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K12 – Design of mooring and anchoring

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K12 - DESIGN OF MOORING AND ANCHORING

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Prodtex IFE Pure Logic HEYERDAHL ARKITEKTER AS H&BB MIKO MARINE AS BUKSÉR OG BERGING FORCE TECHNOLOGY SWERIM

REPORT

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CONCEPT DEVELOPMENT FLOATING BRIDGE E39 BJØRNAFJORDEN

Document name:

K12 - DESIGN OF MOORING AND ANCHORING

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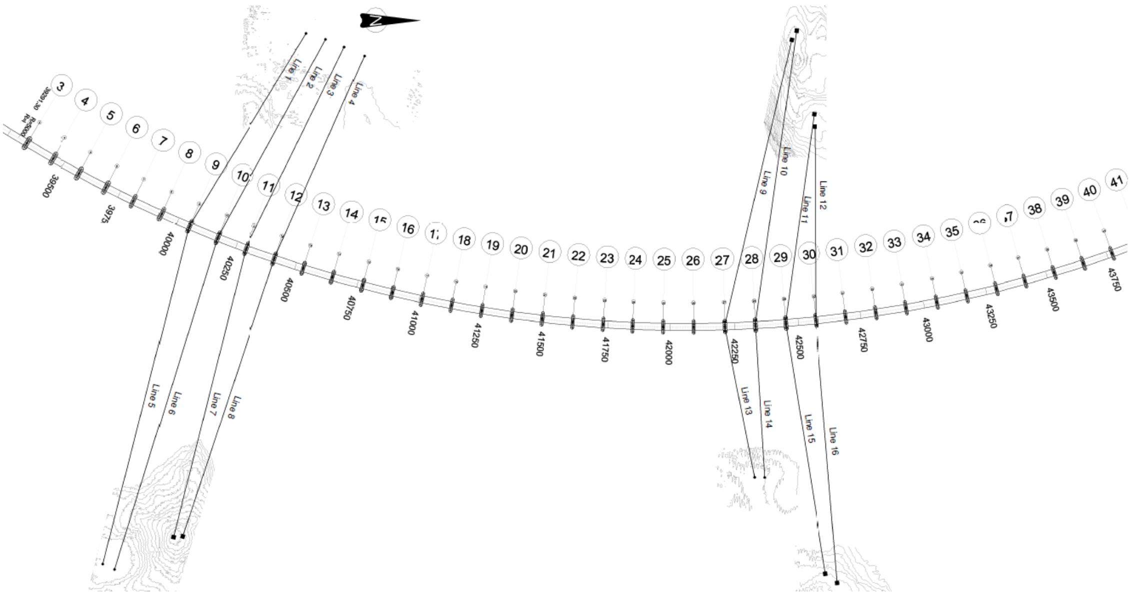
Approved by:	Kolbjørn Høyland

Summary

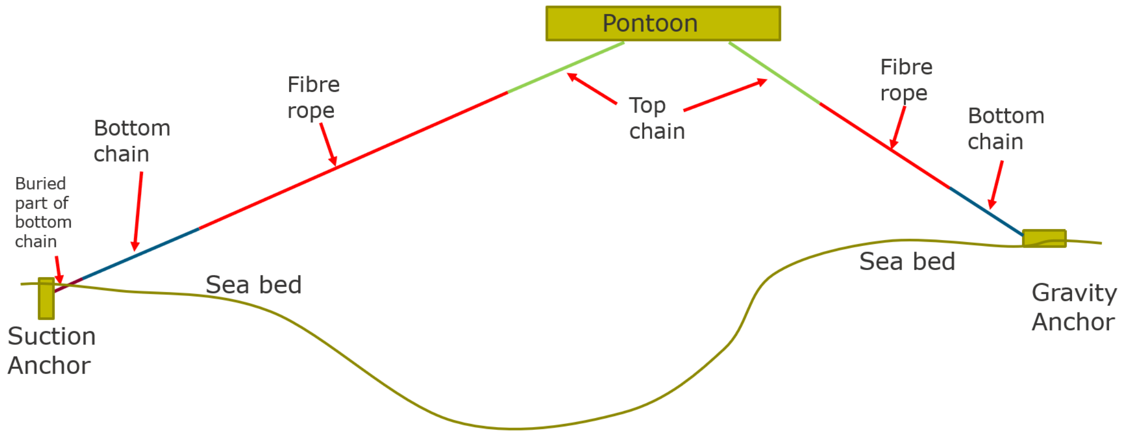
The current report summarizes the mooring system design proposed for the recommended Bjørnafjorden floating bridge concept K12. The concept is generally the same as proposed during the concept evaluation and can easily be adapted to the other concepts that has a mooring system.

Several mooring systems were considered at the start of the project and these are briefly discussed in the current document. The proposed system is a taut system with fibre ropes as the main component and chain segments at pontoon connection and anchor. The mooring system consists of two groups of mooring lines, each group consisting of eight mooring lines. The lines in one group are connected to four pontoons, with one line to each side of each pontoon. The plan view of the mooring system is shown in Figure 1.



> *Figure 1 Mooring plan view*

A principal sketch of the mooring line components for one pair of lines is shown in Figure 2 below.



> *Figure 2 Principle drawing (side view) of one pair of mooring lines.*

The proposed system has a practically linear behaviour for the expected pontoon displacement and provides additional elasticity to absorb ship impact and other accidental loads. The level of pre-tension is set to ensure that slack of the mooring lines is avoided, and the system remain taut. The bottom chain will as long as it is lifted from the seabed, ensure a minimum level of pre-tension.

The selected pre-tension and main dimensions of the mooring line components are summarized in Table 1.

> *Table 1 Anchor line properties*

Line No.	Pre-tension	Botton Chain R4				Polyester fibre rope				Top Chain R4			
		Dim.	Length	Dry weight	MBS	Dim.	Length	Dry weight	MBS	Dim.	Length	Dry weight	MBS
(-)	(MN)	(mm)	(m)	(kg/m)	(MN)	(mm)	(m)*	(kg/m)	(MN)	(mm)	(m)	(kg/m)	(MN)
1	2.3	100	60	200.0	9.9	177	985	22.0	9.8	146	25	426.3	18.9
2	2.1	100	60	200.0	9.9	177	985	22.0	9.8	146	25	426.3	18.9
3	1.8	92	60	169.3	8.5	177	978	22.0	9.8	146	25	426.3	18.9
4	1.8	92	60	169.3	8.5	177	968	22.0	9.8	146	25	426.3	18.9
5	2.0	100	75	200.0	9.9	185	1279	24.1	10.8	146	35	426.3	18.9
6	1.8	100	75	200.0	9.9	185	1274	24.1	10.8	146	35	426.3	18.9
7	1.6	92	50	169.3	8.5	168	1091	19.4	8.8	146	35	426.3	18.9
8	1.6	92	50	169.3	8.5	168	1074	19.4	8.8	146	35	426.3	18.9
9	1.7	92	70	169.3	8.5	177	1047	22.0	9.8	146	50	426.3	18.9
10	1.6	92	175	169.3	8.5	168	952	19.4	8.8	146	50	426.3	18.9
11	1.6	92	70	169.3	8.5	145	725	15.7	6.9	146	50	426.3	18.9
12	1.6	92	50	169.3	8.5	145	675	15.7	6.9	146	50	426.3	18.9
13	2.0	92	50	169.3	8.5	145	633	15.7	6.9	146	25	426.3	18.9
14	1.8	92	50	169.3	8.5	145	627	15.7	6.9	146	25	426.3	18.9
15	1.7	92	150	169.3	8.5	168	897	19.4	8.8	146	25	426.3	18.9
16	1.7	92	100	169.3	8.5	177	982	22.0	9.8	146	25	426.3	18.9

The mooring system is designed with respect to ULS, FLS and ALS. The system fulfils the ULS, FLS and ALS criterion. In general, the bottom chain dimensions are governed by strength criteria in ULS when corroded, the fibre ropes are governed by requirements to necessary stiffness given by the global analyses, and the top chain dimensions are governed by out-of-plane fatigue. All other equipment such as connectors, chain stopper, fairlead etc. are designed to have higher capacity than the mooring line.

The fatigue life is generally 100 years or more for all main mooring line components, except from the top chain at fairlead which has a fatigue life of 25 years. The fatigue damage for the top chain is caused by out-of-plane and in-plane bending of the chain at the fairlead. More refined analysis and design of the fairlead might reduce the damage. Corrosion allowance is accounted for when evaluating the capacity of the mooring lines.

The mooring system is simplified in the global analysis model. The simplification used in the global analysis model is verified in this report by performing local quasi-static and dynamic analysis of the mooring line pairs. Time histories for displacement and local environmental loads on the mooring lines are included in the dynamic analysis. The local analyses performed proves that the results of the global model can be used for design of the mooring system.

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APPENDIX E – PONTOON INTERFACE

APPENDIX F – GRAVITY ANCHOR DESIGN

1 INTRODUCTION

1.1 Current report

This report describes the design of the mooring system for recommended concept K12. The main focus is on evaluation and selection of mooring concept and design of main components. The report comprises the following:

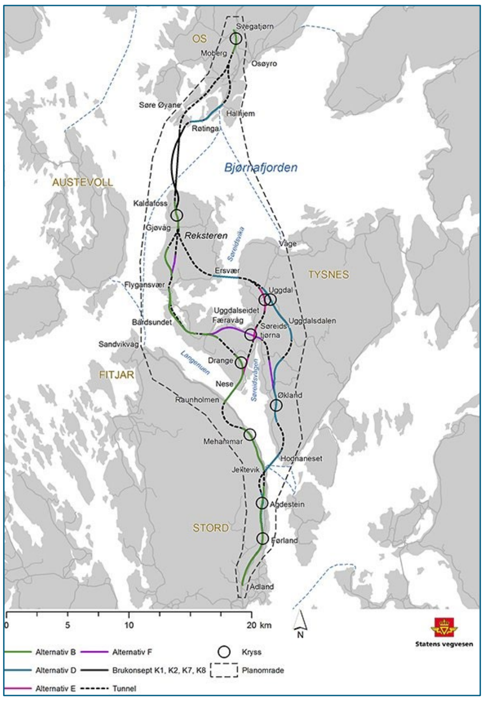
- Mooring concepts overview
- Mooring system screening and selection
- Presentation of selected mooring concept (with layout, components, interfaces etc.)
- Requirements to global model and mooring system
- Design input
- Mooring line design (ULS and FLS)
- Verification analyses
- Installation

The current revision of this report is based on the Bjørnafjorden floating bridge concept K12 model M20.

Updates since last revision

- VIV included
- Mooring line tension (sec. 7), Mooring line Design (sect. 9), Fatigue mooring lines (sect.11) updated according to results from model 20
- Brief section on installation included.
- Updates of all results to consistent with model M20.
- General editorial changes and updated.
- Results from local model in Riflex added

1.2 Project context



Statens vegvesen (SVV) has been commissioned by the Norwegian Ministry of Transport and Communications to develop plans for a ferry free coastal highway E39 between Kristiansand and Trondheim. The 1100 km long coastal corridor comprise today 8 ferry connections, most of them wide and deep fjord crossings that will require massive investments and longer spanning structures than previously installed in Norway. Based on the choice of concept evaluation (KVU) E39 Aksdal Bergen, the Ministry of Transport and Communications has decided that E39 shall cross Bjørnafjorden between Reksteren and Os.

SVV is finalizing the work on a governmental regional plan with consequence assessment for E39 Stord-Os. This plan recommends a route from Stord to Os, including crossing solution for Bjørnafjorden, and shall be approved by the ministry of Local Government and Modernisation. In this fifth phase of the concept development, only floating bridge alternatives remain under consideration.

1.3 Project team

Norconsult AS and Dr.techn.Olav Olsen AS have a joint work collaboration for execution of this project. Norconsult is the largest multidiscipline consultant in Norway, and is a leading player within engineering for transportation and communication. Dr.techn.Olav Olsen is an independent structural engineering and marine technology consultant firm, who has a specialty in design of large floating structures. The team has been strengthened with selected subcontractors who are all highly qualified within their respective areas of expertise:

- Prodtex AS is a consultancy company specializing in the development of modern production and design processes. Prodtex sits on a highly qualified staff who have experience from design and operation of automated factories, where robots are used to handle materials and to carry out welding processes.
- Pure Logic AS is a consultancy firm specializing in cost- and uncertainty analyses for prediction of design effects to optimize large-scale constructs, ensuring optimal feedback for a multidisciplinary project team.
- Institute for Energy Technology (IFE) is an independent nonprofit foundation with 600 employees dedicated to research on energy technologies. IFE has been working on high-performance computing software based on the Finite-Element-Method for the industry, wind, wind loads and aero-elasticity for more than 40 years.
- Buksér og Berging AS (BB) provides turn-key solutions, quality vessels and maritime personnel for the marine operations market. BB is currently operating 30 vessels for harbour assistance, project work and offshore support from headquarter at Lysaker, Norway.
- Miko Marine AS is a Norwegian registered company, established in 1996. The company specializes in products and services for oil pollution prevention and in-water repair of ship and floating rigs, and is further offering marine operation services for transport, handling and installation of heavy construction elements in the marine environment.

- Heyerdahl Arkitekter AS has in the last 20 years been providing architect services to major national infrastructural projects, both for roads and rails. The company shares has been sold to Norconsult, and the companies will be merged by 2020.
- Haug og Blom-Bakke AS is a structural engineering consultancy firm, who has extensive experience in bridge design.
- FORCE Technology AS is engineering company supplying assistance within many fields, and has in this project phase provided services within corrosion protection by use of coating technology and inspection/maintenance/monitoring.
- Swerim is a newly founded Metals and Mining research institute. It originates from Swerea-KIMAB and Swerea-MEFOS and the metals research institute IM founded in 1921. Core competences are within Manufacturing of and with metals, including application technologies for infrastructure, vehicles / transport, and the manufacturing industry.

In order to strengthen our expertise further on risk and uncertainties management in execution of large construction projects Kåre Dybwad has been seconded to the team as a consultant.

1.4 Project scope

The objective of the current project phase is to develop 4 nominated floating bridge concepts, document all 4 concepts sufficiently for ranking, and recommend the best suited alternative. The characteristics of the 4 concepts are as follows:

- K11: End-anchored floating bridge. In previous phase named K7.
- K12: End-anchored floating bridge with mooring system for increase robustness and redundancy.
- K13: Straight side-anchored bridge with expansion joint. In previous phase named K8.
- K14: Side-anchored bridge without expansion joint.

In order to make the correct recommendation all available documentation from previous phases have been thoroughly examined. Design and construction premises as well as selection criteria have been carefully considered and discussed with the Client. This form basis for the documentation of work performed and the conclusions presented. Key tasks are:

- Global analyses including sensitivity studies and validation of results
- Prediction of aerodynamic loads
- Prediction of hydrodynamic loads
- Ship impact analyses, investigation of local and global effects
- Fatigue analyses
- Design of structural elements
- Marine geotechnical evaluations
- Steel fabrication
- Bridge assembly and installation
- Architectural design
- Risk assessment

2 DESIGN BASIS

2.1 Rules and standards

For general design basis data reference is given to Design Basis Bjørnafjorden, Ref. [1] and Design Basis – Mooring and anchor, Ref. [2]. The main rules and standards used for mooring design are summarized in Table 2-1.

Table 2-1 Rules and standards

Design rule / standard	Reference
NORSOK N-004, Design of steel structures	[3]
NORSOK M-001, Material selection	[4]
DNVGL-OS-E301, Position mooring	[5]
DNVGL-RP-C205, Environmental conditions and environmental loads	[6]
DNVGL-RP-C203, Fatigue design of offshore steel structures	[7]
BV Guidance Note NI 604, Fatigue of Top Chain Moring Lines due to In-plane and Out-of-plane Bending's	[8]
Håndbok N400, Bruprosjektering	[9]
NS-EN 1993-1-1, Eurocode 3: Design of steel structures	[10]
NS-EN-ISO 19901-7, Dynamisk posisjonering og forankring av flytende innredninger og flyttbare innredninger til havs	[11]

2.2 Functional requirements

2.2.1 Minimum Design Life

General design life for the mooring system shall be 100 years. Mooring components that have a design life of less than 100 years shall be replaceable. Easy replaceable wear parts shall have lifetime of minimum 25 years. Design life for the different components of the mooring system is presented in Table 2-2. The components with design life of 100 years should be checked with regular inspections and possible degradation processes other than fatigue and corrosion should also be evaluated. All components of the mooring system will be designed with the possibility of replacement during the design life.

Table 2-2 Design life mooring system components

Component	Minimum Design life (Fatigue and Corrosion)
Pontoon outfitting	100 years
Connection equipment	50 years
Top chain	25 years
Polyester rope/steel wire	100 years[1)]
Bottom chain	50 years[1)]

Note 1: Inspection should be carried out regularly and a full integrity evaluation should be performed after 25 years

2.2.2 Marine growth

Marine growth shall be accounted and the marine growth assumed for mooring lines (DNVGL) is summarized in Table 2-3.

> *Table 2-3 Marine growth, DNVGL OS-E301, Ref. [5]*

Water depth	Thickness 59 - 72° N	Density
+2 m to -40 m	60 mm	1325 kg/m^3
Below -40 m	30 mm	1325 kg/m^3

Calculation of mass and weight of marine growth for mooring lines shall be performed according to ref. [5]:

Mass of marine growth:

$$M_{growth} = \frac{\pi}{4}\left[(D_{nom} + 2\Delta T_{growth})^2 - D_{nom}^2\right]\rho_{growth} \cdot \mu \quad (kg/m)$$

Submerged weight of marine growth:

$$W_{growth} = M_{growth}\left[1 - \frac{\rho_{seawater}}{\rho_{growth}}\right]\frac{9.81}{1000} \quad (kN/m)$$

ρ_{growth} = density of marine growth
$\rho_{seawater}$ = density of sea water
D_{nom} = nominal chain or wire rope diameter
ΔT_{growth} = marine growth surface thickness
μ = 2.0 for chain, 1.0 for wire rope.

2.2.3 Corrosion protection

Corrosion protection shall be ensured for all mooring system components such as:

- Chain stopper
- Moonpool
- Fairlead
- Top chain
- Bottom chain
- Anchor
- Connectors

Components, other than the mooring chain, are assumed to be protected by CP design with coating and anodes. Corrosion allowance shall be considered for chain, ref. section 2.4.

Corrosion protection of the mooring system components is expected to be feasible. The application is not significant different to common offshore solutions. Overall CP design is covered in Ref. [12].

2.2.4 Interfaces

Mooring line termination shall be close to pontoon centre and shall be integrated in the pontoon to avoid ships collision with mooring system. The effective moment from the mooring system to the pontoon columns and bridge girder should be limited by reducing the distance from the centre of the pontoon to the moonpools used to guide the mooring lines. This will reduce the moment transferred to the columns and bridge girder.

The mooring design shall accommodate response from global system and fulfil stiffness requirements.

2.2.5 Installation

Pre-tension, load monitoring and adjustment of the mooring line forces shall be possible.

Top chain installation through pontoon shall be possible with low risk of damaging the inner moonpool surface.

2.2.6 Operation

The bridge shall be designed to operate with two line damaged or out of service for 2 years over 25 years lifetime

The mooring system shall be passive, and no active line tension adjustment should take place during operation. It should however be possible to tension the lines if pre-tension is reduced during the design life of the system due to creep, inverse catenary or other effects.

The mooring system shall not be exposed to ships collision.

2.2.7 Maintenance

All mooring components shall be available for inspection except for the buried part of the anchor chains. The connecting point to the anchor shall be available for inspection for gravity anchors.

Replaceable components shall be easy to replaced and replaceable components below water shall be designed for ROV operation.

All mooring lines shall be replaceable.

All components shall be accessible for direct or ROV inspection.

Fatigue exposed areas above water shall have access for visual non-destructive inspection.

The mooring line system shall be equipped with mooring line tension measurement and monitoring system as well as failure detection system. The number of required monitors for each line and pontoon should be evaluated at later stage.

2.3 Component properties

2.3.1 Chain

Material properties according to ref. [13] for chains are summarised in Table 2-4. Studless chain is considered in the project.

> *Table 2-4 Material properties chain*

Parameter	Grade		
	R3	R4	R5
Material Quality	GL-R3	GL-R4	GL-R5
Min yield stress [MPa]	410	580	760
Min tensile Strength [MPa]	690	860	1000
Min Elongation [%]	17	12	12
Min reduction of area [%]	50	50	50
Youngs modulus [MPa]	48160 1)	50850 1)	55182 1)

Note 1: For chain diameter 146mm

Weight of studless chain is taken as $0.02 \cdot d^2$, where d is the nominal diameter of the chain.

2.3.2 Polyester Rope

Rope characteristics according for fibre ropes are summarised in Table 2-5.

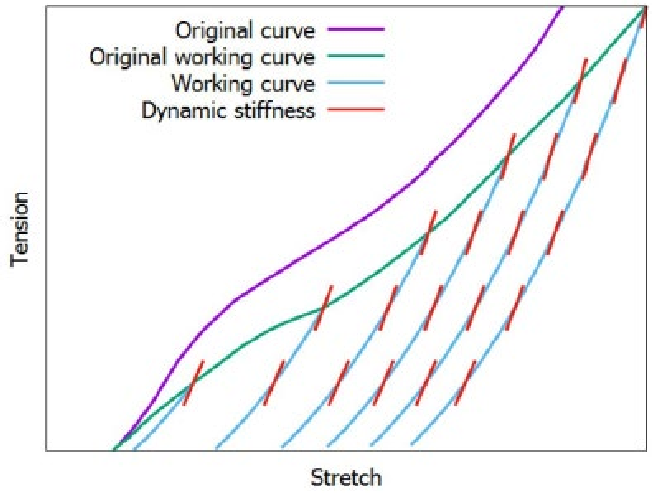
> *Table 2-5 Characteristics fibre rope*

Rope diameter [mm]	MBL [t]	Mass in air (kg/m)	Youngs modulus used in analyses[1] [MPa]
135	600	13.4	4733 1)
145	700	15.7	
155	800	18.1	
168	900	19.4	
177	1000	22.0	
185	1100	24.1	
193	1200	26.5	
205	1250	27.7	
209	1300	28.8	

Note 1: The actual stiffness of the mooring lines may vary severely based on rope construction, effect of load rate and pretension among others. The Young's modulus selected in this phase is close to the existing permanent installations offshore Norway for quasi-static behaviour.

To obtain the correct elasticity during the expected operational rage of motions, it is vital that the rope is bedded in (pre stretched) during the installation phase.

For the current project phase, the rope properties are handeled as pure elastic for both quasi-static and dynamic behaviour due to low variation in mean tension. Reference is made to the Syrope model, Ref. [14] for working curves of the fibre rope.



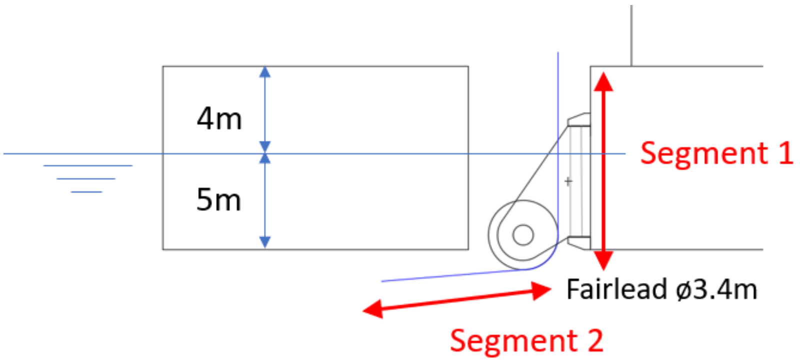
> *Figure 2-1 Syrope model for rope behaviour, Ref. [14]*

2.4 Corrosion allowance

Design basis, ref. [2] defines corrosion allowance of 0.8mm/year for the entire top chain. According to DNV-OS-E301, ref. [5] 0.8mm/year is defined for components in the splash zone and 0.2mm/year for components below splash zone. The extension of the splash zone is from 4m below still water level to 5m above still water level, ref. [5].

For mooring line design the top chain is divided in two segments regarding corrosion allowance. Segment 1 is the chain from top of the pontoon until the lower edge of the pontoon. Segment 2 is from the lower pontoon edge through the fairlead and below, see Figure 2-2.

In fatigue analyses 50% of the chain's corrosion allowance shall be taken into account.



> *Figure 2-2 Segments of top chain with regard to corrosion allowance*

Corrosion allowance for the mooring line components is summarised in Table 2-6. It is expected that the chain at the fairlead will be protected by the fairlead and pontoon corrosion protection system and thus have lower corrosion rates than used in the design.

> *Table 2-6 Corrosion allowance*

Component	Corrosion allowance /year
Top chain segment 1[1]	0.8 mm / year
Top chain segment 2 + fairlead[1]	0.2 mm / year
Fibre rope	-
Bottom chain[1]	0.2 mm / year

Note 1: Ref. [5]

2.5 Mooring line load factors

The philosophy for design of the main components follows DNV-OS-E301 for determining ultimate capacity of the main components, with safety factors according to ISO19901-7, appendix B.2. Consequence class 3.

The following limit states are used:

Condition	Safety factor
ULS – intact condition	2.2
ULS- failure in one line	1.5 (1.1 for analysis with transient effects)
ULS – failure in two lines	1.5 (1.1 for analysis with transient effects)
ALS (environmental 10.000 year return period, ship impact)	1.0

In addition requirements to pretension is controlled by the ULS-EQU condition in [1] with load factor 0.9 on pretension (favourable load)

2.6 Fatigue design data

2.6.1 Material properties

Design S-N curve parameters (for chain) and R-N curve parameters (for fibre rope) are summarised in Table 2-7.

> *Table 2-7 Design fatigue parameters*

Fatigue analyses	a_d	m
Tension-Tension Top- and bottom chain[1]	$6.0 \cdot 10^{10}$	3.0
IPB/OPB Top- and bottom chain[2]	$1.0 \cdot 10^{12.575}$	3.0
Tension- Tension Polyester rope[1]	0.259	13.46

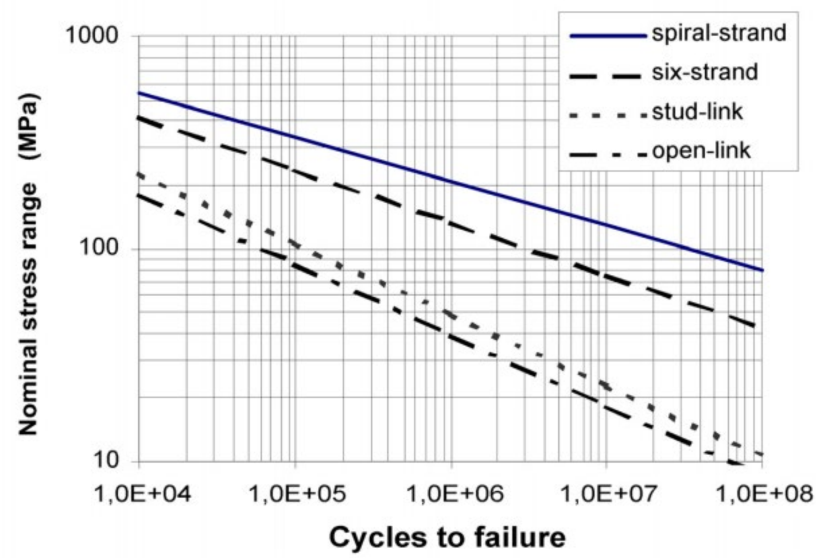
Note 1: Ref. [5]
Note 2: Ref. [8]

With:

a_d = Intercept parameter of the SN-curve

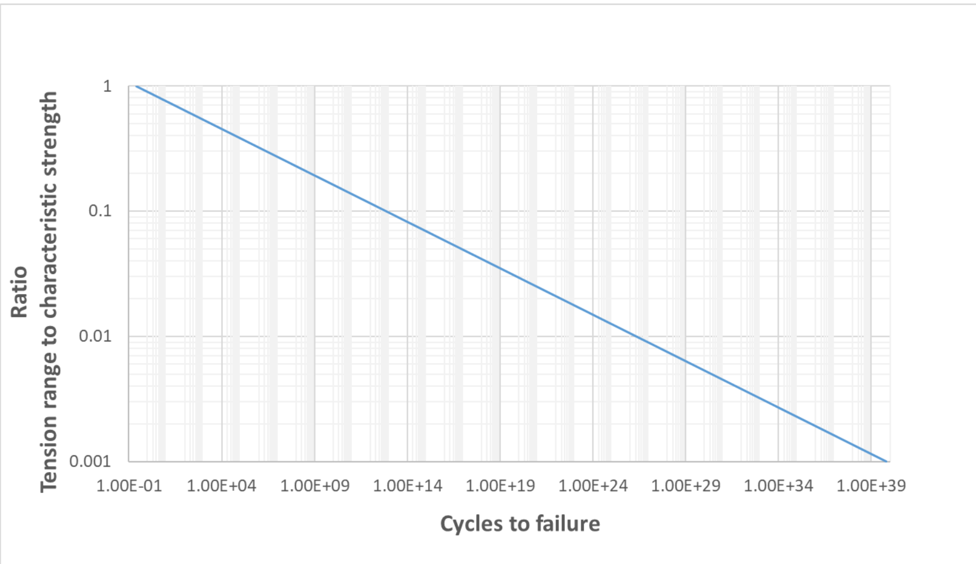
m = the slope of the SN curve

Figure 2-3 shows the design S-N curve for tension-tension fatigue for chain (open link).



> *Figure 2-3 Design S-N curves, Ref. [5]*

Figure 2-4 shows the design R-N curve for tension-tension fatigue for fibre rope.



> *Figure 2-4 Design R-N curve fibre rope*

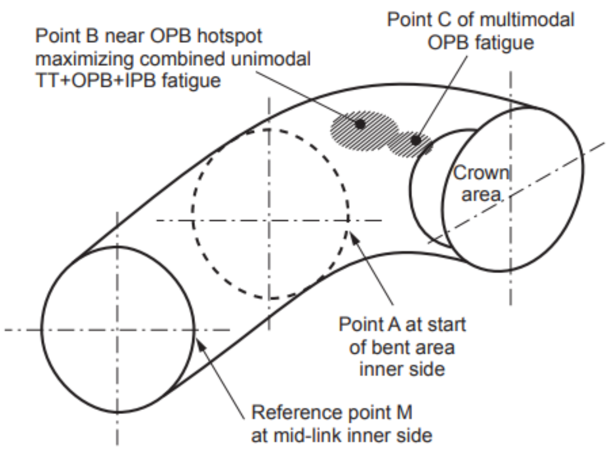
2.6.2 Stress concentration factor (SCF)

Stress Concentration factors used for are summarised in Table 2-8. Figure 2-5 shows the hotspot locations for IPB/OPB fatigue SCF’s.

> *Table 2-8 Stress concentration factor*

Fatigue analyses	Stress concentration factor SCF				
Tension-Tension (TT) Top- and bottom chain [1]	1.15				
Tension-Tension Fibre rope	1.2				
IPB/OPB (combined with TT) Top- and bottom chain [2]	Loading mode	Location			
		A	B	B’	C
	TT	4.48	2.08	1.65	1.04
	OPB	0	1.06	1.15	$1.21.*\gamma_{TT}$ [2]
	IPB	1.25	0.71	0.66	1.50

Note 1: Ref. [5]
Note 2: Ref [8], $0.95 \leq \gamma_{TT} = 1+0.9(Pretension/MBL-0.15)$



> *Figure 2-5 Critical hotspot on chain link for combined fatigue of top chain*

2.6.3 Design fatigue factor

Design fatigue factors (DFF) are summarised in Table 2-9.

> *Table 2-9 Design fatigue factor*

Fatigue analyses	Design fatigue factor DFF
Tension-Tension Top- and bottom chain [1]	10
Tension-Tension Fibre rope[1]	60
IPB/OPB Top- and bottom chain [2]	10

Note 1: Ref. [5]
Note 2: Ref. [8]

3 GENERAL OVERVIEW OF MOORING CONCEPTS

3.1 Mooring systems

A brief overview of different possible concepts for mooring systems if further presented.

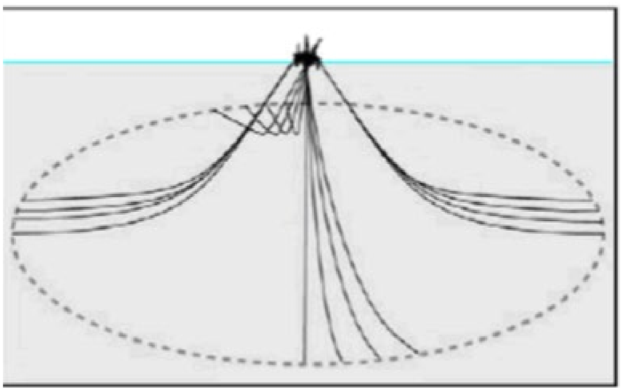
3.1.1 Catenary mooring system

A catenary mooring provides restoring forces through the suspended weight of the mooring lines and changes in lifted mooring line length increasing or decreasing the weight of lifted mooring line. A typical example of a catenary mooring system is shown in Figure 3-1. The catenary line terminates at the sea floor horizontally, where parts of the line is laying on the bottom while the rest is suspended in the sea water. A catenary system with a high pre-tension and heavy chains will be needed to have effective stiffness at small amplitudes of motion.

The stiffness is hence governed by the weight of the line and is referred to as the geometric stiffness of the mooring line. The stiffness increases rapidly as the line is stretched and gives a nonlinear horizontal stiffness. At some point the catenary system will be fully "tensioned" and rely on the stiffness of the mooring components. If the mooring line is fully "tensioned" the load will increase rapidly and lead to failure of the system at small increases in motion.

Catenary systems will typically not have vertical forces at the anchor. A significant length of mooring line is typically laying the seabed to ensure that the line is not fully lifted for the expected maximum excursion. A catenary mooring system will thus often have a higher footprint than a taut mooring system which if further described below.

A catenary system can consist of chain only, or a combination of chain, clump weight and wire, where the restoring forces is mainly governed by heavy bottom chain. The most common catenary system used in the offshore industry today is the chain catenary system or the chain and wire combined catenary system. For greater water depths some sections of the chain are usually replaced by wire to reduce the total weight of the mooring lines. It can also be possible to use clump weights or fibre ropes to improve the behaviour of the system for different site and environmental conditions.



> *Figure 3-1 Catenary system*

3.1.2 Taut leg system

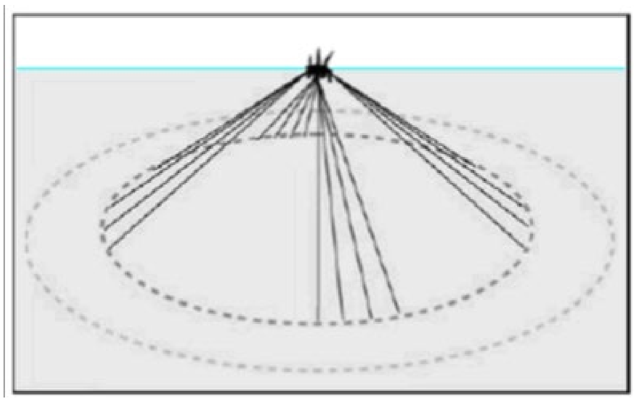
The taut leg mooring system consist of taut mooring lines, often consisting of light weight wire or fibre ropes which is close to neutral in water. This implies that the catenary effect of a free hanging line is negligible, and the restoring forces is governed by elasticity of the fibre rope. The taut leg system obtains restoring forces from axial stretching of the mooring lines. A requirement for the taut leg system is that the mooring line must have sufficient elasticity to withstand the vessel wave motions without overloading.

The most common material used for taut line mooring system is different synthetic fibres, with polyester lines as the most common. Other fibres are also possible such as nylon and HMPE. Nylon is however still not deemed to be qualified for long term mooring. HMPE ropes typically have high stiffness and is thus not suitable for intermediate water depth application.

The lines in a taut line mooring system typically has an angle with respect to the seabed at the anchor implying that the anchors must be designed to withstand both dynamic and static vertical forces. To avoid slack and keep the functional requirements of the mooring group, the mooring lines are pretensioned to a level ensuring that the mooring lines are taut for all possible positions.

The taut line anchor system is more flexible with respect to anchor placement, and for similar conditions the taut line system requires smaller footprint than a catenary system. The overall stiffness of the systems can be tuned by elastic stiffness (construction and diameter) of the mooring lines. This gives an almost linear behaviour for horizontal stiffness.

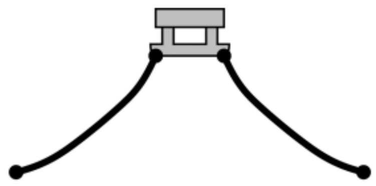
The taut line systems are often preferred for mooring in deeper water. This is due to lower overall weight of the system and a more cost-effective system.



> *Figure 3-2 Taut leg system*

3.1.3 Semi taut leg mooring system

A semi taut leg system is a combination of the two above, where both the catenary effect giving geometrical stiffness and the elastic stiffness during stretching is utilized. A semi-taut system is illustrated in Figure 3-3 below. The anchor point may experience vertical forces during the most severe sea states.



> *Figure 3-3 Illustration of semi-taut system.*

3.1.4 TLP (tension leg system)

Tension leg systems (TLP) are used for offshore oil and gas structures. A TLP system depends on vertical or nearly vertical tethers providing stiffness when the floater moves sidewise based on the increased buoyancy of the floater when pulled down by the tethers. A typical configuration is illustrated in Figure 3-4. The tethers will need to be prestressed to provide restoring for the system. The prestressing level will need to be sufficient to avoid slack in all conditions. The tethers are characterized by high axial stiffness, such that vertical motions of the floater is limited. Generally, the tethers consist of cylindrical steel pipes, but wire or chain may also be utilized. The horizontal stiffness of the TLP system is governed by the water line area of the floater and the water depth. The TLP system is best suited for depths above 300 meters. TLP systems generally requires larger structures to provide sufficient restoring stiffness. Another challenge with TLP systems is redundancy if one or more tethers are lost as this typically will lead to loss of stability of a floater.

> *Figure 3-4 TLP mooring*

3.2 Main components in common mooring systems

3.2.1 Chain

Mooring chain is typically used for mooring of oil&gas floaters in moderate to shallow water, and as subcomponents towards floater and anchor for other applications as aquaculture and deep-water mooring. The chain does generally behave well with respect to seabed contact, sunlight, and it is robust with respect to local wear. Bacterial corrosion has for some cases been observed for bottom chain in contact with the seabed. Mooring chain are typically sensitive to corrosion and fatigue.

Chains are well-defined and necessary design data can easily be found in rules and standards.

The mooring chain is mainly defined by the following parameters:

- Diameter: Defines the weight and size
- Classes (R3, R4, R4s etc): Defines the strength of the chain
- Construction: Stud link or studless chain. Studless chains are typically used for long term mooring.

3.2.2 Fibre rope/ Polyester rope

Fibre ropes has in the later years gained a good track record for offshore floaters in the oil and gas industry. A typical fibre rope for long-term mooring is illustrated below in Figure 3-5. Fibre rope systems has also been utilized in the fishfarming industry for decades with good experience. For long-term mooring systems polyester fibre ropes has best record.

