	14.2	11.0	15.6	13.2	17.0
0°-360°	**100.00**	**11.5**	**15.9**	**13.8**	**17.3**	**16.0**	**18.7**

Table 4 Directional extreme significant wave height (Hs) and spectral peak period (Tp), ref. (8)

Table 1 provides an approach for combination of environmental values when designing mooring lines. If ice, snow, earthquake and sea level are disregarded, two ULS combination remain. The first combination (here denoted as ULS 1) requires the worst wind and waves with 10^{-2} probability of exceedance and the worst current with 10^{-1} probability of exceedance. The second combination (here denoted as ULS 2) requires the worst wind and waves with 10^{-1} probability of exceedance and the worst current with 10^{-2} probability of exceedance. The values are found from Table 2, Table 3 and Table 4 and presented in Table 5.

	Hs	Tp	Wind	Current
Direction [°]	240	240	240	30
	[m]	[s]	[m/s]	[m/s]
ULS 1	16,0	18,7	36	0,87
ULS 2	13,8	17,3	32	1,00

Table 5 ULS design environment actions combinations

Other ways to determine Tp and Hs

If the wave period and the natural period of the platform are within the same range, the platform motions will increase, hence the line tensions will increase. **ÅSGARD MFP METOCEAN DESIGN BASIS**, ref. (8), provides two items that may be used to explore other possible sets of Hs and Tp; Table 6 and Figure 5.

Table 6 provides a period interval for four annual probabilities of exceedance values for Hs. For ULS 1, in accordance with Table 1, q= 10^{-2} are of interest. It is suggested that the spectral peak period interval indicated is checked by a simulation of line tension. The Tp resulting in the largest the largest line tensions should be used as design conditions.

Annual probability of exceedance	Significant wave height H_S – (m)	Spectral peak period T_p – (s)		
		5 %	Mean	95 %
0.63	11.5	13.6	15.9	18.4
10^{-1}	13.8	15.1	17.3	19.7
10^{-2}	16.0	16.4	18.6	21.1
10^{-4}	20.2	18.7	21.1	23.7

Table 6 Wave heights and spectral peak periods; mean values and 90 % confidence band, ref. (8)

The contour lines shown in Figure 5 may, like Table 6, be used to find other possible Hs and Tp combinations. It is advised to evaluate a range of sea states at the top of the contour in order to determine which sea state that provides the largest responses.

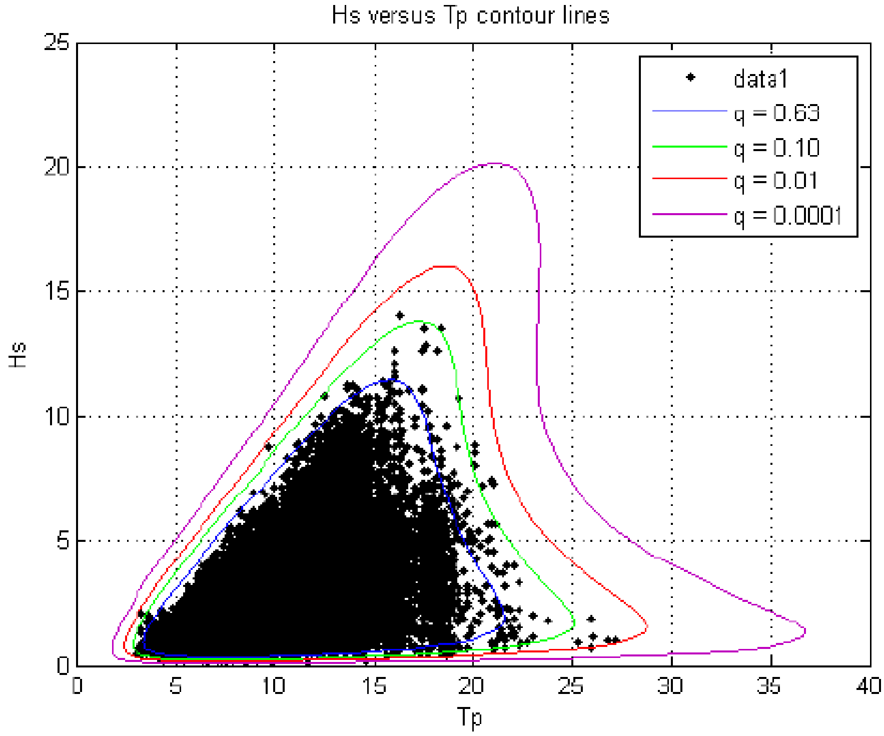

Figure 5 q-probability contour lines of Hs and Tp for omni-directional waves. (8)

In sub-chapter 7.1, the discussion above will be further analyzed.

2.3.2. Design criteria, i)

The mooring line design process described in sub-chapter 2.3 is an iterative process (see Figure 6). The goal is to find mooring line characteristics who comply with the governing rules. The last step of the design procedure is the criteria check, step i). If the mooring line characteristics[1] chosen give satisfactory results, meaning that the design criteria are met, the characteristics can be used for the design. If the design criteria aren’t met, the characteristics must be adjusted. The design procedure is repeated with the adjusted characteristics in accordance with the steps from a) to i).

[1] E.g.: material characteristics, line length and line thickness

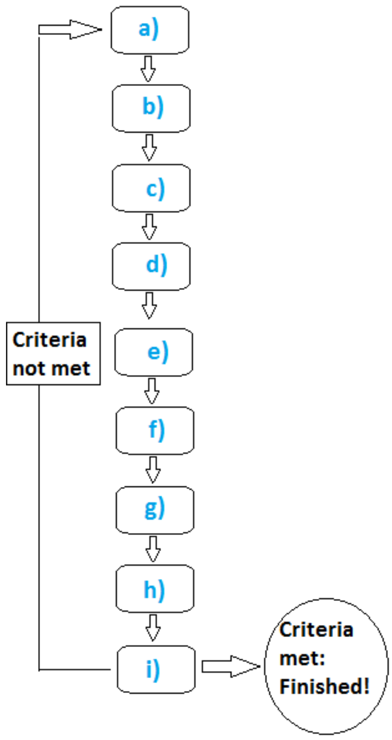

Figure 6 Iterative design procedure

Step i) states the values to check against the design criteria are:

- Maximum structure offset and suspended line length
- Line tension
- Anchor force[2]

2.3.2.1. Maximum structure offset and suspended line length

Clause 10.1 of **ISO 19901-7 (2005),** ref. (6), states the floating structure offset criteria as quoted below:

Floating structure offset limits shall be established by clearance requirements and limitations on the satisfactory performance of equipment such as umbilicals, risers and gangways, and the time equired for the safe operation of any disconnect system. Generally, different criteria apply to intact, redundancy check and transient motion conditions and these are detailed below.

The offset of the floating structure from the sea floor well location shall be controlled to prevent damage to drilling, well intervention or production risers.

2.3.2.2. Safety factors for line tensions

As earlier mentioned, the NMD states through the **Anchoring Regulation 09**, ref.(3), that the mooring line analysis shall be performed in compliance with the procedure indicated by **ISO 19901-7 (2005)**, ref. (6). The safety factors for Norwegian jurisdiction are stated in ISO Annex B. However,

[2] Design requirements for the anchor force are provided by the **NORSOK standard N-003 Actions and Action Effects**, ref. (7), and will not be further discussed in this report.

NMD has declared that adjustments must be made to the safety factors given in ISO Annex B. In this sub-chapter, both the ISO Annex B safety factors and the adjusted NMD safety factors are presented and compared.

Safety factors from ISO Annex B

Clause 10.2 of **ISO 19901-7 (2005)**, ref. (6), presents the line tension ultimate limit design criteria by Table 7 and Table 8. Table 7 presents the safety factors for permanent mooring systems and Table 8 for mobile mooring systems.

A permanent mooring system is by **ISO 19901-7 (2005)**, ref. (6), described as*: system normally used to moor floating structures deployed for long-term operations, such as those for a floating production system.* From this definition, a production platform has a permanent mooring system, and for these Table 7 should be used as design criteria.

Analysis	**Return period**	**Dynamic safety factor**		
Dynamic		*Class 3*	*Class 2*	*Class 1*
Intact condition	100	2,20	2,00	1,50
One failure	100	1,50	1,35	1,20
One failure, transient	100	1,10	1,10	1,05
Two failures	10	1,50	1,35	N/A
Two failures, transient	10	1,10	1,10	N/A

Table 7 Safety factors for tension in mooring lines for permanent moorings, ref. (6)

According to **ISO 19901-7 (2005)**, ref. (6), a mobile mooring system is a *mooring system, generally retrievable, intended for deployment at a specific location for a short time operation, such as those*: *for mobile offshore units.* In other words; a drilling platform is considered to have mobile moorings and should utilize the safety factors given in Table 8.

Analysis	**Return period**	**Dynamic safety factor**		
Dynamic		*Class 3*	*Class 2*	*Class 1*
Intact condition	10	2,20	2,00	1,67
One failure	10	1,50	1,35	1,25
One failure, transient	10	1,10	1,10	1,05

Table 8 Safety factors for tension in mooring lines for mobile moorings, ref. (6)

In both Table 7 and Table 8 there are three consequence classes describing different scenarios. The scenarios are the same for both permanent and mobile mooring systems. See Table 9 for details regarding the consequence classes.

Location relative to other installation	Not in vicinity	In vicinity, but greater than X [a]		In vicinity, but smaller than X [a]	
Direction of mooring line relative to other installation	—	Facing other installation	Facing away from other installation	Facing other installation	Facing away from other installation
Condition					
Standby condition [b]	2	2	2	2	3
Survival condition [c]	1	1	2		

[a] Distance X is given by the distance between the unit and the other installation being such that the unit, after failure of 3 (or all, if less than 3) mooring lines in one corner, will turn clear of the other installation with a smallest distance not less than 10 m in the most adverse phases.

[b] For drilling and production units: condition when risers are connected and the operation is stopped due to weather conditions. For other mobile units operating in the vicinity of other units, standby (or stand-off) condition is when the unit due to weather conditions has been moved away from the other unit as far as practically possible but is still connected to, or located in the vicinity of, the other unit.

[c] For drilling and production units: condition when risers are disconnected due to weather conditions. For other mobile units: condition when normal operation is stopped due to weather conditions.

Table 9 Consequence classes for mooring lines, ref. (6)

Adjustments required from NMD

THE ANCHORING REGULATION 09 §14 item 4, ref.(3), requires adjustments to the safety factors for mobile moorings and the environmental return period for both permanent and mobile moorings, among other changes. The mandatory changes mentioned are quoted from the regulation, and presented below.

§14 item 4)
The calculations shall be prepared pursuant to the methodology given in ISO 19901-7 (2005). The premises and safety factors given in Annex B.2 in the standard shall be used in the analysis. In addition, the following shall apply:

…

d) *a 100-year return period for weather conditions, as described in ISO 19901-7 (2005), A.6.4.2.2, shall be used in all analyses. Characteristics for the season may be used for a non-permanent anchoring. Dynamic analyses shall be carried out.*

e) table *B.3*[3] *of ISO 19901-7 (2005) Annex B is replaced by the following:*

[3] Mark that table B.3 referred to in this quotation is in this report Table 8.

	Consequence class 3	Consequence class 2	Consequence class 1
Intact	1.90	1.80	1.50
One-line-break	1.30	1.20	1.10
One-line-break, transient	1.10	1.10	1.05

Table 10 Safety factors for line tensions in mooring lines for mobile moorings, (3)

After considering the additional requirements from **THE ANCHORING REGULATION 09**,(3), (hereafter called AR09) the two ISO Annex B tables (Table 7 and Table 8) are replaced by Table 11 and Table 12. Mark that Table 9, who describes the consequence classes, remains unchanged.

Analysis	Return period	Dynamic safety factor		
Dynamic		*Class 3*	*Class 2*	*Class 1*
Intact condition	100	2,20	2,00	1,50
One failure	100	1,50	1,35	1,20
One failure, transient	100	1,10	1,10	1,05
Two failures	100	1,50	1,35	N/A
Two failures, transient	100	1,10	1,10	N/A

Table 11 Safety factors for mooring line tensions for permanent moorings in accordance with AR09

Analysis	Return period	Dynamic safety factor		
Dynamic		*Class 3*	*Class 2*	*Class 1*
Intact condition	100	1,90	1,80	1,50
One failure	100	1,30	1,20	1,10
One failure, transient	100	1,10	1,10	1,05

Table 12 Safety factors for tension in mooring lines for mobile moorings in accordance with AR09

Comparison of safety factors from ISO Annex B and AR09

Table 13 compares the requirements from ISO Annex B with the additional requirements from AR09 for permanent mooring system. The table shows that the only difference between the criteria from AR09 and ISO Annex B is the probability of exceedance for two line failures marked in the table by the dotted red box. AR09 is the most secure, since it requires environment conditions with a 100 year period of return for all cases.

Analysis	Return period		Dynamic safety factor					
			Class 3		*Class 2*		*Class 1*	
	ISO Annex B	*AR09*	*ISO Annex B*	*AR09*	*ISO Annex B*	*AR09*	*ISO Annex B*	*AR09*
Intact condition	100	100	2,20	2,20	2,00	2,00	1,50	1,50
One failure	100	100	1,50	1,50	1,35	1,35	1,20	1,20
One failure, transient	100	100	1,10	1,10	1,10	1,10	1,05	1,05
Two failures	10	100	1,50	1,50	1,35	1,35	N/A	N/A
Two failures, transient	10	100	1,10	1,10	1,10	1,10	N/A	N/A

Table 13 Comparison of line tension criteria for permanent from AR09 and ISO Annex B

Table 14 compares the mobile mooring systems requirements from ISO Annex B with the additional requirements from AR09. The values marked by the red dotted boxes are those who differ from each other. The only values that remain unchanged are the safety factors for one line failure, transient, for class 2 and 3. In this case, since the environmental rate of return is higher for AR09, it can be stated that AR09 is safer.
The table shows that the safety factors from AR09 are lower than the safety factors from ISO Annex B (except for the unchanged values). In return, AR09 demand a higher return period for the characteristic values. Further investigation is required to state which rules has the largest *real* safety margin. The problem can be summarized by Equation 2.3.

Analysis	Return period		Dynamic safety factor					
			Class 3		Class 2		Class 1	
	ISO Annex B	*AR09*	*ISO Annex B*	*AR09*	*ISO Annex B*	*AR09*	*ISO Annex B*	*AR09*
Intact condition	10	100	2,20	1,90	2,00	1,80	1,67	1,50
One failure	10	100	1,50	1,30	1,35	1,20	1,25	1,10
One failure, transient	10	100	1,10	1,10	1,10	1,10	1,05	1,10

Table 14 Comparison of line tension criteria for mobile moorings from AR09 and ISO Annex B

$$t_{10} \cdot s_{ISO\,Annex\,B} \qquad \text{v.s} \qquad t_{100} \cdot s_{NMD}$$

Equation 2.3

To investigate which safety factors that really requires the largest safety margin in Table 14, the increase in environmental loads when the environmental return period increases, must be explored. The increase in line tension because of the increased environmental loads can be denoted x (see Equation 2.4).

$$t_{10} \cdot x = t_{100}$$

Equation 2.4

With Equation 2.4 in mind, the problem raised in Equation 2.3 can be described as shown in Equation 2.5.

$$\frac{t_{100}}{x} \cdot s_{ISO\ Annex\ B} \quad \text{v.s} \quad t_{100} \cdot s_{NMD}$$

$$\Rightarrow \frac{s_{ISO\ Annex\ B}}{x} \quad \text{v.s} \quad s_{NMD}$$

Equation 2.5

The increased environmental loads because of the increased environmental values cannot be found without a thorough investigation. However, it seems likely that the increase in loads (x) is at least as large as the increase in environmental values. With this as an assumption, the increase in environmental values at the Halten Bank area is investigated in the following sections.

The environmental conditions presented in Table 15 and Table 16 originates from Table 3 and Table 4, respectively. The tables (Table 15 and Table 16) illustrate the increase in environmental values when the annual period of return is increased from 10 to 100 years at the Halten Bank area. The increase is approximately 10 % for the wind and 20 % for the wave height.
The effects of change in current and wave period values are not considered, since their change effects the environmental loads minor compared to wind speed and wave height.

Wind			
Probability:	0,1	0,01	
Direction	m/s	m/s	Diff. [%]
0	27	30	11,1
30	25	28	12,0
60	23	26	13,0
90	23	25	8,7
120	26	29	11,5
150	27	31	14,8
180	30	34	13,3
210	32	35	9,4
240	32	36	12,5
270	31	35	12,9
300	30	34	13,3
330	28	32	14,3
		Average	*12,2*
		MIN	*8,7*
		MAX	*14,8*

Table 15 Increase in wind speed when q is lowered at Midgard

Waves			
Probability:	0,1	0,01	
Direction	Hs [m]	Hs[m]	Diff [%]
0	10,0	12,1	21,0
30	8,3	10,0	20,5
60	6,5	8,0	23,1
90	5,8	6,7	15,5
120	6,1	7,0	14,8
150	6,9	8,3	20,3
180	9,5	11,6	22,1
210	11,5	13,5	17,4
240	13,5	16,0	18,5
270	12,4	14,9	20,2
300	11,8	14,3	21,2
330	11,0	13,2	20,0
		Average	*19,6*
		MIN	*14,8*
		MAX	*23,1*

Table 16 Increase in wave height and period when q is lowered at Midgard

If it is assumed that the increase in line tension is 20 % when the environmental values change from the maximum in 10 years to the maximum in 100 years, the safety factors from ISO Annex B are modified with x=1,20, and the safety factors can be compared (see Table 17). It is clear that for this assumption, the safety factors stated by AR09 are more conservative than the safety factors given by ISO Annex B.

x=1,20	Dynamic Safety Factors					
Consequence class	*Class 3*		*Class 2*		*Class 1*	
Analysis	**ISO Annex B**	**AR09**	**ISO Annex B**	**AR09**	**ISO Annex B**	**AR09**
Intact condition	1,83	1,90	1,67	1,80	1,39	1,50
One failure	1,25	1,30	1,13	1,20	1,04	1,10
One failure, transient	0,92	1,10	0,92	1,10	0,88	1,10

Table 17 Modified safety factors (mobile moorings)

By implementing the safety factors in MATLAB (or other similar programs), it can quickly be found that if the line tensions increase with more than 15,7 % AR09 is safest for all cases.
For the intact condition, the ISO Annex B safety factor is exceeded already at x=1,112 for consequence class 2 and at x=1,114 for consequence class 1.

3. Probability of line failure

The goal of this report is to examine the annual probability of line failure with various safety factors. In this chapter, two methods for estimating the distribution function for the annual maximum line load are discussed. The distribution function is desirable to find in order to obtain the probability for line failure per year (see **Error! Reference source not found.**).

$$
\begin{aligned}
p\left(\text{line failure pr. year}\right) &= P\left(T_1 > t_c \cdot s\right) \\
&= 1 - F_{T_1}\left(t_c \cdot s\right) \\
&= 1 - \left[F_{T3h}\left(t_c \cdot s\right)\right]^N
\end{aligned}
$$

where

t_c = the characteristic line load

s = safety factor

T_{3h} = the 3 hour maximum line load

T_1 = the annual maximum line load

N = number of 3-hour periods in a year (2920)

F_{T3h} = long term distribution of T_{3h}

F_{T_1} = long term dirstribution of T_1

(assuming that t_c and s are independent and identically distributed)

Equation 3.1

In order to solve **Error! Reference source not found.**, the long term distribution, F_{T3h}, the safety factor, s, and the characteristic line load, t_c, must be known. The safety factor is found by governing regulations. Sub-chapter 2.3.2.2 describes the safety factors for a vessel operating under Norwegian jurisdiction. The characteristic line load will be discussed in the following sub-chapter.

3.1. Characteristic load, t_c

The characteristic load, t_c, is here defined as the expected maximum line tension in the 100 year weather condition.

MIMOSA is a computer program for analysis of moored ships and platforms. It calculates the vessel's wave-frequency and low-frequency motions and corresponding line tensions, ref. (9), using a frequency domain approach. To find the maximum line tension, MIMOSA computes a line tension response spectrum. From expected distributions, MIMOSA can produce the expected largest value in a given time interval (e.g. 3 hours), ref. (10). MIMOSA can therefore be used to find the characteristic load, when the weather conditions are known.

The computer program SIMO may be used finding the characteristic line load. SIMO is a time domain analysis tool, in contrast to MIMOSA who operates in the frequency domain. SIMO generates a time series for the line tension, on the basis of computed wind and wave series. The wind and wave series are computed with random phase angles, ref. (10). As a result of this randomness, the line tension time series will vary for each simulation, meaning that the maximum line tension will change for each simulation, even though the weather conditions are the same. A way to decide the characteristic line load can be to carry out a number of simulations and find the mean value of the maximum line load for each series. The value found by using MIMOSA should be comparable to the value estimated by SIMO.

Because of t_c's definition, the environmental conditions to be implemented in the computer programs must be the worst conditions in 100 years. Here, the worst environmental condition are the once who produces the largest line tensions. Information regarding the environmental conditions can be found from measurements at the platform's operation site. If t_c was to be specified for the Midgard platform, the weather conditions found in sub-chapter 0 would be implemented in either SIMO or MIMOSA.

3.2. Approach 1: Stochastic long term response analysis

The aim of a stochastic long term response analysis is to solve **Error! Reference source not found.** by finding a long term distribution of the 3-hour maximum line tension, $F_{T3h}(t)$.

3.2.1. Long term distribution of T_{3h}

T_{3h} is the 3-hour maximum line tension. The long term distribution of T_{3h} can be found by solving Equation 3.2.

$$\underbrace{F_{T_{3h}}(t)}_{\substack{\text{long term}\\ \text{distribution}\\ \text{of the 3-hour}\\ \text{maximum}\\ \text{line tension}}} = \iint_{hs\,tp} \underbrace{F_{T_{3h}|Hs,Tp}(t|hs,tp)}_{\substack{\text{short term distribution}\\ \text{of T given the sea}\\ \text{state characteristics}}} \cdot \underbrace{f_{HsTp}(hs,tp)}_{\substack{\text{long term distribution}\\ \text{of the sea state characteristics}}} \, \mathrm{d}tp \, \mathrm{d}hs$$

Equation 3.2 ref. (10)

3.2.1.1. Long term distribution of the sea state characteristics

f_{HsTp} is the long term distribution of the sea state characteristics, Hs and Tp. To determine the distribution, the sea state observations from the area in the form of a joint frequency table (scatter diagram) can be used.

