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MASTER’S THESIS

Aquaculture fish farm and large service vessel interaction

Mooring analysis, vessel response and operational evaluation of aquaculture operations

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Abstract

In this master`s thesis a modelling of a floating aquaculture facility and delousing vessel has been carried out using the state-of-the-art analysis software AquaSim, by Aquastructures. Of these models, various analyses have been performed. The purpose of the master`s thesis is to investigate the potential impact a moored service has on the modelled aquaculture fish farm mooring system and how we can use the results from modern analysis software to execute a weather availability and weather window analysis and a risk assessment. The procedure for answering the predetermined research questions was to predefine some cases. The first case includes a static analysis of the system. The second, third and fourth case includes a mooring analysis with and without a moored vessel, and when the two most utilized mooring elements is assumed broken. The results from case 2 and case 3 shows that by mooring a large service vessel alongside the floater with the most utilized mooring lines there is an increase in the axial force in mooring line 15 to mooring line 18, and the bridle ropes and grid ropes connected to the floater named M4 and the buoy strap belonging to buoy A5. The ropes with the greatest increase in axial force were identified as the buoy strap, bridle rope and mooring line 18. The difference in axial force of the two cases shows an increase 14% in the bridle rope, 14% in the grid rope and 7% in mooring line 18.

The fourth case involved looking at the impact of failure in the most utilized mooring lines has on nearby mooring ropes. The most utilized and the ones found critical to the aquaculture fish farm were identified as mooring line 18 and grid rope A4-A5. For the first analysis we looked at what the impact were when mooring line 18 went to failure. When mooring line 18 went to failure the result showed that the load this line carried were allocated amongst the bridle rope, mooring lines, grid rope and the increase in axial force in these ropes where 45%, 13%, 58% and 47% respectively. Grid rope and buoy strap was relived due to the breakage and experienced a decrease in axial force of -24% and -9%.

When grid rope A4-A5 went to failure the results show a significant increase in axial force in the hen foot located underneath the service vessel. The axial force in the hen foot experienced an increase of 146%. Mooring line 17, 18 and attached anchor chain experienced a decrease in axial force along with buoy strap A5. The mentioned moorings decreased by 5%-8%. The results also show that the mooring lines attached to the other three floater did not experience any increase in axial force worth mentioning.

Based on the results from case 2, case 3 and case 4 it was concluded that, although overall minor increase in axial force in the mooring system belonging to floater 4, a mooring analysis should include an evaluation of the impact a large service vessel has on the mooring system.

In addition to the analysis of the degree of utilization of the mooring lines with and without a moored service vessel present, several hydrodynamical analysis were executed. The hydrodynamical analysis investigated the motions of the service vessel when exposed to irregular waves. The RMS values for lateral- and vertical acceleration and roll and pitch calculated of the service vessel hull is compared to the established NORDFORSK, 1987 values (Appendix C). The analysis shows that when the vessel was influenced by a sea state consisting of significant wave heights of 2.0 meters, corresponding wave period of 7.0 seconds and a wave direction of 89°, the limiting factor was lateral acceleration in x-direction. When the vessel was exposed to waves heading from 135°, significant wave height equal 2.0 meter and corresponding wave period of 9.0 seconds the limiting factor was also lateral acceleration in x direction. There were no sea states which led to an exceedance of the RMS in roll in the vessel from these directions, and therefore one final analysis was executed with irregular waves progressing from 175°, significant wave height 2.4 meters and wave period equal to 5.5 seconds which led to roll motion exceeding the recommended RMS values for a safe and effective work environment. From these results three operational limiting sea states criteria where established and used in the next scope of the thesis which includes a weather availability analysis and a weather window analysis. These analyses were performed using the alpha factor method and weather criteria and availability analysis often used in the oil and gas, and offshore wind industry The thesis ends with a risk assessment of a large service vessel during a delousing operation where probability, consequence and risk acceptance criteria are established based on the findings in the thesis.

Sammendrag

I denne masteroppgaven er det blitt gjennomført en modellering av et flytende havbruksanlegg og et avlusningsfartøy. Av disse modellene er det deretter gjennomført ulike analyser av og rundt. Formålet med master prosjektet er å undersøke hvilket utfall en fortøyd brønnbåt vil ha på det eksisterende fortøyningsarrangementet til det modellerte havbruksanlegget. Fremgangsmåten for å finne svar på de forhåndsbestemte problemstillingene var å først å kjøre en fortøyningsanalyse på det modellerte anlegget uten et fortøyd fartøy, for deretter å kjøre samme analyse med et fartøy fortøyd til den merden med de mest utsatte fortøyningskomponentene i systemet. Noen forhåndsbestemte situasjoner ble opprettet og fra analysekjøring 2 og 3 viste resultatet at ved å fortøye en brønnbåt langs den merden med de mest utnyttede fortøyningslinene var det en forhøyning i aksialkreftene i fortøyningsline 15 til 18, haneføtter rundt merd 4, rammetau rundt merd 4 og bøyestropp A5. De komponentene med den største økningen i aksialkraft var bøyestropp og hanefot. I forhold til fortøynings analysen med og uten en fortøyd brønnbåt viser resultatet en økning på henholdsvis 14% og 16%. Fortøyningslinene i nærheten av bøyestropp og hanefot opplevde en økning på 7%.

Etterfulgt av analysekjøring 2 og 3 ble de gjennomført en analyse hvor vi undersøkte utfallet når de mest utnyttede fortøyningsliene identifisert gikk til brudd. De mest utnyttede linene som i tillegg er vurdert som mest kritisk for eksisterende fortøyningssystem ble identifisert som ankerline 18 og rammetau A4-A5. Vi undersøkte først brudd i line 18. Ved brudd i line 18 viser resultatet at lasten som line 18 opprinnelig holdt ble fordelt mellom haneføtter, ankeliner, rammetau og bøyestropp. Hanefot, ankerline 15, ankeline 16, ankerline 17 og ankerkjetting fikk en økning i aksialkraft på hhv. 45%, 13%, 14%, 58% og 47%. Rammetau A4-A5 og bøyestropp fikk en nedgang og ble avlastet på bakgrunn av bruddet. Nedgangen i aksial kraft ble beregnet til hhv. -24% og -9%.

Ved brudd i rammetau A4-A5 var det en stor økning i aksialkraft i hanefoten lokalisert under brønnbåten. Økningen i aksialkraften sammenlignet med intakt tilstand er beregnet til 146%. foruten denne økningen viser resultantene at ankeline 17, ankerline 18, ankerkjetting og bøyestropp A5 får en nedgang i aksialkraft som følge av bruddet. Det er foruten hanefot, fortøyningsline 15 og 16 som opplever en økning i aksialkraft. Disse økningene var på hhv. 8% og 5%. Fortøyningskomponenter koblet til de tre andre merdene viser seg å ikke være bemerkes verdig påvirket av den fortøyde brønnbåten.

Som følge av analysekjøring 2, 3 og 4 konkluderes det med at selv om økningene i aksialkraft jevnt over er små, bør en akkreditert fortøyningsanalyse kunne dokumentere de ekstra kreftene en fortøyd brønnbåt vil utgjøre på fortøyningsarrangementet til anlegget. I tillegg til dokumentert holdekraft i intakt tilstand, bør også ulykkestilstander undersøkes, da denne viste en økning i hanefot som følge av brudd i utsatt line på 146%.

I tillegg til en analysering av utnyttelsesgrad i fortøyningskomponenter er det gjennomført flere hydrodynamiske analyser av det modellerte service fartøyet under ulike sjøtilstander og bølgeretninger. For a vurdere bevegelsene i den modellerte brønnbåten er RMS verdiene for lateral og vertikal akselerasjon samt rotasjon om rull og trim akse hentet ut for hvert steg i analysen og beregnet. Disse RMS-verdiene er deretter sammenlignet med RMS verdiene fastsatt av NORDFORSK, 1987. Analysen viser at når fartøyet er utsatt for en sjøtilstand med en signifikant bølgehøyde på 2.0 meter, en bølgeperiode på 7.0 sekunder og en bølgeretning 89° er den begrensede faktoren lateral akselerasjon i x retning. Når fartøyet opplever bølger fra 135° er den begrensende faktoren også lateral akselerasjon i x retning, dog nå noe lengre bølgeperiode. Den utslagsgivende bølgehøyden og bølgeperioden var her 2.0 meter og 9.0 sekunder. For begge bølgeretningene ble det påvist at lateral akselerasjon var den begrensende faktoren, og derfor ble det gjennomført en analyse der bølgeretningen treffer brønnbåtens side med en bølgehøyde på 2.4 meter, en bølgeperiode på 5.5 sekunder og en bølgeretning på 175°. i denne situasjonen overskred fartøyet den forhåndsbestemte RMS verdien for rull fra NORDFORSK, 1987.

De begrensende bølge parameterne ble så benyttet i en tilgjengelighets analyse, værvindu analyse og risikoanalyse. Det ble her konkludert med at det å benytte numerisk analyse og moderne analyse programmer for å fastsette operasjonelle grenseverdier er en god fremgangsmåte, men at det behøves mer detaljerte modeller av fartøyet og mer detaljert informasjon angående miljødata.

Acknowledgment

This thesis would not have been possible if it weren’t for my supporting girlfriend Oda Maria. Oda Maria has been taking care of our 6 months old baby girl while I have been working late nights writing my master`s thesis, and that’s why I would like to dedicate this paper to her.

I would also like to thank my mother, father, brothers, sisters in laws and friends who have been supporting and encouraging during the master`s program.

Preface

This thesis is the result of two years of studying and marks the ending semester of the master's degree in Maritime operations at the western Norway university of sciences in Haugesund/Emden-leer. After high school and a disappointing career as a football player, I sought work where I could find it. After a couple of years of holding down small position jobs, I decided to take a leap of faith and signed up for six months "Well technology" course. After examining from the course, I got a job as a Roustabout for the Norwegian drilling company "North Atlantic drilling Ltd." And it was here that the fascination for the maritime industry started. During the next four years I worked offshore on the semi-submersible drilling platform, west venture, and got my G5 offshore crane operator certification. When Statoil, now Equinor decided to tighten the spendings in the oil and gas industry I got laid off. But as we say:

"When one door closes, another one opens"

I then decided it was time to go back to school and signed up for a mathematics class which were necessary to apply for higher education. When all the relevant documentation was obtained, I applied for the bachelor`s degree in Marin technology at the Western Norway University of Sciences in Bergen. While studying to become a marine engineer, an interest within the Norwegian aquaculture industry started to arise. So, for my bachelor thesis, myself together with two of my friends and studying buddies decided to choose a subject for our bachelor thesis which included investigating the movements of an aquaculture feeding barge when stationed at exposed locations for the company Endur Sjøsterk AS.

After finishing the bachelor thesis, I started on this master program, and decided to continue to gain knowledge within the aquaculture industry. In addition to the full-time study, I have been working full time as a drift technician for Osland aquaculture AS. The past two years have been both challenging and rewarding.

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Abbreviations

Non-buoyant elements	Elements in the model which sinks under water
Axial force	Tensile force acting in the lengthwise direction of an object
Contingency time	Added time to cover any uncertainty in planned operation time
CSV	Comma separated values
MBL	Minimum breaking load
ULS	Ultimate limit state
ALS	Accidental limit state
RMS	Root mean square
DOF	Degrees of freedom
RQ	Research question
ML	Mooring line
PE	Polyethylene
SE	Southeast direction
N	North direction
SV	South vest direction
E	East direction
OPlim	Operational limiting criteria
CurrDirr	Current direction
Syst.H	System heading
Wave.H	Wave heading

Nomenclature

Symbol	Unit	Explanation
A_1 to A_5	-	*Connection points/grid corners (A side of fish farm)*
B_1 to B_5	-	*Connection points/grid corners (B side of fish farm)*
$A_i - B_i$	-	*Grid ropes going from A side to B side*
M_1 to M_4	-	*Floater 1 through 4*
U, U_A, U_{ref}	m/s	*Average, adjusted and reference wind speed*
T, T_Z, T_P	s	*Average, zero-up-crossing and peak wave period*
T_C, T_R, T_{POP}	s	*Contingency-, reference-, and planned operation time*
t	s	*Time*
ρ	Kg/m^3	*Fluid density*
g, a_x	m/s^2	*Gravitational, fluid acceleration*
u	m/s	*Fluid velocity*
V_c	m/s	*Current velocity*
H, H_z	m	*Wave height, significant wave height*
F_e, F_L, F_w	m	*Effective fetch length, fetch length, fetch width*
β	-	*Fetch length, fetch width ratio*
F_t	N	*Total force*
φ	-	*Velocity potential*
λ	m	*Wavelength*
ζ, ζ_o	m	*Surface elevation, wave amplitude*
$\propto_w, \propto_{w,0}$	-	*Wave slope, maximum wave slope*
c	m/s	*Wave speed*
h/λ	-	*Wave steepness*
ω	$2\pi/s$	*Angular velocity*
k	$2\pi/m$	*Wave number*
Δ	Kg	*Mass*
∇	m^3	*Submerged volume*
V	m^3	*Volume*
A_w	m^2	*Waterplane area*
$\overline{GM_t}, GM_l$	m	*Transvers, longitudinal metacentric height*
r_i	m	*Radius of gyration*
B_i, C_i, A_i	-	*Dampening, spring and added mass*
I_i	m^4	*Moment of inertia*
D	m	*Diameter*
C_D, C_m	-	*Drag, mass coefficients*
η_i	-	*Vessel motion*
γ_m, γ_l	-	*Material, load factor*
P	%	*Probability*

Chapter 1 Introduction and research questions

Delousing, delivery and loading of fish to and from an aquaculture farm requires assistance from large service vessels and barges. These vessels must be temporary moored to the framework of the aquaculture fish farm, and if necessary to the buoys prior to the operations in such a way that the vessels can counteract the environmental conditions that the vessels are being exposed to. In the revised NS9415:2021, required documentations concerning mooring analysis shall now include functional requirements whether a service vessel can be temporarily moored to the floaters [1].

An aquaculture fish farm can be divided into four main components: enclosure, floater, feed barge, and mooring system. The enclosure includes the net bag. The mooring system includes mooring lines, anchors, anchor chains, bridle ropes, grid ropes and buoys. The barge acts as food storage, office, and accommodation for the crew. The main components included in an aquaculture fish farm will be discussed in more detail later in the thesis.

Since the Norwegian Standard NS9415 was established, the number of fish escapes has decreased significantly, nevertheless there are still incidents leading to escaped salmonoids and according to directorate of fisheries in Norway the activity that is most represented in these incidents are delousing and delivery operations [2]. Therefore, the revised version of NS9415:2021 now recommends that the mooring system must be designed to accommodate large, moored service vessels, and the effects must be evaluated and documented. Based on this, the following research questions are formulated.

"To which extent will a large service vessel moored to one of the floaters impact the axial force in the elements used for station keeping of the aquaculture fish farm?"

"How will the load distribute amongst the mooring components if the most utilized mooring line should go to failure?"

"How will the moored service vessels behave when introduced to design wave heights and wave periods in the vicinity of the vessel natural periods?"

"How can we use state of the art hydrodynamical analysis software to define limiting operational criteria for vessel movements and use them in availability and weather window analysis?"

Chapter 2 Aquaculture fish farm design

Before modelling and mooring analysis of an aquaculture fish farm can start, the main components included in such a system will be introduced. As mentioned in the introduction, an aquaculture fish farm can be divided into four main components. These are, enclosure, floater, mooring system and feeding barge. The last main component mentioned is not included in the thesis and will therefore not be presented.

2.1 Enclosure

The enclosure`s objective is to prevent the fish from escaping and mixing with naturally born fishes. The net bag which acts as a containment for the fish comes in different shapes and sizes. The six most common nets are circle nets, squared nets, circle with coned base, coned nets, spaghetti nets, and circle w/sinker tube attached to net. The illustration below is obtained from the product catalogue of Mørenot Aquaculture As [3].

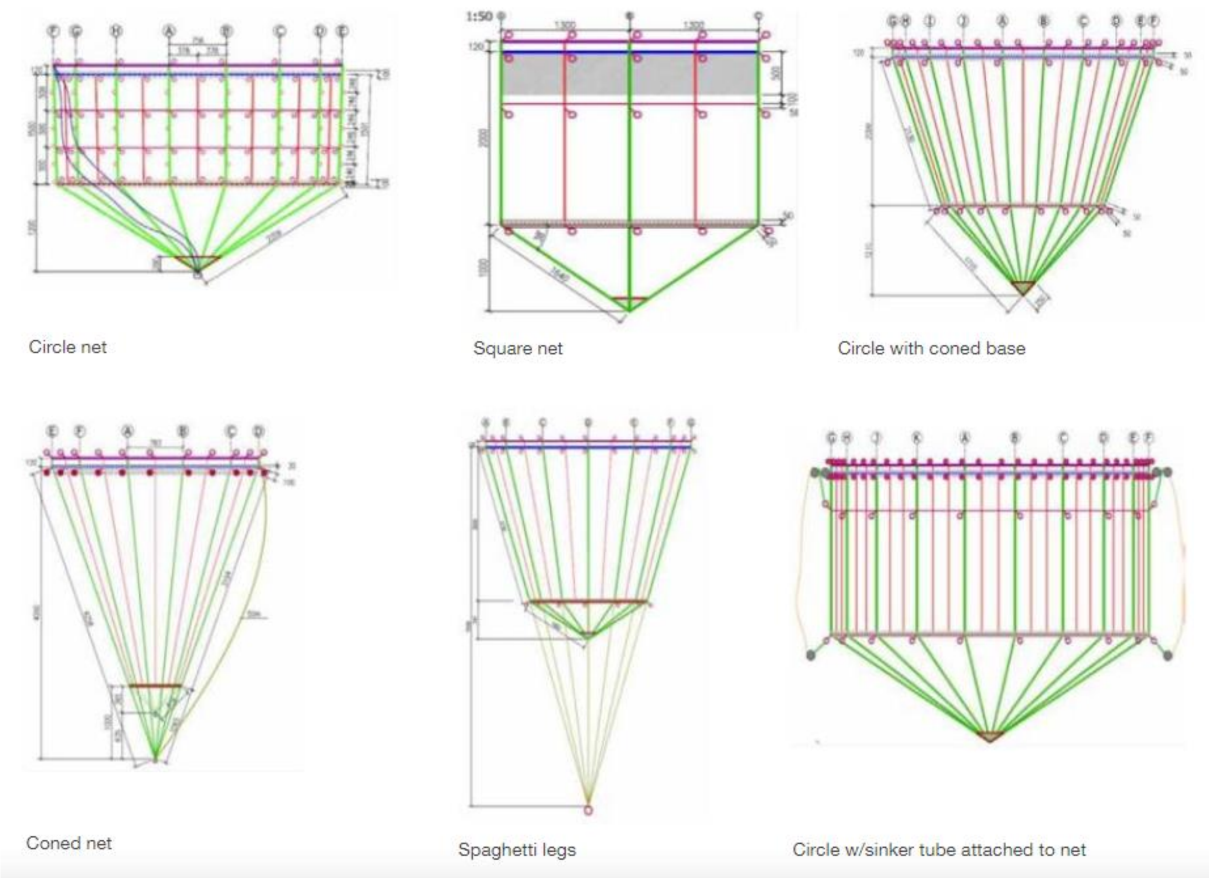

Figure 1 Six commonly used fish nets

The design used for this thesis is the spaghetti net design.

2.2 Floater

The floaters, also called the framework or floating collar has several functions. Its primary function is to support the cages in the water column, secondarily, provide buoyancy to the system, and lastly, act as a work platform [4]. The floaters can be characterised by their flexibility, size, and material properties. In the next three sub-chapters three main characteristics are described.

2.2.1 Flexible framework

The flexible framework is as the name implies, flexible. Flexible frameworks will follow the wave movements well and the material used for the frames are usually plastic (PE) which are flexible to some degree [4]. Depending on the number of fish being bred and the environmental conditions, the flexible framework will vary in circumference and material thickness. Scale Aquaculture AS possesses a big piece of the market in Norway when it comes to design, and manufacturing of these structures. An example of one of their floaters designed for harsh environment and exposed locations are the FR(PL)560 which is designed to operate where significant wave height and current can be as much as 6.0 meters and 1.5 m/s. The floater design chosen for this thesis is the FR(PL)560.