The fibre rope solutions have most often been utilized for deep-water and ultra-deep-water moorings in the oil and gas industry. The main advantages of the fibre rope solution are:

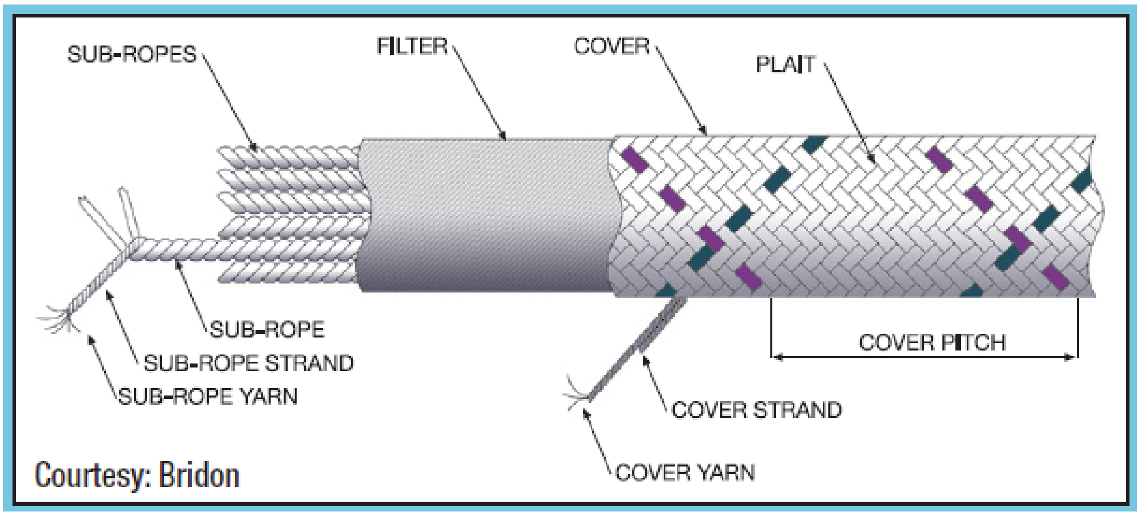
- Light weight system, less requirements to installation, pontoon buoyancy, easy handling,
- Flexible with high elasticity and high allowable elongation
- No corrosion allowance
- Good fatigue performance
- Easy to adjust stiffness by adjusting diameter.

The fibre rope is most suitable for the free hanging segments of the mooring line. It is not suitable for the parts in contact with sea bed, due to its poor behaviour with constant wear and tear and ingress of sand and mud. Fibre ropes are typically also sensitive to UV-light which can cause degradation of the rope. Due to this limitation, the application is also limited in the splash zone and connection to the pontoon. To increase the design life of the rope, a particle filter and protective jacket (cover) may be introduced. The filter stops the intrusion of micro particles and marine growth into the main rope construction, which is important to prevent damage due to internal abrasion.

Fibre ropes can if protected by a suitable jacket be placed at the sea bed during temporary phases of the installation. It is common to use a protective jacket for fibre ropes to avoid damage of the fibre rope during handling, temporary storage at seabed and possible wear from fishing trawlers.

Polyester has excellent fatigue properties, which is a critical parameter for a permanent mooring system with the lifetime expectancy.

Special evaluations during the design is need for the fibre rope solution with respect to creep behaviour, bedding in of the rope and at possible splices. It is also important to ensure that the stiffness variation due to loading rate effects are accounted for if different frequencies ranges are present in the mooring line load.

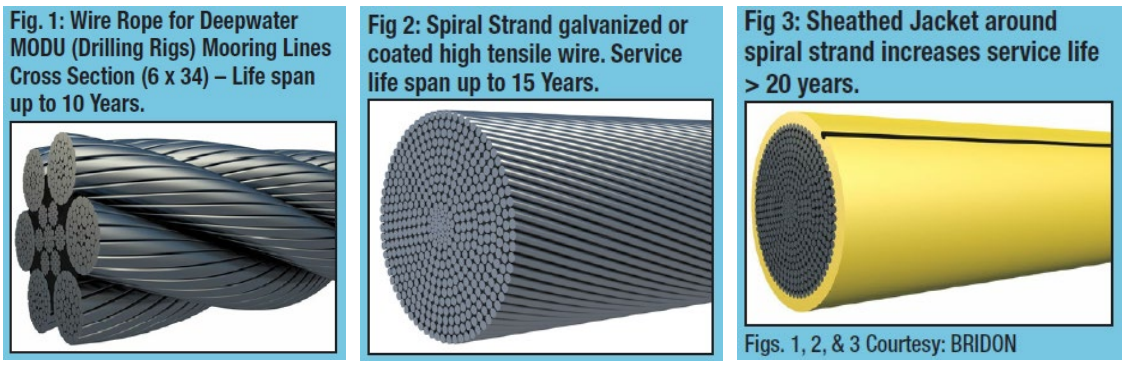


> *Figure 3-5 Typical fibre rope construction*

3.2.3 Steel wire

Steel wire is significantly lighter than chain for similar breaking strength. The available types of steel wire are illustrated in Figure 3-6. Steel wire is commonly used for mooring of offshore floaters in combination with chain. The steel wire cannot be used for segments interacting with the sea bed. For long term mooring systems the wire must be equipped with corrosion protection, which typically is a jacket protecting the spiral strand. It is also common to grease the wire to reduce friction and provide corrosion protection in case of damage to the protective jacket.

Wires are sensitive to steep bending curvatures, and the maximum bending radius is typically 16 times the wire diameter. It is also important that the wire is handled carefully during temporary phases to avoid damage of the protective jacket that is included to avoid corrosion and internal wear.



> *Figure 3-6 different wire constructions*

3.3 Other components

3.3.1 Clump weights

Clump weights can be connected to the mooring lines to optimize or tune the geometrical stiffness of the system. The clump weights can either be distributed along the lines or as discrete weights. The latter can for instance be utilized to avoid slack in fibre rope systems.

3.3.2 Buoyancy elements

Similar as for clump weighs which adds weight to the system, buoyancy elements can be utilized to add lift to the system. Both submerged buoys and surface buoys can be utilized. Submerged buoys are most often used for deep water applications to limit dynamics of the mooring line.

3.3.3 Bend restrictor

Bend restrictors may be used in areas where the line is prone to experience concentrated bending. This may for instance be wire connection to pontoons, where a bend restrictor can be utilized to reduce concentrated curvature and hence hot spots for fatigue.

3.3.4 Connection Equipment

Several connection links between mooring line components may be utilized for a permanent mooring line. The most relevant types and applications are summarized below:

Name	Application	
H- link	Connector between two ropes, ropes and chain or chain-chain	

Splice	Eye-splice termination of rope. The eyes and splice area shown in the photo are protected with polyurethane. It is important that splices are bedded-in to avoid elongation of the system.	 Courtesy: Lankhorst
Ball grab/pin type connector	Subsea connector. Fast connection, typical less than 10 minutes. Good ability to reconnect and connect if change out is required.	 Courtesy: firstSubsea
Fibre rope connector	Connector between two ropes or ropes and chain. Reduces installation time compared to H-link joints and splices.	 Courtesy:Lankhorst

3.3.5 Pontoon outfitting

The mooring line will be connected to the pontoon and anchors. Standard equipment is available for connection and guiding (mainly relevant for pontoons) of the mooring system locally. The following components are foreseen used:

- Moonpool: It is foreseen that the tensioning and locking of the mooring line will be done at the top deck of the pontoon. In order to reduce the moment imposed by imbalance in vertical forces from the mooring system it is proposed that two moonpools will be used to guide the mooring through the hull close to the central column of the pontoon.
- Fairlead: A fairlead will be used within the moonpool to guide the mooring system in the correct direction and limit local bending of the chain. The fairlead will consist of a chain wheel that is attached to the hull and guides the mooring line in the correct direction.
- Chain stopper: A chain stopper will be used to connect the mooring line to the pontoon. The chain stopper can be integrated with the pontoon structure and will consist of a chain lock with relevant support. Several commercial solutions exist for chain stoppers.
- Tensioning: Tensioning of the mooring line should be done from the top of the pontoon. Several alternatives are possible being a temporary linear mooring tensioner (base case), a permanent winch or utilizing a winch on a supporting vessel.
- Chain locker: As a small amount of excess chain is can be present after installation and re-tensioning (if needed) a small chain locker could be relevant. The purpose of the chain locker is to store the excess chain in a secure way.

4 CONCEPT SCREENING AND SELECTION

4.1 Behaviour and Function

At that start of the project several principle mooring restoring stiffness levels were analysed with the global model to check the effect on response and modes of the entire bridge. It was observed that the mooring system should contribute at small amplitudes of transverse bridge displacement. It was also observed that linear stiffness would be beneficial as this gives a predictable and reliable mooring response. The required stiffness to reduce the response of the bridge and alter the eigen modes was rather high and will thus limit the number of possible systems. It was also was considered beneficial to have a system with high elastic capacity ensuring that the system can provide restoring for significantly higher displacements than expected from extreme environmental loads.

4.2 Evaluated systems

Several mooring system configurations were studied and evaluated at the start of the project. The following systems were evaluated:

- Catenary system
- Taut system
- Taut system with intermediate buoyancy element connected to the pontoon to reduce transfer of vertical forces from the mooring system into the bridge
- TLP

A catenary system consisting of chain or chain and wire was evaluated. Such systems have a good track record from the oil&gas industry, but they will typically give a non-linear restoring and require larger offsets to provide significant restoring. In order to provide a high initial stiffness a stiff initial configuration is needed. Such a stiff catenary system will have very limited capacity with respect to extreme offset and be sensitive to installation tolerances. Mooring chains are also typically rather expensive when compared to for instance fibre ropes. A catenary system is thus not proposed.

A taut system consisting of fibre rope with sufficiently high flexibility and good elongation properties is considered to provide a rather linear restoring characteristic from the mooring. Due to practical aspects the fibre rope will typically be connected to chain at seabed/anchor and at the top of the mooring line to ease connection with the pontoon. These short chain segments will not alter the desired linear response of the mooring system as the stiffness of the system will be provided by the axial stiffness of the fibre rope. Taut systems are typically sensitive to creep as this might reduce the effective pre-tension and thus increase the risk of slack. The creep behaviour of known fibre ropes as polyester is well understood and documented from the oil&gas industry and can be accounted for during design and installation. Generally, it is important to ensure that the fibre rope is sufficiently bedded-in before installation to avoid creep due to the rope structure. It is also important to ensure that splices in the fibre rope is bedded-in to avoid elongation at these points during extreme loads. Bedding-in can be ensured by pulling the fibre rope during installation. It is expected that utilizing the installation vessel to pull the bottom chain and fibre rope before connection with the pontoon should provide sufficient bedding-in. A taut system with polyester fibre rope is deemed to be the best solution for the current project.

Taut system with an additional buoyancy element below the pontoon was also studied in the initial phase of the project. Such a system will reduce the vertical load from the mooring system on the pontoon and bridge. This system is described further in the technical note included as Appendix D. The vertical forces from the mooring system was based on evaluation of pontoon size and overall configuration not deemed to be design driving and the solution with an additional buoyancy element was thus not studied further.

A TLP system was briefly considered. A TLP system can provide a rather linear restoring of the pontoons which is activated when the bride is displaced sideways. The required amount for additional buoyancy was however deemed to be significant and would require a significant increase in pontoon dimensions to utilize the TLP stiffness. The bridge girder deformation will also be influenced by a TLP system as the pontoon typically will be pulled down by the tethers. A TLP system was thus not considered further.

4.3 Selected System

A taut line mooring system is proposed, consisting of polyester fibre rope as main component, with mooring chain towards the anchor and pontoon terminations. A principle sketch of the system is shown in Figure 5-3. A taut system based on polyester mooring will give a robust and reliable system with a practically linear restoring stiffness. The lines will generally also have additional capacity with respect to extreme offset beyond the expected ULS offset. The lines are prestressed to avoid "slack" during the expected range of pontoon motions. Slack in this context does not mean that the rope goes into compression, but that it loses its pretension and hence stiffness. As long as the bottom chain is lifted from the ground a minimum level of pre-tension is always ensured. The local analysis will be used to document the behaviour of the proposed configuration for expected extreme offsets.

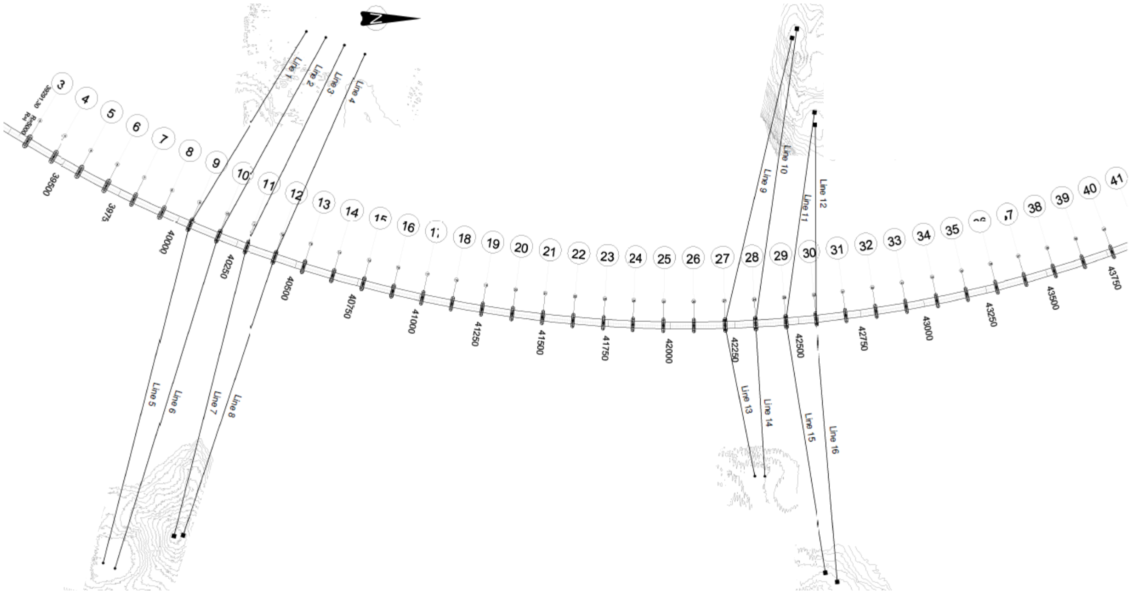
The system will consist of proven components with a track record from the oil&gas industry and other marine industries. Polyester fibre rope has good fatigue properties possibly limiting the need for replacing the main mooring line during operation. The proposed system can rather easily be adapted to new anchor locations as the stiffness is given by the fibre rope geometry and can thus be adjusted based on changes in the design assumptions. The fibre rope dimension will typically be governed by the required stiffness of each mooring line providing significant additional capacity of the rope for extreme offsets in accidental conditions.

5 MOORING SYSTEM

5.1 Layout

5.1.1 Plan view

The mooring system consists of two groups of mooring lines, each group consisting of eight mooring lines. The lines in one group are connected to four pontoons, with one line to each side of each pontoon. The groups are to the extent possible equally spaced along the bridge length (Approximately at 1/3 and 2/3 of the length). The plan view of the mooring system is shown in Figure 5-1.



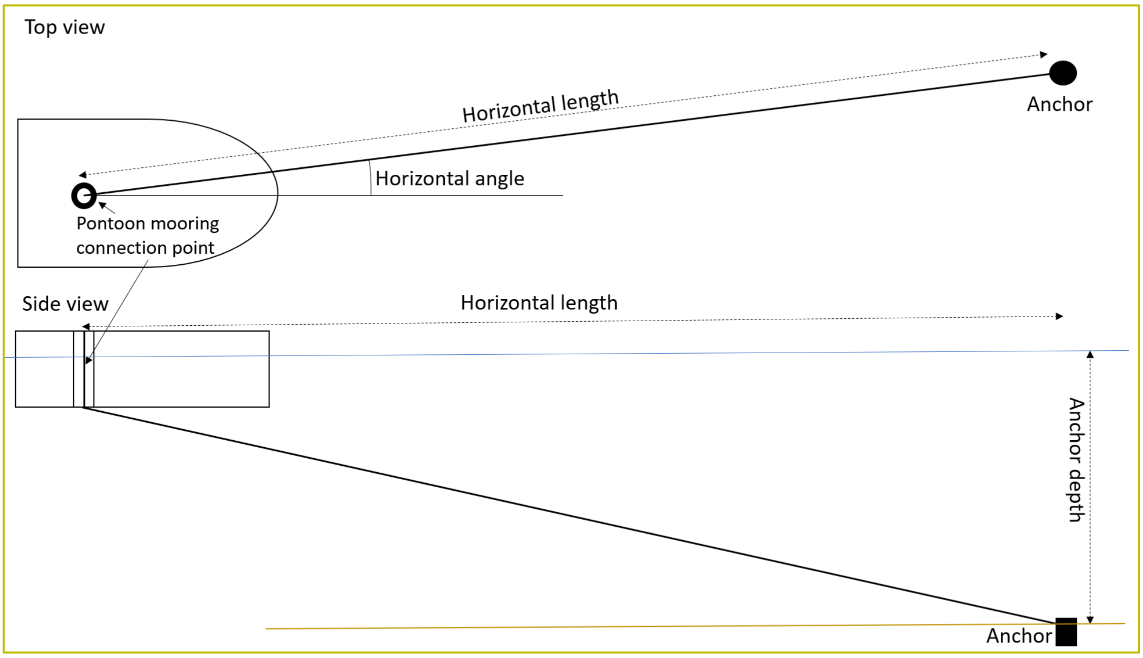
> *Figure 5-1 Mooring plan view*

5.1.2 Anchor positions, line lengths and depths

The geometric properties for the anchor lines is summarized in Table 5-1. Definition of the geometric values is shown in Figure 5-2.

> *Table 5-1 Anchor line geometric properties*

Line No	Horizontal length (m)	Anchor depth	Horizontal Angle (local)	Northing Pontoon (NTM5)	Easting Pontoon (NTM5)	Northing Anchor (NTM5)	Easting Anchor (NTM5)
1	913.5	-561.5	351.2	1 233 333.19	93 406.54	1 233 791.88	92 649.84
2	914.2	-561.2	352.3	1 233 444.16	93 452.09	1 233 868.78	92 673.69
3	905.8	-561.1	353.5	1 233 556.19	93 494.97	1 233 941.73	92 704.51
4	894.1	-561.2	354.3	1 233 669.21	93 535.15	1 234 019.10	92 739.73
5	1343.3	-359.3	188.7	1 233 333.19	93 406.54	1 232 996.20	94 734.33
6	1338.3	-359.2	184.4	1 233 444.16	93 452.09	1 233 042.63	94 756.02
7	1140.6	-291.7	186.1	1 233 556.19	93 494.97	1 233 271.95	94 625.02
8	1121.3	-296.5	180.5	1 233 669.21	93 535.15	1 233 308.72	94 622.53
9	1161.2	-123.2	344.1	1 235 438.93	93 801.78	1 235 699.97	92 679.12
10	1171.4	-123.5	347.9	1 235 558.78	93 796.68	1 235 720.03	92 643.06
11	829.5	-167.2	346.4	1 235 678.47	93 788.72	1 235 789.46	92 972.18
12	759.4	-158.1	353.0	1 235 797.93	93 777.88	1 235 793.91	93 021.29
13	598.6	-382.2	190.2	1 235 438.93	93 801.78	1 235 554.88	94 392.12
14	593.1	-380.5	181.1	1 235 558.78	93 796.68	1 235 594.93	94 392.40
15	992.0	-410.3	184.9	1 235 678.47	93 788.72	1 235 835.63	94 769.60
16	1030.0	-411.8	179.1	1 235 797.93	93 777.88	1 235 882.81	94 805.79

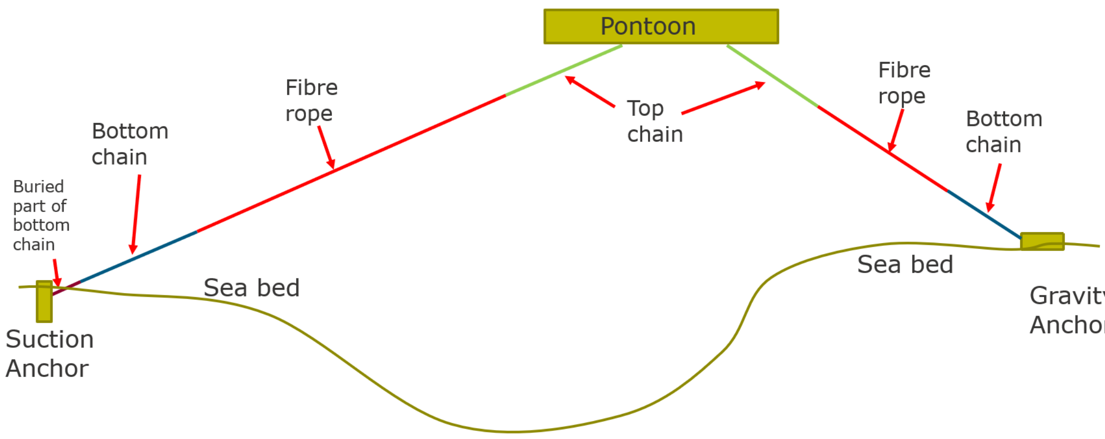


> *Figure 5-2 Definition of local system for angles and horizontal length/depth*

5.2 Mooring line components

A brief explanation of each mooring components and its main characteristics is further described.

5.2.1 Side view



> *Figure 5-3 Principle drawing (side view) of one pair of mooring lines.*

5.2.2 Buried part of bottom chain (for lines to suction anchors only)

Main characteristics:

- Installed together with the anchors
- Not inspectable, and hence more complicated to replace.
- Must be robust wrt. fatigue and corrosion (high design life)

5.2.3 Bottom chain

Main characteristics:

- Sufficient length to prevent contact between fibre rope and seabed.
- Easy connection to preinstalled anchor by ROV.
- Dimensions governed by ULS loads
- Design lifetime may be an issue due to corrosion. Fatigue lifetime is found to not be governing for the bottom chain
- Proven for long term mooring in the oil and gas industry.

5.2.4 Fibre rope

Main characteristics:

- Good elongation characteristics – gives nearly linear force-deformation curve.
- Easy to handle due to low weight
- Fatigue is not expected to be an issue
- Dimensions governed by stiffness requirements from global analyses
- Proven for offshore applications (i.e Aasta Hansteen spar platform and Goliat FPSO)

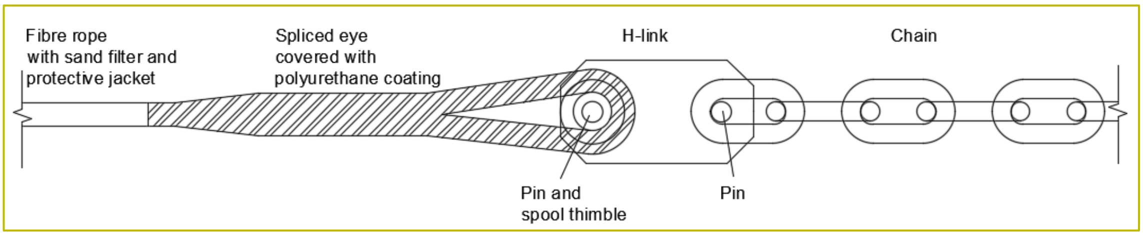
5.2.5 Top chain

Main characteristics:

- Robust during installation and tensioning (wear and tear)
- Gives termination of fibre rope at reasonable depth, reducing risk of damage by ship propeller and degradation by marine growth and UV light.
- Gives tolerances for determining pre-constructed rope lengths with respect to uncertainties in bedding-in lengths and potential post installation creep or shrinking.
- Easy to replace
- Corrosion and fatigue (OPB) is the governing effect for selection of dimension.
- Proven for long term mooring in the oil and gas industry.
- Connected to chain stopper at pontoon deck

5.2.6 Connections

The connection between fibre rope and chain is ensured by a spliced eye with a spool timble on the fibre rope and a H-link connector to the chain. See Figure 5-4.



> *Figure 5-4 Rope-chain connection*

5.2.7 Component specifications

The main dimensions of the mooring lines are summarized in Table 5-2.

> *Table 5-2 Anchor line geometric properties*

Line No.	Pre-tension	Botton Chain R4				Polyester fibre rope				Top Chain R4			
(-)	(MN)	Dim. (mm)	Length (m)	Dry weight (kg/m)	MBS (MN)	Dim. (mm)	Length (m)*	Dry weight (kg/m)	MBS (MN)	Dim. (mm)	Length (m)	Dry weight (kg/m)	MBS (MN)
1	2.3	100	60	200.0	9.9	177	985	22.0	9.8	146	25	426.3	18.9
2	2.1	100	60	200.0	9.9	177	985	22.0	9.8	146	25	426.3	18.9
3	1.8	92	60	169.3	8.5	177	978	22.0	9.8	146	25	426.3	18.9
4	1.8	92	60	169.3	8.5	177	968	22.0	9.8	146	25	426.3	18.9
5	2.0	100	75	200.0	9.9	185	1279	24.1	10.8	146	35	426.3	18.9
6	1.8	100	75	200.0	9.9	185	1274	24.1	10.8	146	35	426.3	18.9
7	1.6	92	50	169.3	8.5	168	1091	19.4	8.8	146	35	426.3	18.9
8	1.6	92	50	169.3	8.5	168	1074	19.4	8.8	146	35	426.3	18.9
9	1.7	92	70	169.3	8.5	177	1047	22.0	9.8	146	50	426.3	18.9
10	1.6	92	175	169.3	8.5	168	952	19.4	8.8	146	50	426.3	18.9
11	1.6	92	70	169.3	8.5	145	725	15.7	6.9	146	50	426.3	18.9
12	1.6	92	50	169.3	8.5	145	675	15.7	6.9	146	50	426.3	18.9
13	2.0	92	50	169.3	8.5	145	633	15.7	6.9	146	25	426.3	18.9
14	1.8	92	50	169.3	8.5	145	627	15.7	6.9	146	25	426.3	18.9
15	1.7	92	150	169.3	8.5	168	897	19.4	8.8	146	25	426.3	18.9
16	1.7	92	100	169.3	8.5	177	982	22.0	9.8	146	25	426.3	18.9

**Note: that the rope lengths are stretched lengths, adjustments due to bedding in and elastic elongation from permanent prestressing are not accounted for.*

5.3 Interface pontoon

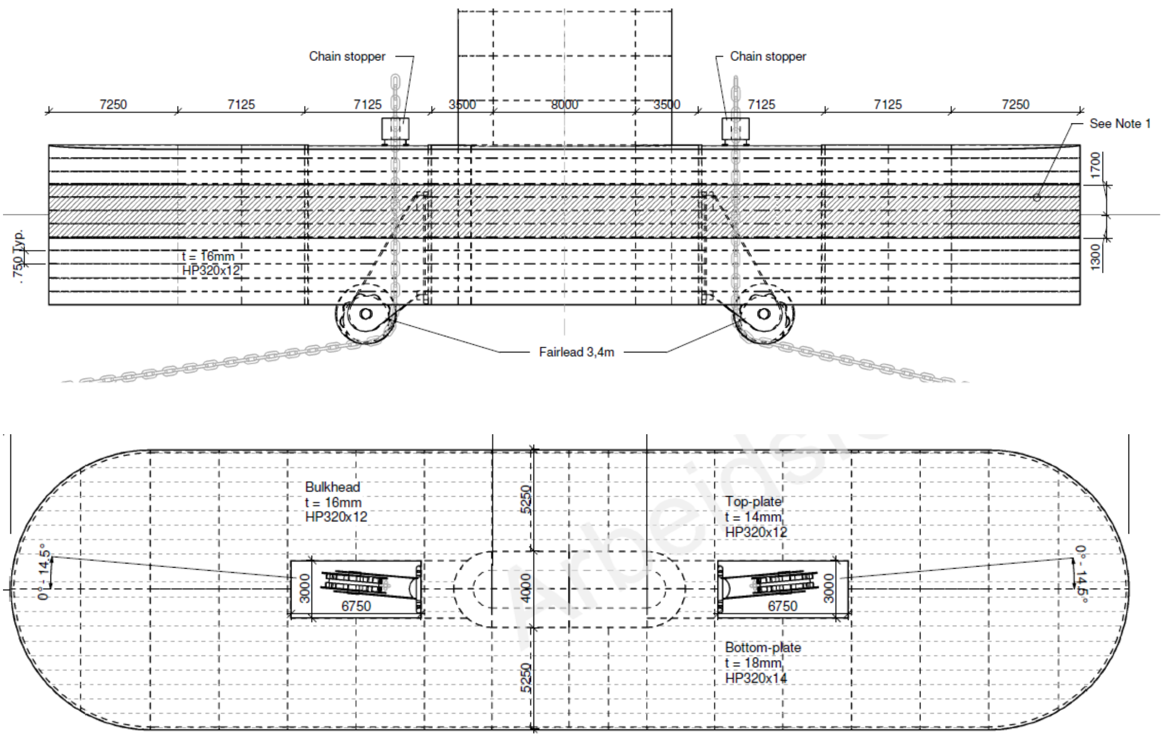
5.3.1 Possible Configurations

Several alternative solutions are possible for pontoon connection. The mooring lines can for instance be connected by using fairlead chain stoppers on the outside of the pontoon. As the proposed system only has two lines per pontoon, the simplest position of the fairlead chain stopper would then be at the end of the pontoon. This will imply that a moment from the vertical components of the mooring force is transferred to the pontoon, column and bridge girder. To reduce this effect, it could be reasonable to connect the mooring lines as close to the centre of the pontoon as possible. It could also be possible to connect the mooring lines within the elongation of the pontoon column, but this is expected to increase the complexity of the pontoon design significantly and will require that the tensioning system is permanently installed within the column or design of penetrations in the columns for tensioning/installation of mooring. It is thus deemed more efficient to use a "moonpool" close to the column with a fairlead at the lower end of the moonpool. This solution will limit the moment transferred to the column and bridge girder and at the same time avoid a significant increase in complexity for the pontoon design.

The design where the mooring line pontoon entry is located underneath and near the centre of pontoon is also favourable as the risk of damaging the mooring system during a ship impact event is avoided. The structural components for the mooring connection are hence sheltered from the damaged areas of the pontoon.

5.3.2 Selected Design

The selected solution for mooring line connection to the pontoon is shown in Figure 5-5. The fairlead is placed within the moonpool.

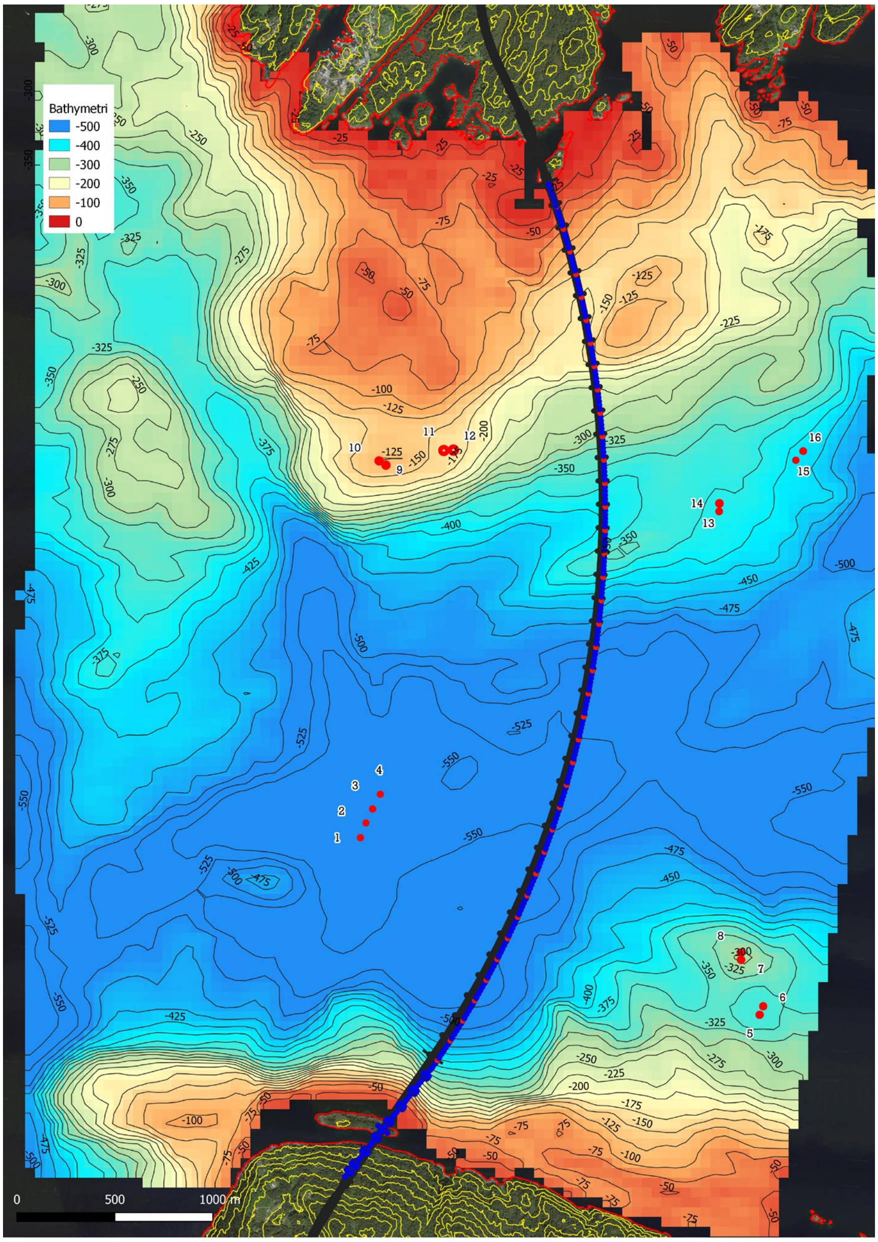


> *Figure 5-5 Mooring connection to pontoon*

The selected design is favourable for installation, inspection, maintenance and different mooring line angles in horizontal plane. The proposed solution has been checked with a general assessment of stresses in the fairlead assembly (ref. Appendix E). The assessment in mainly performed to evaluate the feasibility of the chosen geometry and dimensions. The final solution and design is for the fairlead is expected to be developed by specialist suppliers. Based on experiences from previous projects the proposed design is deemed to consist of conventional solutions. Chain stopper and chain locker will be positioned near the top of the pontoon.

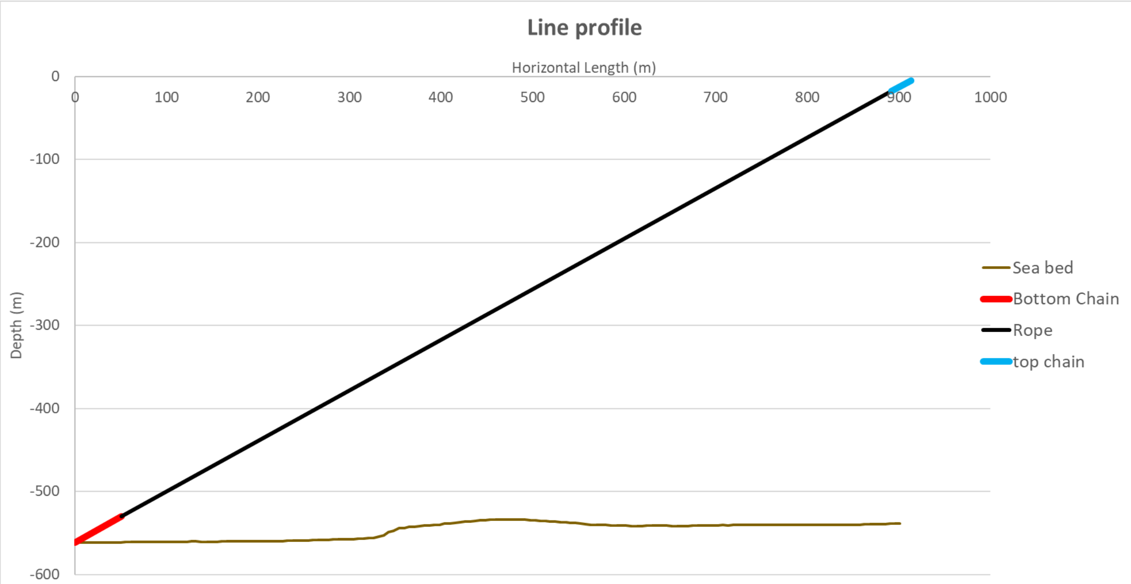
5.4 Line profiles

The seabed and line profiles for all lines are shown in the subsequent section. The top chain, rope and bottom chain is illustrated in the figures. Figure 5-6 shows the anchor locations.