The long term distribution can be conveniently expressed as shown in Equation 3.3.

$$f_{HsTp}(hs,tp) = f_{Hs}(hs) \cdot f_{Tp|Hs}(tp|hs)$$

Equation 3.3 ref. (2)

$f_{Hs}(hs)$ is modeled by a log normal distribution for $hs \le \eta$ and a Weibull distribution for $hs > \eta$ (see Equation 3.4). As an alternative, the 3-parameter Weibull distribution could have been used.

$$f_{Hs}(hs)=\begin{cases}\dfrac{1}{\sqrt{2\cdot\pi}\cdot\alpha\cdot hs}\cdot\exp\left(-\dfrac{(\ln(hs)-\theta)^2}{2\cdot\alpha^2}\right) & \text{for } hs\le\eta\\ \dfrac{\beta}{\rho}\left(\dfrac{hs}{\rho}\right)^{\beta-1}\cdot\exp\left(-\left(\dfrac{hs}{\rho}\right)^{\beta}\right) & \text{for } hs>\eta\end{cases}$$

Equation 3.4 ref. (2)

$f_{Tp|Hs}(tp|hs)$ is modeled by the log normal distribution (see Equation 3.5).

$$f_{Tp|Hs}(tp|hs)=\frac{1}{\sqrt{2\cdot\pi}\cdot\sigma\cdot tp}\cdot\exp\left(-\frac{(\ln(tp)-\mu)^2}{2\cdot\sigma^2}\right)$$

where

$$\mu=a_1+a_2\cdot hs^{a_3}$$

$$\sigma^2=b_1+b_2\cdot\exp(-b_3\cdot hs)$$

Equation 3.5 ref. (8)

For the Midgard platform, **ÅSGARD MFP METOCEAN DESIGN BASIS**, ref. (8), provides the parameters for the distributions above by the use of a scatter diagram with observations from the Halten Bank area. The parameters are presented in Table 18.

	Parameters										
	β	ρ	η	α	θ	a_1	a_2	a_3	b_1	b_2	b_3
	Omni-directional										
Year	1.356	2.472	4.650	0.557	0.806	1.776	0.329	0.450	0.005	0.104	0.300

Table 18 Parameters in the annual omni-directional joint distribution for Hs and Tp, ref. (8)

3.2.1.2. Short term distribution of T_{3h}

To find the long term distribution of T_{3h}, the short term distribution for all sea states must be known (see Equation 3.2). A step by step approach for determining the short term distribution is given below:

1) Specify sea state, i.e. Hs and Tp, from a scatter diagram etc.
2) Run SIMO d times[4] with the 3 hour sea state from 1) together with 100 year wind and current. Collect the maximum line tension for each simulation.
3) Identify the Gumbel distribution for the 3 hour maximum line tensions collected in 2) by estimating the Gumbel parameters, α_G and β_G. The distribution is the
4) Repeat steps 1) to 3) with different sea state characteristics so Gumbel parameters for for all sea states in the scatter diagram are obtained.

[4] d times refers to an optional number of times, preferably d>20

5) Plot α for all sea states. Fit a surface to the plotted α-parameters, resulting in a function for α_G; $\alpha_G(Hs,Tp)$.
6) Plot β for all sea states. Fit a surface to the plotted β-parameters, resulting in a function for β_G; $\beta_G(Hs,Tp)$.
7) Implement the functions for α_G and β_G into the Gumbel distribution. The short term distribution of T_{3h} (see Equation 3.6) will be on the form presented in Equation 3.6.

$$F_{T_{3h}|Hs,Tp}\left(t\left|hs,tp\right.\right)=\exp\left(-\exp\left(-\frac{\left(t-\alpha_G(hs,tp)\right)}{\beta_G(hs,tp)}\right)\right)$$

Equation 3.6

Note that the Gumbel parameters, α_G and β_G, must not be confused with the parameters α and β given in Equation 3.4 and Table 18.

3.2.1.3. Long term distribution of T_{3h}

Once the short term distribution of T_{3h} is estimated, the long term distribution of T_{3h} can be found by solving Equation 3.2. The long term distribution of T_{3h} is necessary for solving **Error! Reference source not found.** hence finding the annual probability of line failure.

It is clear that finding the long term distribution of T_{3h} by approach is a very time consuming. To adjust the work load, an approximation can be done by selecting a set of sea states that covers the range of all sea states, to use in the calculation instead of all sea states. Nevertheless, it is still a time consuming job and it is desirable to find a quicker way to estimate $F_{T3h}(t)$ and/or $F_{T1}(t)$.

3.3. Approach 2: Environmental contour line

The information in this sub-chapter originates from Prediction of Characteristics Responses for Design Purpose sub-chapter 7.5.1 by Haver, ref. (11).

The environmental contour line approach is a simplified method for estimating extreme values with a specified rate of return (e.g. annual probability of exceedance). The advantage of the method versus Approach 1 is that it doesn't require a full long term analysis. The disadvantage is the uncertainty of the results since the approach is a simplification.

The approach is based on the principle that only two short time line tension distribution, $F_{3h}(t)$, is needed to estimate the long turn distribution of the maximum line tensions, $F_{T1}(t)$. The two short term distributions are the distributions for T_{3h} in the worst 100 year and 10 000 year sea state, respectfully. Worst means the most unfavorable sea state regarding line force along the contour line.

A step by step procedure of the approach is given below.

1) Identify the worst sea states with 100 and 10 000 years period of return from known environmental data for the region, e.g. by contour line. Chose different sea states along the contour line, and use SIMO to identify the sea state that produces the largest line tension for both rates of return.
2) Run SIMO d times (different random seeds for each time) with the chosen 3-hour sea state with q=0,01 in 1), combined with wind with 100 years period of return and current with 10

years period of return. Store the maximum line tension from each simulation. Fit a Gumbel model to the set of simulated 3-hour maximum line tension;

$$F_{T_{100}3h|Hs,Tp}\left(t|hs,tp\right)$$

3) Run SIMO d-times (different random seeds for each time) with the chosen 3-hour sea state with q=0,001 from 1) combined with wind with 100 years period and current with10 years period of return. Store the maximum line tension each time. Fit a Gumbel model to the set of simulated 3-hour maximum line tension;

$$F_{T_{10\,000}3h|Hs,Tp}\left(t|hs,tp\right)$$

4) According to **THE NORSOK STANDARD N-003 ACTIONS AND ACTION EFFECTS,** ref. (7), sub-chapter 6.2.2.3 the line tension values between F=0,85 and F=0,95 of the 3-hour extreme value distribution (found in 2) is an appropriate estimate for $T^{(100)}$.

$$F_{T_{100}3h|Hs,Tp}\left(t|hs,tp\right)=0,90 \qquad \rightarrow T^{(100)}$$

5) According to **THE NORSOK STANDARD N-003 ACTIONS AND ACTION EFFECTS,** ref. (7), sub-chapter 6.2.2.3 the line tension values between F=0,90 and F=0,95 of the 3-hour extreme value distribution (found in 3) is an appropriate estimate for $T^{(10\,000)}$.

$$F_{T_{10\,000}3h|Hs,Tp}\left(t|hs,tp\right)=0,90 \qquad \rightarrow T^{(10000)}$$

6) Assuming that the long term distribution of annual line tension maxima can be described as a Gumbel distribution, the Gumbel parameters can be found by solving the two equations with $T^{(100)}$ and $T^{(10\,000)}$ as chosen in 4) and 5) respectively;

$$F_{T_1}(t)=\exp\left\{-\exp\left(-\frac{T^{(100)}-\alpha_T}{\beta_T}\right)\right\}=1-\frac{1}{100}$$

$$F_{T_1}(t)=\exp\left\{-\exp\left(-\frac{T^{(10000)}-\alpha_T}{\beta_T}\right)\right\}=1-\frac{1}{10\,000}$$

7) Once α_T and β_T in 6) are estimated, the long term distribution of T_1 is known;

$$F_{T_1}(t)=\exp\left\{-\exp\left(-\frac{t-\alpha_T}{\beta_T}\right)\right\}$$

8) The probability of line failure is found where the characteristic line load, t_c, is discussed in sub-chapter 3.1 and the safety factor's is described in sub-chapter 2.3.2.2.

3.4. What approach would you select if time domain analyses are necessary?

Mimosa can be used to find an estimate for the maximum line load, but not to find an estimate for the short time distribution of the maximum line tension. Mimosa calculates the line tension by first computing a line tension response spectrum and from expected distributions it produces the largest value in a given time interval, ref. (10).

For MIMOSA to be used to find the long term distribution of the maximum line tension there has to be some randomness implemented in the program. MIMOSA will compute the same maximum line tension every simulation with the same environmental input. With just one value for the maximum line tension, a short term distribution cannot be estimated.

In both approaches discussed above a time domain analysis is necessary. Approach 1 requires time domain analysis to find the short time distribution of maximum line tensions for all sea states. The same is the case for Approach 2, but only for two sea states. SIMO is a time domain analysis program and can therefore be used in the approaches.

4. Annual probability of line failure at Midgard

There are, as stated earlier, line tension data from the model test with the Midgard platform model available. These results will be used to estimate the annual probability of line failure.

The Midgard platform is designed as a permanent instillation, i.e. the safety factor is 2.2 for consequence class 3 (see sub-chapter 2.3.2.2). Here the model test results will be used to investigate how the probability of line failure would be affected if lower safety factor is used (e.g. safety factors for mobile installations). The lower safety factors are, however, of no relevance for the Midgard field development.

4.1.Model test results

The information presented in this sub-chapter regarding the performed model tests originates from **AKER MIDGARD MODEL TESTS MAIN REPORT**, ref. (2).

In the summer of 2010 the Norwegian Marine Technology Research Institute (MARINTEK) preformed tests with the Midgard platform model in an ocean basin. The main objective of the test was to study the air gap and slamming forces in the 100 and 10 000 year weather conditions.

The irregular wave tests were performed for four sea states along the 100 year contour line and four sea states along the 10 000 year contour line, all with a wave heading of both 0° and 315°.

For the model tests, the directions were set to be as follows; waves coming from 0° are propagating along positive x-axis and waves coming from 90° are propagating along positive y-axis, ref. (12). This is illustrated in Figure 7. Figure 8 illustrates the mooring line layout according to the described coordinate system.

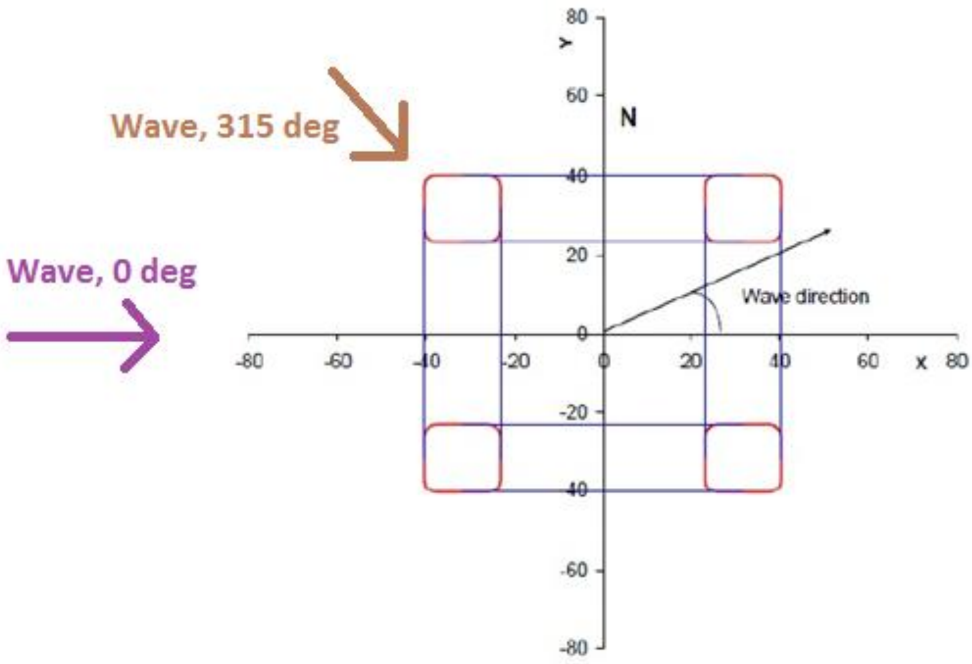

Figure 7 Platform orientation, coordinate system and wave direction, ref. (12)

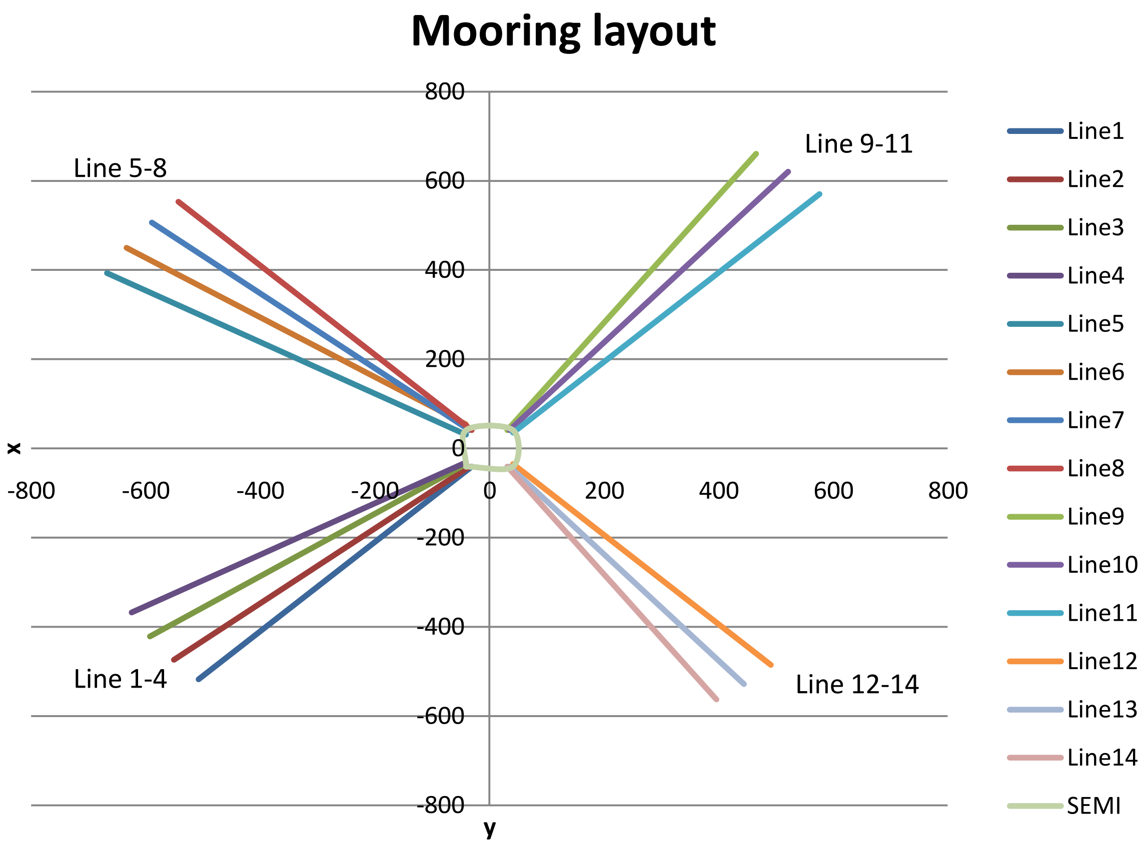

Figure 8 Model mooring line layout

For all test discussed in this report, the wind is taken to be the 100-year wind and the current is taken to be the 10-year current, in accordance with the N-003 (see ULS 1 Table 5).

The environmental conditions used during the model tests are listed in Table 19.

Environment no.	Global contour	Direction (deg)	Hs [m]	Tp [s]	Wind [m/s]	Current [m/s]
1	100	0	12,5	12,9	36,0	0,9
2	100	315	12,5	12,9	36,0	0,9
3	100	0	14,9	15,7	36,0	0,9
4	100	315	14,9	15,7	36,0	0,9
5	100	0	16,1	18,5	36,0	0,9
6	100	315	16,1	18,5	36,0	0,9
7	100	0	14,8	20,2	36,0	0,9
8	100	315	14,8	20,2	36,0	0,9
9	10 000	0	16,1	14,7	36,0	0,9
10	10 000	315	16,1	14,7	36,0	0,9
11	10 000	0	18,9	17,8	36,0	0,9
12	10 000	315	18,9	17,8	36,0	0,9
13	10 000	0	20,2	21,0	36,0	0,9
14	10 000	315	20,2	21,0	36,0	0,9
15	10 000	0	19,0	22,8	36,0	0,9
16	10 000	315	19,0	22,8	36,0	0,9

Table 19 Tested environmental conditions, ref. (2)

First, two tests were performed for each environment described in Table 19. The maximum line tension for both wave headings (0° and 315°) and for both return periods (100 and 10 000) are presented in Table 20 to illustrate the difference in line tension for the two wave headings. It's clear that for 315° wave heading, the line tensions are larger than for 0° wave heading.

Global contour	100		10 000	
Wave heading [deg]	0	315	0	315
Line no.	5	8	5	8
Environment no.	4	3	14	13
Max. tension [kN]	5 003,30	6 139,60	6644,70	8 691,40
Difference [%]	22,7 %		30,8 %	

Table 20 Maximum results from the first model tests

As previously mentioned, the aim of the performed model tests was to assess slamming and air gap. Because of this focus, further measurements were not done for waves with 315° heading even though this condition gave the largest line tensions. Additional tests were only performed for waves with 0° heading. The environmental condition and number of additional tests are presented in Table 21. All line tension results for environment no. 4 and 14 can be found in Appendix B.

Environment no.	Global contour	Hs [m]	Tp [s]	Wind [m/s]	Current [m/s]	No of additional tests:
4	100	14,9	15,7	36	0,9	8
6	100	16,1	18,5	36	0,9	9
14	10 000	20,2	21,0	36	0,9	12

Table 21 Additional tested environmental conditions with 0° heading

4.2. Characteristic line load

The characteristic line load is the expected largest mooring line load the 100-year environment condition. For the annual probability of line failure to be estimated, the characteristic line load must be determined. It's preferred to use the worst sea state along the 100-year contour line, to estimate the characteristic line load. The worst sea state is in this report defined the sea state that produces the largest line tensions.

For the first round of model testing, environment no. 3 gave the largest line tensions of the eight 100 year environments tested. Unfortunately, this environmental condition was only preformed twice. Two tests are not enough to estimate statistical values. Environmental conditions for 0° wave heading are the only environmental conditions with more than two performed tests (see Table 21). They will therefore be used to find the characteristic line load and later the annual probability of line failure, even though they are not considered to be the worst sea states at the 100 and 10 000 year contour lines.

The worst sea state with 0° heading along the 100 year contour line is environment no. 4. This environmental condition is considered when estimating the characteristic line load and later to estimate the annual probability of failure. The maximum line tension results for line 5 (the most exposed line) from the 10 performed tests with environment no. 4 is presented in Table 22.

Hs [m]	14,9
Tp [s]	15,7
Wind [m/s]	36,0
Current [m/s]	0,9
Heading [°]	0
Line	5
Number of tests	10
Test ID-number:	**Line tension [kN]:**
3250	4 589,50
3261	5 003,30
3269	4 926,30
3270	4 429,50
3272	4 475,40
3274	3 912,60
3276	4 930,30
3278	4 709,10
3280	5 117,80
3282	4 588,70
Average (t_c):	*4 668,25*
Standard deviation	*354,18*

Table 22 Maximum line tensions with environment no.4

The characteristic line load is here taken to be the average of the measured line tensions presented in Table 22

Characteristic line load	t_c	4 668,25	kN

Table 23 Characteristic line load from environment no. 4

The consequence of using environment no. 4 instead of no.3 to estimate the annual probability of line failure will be considered in sub-chapter 7.3.

4.3. Annual probability of failure

In Chapter 3, two different methods to estimate the annual probability of line failure were discussed. One of them was the environmental contour method. In this chapter it will be used together with the Midgard model test results to estimate the annual probability of line failure. The annual probability of line failure will be estimated with various safety factors, to investigate if the safety factors are sufficiently safe. The safety factors provided by the existing rules were discussed in sub-chapter 2.3.2.2.

4.3.1. Environmental contour method with model tests

The contour line method is a simplified method for estimating the long term distribution of the annual maximum line load, T_1. The distribution is needed to find the probability of line failure (see Equation 4.1).

$$
\begin{aligned}
P_f &= p(\text{line failure pr. year}) = P(T_1 > t_c \cdot s) \\
&= 1 - F_{T_1}(t_c \cdot s)
\end{aligned}
$$

where

$$
\begin{aligned}
P_f &= \text{ Annual probability of line failure} \\
t_c &= \text{the characteristic line load} \\
s &= \text{safety factor} \\
T_1 &= \text{the annual maximum line load} \\
F_{T_1} &= \text{long term dirstribution of } \mathrm{T}_1
\end{aligned}
$$

Equation 4.1

A step by step procedure for the environmental contour line method is described in sub-chapter 3.3. In this case, the maximum line tensions are found from the model test results, so SIMO simulations aren't necessary.

The aim of the environmental contour method is to estimate a long term distribution for annual maximum line. The basis of the method is the assumption that the line tension value of a high fractile (e.g. 0,90) of the short term distribution for the worst sea states along the 100 and 10 000 year contour line, belongs in the long term distribution of the annual maximum line load. Equation 4.2 displays the set of equations to be solved in order to obtain the long term distribution.

$$
\begin{aligned}
F_{T_1}(t) &= \exp\left\{-\exp\left(-\frac{T^{(100)} - \alpha}{\beta}\right)\right\} = 0{,}9900 \\
F_{T_1}(t) &= \exp\left\{-\exp\left(-\frac{T^{(10\ 000)} - \alpha}{\beta}\right)\right\} = 0{,}9999
\end{aligned}
$$

Equation 4.2

From the model test results, it was found that the worst environmental conditions (with more than two tests performed) was no. 4 for the 100 year contour line and no. 14 for the 10 000 year contour line. The short term maximum line tension distribution for these conditions will be estimated, in order to obtain an estimate for $T^{(100)}$ and $T^{(10\,000)}$.