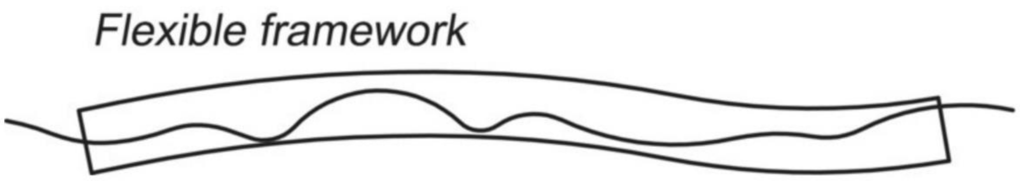

Figure 2 Flexible framework

2.2.2 Stiff framework

A stiff framework does not follow the wave movements the same way as flexible frame does. An example of a stiff frame is a ship. Some aquaculture fish farms use steel constructions for framework. These constructions are characterized by the large amount of environmental loads being absorbed by the frame [4].

Figure 3 Stiff framework

2.2.3 Framework with joints

Framework with movable joints will to some extent follow the wave movements. Steel constructions with joints connecting single elements are typical for these frameworks [4].

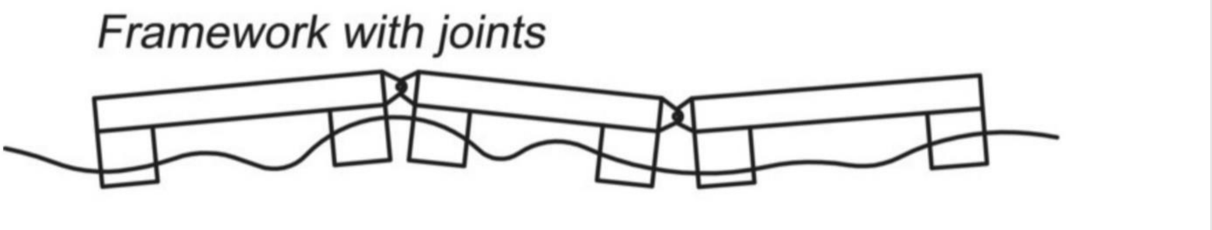

Figure 4 Framework with movable joints

2.3 Mooring system

Constructions and vessels placed at sea are moored to be kept stationary at a specific location. The mooring system must also be configured so that no additional forces due to environmental loads impact the structures unnecessary [5]. In this thesis one part of the scope is looking at the mooring system of a typical aquaculture fish farm configuration and identify which mooring elements are exploited the most given a set of environmental conditions. In addition to this, the impact on these mooring elements will be investigated when a large service vessel is moored alongside the floater with the most utilized and found critical for the station keeping of the aquaculture fish farm.

2.3.1 Mooring Arrangement

Mostly of today`s modern aquaculture fish farms are moored using hen foot mooring. The reason for this arrangement is because of the weight of non-buoyant components pulling the floaters downwards in the water column. The vertical force exerted to the floater by the weight of the mooring lines and environmental loads are counteracted by the grid, buoys, and bridle ropes. From the buoys the mooring lines stretches down to the ocean floor connected to anchors and/or bolts.

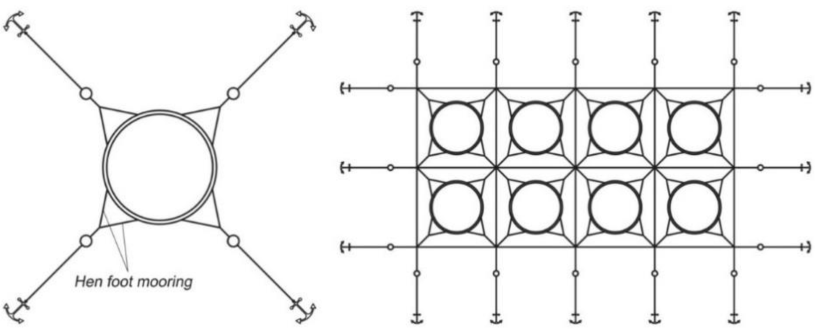

Figure 5 Spread hen foot mooring

2.3.2 Components

The components included in a spread hen foot mooring system are typically ropes, chains, anchor, grid plates and buoys. The dimensions of the components are normally chosen based on the result from a mooring analysis. The figure below illustrates a typical spread hen foot mooring arrangement with description of the components. The illustration is obtained from Odd-Ivar Lekang`s book "*Aquaculture Engineering*" [4].

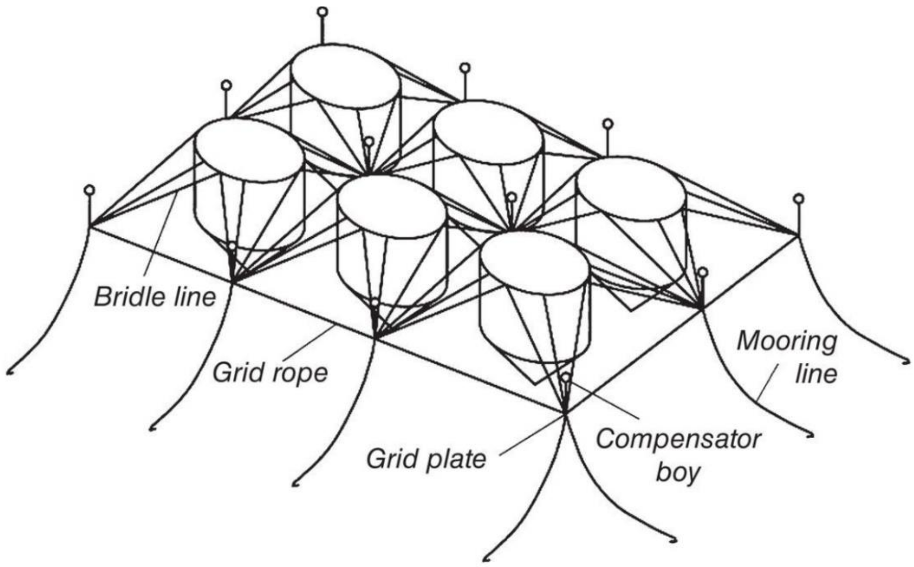

Figure 6 Typical spread hen foot mooring used in the Norwegian aquaculture industry

Figure 5 illustrate a typical spread hen foot mooring spread out using a 2 x 3 grid and 2 x 3 floaters with grid ropes, bridle ropes, buoys, and mooring lines completing the aquaculture fish farm. There are several manufacturing companies which produces the mooring components used in the aquaculture industry. The mooring components used for the modelling of the aquaculture fish farm such as ropes and buoys are in this project gathered from EIVA-SAFEX and will be described in more detail in chapter 5: modelling phase.

Chapter 3 Project foundation

In this chapter the basic background information for the project is established. Before conducting a mooring, hydrodynamical, operational and risk analysis of an aquaculture fish farm and service vessel operations, there are some background information which needs to be stated beforehand. This data concerns the environment surrounding the structures at a specific location including parameters like water depth, fetch length, wave, wind, and current exposure. This information is commonly obtained from a third-party company in the form of a site survey. For this thesis the data is obtained from available weather data, coastal maps, and simple estimation methods from the Norwegian standard NS9415:2009 [6].

3.1 Surrounding environment

The chosen location for the aquaculture facility which the mooring, vessel dynamic and operational analysis shall be performed is a location where a potential floating aquaculture system is exposed to both wind and waves from four main directions. It is not in direct contact to ocean waves, but swell waves may occur from SE direction where the fetch-length is the greatest. Apart from that, the location is local wind generated waves and current dominated. The location will be referred to as site A and in figure 7 an overview of the location is presented with red arrows showing the four main fetch lengths from the aquaculture fish farm to shore. The reason for choosing this location is because of knowledge and affiliation to the fjord system and because there are several fish farms in the area.

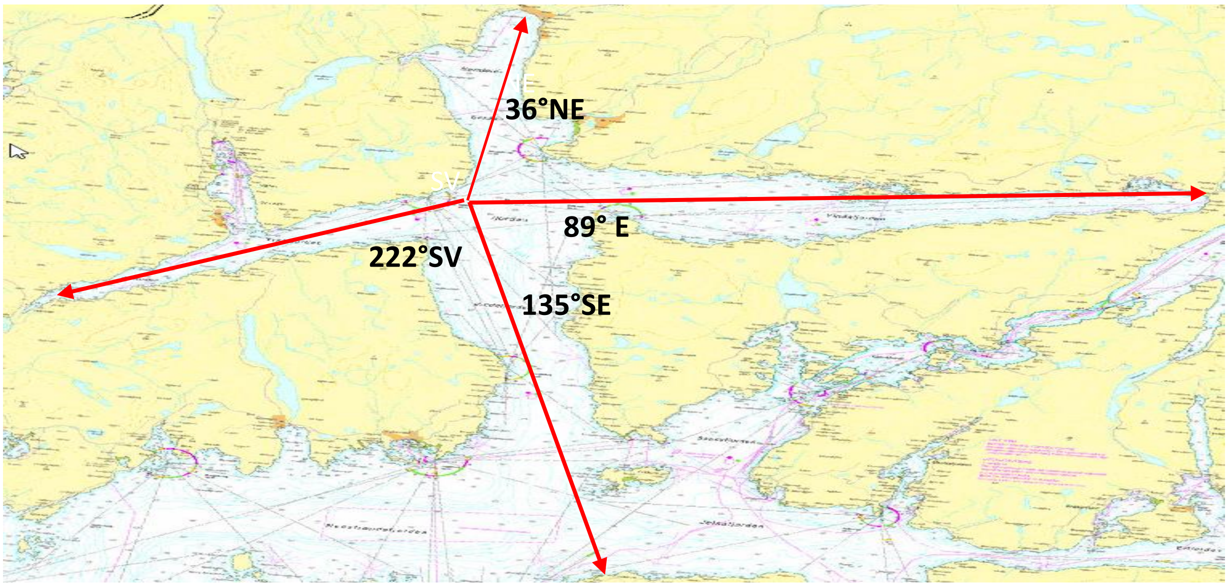

Figure 7 Location A with lines indicating fur main fetch lengths to shore

3.1.1 Fetch length

Fetch length is the distance of undisturbed open water from a chosen coordinate and the furthest unobstructed distance to shore. It is the distance where wind can work over water without any land formation obstructing wind and waves. Based on these distances we can estimate the wave height and corresponding wave period when given a specific wind speed. The fetch lengths and fetch widths are measured using google earth.

Table 1 Measured fetch length and widths

Heading	Fetch length [Km]	Fetch width [Km]
NE (36°)	7	1.9
E (89°)	19.5	4.5
SE (135°)	20	4.2
SV (222°)	12.5	2.1

3.1.2 Water depth

The fjord system is known for its deep waters, and the depths surrounding Site A range between 27 to 600 meters. Figure 8 presents the depth curves surrounding the site (marked with a star in the figure 8).

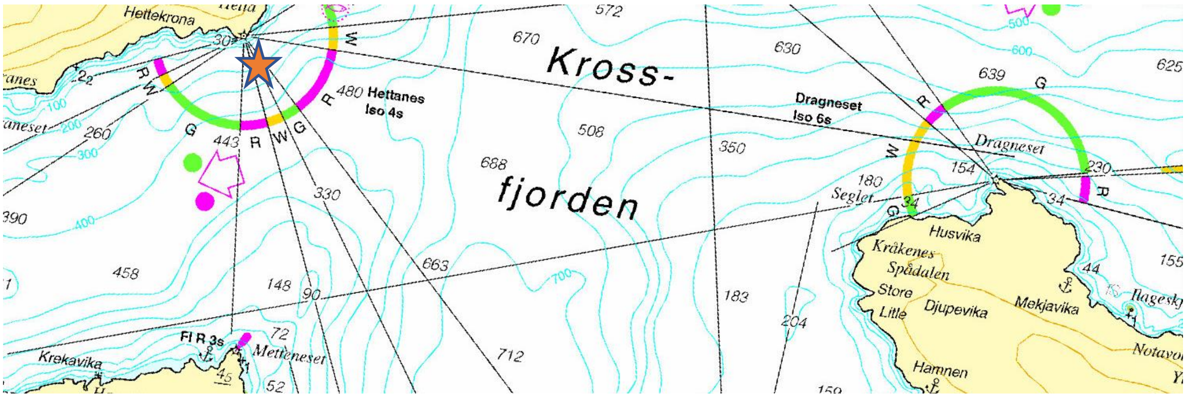

Figure 8 Depth curves surrounding Site A

The depths of the mooring lines are in this thesis set to depths of 100 meters. We could have used the depths from the depths curve, but the objective of this thesis is to investigate the impact a moored vessel has on the overall integrity of the mooring system and therefore simplified to reduce computation time. Another reason for choosing this solution is that the more detailed the modelled system is the bigger the chances are for convergence errors. Convergence is described in more detail in chapter 4.

3.1.3 Seabed conditions

Seabed conditions play a role in how the mooring lines are anchored to the seabed. If the bottom mainly consists of soft sediments, then an anchor of some sort may be the best solution. If there is rock bottom, the fastening of mooring lines is mainly done using bolts. For our model the anchoring of mooring lines is done by fixing the end of the modelled mooring lines in x, y and z translation, simulating bolts at the end of each mooring line.

3.1.4 Current

The data concerning currents for the area are assumed to be 0.34 m/s, 0,42 m/s, 0,3 m/s and 0.2 m/s, and then estimated for a 50 – year return period [6]. The conversion factor 50 – year currents and the product of the currents and conversion factor are listed in table 2.

Table 2 The four main fetch lengths and corresponding current velocity

Direction (from)	Assumed velocity [m/s]	Conversion factor *(50- year return period)*	Velocity [m/s]
NE	0.34	1.85	0,63
E	0.42	1.85	0,78
SE	0.30	1.85	0,70
SW	0.20	1.85	0,37

Chapter 4 Theoretical background

4.1 Environmental parameters

In this sub-chapter a brief introduction to how we can use a simple method using fetch length, fetch width and wind speed to estimate significant wave heights and corresponding wave periods is presented. The method used for this purpose are obtained from the Norwegian standard NS9415:2009.

4.1.1 Estimating significant wave heights and wave periods

Observations have concluded that both the length and the width of an area which the wind is working over have an impact on the development of waves. This means that when estimating the magnitude of wind generated waves both parameters must be included in the calculations. The result of wind working over an area long enough so that the waves no longer increase in size is termed fully developed seas [7]. The generated sea-state are dependent on several factors, such as:

- Windspeed
- Wave friction against shore
- Wind duration
- Fetch length and fetch width
- Water depth
- Current

There are different methods for estimating the wind generated sea-states. For this thesis a simple method which includes fetch length and fetch width valid for limited waters are used. The wind is assumed constant and with a duration resulting in fully developed seas. The following formulas are used to estimate the significant wave height and zero-up-crossing period (T_z).

$$U_A = 0.71 \cdot U_{ref}^{1.23} \tag{4.1}$$

Where U_{ref} (10 meters over sea level, 10 minutes average) is adjusted to a certain level and average time which the next equation is dependent on.

$$H_s = 5.112 \cdot 10^{-4} \cdot U_A \cdot \sqrt{F_e} \tag{4.2}$$

Where F_e is effective fetch length derived from the fetch width and fetch length ratio $\frac{F_w}{F_l}$, and then obtained from figure 9 than solved with respect to the fetch length.

$$F_e = \beta \cdot F_L \tag{4.3}$$

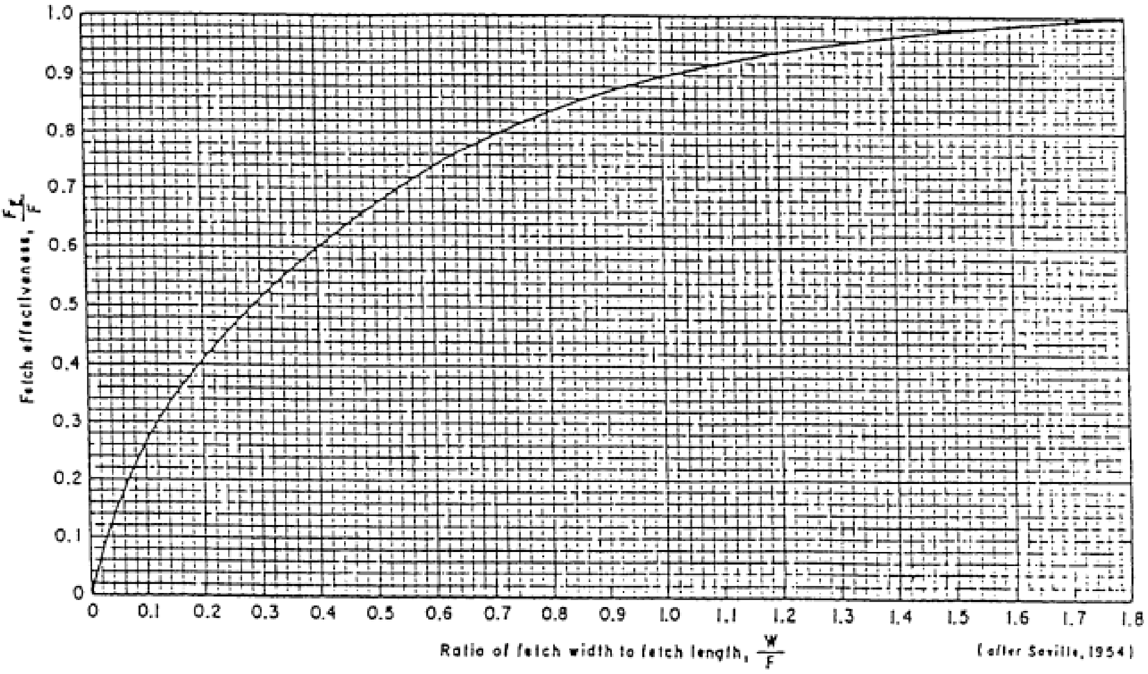

Figure 9 Ratio of fetch width to fetch length

After finding the effective fetch length from figure 9, we can estimate the wave peak period (T_P) and zero-up-crossing period (T_z) using the following equations

$$T_P = 0.06238 \cdot \sqrt[3]{U_A \cdot F_e} \tag{4.4}$$

$$T_Z = 0.71 T_P \tag{4.5}$$

It should be mentioned that it is recommended that this method is used with caution, since swell waves, bottom effects, interference, and reflection from steep hillsides are not accounted for. Nevertheless NS9415:2009 have concluded that the result provided using this method is sufficient and gives a good estimation on the significant wave height and wave period [1].

4.1.2 Regular waves

When observing the water surface most of us will come to the same conclusion that the water surface appears chaotic and random. Calculating water wave mechanics in a mathematical way is a challenging task. To make it less challenging we can describe these irregular, and chaotic sea states, as the sum of several regular waves, with different wavelength and wave heights [8]. Regular waves never occur in real life, but we can generate them in laboratory test tanks and use them to investigate seakeeping model experiments [9]. Description of irregular waves is the next topic of interest, and it is therefore useful to have some basic knowledge about regular waves.

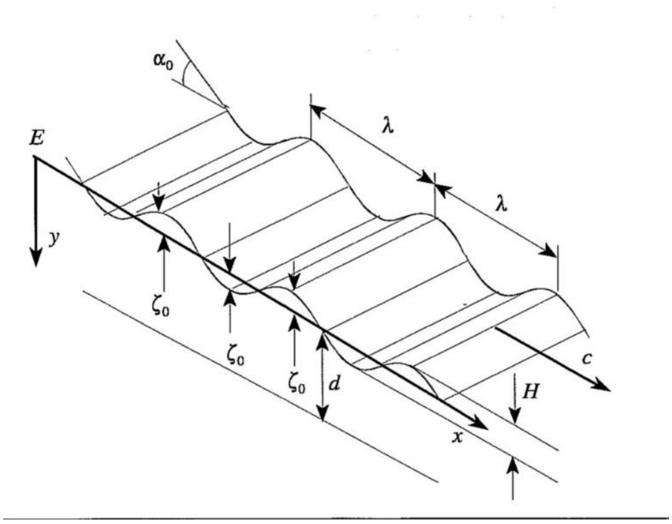

Figure 10 Regular waves

Figure 10 illustrates a wave train consisting of two regular waves where λ is the symbol for wavelength, ζ is the surface elevation, ζ_0 is the wave amplitude, H is the wave height, C is the velocity of an individual crest in the x direction, T is the wave period, α is the wave slope, $\propto_0$ is the maximum wave slope or wave slope amplitude (always positive), and $\frac{H}{\lambda}$ is the wave steepness.