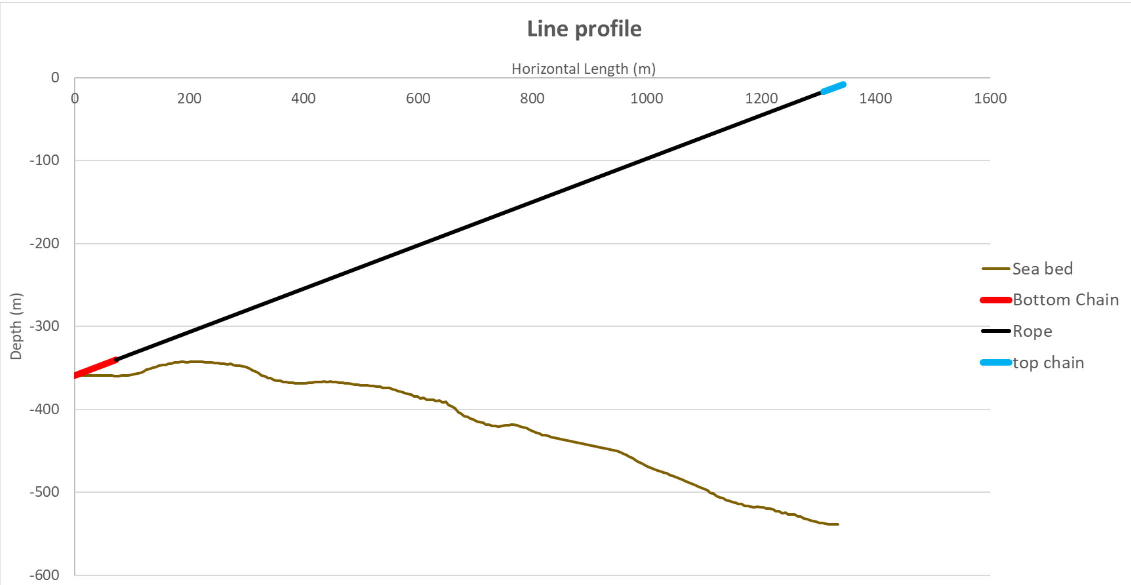
> *Figure 5-6 Bathymetry map showing anchor locations*

5.4.1 Line no. 1,2,3 and 4



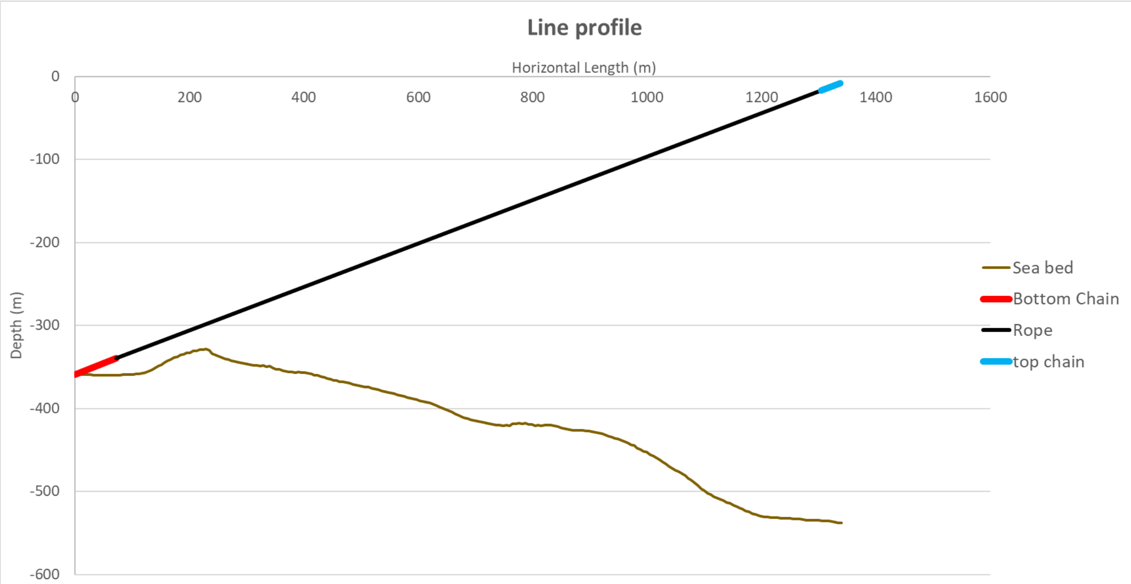
> *Figure 5-7 Line and seabed profile for line 1, 2, 3, 4.*

5.4.2 Line no. 5



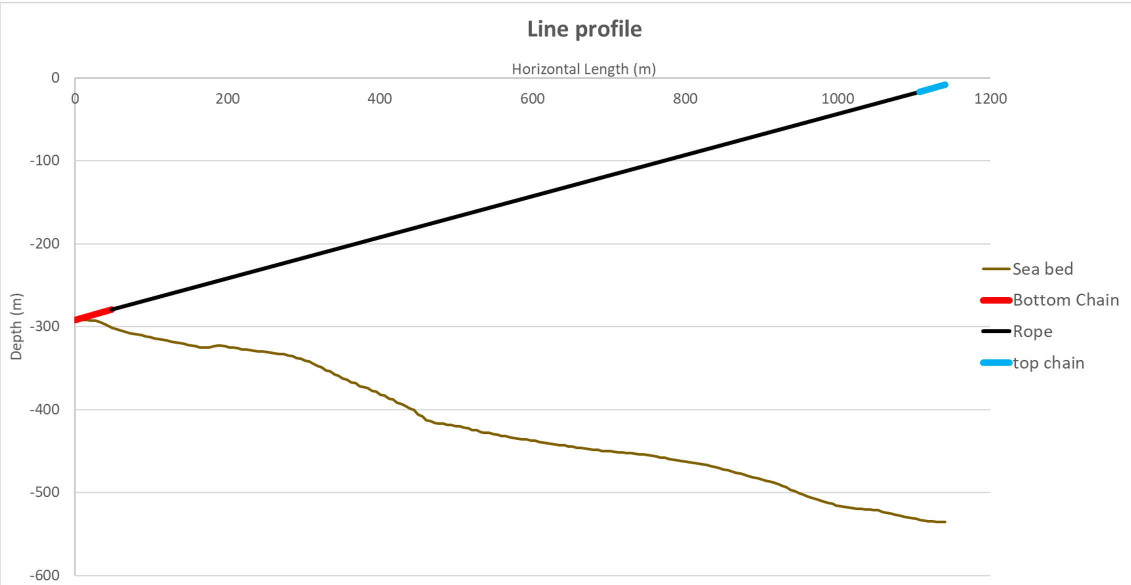
> *Figure 5-8 Line and seabed profile for line 5*

5.4.3 Line no. 6



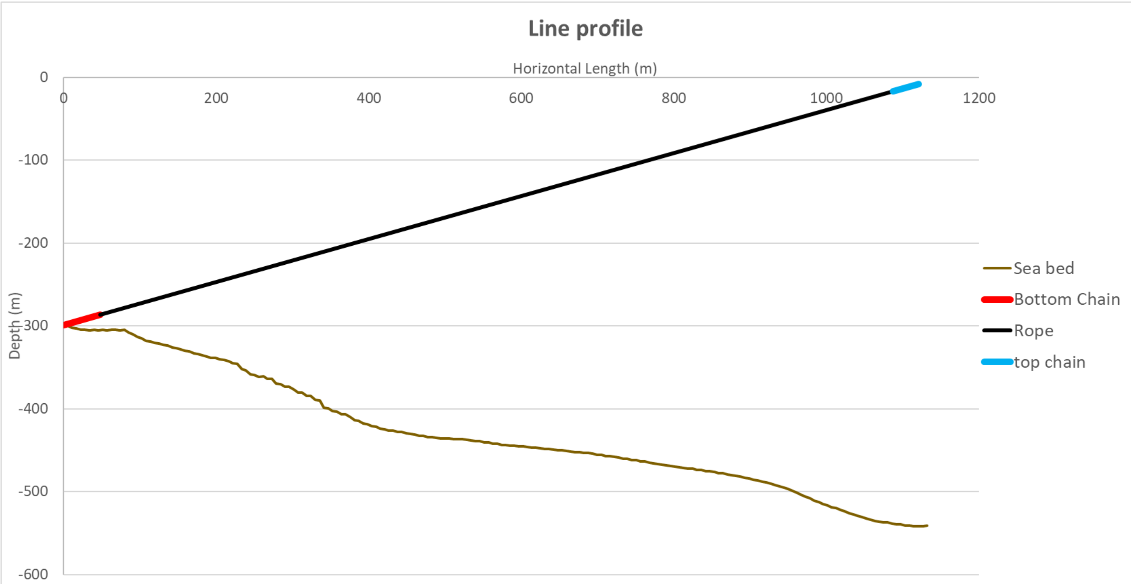
> Figure 5-9 Line and seabed profile for line 6

5.4.4 Line no. 7



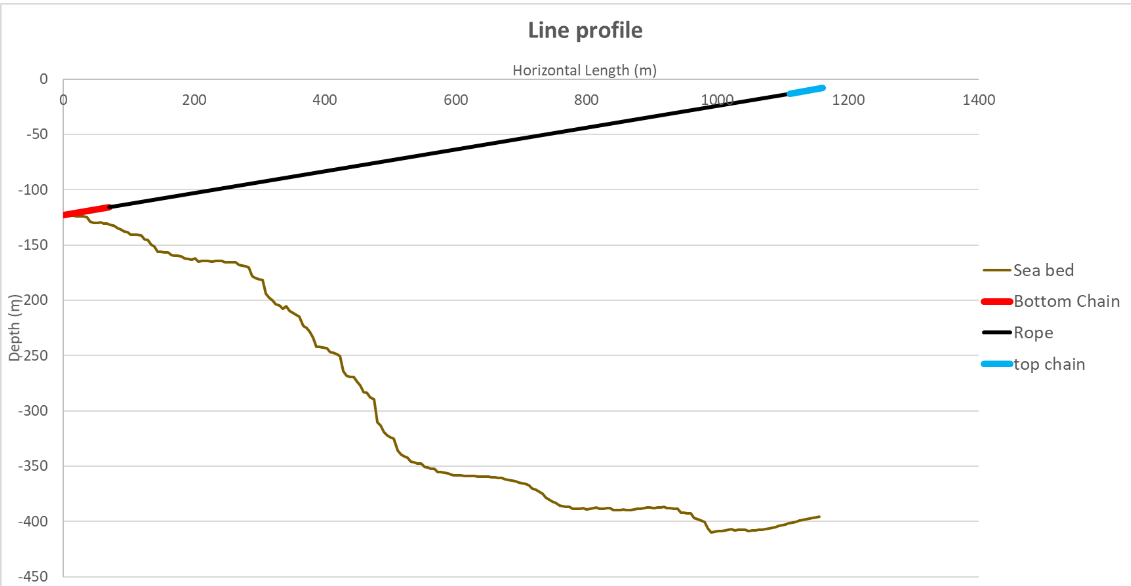
> Figure 5-10 Line and seabed profile for line 7

5.4.5 Line no. 8



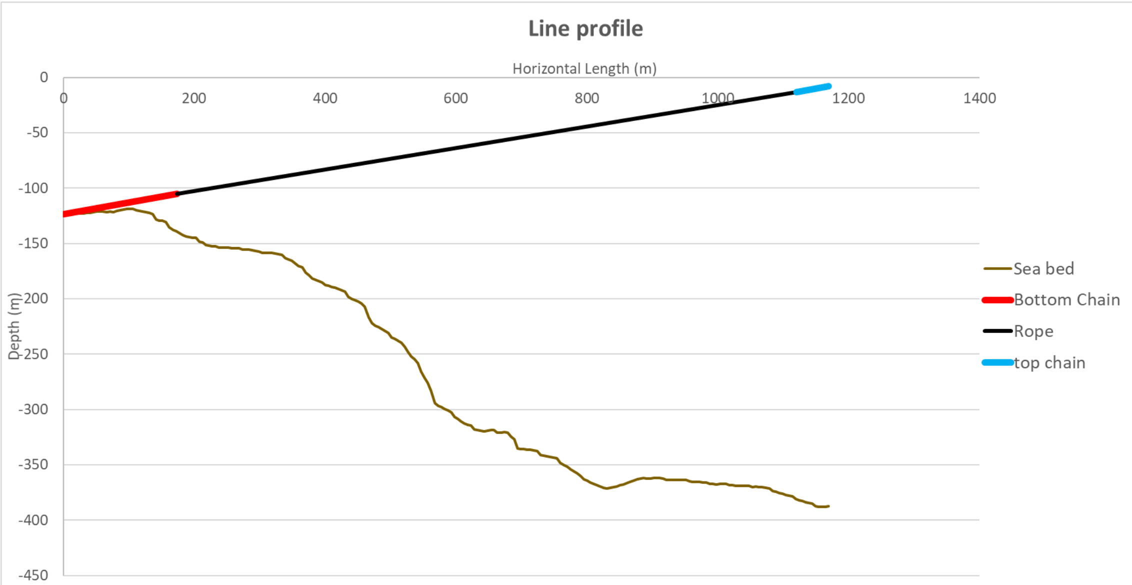
> *Figure 5-11 Line and seabed profile for line 8*

5.4.6 Line no. 9



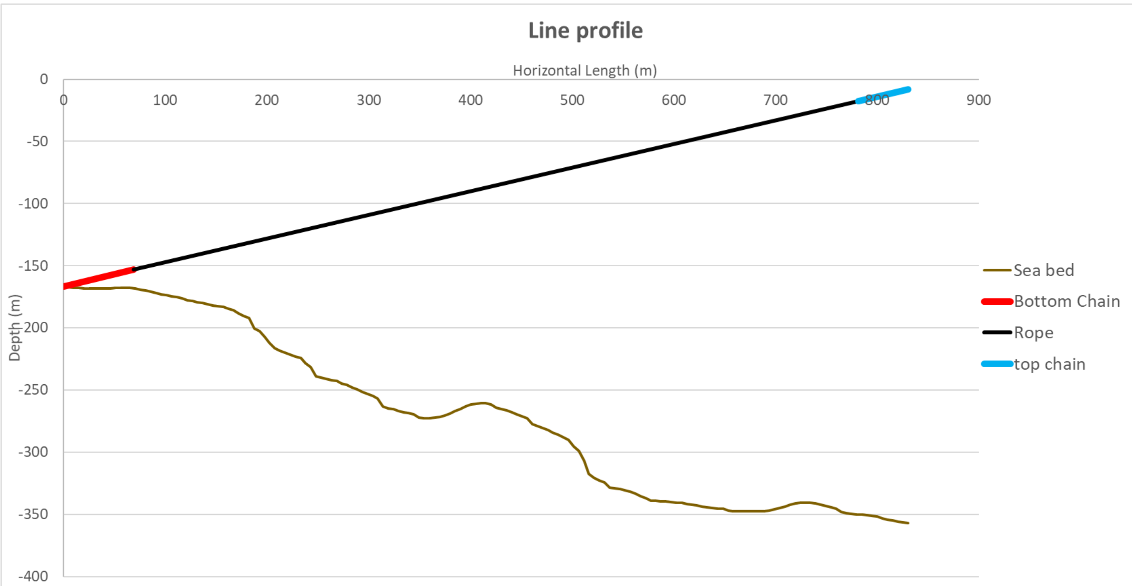
> *Figure 5-12 Line and seabed profile for line 9*

5.4.7 Line no. 10



> *Figure 5-13 Line and seabed profile for line 10*

5.4.8 Line no. 11



> *Figure 5-14 Line and seabed profile for line 11*

5.4.9 Line no. 12

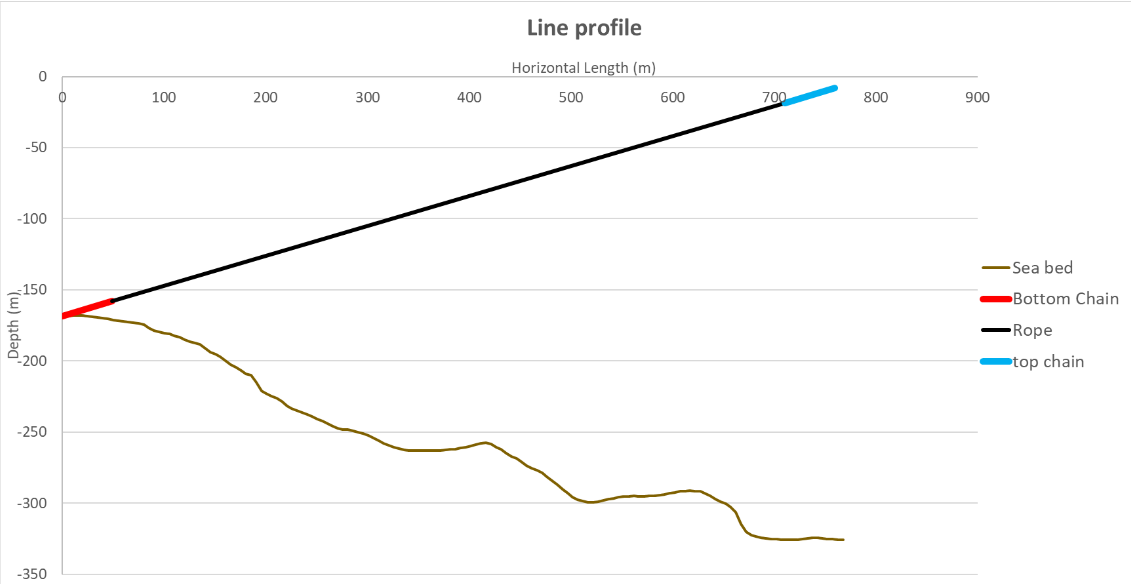


Figure 5-15 Line and seabed profile for line 12

5.4.10 Line no. 13

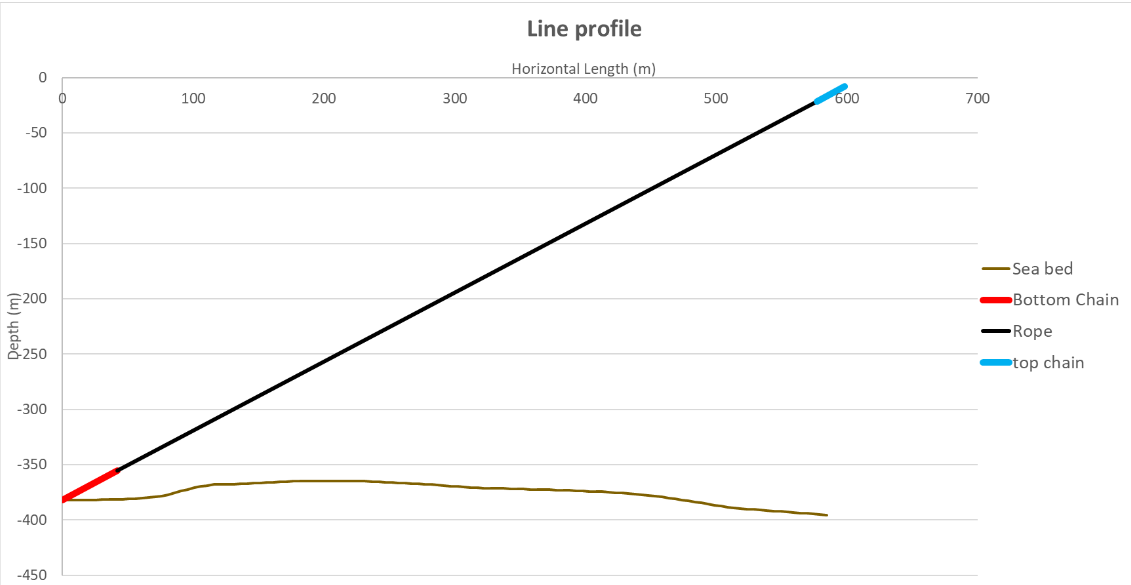
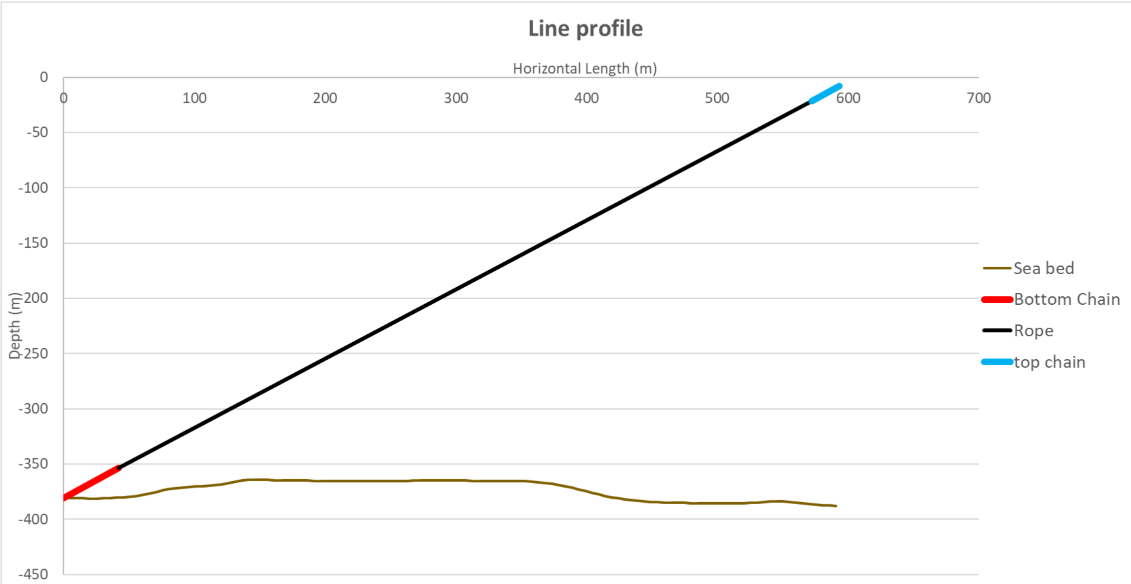


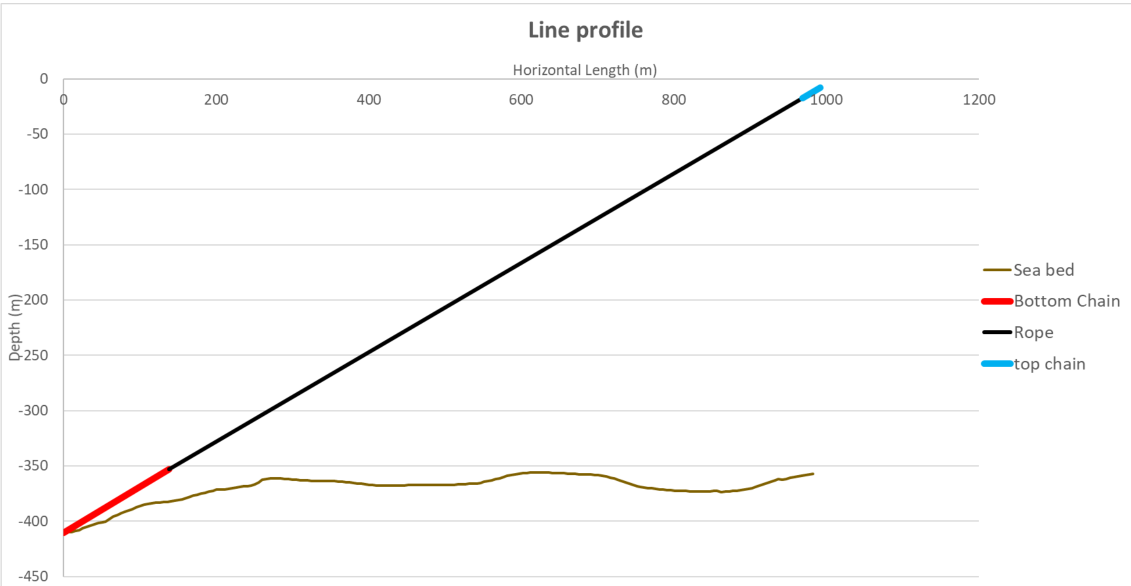
Figure 5-16 Line and seabed profile for line 13

5.4.11 Line no. 14



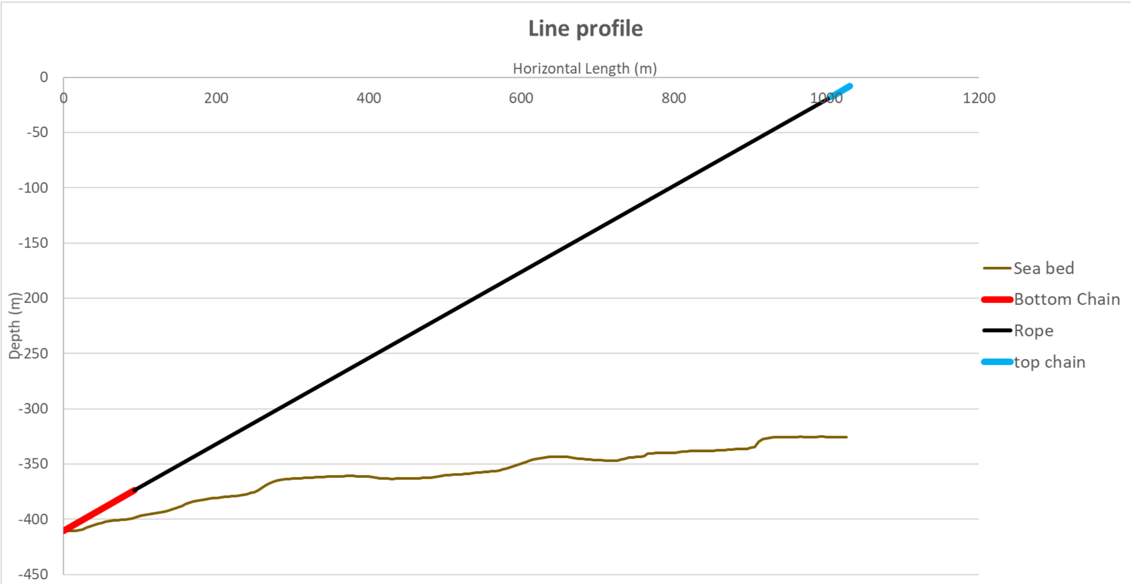
> Figure 5-17 Line and seabed profile for line 14

5.4.12 Line no. 15



> Figure 5-18 Line and seabed profile for line15

5.4.13 Line no. 16



> *Figure 5-19 Line and seabed profile for line 16*

6 GLOBAL MODEL AND MOORING SYSTEM REQUIREMENTS

The global analysis model is described in Ref. [15]. In the global analysis model the mooring system is simplified by use of a single cable element oriented in the correct direction and with correct length. The single element acts as a linear spring, where the stiffness is represented by the mooring line cross sectional area and corresponding elastic Young's modulus. The corresponding elastic stiffness is hence given as $k_{mooringline} = \frac{EA}{L}$.

The main functional requirement for the mooring line groups is to have sufficient horizontal stiffness to provide the same stiffness as assumed in the global analyses. The global analysis indicated that a minimum required stiffness per group would be in the range of 0.6 MN/m. A minimum mooring group stiffness of 0.8 MN/m is thus set as a requirement for the mooring system design to account for uncertainty. This corresponding to 0.1 MN/m per line in the horizontal direction normal to the bridge.

The mooring representation in the global model is based on linear springs with positive and negative tension values. The variation represents the dynamic variation in line force for different pontoon positions. The pre-tensioning level of the final configuration will be set to avoid slack in the mooring system. The mooring line forces are given in terms of local axial direction.

The typical load contributions in the mooring lines is described further in Sec 8.

It is vital for the validity of the global response model that the mooring lines behaves linearly in both loading and unloading for the expected range of motions. This is ensured by defining a prestressing level that ensures that slack does not occur. The assumption of linear behavior is evaluated based on local models of the mooring lines using a dynamic mooring models as described further in Sec. 10. The necessary level of prestressing is given in Sec.7.

7 MOORING LINE PRETENSION

The pretension in the mooring lines are classified as permanent loads, and the necessary prestressing level is chosen to avoid “slack” during the ULS range of pontoon motions. Slack in this context does not mean that the rope goes into compression, but that it practically loses its pretension and hence the required axial stiffness. The fibre rope itself will always experience tension due to heavy top and bottom chain and it could thus be a further potential for reducing the pre-tensioning level in a later phase.

For determining minimum pretension, the philosophy of NS-EN 1990 is adapted, where a factor of 0.9 is used for the favourable loads (EQU) and a load factor of 1.6 is used for the environmental loads (both static and dynamic contributions). The pretension is thus defined as favourable load.

The pretension in each mooring line connected to the same pontoon is tuned to give equal load component normal to the bridge. This may result in different prestressing load in each line due to different line geometry. It will also result in different load components in the vertical direction as well as along the bridge.

The required prestressing loads for each line is shown in Figure 7-1. The pre-tensioning level will be verified by checking if slack occurs in the local analysis of the mooring line.

Line No.	Pretension (MN)
1	2.3
2	2.1
3	1.8
4	1.8
5	2.0
6	1.8
7	1.6
8	1.6
9	1.7
10	1.6
11	1.6
12	1.6
13	2.0
14	1.8
15	1.7
16	1.7

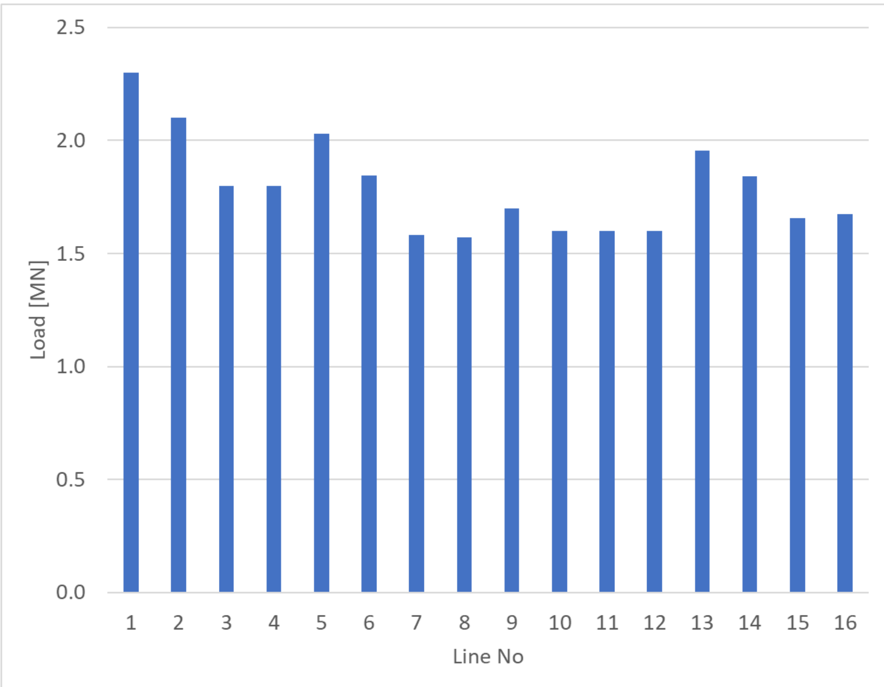


Figure 7-1 Pretension

8 RESPONSE FOR LIMIT STATES

8.1 General

The different load components acting on the mooring system is further described for the different limit states below. The results in this section is based on the global model response.

8.2 ULS Intact - Global tension loads

8.2.1 General

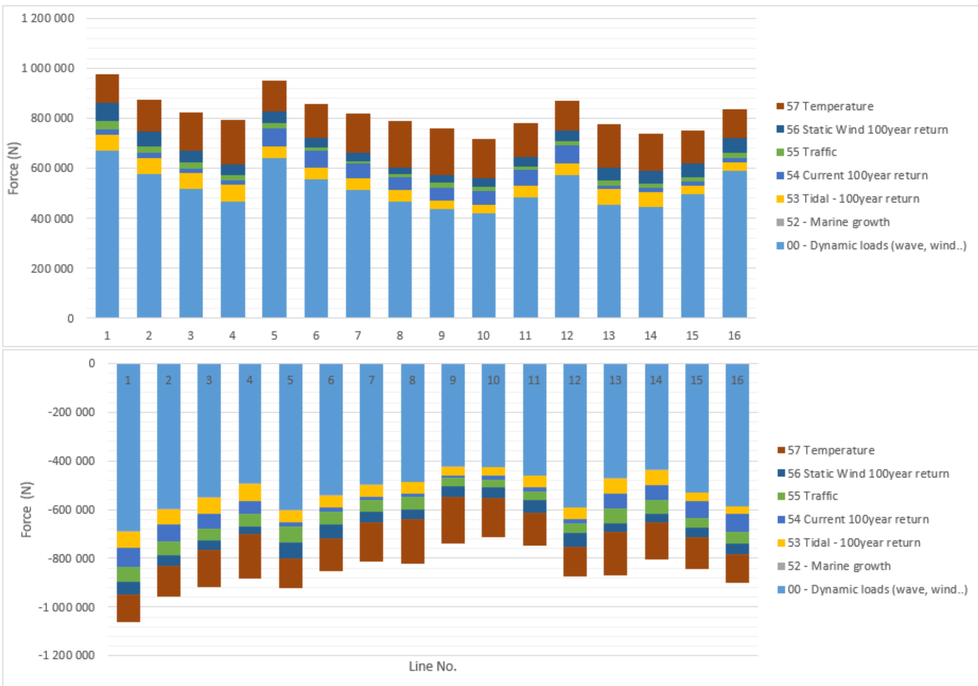
The ULS global loads in the mooring lines are obtained from the analyses model described in Sec. 6. The loads are a result of bridge and pontoon deflection due to global loads.

8.2.2 Response in operational condition

The operational loads mainly consist of:

1. Environmental loads
    a. Dynamic loads
        i. Wind sea
        ii. Swell
        iii. Dynamic component of wind forces
    b. Quasi-static loads
        i. Current
        ii. Tidal loads
        iii. Static components of wind force
        iv. Temperature
        v. Marine fouling on pontoons
2. Traffic loads

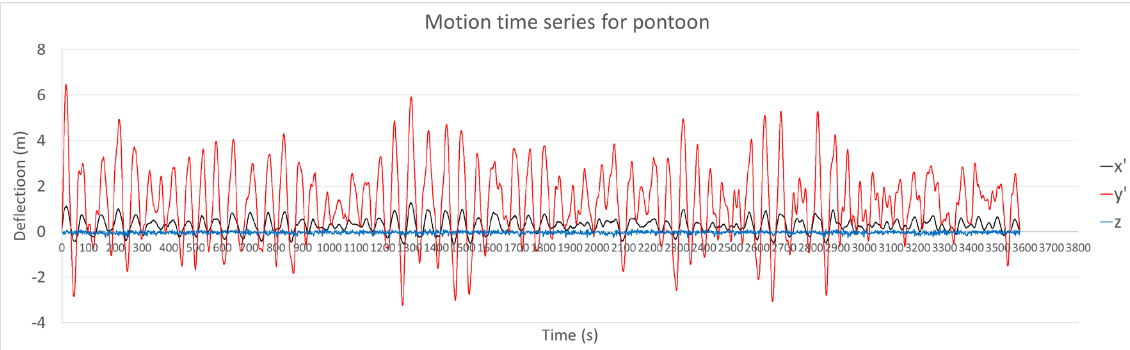
The load response component for each mooring line is summarized in Figure 8-1.



> *Figure 8-1 Load components in mooring line*

The figure shows that approximately 50% of the load component is environmental dynamic loads, while the remaining is traffic and quasi-static environmental loads. Marine growth on the pontoons gives negligible loads in the moorings.

The dynamic loads are from a typical 100 year storm event, where the bridge oscillates with frequencies that is in the range of the natural frequency of the bridge. A typical time series for these kind of motions are shown in Figure 8-2.

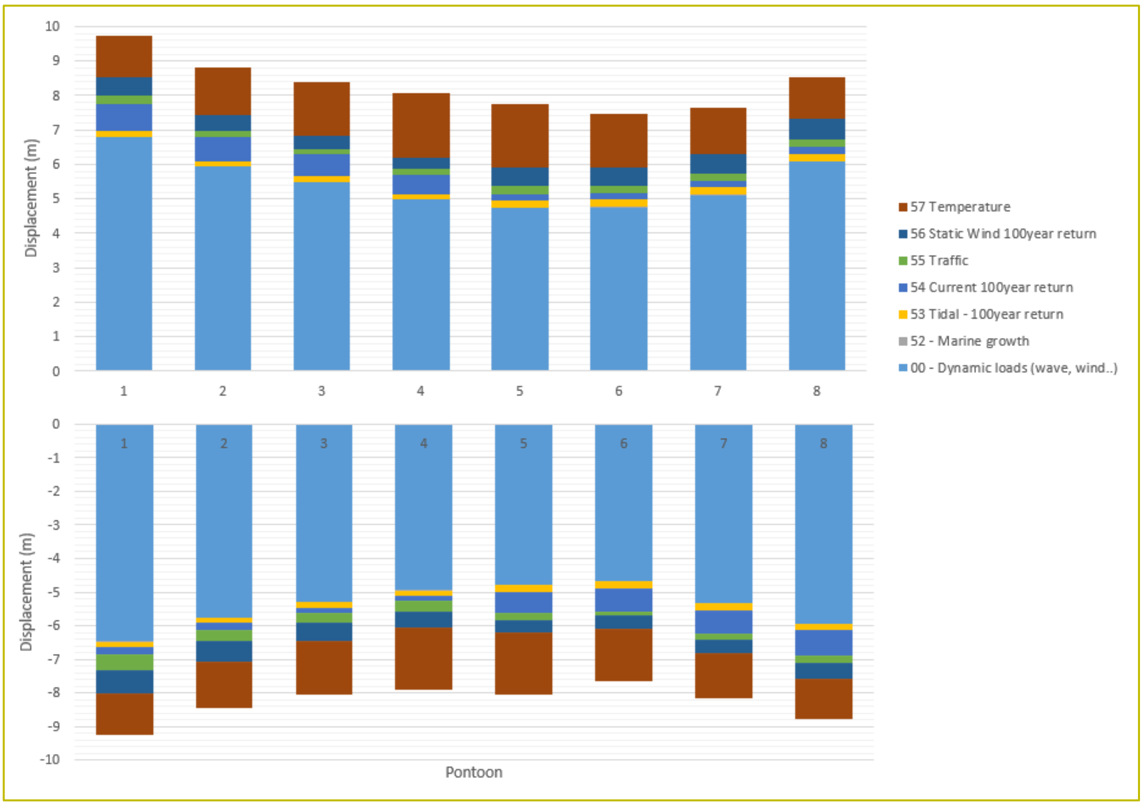


> *Figure 8-2 Typical time series for pontoon deflection. The red shows horizontal movement normal to the bridge, black horizontal movement along the bridge girder and blue is vertical oscillations.*

As seen from the figure, the amplitude normal to the bridge direction is the dominant for the mooring system design. For this load, the governing period is approximately 50-60 s, which corresponds to the first couple of natural frequencies of the bridge.

8.2.3 Pontoon deflection

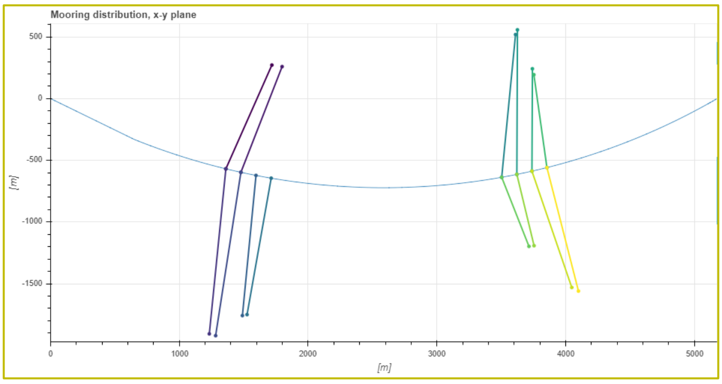
In addition to the mooring line forces, the total horizontal deflection of the pontoons is presented in Figure 8-3 for the pontoons with mooring lines attached. The values presented are unfactored deflections.