4.3.1.1. Short term distribution for environment no. 4

The maximum line tensions from the ten performed model tests with environment no. 4 are displayed in Table 22. In Figure 9, these tensions are plotted to give an idea how the results are spread. The figure shows a fairly even distribution with a difference from maximum to minimum of approximate 1 000 kN. A Gumbel model can be fitted to the data. However, the low number of tests (ten) gives an uncertainty to the accuracy of the distribution, even though the measured results seems evenly spread.

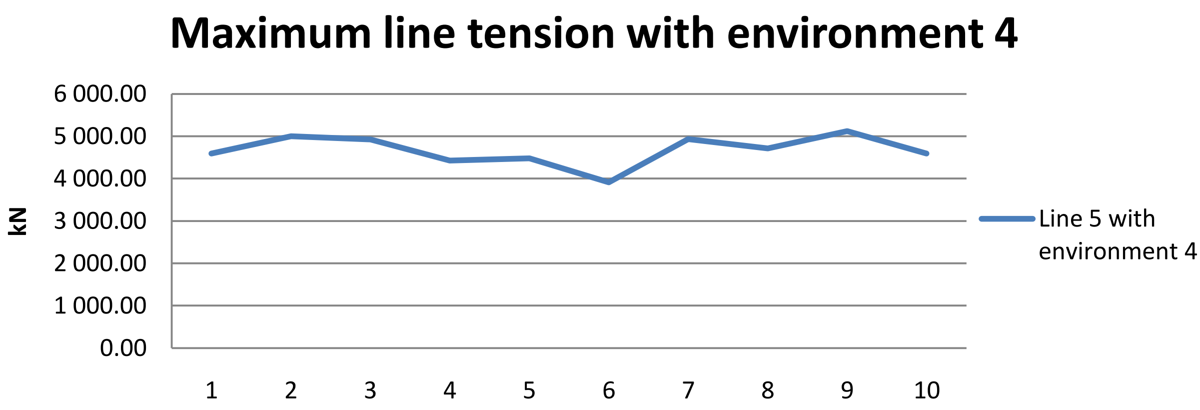

Figure 9 Maximum line tension results - line 5 environment no.4

The measured maximum line tensions are assumed to be Gumbel distributed. The line tensions are plotted in a Gumbel probability plot illustrated in Figure 10 by the red markers. The figure also contains a blue and green line. The blue line represents the Gumbel distribution with Gumbel parameters found from the least square method in Excel. The green line represents the Gumbel distribution with Gumbel parameters found from the moment method.

The line tension results fit both distributions. The extreme results fit the green line best (moment method), so the moment method Gumbel parameters will be used to find the annual probability of line failure. The Gumbel parameters and the associated Gumbel distribution for the short term description are presented by Equation 4.3.

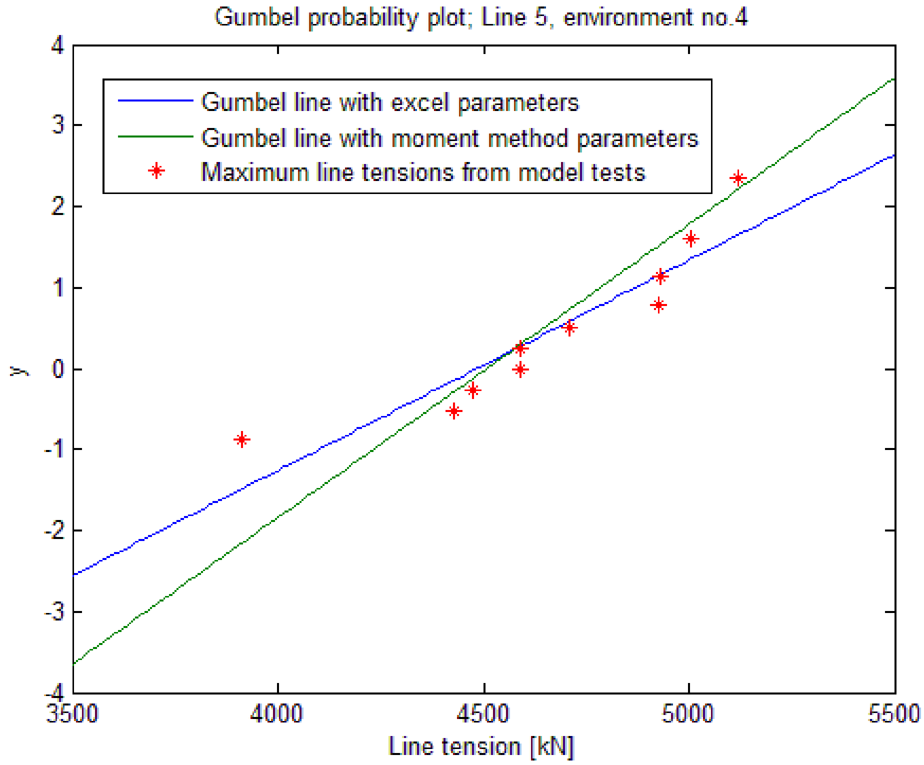

Figure 10 Gumbel probability plot - line 5 environment no. 4

$$\left.\begin{aligned} a &= \frac{1}{\beta} = 0,0036 \\ b &== -\frac{\alpha}{\beta} = -16,33 \end{aligned}\right\} \quad \alpha = 4509, \beta = 276 \quad \rightarrow \quad F_{T_{100}\,3h|4}(t|4) = \exp\left\{-\exp\left(-\frac{t-4509}{276}\right)\right\}$$

Equation 4.3

By choosing the fractile discussed in the detailed environmental contour method description (see sub-chapter 3.3) be 0,90, the line tension value, $T^{(100)}$, for this environmental condition is found to be 5 130,3 kN (see Figure 11).

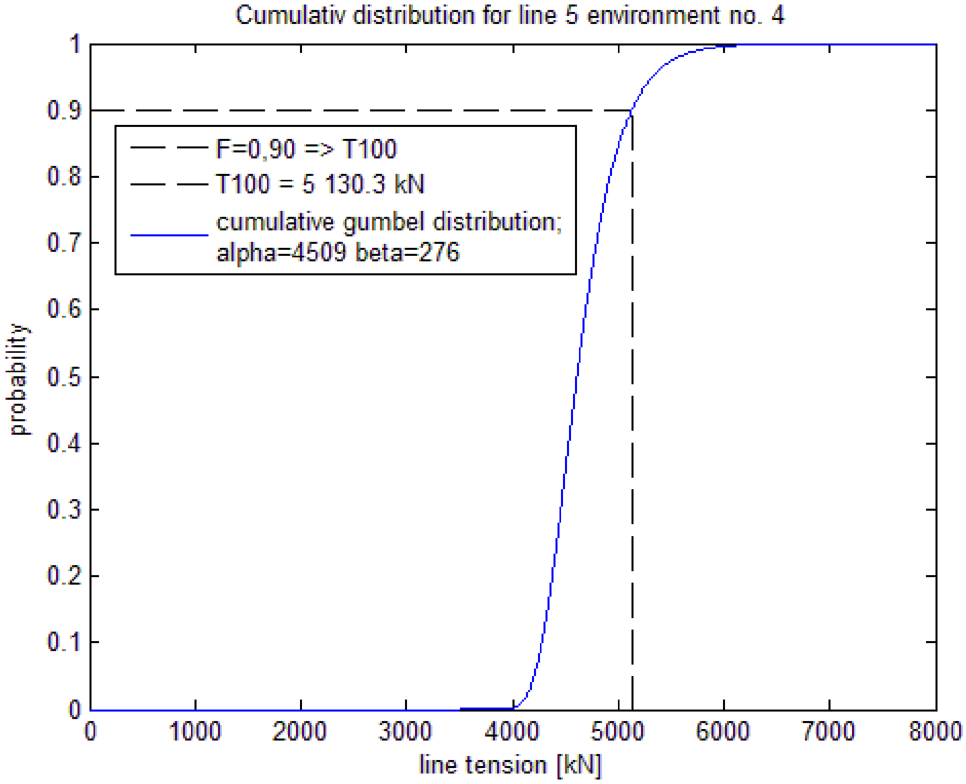

Figure 11 Cumulative distribution - line 5 environment no. 4

4.3.1.2. Maximum line tension distribution for environment no. 14

In total, there are 14 available model tests with environment no.14. How theses 14 line tensions are spread is illustrated in Figure 12. The spread for these results are greater than for the environment no.4. Here, the difference between the maximum and minimum measured tensions is approximately 3 000 kN.

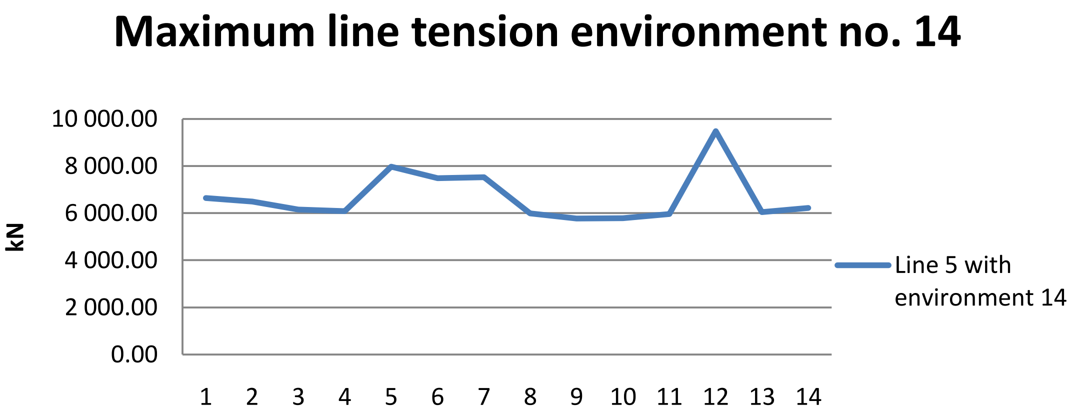

Figure 12 Maximum line tension results - line 5 environment no. 14

The maximum line tension results are assumed to be Gumbel distributed. The results are plotted in a Gumbel probability plot (see Figure 13). The figure also contains to Gumbel lines. The blue line represents Gumbel parameters found by the least square method in Excel, while the green line represents Gumbel parameters found by the moment method. The blue line (Excel) seems to fit the line tensions the best, especially the highest measured tension. Because of this, the Excel parameters will be used as the short term distribution for maximum line tensions for environment no.14 (see Equation 4.4)

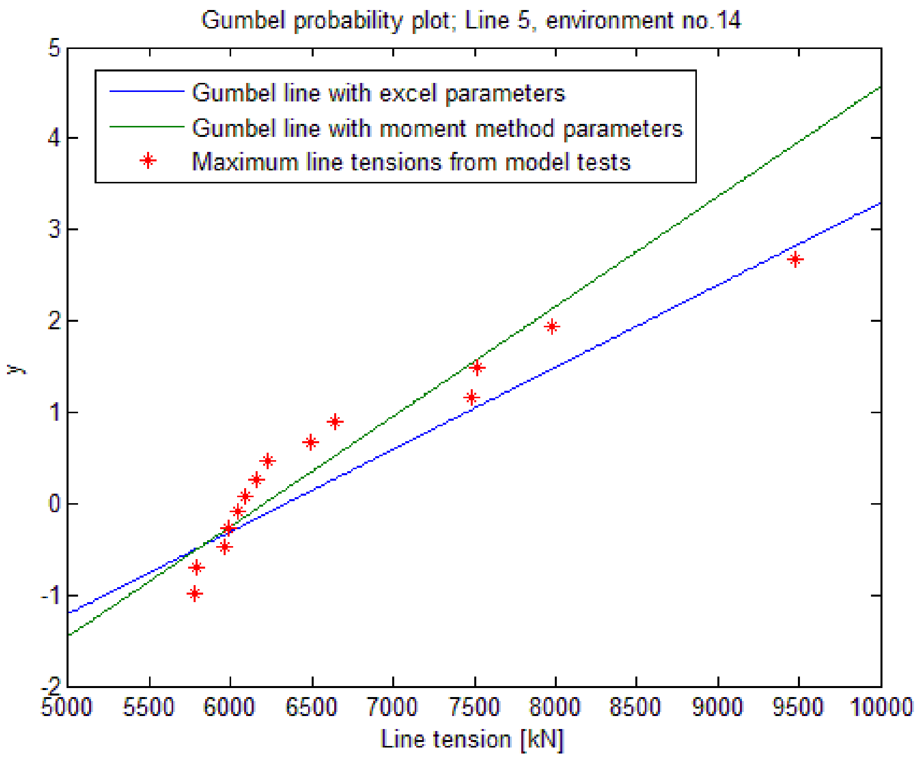

Figure 13 Gumbel probability plot - line 5 environment no. 14

$$\left.\begin{aligned} a &= \frac{1}{\beta} = 0{,}0009 \\ b &== -\frac{\alpha}{\beta} = -5{,}7064 \end{aligned}\right\} \alpha = 6340, \beta = 1111 \quad \rightarrow \quad F_{T_{10\,000}3h|14}(t) = \exp\left\{-\exp\left(-\frac{t-6340}{1111}\right)\right\}$$

Equation 4.4

By choosing the fractile to be 0,90 the line tension value, $T^{(10\,000)}$ for environment no.14 is found to be 88470,9 kN (see Figure 14).

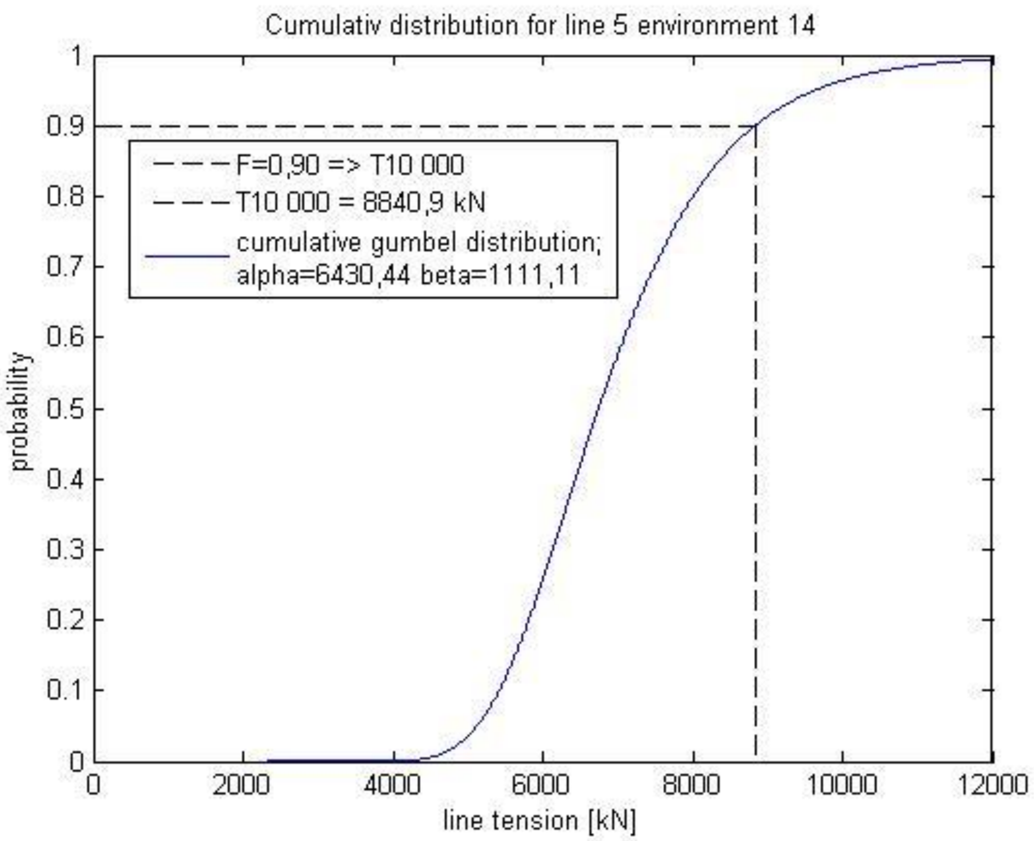

Figure 14 Cumulative distribution - line 5 environment no. 14

4.3.1.3. Long term distribution of T_1

With the two line tensions $T^{(100)}$ and $T^{(10\,000)}$, the long term distribution of T_1 can be simplified by solving the following equation:

$$\left.\begin{aligned} F_{T_1}(t) &= \exp\left\{-\exp\left(-\frac{5130,3-\alpha}{\beta}\right)\right\} = 0,9900 \\ F_{T_1}(t) &= \exp\left\{-\exp\left(-\frac{8840,9-\alpha}{\beta}\right)\right\} = 0,9999 \end{aligned}\right\} \qquad F_{T_1}(t) = \exp\left\{-\exp\left(-\frac{t-6366}{269}\right)\right\}$$

Equation 4.5

4.3.2. Annual probability of failure with various safety factors

The annual probability of failure depends on the safety factor, s (see Equation 4.1). In Chapter 2, safety factors for mooring line tensions for vessels under Norwegian jurisdiction are discussed (see Table 11 and Table 12) and the definitions for consequence classes are described (see Table 9). Here, these safety factors will be used to determine the annual probability of line failure, by using the characteristic line load and long term distribution estimated above.

The Midgard platform is a production platform i.e. the mooring lines are permanent. The safety factors for permanent moorings line are according to the **Anchoring Regulation 09**, ref. (3), as stated in Table 11. The annual probability of failure with the safety factors form the table, are presented in Table 24.

Permanent mooring lines (intact)	Class 3	Class 2	Class 1
Safety factor (AR09)	2,20	2,00	1,50
P(annual line failure)	$4{,}9*10^{-7}$	$1{,}6*10^{-5}$	0,09

Table 24 Annual probability of failure for permanent mooring lines with safety factors from AR09

If the Midgard platform was a drilling platform (mobile mooring lines) the safety factors would, in accordance with the **ANCHORING REGULATION 09**, ref. (3), be given by Table 12. The estimated annual probabilities of line failure with the safety factors for mobile moorings are presented in Table 25.

Mobile mooring lines (intact)	Class 3	Class 2	Class 1
Safety factor (AR09)	1,90	1,80	1,50
P(annual line failure)	$9{,}0*10^{-5}$	$5{,}1*10^{-4}$	0,09

Table 25 Annual probability of failure for mobile mooring lines with safety factors from AR09

In Chapter 2, the difference between the safety factors given by **ISO 19901-7 (2005)** in Annex B and the **ANCHORING REGULATION 09** is debated. The safety factors from ISO Annex B are modified to suite the 100 year environment. These modified safety factors and their associated annual probability of line failure are presented in Table 26.

Mobile mooring lines (intact)	Class 3	Class 2	Class 1
Safety factor (ISO Annex B)	1,83	1,67	1,39
P(annual line failure)	$3{,}0*10^{-4}$	$4{,}9*10^{-3}$	0,47

Table 26 Annual probability of failure for mobile moorings with safety factors from ISO Annex B

Table 27 presents the annual probability of line failure, P_f, for various safety factors by a logarithmic scale.

Safety factor	P_f	-log 10(P_f)
1,5	0,08945	1,048
1,6	0,01635	1,786
1,7	0,00290	2,538
1,8	0,00051	3,292
1,9	8,98E-05	4,047
2,0	1,58E-05	4,801
2,1	2,78E-06	5,556
2,2	4,89E-07	6,310

Table 27 Annual probability of line failure (logarithmic) with various safety factors

Note that the annual probability of line failure presented in this chapter is just an indication. For the values to be more exact, other uncertainties, like material strength, must also be considered.

4.3.3. Correction for not using the worst sea state

When finding the annual probability of line failure, it's necessary to consider the sea state which produces the larger line tensions. As mentioned in sub-chapter 3.1, the environmental condition that produces the larger line tensions (environment no. 3 and 13) had only been tested twice. Because of the low number of data available, they are unsuitable for further statistical use. Since the annual probability is estimated by the use of less severe environment conditions (no. 4 and 14), the reliability of the results are somewhat uncertain.

A way to correct for the effect of using a less severe environment can be to find a factor to adjust the model test results by. E.g. by finding ratios for the average difference in maximal line tension between environment no. 3 and 4 and between environment no. 13 and 14.

To find a potential correction factor, Table 28 and Table 29 were be used. The tables show the maximum, minimum, average and mean value line tensions for environment no. 3, 4, 13 and 14. A likely correction factor the model test results from environment no.4 is 1,30.

For environment no. 14, however, it's difficult to find a good correction factors. The differences presented in Table 29 are quite spread. Mark that for the maximum results, environment no. 14's value is larger than environment no.13's. This is not the case for the average, minimum or the median. The explanation for this unexpected result is the low number of tests performed for environment no.13. Unfortunately, the number seems to be too low to even find a credible correction factor.

It seems likely that the correction factor should be larger for the 10 000 year environment (Table 29), than for the 100 year environment (Table 28). This is not the case for the results presented in the tables.

Finding a correction factor by this approach was not successful. However, the effect of not applying the most severe environment will be further investigated in sub-chapter 7.3 by the use of the computer program SIMO instead of the model test results.

Environment:	3	4	Diff.
	[kN]	[kN]	
Max	6 139,60	5 117,80	1,20
Min	5 966,00	3 912,60	1,30
Average	6 052,80	4 668,25	1,30
Median	6 052,80	4 649,30	1,30

Table 28 Difference: 3 vs. 4

Environment:	13	14	Diff.
	[kN]	[kN]	
Max	8 619,40	9 478,80	0,92
Min	7 101,80	5 777,80	1,23
Average	7 896,60	6 686,50	1,18
Median	7 896,60	6 189,50	1,28

Table 29 Difference: 13 vs. 14

4.4. Statistical uncertainty

The number of model test results has been an issue during the estimation of the long term distribution used for estimation of the annual probability of line failure. This sub-chapter investigates the statistical uncertainty of the estimated long term distribution and annual probability of line failure, due to the limited number of observed results, by using Monte Carlo simulations.

4.4.1. Monte Carlo Simulations

Monte Carlo is a method to generate random samples. Here, the method will be used to generate random samples from the Gumbel distributions found in sub-chapters 4.3.1.1 and 4.3.1.2.

The long term distribution for the model test results are estimated by the environmental contour method; hence the 90 % fractile of the short term distribution of the 100 and 10 000 year environment are used as the basis for the long term distribution. The spread of the simulated 90 % line tensions for both 10 and 10 000 year will be investigated, as well as the spread of the simulated annual probability of line failure.