These waves progress across the surface in a regular orderly fashion. Each wave crest advances at the same steady velocity C so that the waves never overtake each other, and the wavelength and wave period remain constant. The wave shapes remain the same and the whole wave train appears like a rigid corrugated sheer [9].

The surface profile can be calculated using equation 4.5

$$\zeta = \zeta_0 \sin\,(kx - \omega t) \qquad (4.6)$$

4.1.3 Irregular waves

As mentioned, irregular waves can be described as the sum of several regular waves. By looking at the irregular sea state as several regular sinusoidal waves we can describe the sea state using statistical methods. The simplest random wave model is the linear long crested wave model [10]:

$$\zeta(x,t) = \sum_{k=1}^{N} \zeta_{Ak} \cos\left(\omega_k t - k_k x + \varepsilon_k\right) \tag{4.7}$$

where ${\omega_k}^2 = g k_k$ is valid for waves in deep waters. The energy in each wave can be written as:

$$E_k = \frac{1}{2}\rho g {\zeta_{ak}}^2 \tag{4.8}$$

If we calculate the energy of k waves and add enough of them together you will see that the energy in each column forms a continuous function. We now have what is called a wave spectrum which describe the energy distribution in a sea state.

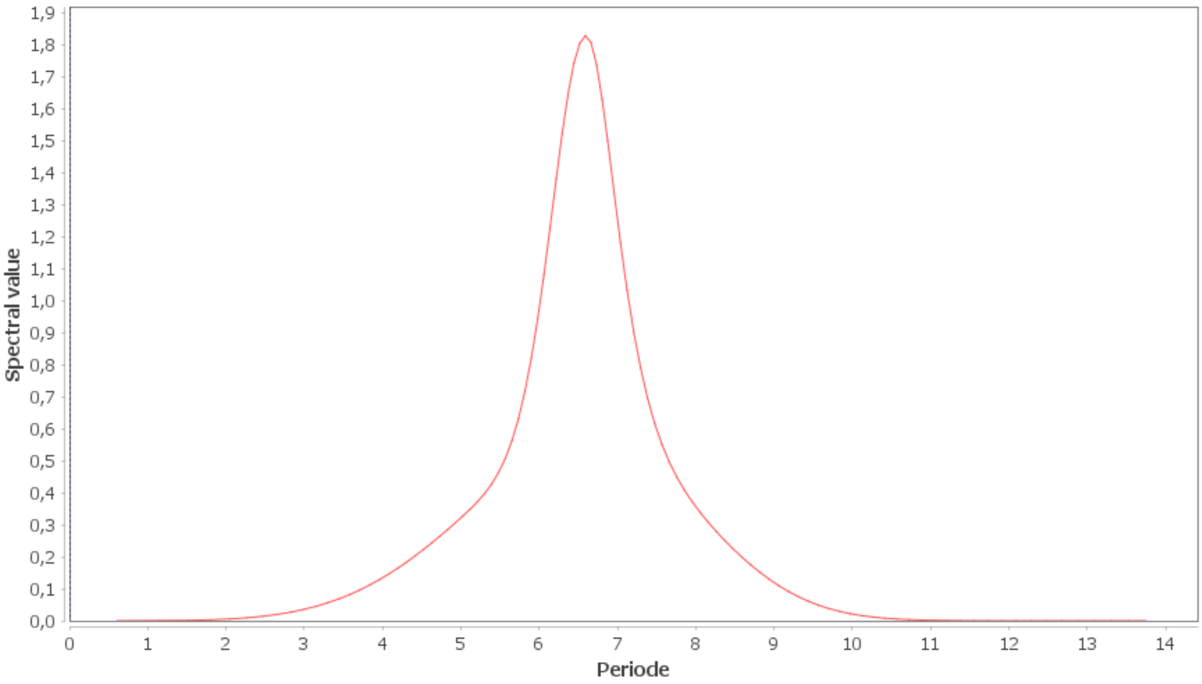

Figure 11 Wave spectrum

Figure 11 illustrates a JONSWAP wave spectrum with a peak period of 7.75 seconds and a significant wave height of 2.4 meters. The area under the curve is the energy distribution of the sea state.

4.2 Vessel response

In this section the basics of floating object response are introduced. It is expected that the reader has some basic knowledge concerning fluid dynamics, hydrodynamics, and mathematics. The theories and mathematical equation are complicated and a complete description of these are beyond the scope of this thesis. The main features of the theories and equations is intended to give an abbreviated presentations of the main features of vessel motions.

In AquaSim a force/displacement convergence criterion for the results to be found valid is necessary [11], and therefore an introduction on how the program solves this will be introduced.

4.2.1 Convergence criteria

The theory presented in this section are from the AquaSim theory manual and re-write by the author. AquaSim carries out time domain analysis where the modelled geometry responds to the predetermined environmental conditions. Normally the chosen environmental sea states are extreme waves, winds, and currents with a return period of 50- and 10-years. The objective is to investigate the stresses, accelerations, forces, rotations, and displacement in the floating object when introduced to a set of environmental conditions. The AquaSim solver uses a given number of initial steps to build up static loads such as currents and wind. When the modelled system reaches static equilibrium through these intimal steps, time varying forces such as waves are incremented [11].

When regular waves or irregular waves impact the aquaculture fish farm and service vessel, the internal and external forces are calculated. If these objects respond strongly non-linear, we may not achieve equilibrium, hence convergence is not reached. If convergence is not reached the results may sometimes be valid, but in general non-converged results are not valid [11].

The convergence criteria in AquaSim are a criterion where forces and displacement are combined. The force/displacement norm calculates an average over the models DOFs and is calculated using equation (4.9) [11].

$$norm = \sum_{t=1}^{N} \Delta force(i)^{\frac{3}{2}} \cdot \Delta displacement(i)^{\frac{1}{2}} \tag{4.9}$$

Iterations (i) are counted over all degrees of freedom in the system with a total of N degrees of freedom. $\Delta force$ is the difference in calculated force between current and previous iteration. $\Delta displcement$ is the difference in displacement from the current and the previous iteration. If the norm divided by the degrees of freedom is lower than the convergence defined by the user than the results has converged [11].

$$chknorm = \frac{NORM}{N} \tag{4.10}$$

When modelling objects in AquaSim we can allocate the elements material properties and an element type. When modelling ropes, wires, chains etc. we characterise them as trusses, and when modelling vessel hulls, floaters, or other shapes, we characterise them as beam elements. When beam or truss is chosen, we can decide which type of load model we want to use. The two load models we can choose from in AquaEdit are Morison's and hydrodynamic load.

4.2.2 Morisons equation

Morison equation is often used to calculate wave forces on constructions parts with a circular cross section. If we take an infinitesimal strip of this circular cross section and denote it, d_z we can calculate the horizontal force of a vertical cylinder using equation (4.11).

$$dF = \rho \frac{\pi D^2}{4} C_M a_x dz + \frac{1}{2} \rho C_D D u|u| dz \tag{4.11}$$

Where ρ is the water density, a_x and u are horizontal water particle acceleration and velocity calculated from the velocity potential of incoming waves. C_M is the mass coefficient and C_D is the drag coefficient. When modelling the mooring lines, bridle rope, grid rope and other submerged cylindrical shaped elements the chosen model is the morisons load.

4.2.3 Strip theory

The other model we can use to calculate the forces in the elements in AquaEdit is hydrodynamic (strip theory). The strip theory is a computational method by which the forces on and the motion of a three-dimensional floating object is determined using results from two-dimensional potential theory [12]. The basic principle of strip theory is that we take the three-dimensional object and divide it into infinitesimal thick slices and calculate the hydrodynamical effect on each strip [9]. For usage of strip theory, it is assumed that [9]:

- The ship is slender (length is much greater than the beam of the ship, or the draught and the beam is much less than the wavelength).
- The hull is rigid (stiff framework, no flexure in the structure occurs)
- Moderate speed
- Small motions
- Wall sided ship hull

- Deep waters ($\frac{h}{\lambda} > 0.5$) [13]
- Presence has no effects on the waves (Froude-Kriloff hypothesis)

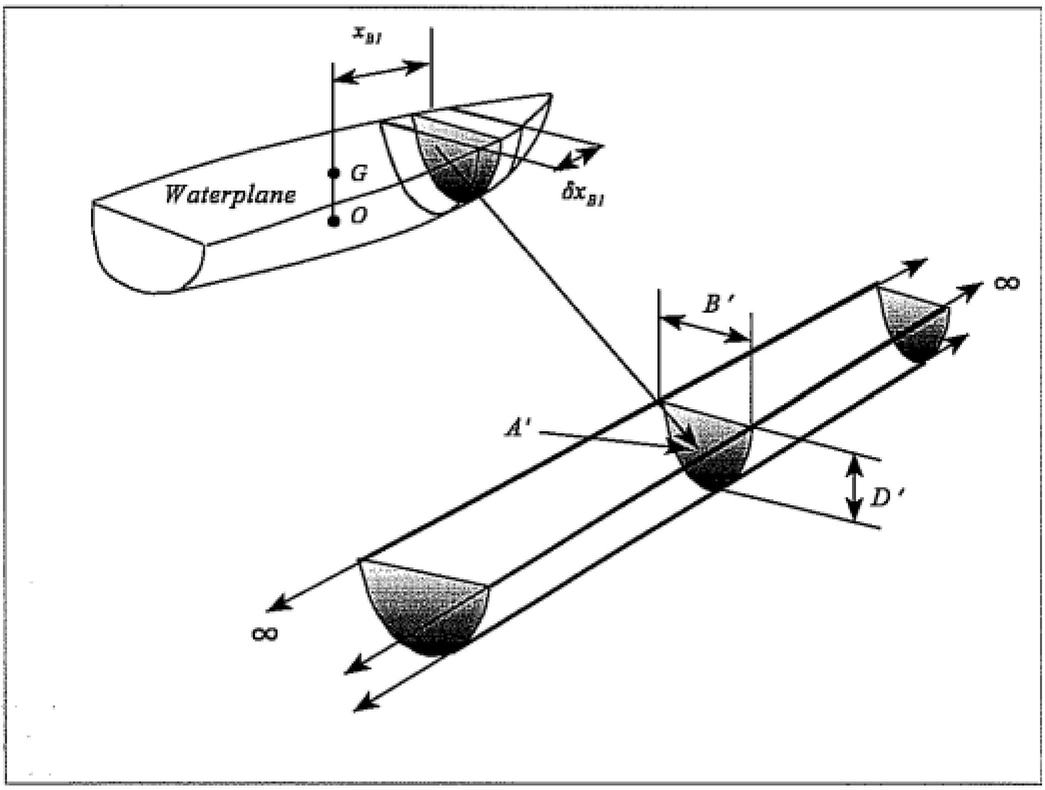

Figure 12 Strip theory [9]

When modelling the service vessel, the hydrodynamic load modelled is used.

4.2.4 Movements of a floating vessel in waves

In an ideal world the ocean is linear, and the vessels travels on an even plane, either forward, backwards, up, and down or side to side, one movement at the time. This is not the case. If we look closer at the water surface, we can see how dynamic the surface of the ocean really is. In real life the surface is bumpy, turbulent, and ever-changing. This will make the vessel move up and down, side to side, forward and backward and rotate about its x, y and z axis most often simultaneous. These movements are due to water waves, water currents and wind. If we investigate the movements in the vessel in regular waves something that never occurs in real life, we can isolate the vessel movements and investigate each movement one at the time or at least some of them. Let's say for example a vessel is assumed fixed at one location in space with its bow facing north and stern facing south. if we also imagine a polar coordinate system in the middle of the vessel with the y axis stretching along the length of the vessel, the x- axis is stretching along the beam of the vessel and finally the z – axis stretching along the height of the vessel. We now introduce a wave train of regular sinusoidal waves with a specific wave height, phase speed, steepness and wave period corresponding to a wavelength equal to the vessel length travelling along the y-axis of the vessel. The regular waves will transfer some of its energy over to the vessel hull making it move upwards and downwards in z-axis, backwards and forward in y direction and the vessel will rotate about its x-axis. These three motions are called and denoted:

Heave η_3

Surge η_1

Pitch η_5

If we now jump forward a couple of hours and assume that the wave direction has changed. The waves are now travelling along the x axis of the vessel towards the vessels starboard side. The waves are still assumed regular and make the vessel move from side to side, up and down and rotate about its y-axis. These three motions are called and denoted:

Heave η_3

Sway η_2

Roll η_4

The last movement is the rotation about the z-axis and is called and denoted yaw (η_6). This is the movement when the ship is turning its heading. Heave, surge, and sway are called translations. Roll, pitch, and yaw are called rotations.

As described, a floating vessel may have six individual movements and we may therefore say that a floating object is a dynamic system with six degrees of freedom (DOF). These degrees of freedom are coupled (simultaneous motions), but to simplify, we can look at the uncoupled (pure motions) motions so that the movements can be described using simple mathematical models.

From dynamics we know that a dynamic system includes three elements: mass, dampening and spring. For this system we use newtons second law of motion.

$$m_i a = \sum F_i = -B_{ij}\dot{\eta_i} - C_{ij}\eta_i + F_i(t) \tag{4.12}$$

Where F_i is the forces working on the vessel mass (m_i) in one of the three directions (x, y, z). B_{ij} is the dampening coefficient, C_{ij} is the spring coefficient, η_i is the position of the vessel measured from the equilibrium position and $F_i(t)$ is the external force working on the vessel. The external force on a floating vessel is the force which the waves are inflicting the vessel when we assume there is no wind or current present. Equation (4.12) is called the equation of motion and is the equation from which we derive the equation for the natural period in a vessel [13]. Before we move on to the natural period of a vessel there are some assumptions and approximations to be made.

If the waves are assumed regular, the motions in the vessel can also be assumed regular. The same goes for irregular waves. If the waves are irregular, we assume that the vessel response will be irregular. If we neglect the viscous forces and use the velocity potential the equation of motion (4.12) can be written as:

$$(I_{ij} + A_{ij})\ddot{\eta}_i + B_{ij}\dot{\eta}_i + C_{ij}\eta_i = F_1 + F_2 \tag{4.13}$$

Where I_{ij} is the moment of inertia, A_{ij} is the added mass or added mass-moment. F_1 is the fluid force on a fixed vessel encountering regular waves (excitation forces) and F_2 is the fluid force when the vessel is oscillating with the same frequency as the encountering waves. (Figure 13)

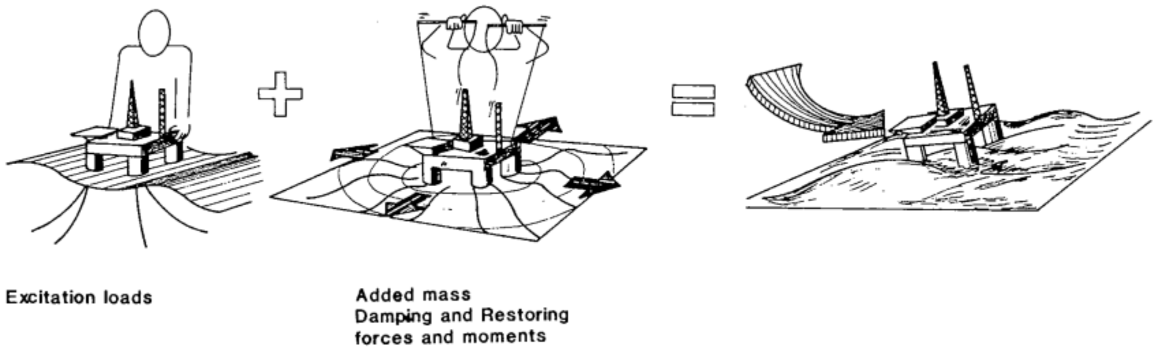

Figure 13 Dynamic system [5]

When force F_1 and F_2 are to be calculated some additional assumptions are necessary. These are:

Irrotational fluid: $$\nabla\, x\, \boldsymbol{V} = 0 \tag{4.14}$$

No fluid flow through the ocean floor $$\frac{\partial \varphi}{\partial \boldsymbol{n}} = \boldsymbol{n} \cdot \boldsymbol{\nabla}\varphi = 0 \tag{4.15}$$

Free surface condition: $$\frac{\partial^2 \varphi}{\partial t^2} + \boldsymbol{g}\frac{\partial \varphi}{\partial z} = 0 \tag{4.16}$$

No flow through the ship hull: $$\frac{\partial \varphi}{\partial \boldsymbol{n}} = \boldsymbol{n} \cdot \boldsymbol{V} = 0 \tag{4.17}$$

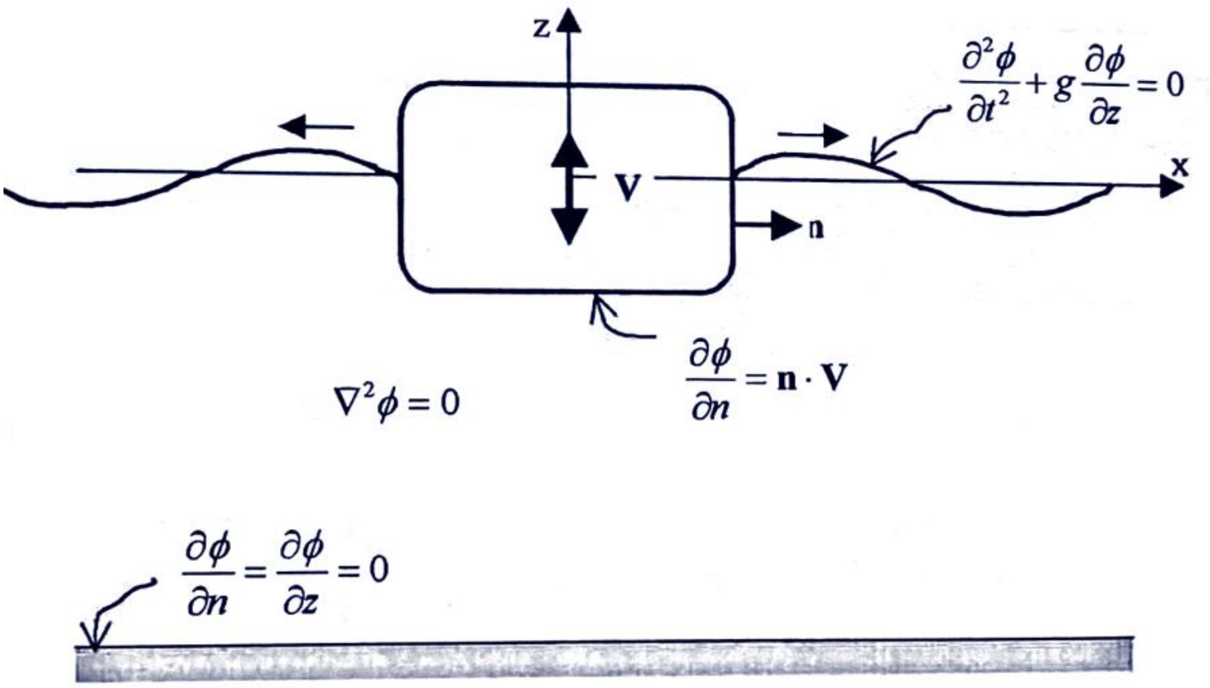

Figure 14 Boundary conditions [13].

4.2.5 Natural periods

The natural periods, referred to eigen periods I AquaEdit is the period where the vessel is in risk of experience resonance. Resonance occurs if an external force is acting on a structure with the same period/frequency as the natural period/frequency of the structure [5]. When the two frequency aligns the oscillating and combined frequency will increase and may create great rotational and/or translational movements in the structure. The natural periods can be calculated in 6 degrees of freedom with three translational movements and three rotational movements. The transitional movements are denoted surge, sway, and heave. While the three rotational movements are denoted roll, pitch, and yaw.