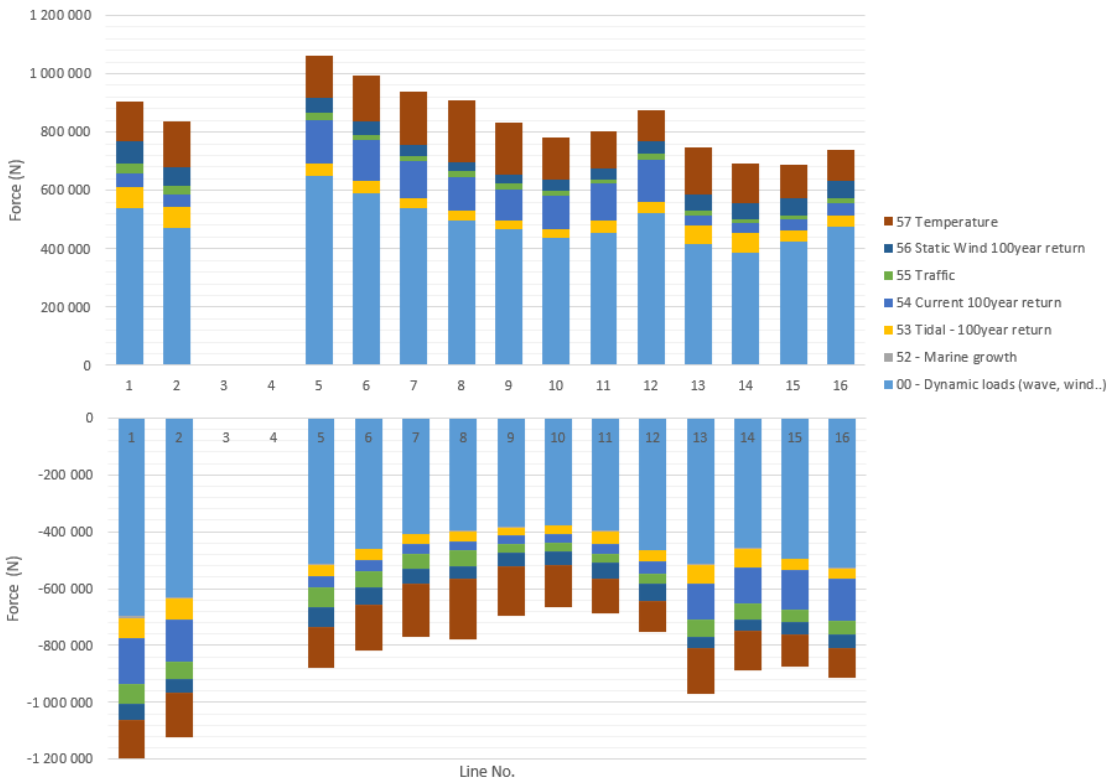
> *Figure 8-3 Pontoon horizontal deflection*

8.3 ULS – two mooring line failures

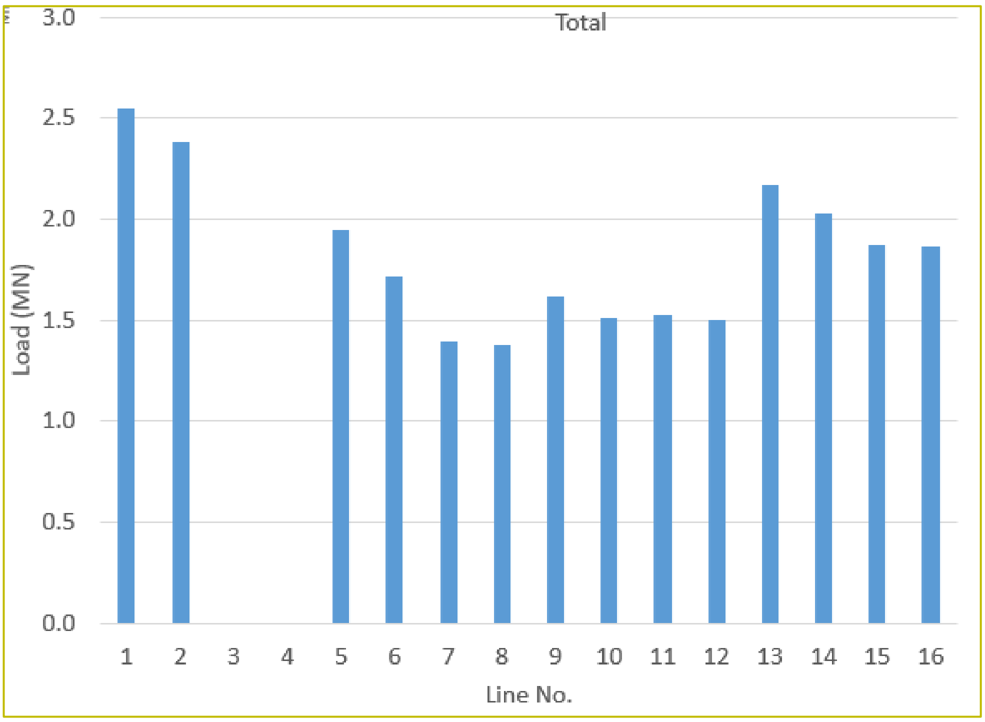
One case with loss of two anchor lines, line no. 3 and 4, are analysed. This case is expected to be governing, as the forces in 3 and 4 will be redistributed to 1 and 2 after a failure. Line 1 and 2 shows high loads for the intact condition. The analyses are performed without mooring lines for line 3 and 4, see Figure 8-4. The model loads are further shown in Figure 8-5.



> *Figure 8-4 Analysis with loss of mooring line 3 and 4*



> *Figure 8-5 Load components in mooring line, change in prestressing level not shown.*



> *Figure 8-6 Prestressing level after loss of two lines*

8.4 FLS Global fatigue loads

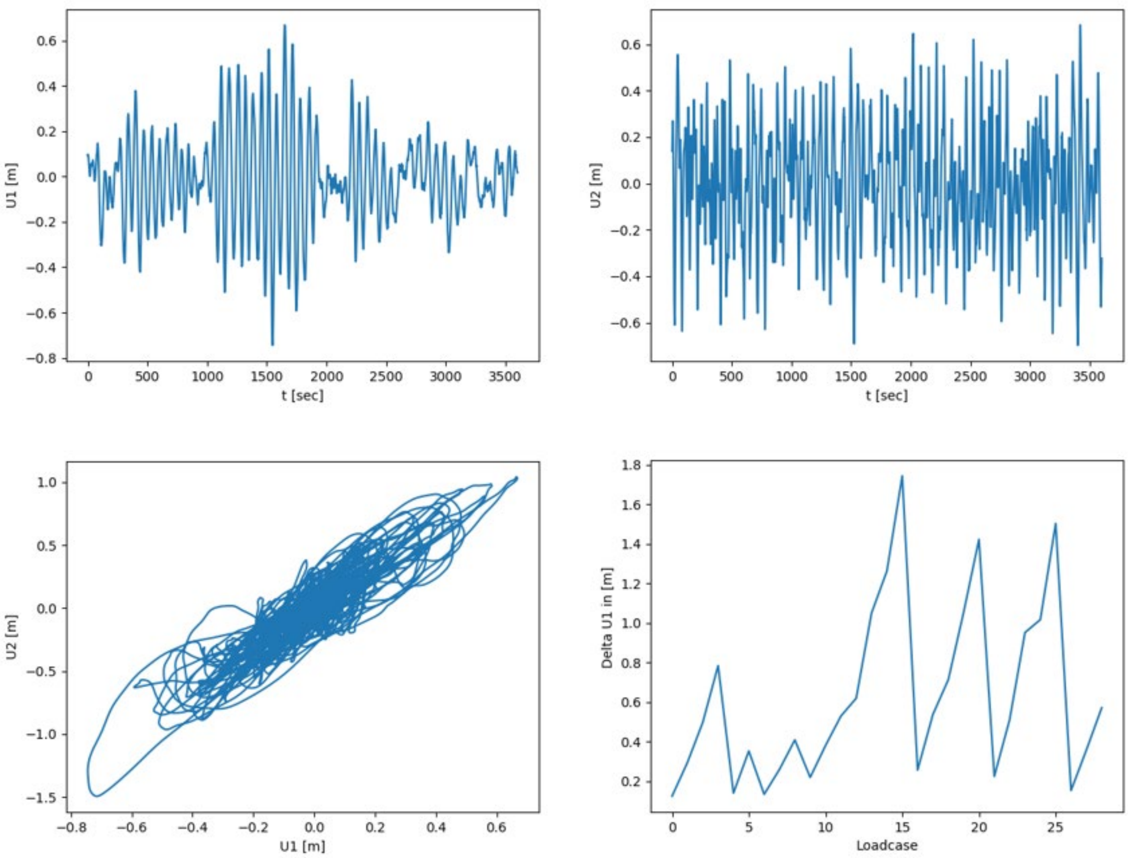
Response from global frequency domain analyses is extracted as timeseries for the sea states:

- Wind sea
- Wind
- Swell

For more details on the sea states and number of load cases for each sea state, reference is given to the Fatigue assessment report, ref. [16].

The timeseries comprise displacements U_i and rotations R_i of the pontoons in 6 DOF's. Response from traffic is neglected.

The figure below shows an example of timeseries for one sea state. The two plots on the top show time history for pontoon displacement in x and y for one load case. The plot on the bottom to the left shows the same displacements plotted together. The plot on the bottom to the right shows maximum delta Ux for all load cases in that sea state.

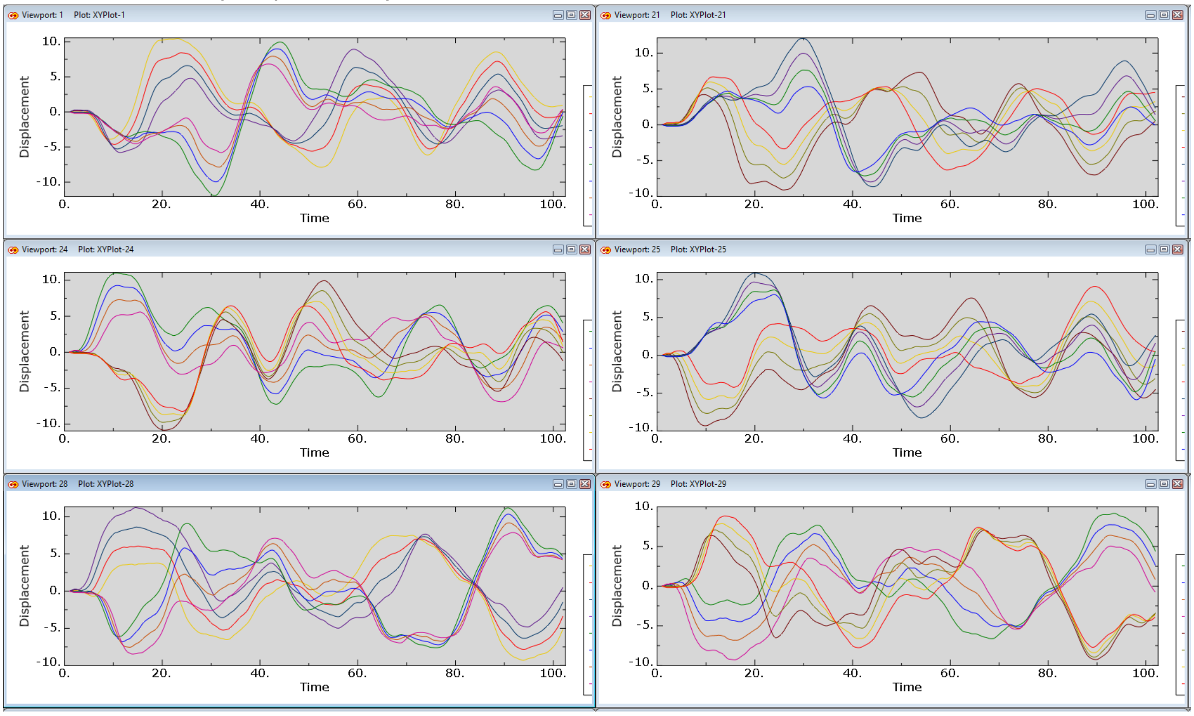


> *Figure 8-7 Example plots of global response*

8.5 Accidental limit state

8.5.1 Ship impact

Reference is made to Ref. [17] for description of the response in the pontoons due to ship impact. The response of the bridge during ship impact is modelled by imposing time series of the displacements in the pontoons with simplified mooring lines included. Linear mooring line behaviour is assumed in the ship impact analyses. A selection of a few times showing total pontoon deflection is further shown in Figure 8-8. Maximum pontoon deflection is 12.5 meters for the ship impact analyses.



> *Figure 8-8 Ship impact time series for pontoon displacements.*

9 MOORING LINE DESIGN

9.1 Design Philosophy

A brief description of the mooring system is given in Sec. 5 of this document.
The philosophy for design of the main components follows DNV-OS-E301 for determining ultimate capacity of the main components, with safety factors according to ISO19901-7, appendix B.2, Consequence class 3. The resulting mooring lines safety factors for the different limit states is presented in sec. 2.5.

For determining minimum pretension to avoid slack, the philosophy of ULS-EQU in NS-EN 1990 is adapted Ref. [1], see Sec. 2.5 and 7.

The capacity of the main components (fibre rope and chain) is based DNV-OS-E301 set as $S_c = 0.95 * S_{mbs}$, where S_{mbs} is the minimum breaking strength (catalogue value) of the component.

Corrosion allowance of chain and steel components is included in the design if they are not protected by a corrosion protection system.

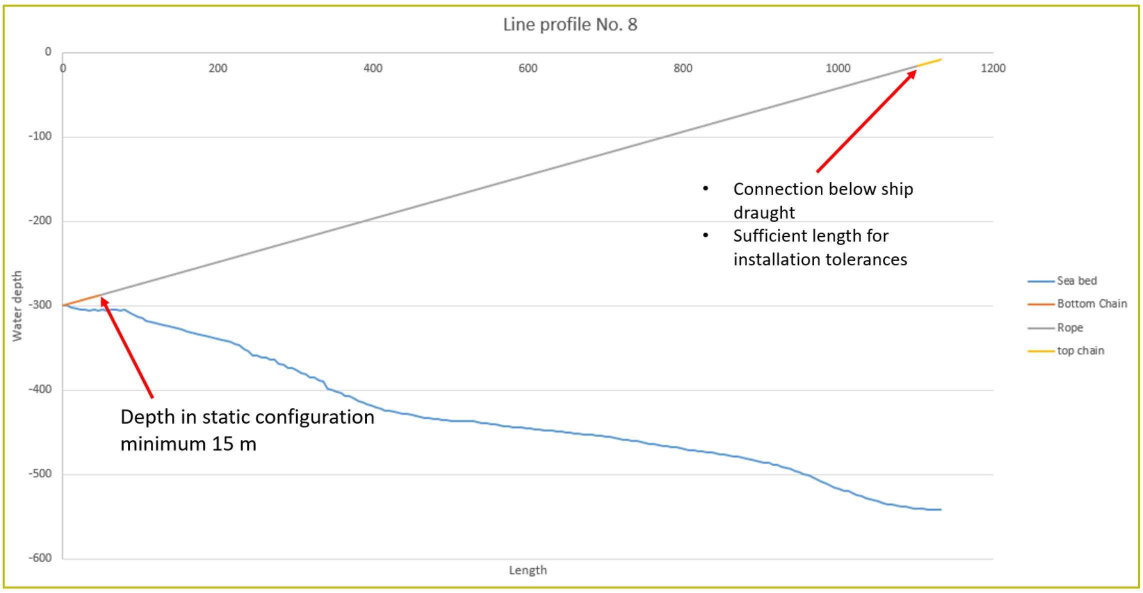
Other components in the system such as connecting links, terminations, fairlead, chain stoppers shall be designed to have strength exceeding the characteristic strength of the main mooring line. Design of such mooring components has not been the focus during the current phase and such components are expected to be provided by relevant suppliers.

The length of the bottom chain is governed by the distance between rope termination and seabed, see Figure 9-1. This is to avoid chafing of the rope towards the sea bed. The vertical minimum distance is initially set to 15 m for the static configuration.

The governing parameter for top chain length is:

- Sufficient length to compensate for variation in rope stiffness and bedding in length during installation and re-tensioning.
- Connection between chain and fibre rope deep enough to avoid ship impacts with the rope. This value is preliminary set to a depth of 12 m.

The requirements for the top and bottom chain length is illustrated in Figure 9-1.



> *Figure 9-1 Requirements to chain length*

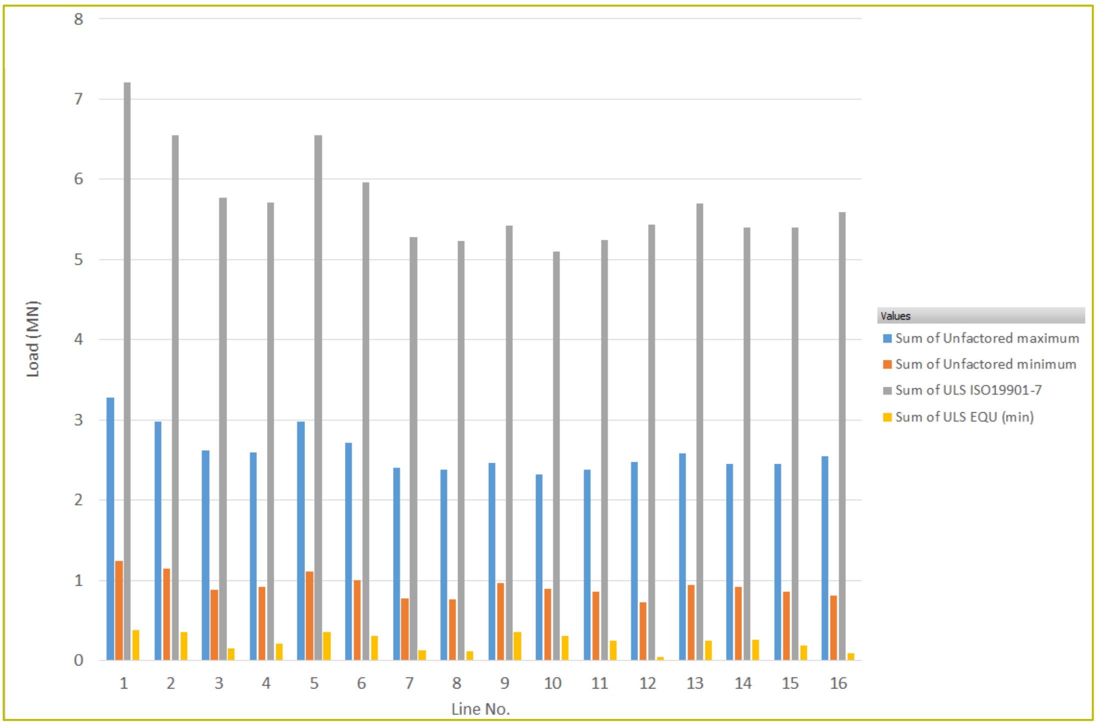
9.2 Load combinations

9.2.1 ULS intact condition

The following nominal and factored loads are shown in Figure *9-2* and Table 9-1:

- Unfactored - Maximum load
  - Characteristic maximum loads from global model including pretension
- Unfactored – Minimum load
  - Characteristic minimum loads from global model including pretension
- Maximum factored:
  - ULS – ISO19901-7 B.2 factors.
  - Safety factor equal 2.2 for intact condition
- Minimum factored:
  - ULS EQU – factorized Minimum loads
  - Factor 0.9 on pretension loads
  - Factor 1.6 on all other loads

As seen from the figure, the maximum dimensioning loads in ULS intact condition is 7.3 MN, and all lines have tension for the minimum factored case. This indicates that the fibre rope is "stretched", and hence contributes to the mooring line stiffness by elastic rope behaviour during all load condition. If the elastic tension of the rope for some reason goes below zero, the line will still have tension, but the tension is then governed by the amount of suspended bottom chain, and the overall stiffness will be reduced.



> Figure 9-2 Unfactored and factored loads

> *Table 9-1 Unfactored and factored loads*

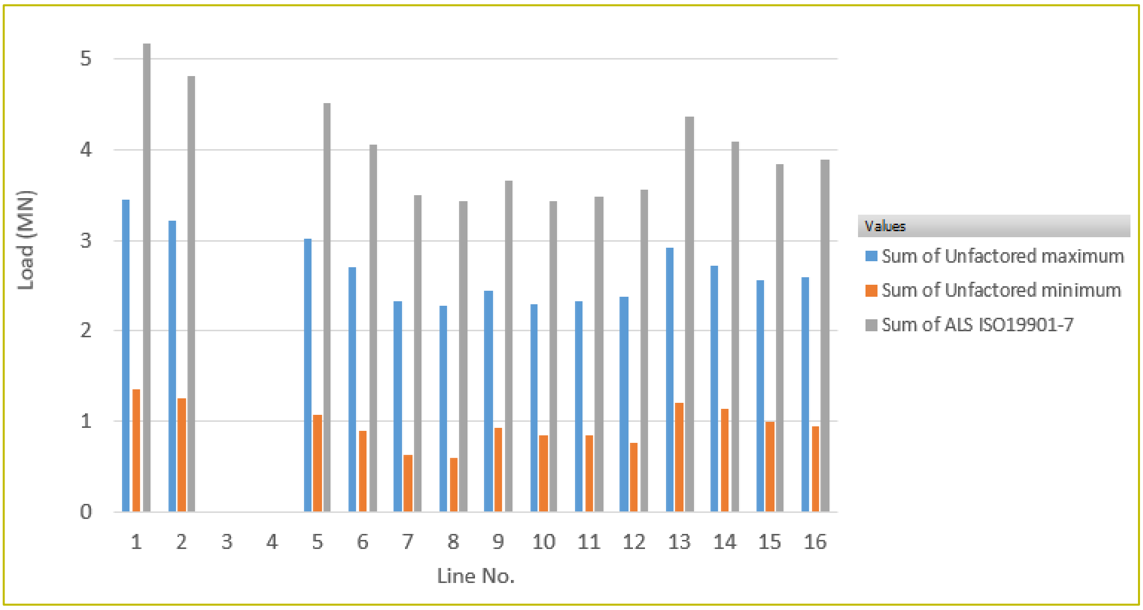
Line No.	Unfactored maximum	Unfactored minimum	ULS ISO19901-7 (max)	ULS EQU (min)
1	3.28	1.24	7.21	0.37
2	2.98	1.14	6.55	0.36
3	2.62	0.88	5.77	0.15
4	2.59	0.92	5.71	0.21
5	2.98	1.11	6.55	0.35
6	2.71	1.00	5.96	0.30
7	2.40	0.77	5.28	0.12
8	2.38	0.76	5.23	0.11
9	2.46	0.96	5.42	0.35
10	2.32	0.89	5.10	0.30
11	2.38	0.85	5.24	0.24
12	2.47	0.73	5.43	0.04
13	2.59	0.94	5.69	0.24
14	2.46	0.91	5.40	0.26
15	2.45	0.86	5.39	0.18
16	2.54	0.80	5.59	0.09

9.2.2 ULS - Two line failure

The following nominal and factored loads are shown in Figure *9-3* and Table 9-2:

- Unfactored - Maximum load
  - Characteristic maximum loads from global model including pretension
- Unfactored – Minimum load
  - Characteristic minimum loads from global model including pretension
- Maximum factored:
  - ULS –ISO19901-7 B.2 factors for twi line failure
  - Safety factor equal 1.5

As seen from the figure, the maximum dimensioning loads in ALS condition is 5.2 MN. This is well below the ULS intact load. For the next phase multiple line failure cases should be analysed to ensure that the worst case is captured, the current check is however deemed to be characteristic for line failure cases.



> Figure 9-3 Unfactored and factored loads

Table 9-2 Unfactored and factored loads

Line No.	Unfactored maximum	Unfactored minimum	ULS ISO19901-7 two line failure
1	3.45	1.35	5.18
2	3.22	1.26	4.82
3	-	-	-
4	-	-	-
5	3.01	1.07	4.52
6	2.71	0.90	4.06
7	2.33	0.63	3.50
8	2.29	0.60	3.43
9	2.45	0.92	3.67
10	2.29	0.85	3.44
11	2.33	0.84	3.49
12	2.38	0.75	3.57
13	2.92	1.20	4.37
14	2.72	1.14	4.09
15	2.56	0.99	3.84
16	2.60	0.95	3.90

As seen, the selected load case with two-line failure shows lower ULS combined loads than the intact condition, and is hence not governing for mooring line design.

More line failure cases should be analysed in the next phase in order to ensure that the most critical line failure case has been identified. It will also be relevant to run transient simulations of line failure.

9.3 Utilizations

9.3.1 ULS - Intact condition

The utilization of the different mooring line segments for the intact condition is summarized in Table 9-3 below. All mooring line segments have sufficient capacity according to the design requirements.

> *Table 9-3 Utilizations intact condition*

Line No	Bottom Chain		Polyester fibre rope	Top Chain	
	Uncorroded	Corroded (50 year)		Uncorroded	Corroded (50 year)
1	0.77	0.95	0.77	0.40	0.76
2	0.68	0.84	0.62	0.36	0.68
3	0.70	0.86	0.70	0.37	0.69
4	0.62	0.77	0.57	0.33	0.62
5	0.72	0.90	0.62	0.32	0.61
6	0.65	0.82	0.62	0.29	0.55
7	0.71	0.89	0.61	0.32	0.60
8	0.64	0.81	0.62	0.29	0.55
9	0.67	0.84	0.58	0.30	0.57
10	0.69	0.87	0.86	0.31	0.59
11	0.63	0.80	0.61	0.28	0.54
12	0.68	0.86	0.84	0.31	0.58
13	0.65	0.82	0.80	0.29	0.55
14	0.66	0.83	0.63	0.30	0.56
15	0.67	0.85	0.83	0.30	0.57
16	0.69	0.86	0.59	0.31	0.59

9.3.2 ULS - Two line failure

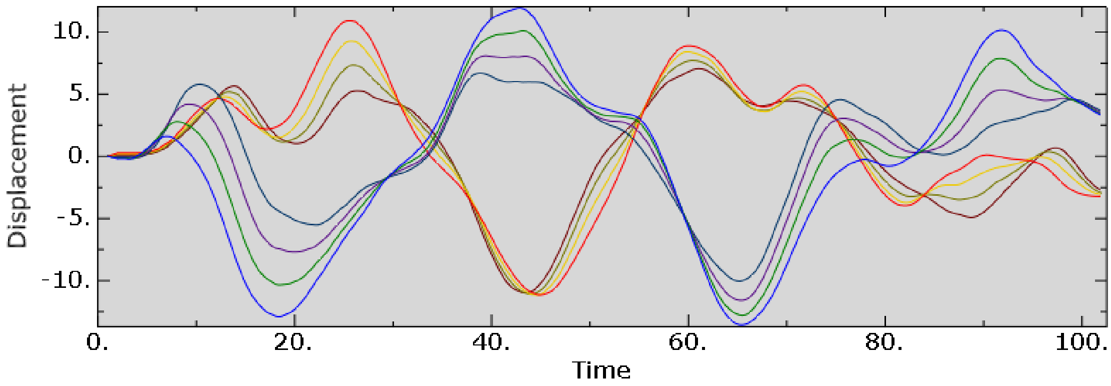
The utilization of the different mooring line segments for the ULS condition failure of two anchor lines is summarized in Table 9-4 below. All mooring line segments have sufficient capacity according to the design requirements. The utilizations for two line failure are lower than the ULS intact conditions for all lines.

> *Table 9-4 Utilizations ULS two line failure condition*

Line No	Bottom Chain		Polyester fibre rope	Top Chain	
	Uncorroded	Corroded (50 year)		Uncorroded	Corroded (50 year)
1	0.55	0.68	0.56	0.29	0.55
2	0.51	0.64	0.52	0.27	0.51
3	-	-	-	-	-
4	-	-	-	-	-
5	0.48	0.60	0.44	0.25	0.48
6	0.43	0.54	0.40	0.23	0.43
7	0.43	0.55	0.42	0.20	0.37
8	0.42	0.53	0.41	0.19	0.36
9	0.45	0.57	0.39	0.20	0.39
10	0.43	0.54	0.41	0.19	0.36
11	0.43	0.54	0.53	0.19	0.37
12	0.44	0.56	0.55	0.20	0.38
13	0.54	0.68	0.67	0.24	0.46
14	0.51	0.64	0.63	0.23	0.43
15	0.48	0.60	0.46	0.21	0.41
16	0.48	0.61	0.42	0.22	0.41

9.3.3 ALS - Ship impact

The maximum deflection in the pontoons during a ship impact is 12.5m. One of the time series from the ship impact analyses with the highest mooring line attachment displacement is shown in Figure 9-4 as an example of loading history, Ref. [17]. The 8 different curves represent the pontoons with mooring line attachment.



> *Figure 9-4 ALS ship impact*

Compared to the ULS total load factor of 2.2, the displacement and hence mooring line forces are of comparable magnitude. Given the reduced load factors in ALS of 1.0, the mooring lines responses will be of lower magnitude than the ULS condition, and hence show lower utilizations. See Figure 8-3 for unfactored ULS deflection for comparison.

10 VERIFICATION ANALYSES – SIMA MODELS

10.1 General

The detailed behaviour of the mooring lines has not been included in the global model where they are modelled as directional springs. A set of local models has been developed to evaluate the achieved restoring stiffness of the mooring lines, including geometrical stiffness due to chain, and to evaluate load acting on the mooring lines. This chapter aims to verify that the results from the global analyses model is valid for mooring line design without more refined analyses. The analyses are conducted in two steps:

1. Static analyses in Simo of the mooring group where the static configuration due to line weight, seabed interaction and pontoon displacement are found. The analyses are performed by prescribed displacements of the pontoons, and the quasi-static line behaviour is investigated for several levels of pontoon displacements. These analyses will verify that the stiffness of the system is as expected for the relevant range of pontoon displacements.
2. Verification analyses in Riflex, where the dynamic behaviour of the mooring lines is included. This model is used to verify the assumptions made in the global analyses for local loads on the mooring lines and marine growth.

This global model is expected to be acceptable for design of the system as the stiffness should be rather linear for the expected range of motion and the fact that local loads on the mooring lines are expected to be small.

The actual behaviour of the mooring lines is investigated by a local models in SIMA.

10.2 Local models

Local mooring analyses of the anchor lines is performed in the software SIMA developed by Sintef Ocean. The following loads and load effects are investigated by using the local models:

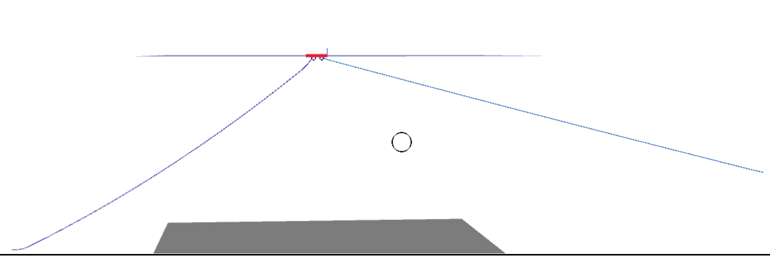
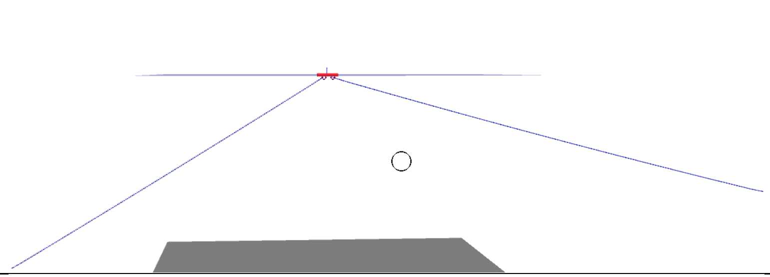
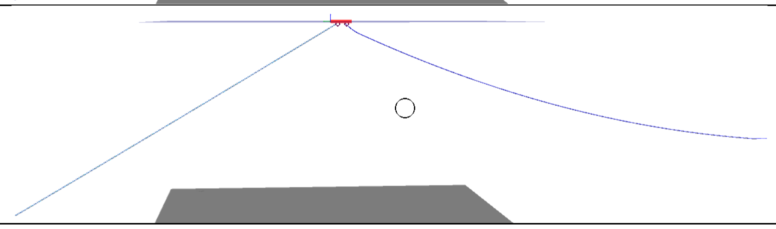
- Permanent static actions (Simo)
    - Submerged weight of the mooring line components.
        - Chain, fibre rope, connections
    - Pretension
    - Weight of additional marine growth
- Environmental actions and action effects (Riflex)
    - Current on the lines
    - Wave actions on the lines
    - Dynamic line tension due to low frequency motions from the global analyses
    - Modal analyses for VIV screening

10.3 Anchor group static characteristics

10.3.1 Quasi-static analyses

The results for each group are presented is Sec. 10.3.2 to 10.3.9. A prescribed deflection normal to the bridge direction is applied, and the result are presented in terms of initial static configuration of the lines, force-deformation characteristics of both lines is direction normal to bridge, and comparison of the stiffness characteristics of the mooring group. The mooring line groups behaves as expected in the range of deflections that are deemed relevant based on the global analysis performed.

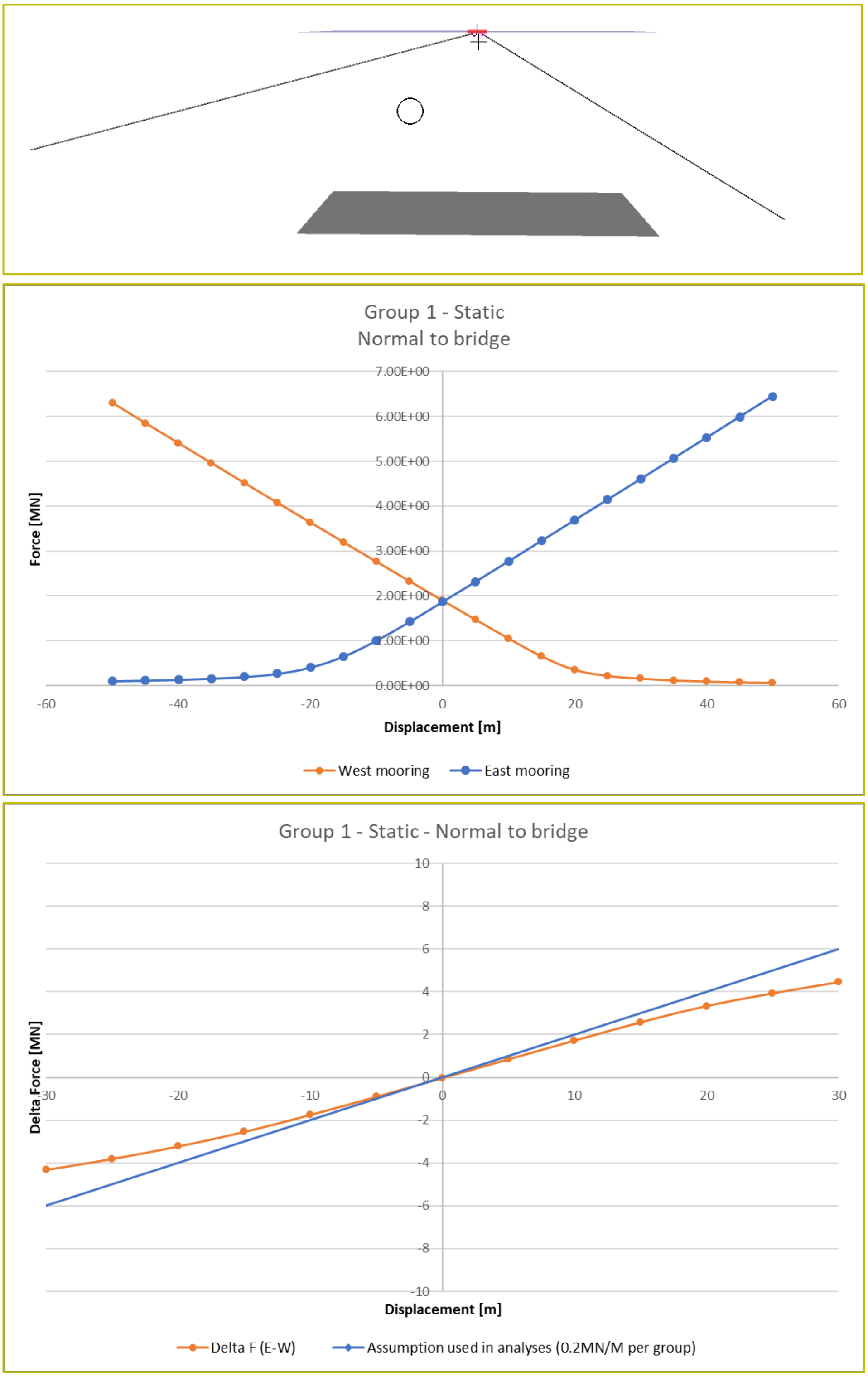
The expected deformation during ULS load combination is in the range +- 10m, and the lines must behave close to linear in this region of motions. It is chosen to apply deformations above this level in the analyses to highlight that the moorings will have capacity for deflections far above the expected values. An example is depicted in Figure 10-1.

Pontoon deflection 30 m to left hand side		Left line: 0.3 MN Right line: 4.9MN
Static configuration with desired pretension		Left line: 2.0 MN Right line: 2.3MN
Pontoon deflection 30 m to right hand side		Left line: 4.9 MN Right line: 0.3MN

> *Figure 10-1 Example of mooring line behaviour*

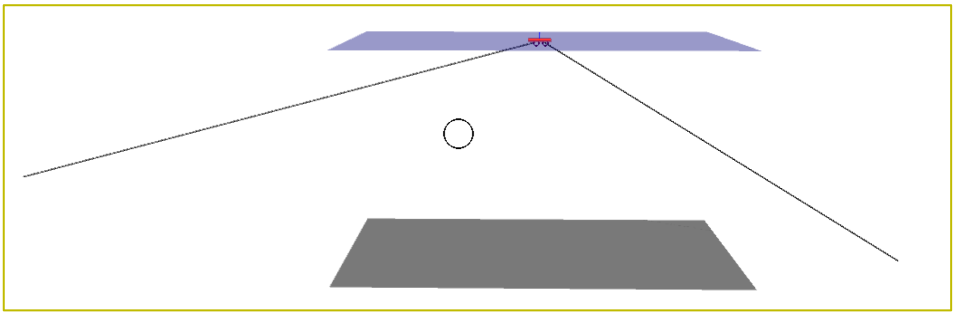
These analyses are also used to verify the bottom chain length to ensure that contact between the fibre rope and seabed does not occur.