4.4.1.1. Monte Carlo Simulation for environment no.4

For the measured results for environment no.4, the tensions can be fitted to a Gumbel distribution on the form:

$$F_{T_{100}3h|4}(t|4) = \exp\left\{-\exp\left(-\frac{t-4509}{276}\right)\right\}$$

Equation 4.6

10 simulations with 10 number of observations[5] are simulated in MATLAB, by letting $F_{T1003h}(t)$ be a random number between 0 and 1 (see Equation 4.7).

$$t_{simulation} = 4509 + 276 \cdot (-\ln(-\ln(rand)))$$

Equation 4.7

The simulated line tensions for environment no.4 are presented in Table 30.

[kN]	Samples									
Observations	1	2	3	4	5	6	7	8	9	10
1	4 947	4 339	4 747	4 800	4 562	4 439	4 855	4 993	4 497	4 247
2	5 148	5 479	4 176	4 167	4 519	4 772	4 423	4 422	4 974	4 213
3	4 309	5 373	5 009	4 440	4 873	4 747	4 615	4 946	4 681	4 635
4	5 172	4 599	5 250	4 199	4 916	4 344	4 793	4 414	4 651	4 892
5	4 724	4 924	4 771	4 275	4 366	4 300	5 105	5 230	5 185	5 250
6	4 276	4 324	4 863	4 961	4 602	4 609	5 387	4 495	4 447	4 312
7	4 441	4 549	4 844	4 788	4 568	5 390	4 649	4 375	4 862	4 667
8	4 648	5 180	4 527	4 471	4 738	4 488	4 321	4 420	4 858	4 586
9	5 375	4 911	4 747	5 330	4 804	4 681	4 331	4 709	4 518	4 098
10	5 429	5 389	4 352	4 174	4 859	4 397	4 425	4 589	4 666	4 486

Table 30 Monte Carlo Simulated results, environment no. 4

[5] Same number of observations as the model test

Each sample is fitted to a Gumbel distribution by the least square method in Excel and the cumulative distribution is plotted in MATLAB. The result can be seen in Figure 15 including the original distribution. The 90 % fractile line is marked on the figure to illustrate the spread in 90 % value for the ten samples.

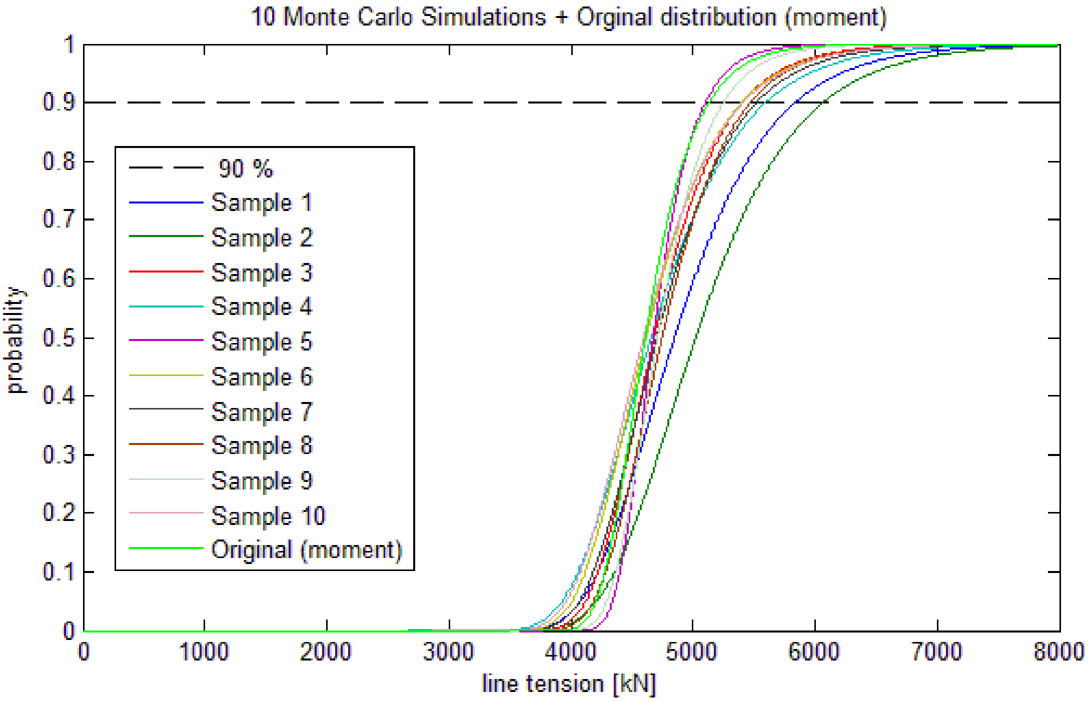

Figure 15 Cumulative distributions of simulated observations

Table 31 presents the maximum and minimum 90 % line tension value and compares it to the estimated 90 % model test value (moment method). The difference of approximately 1 000 kN for the maximum and minimum values indicate a significant spread in values. The difference from the maximal 90 % value to the minimum value is about 20 %.

	$T_{F=0,90}$
Simulated max:	6 070,82 kN
Simulated min:	5 102,81 kN
Model test:	5 130,30 kN

Table 31 90% fractile line tension results

Figure 16 shows a Gumbel plot of all the sample distributions and the original distributions. Sample 5 separates itself the most from the rest of the distributions.

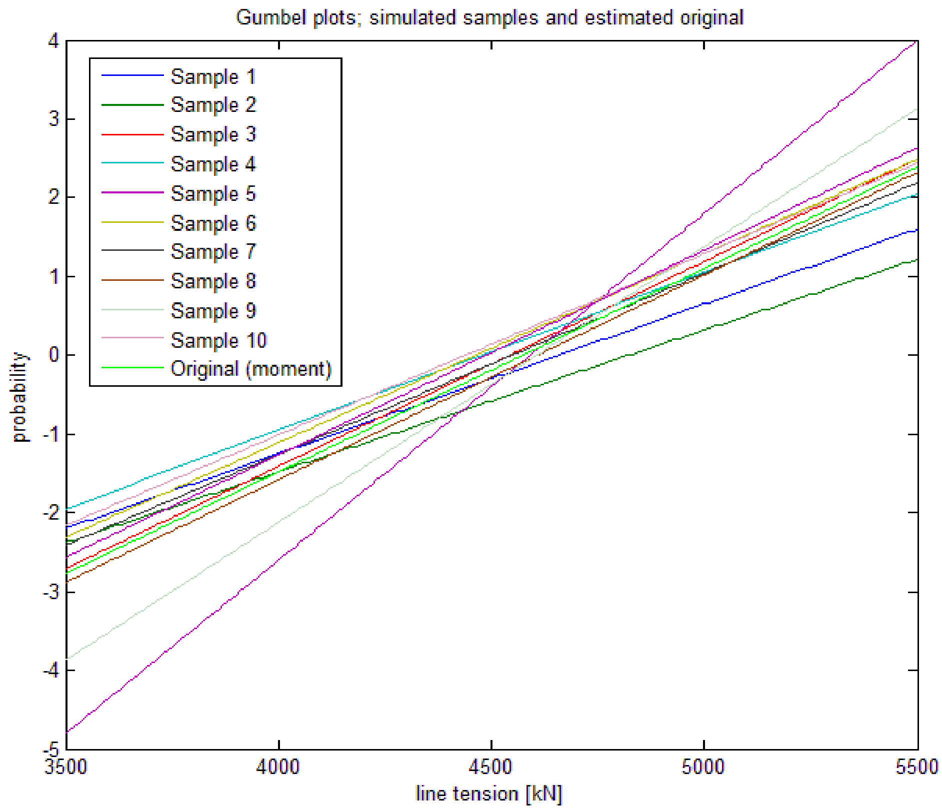

Figure 16 Simulated sample and original in Gumbel plot

Because of the spread there are uncertainties associated with the 90 % fractile and the use of the environmental contour method for estimating the annual probability of line failure with the given model test results.

4.4.1.2. Monte Carlo Simulations for environment no.14

For the measured results for environment no. 14, the line tensions are fitted to a Gumbel distribution on the form[6]:

$$F_{T_{10\ 000}3h|14}(t|14) = \exp\left\{-\exp\left(-\frac{t-6340}{1111}\right)\right\}$$

Equation 4.8

10 simulations with 14 number of observations[7] are simulated in MATLAB, by letting $F_{T(10\ 000)3h}(t)$ be a random number between 0 and 1 (see Equation 4.9).

$$t_{simulation} = 6340 + 1111 \cdot (-\ln(-\ln(rand)))$$

Equation 4.9

[6] See Chapter 4.3.1.2 for details

[7] Same number of observations as the model test

The simulated line tensions are presented in Table 32.

[kN]	Samples									
Observations	1	2	3	4	5	6	7	8	9	10
1	4 472	8 524	6 490	5 396	7 267	6 706	8 587	6 168	5 885	5 936
2	7 859	7 014	5 119	5 556	6 593	6 547	6 913	9 151	5 494	6 618
3	8 119	6 912	8 873	9 472	6 902	6 581	7 170	6 530	6 124	9 985
4	8 519	5 609	9 527	9 790	6 123	6 154	7 040	5 758	6 192	6 901
5	5 335	8 384	6 719	6 999	7 698	6 775	5 838	8 899	6 511	6 816
6	6 437	7 168	6 713	5 190	5 773	6 782	6 138	10 662	6 773	5 918
7	6 009	6 289	6 249	5 928	7 428	8 121	6 656	6 556	5 341	6 712
8	8 007	6 790	8 841	6 296	5 754	7 975	5 914	5 466	6 017	7 176
9	6 533	6 443	6 345	8 146	6 342	7 254	8 314	6 003	8 013	7 395
10	8 972	5 288	5 466	4 753	7 182	6 373	5 794	6 464	4 938	6 424
11	5 748	5 945	7 889	5 067	7 889	8 081	5 899	7 068	9 236	6 339
12	6 021	5 520	6 407	5 701	5 317	6 855	5 707	6 016	7 627	11 246
13	5 611	5 755	5 951	7 273	9 245	6 289	5 905	7 097	6 711	5 022
14	5 573	5 945	6 449	7 633	7 863	9 413	6 546	7 537	7 010	8 678

Table 32 Monte Carlo Simulated results, environment no. 14

Each sample is fitted to a Gumbel distribution and the cumulative distribution is plotted in MATLAB. The plot can be seen in Figure 17. The figure illustrates that the value of the 90 % fractile is relatively spread.

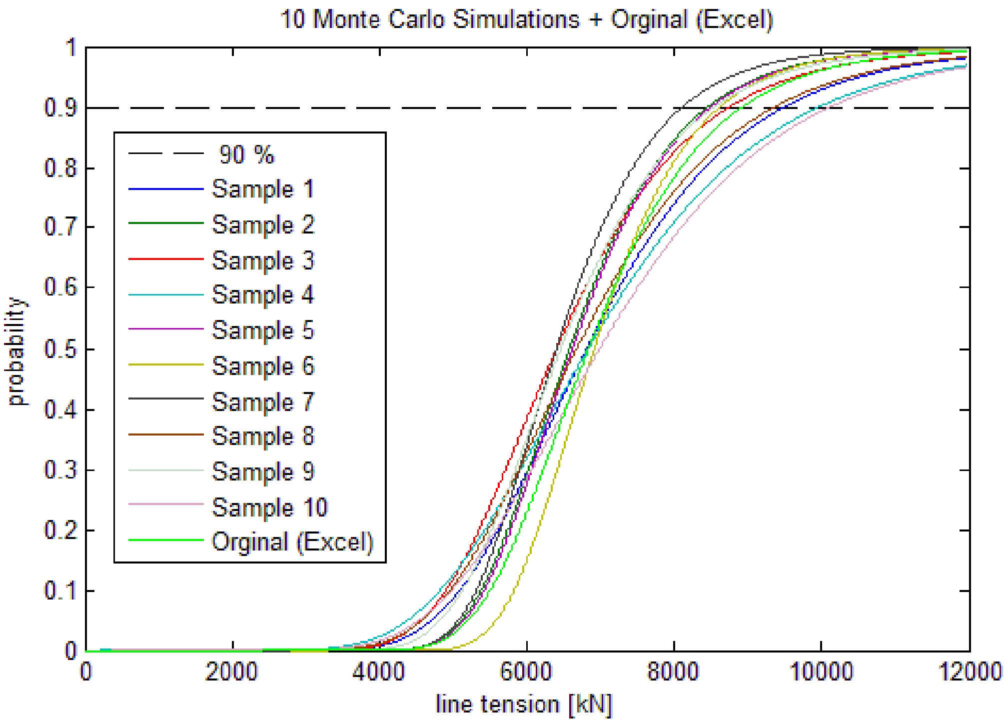

Figure 17 Cumulative distribution of simulated observations and original distribution

Table 33 compares the maximum and minimum 90 % line tensions indicated in Figure 17 by the crossing with the dotted line. The table states that the difference from the maximum 90 % fractile line tension to the minimum is approximately 2 000 kN.

	$T_{F=0,90}$
Simulated max:	10 126,78 kN
Simulated min:	8 118,15 kN
Model test:	8 840,90 kN

Table 33 90% fractile line tension results

A Gumbel plot or the simulated distributions and the original distribution is shown in Figure 18. Here you see that the spread is especially large for the high tension values, like the 90 % fractile value. The 90 % fractile estimated in sub-chapter 4.3.1.2 can, on the basis of the above discussed matters, therefore be said to be uncertain.

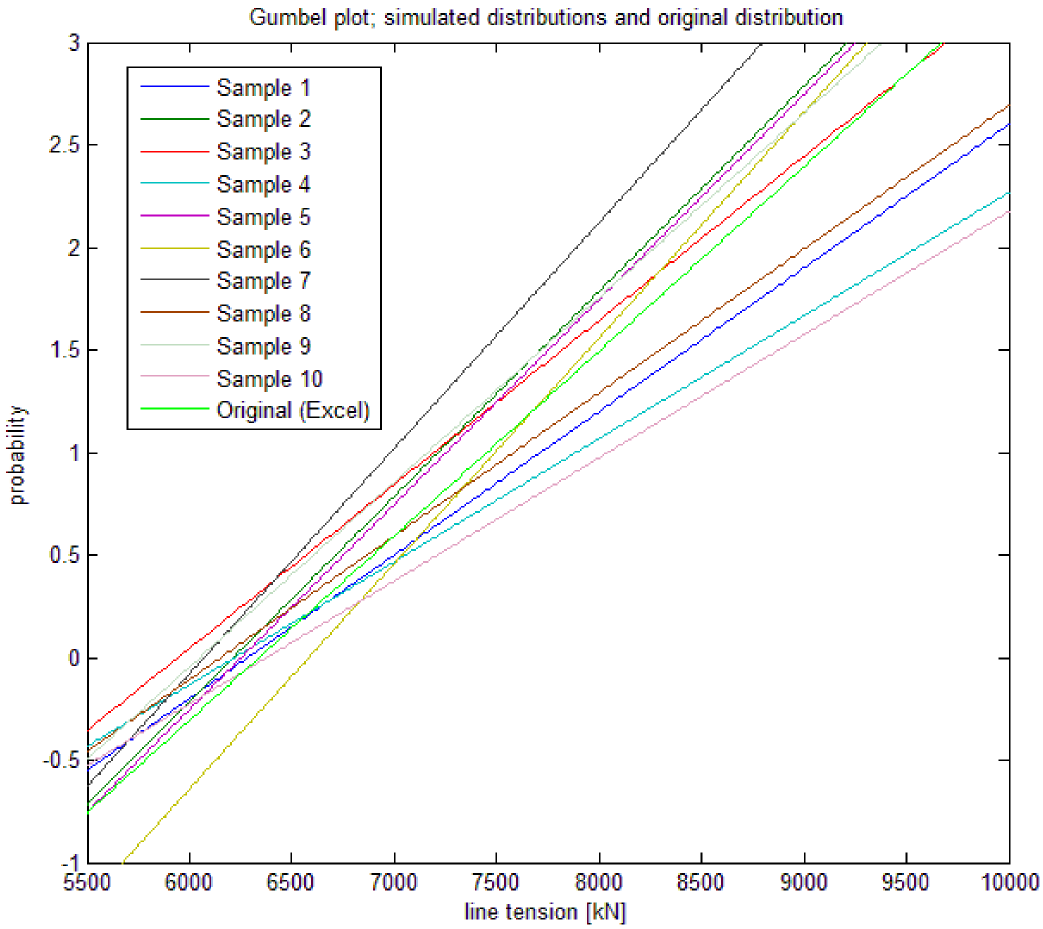

Figure 18 Simulated and original distribution in a Gumbel plot

4.4.1.3. Simulated annual probability of line failure

As for the model test results, the contour line method has been used to estimate the annual probability of line failure for the Monte Carlo simulated line tensions. The result can be seen in Table 34 and Table 35. The tables indicate the spread in annual probability estimates for eight different safety factors (see the maximum and minimum annual probabilities). The spread is, as expected, greater for the lower safety factors.

	Annual probability of line failure							
Safety factor	**1,5**	**1,6**	**1,7**	**1,8**	**1,9**	**2,0**	**2,1**	**2,2**
Sample 1	0,3645	0,0701	0,0116	0,0019	0,0003	4,8E-05	7,7E-06	1,2E-06
Sample 2	0,0570	0,0035	0,0002	0,0000	7,1E-07	4,2E-08	2,5E-09	1,4E-10
Sample 3	0,0912	0,0135	0,0019	0,0003	3,9E-05	5,6E-06	8,0E-07	1,1E-07
Sample 4	0,8624	0,3746	0,1051	0,0259	0,0062	0,0015	3,5E-04	8,2E-05
Sample 5	0,0404	0,0062	0,0009	0,0001	2,1E-05	3,1E-06	4,6E-07	6,9E-08
Sample 6	0,1366	0,0202	0,0028	0,0004	0,0001	7,5E-06	1,1E-06	1,5E-07
Sample 7	0,0315	0,0026	0,0002	1,2E-05	0,0000	1,2E-07	9,9E-09	8,2E-10
Sample 8	0,3692	0,0846	0,0168	0,0032	0,0006	0,0001	2,3E-05	4,4E-06
Sample 9	0,0422	0,0059	0,0008	0,0001	1,5E-06	2,2E-06	3,0E-07	4,1E-08
Sample 10	0,8141	0,3590	0,1109	0,0306	0,0082	0,0022	5,7E-04	1,5E-04
Average:	0,2809	0,0940	0,0251	0,0063	0,0015	0,0004	9,6E-05	2,4E-05
Min:	0,0315	0,0026	0,0002	0,0000	1,6E-05	4,2E-08	2,5E-09	1,5E-10
Max:	0,8624	0,3746	0,1109	0,0306	0,0082	0,0022	5,7E-04	1,5E-05
Standard deviation:	0,3199	0,1466	0,0440	0,0117	0,0030	0,0007	2,0E-04	5,2E-05

Table 34 Simulated annual probability of line failure

	$-\log(P_f)$							
Safety factor:	**1,5**	**1,6**	**1,7**	**1,8**	**1,9**	**2,0**	**2,1**	**2,2**
Sample 1	0,44	1,15	1,94	2,73	3,52	4,32	5,11	5,91
Sample 2	1,24	2,46	3,69	4,92	6,15	7,38	8,61	9,84
Sample 3	1,04	1,87	2,71	3,56	4,41	5,25	6,10	6,95
Sample 4	0,06	0,43	0,98	1,59	2,21	2,83	3,46	4,08
Sample 5	1,39	2,21	3,04	3,86	4,69	5,51	6,34	7,16
Sample 6	0,86	1,70	2,55	3,41	4,26	5,12	5,98	6,84
Sample 7	1,50	2,58	3,67	4,75	5,83	6,92	8,00	9,09
Sample 8	0,43	1,07	1,77	2,49	3,21	3,92	4,64	5,36
Sample 9	1,38	2,23	3,09	3,95	4,80	5,66	6,52	7,38
Sample 10	0,09	0,44	0,96	1,51	2,09	2,66	3,24	3,82
Average:	0,55	1,03	1,60	2,20	2,81	3,42	4,02	4,62
Min:	0,06	0,43	0,96	1,51	2,09	2,66	3,24	3,82
Max:	1,50	2,58	3,69	4,92	6,15	7,38	8,61	9,84
Standard deviation:	0,55	0,80	1,00	1,18	1,37	1,56	1,75	1,94

Table 35 Simulated annual probability of line failure, $-\log_{10}$

The information from Table 35 has been plotted in Figure 19 to better illustrate the difference in probability for the various samples and their dependent safety factors. From this diagram it’s clear that for safety factor 2,2, there are great differences in the probability for the various samples. Especially sample 2 and 7 stand out with considerably lower probability for line failure than the rest.

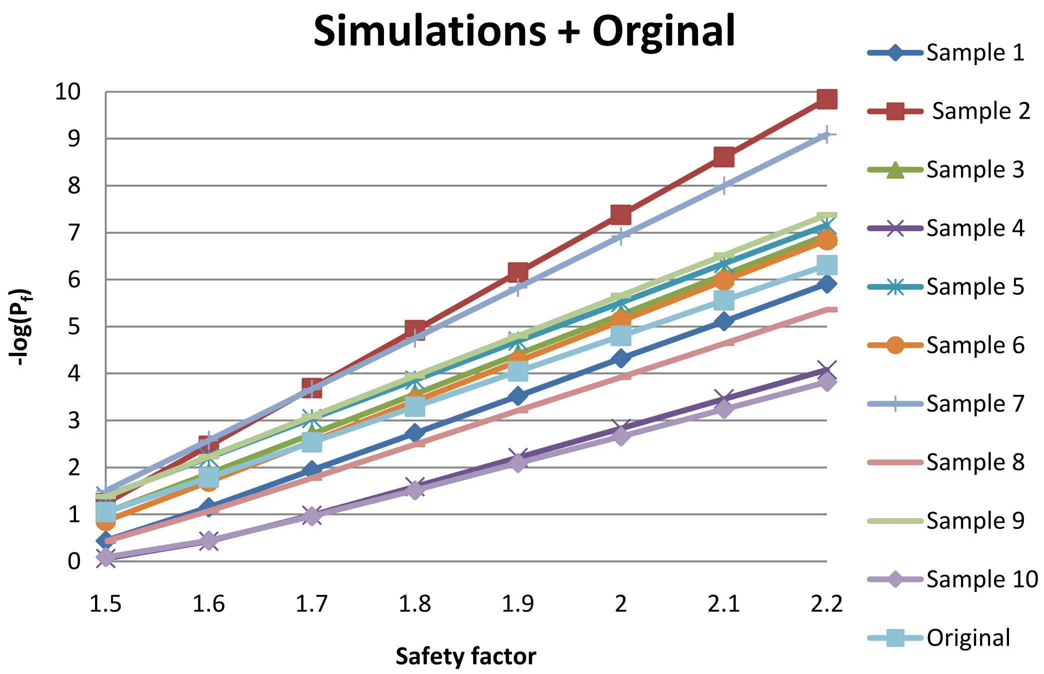

Figure 19 Log plot, simulated + original annual probabilities of line failure

4.4.2. Statistical uncertainty conclusion

Because of the low number of test results available for use in connection with the environmental contour line method for predicting the annual probability of failure, the statistical uncertainties of the annual probability results must be checked. Sub-chapter 4.4.1.1 states that the 90 % fractile used to estimate the long term distribution of T_1 (used to find the annual probability of line failure), has high uncertainties. The same is stated for the 90 % fractile in sub-chapter 4.4.1.2.