The natural period in heave for a freely undamped, uncoupled floating body can according to O.M Faltinsen be written as [5]:

$$T_{\eta_3} = 2\pi\sqrt{\left(\frac{M + A_3}{\rho g A_w}\right)} \tag{4.20}$$

$A_3 = added\ mass$

$g = gravitational\ accelleration$

$A_w = waterplane\ area$

$\rho = fluid\ density$

Often the most critical movement for a floating structure is the rotation about axis referred to as the roll axis. The roll motion denoted η_4 can be written as:

$$T_{\eta_4} = 2\pi \sqrt{\left(\frac{Mr_4{}^2 + A_4}{\rho g V \overline{GM_t}}\right)} \tag{4.21}$$

$r_4 = roll\ radius\ of\ gyration\ (for\ ship\ hull\ this\ is\ \approx\ 0.35B)$
$A_4 = roll\ added\ moment$
$\overline{GM_t} = transverse\ metacentric\ height$

The roll, pitch and heave motions are the motions which are the driving factor when it comes to snap loads in vessel moorings, therefore the natural period of the vessel in pitch should also be evaluated. The pitch motion can be written as

$$T_{\eta_5} = 2\pi \sqrt{\left(\frac{Mr_5{}^2 + A_5}{\rho g V \overline{GM_l}}\right)} \tag{4.22}$$

$r_5 = pitch\ radius\ of\ gyration\ (for\ a\ ship\ shaped\ vessel\ this\ is\ typical\ 0.25L)$
$A_5 = pitch\ added\ moment$

$\overline{GM_l} = longituidal\ metacentric\ height$

4.3 Mooring analysis

Mooring of floating aquaculture fish farms are quite extensive. The main objective of the mooring system is to keep the fish farm stationary regardless of wind waves and currents. This requires that the mooring lines are sufficiently pre-tensed. Because of the relatively small buoyancy characteristics of the floaters the mooring lines and floaters are connected via buoys. The buoys are used to compensate this pretension in the mooring lines and prevents the floaters from sinking due to vertical force from the weight of the mooring lines and net bag [7] [5].

Because of the complexity of a mooring arrangement, it is difficult to calculate the axial tension load in the mooring lines when introduced to multiple environmental parameters like waves, currents and wind, and therefore unique computer software's are programmed to perform this task. In this thesis we will use AquaSim to calculate these forces. Nevertheless, there are some tasks we can investigate using less advanced approaches. Through the next couple of pages, methods for calculating the vertical forces in buoy lines and mooring line size are described. This approach is used when calculating the necessary size of the buoys for the aquaculture fish farm under investigation.

4.3.1 Calculation of necessary properties of mooring lines and buoys

To take the inaccuracy into account when calculating and describing the environmental load affecting aquaculture fish farms moorings, a load factor γ_l is recommended to compensate for possible inaccuracy.

$$F_t = \gamma_l \cdot F_e \tag{4.23}$$

Where F_t represents the total force, F_e calculated environmental force and γ_l is the load factor (1.15) [6]. In addition to compensations for the loads we also need to compensate for possible inaccuracy when testing material, and minor variations in the materials. For this it is recommended to use a material factor γ_m. (1.1 to 5 depending on the material). To find the size of the mooring lines necessary, the following equation can be used.

$$F_R = \gamma_m \cdot F_t \tag{4.24}$$

Where F_R represents mooring forces (the force the mooring line must tolerate), F_T calculated total forces including load-factor, and γ_m material factors [1]

Table 3 Material factors

Chain	1.5
Synthetic rope with knot	5.0
Synthetic rope	3.0
Synthetic rope especially resistant to ageing, wave, and water absorption	1.5

To show how a simple mooring analysis can be performed, an example is provided where mooring line and buoys are estimated. In this example we assume environmental load of 1.0 tonnes

Table 4 Mooring example

Information	
Environmental load F_e	1.0 tonnes = 9.81 KN
Water depth	100 m
Bottom conditions	Sand
Current velocity	1.0 m/s
Objective: Find the length and type of mooring line, buoy type and size, and anchor type and size to keep the farm in position. The bullet points present the procedure.	

- Calculating the angle of mooring line
- setting the mooring line length
- calculating the force on the buoy.

Finding the angle that the mooring line has from the bottom and to the surface:

$$sin \propto = \frac{water\ depth}{mooring\ line\ lenght} = \frac{100}{300} = 19{,}47^{\circ}$$

Calculating the force in x direction on the mooring line:

$$cos \propto = \frac{F_e}{x} \rightarrow cos \propto = \frac{9.81KN}{x} \rightarrow x = \frac{9.81KN}{\cos(19{,}47°)} = 10.4\ KN$$

The mooring line must therefore tolerate a force of 10.4KN.

Calculating the force in y-direction:

$$sin \propto = \frac{y}{x} \rightarrow y = xsin \propto = 10.4\ KN \cdot \sin(19.47°) = 3.50\ KN$$

The buoy will therefore be dragged down with a force of 3.50KN, and we can now describe the buoy and the required buoyancy. We set the buoyancy requirement to twice the force in y-direction on the mooring line (7.0 KN).

$$F_B = \rho_w \cdot g \cdot V_{buoy} \rightarrow V_{buoy} = \frac{F_B}{\rho_w \cdot g} = \frac{7000N}{1025 \cdot 9{,}81} = 0.70 = 700L$$

This means that the buoy needs a volume of 700L to stay in position. In addition, the buoy needs enough volume to compensate its own weight. Later in the thesis, the size of the buoys is estimated using a simple excel program. The equations which excel uses to determine these are the equation mentioned here. The example is obtained from Odd Ivar Lekang book *“Aquaculture Engineerig”* [4].

4.4 Risk assessment

The new revised NS9415:2021 recommends a risk assessment where the probability and consequence are assessed and evaluated. The evaluation is based on a risk matrix. In the risk matrix we get the risk acceptance criteria and shall act as support in decision making [1]. The risk assessment must according to NS9415:2021 include some basics. These basics are:

- System description
    - Description of prerequisites, assumptions, and simplifications
- Identification of hazards and unwanted incidents
- Analysis of cause and probability
- Analysis of consequences
- Description of risk compared to risk acceptance criteria
- Identification of possible risk reducing measurements

An excel spreadsheet has been created by the writer to describe: the probability and consequence, risk assessment and risk matrix. The following figures presents the chosen setup for the risk assessment of large service vessel operations in the aquaculture industry. The results of the risk assessment are presented in chapter 8.

Probability	1 Very unlikely	2 Less likely	3 Likely	4 more likely	5 very likely	6 Expected
occurrences	rarer than every 10th year	Between once every 5th year & once every 10th year	Between once every year & once every 5th year	Between once a month & once every year	Between once a month & every week	Between once a day & once a
Consequence (type damage/loss)	1 (A) Harmless	2 (B) a certain danger	3 (C) dangerous	4 (D) critical	5 (E) disastrous	
Life and helth	no physical or psychological harm	few or minor physical or psychological harm	serious physical or psychological harm witout permanent injury	serious physical/psychological harm with permanent injury	faitality	
environental	no measurable environmental impact	short-term reversible environmental impact or single emssion	prolonged reversible environmental damage or repeated discharges	possible irreversible environmental damage	irreversible environmental damage	
Operation, production and service	No effect on pimary functions	minor reduction on primary functions that can be solved with simple means within a short period of time	primary activities are noticeably reduced, but can be restored within a reasonable time	primry activities have been significantly reduced over a long period of time. Recovery will be demanding.	primary function is permanently impaired.	
economic and material values	no financial harm	minor financial loss that can be recovered.	Significant financial loss that can be recovered.	irreparable financial losses	Significant and irreparable financial loss	
Credibility and reputation	no impact on credibility. No reduced recruitment or funding.	weakend local cooperation and credibility. Somewhat reduced recruitment or financing.	weakenend regional cooperation and credibility. Reduced recruitment or financial.	weakened national cooperation and credibility. Reduced recruitment and significant reduction in financing.	weakenend international and national cooperation and credibility. Significantly reduced recruitment and financing.	
Fish escape	zero escape fish	more than 5 fishes	more than 100 fishes	more than 1000 fihes	more than 500.000 fishes	

Figure 15 Probability and consequence

Risk Assesment

Prosject: master thesis Created by: Martin R. Vestbø date:

Analyse object	#	Unwanted incident	cause	root cause	Consequence (hazard type/loss)	Initial risk (without measures): Probability	Consequence	Risk acceptance	risk reducing measures	Residual Risk (after mesures): Residual probability	Residual consequence	Risk acceptance
Mooring system	1	Line break			-	1	4	Moderate		1	3	acceptable
					-	1	4	Moderate		1	4	Moderate
					-	1	4	Moderate		1	4	Moderate
					-	3	3	Moderate		1	3	acceptable
	2				-	3	3	Moderate		2	3	Moderate
					-	3	3	Moderate		2	3	Moderate
					-	3	3	Moderate		3	3	Moderate
					-	3	3	Moderate		3	3	Moderate

Figure 16 Excerpt of the risk assessment

Risik matrix

Probability \ Consequence	1	2	3	4	5
6	Moderate	critical	critical	critical	critical
5	acceptable	Moderate	critical	critical	critical
4	acceptable	Moderate	Moderate	critical	critical
3	acceptable	acceptable	Moderate	critical	critical
2	acceptable	acceptable	Moderate	Moderate	critical
1	acceptble	acceptable	acceptable	Moderate	critical

Figure 17 Risk matrix

4.5 Weather criteria and availability analysis

A weather window is assumed safe when all relevant metrological parameters are lower than the predetermined threshold parameters, and not safe when one of these limiting criteria are exceeded. For evaluation of operational weather windows, the thresholds are based on the vessels and crews individual operational limiting criteria. According to DNV-RP-H103 marine operations consist of two phases [14]:

1. Design and planning.
2. Execution of the operations.

The design and planning phase shall select seasons when the marine operations can be carried out and provide weather criteria for starting and interrupting the operations (the availability analysis). The analysis shall be based on historical data covering a period of at least 5-10 years [14].

Execution of marine operations shall be based on the weather forecast, the Near Real Time (NRT) data (data with a time history 1-5 hours) and, if justified, Real Time (RT) data (data with a time history 0 – 1 hours) [14].

To evaluate the availability of a specific site, hindcast wave data for the location is obtained from a public third party in CSV format. This is historical data gathered over 41 years where significant wave height, corresponding peak period, wind speed and directions are logged once every hour. With this data an evaluation on the site's availability is evaluated. The thresholds will be established through some predetermined hydrodynamical analysis found in chapter 6.4. The result will be presented using plots in excel showing a plot line of significant wave height, operational limiting criteria and alpha factor adjusted operational limiting criteria. In NS9415:2021 it says that:

"For adjacent floating units moored to an aquaculture farm for a limited time-period up to four months, the combinations of environmental conditions must be evaluated based on the forecasted environmental conditions such as weather forecasts. And if the adjacent floating body can be detached from the facility within the time the vessel threshold is reached" [1].

After establishing the availability of a location, a method on how we can evaluate real time (RT) weather windows using the alpha factor method will be presented.

4.5.1 Alpha factor method

The alpha factor method is used to cover any uncertainties in the monitoring and forecasting of the environmental conditions [15]. We use an alpha factor less than or equal to one to make sure that the predetermined environmental parameters (threshold parameters) are not exceeded. The method can be divided into three steps [15]:

Step 1. Define operational design limiting criteria, $OP_{lim,D}$

Step 2. Define the operation period, T_R

Step 3. Choosing an α (alpha factor) and calculate $OP_{lim,O}$

Step 1: Involves defining the operational limiting design criteria and must be less than applied environmental criteria $OP_{lim,O}$. $OP_{lim,D}$ can be based on maximum wind and waves for safe working or transfer conditions for personnel, equipment specified weather restrictions, limiting weather conditions of diving system (if any) or limitations identified in risk assessment based on operational experience with involved vessel(s) [15].

Step 2: Marine operations with a reference period (T_R) less than 72 hours may be defined as weather restricted [15]. T_R is used both to define the required weather window and as basis for selection of the alpha factor. The operation shall only be considered completed when the vessel is in a safe condition. The equation for estimating the reference period is (4.25) Where T_{POP} is the planned operation time and T_c is the maximum contingency time are.

$$T_R = T_{POP} + T_C \tag{4.25}$$

The maximum contingency time is added to cover any uncertainties in the planned operation time and if planned operation time and required time for contingency situations are not assessed the reference time should be set to twice the planned time [15].

$$T_c > 2 \cdot T_{POP} \tag{4.26}$$

Step 3: Use T_R and $OP_{lim,D}$ as inputs to find the alpha factor. The operational criteria $OP_{lim,O}$, are according to DNV-OS-H101 defined as [15].

$$OP_{lim,O} = \propto \cdot OP_{lim,D} \tag{4.27}$$

An operation may at this point be divided into sub operations for which different α and $OP_{lim,O}$ are defined. The alpha factors can be obtained based on $OP_{lim,D}$ and T_R. Table 5 shows the significant wave height, alpha values, “rules” obtained from DNV-RP-H101.

Table 5 Significant wave height - alpha factor

Operational	Design wave height		
Period [hours]	$1 < H_s < 2$	$2 < H_s < 4$	$H_s > 4$
$T_R < 12$	0.68	0.76	0.60
$T_R < 24$	0.63	0.71	0.75
$T_R < 48$	0.56	0.64	0.67
$T_R < 72$	0.51	0.59	0.63

Chapter 5 Modelling phase

At this point it is a good time to repeat the first two research questions from now on referred as RQs:

- *To which extent will a large service vessel moored to one of the floaters impact the axial force in the elements used for station keeping of the aquaculture fish farm?*
- *How will the load distribute amongst the mooring lines if the most utilized mooring line should go to failure?*

To be able to answer these RQs, the vessel and aquaculture fish farm must be modelled. The chosen vessel is a large service vessel, and the model design is obtained from one of shipping company Rostein`s service vessels [16]. The vessel is chosen because of its broad usage in the aquaculture industry. The modelling and analyses phase are all done using the software AquaSim from Aquastructures AS. In this chapter a brief introduction to the software will be presented and thereafter the geometry and modelling procedure of the vessel and aquaculture fish farm is described.

5.1 Software

AquaSim is an analysis software developed by Aquastructures AS for load calculations on marine floating structures. When talking about loads wind, waves and currents are typical loads in addition to loads induced through operations. The software is used daily by the aquaculture and oil and gas industry. AquaSim field of application are mooring analysis, global analysis, net analysis, and marine operations. AquaSim includes four sub programs, AquaEdit, AquaTool, AquaView and AquaHarmony. For this thesis the sub-programs AquaEdit and AquaView have been used.

In AquaEdit we build our geometrical models and edit the structural and hydrodynamical properties through a graphical interphase. The AquaSim solver derives the results from given geometrical, properties, loads and environmental inputs [17].

AquaSim handles global analysis and interactions of force transmitted between stiff and flexible components. AquaSim establishes simultaneously a visual simulation of displacement, accelerations, and deformations in the structure AquaSim calculates for each step the local section forces, stresses, and stress ranges in each system component, applicable to local analysis and fatigue assessments.

AquaSim is based on real-time simulations, which implies that AquaSim considers nonlinear effects, such as geometrical changes in the components cross-section, to continuously maintain the correct relation between the applied forces and the resulting displacement.

AquaSim considers hydroelasticity, handling the interactions and coupled dynamics between the external loads and the construction. Deformations and changes in the global structural geometry will imply changes in the load scenario applied to the construction.

The results are graphically viewed in AquaView and presented in table and diagrams in AquaTool [18].

5.2 Sea cages and moorings

The chosen sea cage is of the type flexible sea cage construction described in chapter 2. This type of framework follows the wave elevation quite well and are flexible compared to stiff framework and framework with movable joints. Framework chosen for this thesis is four flexible sea cages with a circumference of 200 meters. The floater is modelled with a double tube cross-section with 72 segments and possesses the material properties and design of the floater FR(PL)560 from Scale AQ [19]. The design is chosen for the same reason as for the vessel design, its broad usage in the industry.

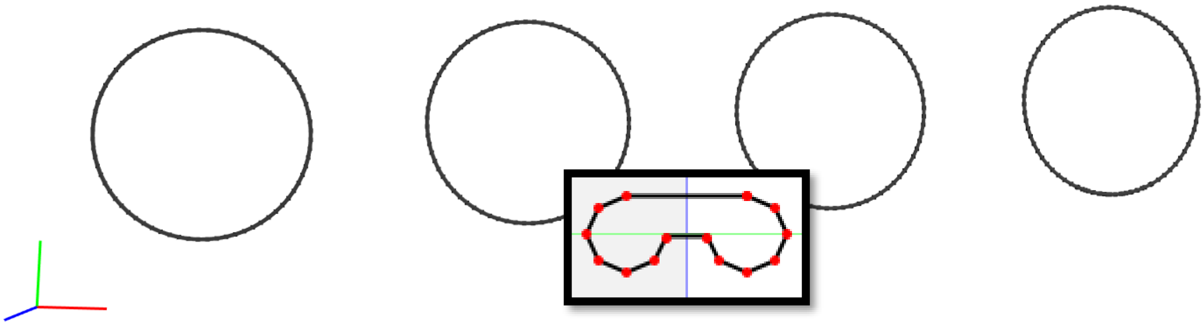

Figure 18 Modelled floaters and visual cross section

Mounted underneath the floater we find the enclosure. The enclosure (net-bag) stretches 40 meters in negative z-direction and at the bottom of the net bag a point load of 4000 Kg is placed to represents the weight of the net-bag. From the bottom rope 36 ropes stretches down to a total of 85 meters below the sea surface. These ropes are referred to as spaghetti ropes. At the end of these ropes another point load is placed. This load is 800 Kg. The point load is placed to prevent the net bag from deforming during strong currents and waves. An illustration of the modelled spaghetti net is shown in figure 19.

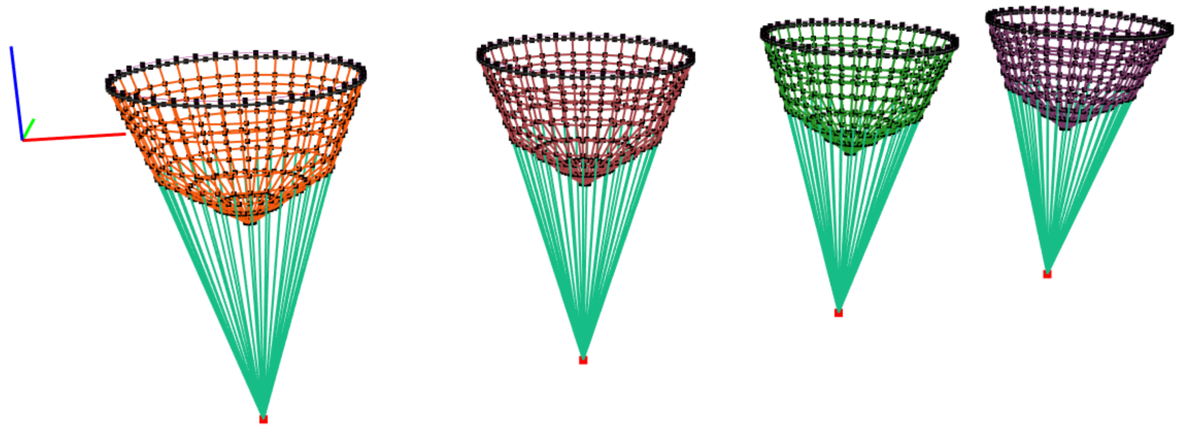

Figure 19 Modelled spaghetti nets with spaghetti ropes and point loads

After modelling the enclosure, the grid is modelled. The grid size for this project is a 1 by 4 grid. Each grid rope is 100 meters, and the entire grid is placed 10 meters below the surface. The objective of the grid is absorbing most of the environmental loads, and thereby shielding the enclosure.