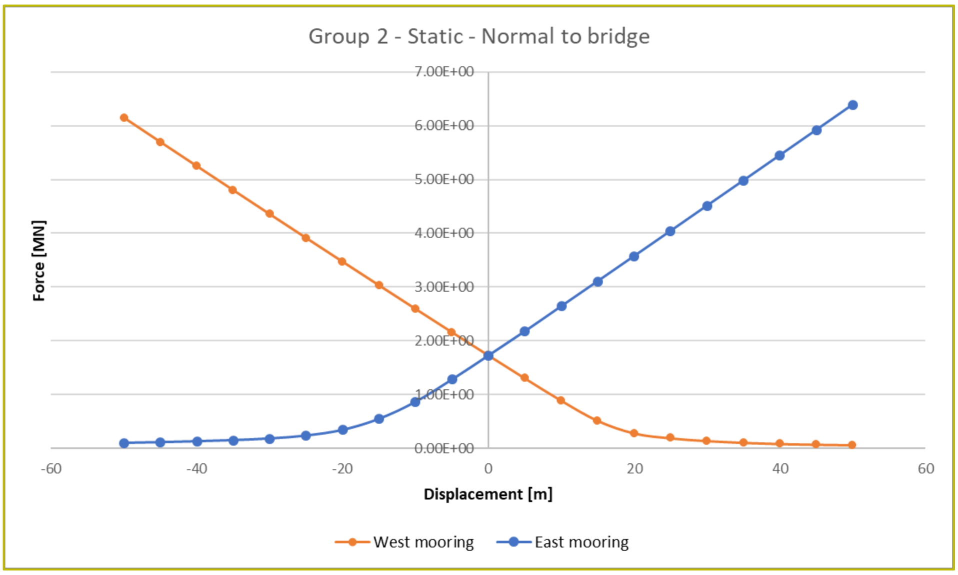
10.3.2 Restoring curves group 1

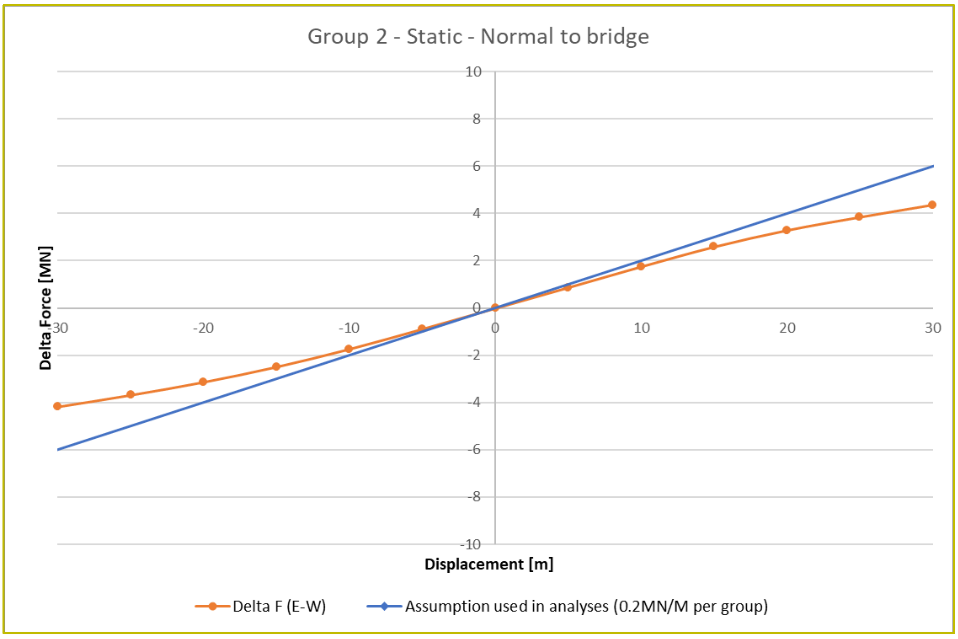


> *Figure 10-2 Static configuration, line behaviour and anchor group stiffness for group 1*

10.3.3 Restoring curves group 2

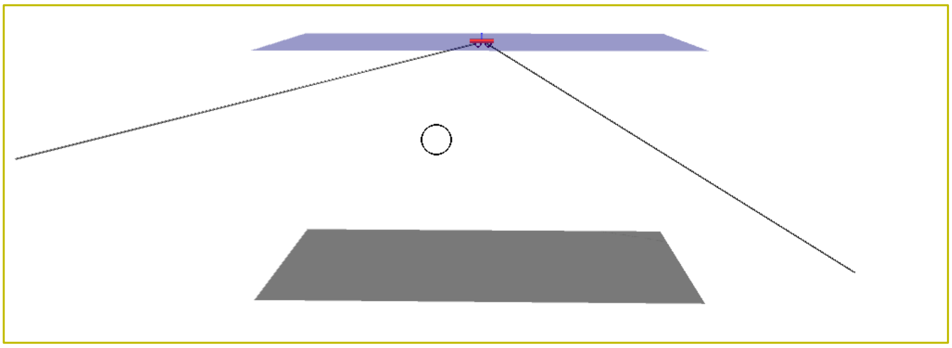


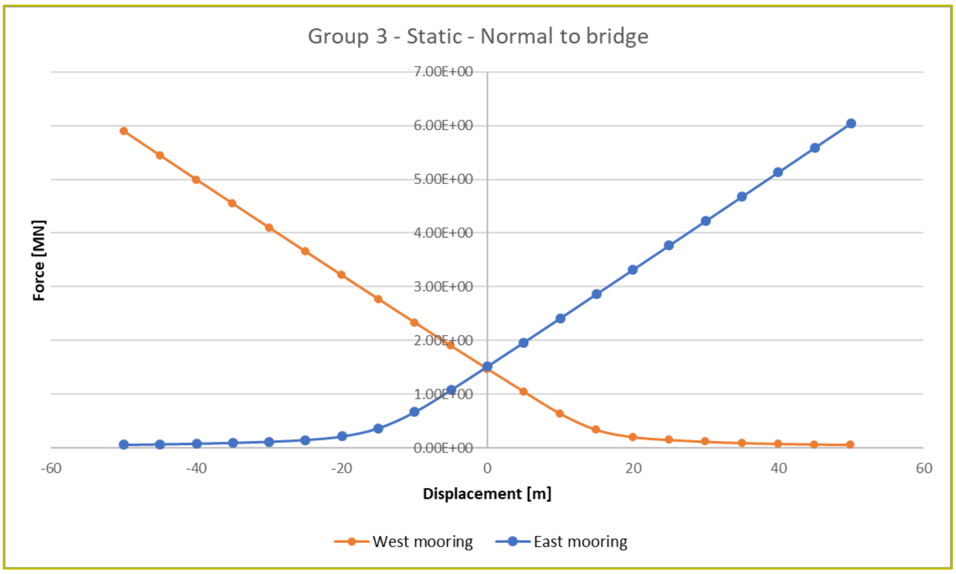


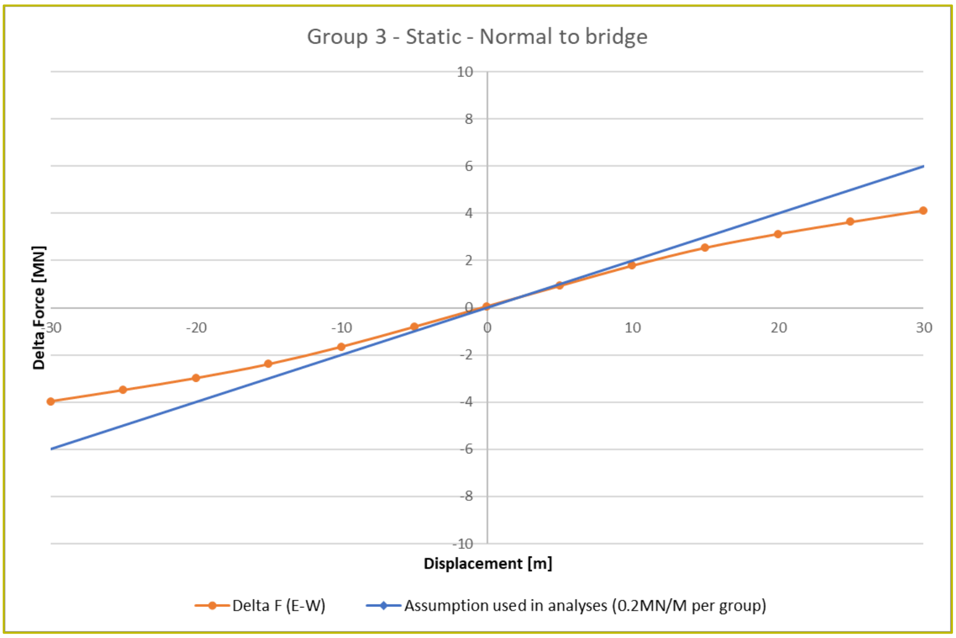


> *Figure 10-3 Static configuration, line behaviour and anchor group stiffness for group 2*

10.3.4 Restoring curves group 3

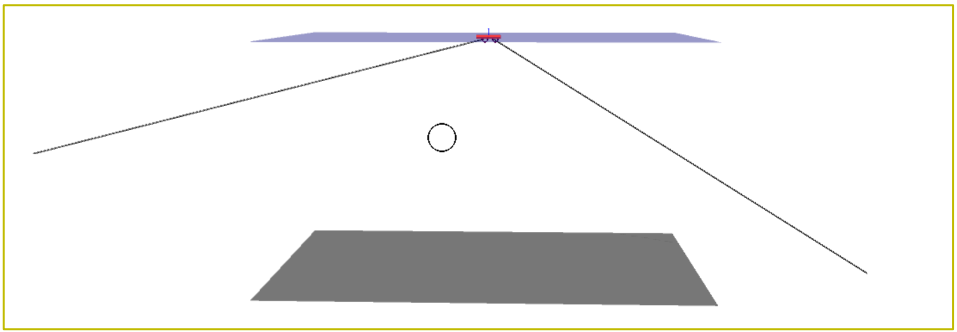


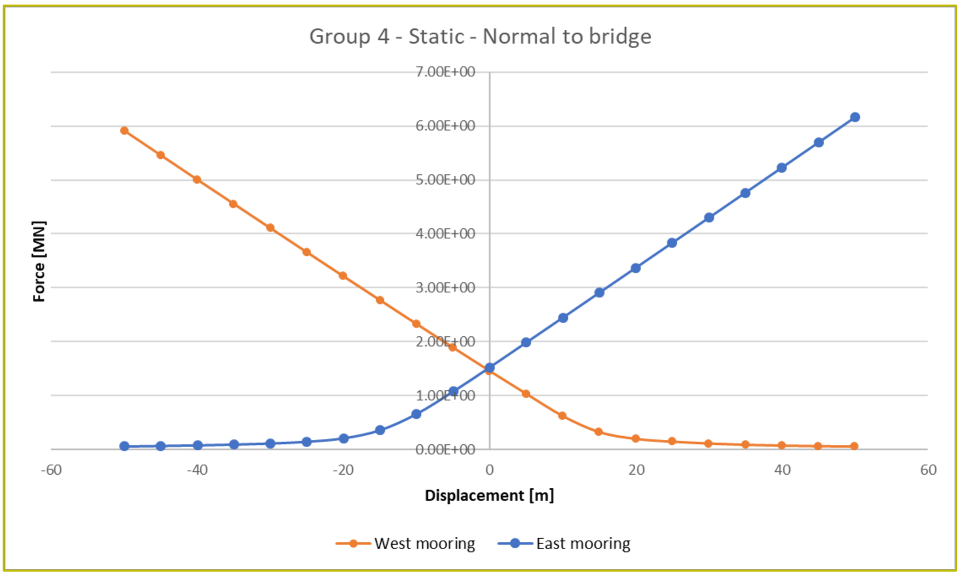


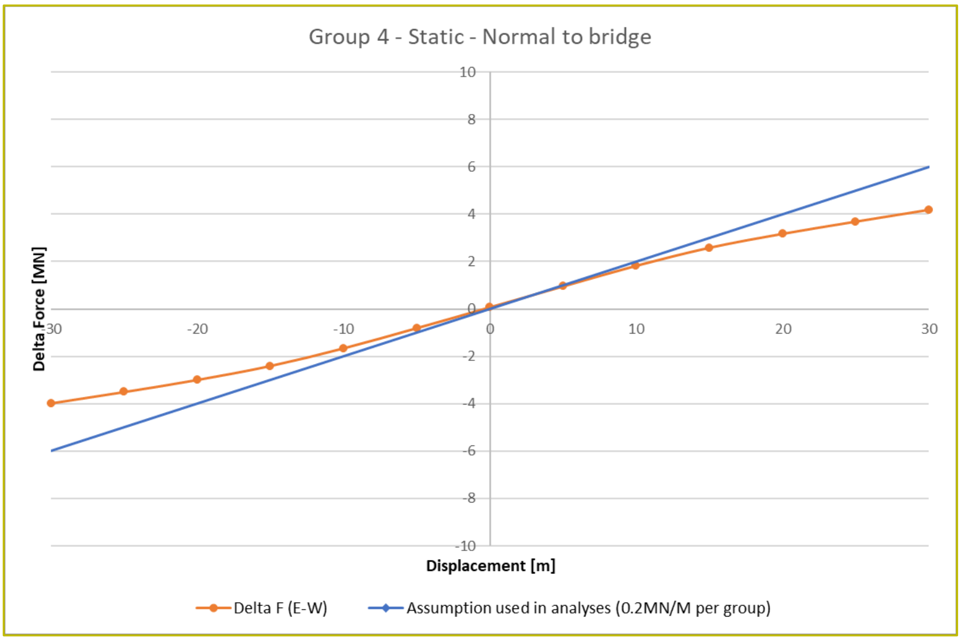


> *Figure 10-4 Static configuration, line behaviour and anchor group stiffness for group 3*

10.3.5 Restoring curves group 4

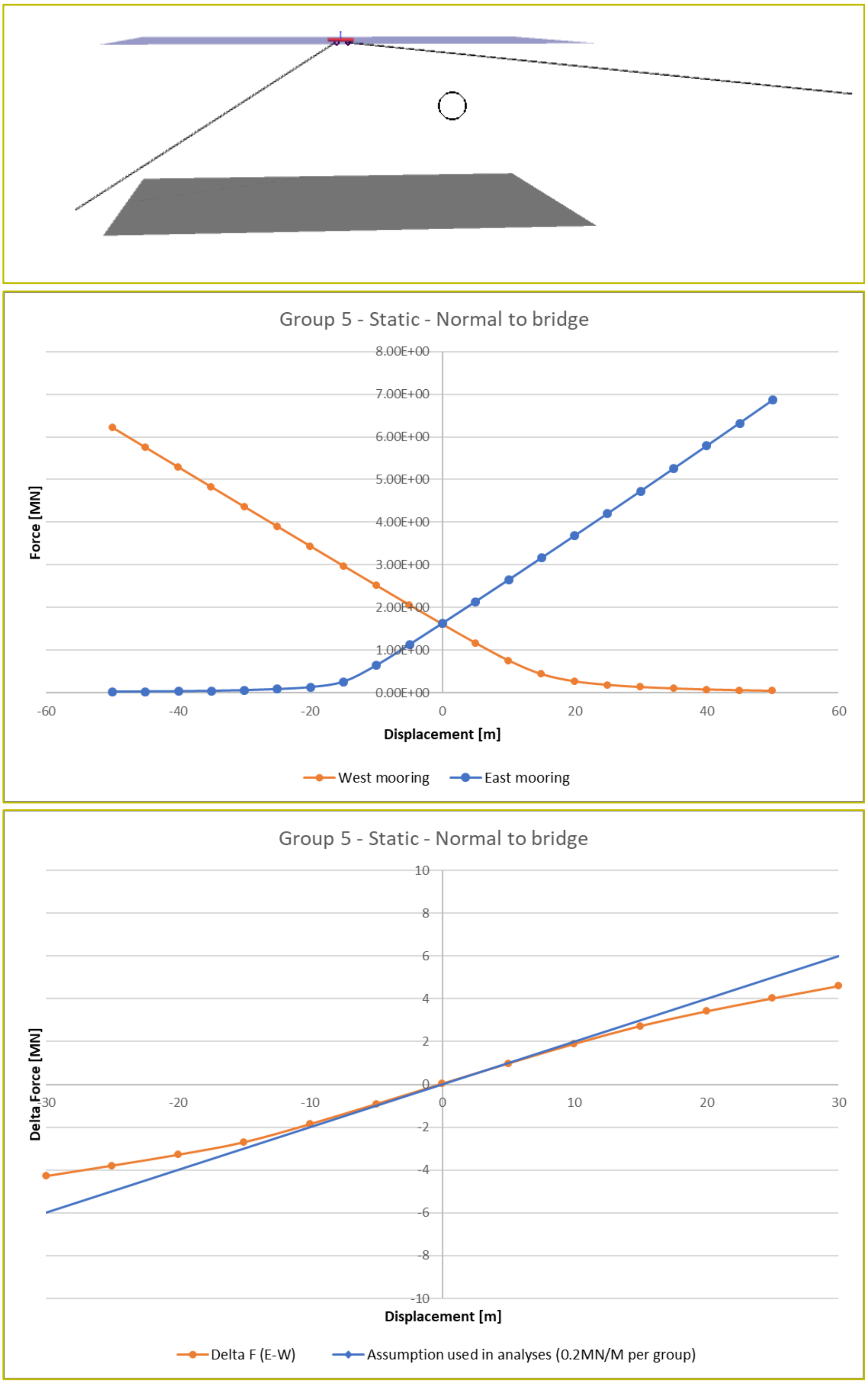






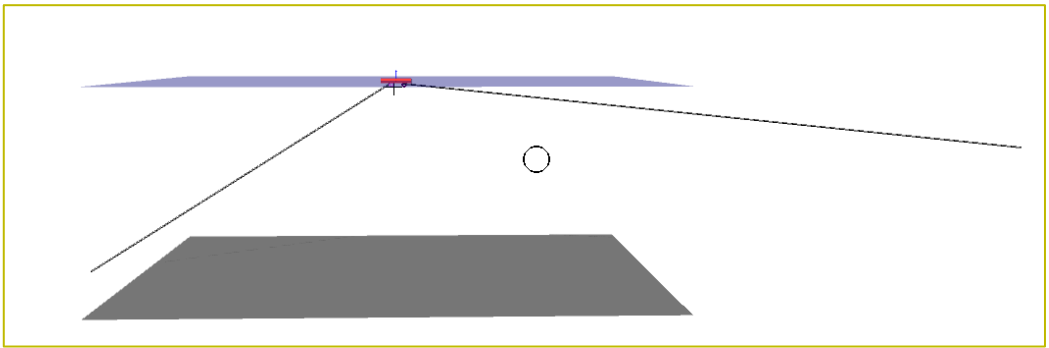
> *Figure 10-5 Static configuration, line behaviour and anchor group stiffness for group 4*

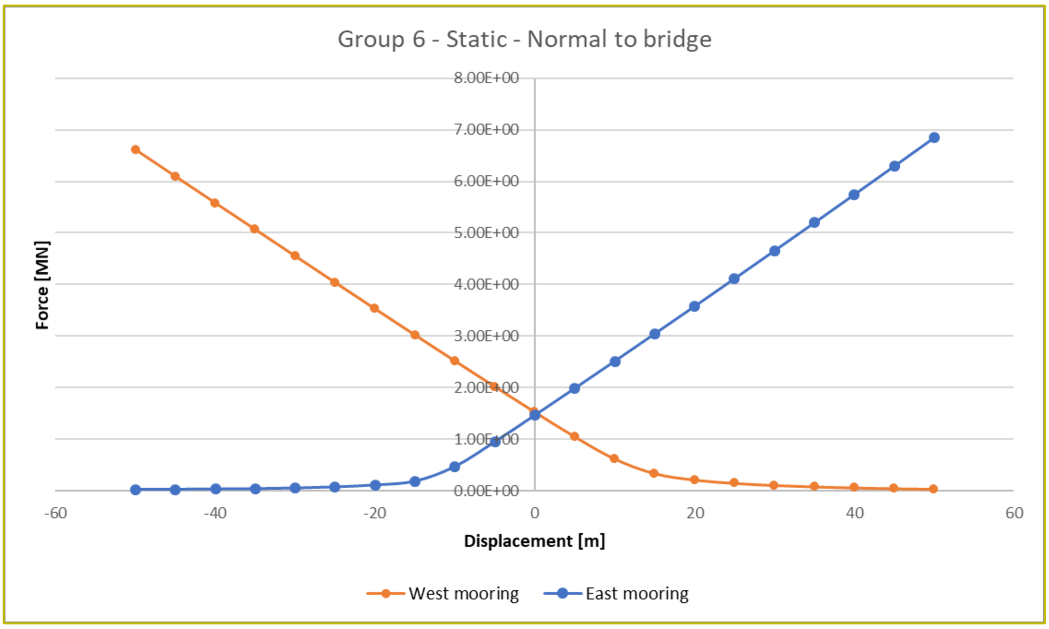
10.3.6 Restoring curves group 5

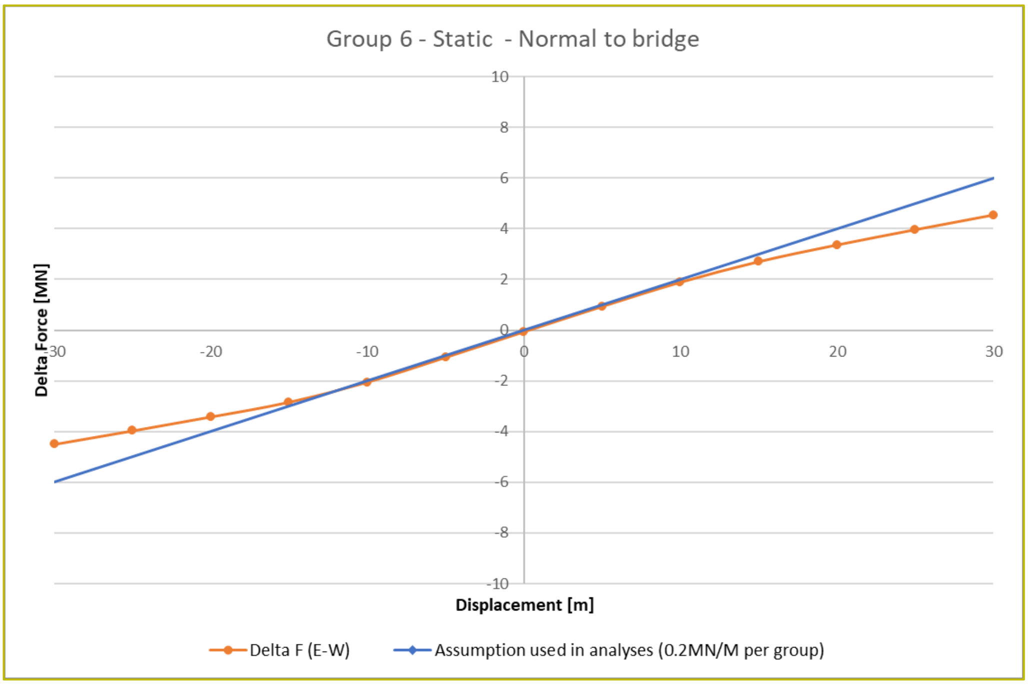


> *Figure 10-6 Static configuration, line behaviour and anchor group stiffness for group 5*

10.3.7 Restoring curves group 6

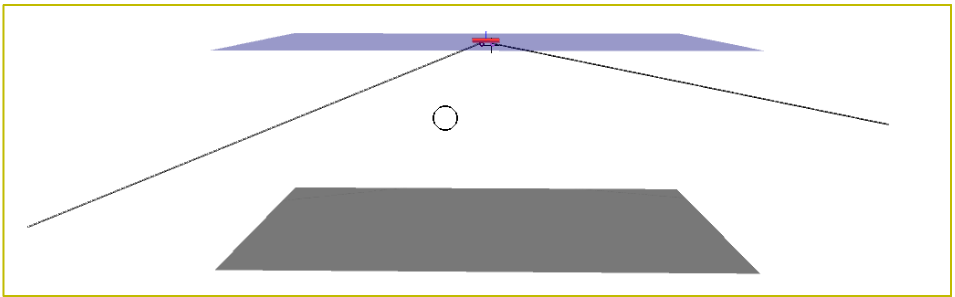


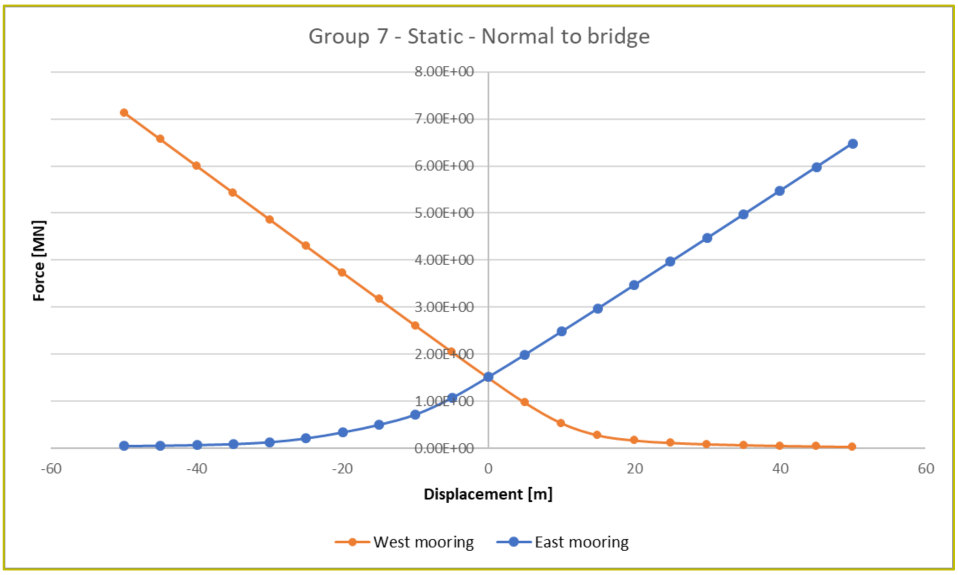


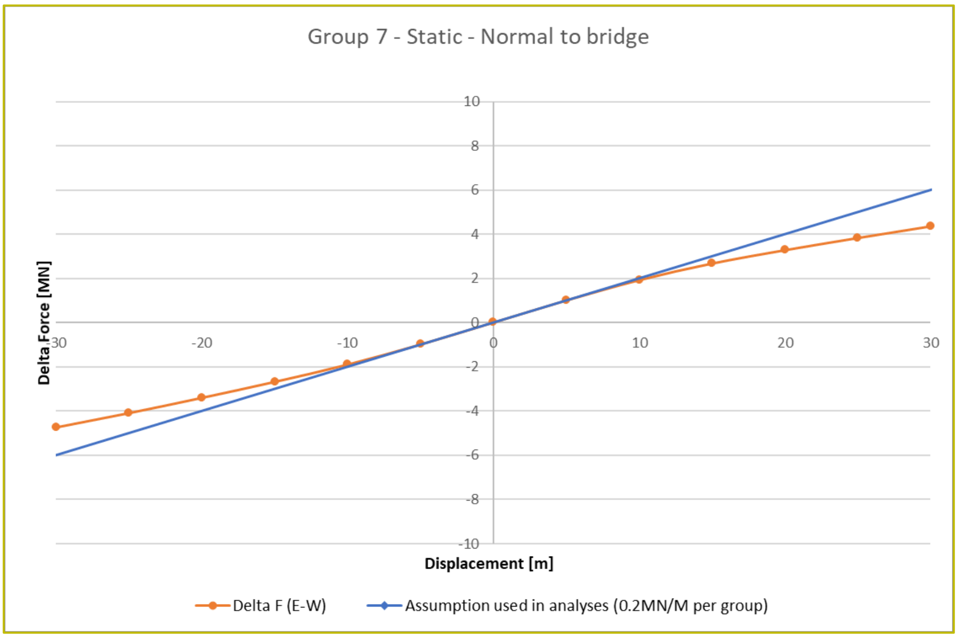


> *Figure 10-7 Static configuration, line behaviour and anchor group stiffness for group 6*

10.3.8 Restoring curves group 7

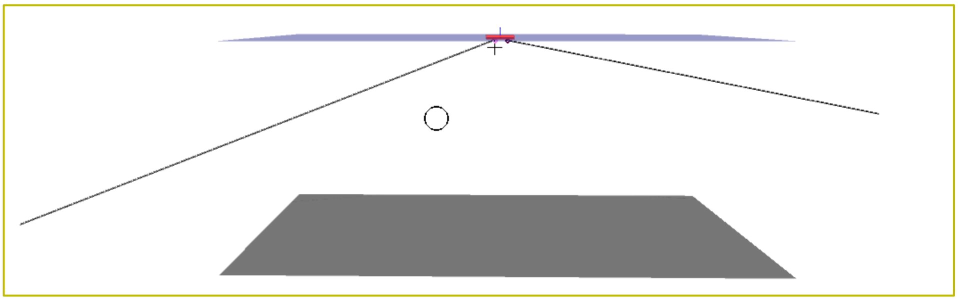


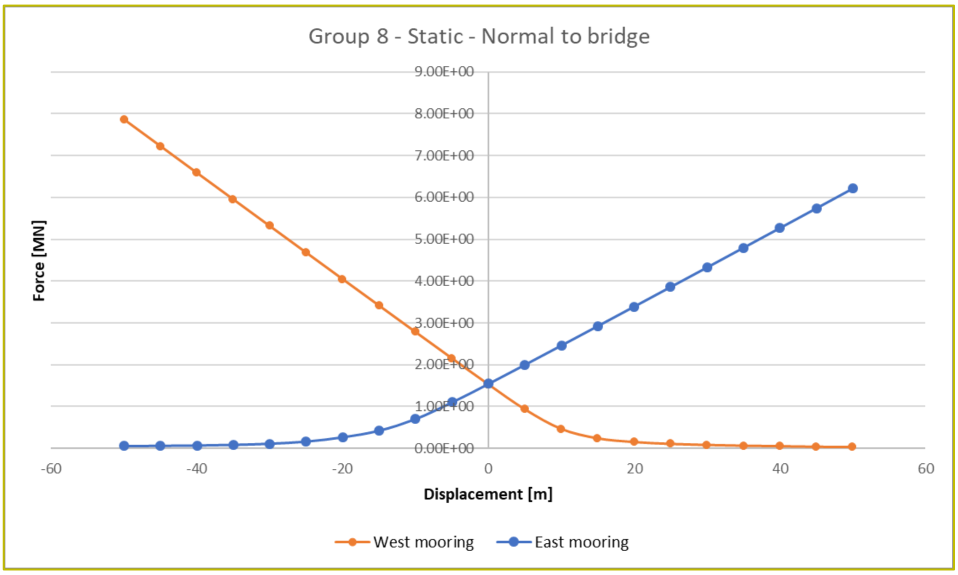


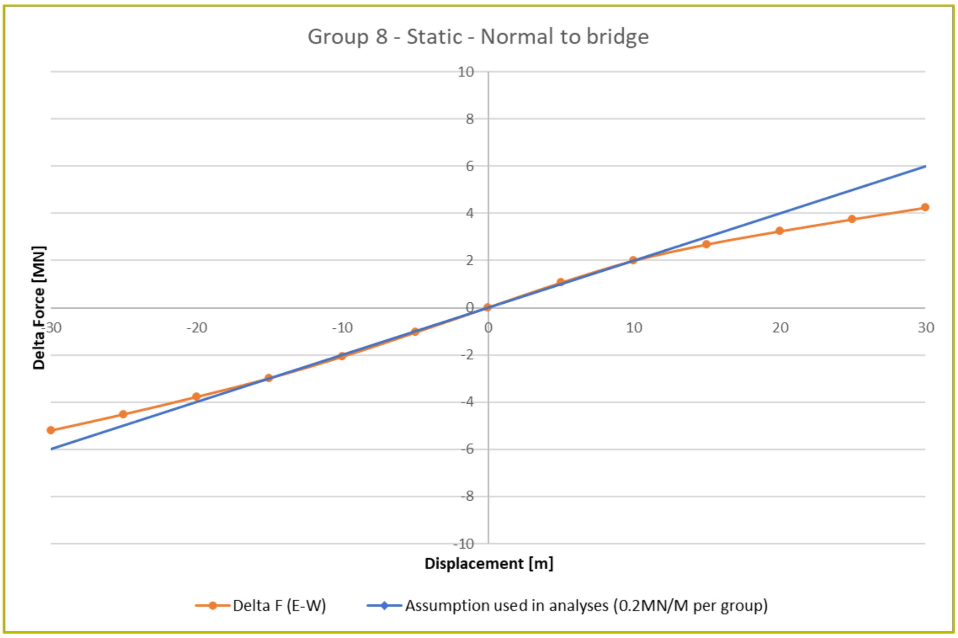


> *Figure 10-8 Static configuration, line behaviour and anchor group stiffness for group 7*

10.3.9 Restoring curves group 8



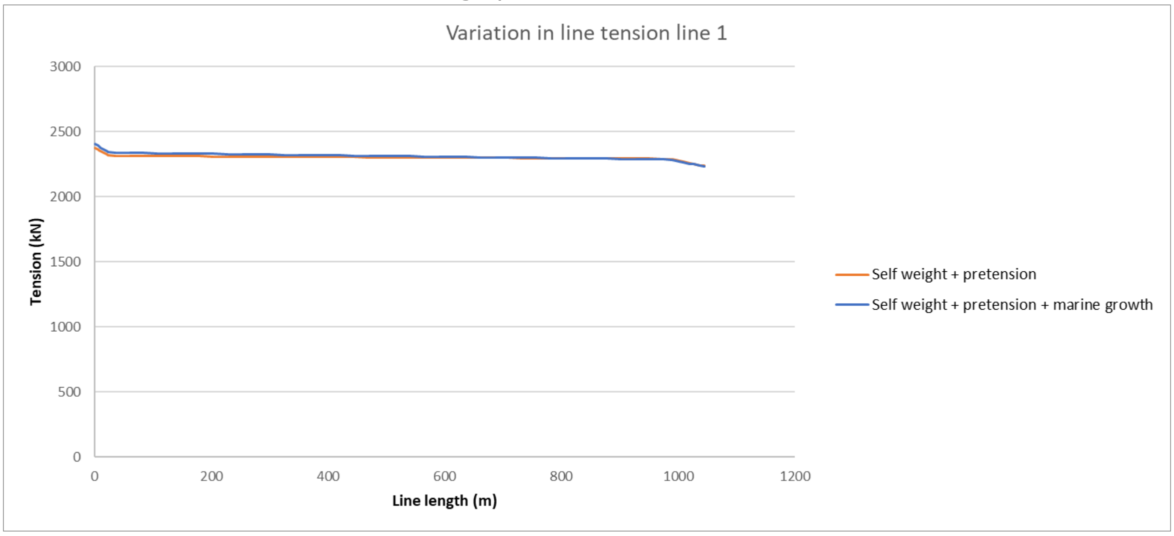




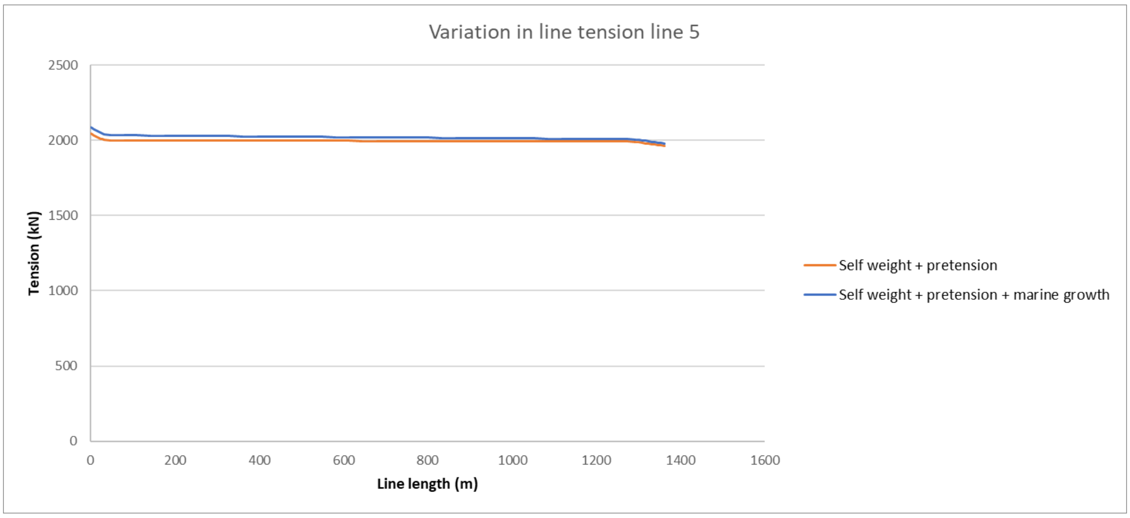
> *Figure 10-9 Static configuration, line behaviour and anchor group stiffness for group 8*

10.4 Marine growth

The effect of marine growth has been checked to evaluate the impact on the line tension. The tension along the line for line no. 1 and no. 5 is shown in Figure 10-10 and Figure 10-11 for line 1 and 4, respectively. Result are presented both with and without marine growth. As seen, the overall variation in tension along the line is small due to a light weight mooring system. When the lines experience marine growth, an increase in tension of 30 kN for line 1 and 40 kN for line 5 is observed at the fairlead. Such minor increases are not expected to influence the behaviour of the mooring system.



> *Figure 10-10 Variation in tension for line 1 due to pretension, self weight and marine growth.*

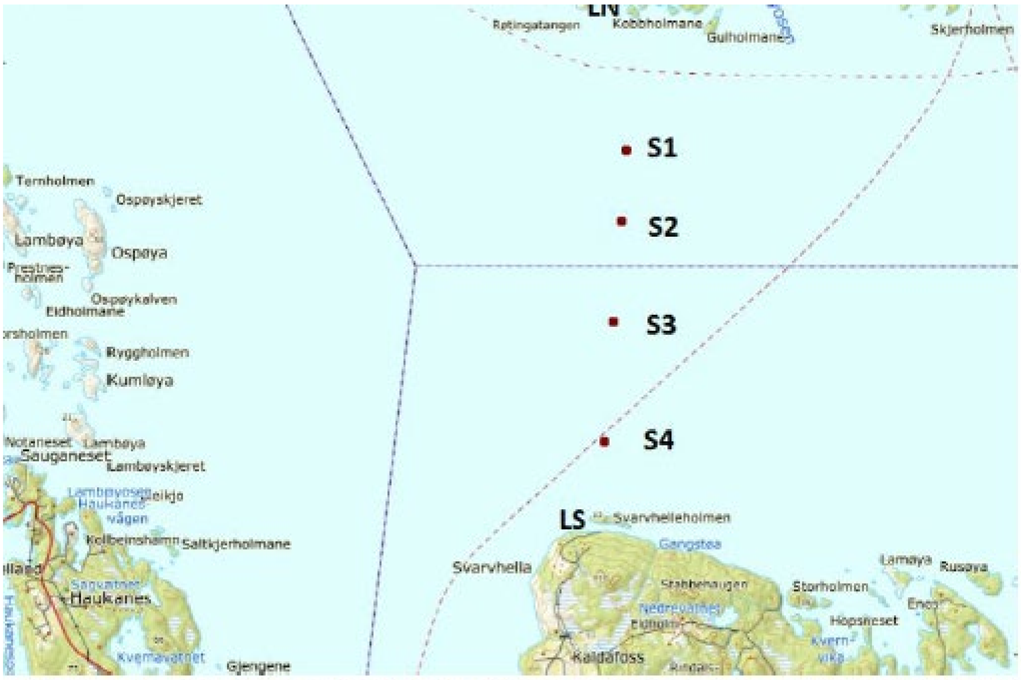


> *Figure 10-11 Variation in tension for line 5 due to pretension, self weight and marine growth*

10.5 Current

10.5.1 Environmental data

The effect of current loads on the mooring lines is investigated. Extreme currents and current profile are taken from Metocean Design Basis, Ref. [18]. The first anchor group lies approximately 1200 meters from the southern shore, between S3 and S4, see Figure 10-12.



The locations of the stations (S1-S4) and northern and southern shore, LN and LS respectivel

LS	S4	S3	S2	S1	LN
0	700	1900	2900	3600	4900

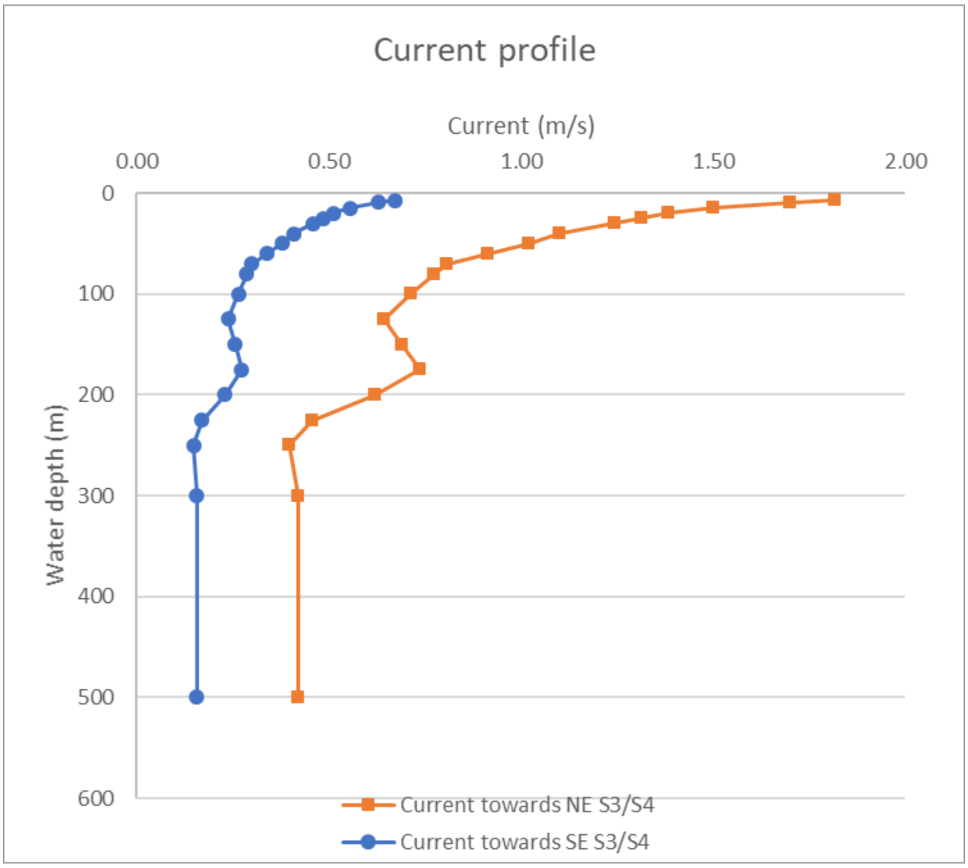
Table 17 Distance from land at the southern shore (LS) to each location given in Table 16 in meter. LN marks the northern shore.