The simulated annual probability shows that for high safety factors, the spread in probability is large and the annual probability should be considered as uncertain.

On the basis of the considerations above, the annual probability of failure calculated in sub-chapter 4.3.2 has to high uncertainty to be regarded as anything else than an indication.

To be able to estimate the annual probability of line failure with less uncertainty, more model tests must be preformed. If this is to be done, the author suggests that the new model tests are performed for the environmental conditions with 315° wave heading, since this is the condition that will produce the largest line tensions.

5. Annual probability of line failure with SOMO simulations

In Chapter 4, the agenda was to find an estimate for the annual probability of line failure for the Midgard platform, based on model test results. In this chapter, the aim is also to estimate an annual probability of line failure for the Midgard platform. However, the estimate will now be based on line tension results from analysis by the computer program SIMO.

5.1.SIMO simulations

To analyze the platform movements and line tensions in SIMO, a sys-file was created. A sys-file contains all information regarding the platform specifications (including positioning systems) and the environmental specifications. The sys-file was created using a sif-file[8] (produced by Aker Solutions), and the SIMO module Inpmod. Information regarding the linear damping, wave drift forces, wind force coefficients, quadratic current force coefficients, positioning system and environmental specifications were added to the sys-file manually. The linear damping, wave drift forces, wind force coefficients and quadratic current force coefficients were provided by Aker Solutions while the positioning system[9] and environmental specifications[10] was produced by the author.

The environmental conditions to be used in SIMO are the same 100 and 10 000 year values used in Chapter 4 for calculation of the annual probability of failure (see environment no. 4 and 14 in Table 19).

5.1.1. Verification of the SIMO results

To make sure that the created sys-file gives satisfactory results, the linear damping, offset and line tensions are discussed in the following sub-chapters.

Linear damping

The linear damping was provided by Aker Solutions, as can be seen in the table below.

	1	2	3	4	5	6
1	718,00	0,00	0,00	0,00	-899,70	0,00
2	0,00	718,20	0,00	899,60	0,00	0,00
3	0,00	0,00	-0,07	0,00	0,00	0,00
4	0,00	843,30	0,00	1061,00	0,00	0,00
5	-843,30	0,00	0,00	0,00	1063,00	0,00
6	0,00	0,00	0,00	0,00	0,00	1 470 000,00

Table 36 Linear damping from Aker Solutions

When this damping was implemented in the sys-file, the dynamic analysis in SIMO failed. The damping in surge, sway and heave was adjusted to stabilize the platform. The adjusted linear damping was used for all calculations presented in this report and can be seen in Table 37. The adjustment for the damping was done in cooperation with Knut Mo at MARINTEK.

[8] A .SIF-file is produced by a global response analysis is Wadam. It contains transfer functions for rigid body responses together with transfer functions for off-body kinematics and the rigid body matrices, ref. (16).
[9] Presented in Appendix C.a
[10] Presented in Appendix C.b

	1	2	3	4	5	6
1	1 000,00	0,00	0,00	0,00	-899,70	0,00
2	0,00	5 000,00	0,00	899,60	0,00	0,00
3	0,00	0,00	1 000,00	0,00	0,00	0,00
4	0,00	843,30	0,00	1 061,00	0,00	0,00
5	-843,30	0,00	0,00	0,00	1 063,00	0,00
6	0,00	0,00	0,00	0,00	0,00	1 470 000,00

Table 37 Linear damping used in report

Offset

The platform is model in SIMO as can be seen in Figure 20.

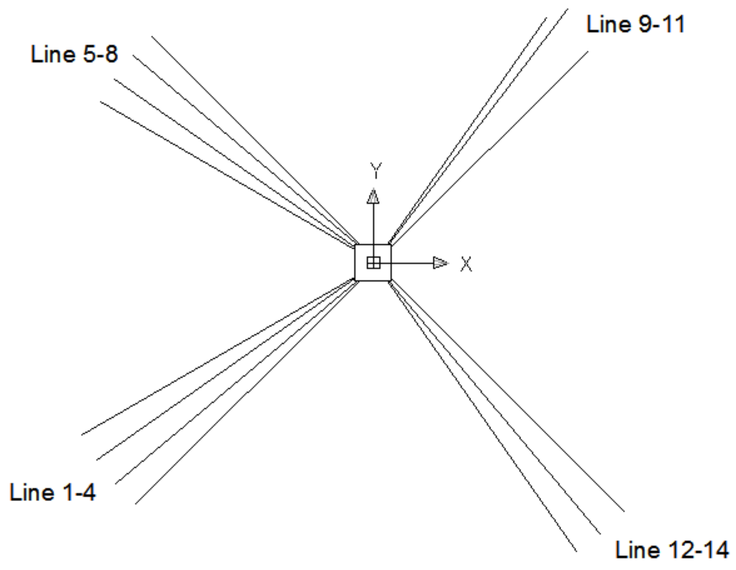

Figure 20 Mooring lines

The platform should move in the direction the wind, wave and current propagate in. The maximum line tension should be found in the lines opposite of the movement. A table with the (mean) x-position and y-position from SIMO with various propagation directions can be seen in Table 38. The table indicates that the platforms movement is as expected according to the environmental propagation directions.

	SIMO		MODEL TEST	
Direction [°]	X [m]	Y [m]	X [m]	Y [m]
0	27,63	0,36	31,01	0,33
90	-1,49	25,09	-	-
180	-33,06	-0,50	-	-
270	-0,21	-24,45	-	-

Table 38 Mean drift and direction with environment no.4

Compared with the model tests (only test available for 0 degrees), we see from Table 38, that the displacement in x-direction from SIMO is smaller than for the model test. To compensate for this, the wind speed is increased by 10 %. Results where the wind speed is increased will be marked with *. It can be seen from Table 39 that the 10 % increase in wind speed gives the SIMO results greater coherence with the model test results. Even the standard deviation is within the same region.

Environment no.4	SIMO*		MODEL TEST	
	X [m]	Y [m]	X [m]	Y [m]
MIN	16,65	-0,39	15,98	-4,32
MAX	53,01	1,26	52,24	2,32
MEAN	30,97	0,43	31,01	0,33
Standard deviation	4,76	0,30	5,13	1,02

Table 39 SIMO* and Model test offset, environment no.4*/4

The total surge motion of the platform from SIMO with environment no.4* can be seen in Figure 21. The motion is as expected from the values presented in Table 39.

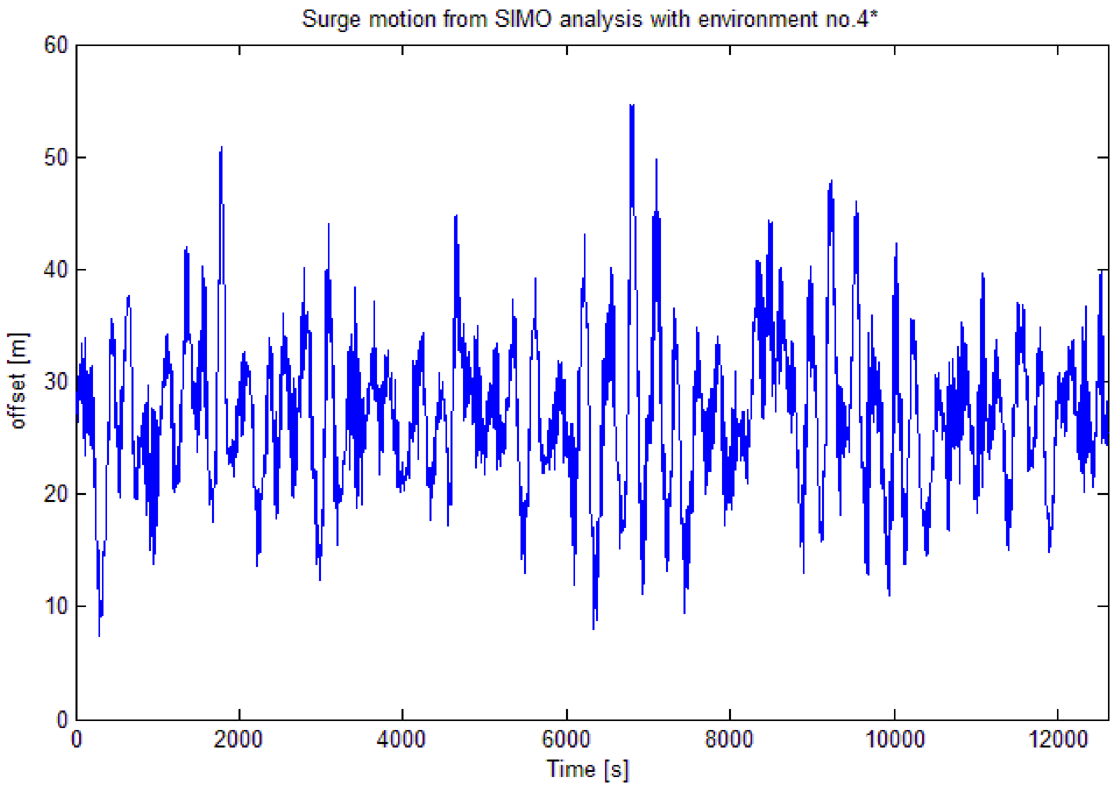

Figure 21 Surge time series (environment no.4*)

Platform offset with no wind or waves is presented in Table 40. As expected, the movement is almost non-existence for this case. There are no model test results for this case and a comparison between the SIMO and model test results cannot be made.

	min	max	mean
X-Translation LF-motion	2,754	2,754	2,754
Y-Translation LF-motion	-5,83E-02	-5,83E-02	-5,83E-02
Z-Translation LF-motion	-2,188	-2,188	-2,188
X-Rotation LF-motion	-6,27E-03	-6,22E-03	-6,25E-03
Y-Rotation LF-motion	-2,659	-2,659	-2,659
Z-Rotation LF-motion	-2,99E-04	-2,94E-04	-2,97E-04

Table 40 Platform offset with no wind or waves

Platform offset with no current or waves (i.e. only wind*) are presented in Table 41. The table indicates that the wind is important for the total mean drift (see Table 39) of the platform.

	min	max	mean
X-Translation LF-motion	8,327	37,8	22,84
Y-Translation LF-motion	1,85E-02	1,701	0,8111
Z-Translation LF-motion	-2,478	-2,024	-2,236
X-Rotation LF-motion	-0,7216	0,7305	2,30E-02
Y-Rotation LF-motion	-6,135	-2,032	-4,208
Z-Rotation LF-motion	-3,395	0,1289	-1,531

Table 41 Platform offset with no current or waves*

The surge motion of the platform when subjected to wind speed 39,6 m/s of 0° are presented in Figure 22. It emphasizes the values from Table 41.

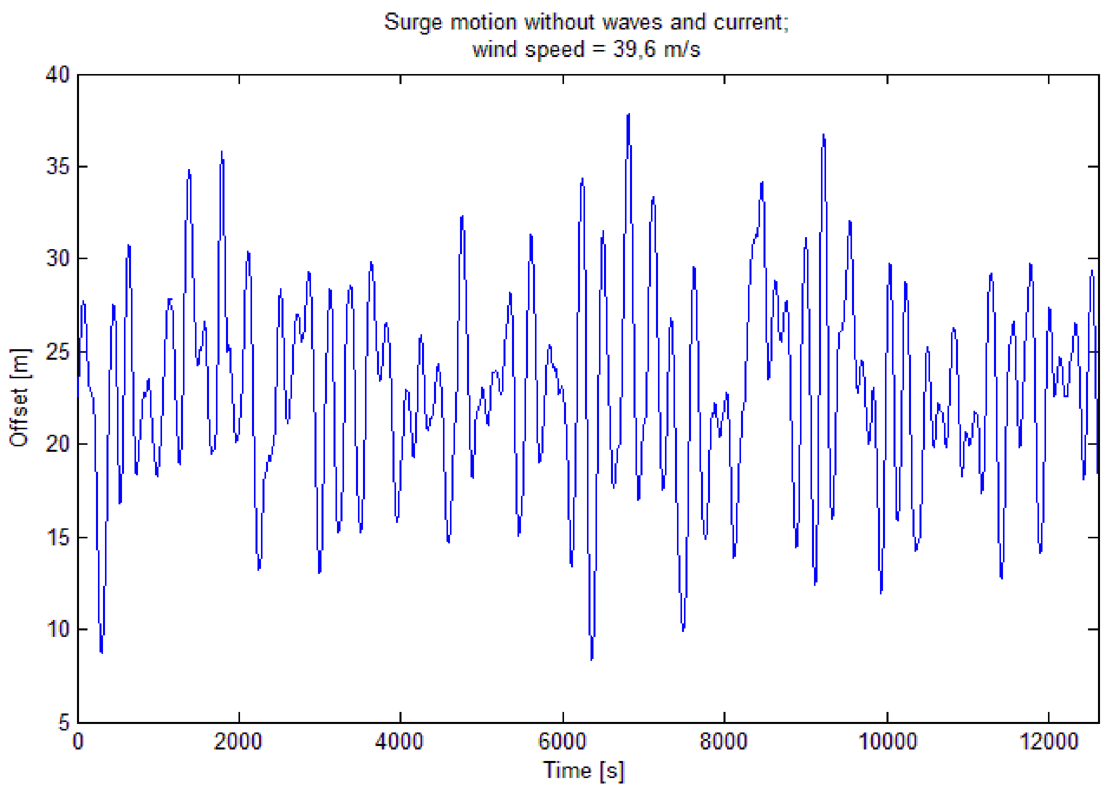

Figure 22 Surge time series, only wind*

Platform offset with no current or wind (i.e. only waves) is presented in Table 42. The table indicates that waves are less important than wind in terms of mean drift. The dynamic amplitude for pure waves is more than double the amplitude for pure wind, indicating that the dynamic amplitude for the total offset is mainly dominated by the waves.

	min	max	mean
X-Translation Total motion	-16,52	25,08	3,559
Y-Translation Total motion	-8,39E-02	1,82E-02	-8,80E-03
Z-Translation Total motion	-10,82	6,651	-2,196
X-Rotation Total motion	-1,92E-02	1,04E-02	-1,23E-03
Y-Rotation Total motion	-8,587	3,849	-2,673
Z-Rotation Total motion	-8,11E-02	4,13E-02	-1,24E-02

Table 42 Platform offset with waves only

Line tension

The platform movement when wind, wave and current propagate in positive x-direction (0 degrees) is illustrated by Figure 23. The turquoise square marks the original position.

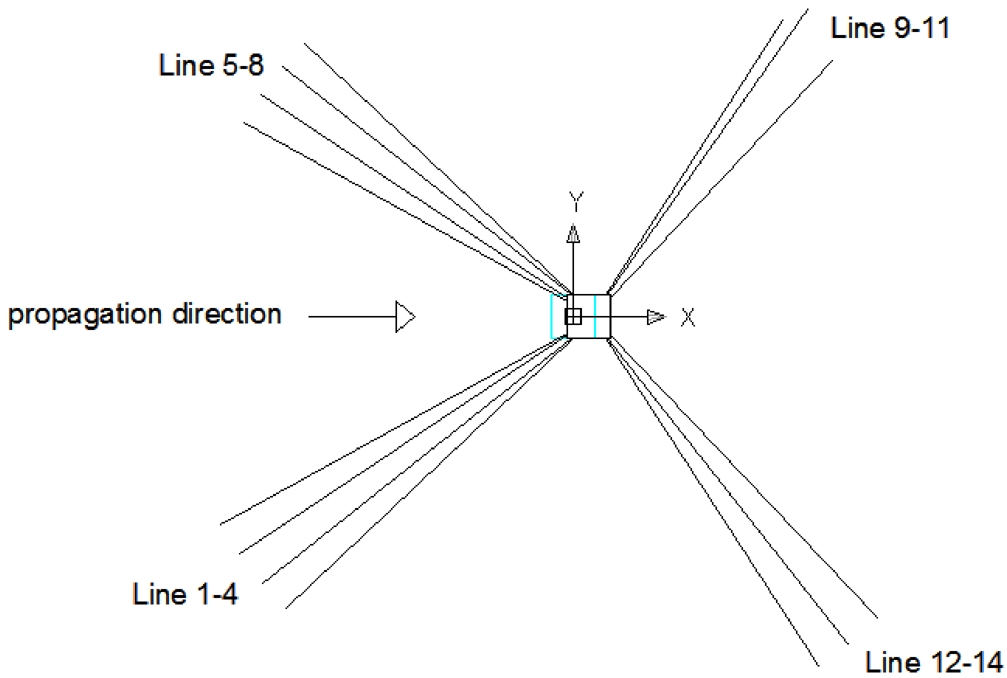

Figure 23 Platform displacement

From Figure 23, it’s clear that when the environmental forces are propagating along the positive x-axis, lines from 1-8 will have greater tension than lines from 9-14. Table 43 confirms this. It presents the maximum line tensions for propagation direction 0 (environment no.4*).

Hs	14,9	14,9	[m]	
Tp	15,7	15,7	[s]	
Current	0,9	0,9	[m/s]	
Wind	36,0	39,6	[m/s]	
Environment	4	4*	[-]	
Line:	Model test [kN]	SIMO [kN]	Diff. [kN]	Diff. [%]
1	4 258	3 347	911	27 %
2	4 292	3 542	750	21 %
3	4 510	3 735	775	21 %
4	4 683	3 956	727	18 %
5	4 590	3 975	615	15 %
6	4 397	3 740	657	18 %
7	4 161	3 564	597	17 %
8	3 898	3 355	543	16 %
9	2 586	2 103	483	23 %
10	2 517	2 079	438	21 %
11	2 451	2 062	389	19 %
12	2 467	2 068	399	19 %
13	2 514	2 090	424	20 %
14	2 525	2 114	411	19 %

Table 43 SIMO and Model test maximum line tension results for environment no. 4/4*

From Table 43, it can be seen that the results obtained by SIMO don't match the model test results for the corresponding environments no. 4 and 4*. The line tension values are about 20 % larger for the model test maximal values than the maximum SIMO values.

Table 44 compares the 10 000 year values (environment no. 14 and 14*) from the model tests with the SIMO results. As for the 100 year line tensions, there is a gap between the SIMO and model test results. The difference is also here about 20 %. Note that for the most exposed line (Line 5), the difference is only 13 %.

Hs	20,2	20,2	[m]	
Tp	21,0	21,0	[s]	
Current	0,9	0,9	[m/s]	
Wind	36,0	39,6	[m/s]	
Environment	14	14*	[-]	
Line:	Model test [kN]	SIMO [kN]	Diff. [kN]	Diff. [%]
1	4 582	3 848	734	19 %
2	4 565	4 149	416	10 %
3	4 797	4 441	356	8 %
4	5 021	4 759	262	6 %
5	5 320	4 702	618	13 %
6	4 951	4 373	578	13 %
7	4 791	4 089	702	17 %
8	4 403	3 790	613	16 %
9	2 764	2 205	559	25 %
10	2 724	2 192	532	24 %
11	2 687	2 183	504	23 %
12	2 651	2 197	454	21 %
13	2 694	2 209	485	22 %
14	2 708	2 227	481	22 %

Table 44 SIMO and Model test maximum line tension results for environment no. 14/14*

Another ting to note regarding the line tensions, is the increase when moving from environment no. 4/4* (100 year values) to no. 14/14* (10 000 year values). The average line tension is 43 % higher for environment no. 14 than for environment no. 4. The increase is only 24 % for environment no. 4* and 14*. This means that the characteristic line load will be closer to the extreme loads for the SIMO results (4* and 14*) than for the model test results (4 and 14). This difference is as important as the line tension difference within the same return period (100 or 10 000) provided by Table 43 and Table 44. If this difference is comparable, the wind speed could be used to provide more or less the same line tensions.

The coefficient of variance of a line is the standard deviation of the line tension divided by the average line tension. The line tension coefficient of variance is presented in Table 45. For the 100 year storms (environment no. 4 and 4*), the coefficient of variance is smaller for the SIMO results than for the model test results, meaning that the SIMO results have more spread than the model test results. For the 10 000 year storm (environment no. 14 and 14*), the difference is larger, but here it's the other way around; the coefficient of variance is larger for the model test results than for the SIMO results, meaning that the SIMO results are less spread than the model test results. For the maximum line tension distributions from the model test and SIMO to be comparable, leading to the annual probability of line failures to be comparable, the coefficient of variance should be approximately the same.

It is expected that the coefficient of variance increases as the return period increases. However, the increase for the SIMO results is significantly lower than the model test results. This is also not a surprise, considering that the SIMO line tension values increase less from environment no. 4* to no. 14* than what is observed for the model test results.

	Coefficient of variance			
Result from	Model test	SIMO	Model test	SIMO
Environment no.	4	4*	14	14*
Line 5	0,0758	0,0495	0,1592	0,0971

Table 45 Coefficient of variance SIMO results vs. Model test results

Conclusion

The linear damping has been changed, from what Aker Solutions originally suggested. However, the changes are relatively small and done after consultation, ref. (10).

After adjusting the wind speed, the offset is approximately the same. However, the line tensions are still around 20 % lower than the model test results. The aim of this task is not to create a SIMO model that reproduces the exact same results as the model tests show, but to estimate the annual probability of line failure. The ideal situation is clearly that the results are as close as possible, but as important as the actual tension is the coefficient of variance. For both sea states, the coefficient of variance found in SIMO is different from the model test. For environment no. 4/4*, the

5.2.Performed simulations

20 analyses for environment no.4* was completed in SIMO and 20 analyses for environment no.14*. The simulations were executed by changing the random seed generator for wind and wave each simulation.