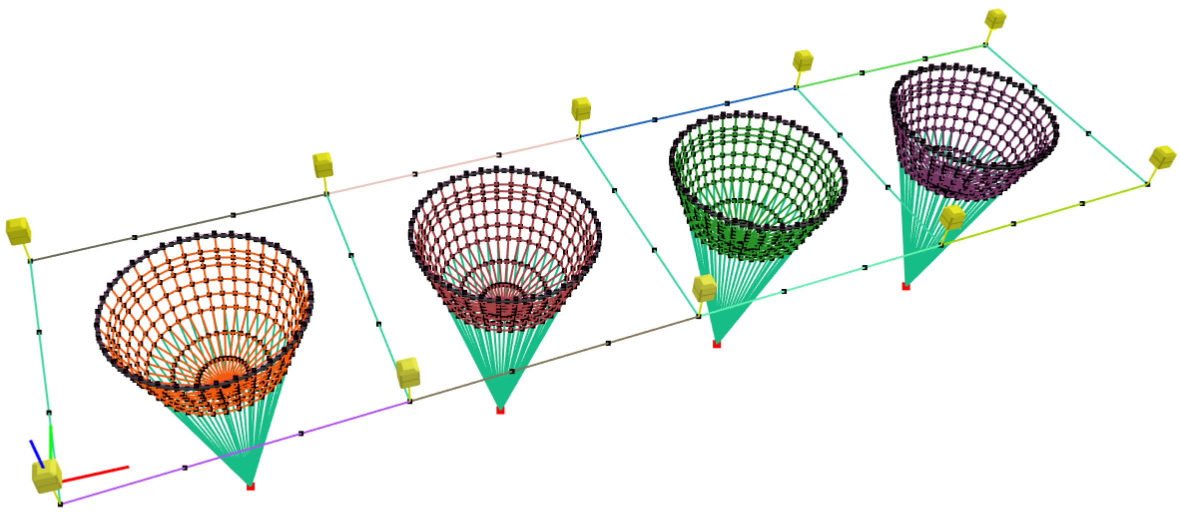

Figure 20 Mooring grid surrounding the floaters and enclosures.

In each corner of the grid a buoy strap and buoy are modelled to compensate the weight of the mooring line and grid ropes. The mooring lines and grid rope are composed of material that possesses negative buoyancy, meaning that they sink. The total system is then moored to the sea floor using 22 mooring lines with ideal length to depth ratio. At the end of each mooring line a 25-meter-long segment composed of an anchor chain which again is fixed to the sea floor is placed. The length and depth ratio of the mooring lines are 3:1 (length is three times the depth). This is the ideal ratio for mooring lines [4]. Figure 21 illustrates the modelled aquaculture fish farm in its entirety. At the end of each mooring line anchor chains are modelled. These types of chain are frequently used to avoid chafing and to dampen the movements in the mooring lines making them move more smoothly in the water and thus avoiding snap loads [4].

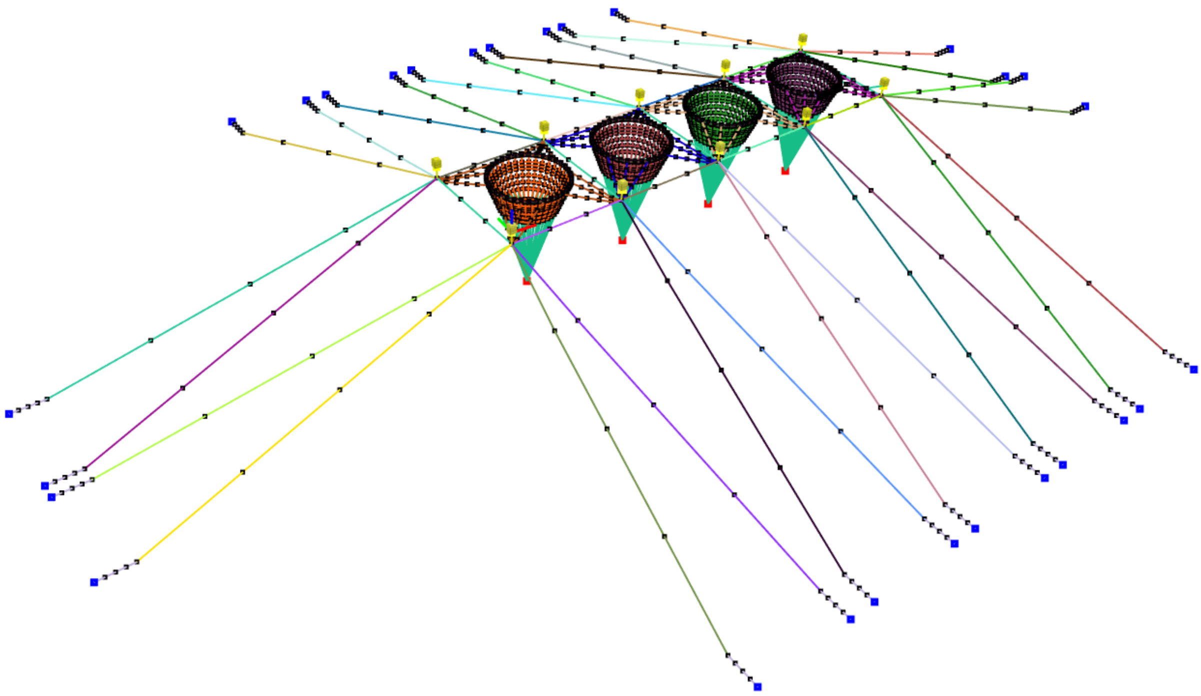

Figure 21 Complete aquaculture fish farm system

The floater is modelled as type beam and the ropes are modelled as type truss. The properties of the different components are listed in table 6. The dimension of the components is chosen based on intuition and may be over- or under dimensioned, something the results from the mooring analysis will tell us.

Table 6 Material properties of modelled trusses

Component	E-modulus	Diameter	Weight in air	MBL
Bridle rope	$2.0 \cdot 10^9 \left[\frac{N}{m^2}\right]$	48 $[mm]$	1.984 $\left[\frac{Kg}{m}\right]$	$3.2667 \cdot 10^5 [N]$
Mooring lines	$2.0 \cdot 10^9 \left[\frac{N}{m^2}\right]$	56 $[mm]$	2.7 $\left[\frac{Kg}{m}\right]$	$4.3556 \cdot 10^5 [N]$
Grid rope	$2.0 \cdot 10^9 \left[\frac{N}{m^2}\right]$	56 $[mm]$	2.7 $\left[\frac{Kg}{m}\right]$	$4.3556 \cdot 10^5 [N]$

According to NS9415 a traditional mooring analysis, the product of calculated axial force, load factor and material factor is compared to the components MBL. If this product is greater than 100% of the components MBL, then a bigger dimension, or a higher MBL of the component must be chosen before launching the fish farm [6].

5.3 Service vessel

The goal when modelling the service vessel has been to make it as realistically as possible so that the results would become accordingly. The geometry and hydrostatic properties are chosen and calculated based on Rostein shipping delousing vessel design with some alterations and simplifications, Rostein design is illustrated in figure 22. The main dimensions are listed in table 7.

Figure 22 Rostein AS delousing vessel [16]

5.3.1 Main vessel dimensions

Table 7 Main vessel dimensions

Delousing vessel Hull		
Length (L)	m	80
Breadth (B)	m	15
Draft (D)	m	4.6
Freeboard (f)	m	2.4
Weight (M)	Kg, Kg/m	1003680, 29520
KG	m	1.8
$\overline{GM_T}$	m	4.4
$\overline{GM_L}$	m	39.52

The wheelhouse and upper part of bow is modelled without any weight and will only act as a visual component to illustrate the area of attack which the wind can work on. The weight of the vessel is calculated based on the vessel simplified hull shape and main dimensions. The weight may differ from the actual vessel design. Figure 23-25 presents the end results of the modelled vessel from different angles.

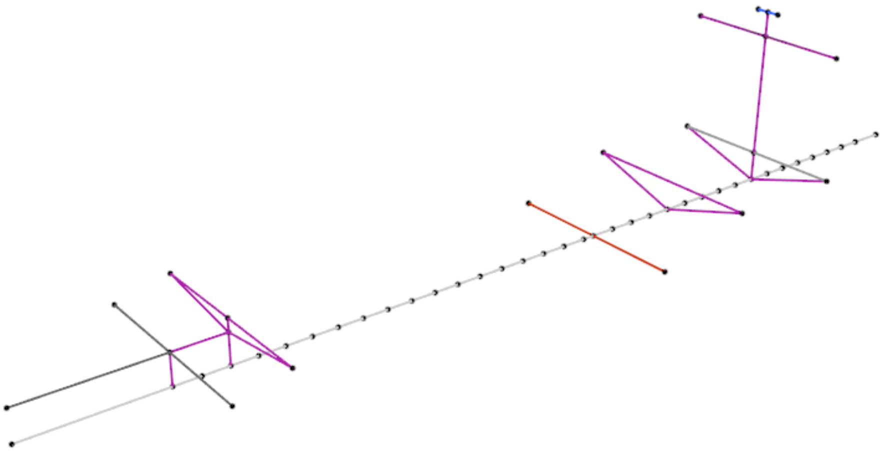

Figure 23 Iso view of modelled vessel

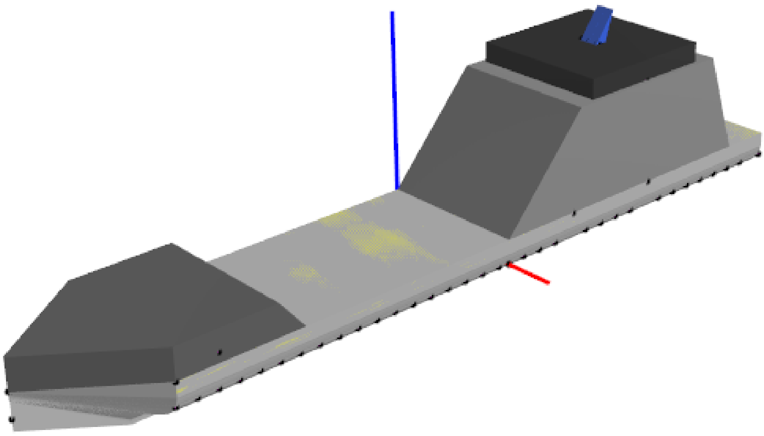

Figure 24 Iso view of modelled vessel with cross-section

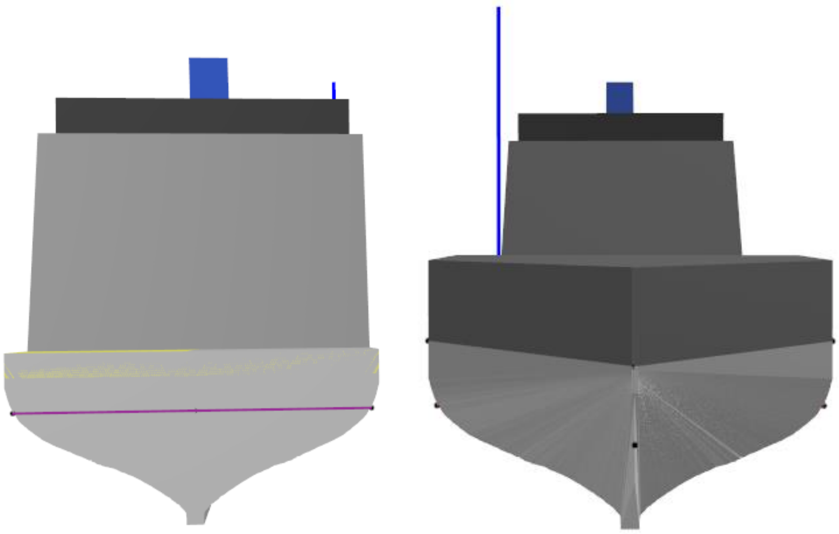

Figure 25 Modelled vessel front and stern

Figure 23 illustrates the model as it is initially modelled as "lines". These lines are given individual unique cross sections which can be altered in AquaEdit. When the function "show cross sections" are switched on, we can see the shape of the vessel (figure 24 and 25). The next figure presents the modelled vessel, when merged together with the modelled aquaculture fish farm.

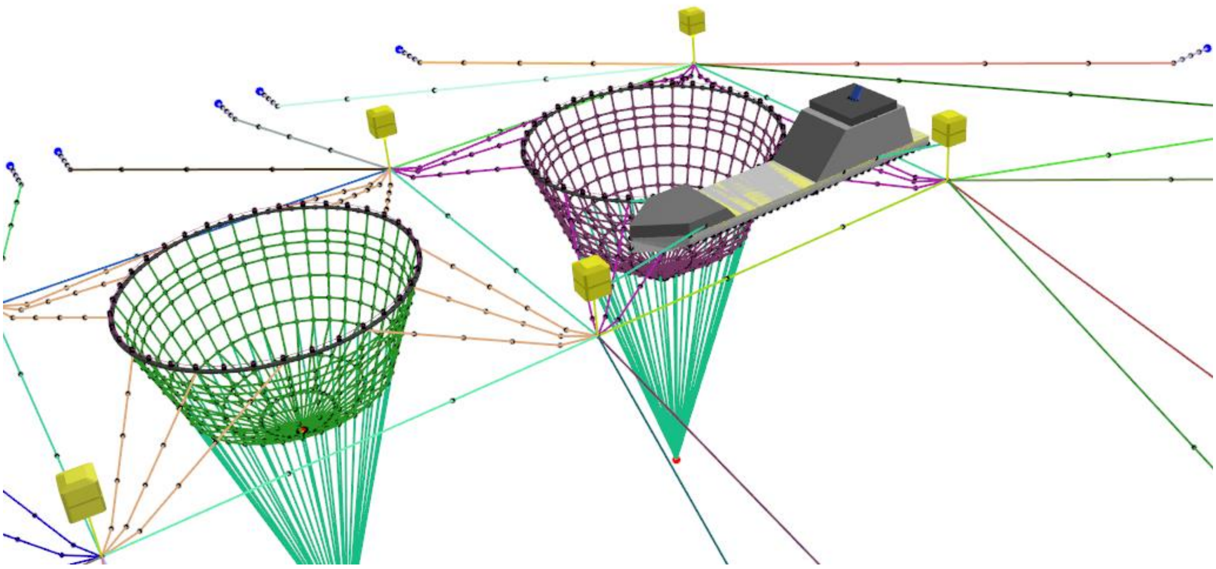

Figure 26 Modelled vessel, floater, enclosure, mooring lines, and buoys

Chapter 6 Analyse phase

As described in the introduction the analysis involves investigating the impact that a moored service vessel has on the overall integrity of the aquaculture farm`s mooring system. Therefore, some cases are established. The first case involves a static analysis of the aquaculture fish farm. The second case involves a mooring analysis of the aquaculture fish farm exposed to regular waves, currents, and wind. The third case involves a mooring analysis when a service vessel is moored alongside the enclosure with the most utilized mooring lines identified in case 2. For the fourth case, we look at the axial tension forces in the mooring lines when the most utilized mooring line goes to failure. The fifth case is an analysis of the service vessel`s natural periods and finally, the sixth case includes vessel motions in irregular waves.

When the first six cases are completed the results from case 5 and case 6 will be used in an operational analysis where we look at how we can use the results from numerical analysis to plan and execute operations with a weather criteria and availability analysis and thereby increase the safety of the crew on aquaculture fish farms and service vessels. In this part we will use “Seakeeping performance of ships” gathered from the NORDFORSK, 1987 project as reference when comparing the movements in the service vessel.

6.1 Environmental conditions

Based on the equations stated in chapter 4 and the fetch lengths of Site A, the following parameters are estimated.

Table 8 Environmental conditions

Environmental conditions

Heading	F_L [km]	F_W [km]	$\frac{F_W}{F_L}$	$\frac{F_e}{F}$	F_e [km]	U_{ref} [m/s]	U_A [m/s]	H_s [m]	T_p [s]	T_z [s]
NE (36°	7	1.9	0.3	0.51	3.57	24	24.85	0.76	2.78	1.98
E (89°)	19.5	4.5	0.2	0.4	7.8	24	35.39	1.60	4.06	2.88
SE (135°)	20	4.2	0.2	0.4	8.0	24	46.57	2.13	4.49	3.19
SV (222°)	12.5	2.1	0.2	0.4	5.0	24	46.57	1.68	3.84	2.72

The reference wind with a return period of once every 50 years is obtained from NS-EN-1991-1-4 [20].

6.2 Mooring analysis

This is sub-chapter provide the method used to answer the RQs and what parameters that are included in different predetermined cases. The first case is the static mooring analysis. The static analysis objective is firstly to identify the vertical forces in the buoy lines so that we can determine the necessary size of the buoys. Secondly, to verify that the modelled aquaculture farm has enough buoyancy to stay afloat and lastly, to identify if there are any faults in our model. The second case objective is to identify the most utilized mooring lines. After case 2 we will continue to case 3 where the axial load in the mooring lines is analysed when a service vessel is moored alongside the floater with the most utilized mooring lines which was identified in case 2. The result from case 2 and 3 will then be compared to answer the first RQ.

"To which extent will a large service vessel moored to one of the floaters impact the axial force in the elements used for station keeping of the aquaculture fish farm?"

The results from case 4 will answer the second RQ.

"How will the load distribute amongst the mooring lines when the most utilized elements go to failure (ALS)?"

The cases generated to answer the first two RQs are summarized in table 9 to 12.

Table 9 Case 1: static analysis

Case 1
Static analysis of the aquaculture fish farm
Objective: Primarily, to identify the vertical forces in the buoy lines due to the weight of non-buoyant elements in the system. Secondarily, to verify that the floater provides enough buoyancy to stay afloat and lastly, to discover any faults in the model.

Table 10 Case 2: Mooring analysis

Case 2

Mooring analysis of the aquaculture farm **excluding** *service vessel*

Environmental conditions

Sea state	$System.H$	H_s [m]	$Wave.H$	T_z $[s]$	$V_c \left[\frac{m}{s}\right]$	$CurrDirr$	U_{ref} $\left[\frac{m}{s}\right]$	Waves
1	90°	0.76	36°	1.98	0.63	205°	12	Regular
2	90°	1.60	89°	2.88	0.78	270°	12	
3	90°	2.13	135°	3.19	0.70	315°	12	
4	90°	1.68	222°	2.72	0.37	40°	12	
System.H = orientation of system from North clockwise			Wave.H = wave heading from		Vc = velocity of the current		Uref = windspeed at 10 m	CurrDirr = direction of the current towards

Objective: Identifying the most utilized elements used for station keeping of the aquaculture fish farm.

Table 11 Case 3: Mooring analysis including moored service vessel

Case 3

Mooring analysis of the aquaculture farm **including** *service vessel*

Sea state	$System.H$	H_s [m]	$Wave.H$	T_z $[s]$	$V_c \left[\frac{m}{s}\right]$	$CurrDirr$	U_{ref} $\left[\frac{m}{s}\right]$	Waves
1	85°	0.76	36°	1.98	0.63	205°	12	Regular
2	85°	1.60	89°	2.88	0.78	270°	12	
3	85°	2.13	135°	3.19	0.70	315°	12	
4	85°	1.68	222°	2.72	0.37	40°	12	
System.H = orientation of system from North clockwise			Wave.H = wave heading from		Vc = velocity of the current		Uref = windspeed at 10 m	CurrDirr = direction of the current towards

Objective: Answer the first RQ, which involves investigating to what extent the moored service vessel impacts the most utilized elements identified in case 2

Table 12 Case 4: Accidental limit state analysis

Case 4
ALS
Failure in the most utilized mooring line(s)
Objective: To investigate to which degree removing the most utilized element will have on the nearby mooring components.

6.3 Results mooring analysis

The result from each of the individual cases will in this part of the thesis be presented and commented using figures from AquaView and plots from excel. We will start on case 1 and work our way through the first four cases. Since the objective of the mooring analysis is to investigate the impact a moored service vessel will have on the station keeping elements the material properties of these elements are listed (see table 13)

Table 13 Dimensions and MBL of modelled trusses

Component	**Dimension**	**Maximum breaking load** (MBL)
Bridle rope	48	33.3 T
Mooring lines	56	44.4 T
Grid rope	56	44.4 T
Buoy line	40	23.8 T

The equation used to convert the unit from newton to metric tonnes is (6.1). Where axial force is in newtons and g is the gravitational acceleration $[\frac{m}{s^2}]$.

$$\frac{axial\ force}{g \cdot 1000} \tag{6.1}$$

6.3.1 Case 1: Static analysis

Case 1
Static analysis of the aquaculture fish farm
Objective: Identify the vertical forces in buoy strap due to the weight of mooring system. Verify that the floater provides enough buoyancy to stay afloat. Check for other faults in the model.

The static analysis is an analysis without environmental loads present except for hydrostatic pressure from the water. The objective is to identify the vertical forces in the buoy lines due to the weight of the non-buoyant elements in the system and to verify that the modelled aquaculture fish farm has enough buoyancy to stay afloat. The first figure illustrates the aquaculture system and the local axial forces in the mooring lines, buoy lines, grid ropes and bridle ropes. The colure scale on the left-hand side shows the range of axial force starting from grey to red (minimum to maximum). The results show that it is the grid ropes which are most utilized in static equilibrium. No apparent faults in the model were discovered.