> *Figure 10-12 Extract from metocean Design Basis. Shows location of current measurements*

Table 10-1 Design current at 15 m and directional weighting factors

Loc.	Design current at depth 15m	Weighting factor for directionality							
	(m/s)	N	NE	E	SE	S	SW	W	NW
S1	1.23	0.74	1	0.7	0.41	0.3	0.3	0.37	0.48
S2	1.21	0.69	1	0.73	0.36	0.33	0.35	0.39	0.39
S3	1.39	0.7	1	0.84	0.37	0.33	0.28	0.34	0.32
S4	1.65	0.67	0.64	1	0.79	0.4	0.33	0.37	0.22

The current towards NE gives the largest values with weighting factor 1 and is chosen. The weighting factor for S3 is chosen. This is almost transverse to the investigated mooring lines, and is expected to be the governing direction. The resulting current profiles is shown is Figure 10-13. The current profile for direction along the mooring lines is also shown.



> *Figure 10-13 current profiles for anchor line group 1.*

10.5.2 Results

The current is applied as a static load in Riflex. Drag factors including marine growth according to [5] is applied to the mooring chains and fibre rope. Additional increase of the drag coefficient due to possible VIV is added (an additional factor of 2 for drag coefficient according to [6]).

The results are presented as deflection and additional load and on mooring line 1 and 5. Maximum deflection is 16m for line 5 for the case with increased drag factor due to VIV.

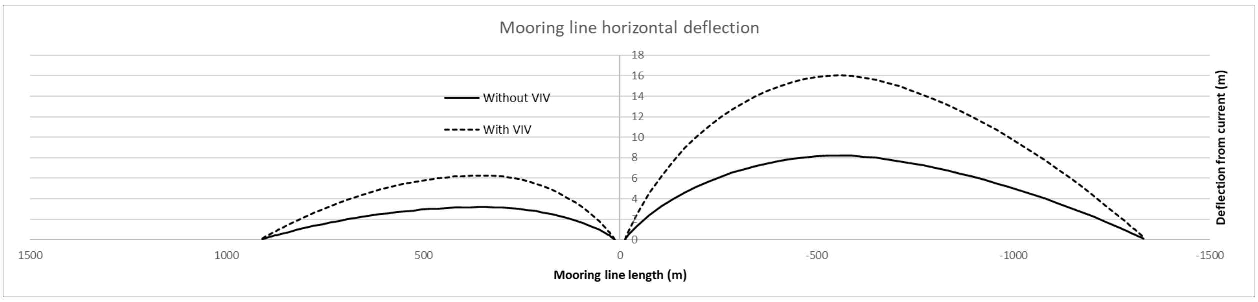


Figure 10-14 Deflection pattern on mooring line with current

The additional loads in the mooring lines is for the different cases are summarized in Table 10-2.

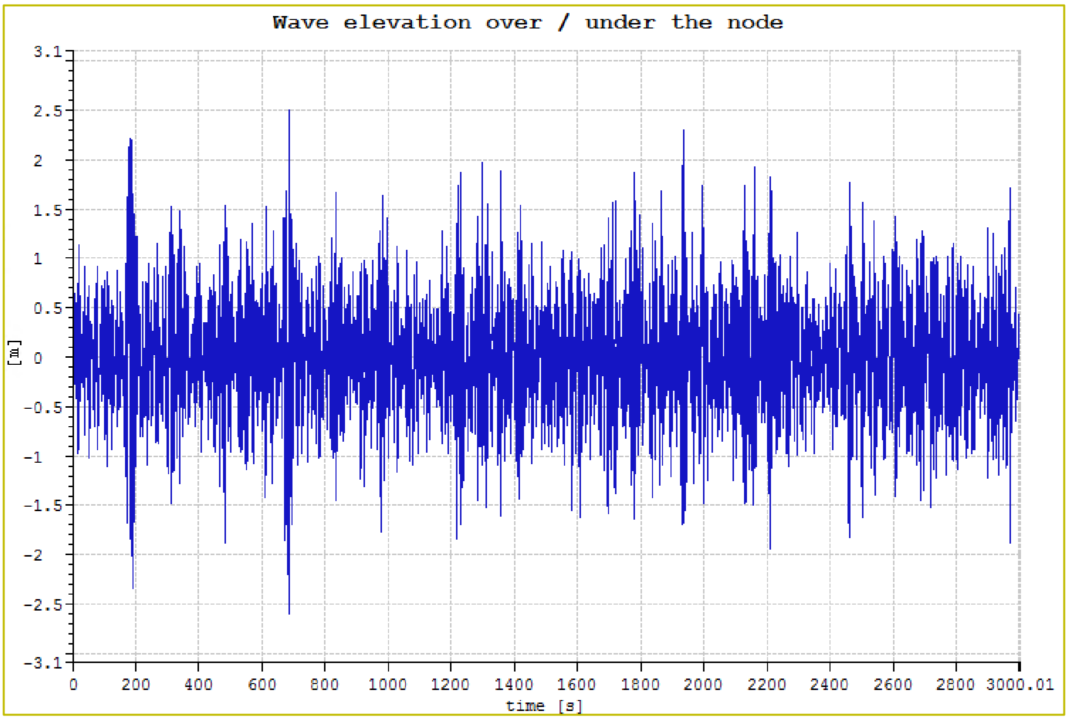
Table 10-2 Additional loads from current on mooring line

Line No.	Without VIV	With VIV
Line 1	5.6 kN	17.2 kN
Line 5	15.9 kN	53.4 kN

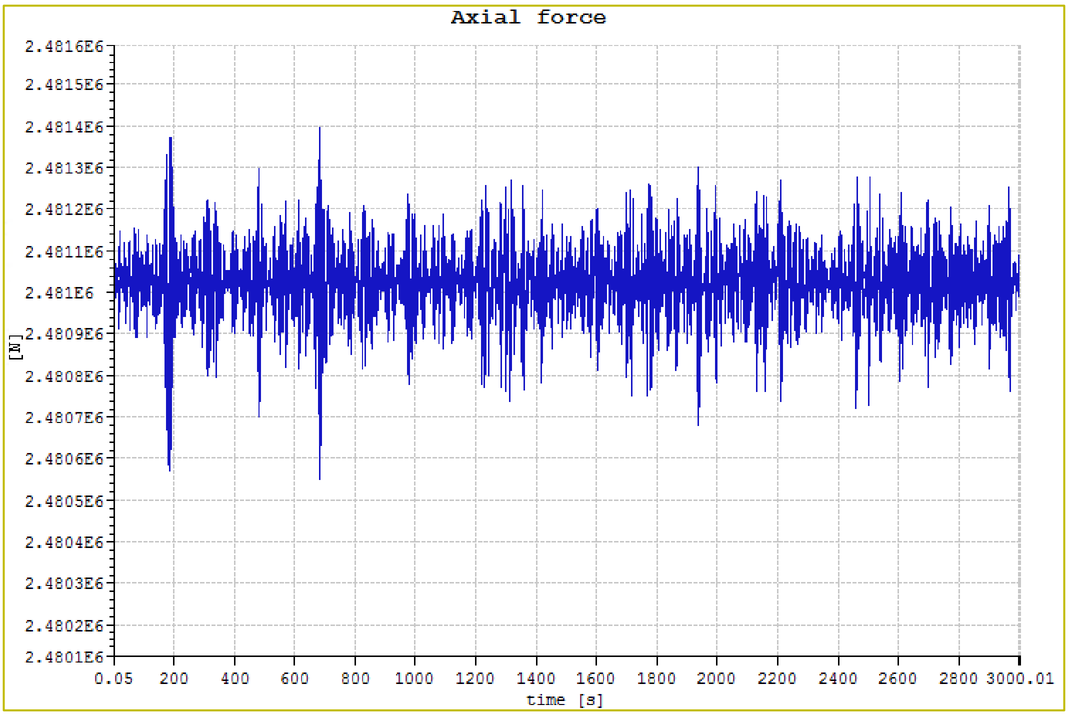
The analyses for the first group cover both the longest and the deepest mooring line and the most severe design current. The analyses are hence considered to give a good estimate of the expected load increase due to current. Additional analyses of the remaining lines are not considered necessary for this phase, as the increase in tension is small compared to the tensions from the global analysis. It should also be noted that the actual current profile, direction and speed is uncertain. The actual combination of current and extreme wind and waves is also expected to give a lower return period for the current that should be combined with the extreme storm. Typically, the 100 year waves and 100 year winds are combined with 10 year current for design of mooring systems in the North Sea, Ref [5].

10.6 Waves

Response in the mooring lines from waves is investigated by applying a wind sea state with Hs=2.3m and Tp=5.3 s. The resulting wave elevation time series and corresponding tension in the line element closest to the fairlead is shown in Figure 10-15 and Figure 10-16, respectively. As shown, the variation is approximately +- 0.5 kN. It is thus concluded that local wave loads on the mooring lines are negligible.



> *Figure 10-15 Wave elevation time series generated by Riflex.*



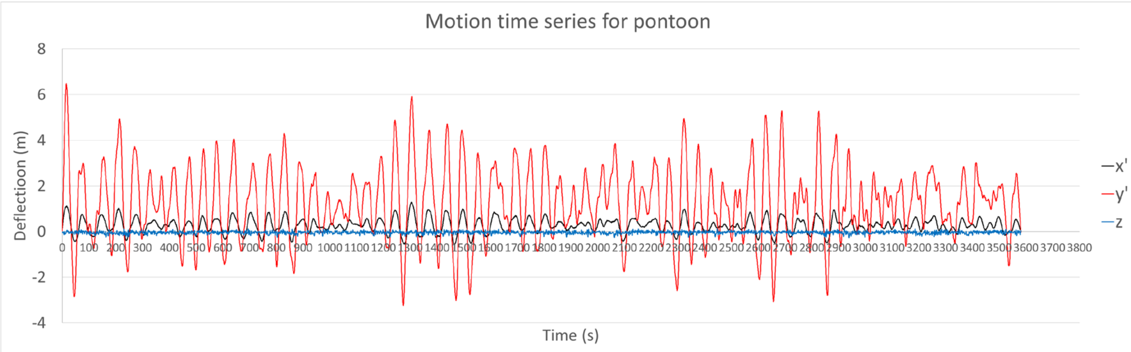
> *Figure 10-16 Axial tension (N) in the element closest to the fairlead.*

10.7 Dynamic mooring line response from global loads

A comparison of the forces in the mooring lines by 3Dfloat and Riflex is performed. The comparison is performed to ensure that the actual mooring line design composed of heavy chain and flexible fibre rope behaves as the simplified 3Dfloat mooring lines.

The Riflex model is used to verify the response of the mooring lines for global motions of the pontoons. The Riflex model includes correct physical properties for all segments of the line, such as correct segment length, segment mass and stiffness, marine growth and hydrodynamic properties. The mooring lines in the 3Dfloat model is modelled as a one element truss, where only the global stiffness is covered.

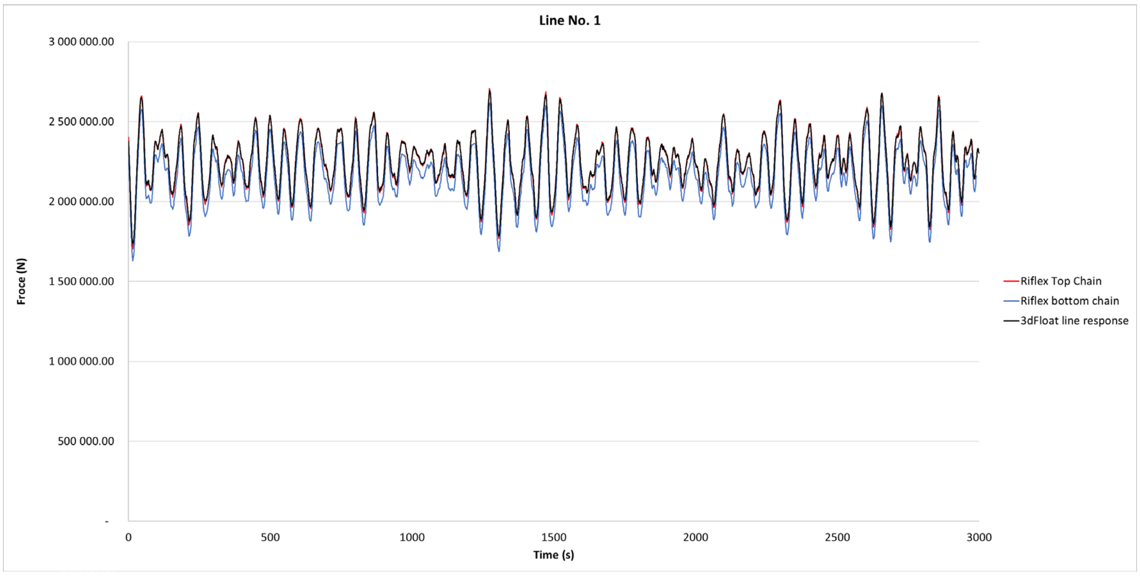
The Riflex analysis is performed by applying a prescribed motion times series from the global analysis for the considered pontoon. The motion time series data is obtained from the 3Dfloat response analyses and the seed giving the largest amount of response in mooring line 1 is used. The time series used is presented in Figure 10-17. Both analyses with and without marine growth are conducted, and marine growth is not found to give additional load effects other than static change in tension.



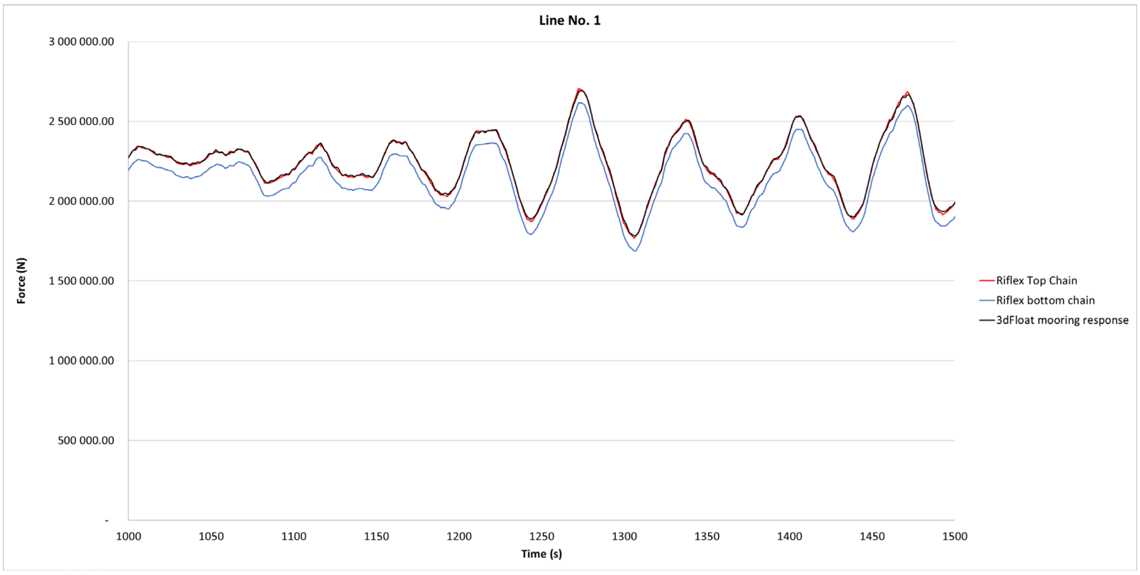
> *Figure 10-17 Motion time series used in dynamic analysis. y' is normal to the bridge and x' is parallel to the bridge.*

The time series is applied to the pontoon in Riflex, with a simulation length of 3000 s and time step 0.05s. The response in the mooring line 1 and 5 from the riflex model is then compared to the response obtained by the global analyses in 3Dfloat.

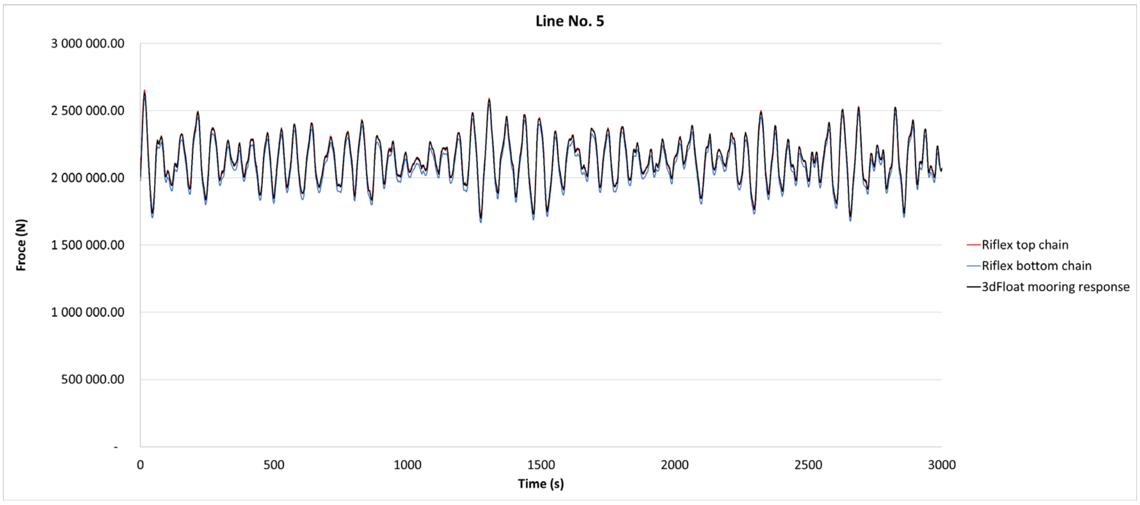
Figure 10-18 and Figure 10-20 shows the comparison of the mooring line forces for line 1 and line 5, respectively. Results from Riflex is presented both for the top chain near the fairlead and for the bottom chain near the anchor.



> *Figure 10-18 Response comparison for line 1*



> *Figure 10-19 Response comparison for line 1, magnified for maximum response around time t=1250s for better visibility*



> *Figure 10-20 Response comparison for line 5*

The results show very good agreement between the global model in 3Dfloat and the more refined Riflex model for the considered mooring lines. No significant dynamic amplification of responses or resonance effects are seen from the Riflex model. This indicated that the forces obtained from the global model can be used directly in the design, and the mooring lines behaves as expected during dynamic loading.

10.8 Modal analyses

A modal analysis is performed for the Riflex model to obtain the natural frequencies of the mooring lines for VIV evaluation. This analysis is based on the same model as in Sec. 10.4 - 10.7. Reference is made to Sec. 11.4 and appendix C for details.

10.9 Concluding remarks

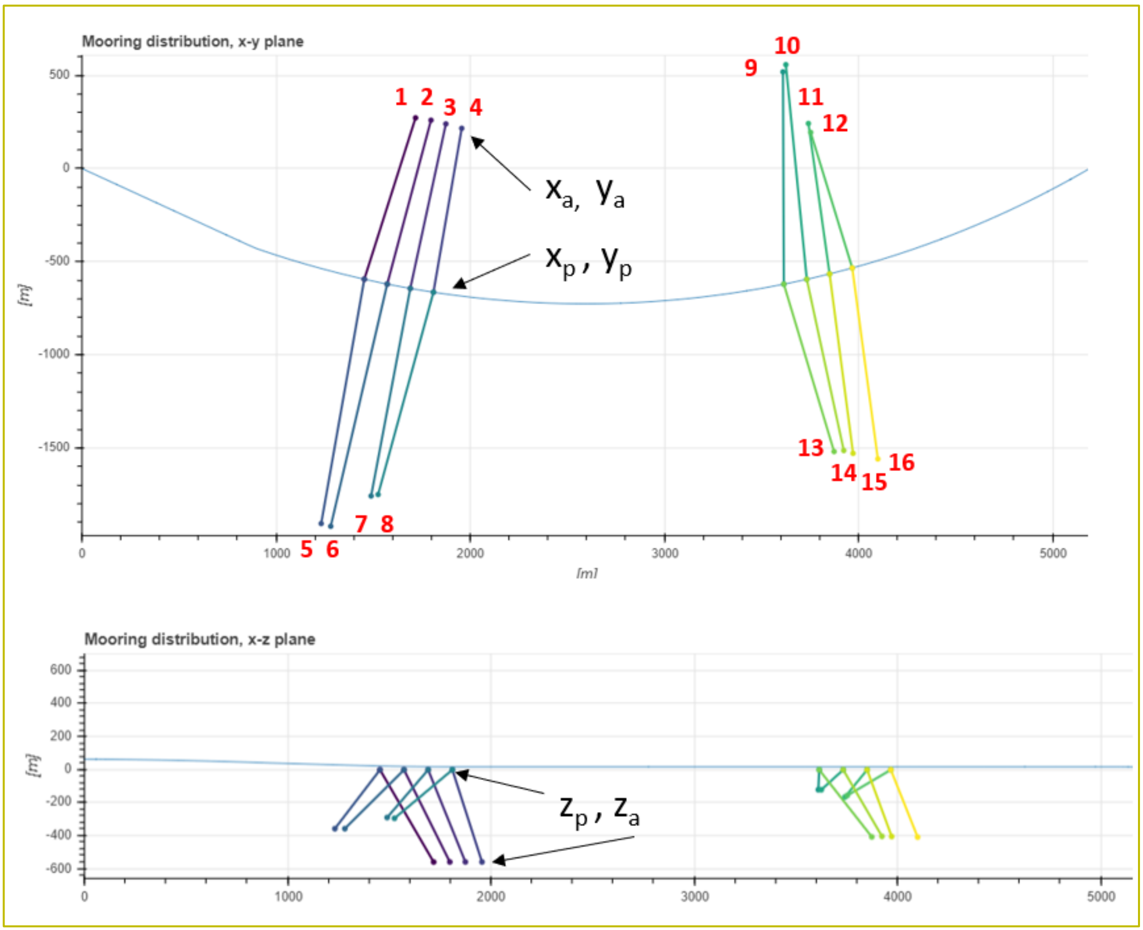
The results from the local models show that using the tensions as estimated with the global model is sufficient for designing of the mooring system. The stiffness used in the global model is based on the quasi-static checks deemed to be representative for the expected range of bridge motion. Environmental loads acting directly on the lines gives negligible increase in mooring line tension.

11 FATIGUE MOORING LINES

11.1 Analysis Input

11.1.1 Pontoon and anchor position

Line numbering and coordinate definition is shown in Figure 11-1. Index p is for pontoon and index a is for anchor.



> *Figure 11-1 Mooring line numbering and coordinate definition (ref. Table 11-1)*

Coordinates for pontoons and anchors are summarised in Table 11-1.

Line ID	xp [m]	yp [m]	zp [m]	xa [m]	ya [m]	za [m]
01	1361.09	-569.01	-5.00	1718.35	271.75	-561.50
02	1477.77	-597.04	-5.00	1797.90	259.26	-561.20
03	1595.07	-622.32	-5.00	1874.55	239.32	-561.10
04	1712.96	-644.71	-5.00	1956.20	215.65	-561.20
05	1361.09	-569.01	-5.00	1232.44	-1906.10	-359.30
06	1477.77	-597.04	-5.00	1281.51	-1920.85	-359.20
07	1595.07	-622.32	-5.00	1489.50	-1758.05	-291.70
08	1712.96	-644.71	-5.00	1525.53	-1750.27	-296.50
09	3503.24	-637.47	-5.00	3610.80	518.72	-123.20
10	3620.92	-614.05	-5.00	3625.44	557.31	-123.50
11	3738.03	-587.87	-5.00	3741.75	241.66	-167.20
12	3854.48	-558.90	-5.00	3753.25	193.70	-158.10
13	3503.24	-637.47	-5.00	3714.95	-1197.41	-382.20
14	3620.92	-614.05	-5.00	3754.63	-1191.90	-380.50
15	3738.03	-587.87	-5.00	4047.37	-1530.36	-410.30
16	3854.48	-558.90	-5.00	4099.29	-1559.35	-411.80

Note: xp,yp,zp = coordinates of pontoon, xa,ya,za = coordinates of anchor

> *Table 11-1 Pontoon and anchor global coordinates*

11.1.2 Mooring line characteristics

Mooring line characteristics are summarised in Table 11-2.

Line ID	Ltc [m]	Lac [m]	Dtc [m]	Dac [m]	Dfr [m]	Ec [MPa]	Efr [MPa]	P [MN]	MBLfr [MN]
01	25	60	0.146	0.100	0.177	50850	4730	2.3	10.0
02	25	60	0.146	0.100	0.177	50850	4730	2.1	10.0
03	25	60	0.146	0.092	0.177	50850	4730	1.8	10.0
04	25	60	0.146	0.092	0.177	50850	4730	1.8	10.0
05	35	75	0.146	0.100	0.185	50850	4730	2.0	11.0
06	35	75	0.146	0.100	0.185	50850	4730	1.8	11.0
07	35	50	0.146	0.092	0.168	50850	4730	1.6	9.0
08	35	50	0.146	0.092	0.168	50850	4730	1.6	9.0
09	50	70	0.146	0.092	0.177	50850	4730	1.7	10.0
10	50	175	0.146	0.092	0.168	50850	4730	1.6	9.0
11	50	70	0.146	0.092	0.145	50850	4730	1.6	7.0
12	50	50	0.146	0.092	0.145	50850	4730	1.6	7.0
13	25	50	0.146	0.092	0.145	50850	4730	2.0	7.0
14	25	50	0.146	0.092	0.145	50850	4730	1.8	7.0
15	25	150	0.146	0.092	0.168	50850	4730	1.7	9.0
16	25	100	0.146	0.092	0.177	50850	4730	1.7	10.0

Note: Ltc/Lac = length of top chain/ bottom *chain, Dtc/Dac/Dfr = diameter of top chain/* bottom *chain/ fiber rope, Ec/Efr = Youngs modulus chain/fiber rope, P = pretension,MBLfr=MBL fibre rope*

> *Table 11-2 Mooring line characteristics*

11.1.3 Combination matrix

The combination matrix is used to generate load combinations. The combination matrix combines load cases from wind sea, wind and swell and defines a probability for each combination. The same combination matrix is used as for global fatigue analyses for the bridge. For the full case matrix reference is given to the Fatigue assessment report, ref. [16]. A further refinement of the load case matrix for fatigue design of the mooring should be performed in the next phase as different load cases to some extent will be design driving for the mooring system and other components of the bridge.

11.2 Methodology

11.2.1 Failure modes

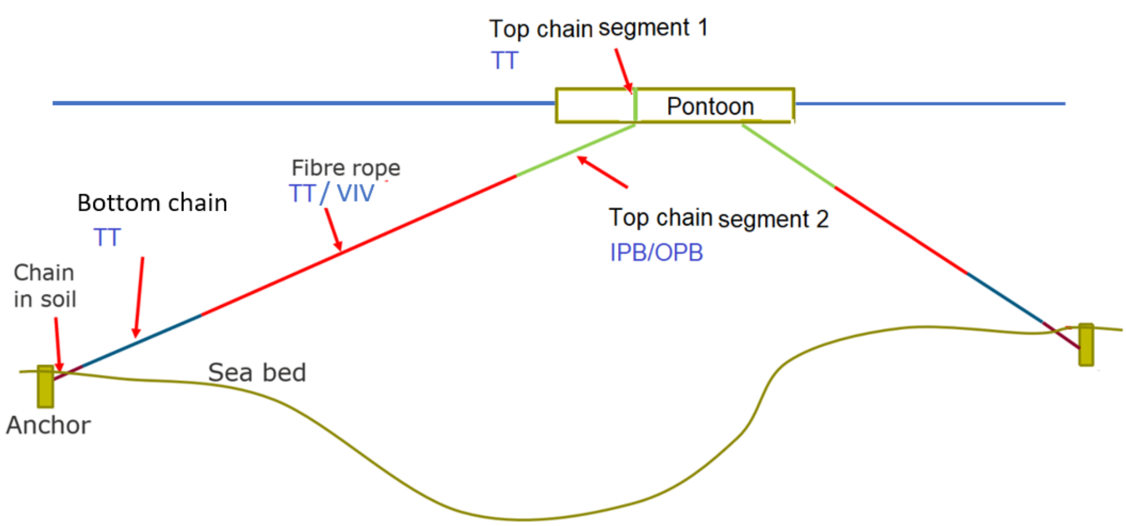
Fatigue analyses are carried out for the main mooring line components such as top chain, bottom chain and fibre rope. The following failure modes are investigated:

- Tension-Tension (low cycle fatigue) TT
- In-plane Out-of-Plane Bending (low cycle fatigue) IPB/OPB
- Vortex induced vibrations (high cycle fatigue) VIV

Table 11-3 and Figure 11-2 present the relevant and analysed failure mode for each component. VIV on top- and bottom chain is written in parentheses as VIV is not expected on chains itself. However, VIV on fibre rope will cause a stress range in the entire mooring line and hence also indirectly affect fatigue damage of the chains.

Component	Fatigue failure mode
Top chain – segment 1	Tension -Tension (VIV on fibre rope)
Top chain – segment 2	In-plane out-of-plane bending (at fairlead) (VIV on fibre rope)
Bottom chain	Tension -Tension (VIV on fibre rope)
Fibre rope	Tension -Tension Vortex induced vibrations

> *Table 11-3 Fatigue failure mode per component*



> *Figure 11-2 Fatigue failure mode per component*

11.2.2 Software

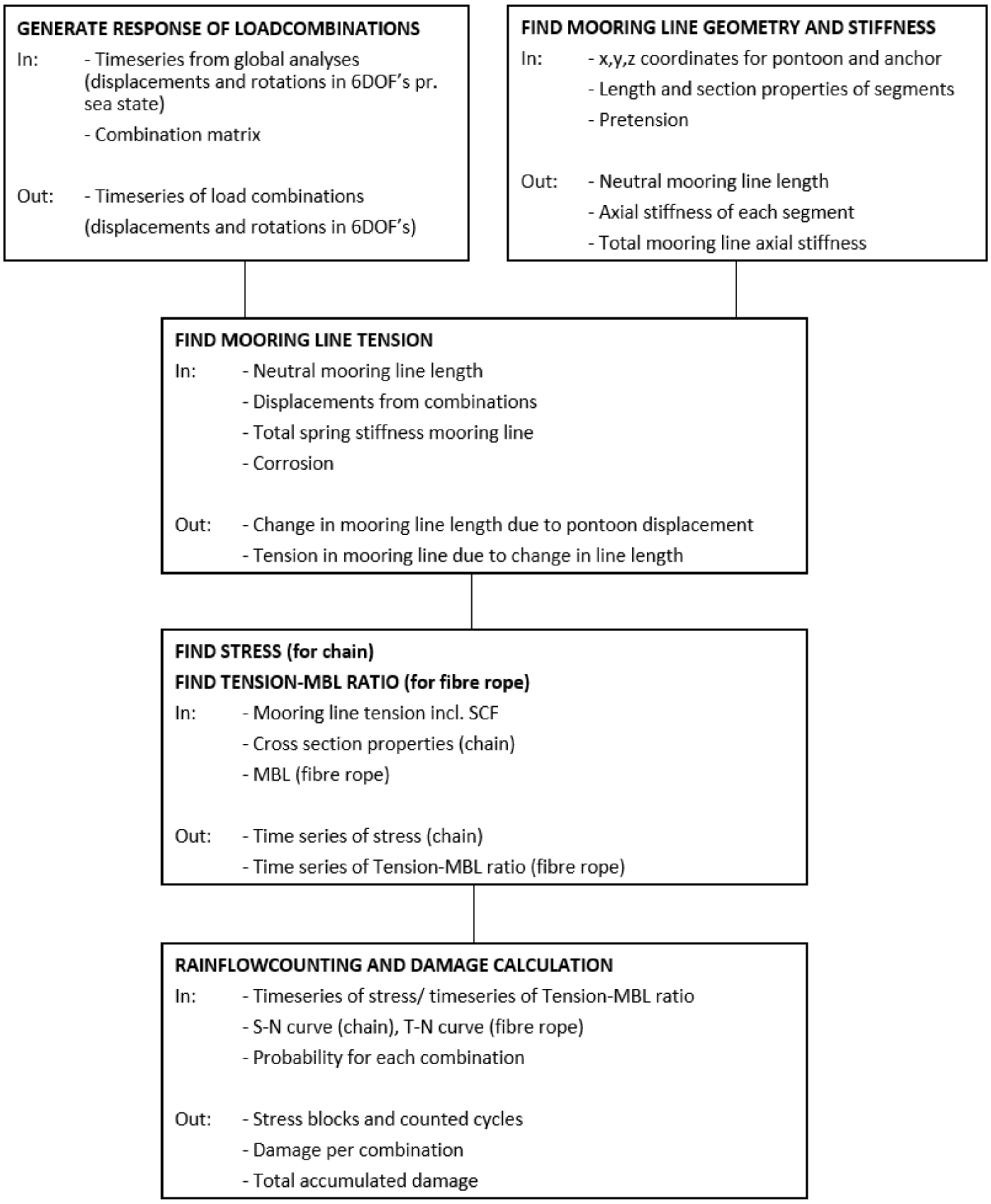
The following software has been used for mooring line fatigue analyses:

- Scripting with Python software package, for general design calculations and data processing
- Sofistik, for interlink stiffness analyses, as part of IPB/OPB fatigue calculation

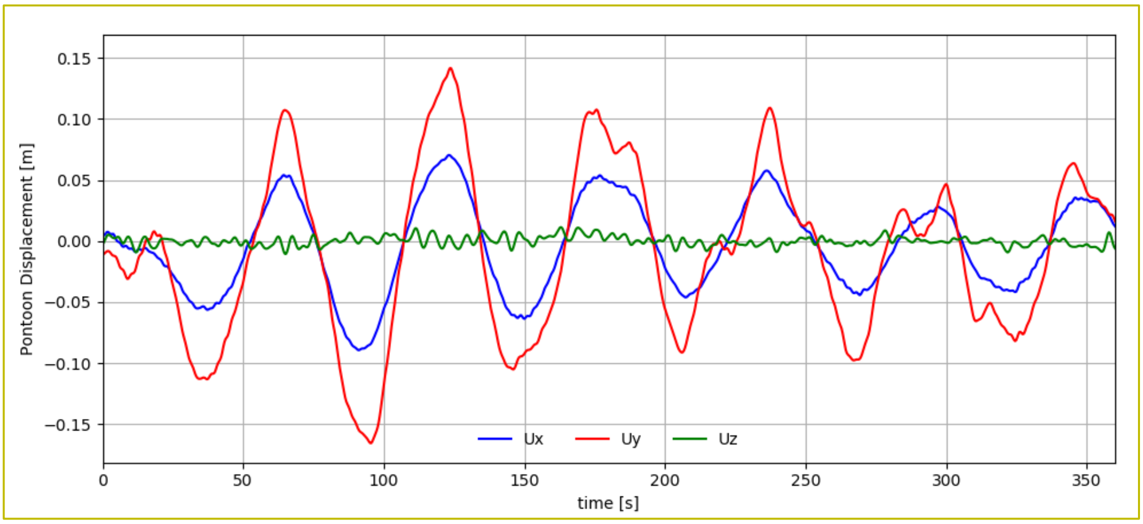
- SIMA, Marine operations and mooring analysis software for eigenmode calculation
- Mathcad, for hand calculation, local design verification

11.2.3 Tension-Tension fatigue

Tension-tension fatigue for chain and fibre rope is calculated according to DNVGL-OS-E301, Ref. [5]. The following flowchart summarises the methodology used in this project. Further details to each step are listed subsequent to the chart.



Response of load combinations
Response for load combination is calculated by superposition of the response from load cases according to the combination matrix. For tension-tension fatigue displacements in global directions Ux, Uy and Uz – direction are expected to be governing. Typical extract from time series is shown in Figure 11-3.



> *Figure 11-3 Typical extract from generated response time series (one load combination)*

Neutral mooring line geometry and stiffness
Initial mooring line length L_i is calculated based on neutral position of pontoons (x_p, y_p, z_p) and anchors (x_a, y_a, z_a),

$$L_i = \sqrt{(x_a - x_p)^2 + (y_a - y_p)^2 + (z_a - z_p)^2}$$

Component stiffness k_j for each segment j of the mooring line is calculated:

$$k_j = \frac{E_j \cdot A_j}{L_j}$$

With
E_j = Youngs modulus segment
A_j = Cross section segment

The total stiffness k_{tot} of the line is calculated with:

$$k_{tot} = \sum \frac{1}{1/k_j}$$

Mooring line tension
The change in mooring line length L_d due to pontoon displacement U_i is calculated.

$$L_d = \sqrt{(x_a - x_p - U_x)^2 + (y_a - y_p - U_y)^2 + (z_a - z_p - U_z)^2}$$

Total mooring line tension F_t is calculated from the change in mooring line length and mooring line stiffness. Pretension P is included.

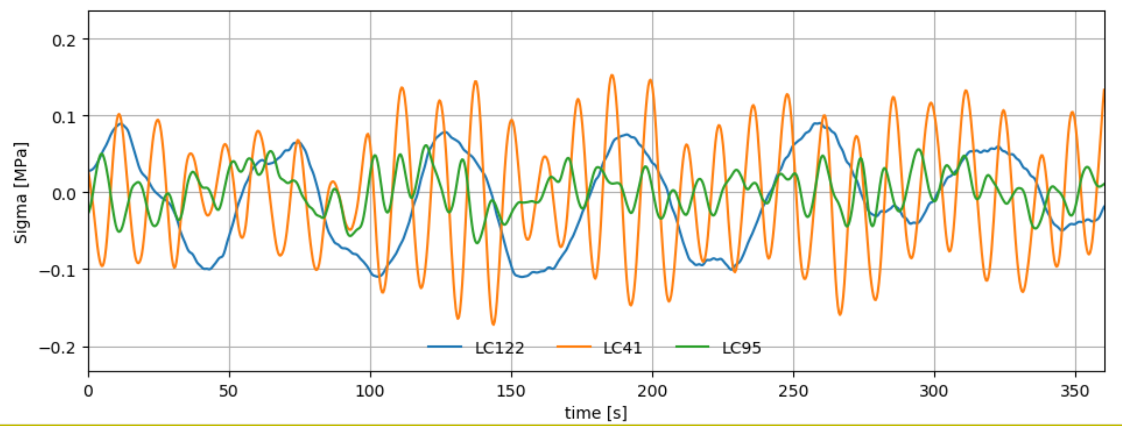
$$F_t = P + (k_{tot} * (L_d - L_i))$$

Stress calculation (for chain)

The stress σ_t in the top chain is calculated based on mooring line tension, top chain cross section A_{tc}, corrosion and stress concentration factor SCF. Corrosion allowance is applied according to Table 2-6 as a reduction of diameter. In fatigue analyses 50% of the chain's corrosion allowance shall be taken into account.

$$\sigma_{TT} = \frac{F_t}{A_{tc}} * SCF$$

Typical extract from time series is shown in Figure 11-4.