5.3. Characteristic line load

The characteristic line load is taken to be the average load of the most exposed line. As for the model tests, the SIMO results show that line 5 has the maximum line tension for all analysis. Line 4 has the highest average line tension. However, line 5 has the maximum result and it is therefore regarded as the most exposed line. The characteristic line load is as presented in Table 46.

Environment no.4*, Line 5		
Analysis no./Seed:		
1	3 975	kN
2	3 379	kN
3	3 393	kN
4	3 492	kN
5	3 375	kN
6	3 773	kN
7	3 800	kN
8	3 426	kN
9	3 449	kN
10	3 423	kN
11	3 824	kN
12	3 772	kN
13	3 486	kN
14	3 607	kN
15	3 635	kN
16	3 759	kN
17	3 474	kN
18	3 588	kN
19	3 578	kN
20	3 729	kN
Average (tc)	3 597	kN
Standard deviation	178	kN

Table 46 Maximum line tensions SIMO Line 5, environment no.4*

5.4. Annual probability of failure

To estimate the annual probability of line failure for the model created in SIMO, the environmental contour line method is used. The same method was used to estimate the annual probability of line failure on the basis of model test results (see chapter 4). The environmental contour line method is described in detail in sub-chapter 3.3.

5.4.1. Short term distribution for environment no.4*

The maximum line tensions for 20 SIMO analyses of line 5 of the Midgard platform was presented in Table 46. These maximum line tensions are plotted in a Gumbel plot (see red stars in Figure 24).

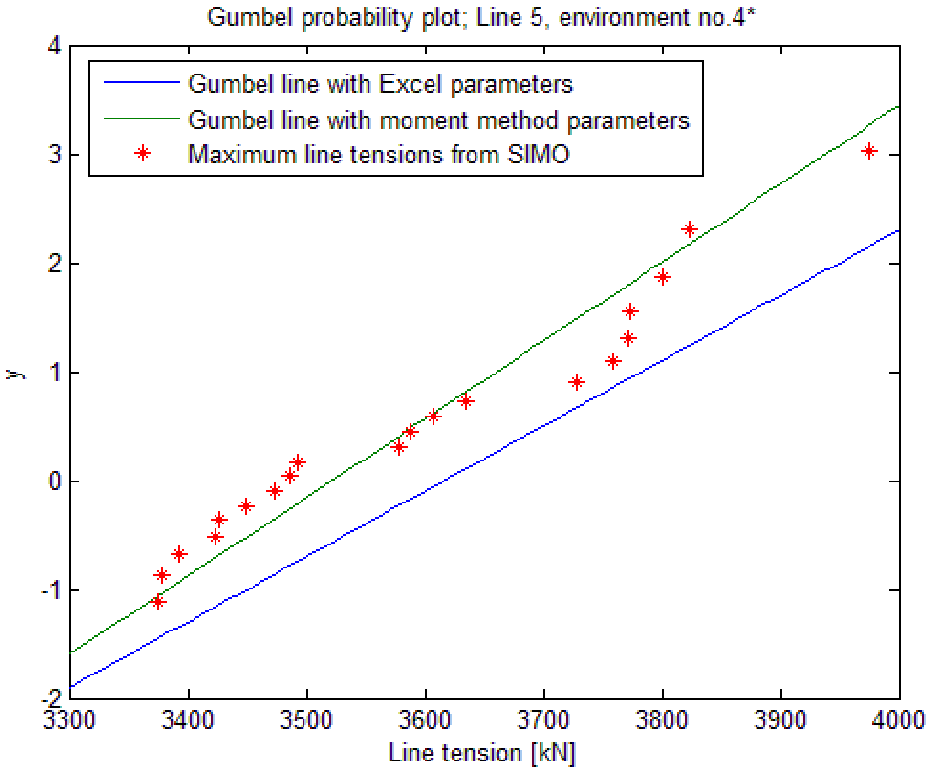

Figure 24 Gumbel plot, Line 5, Environment no.4*

Figure 24 also holds two Gumble lines. The green line is estimated based on the moment method, while the blue line is based on linear regression by Excel. The green line fits best to the maximum line tensions from SIMO, therefore the Gumbel parameters from the moment method will be used as the short term distribution.

$$\alpha = 3517, \beta = 139 \qquad \rightarrow \qquad F_{T_{100}3h|4^*}(t|4^*) = \exp\left\{-\exp\left(-\frac{t-3517}{139}\right)\right\}$$

Equation 5.1

From the short term distribution in Equation 5.1 with F=0,90, $T^{(100)}$, is 3 828,90 kN.

5.4.2. Short term distribution for environment no.14*

The most exposed line for environment no. 14* is line no.5. The maximum line tension for line 5 from each analysis can be seen in Table 47.

Environment no.14*		
Analysis no./Seeds:		
1	4 702	kN
2	3 757	kN
3	4 087	kN
4	4 488	kN
5	4 167	kN
6	5 410	kN
7	4 757	kN
8	4 390	kN
9	4 105	kN
10	4 120	kN
11	4 922	kN
12	4 818	kN
13	4 113	kN
14	4 357	kN
15	5 260	kN
16	4 967	kN
17	4 435	kN
18	4 679	kN
19	3 979	kN
20	4 496	kN
Average	4 500	kN
Standard deviation	437	*kN*

Table 47 Maximum line tension SIMO line 5, environment no.14*

The line tensions from Table 47 are plotted in a Gumbel plot together with two Gumbel lines in Figure 25. The line tensions are evenly spread and fit both the Excel Gumbel parameters and the moment method Gumbel parameters. The moment method Gumbel parameters seem to fit the values slightly better than the Excel Gumbel parameters. According to the Gumbel parameters found by the moment method, the short term distribution will be as follows:

$$\alpha = 4304, \beta = 341 \rightarrow \quad F_{T_{10\ 000}\,3h|14*}(t|14*) = \exp\left\{-\exp\left(-\frac{t-4304}{341}\right)\right\}$$

Equation 5.2

From the short term distribution with F=0,90, $T^{(10\ 000)}$, will be 5 071 kN.

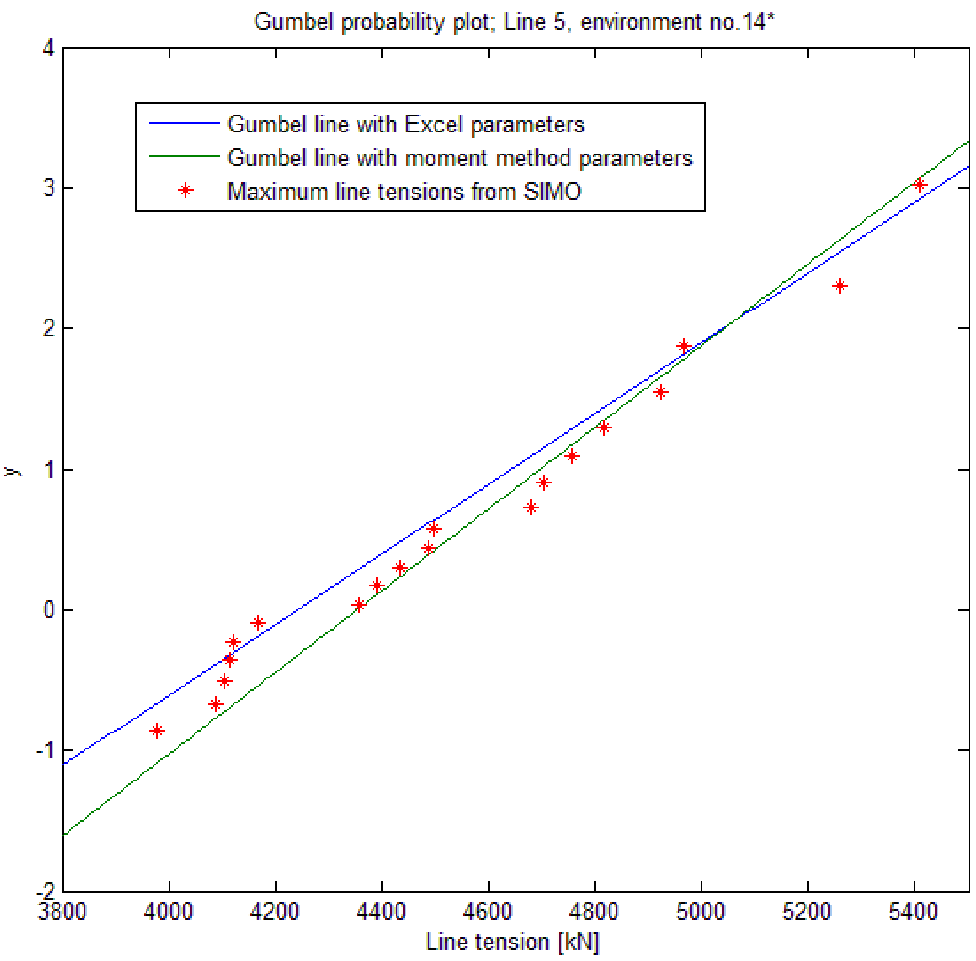

Figure 25 Gumbel plot, Line 5, Environment no.14*

5.4.3. Long term distribution of T_1

With the two line tensions, $T^{(100)}$ and $T^{(10\,000)}$ decided in the above sub-chapters, the long term distribution can, according to the environmental contour method, be estimated as:

$$\left.\begin{array}{l} F_{T_1}(t) = \exp\left\{-\exp\left(-\dfrac{3829-\alpha}{\beta}\right)\right\} = 0{,}9900 \\ F_{T_1}(t) = \exp\left\{-\exp\left(-\dfrac{5071-\alpha}{\beta}\right)\right\} = 0{,}9999 \end{array}\right\} F_{T_1}(t) = \exp\left\{-\exp\left(-\dfrac{t-4243}{90}\right)\right\}$$

Equation 5.3

5.4.4. Annual probability of line failure with various safety factors

The annual probability of line failure has been estimated with various safety factors. The results can be seen in Table 48. Note that for safety factor 2,1 and 2,2, the probability is zero. The –log10 scaling is not possible when a number is zero, hence the notation *#NUM!*.

Safety factor	P_f	-log 10
1,5	2,72E-06	5,57
1,6	4,98E-08	7,30
1,7	9,13E-10	9,04
1,8	1,67E-11	10,78
1,9	3,07E-13	12,51
2,0	5,66E-15	14,25
2,1	0	#NUM!
2,2	0	#NUM!

Table 48 Annual probability of line failure with varying safety factors (SIMO z=263 m)

5.5. Annual probability: SIMO vs. Model test

By comparing the estimated probability of line failure based on SIMO with the probability based on the model test results (see Figure 26), you see that the difference huge. The annual probabilities from SIMO are for any safety factors lower than the probability from the model test with safety factors until from 1,5 including 2,0.

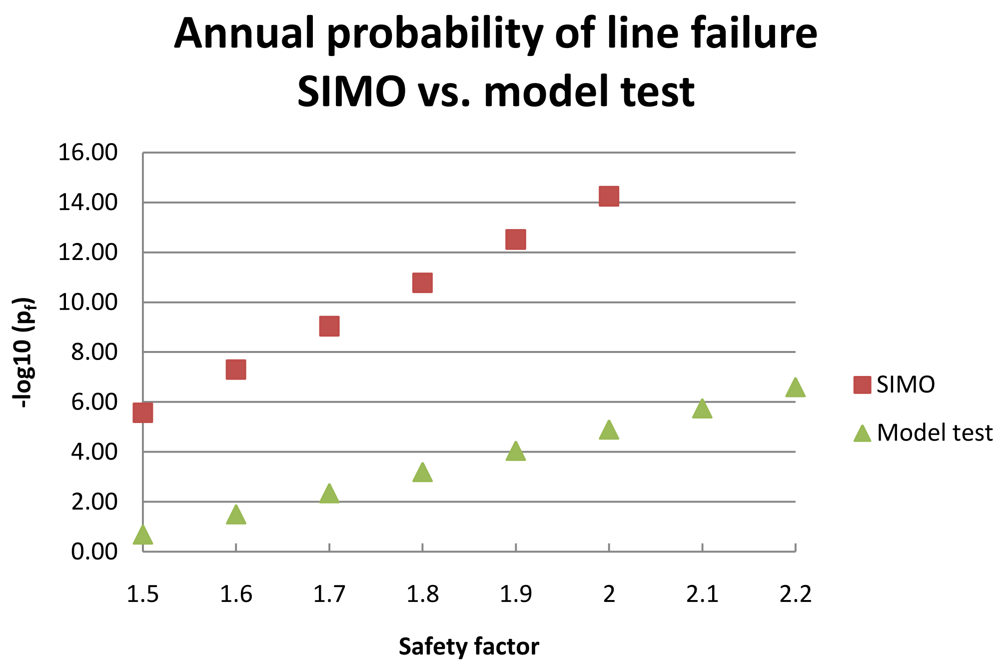

Figure 26 Annual probability with various safety factors, -log10 plot

A Gumbel plot for the short term distributions for environment 4/4* and 14/14* has been presented in Figure 27 and Figure 28, respectfully.

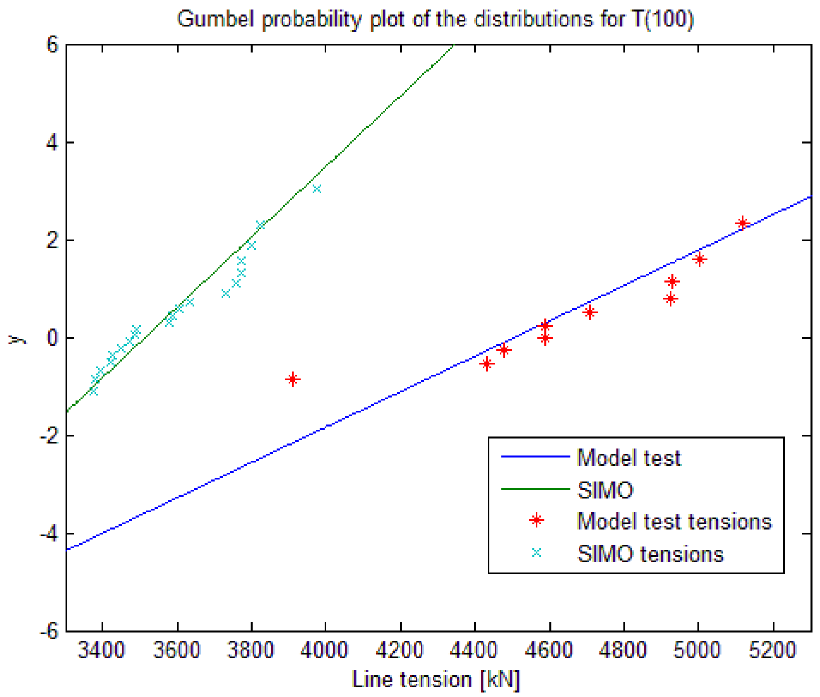

Figure 27 Gumbel probability plot for environment no. 4 and 4*

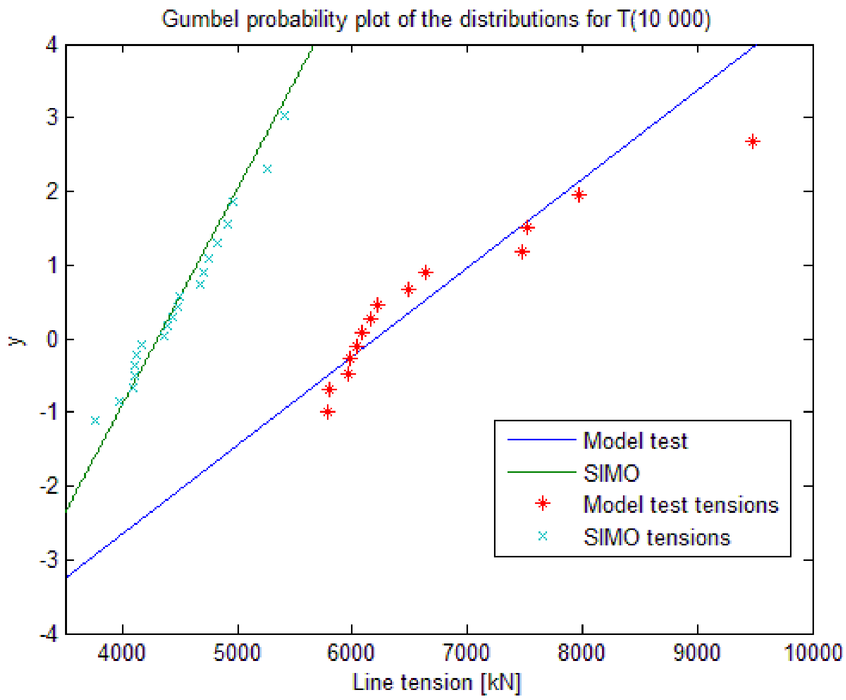

Figure 28 Gumbel probability plot for environment no. 14 and 14*

5.6.Storm wind and wave occurrence simultaneously

In sub-chapter 2.3.1.1, the combination of environmental forces for design conditions are discussed. According to the NORSOK standard N-003 Action and Action Effects, ref. (7), wind and wave with 100 year return period should be combined for ULS 1. This combination was used during the Midgard model tests and also in the SIMO-calculations presented in this report. The combination is considered to be conservative. To investigate rather or not this is the case, hindcast data from the Halten Bank (65° N, 7° E) is used. The data has been collected from measurements done every 3rd hour from 1th of September 1957 at 06:00 till 31th of December 2008 at 18:00.

According to **GRANE FIELD METOCEAN DESIGN BASIS**, ref. (13), wind speed higher than 15 m/s is underestimated. Consequently, the wind speeds used in this report have been corrected by Equation 5.4:

$$U_{cor} = U + p(U - U_{min}) \qquad \text{for } U \geq U_{min}$$

Where

$$U_{cor} = \text{corrected wind speed [m/s]}$$

$$U_{min} = 15\,\text{m/s}$$

$$p = 0,20$$

Equation 5.4 ref. (13)

Figure 29 show all wind speeds (WSP) and wave heights (Hs) plotted. In total there are almost 150 000 measurements.

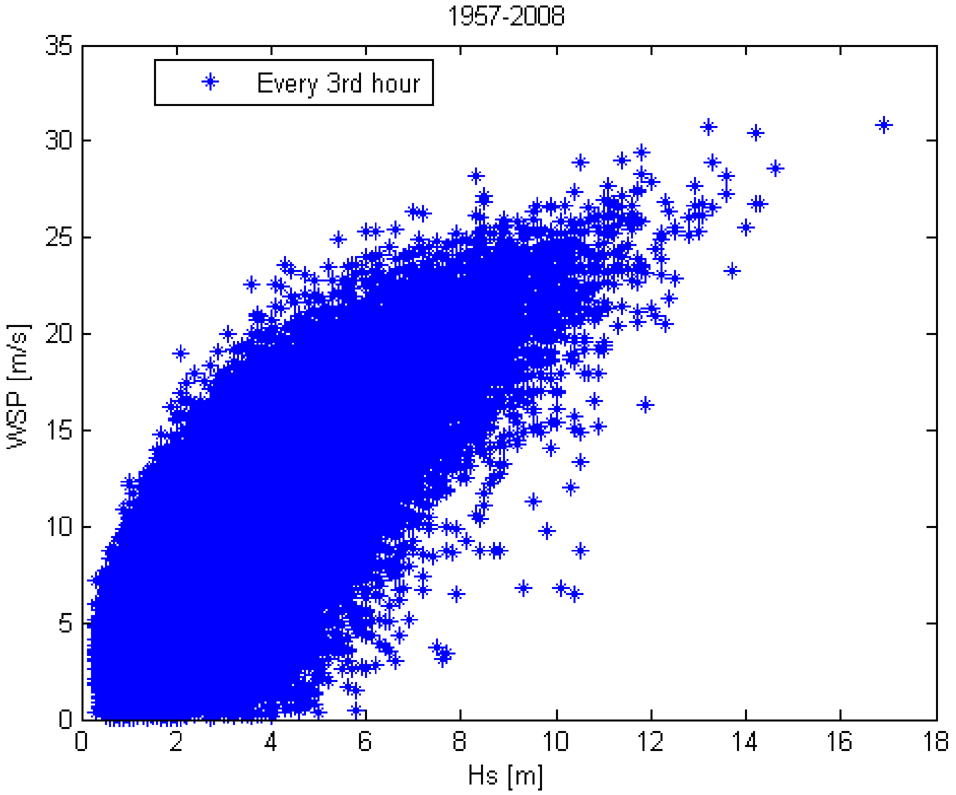

Figure 29 All wind speed and wave height occurrences

In sub-chapter 0, the design sea state was recommended to be Hs=16,0 and Tp=18,7 s (see Table 5). For the Midgard model tests and the SIMO analysis, the design sea state is Hs=14,9 m and Tp=15,7 m/s. These two sea states will be used in the following sub-chapter to investigate the conservatism of using 100 year values for both wind and wave. The investigation is carried out by using the measurements to estimate the wind speed corresponding to a storm wave peak.

Hs>10 m

Figure 30 shows all wind speeds with wave peaks higher than 10 m/s and their corresponding wind speeds. The wave peaks are measurements with at least 48 hours between them. This is to make sure that only the largest wave peak of the same storm is considered.