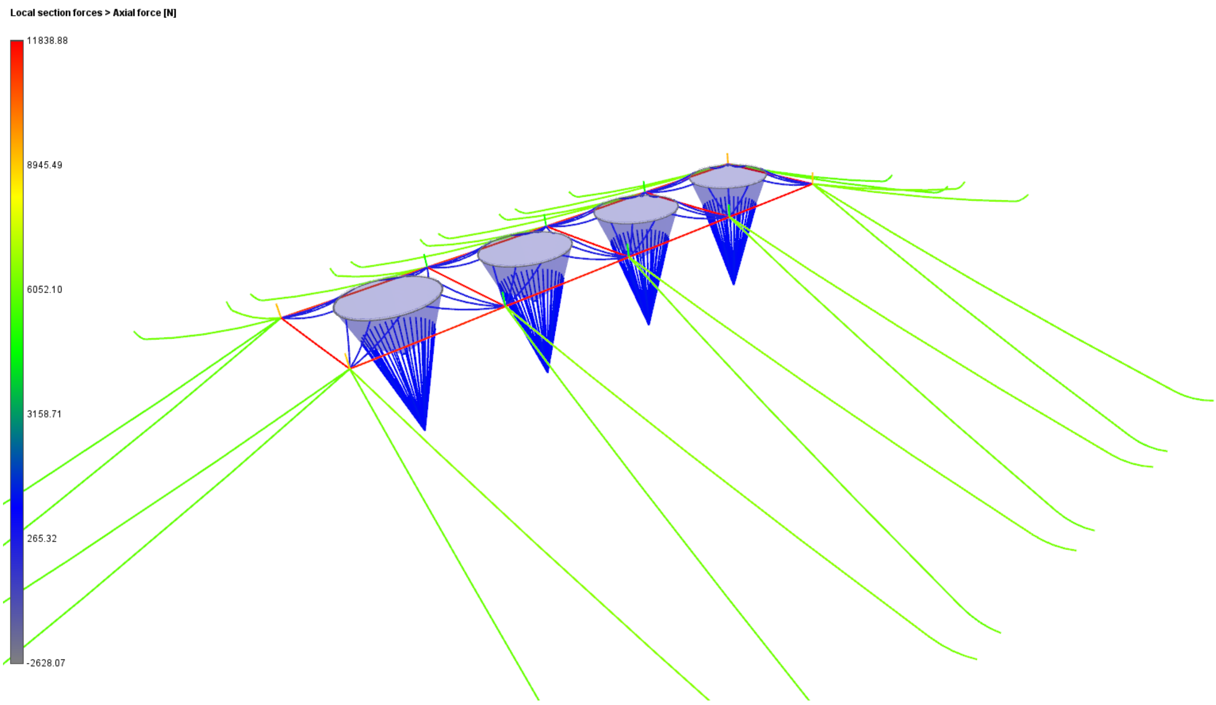

Figure 27 Local section forces - axial load

By investigating the vertical force in each buoy line, we can choose suitable buoys. A simple program has been created in Excel for this reason. An excel file is programmed so that we can enter the vertical force in each buoy strap and then give us the recommended buoy size using the equations described in chapter 4.3. The types of buoys used are obtained from EIVA-SAFEX`s website [21].

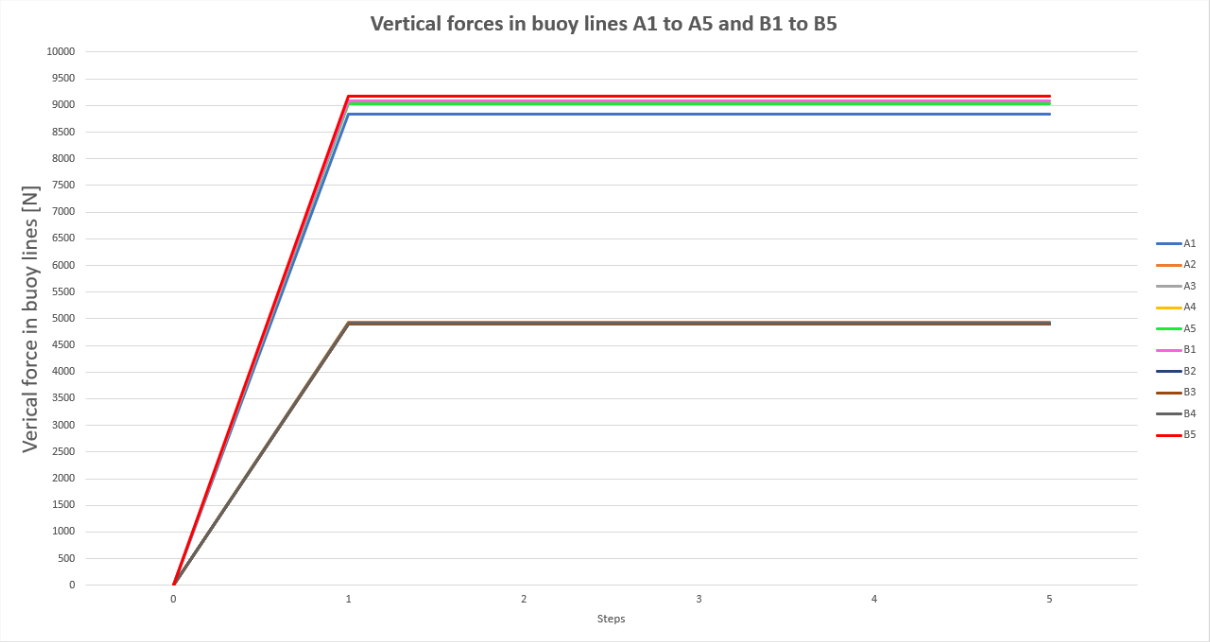

Figure 28 Results from AquaSim vertical force in buoy lines

The result when entering the calculated vertical forces gives us the following recommendations:

Buoy analysis				
Buoyline	Displacement [m]	Vertical force [N]	Volume buoy [L]	Recommended Buoy
A1	0.436	8843.7	1759	FFB2000
A2	0.243	4933.24	981	FFB1000
A3	0.241	4906.08	976	FFB1000
A4	0.242	4914.07	977	FFB1000
A5	0.445	9032.7	1797	FFB2000
B1	0.447	9078	1806	FFB2000
B2	0.241	4902	975	FFB1000
B3	0.241	4895.5	974	FFB1000
B4	0.242	4923	979	FFB1000
B5	0.452	9174.7	1825	FFB2000

Figure 29 Result of the buoy analysis

The recommended buoy for this system is Activa FFB2000 and Activa FFB1000. The results can be view in more detail in the excel file *"Master thesis"*.

Activa FFB 1000	Activa FFB 2000
1141 liter	2180 liter
1064 kg	2040 kg
106 kg	210 kg
120 x 120 x 124 cm	162 x 162 x 122 cm
22 t	52 t

Figure 30 Recommended buoys for this aquaculture system

After choosing the buoys, the displacement in z-direction of the floaters is investigated. The floater shows a negligible (-0.001 m) displacement in negative z-direction. From this we can conclude that the floaters provide sufficient buoyancy, and we can continue to the next case.

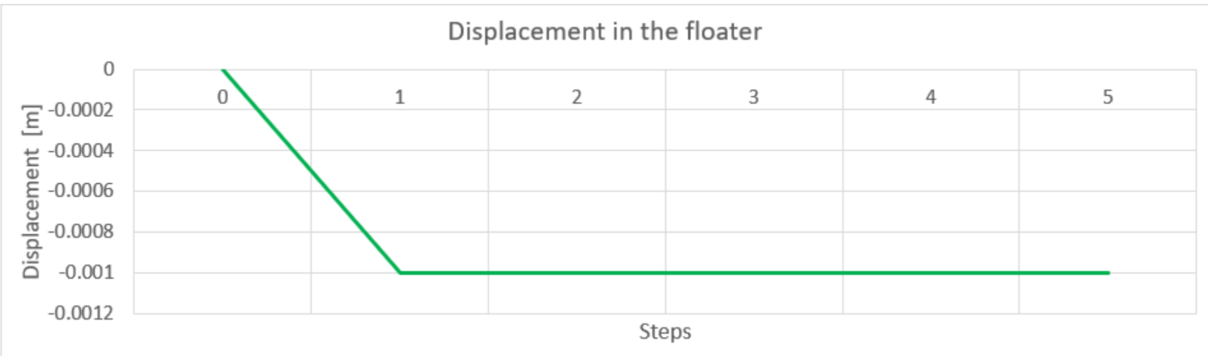

Figure 31 Floater displacement in z-direction

6.3.2 Case 2: Mooring analysis, excluding service vessel

Case 2								
Mooring analysis of the aquaculture farm **excluding** *service vessel*								
Environmental conditions								
Sea state	$System.H$	H_s [m]	$Wave.H$	T_z $[s]$	$V_c\left[\frac{m}{s}\right]$	$CurrDirr$	U_{ref} $\left[\frac{m}{s}\right]$	Waves
1	85°	0.76	36°	1.98	0.63	205°	12	Regular
2	85°	1.60	89°	2.88	0.78	270°	12	
3	85°	2.13	135°	3.19	0.70	315°	12	
4	85°	1.68	222°	2.72	0.37	40°	12	
System.H = orientation of system from North clockwise		Wave.H = wave heading from		Vc = velocity of the current			Uref = windspeed at 10 m	CurrDirr = direction of the current towards

Objective: calculating the axial force in the mooring lines so that we can compare this to the results found in case 3.

The second case involves the mooring analysis without a moored service vessel. The environmental conditions are now included, and the system will be exposed to regular wind, regular waves and current from four main directions. The results are obtained from a generated max out file which gives us the maximum utilized mooring lines based on all four sea states [17].

When looking at the axial force in the mooring lines from each sea state, the ones most utilized are the mooring lines with an easterly orientation and in the grid-rope located on the south side of M4.

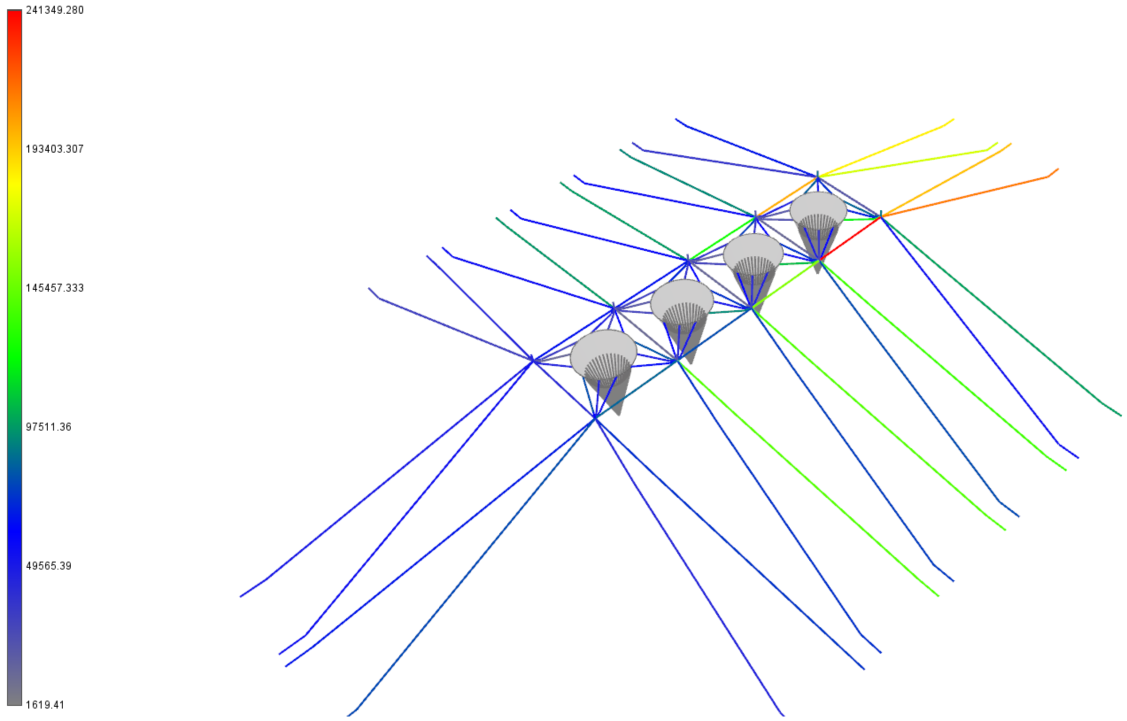

Figure 32 Mooring analysis of aquaculture farm without service vessel

The most utilized ropes are mooring lines 15, 16, 17 and 18 and grid rope A4-A5. The results are shown in the table below.

Table 14 Results of most utilized mooring lines case 2

Component: name	Axial force [N]	Axial force [tonnes]	Due to Sea state #
Bridle rope	119044	12	3
Grid rope A4-A5	241349	25	2
Mooring line 15	185008	19	2
Mooring line 16	172033	18	2
Mooring line 17	195917	20	2
Mooring line 18	212214	22	2
Anchor chain	212071	22	2
Buoy line	89359	9	2

In the next chapter we will perform the same mooring analysis, although this time the service vessel described in chapter 5.3 will be moored alongside cage M4.

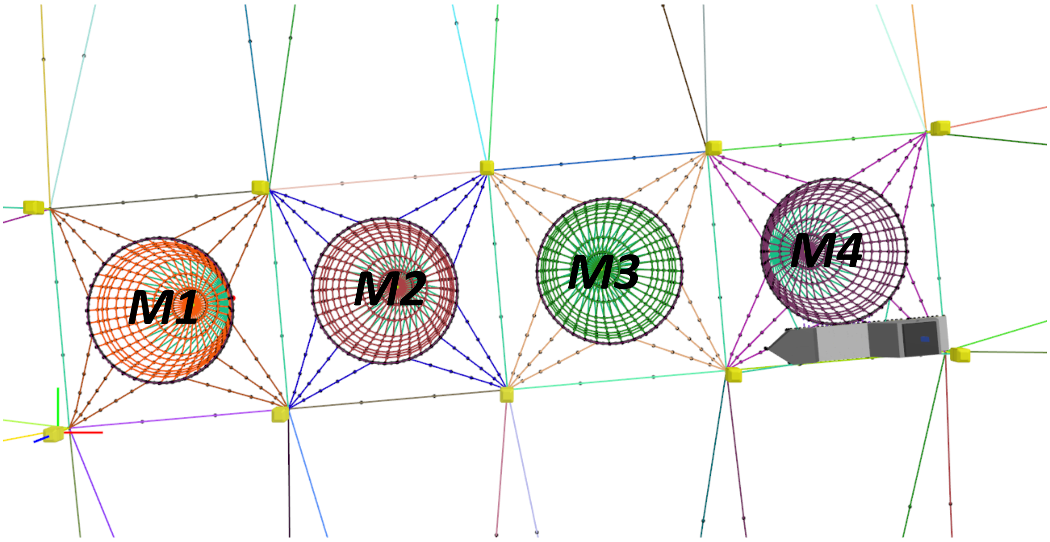

Figure 33 Aquaculture fish farm and service vessel

1. ***Bridle rope***
2. ***Grid rope A4-A5***
3. ***ML 15***
4. ***ML 16***
5. ***ML 17***
6. ***ML 18***
7. ***Anchor chain***
8. ***Buoy strap***

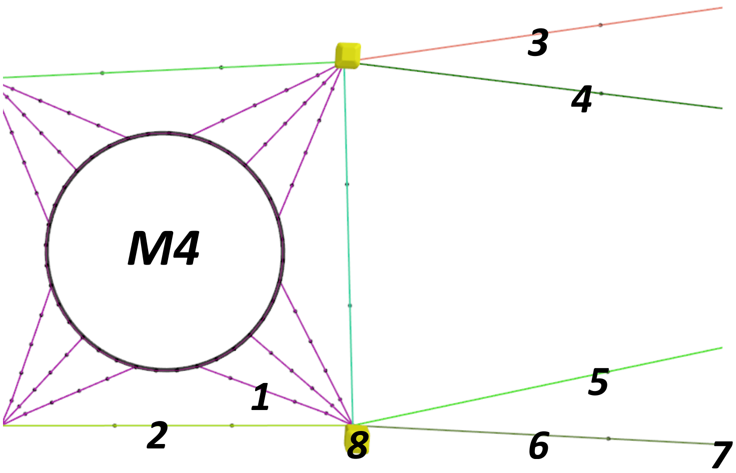

Figure 34 Most utilized mooring lines numbered and labelled

6.3.3 Case 3: Mooring analysis, including service vessel

Case 3

Mooring analysis of the aquaculture farm **including** *service vessel*

Sea state	$System.H$	H_s [m]	$Wave.H$	T_z $[s]$	V_c $\left[\frac{m}{s}\right]$	$CurrDirr$	U_{ref} $\left[\frac{m}{s}\right]$	Waves
1	85°	0.76	36°	1.98	0.63	205°	12	Regular
2	85°	1.60	89°	2.88	0.78	270°	12	
3	85°	2.13	135°	3.19	0.70	315°	12	
4	85°	1.68	222°	2.72	0.37	40°	12	
System.H = orientation of system from North clockwise			Wave.H = wave heading from		Vc = velocity of the current		Uref = windspeed at 10 m	CurrDirr = direction of the current towards

Objective: Answer the first RQ which involves concluding if fish cage moored service vessels will impact the aquaculture mooring system

To answer the RQ, and the impact a moored service vessel has on the mooring system system, we will look at frame rope (A4-A5) and mooring lines 15 to 18. These ropes where identified as the most utilized ropes and the causing sea state where sea state 2. The results from case 3 will be compared to the results from case 2.

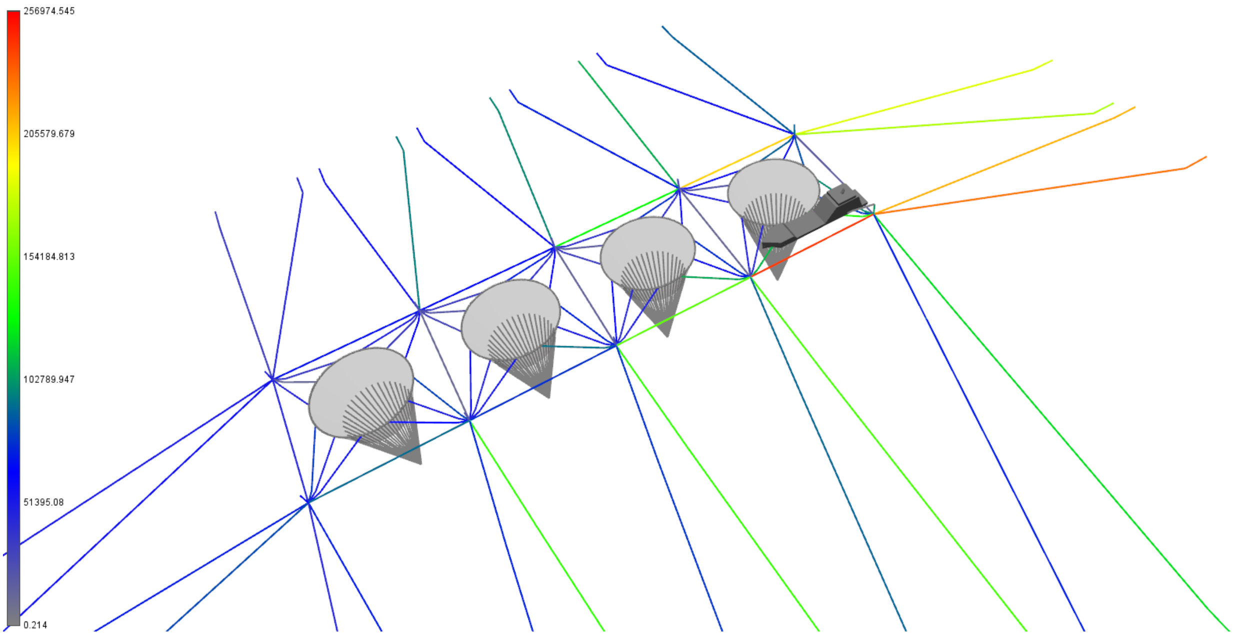

Figure 35 Mooring analysis with service vessel

Table 15 Results of mooring analysis with service vessel case 3

Component: name	Axial force [N]	Axial force [tonnes]	Due to Sea state #
Bridle rope	135559	14	3
Grid rope A4-A5	242054	25	2
Mooring line 15	185542	19	2
Mooring line 16	173930	18	2
Mooring line 17	210942	22	2
Mooring line 18	226971	23	2
Anchor chain	226831	23	2
Buoy line	103460	11	2

Comparison of case studies 2 and 3

The results show that there are some differences in the axial tension force in the mooring lines when the system includes a moored service vessel. The difference is small but present. The following table contains the results from case 2 and case 3 and the difference between them.