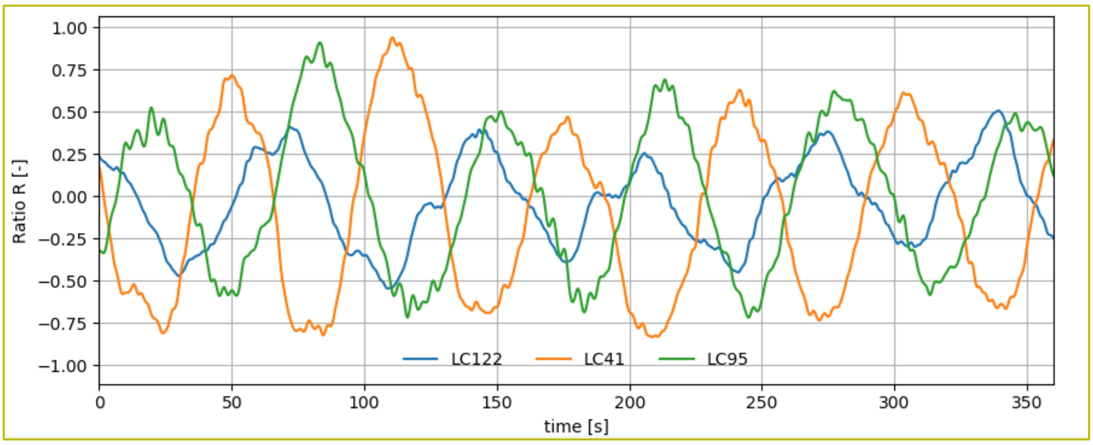
> *Figure 11-4 Typical extract from generated stress time series (three load combinations)*

Tension-MBL ratio calculation (for fibre rope)

The ratio R is calculated from mooring line tension and the minimum breaking strength S_{mbs} according to ref. [5].

$$R = \frac{F_t}{0.95 * S_{mbs}} * SCF$$

Typical extract from time series is shown in Figure 11-5.



> *Figure 11-5 Typical extract from generated tension-MBL ratio time series (three load combinations)*

Rainflow counting and damage calculation
Rainflow counting is carried out on the timeseries for stresses. Number of cycles n_i at stress s_i is calculated.

Damage calculation for tension-tension fatigue is carried out according to DNVGL-OS-E301, Ref. [5]. Component capacity against tension fatigue $n_c(s)$ (number of cycles to failure) is calculated with:

$n_c(s) = a_d * s^{-m}$ (for chain)

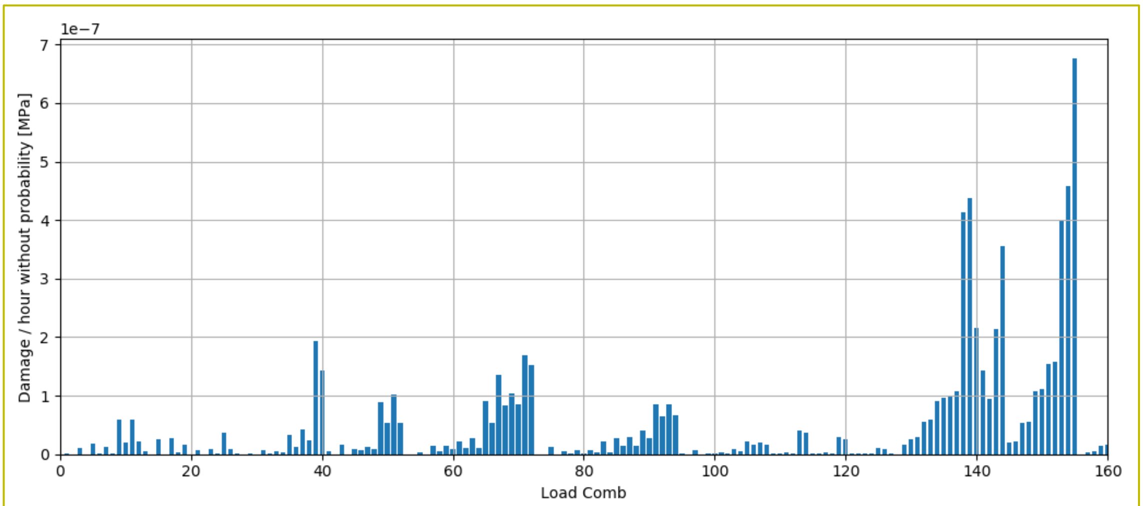
$n_c(R) = a_d * R^{-m}$ (for fibre rope)

Damage d_i for each sea state is determined from the actual number of cycles n_i encountered at stress s_i / ratio R_i and the number of cycles to failure. The fatigue damage accumulation method (Palmgren-Minor rule) is used. The Palmgren-Minor rule is as follows for chain and fibre ropes respectively;

$$d_i = \sum \frac{n_i}{n_{ci}(s)}$$

$$d_i = \sum \frac{n_i}{n_{ci}(R)}$$

Figure 11-6 shows a typical plot of damage per hour for all load combinations.



> *Figure 11-6 Typical plot of damage/hour for load combinations*

The total damage D_{tot} at lifetime is calculated from the damage d_i at each sea state including probability p_i, total number of occurrences in one year N_{1year}, the lifetime and design fatigue factor DFF.

$$D_{tot} = DFF * years * \sum d_i * p_i * N_{1year}$$

11.2.4 In-plane and Out-of-plane bending fatigue

In-plane and Out-plane fatigue is calculated according to BV Guidance Note NI 604, Ref. [5]. The following flowchart summarises the methodology used in this project. Further details to each step are provided after the chart. More refined analysis might be performed for the next phase of the project.

INTERLINK STIFFNESS ANALYSIS

In: - Minimum and maximum tension and angles at fairlead for all sea states
- Chain properties (diameter, link length, material properties (E, fy, fu), friction steel-steel)
- Interlink moment and stiffness curve

Out: - Sliding threshold between to links
- Relation btw. line tension (T) / angle (α) at fairlead and interlink moment (M) between first two links after fairlead, → function for M(T, α)

GENERATE RESPONSE OF LOADCOMBINATIONS

In: - Timeseries from global analyses (displacements and rotations in 6DOF's pr. sea state)
- Combination matrix

Out: - Timeseries of load combinations
(displacements and rotations in 6DOF's)

FIND MOORING LINE GEOMETRY AND STIFFNESS

In: - x,y,z coordinates for pontoon and anchor
- Length and section properties of segments
- Pretension

Out: - Neutral mooring line length, vertical and horizontal angle
- Axial stiffness of each segment
- Total mooring line axial stiffness

FIND MOORING LINE TENSION AND IN-PLANE OUT-PLANE BENDING MOMENT

In: - Neutral mooring line length
- Displacements and rotations from combinations
- Total spring stiffness mooring line
- Corrosion

Out: - Change in mooring line length due to pontoon displacement
- Tension in mooring line due to change in line length
- Bending moment (in-plane, out-of-plane) due to rotations of pontoon

FIND STRESS IN CHAIN

In: - Mooring line tension incl. SCF
- In-plane and out-of-plane bending moments btw. Chain links incl. SCF
- Cross section properties chain

Out: - Time series of stress in chain

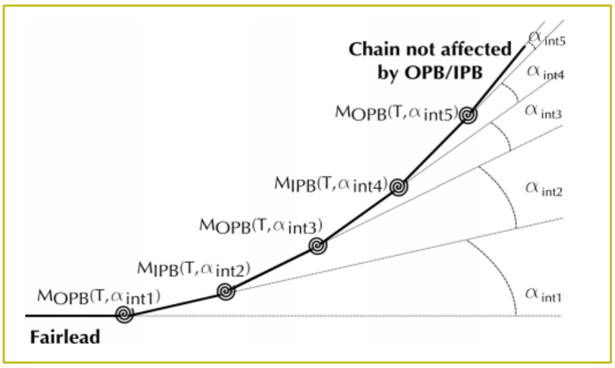
RAINFLOWCOUNTING AND DAMAGE CALCULATION

In: - Timeseries of stress
- S-N curve
- Probability for each combination

Out: - Stress blocks and counted cycles
- Damage per combination
- Total accumulated damage

Interlink stiffness analyses
Interlink stiffness analyses are carried out to find the relation between mooring line tension and angle at fairlead, and the interlink moment between the first two links after fairlead. This relation is established to calculate timeseries of bending moment from given timeseries with translations and rotations of the pontoons.

Based on the method describe in ref. [8] a beam model shall be established to evaluate bending moments between two adjacent links. The schematics of the beam model is shown in Figure 11-7.



> *Figure 11-7 Example of beam model of chain for interlink angle estimation, ref. [8]*

The interlink stiffness analyses comprises the following three main steps:

- A: Calculation of working law for interlink stiffness (as input to beam model)
- B: Calculation of beam model with varying tension and angles at fairlead
- C: Determination of bending moment function (with dependency on tension and angles at fairlead)

<u>A – Calculation of interlink stiffness working law</u>
The working law for interlink stiffness is established based on the parametric function given in ref. [8] Appendix 1:

$$M_i(\alpha_{int}, T, d) = \frac{\pi * d^3}{16} * C * \frac{P(\alpha_{int})}{G + P(\alpha_{int})} * \left(\frac{T}{0.14 * d^2}\right)^{a(\alpha_{int})} * (\frac{d}{100})^{2a(\alpha_{int})+b(\alpha_{int})}$$

With:

α_{int}	:	Interlink angle, in degree
T	:	Mooring line tension, in kN
d	:	Chain diameter, in mm

C = 354

G = 0,93

$P(\alpha_{int}) = \alpha_{int} + 0,307\ \alpha_{int}^3 + 0,048\ \alpha_{int}^5$

$a(\alpha_{int}) = a_1 + a_2 \tanh(a_3\ \alpha_{int})$

$b(\alpha_{int}) = b_1 + b_2 \tanh(b_3\ \alpha_i nt)$

In seawater, the value of M_i (α_{int} ,T, d) is limited by the sliding moment between links (see Sec 3, [3.1.2]).

Note 1: The Best Fit model of interlink moment using least square method developed in JIP Chain OPB can also be used.

Table 1 : Parameters a_1, a_2, a_3, b_1, b_2 and b_3

$a_1 = 0,439$	$a_2 = 0,532$	$a_3 = 1,020$
$b_1 = -0,433$	$b_2 = -1,640$	$b_3 = 1,320$

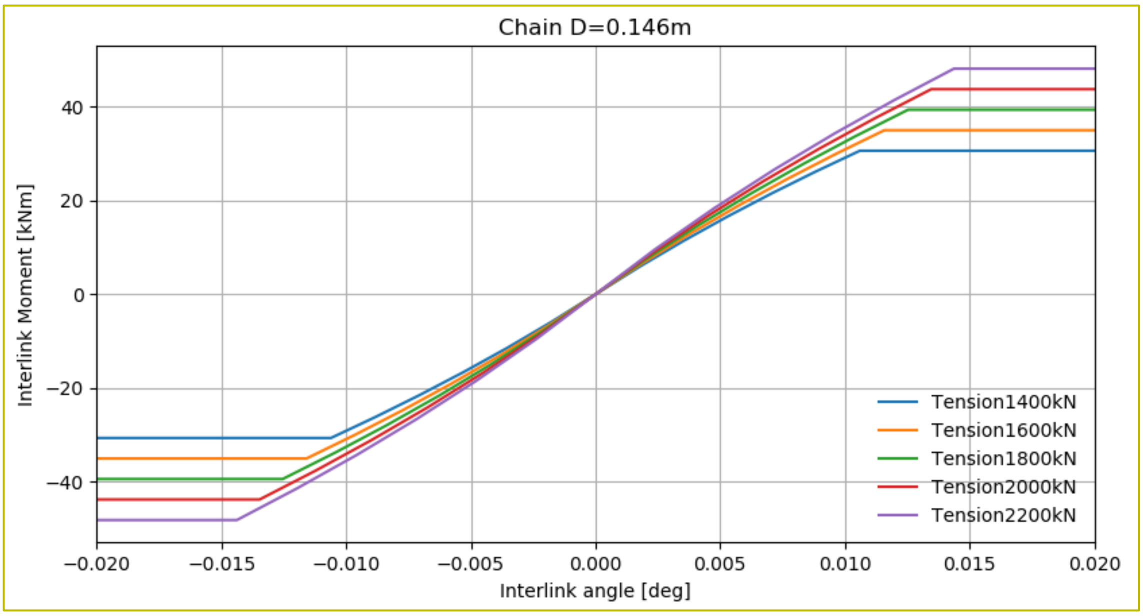
The sliding threshold is:

$$M_{tres} = \mu * T * d/2$$

with:

T	:	Actual tension
µ	:	Friction coefficient
d	:	Chain nominal diameter.

Typical working law for various line tension is shown in Figure 11-8.

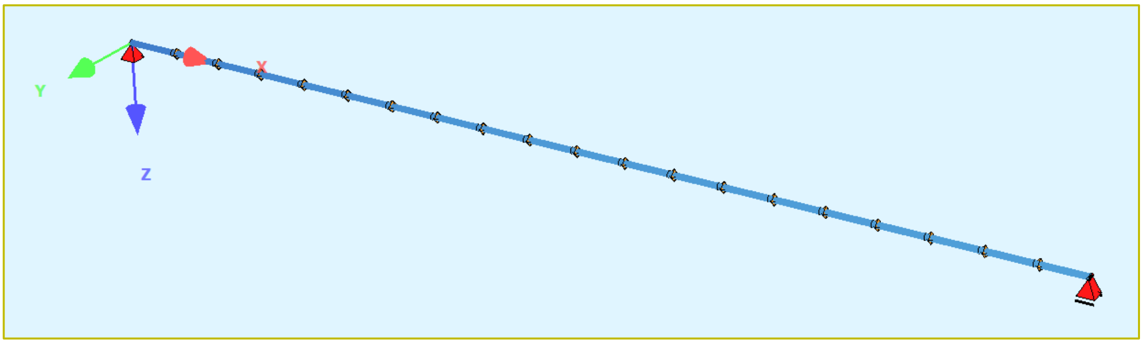


> *Figure 11-8 Typical working law top chain*

<u>B – Beam model</u>

A summary of the interlink stiffness analysis model is presented in Appendix B.

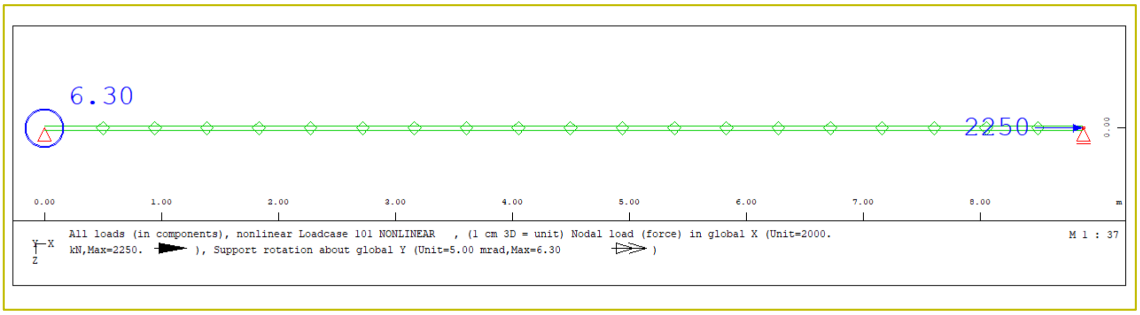
The beam model is established using the Finite element software Sofistik. The beam model comprises 20 links with beam cross section properties rotated about 90deg between two adjacent links. Boundary conditions are chosen as for a simply supported beam, see Figure 11-9.



> *Figure 11-9 Beam model interlink stiffness analyses*

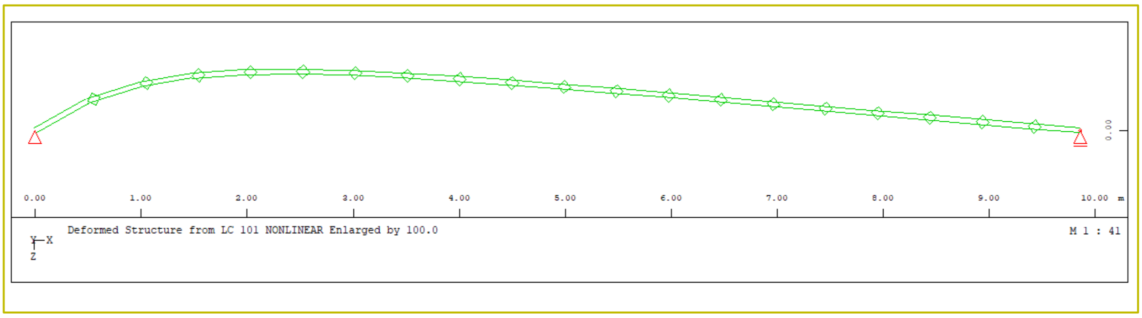
Interlink stiffness is defined between the beams, by applying a spring stiffness working law (moment against rotation).

Loading of the model is applied in form of rotations at the pinned end and tension at the sliding end. For typical load application see Figure 11-10.



> *Figure 11-10 Typical loading of interlink stiffness model*

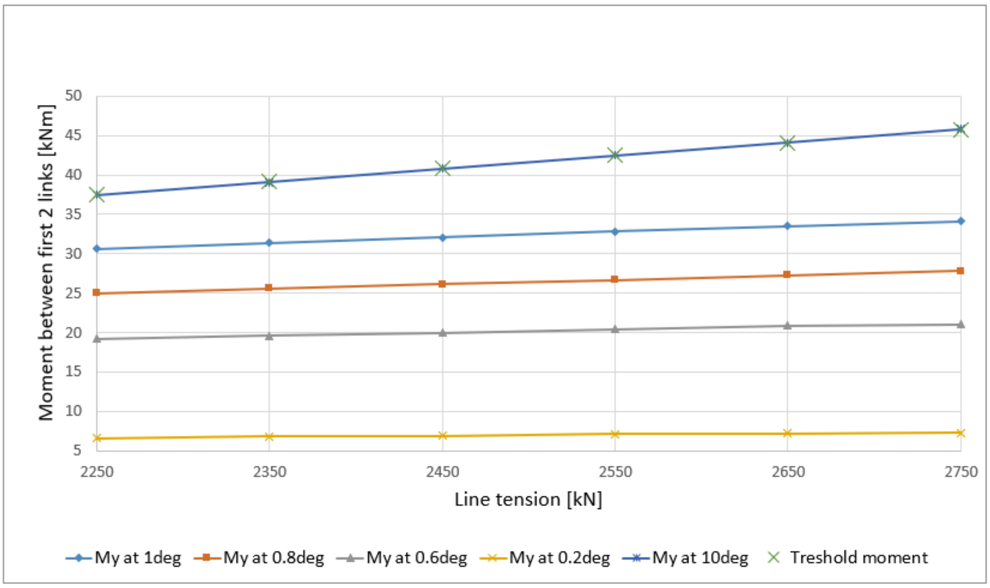
Typical deformation plot from beam model analyses is shown in Figure 11-11.



> *Figure 11-11 Typical deformation plot of beam model*

<u>C – Determination of bending moment function</u>

Screening is carried out with respect to the rotation angle at fairlead, see Figure 11-12. For a given chain dimension both the angle at fairlead and the line tension is varied. From the screening results it is concluded that the relation between angle at fairlead and bending moment between the first two links is sufficiently represented by linear relation between angle and moment.



> *Figure 11-12 Interlink stiffness, screening of moment dependency on angle at fairlead*

Further a function has been established describing the relation of the line tension to the bending moment between the first two links after fairlead. A separate function has been established for each chain dimension. A second order function has been chosen to be sufficient for the curve fitting and the general expression is used:

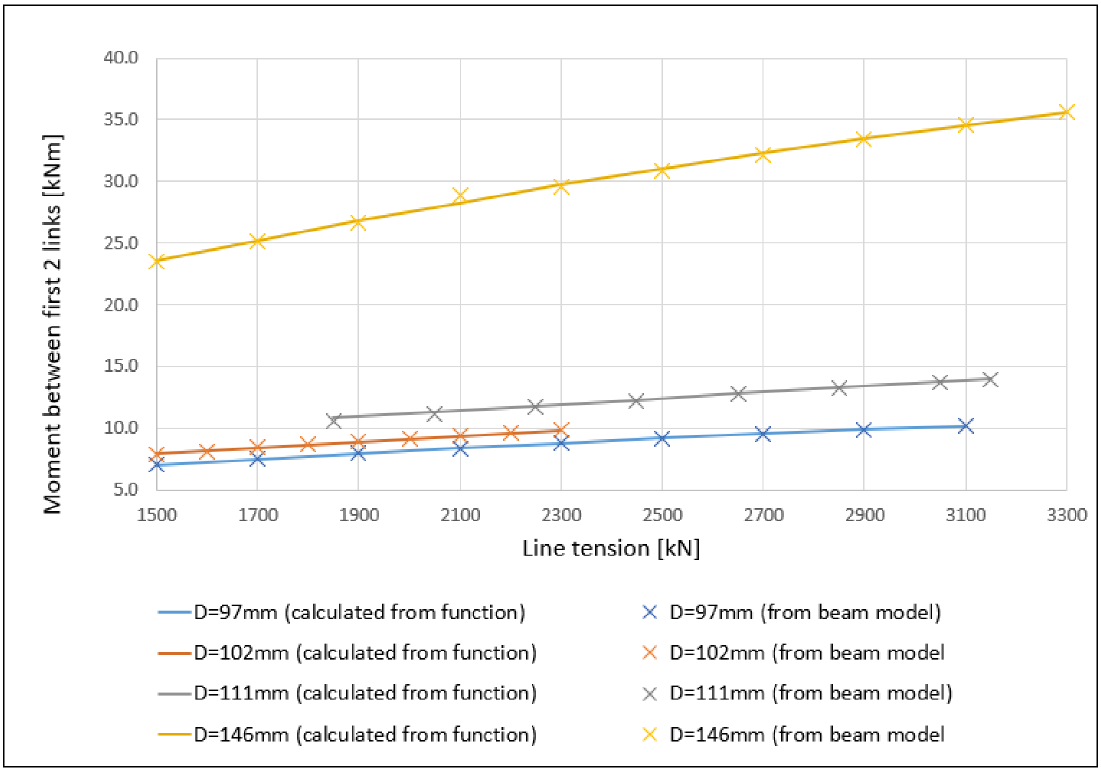
$$y = a + bx + cx^2$$

Bending moment for normalised rotation at fairlead is:

$$M_b(F_t) = a + b * F_t + c * {F_t}^2$$

Results from beam model are used to determine curve fitting parameters a, b and c for different chain dimensions. Figure 11-13 shows calculated the moment curves $M_b(F_t)$ for different chain dimensions. Results from beam model are plotted in as well and they show good correspondence.

The established moment function will be used to calculate timeseries of bending moments.



> *Figure 11-13 Relation line tension – moment between first two links*

Response of global load combinations
Response for load combination is calculated based on the same method as described for tension-tension fatigue, by superposition of the response from load cases according to the combination matrix. For further investigation of in-plane/ out-of-plane fatigue of the chain displacements and rotations in global directions Ux, Uy, Uz, Rx, Ry and Rz are of interest.

Neutral mooring line geometry and stiffness
Initial mooring line length L_i is calculated based on the same method as described for tension-tension fatigue.

Additionally, the horizontal and vertical mooring line angle α_h and α_v are calculated to find rotations for in-plane and out-of-plane mooring line local directions.

Mooring line stiffness k_{tot} is calculated based on the same method as described for tension-tension fatigue.

Mooring line tension and in-plane out-plan bending moment
Mooring line tension F_t is calculated based on the same method as described for tension-tension fatigue.

In-plan and out-of-plane bending moments are calculated based on the relationship found in interlink stiffness analyses. The maximum moment is limited by the threshold moment M_{tres}

$$M_{zz} = \left(\mathrm{a} + \mathrm{b} * F_t + \mathrm{c} * {F_t}^2\right) * Rot_{zz} \leq M_{tres}$$

$$M_{xy} = \left(\mathrm{a} + \mathrm{b} * F_t + \mathrm{c} * {F_t}^2\right) * Rot_{xy} \leq M_{tres}$$

Stress in top chain
Stress from tension in the top chain is calculated based on the same method as described for tension-tension fatigue.

Stress from in-plane and out-of-plane bending moment is calculated from bending moments and chain cross section properties. Two adjacent links are considered as they have similar moment with cross section properties 90deg rotated.

Link1

$$\sigma_{IPB} = \frac{SCF * 2.33 * M_{zz}}{\pi * {D_{corroded}}^3}$$

$$\sigma_{OPB} = \frac{SCF * 16 * M_{xy}}{\pi * {D_{corroded}}^3}$$

Link2

$$\sigma_{IPB} = \frac{SCF * 2.33 * M_{xy}}{\pi * {D_{corroded}}^3}$$

$$\sigma_{OPB} = \frac{SCF * 16 * M_{zz}}{\pi * {D_{corroded}}^3}$$

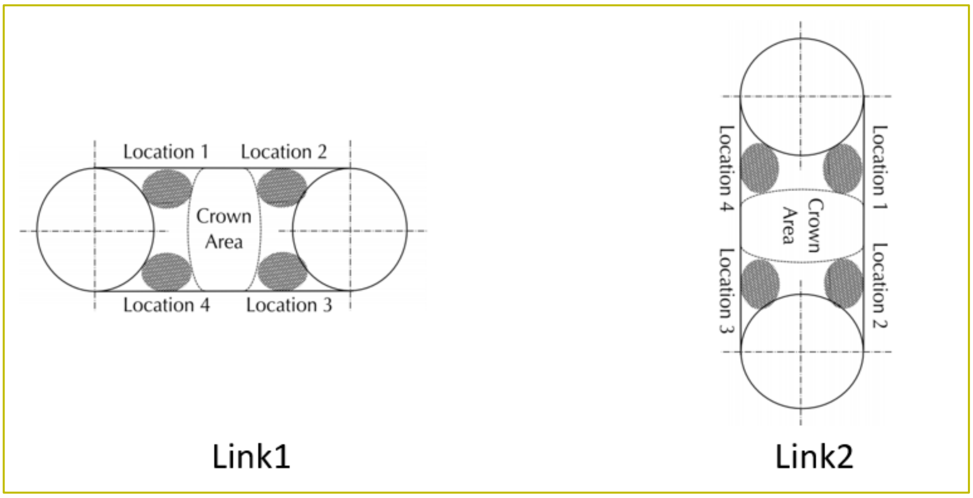
The total combined stress is calculated according to ref. [8]:

$$\sigma_{comb} = Z_{corr} * (\Delta\sigma_{TT} \pm Z_s * \Delta\sigma_{OPB} \pm Z_s * \Delta\sigma_{IPB})$$

With factors Z_{corr} and Z_s according to ref. [8]:

$$Z_{corr} = 1.08$$
$$Z_S = 1.06$$

The combined stress shall be calculated in four possible locations due to symmetry planes of the chain link and the phase difference between the loadings. For further details see Figure 11-14 and ref. [8]:



> *Figure 11-14 Anti-symmetrical fatigue failure locations, ref. [8]*

Rainflow counting and damage calculation
Rainflow counting and damage calculation is based on the same method as describe for tension-tension fatigue for the different relevant hot-spots.

11.2.5 Vortex induced vibrations

According to DNVGL-OS-E301, Ref. [5] taut mooring systems with fibre ropes may be exposed to vortex induced vibrations. Vortex induced vibration (VIV) is caused by vortex shedding giving rise to oscillatory forces. It is assumed that chains are not affected by VIV Ref. [5]. However VIV occuring along the fibre rope will cause a tension variation in the entire mooring line. These tension variations needs to be evaluated also for the chain. Possible VIV response due to waves has not been considered for VIV.

Vortex induced vibrations may be split into:

- Cross flow (CF) vibrations with vibration amplitude in the order of 1 diameter
- Pure in-line (IL) vibrations with amplitudes in the order of 10-15% of the diameter
- CF induced IL vibrations with amplitudes of 30-50% of the CF amplitude.

For VIV screening in this phase focus is set on cross flow vibrations as it is expected that in-line vibrations will give limited contributions. The assessment is carried out in accordance to DNVGL-RP-C205, Ref. [19]. The assessment of cross flow amplitudes is based on VIV amplitude of 0.9 times the fibre rope diameter, which should be conservative for fatigue analysis. VIV due to waves has not been considered

The simplified method used for VIV investigation is presented in the following flow chart:

CROSSFLOW SCREENING

In:
- Environmental data (current)
- Fibre rope properties
- Reduced velocity criterion according to DNVGL-RP-C205

Out:
- Upper bound natural frequency where vortex shedding may occur $\mathbf{f_{imax}}$

LOCAL MODEL

In:
- Mooring group geometry
- Mooring line characteristics

Out:
- Eigenmode shapes and corresponding frequencies
- Number of peaks for mode shape with $\mathbf{f_{imax}}$

MODE SHAPE EVALUATION

In:
- Output from local model
- Mooring line length and fibre rope diameter
- Sine curve properties

Out:
- Arc length of mode shape with f_{imax} and response amplitude 0.9D

DAMAGE CALCULATION

In:
- Arc length from mode shape evaluation
- Mooring line properties
- Fatigue properties

Out:
- Tension range due to change in length at eigenmode with $\mathbf{f_{imax}}$
- Damage calculation for tension range

Cross flow screening

For cross flow screening the criterion for cross flow VIV response model from Ref. [19] is used. Cross flow vortex shedding excitation may occur when:

$$3 \leq V_R \leq 16$$

$$V_R = \frac{u}{f_i * D}$$

With:

V_R	=	Reduced velocity
u	=	instantaneous flow velocity normal to member axis (m/s)
f_i	=	the i'th natural frequency of the member (Hz)
D	=	Fibre rope diameter (m)

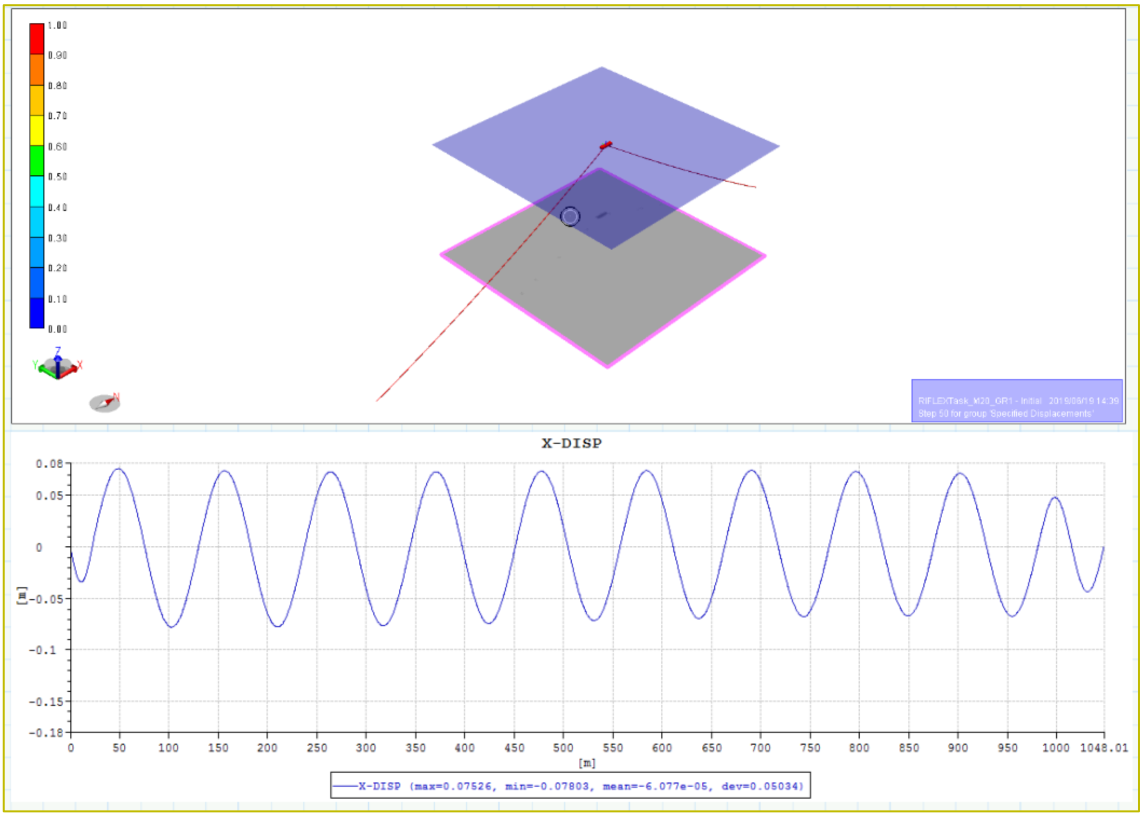
The upper bound natural frequency where vortex shedding may occur is calculated by lower boundary of the cross flow criterion (3) and high current.

$$f_{imax} = \frac{u_{max}}{3 * D}$$

Current flow velocity u_{max} is taken from [18]. Current for 10 year return period is chosen to be sufficient for this assessment. The current is not uniform over water depth and along mooring line. Assuming that the maximum flow on the water surface acts along the entire mooring line is far too conservative and not realistic for this simplified assessment. The average current between water depth 10m and 100m is thus used.

Eigenmode calculation on local model

The local model as described in section 10 is utilised to calculated eigenmodes and corresponding natural frequencies. Figure 11-15 shows a typical geometry analysed with the local analysis model in Riflex and an eigenmode plot for natural frequency f_i. Number of sine waves and peaks (i) can be counted on this plot.



> *Figure 11-15 Typical geometry and eigenmode plot from local Reflex model*

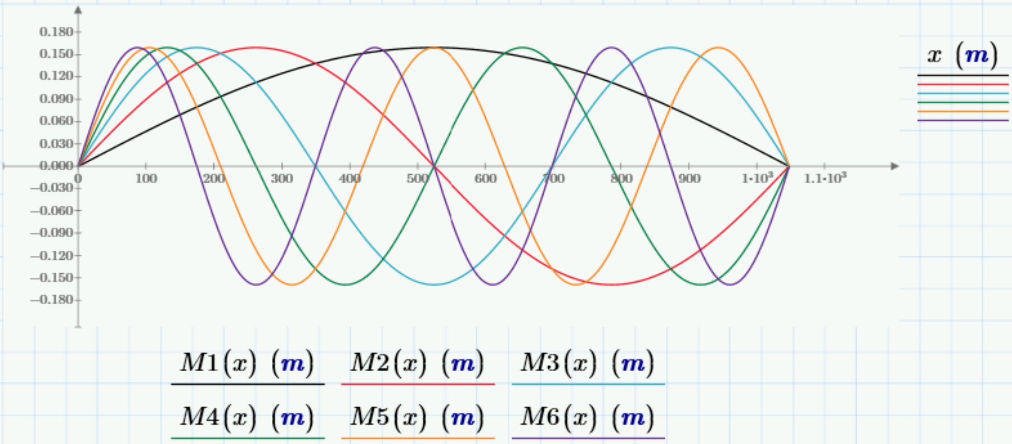
Mode shape evaluation

Mode shapes are assessed to determine the change in mooring line length when eigenmodes are excited. Change in length shall be used to calculate tension range.

The mode shape is approximated by sinus waves to represent the mode shape. This simplification is deemed to be conservative if the number of "waves" along the mooring line is captured. Based on the typical mode shape in Figure 11-15 it is observed that the actual amplitude is reduced at the chain segments thus reducing the actual elongation of the mooring line which is not accounted for in the simplified approach. Typical mode shape estimates and the arc length formula is shown in Figure 11-16. Maximum response amplitude of 0.9*D_{fr} is used according to Ref. [6].

$$M1(x) := \sin\left(\frac{\pi \cdot x}{L_{tot}}\right) \cdot 0.9\ D_{fr} \qquad M4(x) := \sin\left(\frac{4\ \pi \cdot x}{L_{tot}}\right) \cdot 0.9\ D_{fr} \qquad M5(x) := \sin\left(\frac{5\ \pi \cdot x}{L_{tot}}\right) \cdot 0.9\ D_{fr}$$

$$M2(x) := \sin\left(\frac{2\ \pi \cdot x}{L_{tot}}\right) \cdot 0.9\ D_{fr} \qquad M3(x) := \sin\left(\frac{3\ \pi \cdot x}{L_{tot}}\right) \cdot 0.9\ D_{fr} \qquad M6(x) := \sin\left(\frac{6\ \pi \cdot x}{L_{tot}}\right) \cdot 0.9\ D_{fr}$$



Length of line in modeshape i

$$l(i) := \int_0^{L_{tot}} \sqrt{1 + \left(0.9\ D_{fr} \cdot \frac{i\ \pi}{L_{tot}}\right)^2 \cdot \cos\left(\frac{i\ \pi \cdot x}{L_{tot}}\right)^2}\ \mathrm{d}x$$

Delta in length for modeshape i

$$\Delta L(i) := l(i) - L_{tot}$$

> *Figure 11-16 Mode shape evaluation and arc length calculation*

Damage calculation
damage calculation is based on the same method as describe for tension-tension fatigue.

11.3 Results low cycle fatigue - Tension-Tension and IPB/OPB

11.3.1 General

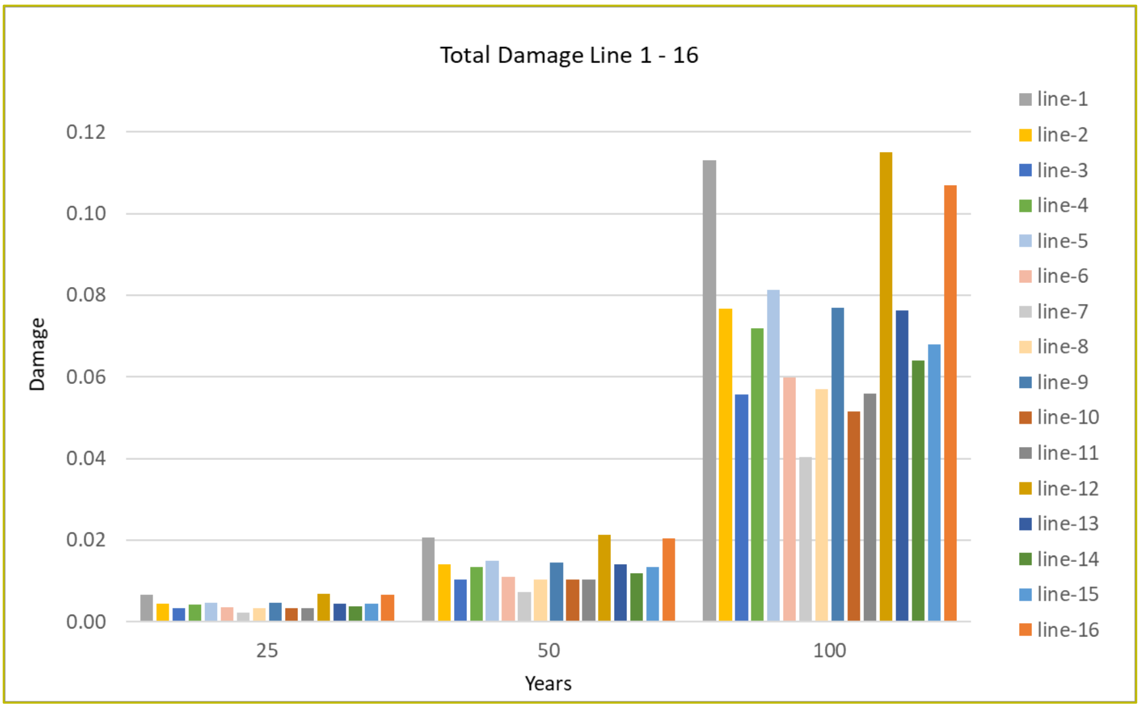
Results for low cycle Tension-Tension (T-T) fatigue as well as IPB/OPB are summarized in the subsequent section. Supplementary result plots per line reference is provided in Appendix A.