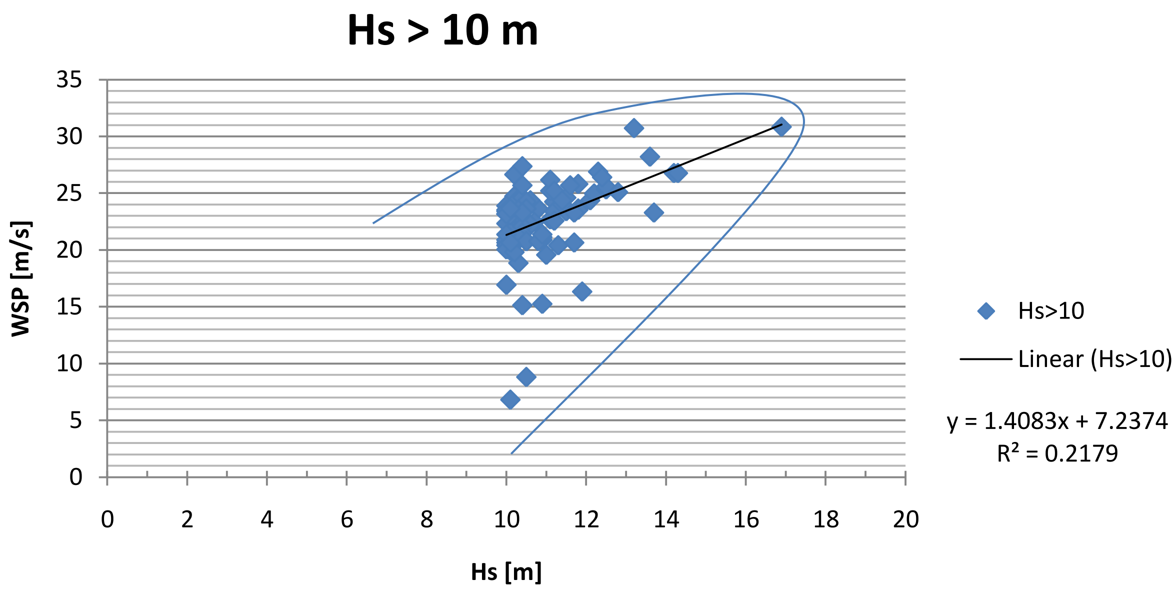

Figure 30 Hs>10 m with corresponding WSP

To estimate a value for the wave heights corresponding wind speed, a contour line has been added to Figure 30. The contour line is handmade based on the author's judgment. The contour line provides a wind speed range for the 100 year wave height as presented in Table 49.

Hs [m]	WSP min [m/s]	WSP max [m/s]
14,9	19	33
16,1	23	33

Table 49 WSP range given Hs

A linear trend line has been estimated in excel and can be seen in Figure 30. Estimating according the trend line, the wind speeds will be as given in Table 50.

Hs [m]	WSP linear [m/s]
14,9	28,2
16,1	29,9

Table 50 WSP from linearity given Hs

The storm wind peak and wave peak doesn't necessarily occur at the same time. In Figure 31, the affect of this is considered. All wave heights are found as before but the corresponding wind speed is further investigated. The highest wind measured up to 12 hours before and 12 hours after a measured wave peak is considered to be the corresponding wind speed. As can be seen in the figure, this makes the contour line narrower. However, the effect for the storm wave heights Hs=14,9 m and Hs=16,1 m is minimal (see WSP (+-12h) range given Hs and Table 52).

Hs [m]	WSP min [m/s]	WSP max [m/s]
14,9	22	33
16,1	24	33

Table 51 WSP (+-12h) range given Hs

Hs [m]	WSP linear [m/s]
14,9	27,8
16,1	28,9

Table 52 WSP (+-12h) from linearity given Hs

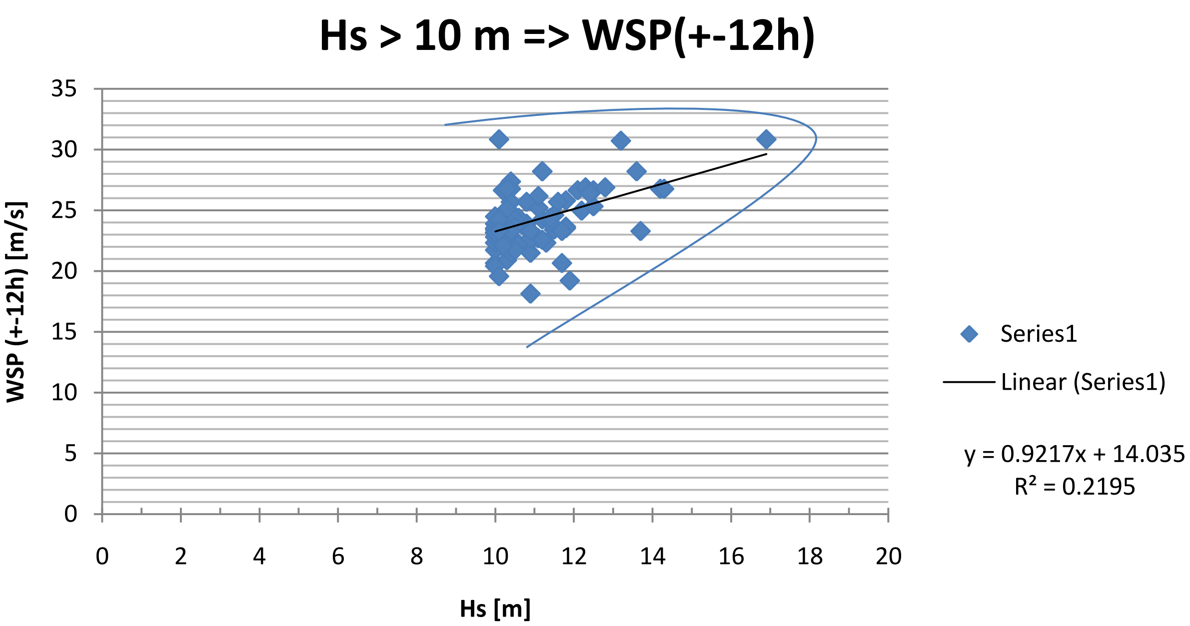

Figure 31 Hs>10 m with corresponding WSP (+-12h)

Joint occurrence of storm values

For both the contour line and the linear trend line, the wind speed value is significantly less than the 100 year value of 36 m/s for the wind speed. This indicates that the ULS design combination is, as expected, a conservative combination.

For the conclusion to be more reliable, it is desirable to have measurements from a large period at hand. It is also recommended to use the counter line method to find the contour line, and not a visual estimate, as was the case here.

6. Annual probability with varying depth

The effect of varying the water depth has been investigated by estimating the annual probability of line failure for z= 175 m and z=526 m.

z_1	263 m	Base case
z_2	175 m	Half base case
z_3	526 m	Double base case

Table 53 Depths evaluated in SIMO

The SIMO sys-file used in Chapter 5 is modified by changing the water depth and the line length. The rest of the specifications remain unchanged.

6.1.Scaling of the line length

When the water depth is changed, the positioning system must, in some way, also change. Here, the anchoring position is kept constant. The only thing that's changed is the line length.

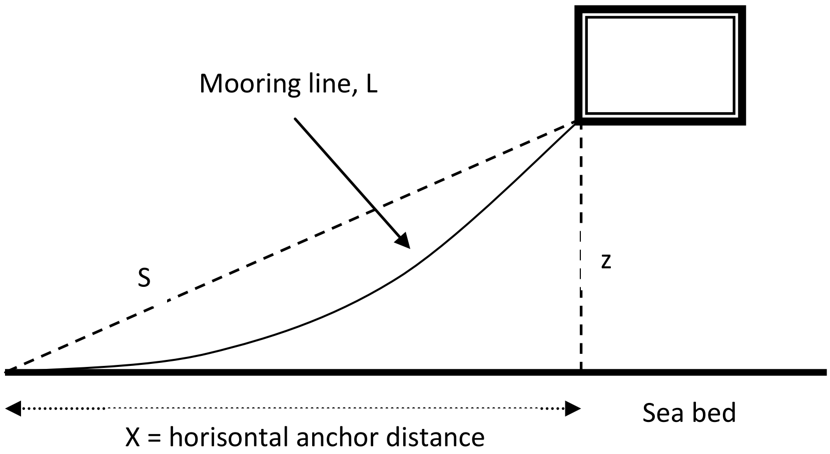

Figure 32 Line scaling

X is the horizontal distance from the anchor to the line end at the platform. This distance is constant for all depths. When the depths vary, the stapled line S (the shortest distance from fairlead to anchor) varies by Pythagoras. The line length, L, for the depth z_1 is given in the sys-file description under "Positioning system data, line characteristic specification". The difference between L and S is divided by z, to find a ratio for the excessive line length and the depth. This ratio is used to find the line length L, for depth z_2 and z_3.

6.2.Annual probability with z=175 m

With the SIMO sys-file modified to fit the new depth, z=175 m, there were performed 10 analysis for environment no.4* and 14 analysis with environment no.14*. The maximum line tension of the most exposed line (line 5) for the two environmental conditions are presented in Table 54 and Table 55, respectfully.

Most exposed line:	5	
1	4 792	kN
2	3 404	kN
3	3 374	kN
4	4 070	kN
5	3 896	kN
6	4 031	kN
7	3 751	kN
8	3 524	kN
9	3 726	kN
10	3 478	kN
average	*3 805*	*kN*
std	*428*	*kN*

Table 54 Maximum line tensions, environment no. 4*, z=175

Most exposed line:	5	
1	7 067	kN
2	5 312	kN
3	5 719	kN
4	6 159	kN
5	6 220	kN
6	6 857	kN
7	5 230	kN
8	5 228	kN
9	5 360	kN
10	5 553	kN
11	6 345	kN
12	5 233	kN
13	4 499	kN
14	5 220	kN
average	*5 871*	*kN*
std	*719*	*kN*

Table 55 Maximum line tensions, environment no.14*, z=175 m

The annual probability of line failure for the line tensions above is estimated by the environmental contour line method (see sub-chapter 3.3 for details regarding the method). The annual probability results can be seen in Table 56.

Safety factor	P_f	-log 10 (P_f)
1,5	0,1282	0,90
1,6	0,0172	1,77
1,7	0,0022	2,66
1,8	0,0003	3,56
1,9	3,5E-05	4,50
2	4,4E-06	5,35
2,1	5,6E-07	6,25
2,2	7,1E-08	7,15

Table 56 Annual probability of line failure with z=175 m

6.3. Annual probability with z=526 m

With the SIMO sys-file modified to fit the new depth, z=526 m, there were performed 10 analysis for environment no.4* and 14 for environment no.14*. The maximum line tension of the most exposed line (line 5) under environment no. 4* and 14*, is presented in Table 57 and Table 58, respectfully.

Most exposed line:	5	
1	4 003	kN
2	3 971	kN
3	3 946	kN
4	3 935	kN
5	3 882	kN
6	4 078	kN
7	4 243	kN
8	3 962	kN
9	3 981	kN
10	4 040	kN
average	*4 004*	*kN*
std	*1 00*	*kN*

Table 57 Maximum line tensions with z=526 m and environment no.4*

Most exposed line:	5	
1	4 346	kN
2	4 317	kN
3	4 309	kN
4	4 401	kN
5	4 401	kN
6	4 588	kN
7	4 588	kN
8	4 430	kN
9	4 324	kN
10	4 290	kN
11	4 626	kN
12	4 272	kN
13	4 360	kN
14	4 376	kN
average	*4 399*	*kN*
std	*117*	*kN*

Table 58 Maximum line tensions with z=526 m and environment no.14*

The annual probability with z=526 m is estimated by the environmental contour line method. The results are rather sensational. For all safety factors from 1,4 and up, the annual probability of line failure is zero.

6.4. Verification of the results

The period of surge for all the three depth cases has been compared (see Table 59). The periods are similar. This means that the platform movement should follow the same pattern, even though the depth is changed.

Z [m]	Period of surge [s]
263	28,56
175	29,03
526	29,34

Table 59 Period of surge

6.5. Conclusion

Figure 33 is a log10 plot of the annual probability of line failure for two SIMO cases and for the model test data. It shows that the SIMO probability for z=175 m are similar to the probability the model test data. This is considered a coincidence, and no conclusions will be drawn from it.

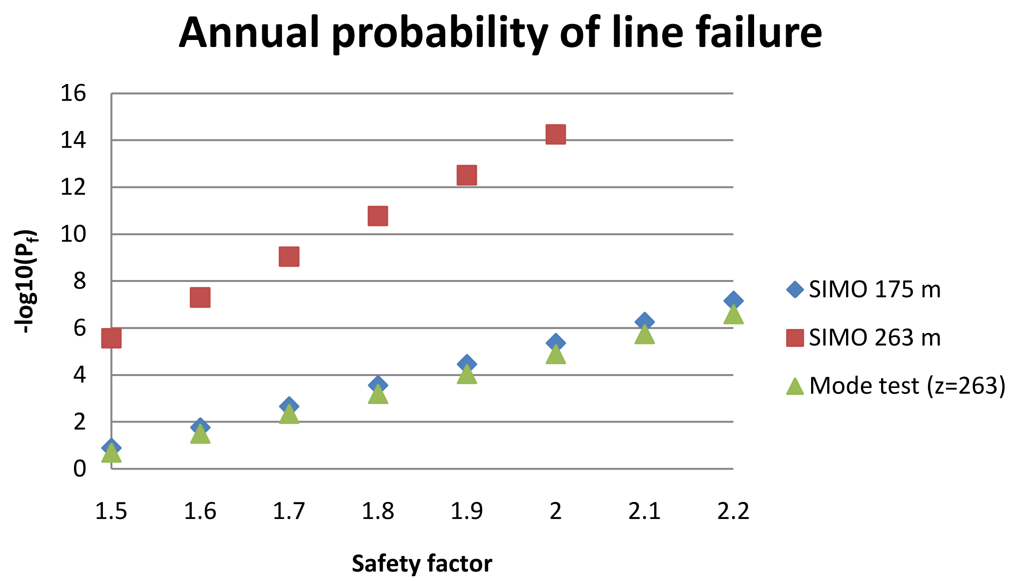

Figure 33 Annual probability, log scale, varying depth

By comparing the annual probability of line failure for the three cases found in SIMO, it seems at the probability increases with decreasing depth. Hence, platforms on shallow water are more likely to experience line breakages than platforms at deep water.

7. Additional considerations

In the previous chapters, problems have been raised without being further evaluated. In the following sub-chapters, some of these problems are discussed.

7.1. Determining the worst sea state

In sub-chapter 0 the environment design conditions at the Midgard field is discussed. The sub-chapter addresses the issue of determining the worst sea state (Hs and Tp) with only considering the environmental statistics. In Chapter 5 a SIMO model for the Midgard platform is created. This model is here used to further investigate the issue raised in sub-chapter 0. The sea states to be tested in SIMO are given in Table 60 and the reasons for the choices are explained below.

A) Originally, the design sea state at the Midgard field is, in sub-chapter 2.3.1.2 Table 5, set to be Hs=16 m and Tp=18,7 s.
B) In sub-chapter 2.3.1.2 Table 6 shows the omni-directional extreme significant wave heights and corresponding spectral peak periods; mean values and 90 % confidence band. For annual probability of exceedance, $q=10^{-2}$, the significant wave height is 16,0 m and the 5% spectral peak period is 16,4 s.
C) In sub-chapter 2.3.1.2 Table 6 shows the omni-directional extreme significant wave heights and corresponding spectral peak periods; mean values and 90 % confidence band. For annual probability of exceedance, $q=10^{-2}$, the significant wave height is 16,0 m and the 95% spectral peak period is 21,1 s.
D) The sea state used in Chapter 4 to estimate the annual probability of line failure, was, due to number of test results available, Hs=14,9 m and Tp=15,7 s.

Test:	Hs [m]	Tp [s]	Wind [m/s]	Current [m/s]	Max line tension [kN]
A	16,0	18,7	36	0,90	3489
B	16,0	16,4	36	0,90	3167
C	16,0	21,1	36	0,90	3548
D	14,9	15,7	36	0,90	3187

Table 60 Worst sea state investigation

It can be seen from Table 60, that the worst sea state is not D, who was used when estimating the annual probability of failure in Chapter 4, 5 and 6.

The worst sea state of the tested values is A, which has the highest Tp of A, B and C. Further analysis, with different sea states must be done to indentify the worst sea state with confidence, but this will not be prioritized in this report.

7.2. Short term distribution fractile

In sub-chapter 4.3 the annual probability of line failure was estimated based on maximum line tension values from model tests. The environmental contour method (for details, see sub-chapter 3.3) was used to estimate the probability. The method requires an estimate for $T^{(100)}$ and $T^{(10\,000)}$. They are assumed to be given by the 3 h extreme value distributions for 100 and 10 000 year environmental values, respectfully. $T^{(100)}$ should be between F=0,85 and F=0,95. $T^{(10\,000)}$ should be between F=0,90 and F=0,95. In sub-chapter 4.3, they were both set as F=0,90. Here, it's investigated what would happen to the annual probability of line failure when these are chosen differently. The following notation will be used for the high fractile value of the 3 h extreme value distributions:

$$F_{T_{100}\,3h|Hs,Tp}\left(t\,|\,hs,tp\right)=\alpha^{(100)}$$

$$F_{T_{10\,000}\,3h|Hs,Tp}\left(t\,|\,hs,tp\right)=\alpha^{(10000)}$$

Equation 7.1

Two combinations have been used to estimate the annual probability of line failure, in addition to the combination used in sub-chapter 4.3. The results can be seen in Table 61. The results have been plotted in a -log10-plot together with the probability found in sub-chapter 4.3 (see Figure 34).

	Safety factor	P_f	$-\log10(P_f)$
$\alpha^{(100)}=0{,}85$, $\alpha^{(10\,000)}=0{,}90$	1,5	0,0729	1,14
	1,6	0,0140	1,86
	1,7	0,0026	2,58
	1,8	0,0005	3,31
	1,9	9,0E-05	4,05
	2,0	1,7E-05	4,78
	2,1	3,1E-06	5,51
	2,2	5,8E-07	6,24
$\alpha^{(100)}=0{,}90$, $\alpha^{(10\,000)}=0{,}95$	1,5	0,2756	0,56
	1,6	0,0743	1,13
	1,7	0,0183	1,74
	1,8	0,0044	2,35
	1,9	0,0011	2,97
	2,0	0,0003	3,60
	2,1	6,1E-05	4,22
	2,2	1,5E-05	4,84

Table 61 Annual probability of line failure, various fractiles

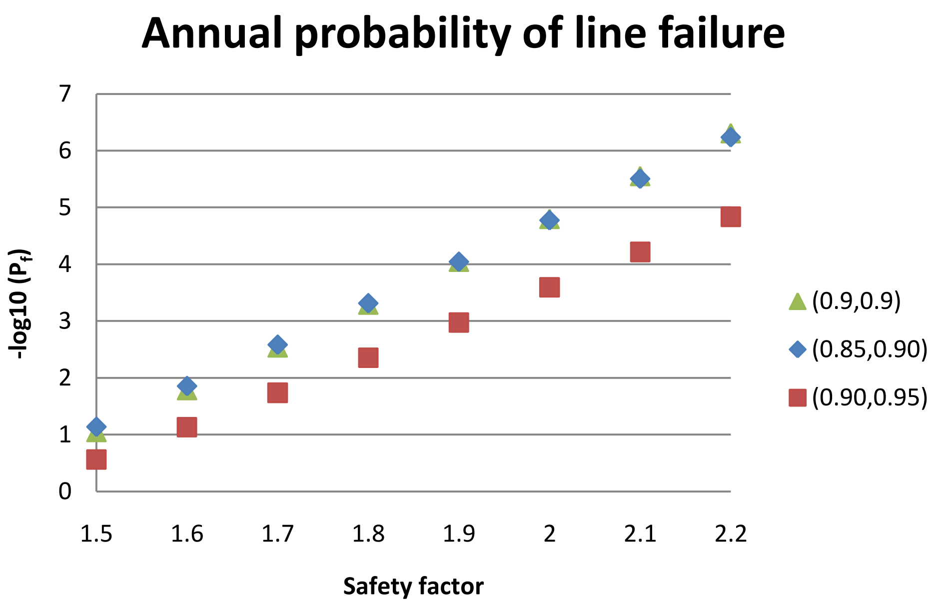

Figure 34 Annual probability of line failure, -log10 plot, high fractile

7.3. Effect of changing environment direction

In sub-chapter 4.1 the model test results were presented. It was found that the line tensions were greater for the environment with 315° heading, than for 0°. But since there were only two tests performed with 315° heading, it couldn't be used to estimate the annual probability of line failure.

By using the SIMO model created in Chapter 5, the effect of not using 315° heading can be investigated.

7.3.1. Results

By using the SIMO model for environment no. 3*, the maximum line tension results will be as presented in Table 62 together with the corresponding environment with heading 0°. The maximum line tension is 4 713 kN for environment no.3* (Line 8) and 3 975 kN for environment no.4* (Line 5). The difference is 19 %, which is similar to the difference of the model test results (see Table 20).

Hs	14,90	14,90	m
Tp	15,70	15,70	s
C	39,60	39,60	m/s
W	0,90	0,90	m/s
Head	315,00	0,00	deg
Line			
1	2 095	3 347	kN
2	2 199	3 542	kN
3	2 291	3 735	kN
4	2 428	3 956	kN
5	4 564	3 975	kN
6	4 646	3 740	kN
7	4 695	3 564	kN
8	4 713	3 355	kN
9	2 905	2 103	kN
10	2 775	2 079	kN
11	2 652	2 062	kN
12	1 947	2 068	kN
13	1 939	2 090	kN
14	1 932	2 114	kN

Table 62 SIMO maximum line tension environment no.3* and no.4*

There are 20 analysis performed in SIMO with environment no. 3* and 13*. The maximum line tensions for line 8 (the most exposed line) for these analysis are presented in Table 63.

Line 8			
Environment	3*	13*	
Analysis/Seed			
1	4713	4756	kN
2	4061	4764	kN
3	4051	4673	kN
4	3968	4793	kN
5	4038	5042	kN
6	4127	5374	kN
7	4690	5637	kN
8	4136	5382	kN
9	3948	4982	kN
10	4055	4836	kN
11	3846	4670	kN
12	4247	5064	kN
13	3980	4889	kN
14	4313	5420	kN
15	4078	5183	kN
16	4500	5303	kN
17	4053	4849	kN
18	4266	5484	kN
19	4465	5281	kN
20	4756	5901	kN
average	4179	5024	kN
std	282	314	kN

Table 63 SIMO maximum line tensions Line 8

By using the maximum line tension results above and the environmental contour method (see sub-chapter 3.3 for details), the annual probability of line failure, P_f, can found to be as presented in Table 64. The annual probability is estimated by the least square method (in Excel) and by the moment method. The probability is, in both cases, extremely low.

	Excel		Moment method	
Safety factor	P_f	log 10	P_f	log 10
1,5	2,40E-07	6,62	2,28E-10	9,64
1,6	2,40E-09	8,62	3,42E-13	12,47
1,7	2,40E-11	10,62	0	#NUM!
1,8	2,40E-13	12,62	0	#NUM!
1,9	2,44E-15	14,61	0	#NUM!
2,0	0	#NUM!	0	#NUM!
2,1	0	#NUM!	0	#NUM!
2,2	0	#NUM!	0	#NUM!

Table 64 Annual probability of line failure (315 deg)

The annual probability of line failure found for 315° heading by the Excel is compared with the probability found for 0° heading with the same wind, wave and current values in Table 65.