	Case 2	Case 3	Difference
Component:	Axial tension load	Axial tension force	Axial tension force
name	[tonnes]	[tonnes]	%
Bridle rope	12	14	13.9
Grid rope A4-A5	25	25	0.3
Mooring line 15	19	19	0.3
Mooring line 16	18	18	1.1
Mooring line 17	20	22	7.7
Mooring line 18	22	23	7.0
Anchor chain	22	23	7.0
Buoy line	9	11	15.8

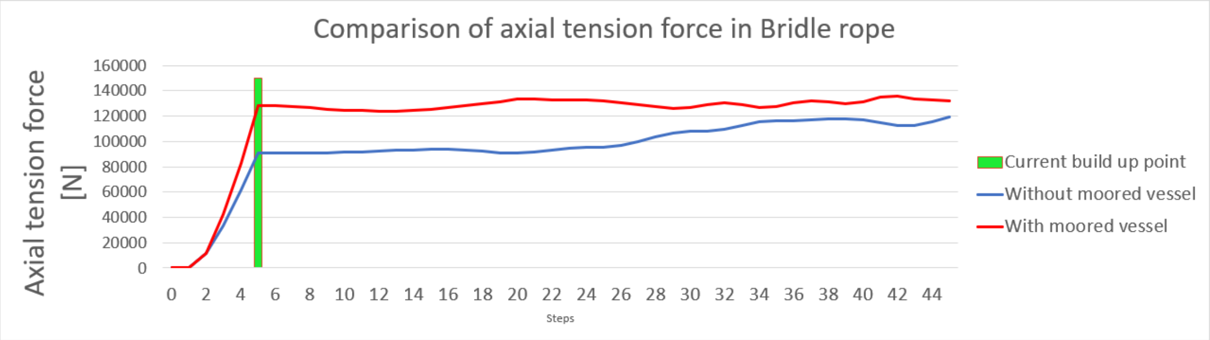

Figure 36 Axial force in bridle rope with and without moored service vessel

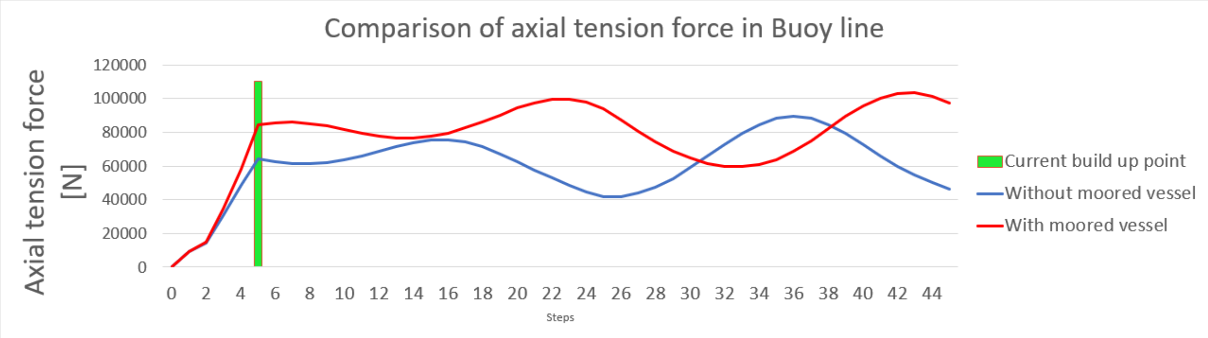

Figure 37 Comparison of axial force in buoy strap with and without service vessel

Figures 36 and 37 show the difference in the axial force with and without the service vessel moored alongside the floater with the most utilize mooring elements. The blue line represents the force in the element without the moored vessel. The red line represents the axial force with the moored vessel present. And the green bar illustrates the point where the current has reached maximum value and where the waves start to build up (increments).

6.3.4 Case 4: Accidental limit state (ALS)

Case 4
ALS (Accidental limit state)
Failure in the most utilized mooring line
Objective: How will the load distribute amongst the mooring lines if the most utilized mooring line should go to failure?

The most critical and utilized ropes are identified as mooring line number 18 and grid rope (A4-A5). Firstly, we look at how the load distribute amongst the lines when mooring line 18 goes to failure, secondly, we look at the same situation for when the grid rope (A4-A5) breaks. The increase or decrease in axial tension force will then be compared to the intact mooring system when a service vessel is attached to the floater (case 3). The word fault, break and breakages and so on, are all used to describe the state of the mooring elements when losing their holding power.

Failure in mooring line 18

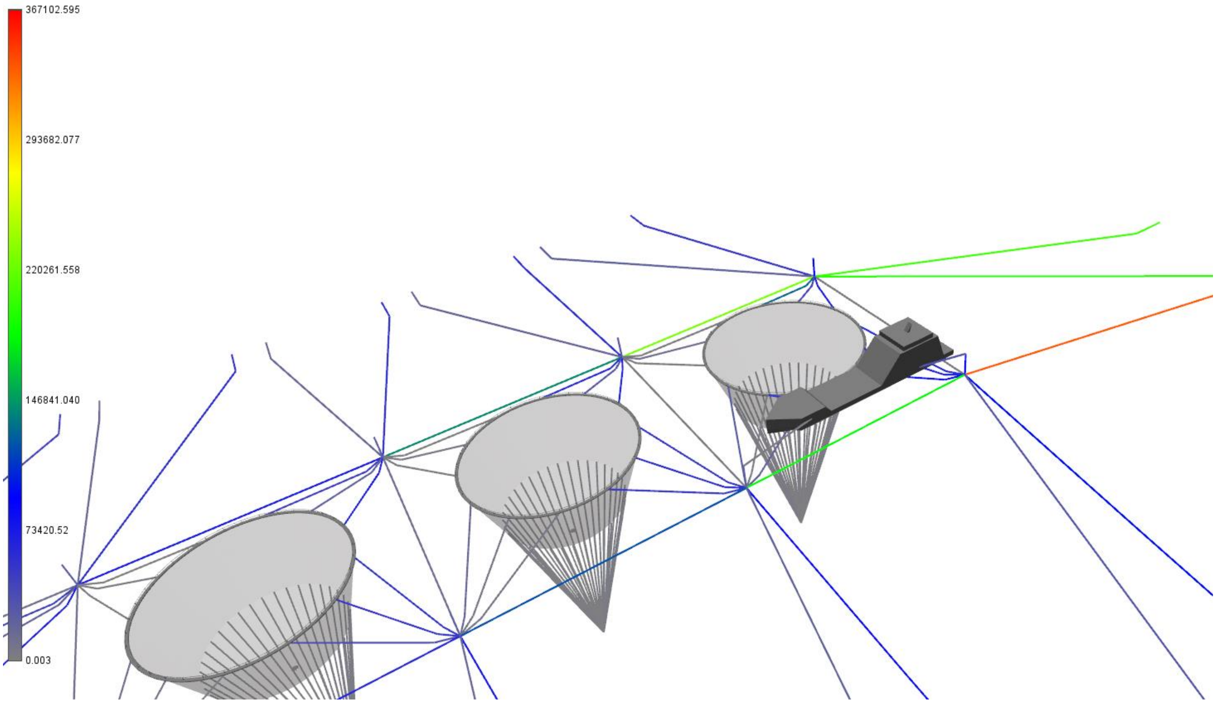

Figure 38 Axial force in mooring lines when mooring line 18 breaks

Table 16 Axial force in mooring lines, grid rope and anchor chain after accident

Component:	Case 3 (intact)	Failure in mooring line 18	Increase/decrease in axial tension force
name	[tonnes]	[tonnes]	%
Bridle rope	9	13	+45
Grid rope A4-A5	25	19	-24
Mooring line 15	19	21	+13
Mooring line 16	18	20	+14
Mooring line 17	22	34	+58
Mooring line 18	23	-	-
Chain	23	34,00	+47
Buoy line	11	10	-9

Compared to case 3 where we calculated the axial tension force in the most utilized mooring lines, buoy lines, bridle ropes, grid ropes and anchor chain we can see that in the case of breakage of mooring line 18 the force in the bridle rope goes up 45%, the grid rope decrease by 24%, mooring line 15 increase with 13%, mooring line 16 increase by 14%, anchor chain increase by 47% and the buoy line decrease with 9%. Based on the results it seems that it is the mooring line closest to mooring line 18, the anchor chain at the end of mooring line 17 and the bridle rope which takes the consequence of the breakage.

Failure in grid rope A4-A5

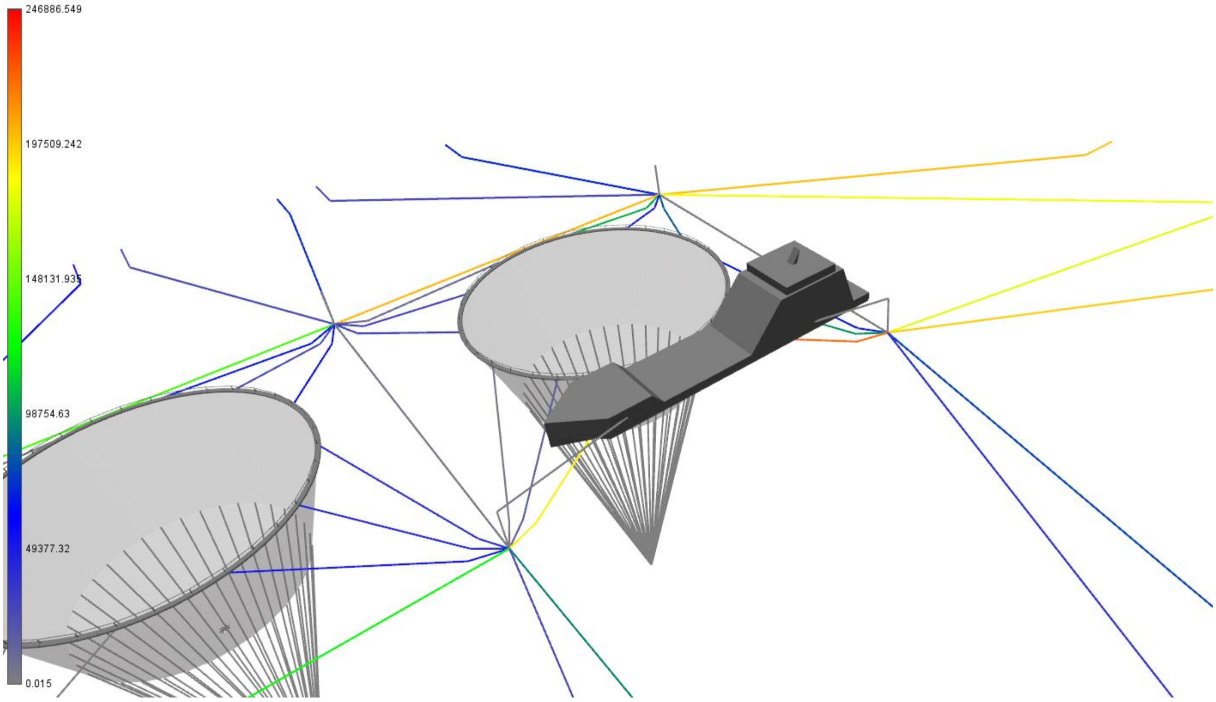

Figure 39 Axial force in mooring lines when grip rope A4-A5 breaks

Table 17 Axial force in mooring lines, grid rope, anchor chain and bridle rope after accident

Component	Case 3	Failure in grid rope A4-A5	Increase/decrease in axial force
name	[tonnes]	[tonnes]	%
Bridle rope	9	23	+146
Grid rope A4-A5	-	-	-
Mooring line 15	19	20	+8
Mooring line 16	18	19	+5
Mooring line 17	22	34	-15
Mooring line 18	23	20	-13
Anchor chain	23	34	-12
Buoy line	11	10	-14

From the results of the ALS when the grid rope A4-A5 breaks, it seems that it is the bridle rope which takes up the force of the faulted grid rope. As seen in table 17 the increase in bridle rope is 146%. I addition to absorb the forces from the grid rope it seems like the bridle rope takes up some of the loads of the rest of the ropes as well.

In the introduction we mentioned the revised requirements in NS9415:2021 for mooring analysis, and that the functional requirements concerning sea fastening of large service vessel alongside aquaculture fish farms should be analysed and documented. The rope most utilized when the grid rope goes to failure is one of the hen feet under the vessel (red line). Although a significant increase in axial tension force in this bridle rope, the MBL is not exceeded. The results from the case 2, 3 and 4 shows that when choosing material property and dimension of mooring lines, bridle ropes and grid ropes ULS and ALS should be performed with a service vessel moored alongside the floater with the most utilized ropes.

6.4 Vessel dynamics

Criteria for acceptable levels of ship motions have been discussed in the Nordic co-operative project "Seakeeping performance of ships" (NORDFORSK, 1987) [5]. Values for lateral and vertical accelerations and roll motions have been set for optimal human efficiency and safety. The values from NORDFORSK, 1987 will in this part be compared to values measured in the main hull of the modelled service vessel when exposed to irregular sea states. In addition to roll motion, the pitch motion is also investigated using the same criteria as for roll (4º).

The chosen wave headings are 89°, 135° and 175°. The headings are chosen because of the service vessel orientation ($85°\ from\ North$) and because these directions are estimated to generate the biggest wave heights. The vessel is placed pointing towards 265°. It is assumed that the dominating movement when influenced by waves originating from east, to be pitch and lateral acceleration (x acceleration in this case). When the vessel experience waves coming from 175° it is assumed that the vessel is dominated by roll motion and lateral acceleration (acceleration along y axis in this case). Waves heading from 135° is assumed to be the direction where combined roll and pitch motion and lateral accelerations in both x- and y-direction are the dominating motions in the vessel.

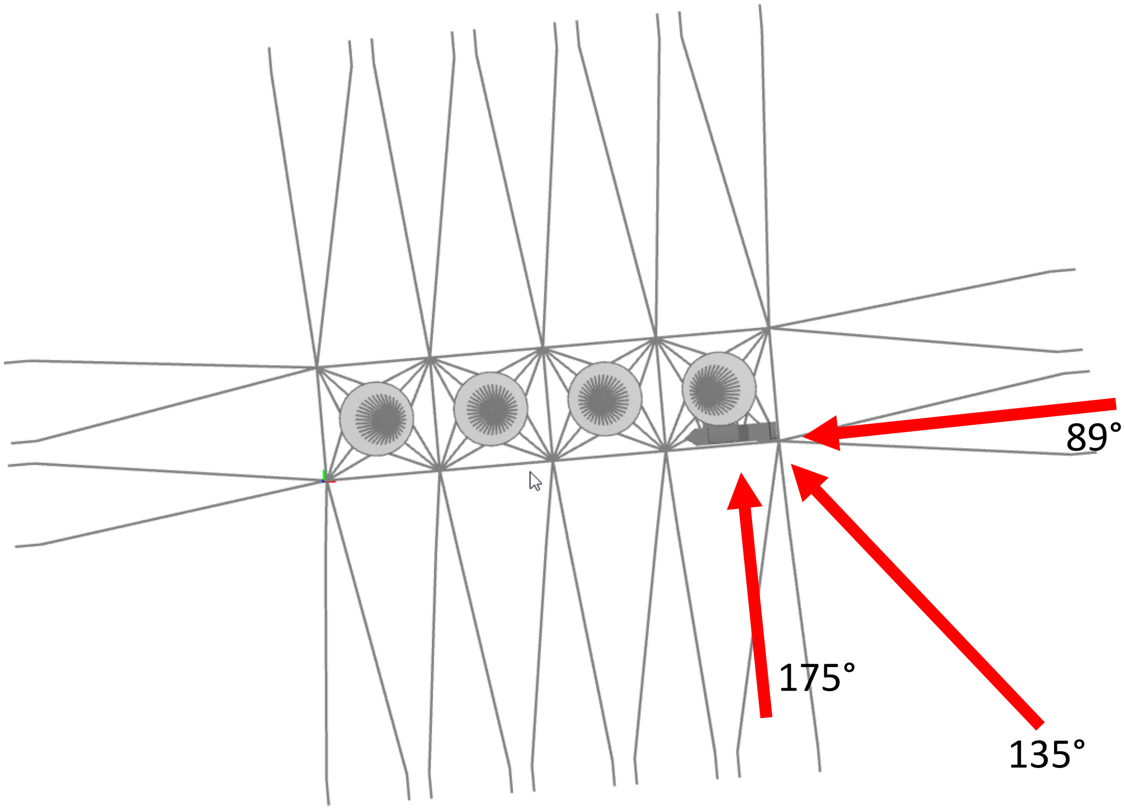

Figure 40 Wave headings

Table 18 and 19 summarize the cases used to answer the third RQ. Current and wind is now excluded from the analysis.

"How will the moored service vessels behave when introduced to design wave height and wave periods in the vicinity of the vessel eigenvalues?"

Table 18 Analysis of vessel natural periods

Case 5	
Natural period analysis of service vessel	
Translations	**Rotations**
Heave	*Yaw*
Surge	*Pitch*
Sway	*Roll*

Objective*: Calculate the vessels natural period in six DOF*

Table 19 Case 6: Hydrodynamical analysis

Case 6					
Hydrodynamical analysis					
Sea state	$System.H$	H_s [m]	$Wave.H$	T_z [s]	Waves
1	90°	$0.75 \leq H_s \leq 2.5$	89°	5.5	Irregular JONSWAP
2	90°	2.0	89°	$0.75 \leq T_z \leq 2.5$	
3	90°	2.0	135°	$2.0 \leq T_z \leq 5.5$	
4	90°	2.0	135°	$5.5 \leq T_z \leq 9.0$	
5	90°	2.0	175°	$2.6 \leq T_z \leq 3.8$	
6	90°	2.0	175°	$4.0 \leq T_z \leq 7.5$	
7	90°	$2.0 \leq H_s \leq 3.4$	175°	5.5	
System.H = orientation of system from North clockwise			Wave.H = wave heading from		CurrDirr = direction of the current towards

The reason for performing this analysis is to investigate which direction, wave period and wave height the vessel will experience the greatest movements and to establish some operational limiting criteria for wave period and wave height. One of these operational limiting criteria will then be our chosen as the operational limiting design criteria when performing a simple availability and weather window analysis.

6.5 Results Vessel dynamics

6.5.1 Case 5: Eigenvalue analysis

Table 20 Natural period when the vessel is floating freely

Unmoored

DOF	Natural periods [s]
Roll	2.5
Pitch	6.0
Heave	5.50

Table 21 Natural periods of the vessel when the weight of the vessel mooring lines are included

Moored

DOF	Natural periods [s]
Roll	6.7
Pitch	13.8
Heave	7.5

The values from the eigenvalues analysis are the results of the simplified vessel, and therefor may differ from a full-scale vessel. The natural periods of the vessel when the weight of the trusses is excluded (unmoored) is presented in table 20 and the natural period of the vessel when the weight of the trusses is included (moored) is presented in table 21. In the next case, case 6 we will iterate towards the most critical sea state and use one of these sea state in the risk assessment and availability and weather window analysis.

6.5.2 Case 6: Hydrodynamical analysis

In the following sub chapters the iteration towards operational limiting design criterias with regards to vessel motions is presented.