11.3.2 T-T top chain – segment 1

Results for pure tension-tension fatigue are summarised in Table 11-4 and Figure 11-17. Damage is presented for 25, 50 and 100 years and is well below 1 for all lines at calculated lifetimes. The combined damage due to T-T and IPB/OPB at fairlead is given in Section 11.3.2.

Line ID	Damage (incl. DFF)		
	25 years	50 years	100 years
01	6.63E-03	2.08E-02	1.13E-01
02	4.50E-03	1.41E-02	7.68E-02
03	3.32E-03	1.04E-02	5.57E-02
04	4.29E-03	1.34E-02	7.18E-02
05	4.78E-03	1.50E-02	8.14E-02
06	3.51E-03	1.10E-02	5.98E-02
07	2.36E-03	7.40E-03	4.04E-02
08	3.34E-03	1.05E-02	5.70E-02
09	4.63E-03	1.44E-02	7.70E-02
10	3.38E-03	1.03E-02	5.16E-02
11	3.35E-03	1.04E-02	5.58E-02
12	6.81E-03	2.13E-02	1.15E-01
13	4.52E-03	1.41E-02	7.63E-02
14	3.79E-03	1.18E-02	6.40E-02
15	4.39E-03	1.35E-02	6.80E-02
16	6.61E-03	2.05E-02	1.07E-01
Max	**6.81E-03**	**2.13E-02**	**1.15E-01**

> *Table 11-4 Pure T-T fatigue damage, top chain TT*



> *Figure 11-17 Fatigue damage, top chain TT*

11.3.3 IPB/OPB top chain segment 2

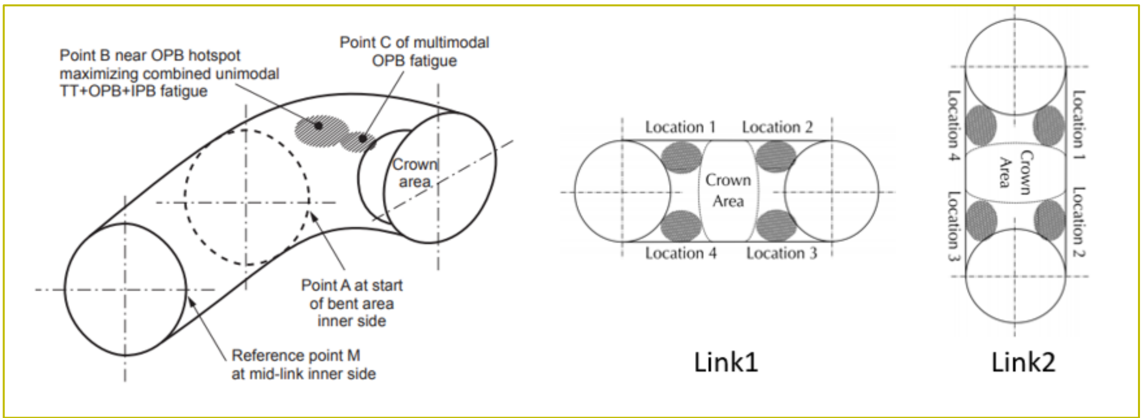
Results for in-plane and out-plane fatigue combined with tension-tension fatigue are summarised in Table 11-5. Damage is presented for 25years and the four different SCF locations (see Figure 11-18). Damage is below 1.0 for all SCF locations for 25years of design life.

The maximum damage is found for SCF case C ref. Table 11-5. Figure 11-19 presents results for case C. The x axis in this figure presents the four locations of link 1 and 2 with link2 being 90deg rotated in regard to link 1 (see also Figure 11-18).

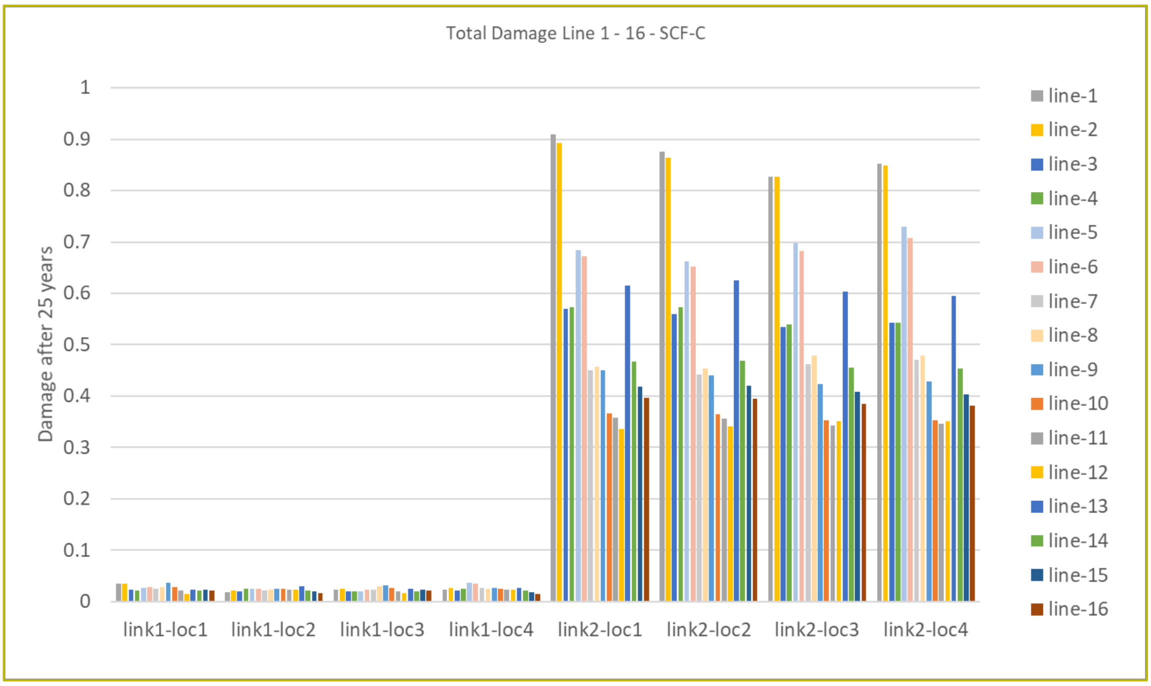
Line ID	Damage - 25year-(incl. DFF) Maximum of location 1-4 and link 1 and 2			
	SCF hotspot A	SCF hotspot B	SCF hotspot B'	SCF hotspot C
01	3.72E-02	0.68	0.85	0.91
02	2.88E-02	0.67	0.83	0.89
03	1.69E-02	0.43	0.53	0.57
04	2.41E-02	0.43	0.54	0.57
05	3.46E-02	0.55	0.68	0.73
06	2.75E-02	0.53	0.66	0.71
07	1.63E-02	0.35	0.44	0.47
08	2.61E-02	0.36	0.45	0.48
09	3.73E-02	0.34	0.42	0.45
10	2.34E-02	0.27	0.34	0.37
11	2.12E-02	0.27	0.34	0.36
12	3.34E-02	0.27	0.33	0.35

13	2.86E-02	0.47	0.58	0.63
14	1.83E-02	0.35	0.44	0.47
15	2.38E-02	0.31	0.39	0.42
16	3.21E-02	0.30	0.37	0.40
Max	**0.04**	**0.68**	**0.85**	**0.91**

> *Table 11-5 Fatigue damage, top chain IPB/OPB*



> *Figure 11-18 SCF and failure locations*



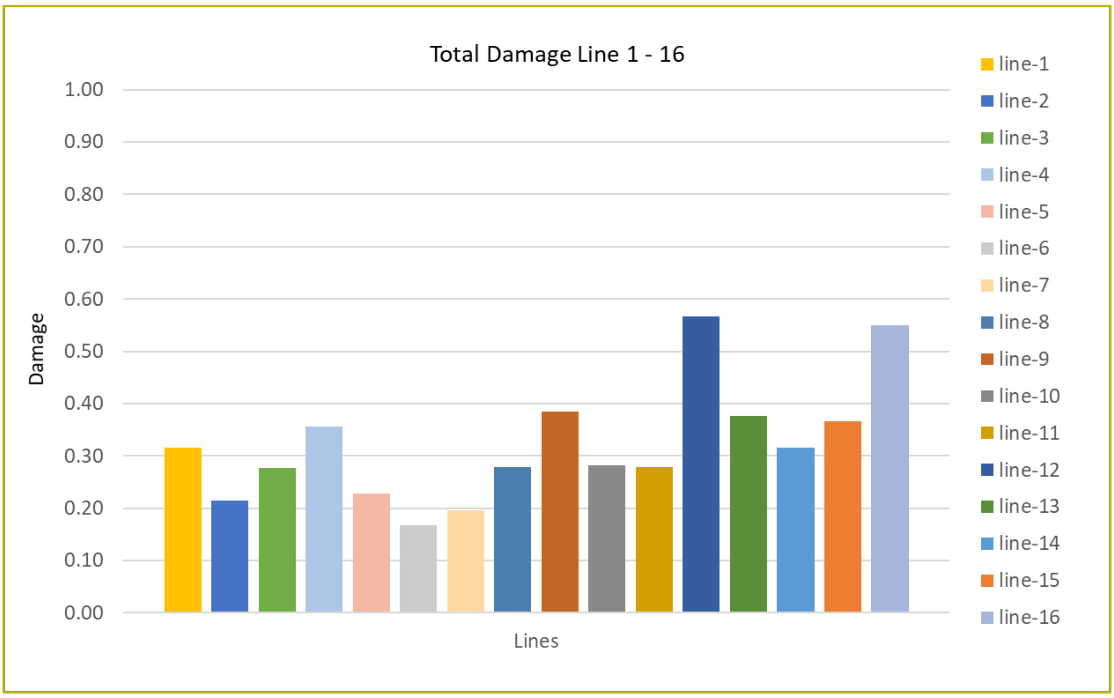
> *Figure 11-19 Fatigue damage, top chain IPB/OPB – SCF hotspot C*

11.3.4 T-T bottom chain

Results for tension-tension fatigue of the bottom chain are summarised in Table 11-6 and Figure 11-20. Damage is presented for 100 years and is well below 1 for all lines.

Line ID	Damage (incl. DFF) 100 years
01	0.32
02	0.21
03	0.28
04	0.36
05	0.23
06	0.17
07	0.20
08	0.28
09	0.39
10	0.28
11	0.28
12	0.57
13	0.38
14	0.32
15	0.37
16	0.55
Max	**0.57**

> *Table 11-6 Fatigue damage, bottom chain TT*



> *Figure 11-20 Fatigue damage, bottom chain TT*

11.3.5 T-T fibre rope

Results for tension-tension fatigue are summarised in Table 11-7 and Damage is presented for 100 years and is negligible for all cases. The low damage is as expected given the fact that polyester ropes has excellent fatigue properties.

Line ID	Damage (incl. DFF) 100 years
01	5.46E-15
02	2.34E-15
03	8.01E-17
04	5.17E-16
05	3.16E-16
06	2.27E-16
07	6.36E-17
08	7.53E-16
09	2.76E-16
10	5.11E-16
11	4.86E-14
12	3.84E-12
13	3.81E-14
14	3.18E-14
15	7.96E-15
16	2.54E-14
Max	**0.00**

> *Table 11-7 Fatigue damage, fibre rope TT*

11.4 Results high cycle fatigue VIV

For detailed calculations and results of the VIV assessment see Appendix C

Table 11-8 presents VIV damage for fibre rope and it is thus concluded that VIV is not critical for the fibre ropes. The fatigue damage due to VIV for the bottom chain is given in Table 11-9.

Component	**Damage (incl. DFF) 100 years**
Fibre rope	5E-30

> *Table 11-8 VIV damage fibre rope*

Table 11-9 presents VIV damage for bottom chain. Damage from VIV isolated is not critical.

Component	**Damage (incl. DFF) 100 years**
Bottom chain	0.022

> *Table 11-9 VIV damage fibre bottom chain*

For bottom chain the combination of fatigue damage from two dynamic processes is checked according to DNVGL-RP-C203, Ref. [7] based on the following formula:

$$D = D_1 * \left(1 - \frac{v_1}{v_2}\right) + v_2 * \left[\left(\frac{D_1}{v_1}\right)^{\frac{1}{m}} + \left(\frac{D_2}{v_2}\right)^{\frac{1}{m}}\right]^m$$

With

D1	=	calculated fatigue damage for high frequency response
D2	=	calculated fatigue damage for low frequency response
v1	=	mean zero up-crossing frequency for high frequency response
v2	=	mean zero up-crossing frequency for low frequency response
m	=	inverse slope of the S-N curve = 3.0

Table 11-10 presents the design life for bottom chain for combined fatigue damage from two dynamic processes. Design life is above 100 years.

Component	**Design life for combined fatigue (low cycle and high cycle)**
Bottom chain	>100 years

> *Table 11-10 Design life from combined fatigue in bottom chain*

The top chain has larger dimension and damage contribution from VIV will be very low. In addition, design life for the top chain is only 25 years due to IPB/OPB. VIV contribution on top chain is considered not to be critical.

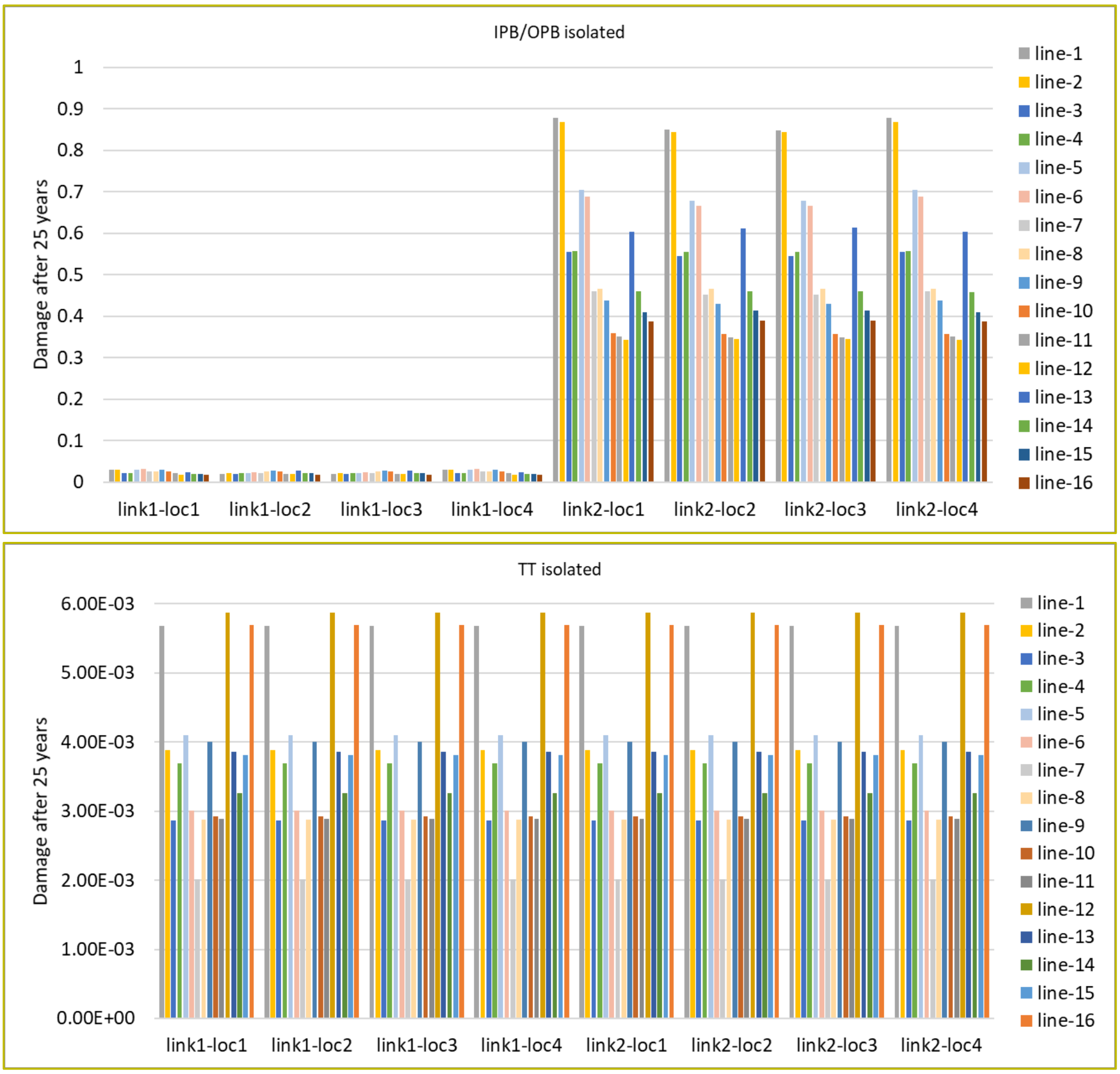
11.5 Sensitivities

11.5.1 General

Sensitivities are carried out to study driving failure modes and assure robustness.

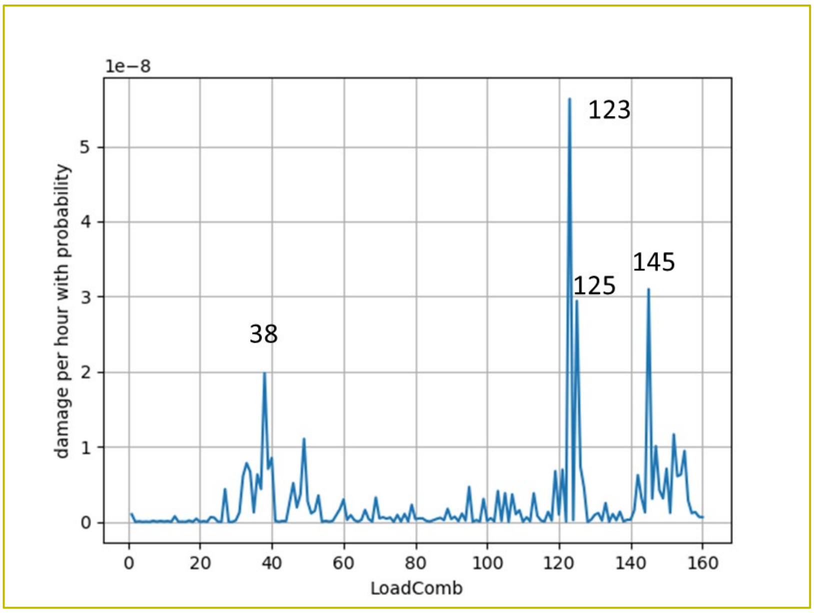
11.5.2 IPB-OPB isolated and TT isolated

Results from top chain segment 1 (TT, ref. Figure 11-17), and segment 2 (TT combined with IPB/OPB, ref. Figure 11-19) indicate that bending is the driving failure mode for the top chain. However, fatigue analyses for segment 1 and 2 are based on different design standards and have different input such as corrosion allowance. An additional sensitivity takes the IPB/OPB model for segment 2 and isolates both failure modes tension-tension and bending. The results are presented in Figure 11-21. The results confirm that bending at fairlead is the driving failure mode for the top chain segment 2.

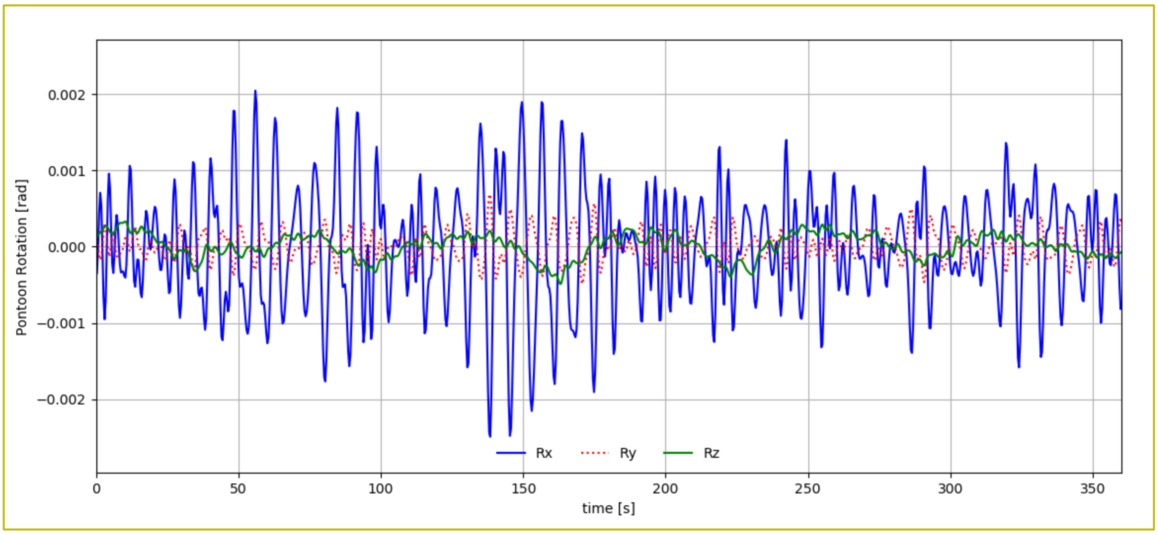


> *Figure 11-21 Damage IPB/OPB isolated – TT isolated*

As it is obeserved that bending is the driving failure mode it is also investigated which global movement (rotation) is driving for this failure mode. The plot in Figure 11-22 shows damage per hour with probability. There are a few load combinations that have a significant contribution to the total damage. Load combination 123 is selected to extract pontoon rotations in global directions, see Figure 11-23. Rotation Rx (rotation about global x-axis) is governing. It is advised to evaluate the load case matrix for the mooring design to refine the matrix for the critical load cases.



> *Figure 11-22 Damage IPB/OPB for 160 load combinations (/hour, with probability)*



> *Figure 11-23 Pontoon rotation (3DOF's), LoadComb 123*

11.5.3 Effect of pretension

Sensitivity on pretension has been carried out for IPB/OPB of the top chain at fairlead and SCF case C (Ref. Table 2-8). SCF case C is selected as it was found to be critical with respect to OPB/IPB above. Pretension has been increased with 5% and 10%. The Sensitivity results for pretension are shown in Figure 11-24.
The damage increases quite significantly with the variation in pre-tension implying the installation method need to limit the deviation in achieved pre-tension.

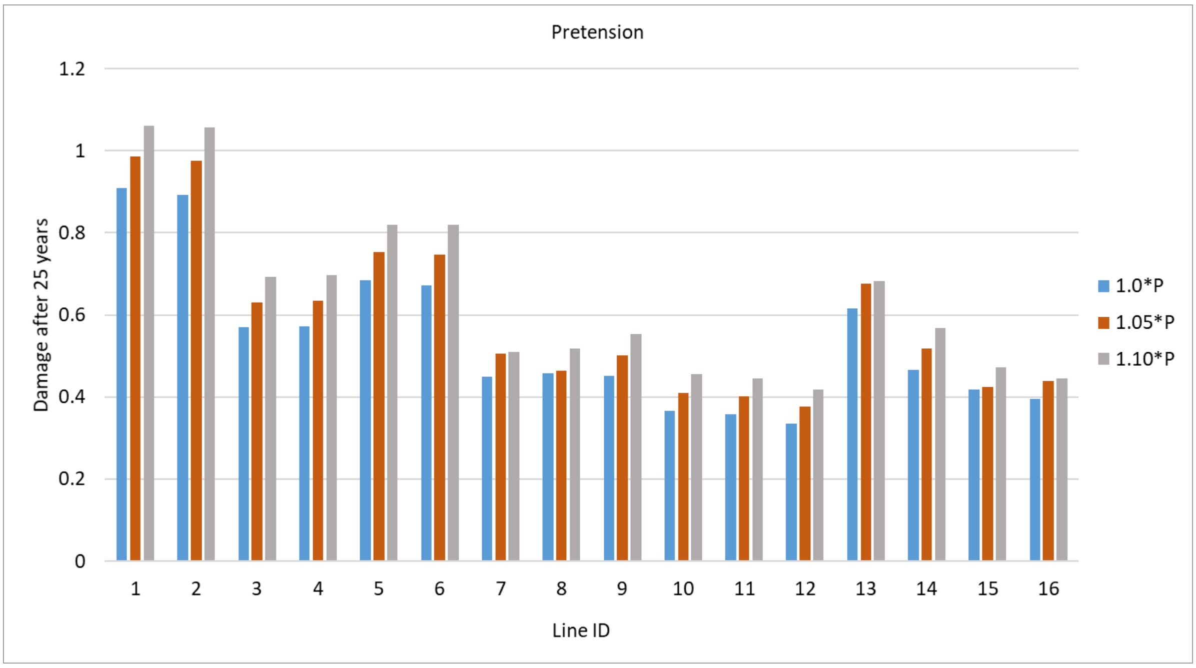


Figure 11-24 Sensitivity Pretension

12 ANCHOR DESIGN

Simplified anchor design has been performed to verify sufficient structural capacity of the anchors. The global dimensions are determined in Marine geotechnical design, ref. [20].

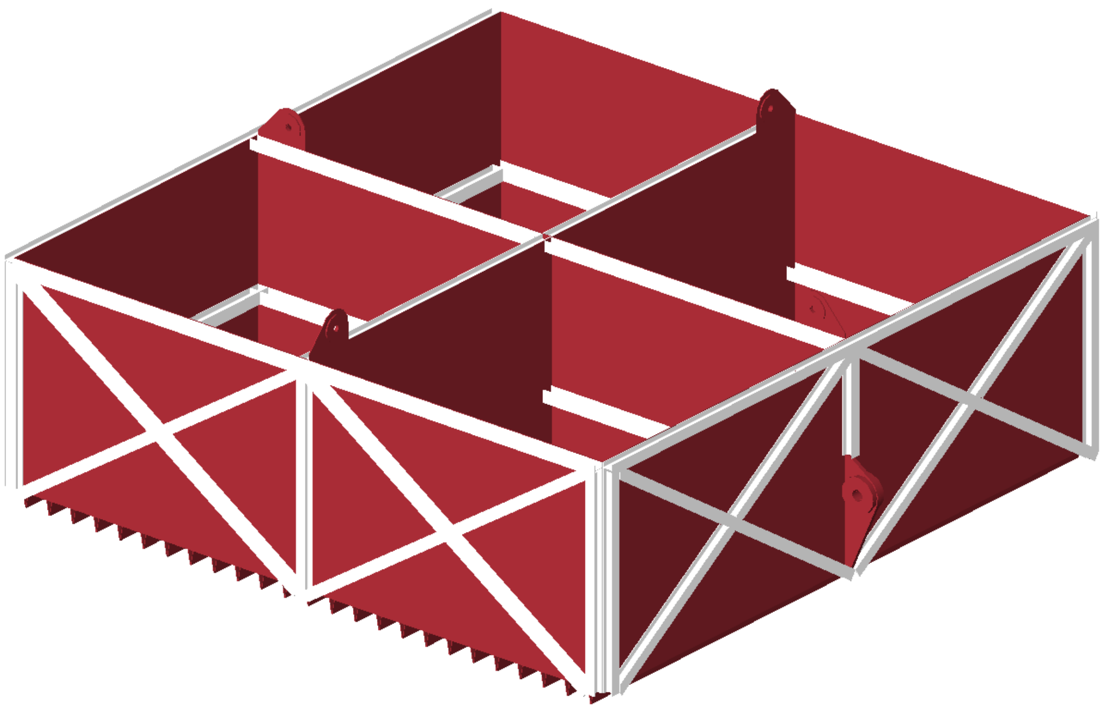
12.1 Gravity anchor

The gravity anchor is proposed to be constructed of steel and afterwards filled with olivine after installation. The geometry is B x L = 15 x 15 m and the height is 5.3 m, where the skirts are 0.3 m long. Plates and diagonal stiffeners are introduced to ensure that the forces acting on the padlock is uniformly distributed across the anchor. Horizontal stiffeners are also included to take care of the bending moments caused by earth-pressure.

It's assumed that the gravity anchor is placed on prepared crushed rock or gravel. The ribs are v-shaped and consists of two plates welded. The ribs are oriented transversally to the mooring load for maximum efficiency and a c/c of 600 mm is proposed.

The total weight of the anchor is estimated to be roughly 160 ton and has a volume space of 1125 m^3. Rough calculations of anchor design given in Appendix F. It is also proposed for the current anchor design to paint and use galvanic anode to avoid corrosion and thereby ensuring 100 years of life service.

Not detail calculation of hydrodynamic loads during installation nor detailed calculation of the padlock and hinges is performed. However, based on calculations from the last phase by Multiconsult, ref. [21], it's assumed sufficient capacity is achieved with the same dimensions for the hinges and padlocks. Furthermore, the hydrodynamic load is assumed to be lower since the anchor size is smaller.



> *Figure 12-1 Illustration of gravity anchor type used in calculations.*

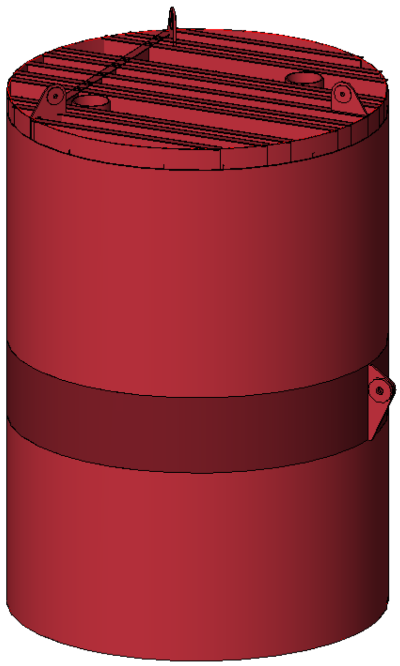
12.2 Suction anchor

A single cylindrical shell with a flat top cap, as suggested in the last phase by Multiconsult, ref. [22], is considered in the current anchor configuration. The global dimensions are determined from marine geotechnical calculations and are summarized in Table 12-1. Reinforced plate with an inner stiffener is introduced to ensure evenly distribution of the load from padlock, as shown in Figure 12-2. The reinforced plate also acts as a ring stiffener and thereby reducing the risk of ovalization of the anchor.

> *Table 12-1 Summary of anchor dimensions and total weight used in marine geotechnical calculations, ref. [20].*

Anchors	Diameter	Length	Tolerance	Total skirt length	Assumed weight, W
[#]	[m]	[m]	[m]	[m]	[kN]
1, 2, 3, 4, 5, 6	9	11.5	1	12.5	2254
13, 14	9	10	1	11	2054

The plate thickness is determined from the weight necessity required in geotechnical calculations. However, this is recommended to be optimized at a later stage to ensure more cost-efficient design. A plate thickness of 50 mm is assumed in the calculations, with reinforced plate and inner stiffener with 70 mm thickness which 2.5 m high. It is also proposed for the current anchor design to paint and use galvanic anode to avoid corrosion and thereby ensuring 100 years of life service.

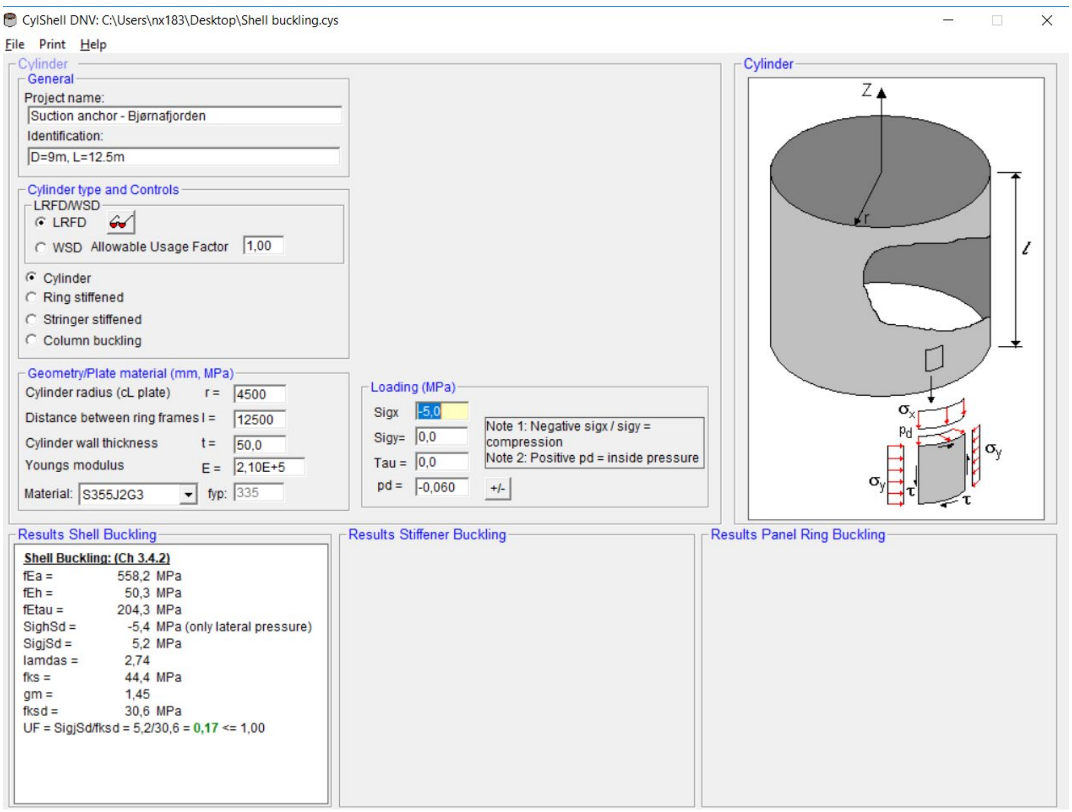


> *Figure 12-2 Illustration of suction anchor type used in calculations.*

> *Table 12-2 Summary of penetration calculations results.*

Parameter	Anchors 1-6	Anchors 13 & 14
Weight, W’	1967 kN	1792 kN
Penetration from self-weight (design resistance)	6.17 m	5.87 m
Skirt length	12.5 m	11 m
Q_{tip}	523.9 kN	472 kN
Q_{tot}	4452 kN	3598 kN
Δu_n	-39 kPa	-29 kPa
Q_d	5788 kN	4677 kN
$Q_{d,tip}$	681 kN	614 kN
Δu_d	-60 kPa	-46 kPa

Penetration calculation is calculated according to DNV standards. Detailed calculations are given in marine geotechnical calculations, ref. [20]. Simplified calculation is performed for the anchors with largest suction using CylShell DNV. It’s assumed that the length between the ring frames is 12.5 m and that the soil gives no support. Furthermore, 5 MPa contact pressure is included to account for possible impact load, ex. boulders. It can be seen from the calculations that the suction anchor has sufficient structural capacity and can thus be further optimized to achieve a more cost-efficient design.



> *Figure 12-3 Structural capacity of suction anchor.*

13 INSTALLATION

The installation of the mooring system will be based on conventional technology. The overall installation is further detailed in the report on Execution of construction [23]. The actual installation of each mooring line will be performed at the top of the column using a linear chain tensioner. The liner chain tensioner will temporarily be installed on a suitable support structure on top of the pontoon. A chain stopper will be installed at the top of the column to secure the mooring chain when the correct pre-tension is achieved.

The pontoon has a moonpool for guiding of the mooring to the top of the pontoon deck as described further in Section 5.3. This ensures that a very limited moment is transferred to the column and bridge girder and protects the mooring system from possible ship impact. A fairlead located at the bottom of the moonpool will be utilized to ensure the correct angle of the mooring lines and to limit wear of the chain when bended. The fairlead will also be utilized during the installation to guide the mooring chain.

Based on the sensitivity performed for the effect of pre-tension on IPB/OPB fatigue it is necessary to ensure limited variation in actual installed pre-tension. A chain stopper will typically be developed for a given mooring line local orientation, meaning that every other link can be locked. This implies a possible change in line length of 2 mooring link lengths. This should be accounted for during installation. The actual configuration can be verified by use of catenary equation estimates of as installed lengths in addition to tension measurements. The final procedure needs to be detailed at a later stage.

Monitoring of the mooring system will be relevant both in terms of ensuring the correct restoring and pre-tension over the life time of the system as well as the initial configuration. It could also be possible to monitor fatigue loads in the mooring system if relevant. Monitoring pre-tension and overall stiffness might require a different system than monitoring of fatigue loads.

In order to reduce the effect of bedding-in during operation the fibre rope should be stretched prior to installation. This could be done during the installation of the fibre rope it is preinstalled together with the anchor and bottom chain. The installation vessel can then be utilized to stretch the fibre rope and thus significantly reducing the expected elongation. For positions with suction anchors the bottom chain should anyway be pulled by the installation vessel to reduce the effect of inverse catenary for the buried chain. The fibre ropes can alternatively be stretched at the fabrication facility or at quay side for instance utilizing an installation vessel if they are not pre-installed. The produced length of the fibre ropes shall be adjusted to match the target length of the fibre rope after bedding-in. Minor differences in length after bedding-in can be adjusted by the cutting the top chain during installation.

14 FURTHER WORK

A few items for further work have been highlighted. More items can be relevant, but the following has initially been identified:

- *Global analysis with mooring lines modelled including chain and fibre ropes.* This will ensure that the mooring system can be directly designed with the global model.
- *Improved fibre rope model (Syrope model).* The modelling of fibre ropes can be improved to include the effects highlighted in the paper by Falkenberg, Ref [14]. This could improve the accuracy of the analysis, but further verify the assumptions used in the current work.
- *Reduction in pretension levels.* Based on the local analysis and review of the methodology for design of mooring system it could be possible to reduce the level of pretension for the mooring system. This could reduce the costs slightly and reduce OPB/IPB damage.
- *Refined fatigue analysis based on FLS matrix specifically developed for mooring fatigue.* The FLS matrix used for design of the mooring system is not specifically developed for design of the mooring system. It is advised to develop an additional FLS matrix specifically for design of mooring system. The target should be to limit the damage per FLS case to approximately 5-10% of the total damage.
- *Further design and analysis for OPB/IPB.* To reduce the damage due to OPB/IPB it can be possible to perform more refined analysis and evaluations as well as exploring alternative design solutions that can reduce the local bending of the chains at the fairlead.
- *Alternative fairlead solutions.* There are other fairlead configurations that can be relevant. It can for instance be relevant to evaluate the use of a fairlead chain stopper either on the pontoon hull or possibly inside the moonpool.
- *Improved specification of components.* For further development of the mooring system it is advised, together with the suppliers, to identify and specify the requirements for different subcomponents of the system. This could for instance be the fibre rope, connectors and chain stopper.
- *More line failure cases*. It is advised to run more line failure cases for the next phase in order to ensure that the most critical line failure case has been identified. It will also be relevant to run transient simulations of line failure.
- *Detailed structural design of anchors*. Rough calculations have been performed both for gravity and suction anchor, thus more detailed calculations including fatigue is necessary. It's also recommended to optimize the anchors with respect to capacity and cost.

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