	315°		0°	
Safety factor	P_f	-log 10(P_f)	P_f	-log 10(P_f)
1,5	2,40E-07	6,62	2,72E-06	5,57
1,6	2,40E-09	8,62	4,98E-08	7,30
1,7	2,40E-11	10,62	9,13E-10	9,04
1,8	2,40E-13	12,62	1,67E-11	10,78
1,9	2,44E-15	14,61	3,07E-13	12,51
2,0	0	#NUM!	5,66E-15	14,25
2,1	0	#NUM!	0	#NUM!
2,2	0	#NUM!	0	#NUM!

Table 65 Annual probability of line failure (315 deg and 0 deg)

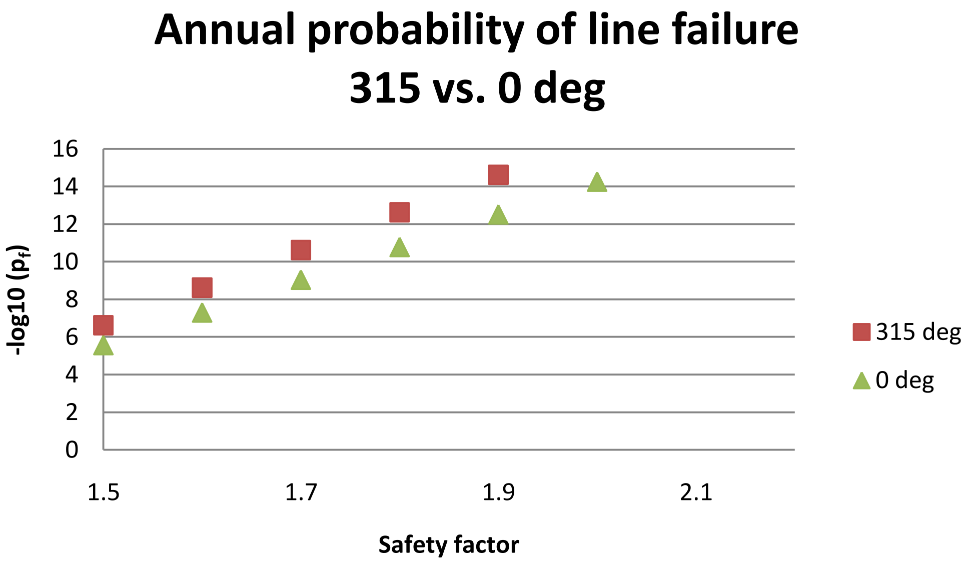

Figure 35 Annual probability of line failure, -log10 plot

7.4. Increased values

In section 5.1.1 the difference in line tension increase found by comparing the model test results and the SIMO results were discussed. Here, the difference is further investigated.

7.4.1. Probability with increased values

The SIMO results for 100 year environment (no.4*) have been multiplied by 1.43 to produce 10 000 year values with the same line tension increase from 100 to 10 000 values, as found for the model tests. The annual probability of line failure, P_f, for the increased SIMO results (SIMOx1,43) has been plotted in a –log-plot with the probability found by the model tests and the original SIMO results. The plot can be seen in Figure 36.

Even with the modification on the 10 000 year values, the SIMO probabilities are significantly lower than the model test results.

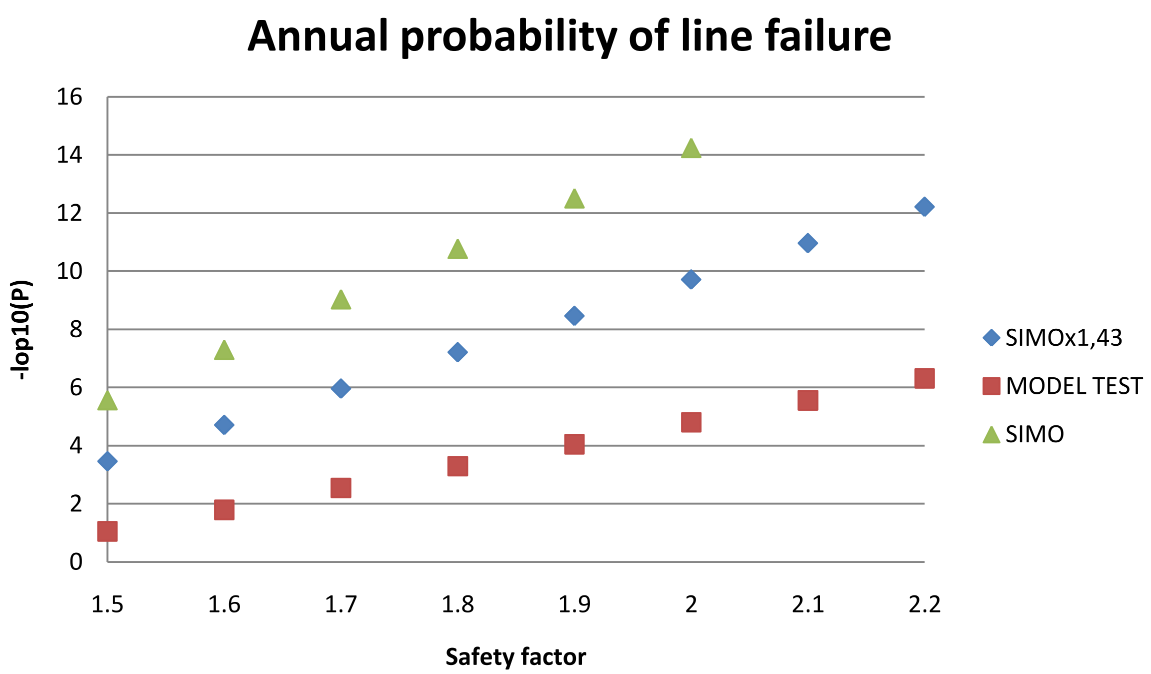

Figure 36 Annual probability of failure

8. Conclusion and further work

The aim of this report was to estimate the probability of line failure for a semi-submersible platform as a function of safety factor. The semi-submersible platform used to investigate the annual probability of line failure was the production platform Midgard. By using the environmental contour method, the annual probability of line failure was found to be sufficient for the applicable safety factor (2,2 for production platforms in consequence class 3). However, it was found that the probability, if the platform was under consequence class 1, was 9 %. This is totally unacceptable. If the probability is 10 %, the platforms mooring lines would break once in 10 years.

For the model test, there are only 10 available results for 100 year return period and 14 results available for 10 000 year return period. It is desirable to have at least 20 results for both return periods. The author therefore recommends more model tests to be performed as further work. Also, in the model test there were only performed two tests for waves with heading 315°. This seems to be the worst wave direction, so for further work, more model tests should be performed with this wave heading.

Because of the uncertainties tied to the probability estimated based on the model test data (the direction and number of performed tests), a SIMO sys-file was created for the platform. The idea was to evaluate the annual probability of failure in SIMO with the desired number of tests. The SIMO model would also provide the possibility for testing more scenarios like wave direction and water depth.

The annual probability of mooring line failure estimated based on the maximum line tensions produced by SIMO are significantly lower than for the model test results. The SIMO offset matches the model offset in all ways (max, min, mean and standard deviation), but the line tensions found in SIMO are significantly lower for both 100 and 10 000 year return period. The coefficients of variance of the results are also different. The author has not successfully determined the reason for the difference in line tensions from SIMO and the model test. It is therefore recommended for further work. A possibility could be to perform a coupled analysis with SIMO and RIFLEX, to investigate if it is the simplified solution in SIMO and the dynamics performed here that is the reason for the difference.

By using the sys-file for the Midgard platform, the effect of varying water depth was investigated. The results indicate that the probability of line failure increases as the water depth decreases. The results are based on fixed anchor location and alternating line length. Scaling both line length and anchor positions is recommended for further investigations on the topic.

Through SIMO, it was investigated rather or not the environment heading had an effect on the annual probability of line failure. The background for the study was that the most severe direction from the model tests (315°) had only two test results available, and could therefore not be used in statistical use. The test showed that the probability decreased even more. However, it is important to keep in mind that the SIMO results has been proven to under predict line tensions, so the credibility of the result is highly questioned. Intuitively, one would think that higher line tensions would leave to higher probabilities of line failure.

The probabilities found in this report should in reality probably be higher for all cases. In this report, only the environment is considered. Probabilities linked to the material and so on, has been neglected. Investigation regarding this approximation is suggested as further work.

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10. Appendix

A. Master thesis description

M.Sc. thesis 2011

for

Stud.techn.

Maren Kjøstvedt Olsen

Estimation of annual probability of mooring line failure as a function of safety factor

(Estimering av årlig sannsynlighet for ankerlinebrudd som funksjon av sikkerhetsfaktor.)

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.

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.:

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

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 weater 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. Including how the weather should be specified for the design calculation. Reference shall be made to governing rules.

2. Discuss various ways of obtaining $F_T(t)$ and/or $F_T(t)$. What approach would you select if time domain analyses (SIMO) are necessary? Can Mimosa be used in connection? If so how could it be used?

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. Use MIMOSA (if possible) and/or SIMO to do the same as was done based on model test data. Investigate the conservatisms baked into the assumption that 10^{-2} wave condition and 10^{-2} wind condition occur simultaneously. The actual joint occurrence of storm peak sea state and storm peak wind speed shall be discussed using hindcast data.

5. Repeat adequate parts of 4) for two more depths. One case 2/3 of base case depth and one case twice as deep as the base case.

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

The work may show to be more extensive than anticipated. Some topics may theref.ore 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 ref.erences 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.

B. Model Test Data

The data presented below is from the model tests performed by MARINTEK with the Midgard model.

Global contour 100									
14,90	14,90	14,90	14,90	14,90	14,90	14,90	14,90	14,90	14,90
15,70	15,70	15,70	15,70	15,70	15,70	15,70	15,70	15,70	15,70
0,90	0,90	0,90	0,90	0,90	0,90	0,90	0,90	0,90	0,90
36,00	36,00	36,00	36,00	36,00	36,00	36,00	36,00	36,00	36,00
0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
3269	3270	3272	3274	3276	3278	3280	3282	3250	3261
4124,80	3992,60	3999,30	3568,60	4205,70	4247,30	4204,60	3806,30	4 257,80	4 077,50
4336,60	4150,70	4195,10	3683,10	4454,10	4430,70	4434,80	3940,70	4 292,20	4 148,90
4424,20	4156,20	4221,50	3715,50	4492,70	4484,90	4563,10	4067,60	4 509,90	4 394,70
4694,40	4312,70	4447,90	3848,70	4906,70	4840,90	4868,50	4300,40	4 682,60	4 592,20
4926,30	4429,50	4475,40	3912,60	4930,30	4709,10	5117,80	4588,70	4 589,50	5 003,30
4619,30	4242,40	4293,40	3809,60	4662,30	4442,00	4857,60	4387,70	4 396,80	4 714,90
4471,90	4086,50	4173,30	3687,20	4485,20	4365,60	4732,10	4283,00	4 160,60	4 497,60
4062,10	3865,50	3882,10	3490,40	4144,10	4022,00	4305,10	3954,50	3 898,00	4 166,30
2558,90	2896,70	2621,60	2587,40	2548,90	2648,30	2656,50	2638,60	2 586,00	2 578,70
2507,80	2851,10	2566,10	2531,20	2503,70	2621,90	2608,20	2593,40	2 516,70	2 532,80
2490,10	2802,30	2551,50	2505,60	2460,70	2546,00	2511,20	2532,20	2 450,50	2 499,20
2581,50	3011,20	2827,50	2854,60	4362,60	3025,30	2964,10		2 466,90	2 512,50
2644,50	3102,30	2875,70	2907,20	2884,20	2929,60	2914,80	2967,20	2 513,50	2 576,40
2556,60	2926,30	2672,40	2666,40	2670,10	2634,00	2561,70	2617,00	2 524,90	2 598,60
4 926,30	4 429,50	4 475,40	3 912,60	4 930,30	4 840,90	5 117,80	4 588,70	4 682,60	5 003,30
5	5	5	5	5	4	5	5	4	5

Model test results for environment 4

	"Worst" sea state 10 000 (no.: 14)													
	20,20	20,20	20,20	20,20	20,20	20,20	20,20	20,20	20,20	20,20	20,20	20,20	20,20	20,20
	21,00	21,00	21,00	21,00	21,00	21,00	21,00	21,00	21,00	21,00	21,00	21,00	21,00	21,00
	0,90	0,90	0,90	0,90	0,90	0,90	0,90	0,90	0,90	0,90	0,90	0,90	0,90	0,90
	36,00	36,00	36,00	36,00	36,00	36,00	36,00	36,00	36,00	36,00	36,00	36,00	36,00	36,00
	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	3100	3111	3120	3121	3122	3124	3125	3126	3129	3131	3142	3144	3146	3148
1	5 365,00	5 366,50	5 483,20	4 970,30	5 969,80	5 888,80	5 971,90	4 944,40	5 056,80	4 724,60	4 773,80	6 954,10	4 769,60	5 516,30
2	5 408,90	5 391,20	5 606,50	5 053,30	6 069,60	5 977,20	6 279,20	5 019,70	5 301,60	4 968,50	5 048,50	7 508,60	5 043,40	5 762,10
3	5 675,60	5 770,80	5 737,30	5 291,50	6 384,10	6 425,10	6 717,10	5 344,90	5 312,80	5 094,20	5 067,90	7 949,30	5 262,20	5 990,50
4	6 131,00	6 219,00	6 241,30	5 747,10	7 079,00	7 007,20	7 417,60	5 703,20	5 685,20	5 620,90	5 765,60	8 733,00	5 814,00	6 525,90
5	6 644,70	6 491,50	6 156,80	6 089,50	7 977,30	7 479,80	7 518,10	5 986,00	5 777,80	5 792,20	5 957,70	9 478,80	6 039,30	6 222,30
6	6 182,50	5 911,70	5 765,50	5 648,10	6 984,20	6 717,50	6 786,50	5 684,90	5 472,20	5 320,30	5 312,00	8 937,80	5 484,60	5 766,20
7	5 800,50	5 542,20	5 497,90	5 416,90	6 535,60	6 296,50	6 420,20	5 399,70	5 449,20	5 147,10	5 112,10	8 466,10	5 262,10	5 558,40
8	5 324,50	4 981,00	5 083,40	4 971,60	5 679,40	5 647,70	5 763,50	4 987,70	5 016,00	4 718,60	4 682,90	7 597,50	4 664,30	5 084,10
9	2 900,10	2 857,20	2 749,80	2 787,50	2 678,20	2 665,40	2 786,50	2 709,30	2 771,60	2 789,70	2 902,30	2 794,20	2 776,80	2 824,70
10	2 809,20	2 824,30	2 694,20	2 720,50	2 651,90	3 022,90	2 765,60	2 649,90	2 689,90	2 723,90	2 842,80	2 713,10	2 779,10	2 811,20
11	2 769,50	2 762,00	2 663,40	2 678,30	2 594,50	2 568,50	2 744,90	2 669,80	2 649,80	2 625,30	2 760,10	2 682,80	2 718,00	2 749,90
12	2 821,10	2 668,40	2 747,90	2 645,30	2 697,00	2 643,50	2 705,40	2 643,50	2 699,70	2 612,50	2 721,90	2 664,90	2 626,00	2 660,80
13	2 905,90	2 749,60	2 837,80	2 722,20	2 751,40	2 695,50	2 778,70	2 695,90	2 773,70	2 681,80	2 762,00	2 724,10	2 671,50	2 746,90
14	2 882,80	2 740,90	2 848,20	2 735,70	2 762,10	2 731,10	2 806,00	2 715,60	2 767,80	2 682,20	2 769,00	2 735,20	2 679,70	2 759,00
Max:	6 644,70	6 491,50	6 241,30	6 089,50	7 977,30	7 479,80	7 518,10	5 986,00	5 777,80	5 792,20	5 957,70	9 478,80	6 039,30	6 525,90
Line:	5	5	4	5	5	5	5	5	5	5	5	5	5	4

Model test results for environment 14

C. SIMO sys-file

The complete sys-file can be found on the attached CD.

a. Environment specifications

```
'**************************************************
 ENVIRONMENT DATA SPECIFICATION
'**************************************************
 Wind, wave and current data for the Midgard platform
 100 year Waves & wind + 10 year current
 Irregular    ( Hs = 14.9 m; Tp = 15.7 sec )
'===================================================
 IRREGULAR WAVE SPECIFICATION
'===================================================
'  CHIRWA
Wave100
'  IWASP1  IWADR1  IWASP2  IWADR2
  24      0       0                 0
'--------------------------------------------------
 WAVE SPECTRUM WIND
'--------------------------------------------------
'  SIWAHE  TPEAK
  14.9       15.7
'--------------------------------------------------
 WAVE DIRECTION PARAMETERS
'--------------------------------------------------
'  WADIR1  EXPO1   NDIR1
  0.   0      0
'===================================================
 WIND SPECIFICATION
'===================================================
'CHWIND
 Wind100
'IWITYP
'sletringen
  4
' WIDIR  ZREF  ALPHWI   WINREF  GAMMA  FRIC
  0.  10.   .11     39.6    10.   .0020
'===================================================
 CURRENT SPECIFICATION
'===================================================
'CHCURR
 Current10
'NCUR
 2
'CURVEL  CURDIR  CURLEV
 0.9     0.0       0.0
 0.3     0.0     -258.0
```

b. Positioning system

```
'**********************************************************
POSITIONING SYSTEM DATA
'**********************************************************
14 mooring lines
4 in two corners and 3 in two corners
'-----------------------------------------------------------
CATENARY SYSTEM DATA
'-----------------------------------------------------------
'LINE DATA
' iline  lichar  imeth   iwirun
' xbdy   ybdy    zbdy
' xgbl   ygbl          xwinch
' ifmopo ftime   btens
'-----------------------------------------------------------
LINE DATA
1       1       3       0
-31.2   -41.05   -11.88
-507.56   -517.4   0
0   0   23040
LINE DATA
2       1       3       0
-35   -41.05   -11.88
-551.06   -474.08   0
0   0   23040
LINE DATA
3       1       3       0
-41.05   -35   -11.88
-592.89   -421.4   0
0   0   23040
LINE DATA
4       1       3       0
-41.05   -31.2   -11.88
-624.46   -368.03   0
0   0   23040
LINE DATA
5       2       3       0
-41.05   31.2   -11.88
-667.76   393.03   0
0   0   23040
LINE DATA
6       2       3       0
-41.05   35   -11.88
-633.84   450.08   0
0   0   23040
LINE DATA
7       2       3       0
-35   41.05   -11.88
-589.36   506.21   0
0   0   23040
LINE DATA
```

```
8       2       3       0
-31.2   41.05   -11.88
-542.91   552.76   0
0   0   23040
LINE DATA
9       3       3       0
31.2   41.05   -11.88
465.18   660.84   0
0   0   23040
LINE DATA
10       3       3       0
35   41.05   -11.88
521.35   620.66   0
0   0   23040
LINE DATA
11       3       3       0
41.05   35   -11.88
576.07   570.02   0
0   0   23040
LINE DATA
12       4       3       0
41.05   -35   -11.88
491.21   -485.16   0
0   0   23040
LINE DATA
13       4       3       0
35   -41.05   -11.88
444.22   -528.73   0
0   0   23040
LINE DATA
14       4       3       0
31.2   -41.05   -11.88
396.35   -562.54   0
0   0   23040
'-------------------------------------------------------
LINE CHARACTERISTICS DATA
'-------------------------------------------------------
' lichar   linpty   npth   nptv  vrange
   1       2       40     3      20.
'  nseg   ibotco   slope   zglb   tmax     thmin
    3       1       0.    -263.0  23040.     0.
' iseg   ieltyp   nel   ibuoy   sleng   fric
  1      0      50      0    600    1.
         2      0      16      0    161.7   1.
         3      0      3      0    28.125   1.
' iseg   dia    emod    emfact    uwia    watfac   cdn   cdl
  1    .158  5.49e7    2.     5.02272     .87      3.3   .14
         2    .158  5.49e7    2.     5.02272     .87      3.3   .14
         3    .158  2.16e7    2.     5.3         .87      4.2   .18
'-------------------------------------------------------
LINE CHARACTERISTICS DATA
'-------------------------------------------------------
```

```
' lichar   linpty    npth    nptv   vrange
    2       2       40     3      20.
'  nseg    ibotco    slope   zglb   tmax     thmin
    3       1       0.    -263.0  23040.     0.
' iseg   ieltyp   nel   ibuoy   sleng   fric
   1      0      50      0    650     1.
          2      0      16      0    161.7   1.
          3      0      3       0    28.125   1.
' iseg   dia    emod    emfact   uwia    watfac   cdn   cdl
   1    .158  5.49e7    2.     5.02272     .87      3.3   .14
          2    .158  5.49e7    2.     5.02272     .87      3.3   .14
          3    .158  2.16e7    2.     5.3          .87      4.2   .18
'-------------------------------------------------------
LINE CHARACTERISTICS DATA
'-------------------------------------------------------
' lichar   linpty    npth    nptv   vrange
    3       2       40     3      20.
'  nseg    ibotco    slope   zglb   tmax     thmin
    3       1       0.    -263.0  23040.     0.
' iseg   ieltyp   nel   ibuoy   sleng   fric
   1      0      50      0    670     1.
          2      0      16      0    158.3   1.
          3      0      3       0    28.125   1.
' iseg   dia    emod    emfact   uwia    watfac   cdn   cdl
   1    .158  5.49e7    2.     5.02272     .87      3.3   .14
          2    .158  5.49e7    2.     5.02272     .87      3.3   .14
          3    .158  2.16e7    2.     5.3          .87      4.2   .18
'-------------------------------------------------------
LINE CHARACTERISTICS DATA
'-------------------------------------------------------
' lichar   linpty    npth    nptv   vrange
    4       2       40     3      20.
'  nseg    ibotco    slope   zglb   tmax     thmin
    3       1       0.    -263.0  23040.     0.
' iseg   ieltyp   nel   ibuoy   sleng   fric
   1      0      50      0    550     1.
          2      0      16      0    158.3   1.
          3      0      3       0    28.125   1.
' iseg   dia    emod    emfact   uwia    watfac   cdn   cdl
   1    .158  5.49e7    2.     5.02272     .87      3.3   .14
          2    .158  5.49e7    2.     5.02272     .87      3.3   .14
          3    .158  2.16e7    2.     5.3          .87      4.2   .18
```