Table 22 Tz = 5.5 s and 0.75 < Hs < 2,5

RMS values wave heading 89°

	Pitch [°]	Roll [°]	Lateral acceleration $\left[\frac{m}{s^2}\right]$	Vertical acceleration $\left[\frac{m}{s^2}\right]$
NORDFORSK	4.0	4.0	0.69	1.47
H_s				
0.75	0.214	0.106	0.256	0.022
1.00	0.259	0.132	0.341	0.033
1.25	0.269	0.081	0.371	0.032
1.50	0.373	0.180	0.509	0.046
1.75	0.435	0.211	0.593	0.057
2.00	0.493	0.252	0.677	0.066
2.25	0.551	0.279	0.760	0.075
2.50	0.498	0.190	0.686	0.077

The first dynamical analysis shows that the RMS values calculated exceed the recommended NORDFORSK value for lateral acceleration when the significant wave height is 2.25 meters, and the wave period is 5.5 seconds. For this run we kept wave period constant and increased the significant wave height. Based on the results it seems that lateral acceleration, pitch, and roll has its peak somewhere between 2,0 and 2,25 meters. In the next three analysis we will keep significant wave height on a constant value of 2.0 meter and vary the wave period.

Table 23 Hs = 2.0 and 5.5 < Tz < 9.0

RMS values wave heading 89°

	Pitch [°]	Roll [°]	Lateral acceleration X $\left[\frac{m}{s^2}\right]$	Lateral acceleration Y $\left[\frac{m}{s^2}\right]$	Vertical acceleration $\left[\frac{m}{s^2}\right]$
NORDFORSK	4.0	4.0	0.690	0.690	1.47
T_z					
5.5	0.501	0.059	0.654	0.037	0.062
6.0	0.716	0.074	0.689	0.044	0.044
6.5	0.853	0.067	0.680	0.047	0.047
7.0	0.896	0.068	0.690	0.051	0.051
7.5	0.928	0.073	0.699	0.057	0.057
8.0	0.921	0.075	0.706	0.058	0.058
8.5	0.907	0.072	0.720	0.057	0.057
9.0	0.883	0.081	0.739	0.059	0.077

From table 23 we now see that the lateral x-acceleration exceeds the recommended RMS values from NORDFORSK when the wave period reaches 7.0 seconds. The wavelength is now 76.5 meters, and the waves are propagating against stern of service vessel, pushing it forward. Figure 40 illustrates the changes in lateral acceleration when a wave train composed of 50 irregular waves with a significant wave height of 2.0 meters and a corresponding wave period of 7.0 seconds influence the vessel.

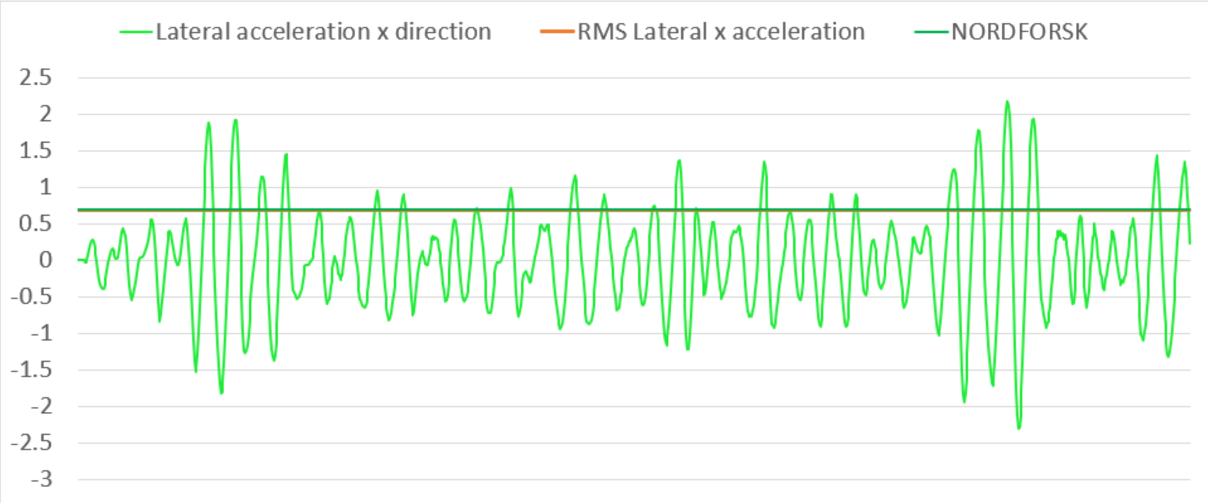

Figure 41 Changes in lateral acceleration during 50 irregular waves

We have now investigated motions in the vessel with waves propagating from 89° and will now look at the motions with a wave heading from 135°.

Table 24 Hs = 2.0 and 2.0 < T_z < 5.5

RMS values wave heading 135°

	Pitch [°]	Roll [°]	Lateral acceleration X $\left[\frac{m}{s^2}\right]$	Lateral acceleration Y $\left[\frac{m}{s^2}\right]$	Vertical acceleration $\left[\frac{m}{s^2}\right]$
NORDFORSK	4.0	4.0	0.690	0.690	1.47
T_z					
2.0	0.214	0.106	0.256	0.042	0.022
2.5	0.109	0.169	0.166	0.042	0.058
3.0	0.139	0.257	0.267	0.040	0.050
3.5	0.194	0.331	0.352	0.047	0.055
4.0	0.310	0.435	0.423	0.062	0.066
4.5	0.455	0.441	0.074	0.074	0.077
5.0	0.668	0.566	0.085	0.091	0.095
5.5	0.853	0.836	0.126	0.122	0.146

When the significant wave height is kept constant at 2.0 meters, and we vary the wave period from 2.0 seconds to 5.5 seconds the calculated RMS values stay below the recommended NORFORSK values for lateral and vertical accelerations and roll and pitch motions. In the next analysis we will keep increasing the wave period until one of the parameters is exceeded.

Table 25 Hs = 2,0 and 5.5 < T_z< 9.0

RMS values wave heading 135°

	Pitch [°]	Roll [°]	Lateral acceleration X $\left[\frac{m}{s^2}\right]$	Lateral acceleration Y $\left[\frac{m}{s^2}\right]$	Vertical acceleration $\left[\frac{m}{s^2}\right]$
NORDFORSK	4.0	4.0	0.690	0.690	1.47
T_z					
5.5	0.968	0.983	0.593	0.141	0.171
6.0	0.932	1.018	0.567	0.141	0.171
6.5	0.958	1.138	0.586	0.152	0.187
7.0	0.943	1.149	0.615	0.150	0.195
7.5	0.909	1.112	0.642	0.141	0.188
8.0	0.876	1.078	0.659	0.134	0.183
8.5	0.838	1.037	0.681	0.127	0.172
9.0	0.812	0.994	0.702	0.121	0.176

When the waves are propagating from 135° the lateral x-acceleration is exceeded when the wave period is 9.0 seconds. The waves are now hitting the vessel port, stern, inducing lateral acceleration in x and y direction at the same time making the vessel rotate about x and y axis (roll and pitch). By the calculated values we can see that the acceleration in x direction exceeds the NORDFORSK value for lateral x acceleration.

The result from our analysis so far shows that when the waves are propagating from the East the lateral x acceleration is the limiting factor. When the wave heading is from South-East the limiting factor is also the lateral x acceleration. We therefore conclude that the operational limiting parameters for this operation is when the sea states progressing from 89° and 135° are:

Table 26 Operational limiting criteria for east and South-East direction (89°,135°)

Wave heading 135°	Wave heading 89°
$OP_{lim,Tz} = 9.0\ s$	$OP_{lim,Tz} = 7.0\ s$
$OP_{lim,Hs} = 2.0\ m$	$OP_{lim,Hs} = 2.0\ m$
$OP_{lim,U} = 12\ \frac{m}{s}$	$OP_{lim,U} = 12\ \frac{m}{s}$

Table 27 Hs = 2,0 and 2,0 < T_z< 3.8

RMS values wave heading 175°

	Pitch [°]	Roll [°]	Lateral acceleration X $\left[\frac{m}{s^2}\right]$	Lateral acceleration Y $\left[\frac{m}{s^2}\right]$	Vertical acceleration $\left[\frac{m}{s^2}\right]$
NORDFORSK	4.0	4.0	0.690	0.690	1.47
T_z					
2,6	0.278	2.823	0.270	0.305	0.352
2,7	0.271	2.858	0.263	0.254	0.404
2,8	0.278	2.885	0.265	0.249	0.442
3,0	0.290	2.942	0.282	0.254	0.523
3,2	0.313	3.006	0.312	0.264	0.586
3,4	0.317	2.950	0.330	0.265	0.597
3,6	0.344	3.121	0.373	0.280	0.661
3,8	0.356	3.180	0.403	0.286	0.669

The waves are now travelling against the vessel from the south (90° from north of the vessel). The NORDFORSK values are not exceeded, but the RMS roll is closing in on four degrees. Therefore, we will keep increasing the wave period in the next analysis until the recommended RMS value in roll is reached.

Table 28 Hs = 2.0 and 4.0 < T_z < 7.5

RMS values wave heading 175°

	Pitch [°]	Roll [°]	Lateral acceleration X $\left[\frac{m}{s^2}\right]$	Lateral acceleration Y $\left[\frac{m}{s^2}\right]$	Vertical acceleration $\left[\frac{m}{s^2}\right]$
NORDFORSK	4.0	4.0	0.690	0.690	1.47
T_z					
4,0	0.366	3.239	0.431	0.293	0.668
4,5	0.371	3.371	0.491	0.297	0.625
5,0	0.371	3.450	0.537	0.291	0.571
5,5	0.370	3.474	0.572	0.276	0.518
6,0	0.363	3.443	0.601	0.257	0.465
6,5	0.352	3.369	0.626	0.237	0.412
7,0	0.340	3.256	0.647	0.221	0.378
7,5	0.329	3.120	0.664	0.208	0.356

The analysis shows that the RMS roll, peaked when the wave period was 5.5 seconds and when waves are entering the vessels side. Therefore, one last analysis is performed by increasing the wave height and keeping at T_z constant at this value.

Table 29 $T_z = 5.5\ seconds\ and\ 2.0 \leq H_s \leq 3.4\ meters$

RMS values wave heading 175°

	Pitch [°]	Roll [°]	Lateral acceleration X $\left[\frac{m}{s^2}\right]$	Lateral acceleration Y $\left[\frac{m}{s^2}\right]$	Vertical acceleration $\left[\frac{m}{s^2}\right]$
NORDFORSK	4.0	4.0	0.690	0.690	1.47
H_s					
2,0	0.369	3.475	0.572	0.272	0.504
2,2	0.399	3.815	0.631	0.300	0.558
2,4	0.431	4.218	0.719	0.330	0.606
2,6	0.456	4.485	0.753	0.347	0.640
2,8	0.483	4.807	0.816	0.373	0.689
3,0	0.509	5.124	0.879	0.397	0.735
3,2	0.536	5.445	0.942	0.942	0.424
3,4	0.567	5.769	1.005	0.444	0.823

When we kept T_z constant at 5.5 seconds and investigate an interval of significant wave heights between 2.0 and 3.4 we can see that the recommended NORDFORSK RMS value is exceeded when the significant wave height is 2.4 meters. The lateral acceleration in x direction is also exceeded at this sea state. Based on these results the operational limiting sea state parameters are set to:

Table 30 Operational limiting criteria for south direction (175°)

Wave heading 175°
$OP_{lim,Tz} = 5.5\ s$
$OP_{lim,Hs} = 2.4\ m$
$OP_{lim,U} = 12\ \frac{m}{s}$

Operational limiting criteria are now established for the modelled vessel in three directions 89°, 135° and 175°. With the usage of the operational limiting criteria in table 30, we will first perform an availability and weather window analysis, and thereafter conduct a risk assessment on a planned operation. For the planning and execution, the parameter used is the significant wave height parameter.

Chapter 7 Operational analysis results

Based on the results from case 5 and 6 we will analyse weather windows for performing service vessel operations. A weather window analysis will be performed using historical wave data for the planning and execution. The planning will use 10 years of historical wave data (2010-2020) while we will use a random period of one week during a winter month to illustrate how execution of an operation can be done using the alpha factor method and operational limiting criteria gained from hydrodynamical analysis.

7.1.1 Planning

The period chosen to investigate the availability of an aquaculture site is 2010 to 2020. The raw data is obtained from a public third party. The raw data is not data specifically from the location of Site A, but for this thesis we assume that it is. The purpose of this part of the thesis is how we can use wave data to investigate the availability of a location based on operational limiting criteria established by using hydrodynamical analysis software (in this case AquaSim).

As mentioned earlier in the thesis, we will use the results from case 5 and 6 to determine the operational limiting criteria ($OP_{lim,D}$). From case 5 we calculated the modelled vessels natural periods. We then moved on to case 6 where the RMS values for pitch, roll and lateral, and vertical acceleration was estimated based on several hydrodynamical analysis. For the first analysis we kept wave period constant (5.5 seconds) and varied the significant wave height. The following analysis we kept significant wave height constant and varied the wave period and wave heading. The last analysis we again kept the wave period constant and varied the significant wave height. The results showed that by keeping the wave period constant in the vicinity of the vessels natural period in pitch, the RMS values did not vary significantly. On the other hand, when varying the wave period and keeping the wave height on a constant value, we saw that pitch motion and lateral acceleration exceeded the NORDFORSK RMS values at 7.0- and 9.0-seconds wave periods when the wave headings were 89 and 135 degrees.

Based on the results the determined threshold values for significant wave height, wave period and wind speed for sea states from 89°, 135° and 175° has been chosen to be:

Table 31 Operational limiting criteria for wave heading 89 degrees

Operational limiting criteria for sea states from 89° (East)	
$OP_{lim,Hs}$	2.0 [m]
$OP_{lim,Tz}$	7.0 [s]
$OP_{lim,U}$	12 [m/s]

Table 32 Operational limiting criteria for wave heading 135 degrees

Operational limiting criteria for sea states from 135° (South-East)	
$OP_{lim,Hs}$	2.0 [m]
$OP_{lim,Tz}$	9.0 [s]
$OP_{lim,U}$	12 [m/s]

Table 33 Operational limiting criteria for wave heading 175 degrees

Operational limiting criteria for sea states from 175° (South-East)	
$OP_{lim,Hs}$	2,4 [m]
$OP_{lim,Tz}$	5.5 [s]
$OP_{lim,U}$	12 [m/s]

The established operational limiting criteria are now used together with wave data from a specific site location to identify the number of hours for each month it is possible for the modelled vessel to stay below pre-determined threshold values (operational limiting criteria for sea states). The limiting criterion for this evaluation is the significant wave height criteria.

Table 34 Significant wave height values for each month during a 10-year period

Significant Wave Heights values for each month during a 10-year period

Months	0.0 < Hs < 0.4	0.4< Hs < 0.8	0.8 < Hs < 1.2	1.2 < Hs < 1.6	1.6 < Hs < 2.0	2.0 < Hs < 2.4
JAN	3799	1972	1082	674	330	150
FEB	3626	1781	1034	557	226	104
MAR	4613	1833	1107	371	200	48
APR	5642	1674	391	157	41	15
MAI	5740	1334	243	65	21	23
JUN	5952	989	143	54	32	27
JUL	5751	1475	174	40	0	0
AUG	5394	1608	332	69	19	16
SEP	4389	1566	679	350	116	56
OKT	4137	1693	1014	390	124	72
NOV	3917	1564	919	393	227	122
DES	3047	1677	980	661	466	308
Total hours	56007	19166	8098	3781	1802	941
% of total	62 %	21 %	9 %	4 %	2.0 %	1.0 %

Number of hours significant wave heights value for each month in a 10 year period												
Month	0.0 < Hs < 0.4	0.4< Hs < 0.8	0.8 < Hs < 1.2	1.2 < Hs < 1.6	1.6 < Hs < 2.0	2.0 < Hs < 2.4	2.4 < Hs < 2.8	2.8 < Hs < 3.2	3.2 < Hs < 3.6	3.6 < Hs < 4.0	4.0 < Hs < 4.4	Total hours
JAN	3799	1972	1082	674	330	150	94	48	22	13	0	8184
FEB	3626	1781	1034	557	226	104	57	42	20	17	0	7464
MAR	4613	1833	1107	371	200	48	5	2	2	3	0	8184
APR	5642	1674	391	157	41	15	0	0	0	0	0	7920
MAI	5740	1334	243	65	21	23	6	8	0	0	0	7440
JUN	5952	989	143	54	32	27	2	1	0	0	0	7200
JUL	5751	1475	174	40	0	0	0	0	0	0	0	7440
AUG	5394	1608	332	69	19	16	2	0	0	0	0	7440
SEP	4389	1566	679	350	116	56	30	9	4	1	0	7200
OKT	4137	1693	1014	390	124	72	8	2	0	0	0	7440
NOV	3917	1564	919	393	227	122	40	8	8	2	0	7200
DES	3047	1677	980	661	466	308	210	73	11	5	2	7440
Total	56007	19166	8098	3781	1802	941	454	193	67	41	2	90552
Total %	62 %	21 %	9 %	4 %	2.0 %	1.0 %	0.5 %	0.2 %	0.1 %	0.05 %	0.002 %	100 %

Figure 42 First results presented in a pivot table generated in the excel file “Availability and weather window analysis

From table 34 we can see the number of hours the significant wave height was under 2.4 meters for each calendar month during a period of 10 years. Based on this we can with a certain confidence say that the this is what is expected for the next 10 years. inside each row there is data for each month over a 10-year period. The next table presents the same data but now as percentage of the total sum of each row.

Table 35 10-year wave data separated into 12 months

Significant Wave Heights values for each month during a 10-year period

Months	0.0 < Hs < 0.4	0.4< Hs < 0.8	0.8 < Hs < 1.2	1.2 < Hs < 1.6	1.6 < Hs < 2.0	2.0 < Hs < 2.4
JAN	46 %	24 %	13 %	8 %	4 %	2 %
FEB	49 %	24 %	14 %	7 %	3 %	1 %
MAR	56 %	22 %	14 %	5 %	2 %	1 %
APR	71 %	21 %	5 %	2 %	1 %	0.2 %
MAI	77 %	18 %	3 %	1 %	0.28 %	0.31 %
JUN	83 %	14 %	2 %	1 %	0.44 %	0.38 %
JUL	77 %	20 %	2 %	1 %	0 %	0 %
AUG	73 %	22 %	4 %	1 %	0.3 %	0.2 %
SEP	61 %	22 %	9 %	5 %	2 %	1 %
OKT	56 %	23 %	14 %	5 %	2 %	1 %
NOV	54 %	22 %	13 %	5 %	3 %	2 %
DES	41 %	23 %	13 %	9 %	6 %	4 %

Number of hours significant wave heights value for each month in a 10 year period												
Month	0.0 < Hs < 0.4	0.4< Hs < 0.8	0.8 < Hs < 1.2	1.2 < Hs < 1.6	1.6 < Hs < 2.0	2.0 < Hs < 2.4	2.4 < Hs < 2.8	2.8 < Hs < 3.2	3.2 < Hs < 3.6	3.6 < Hs < 4.0	4.0 < Hs < 4.4	Total hours
JAN	46.42 %	24.10 %	13.22 %	8.24 %	4.03 %	1.83 %	1.15 %	0.59 %	0.27 %	0.16 %	0.00 %	100.00 %
FEB	48.58 %	23.86 %	13.85 %	7.46 %	3.03 %	1.39 %	0.76 %	0.56 %	0.27 %	0.23 %	0.00 %	100.00 %
MAR	56.37 %	22.40 %	13.53 %	4.53 %	2.44 %	0.59 %	0.06 %	0.02 %	0.02 %	0.04 %	0.00 %	100.00 %
APR	71.24 %	21.14 %	4.94 %	1.98 %	0.52 %	0.19 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	100.00 %
MAI	77.15 %	17.93 %	3.27 %	0.87 %	0.28 %	0.31 %	0.08 %	0.11 %	0.00 %	0.00 %	0.00 %	100.00 %
JUN	82.67 %	13.74 %	1.99 %	0.75 %	0.44 %	0.38 %	0.03 %	0.01 %	0.00 %	0.00 %	0.00 %	100.00 %
JUL	77.30 %	19.83 %	2.34 %	0.54 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	100.00 %
AUG	72.50 %	21.61 %	4.46 %	0.93 %	0.26 %	0.22 %	0.03 %	0.00 %	0.00 %	0.00 %	0.00 %	100.00 %
SEP	60.96 %	21.75 %	9.43 %	4.86 %	1.61 %	0.78 %	0.42 %	0.13 %	0.06 %	0.01 %	0.00 %	100.00 %
OKT	55.60 %	22.76 %	13.63 %	5.24 %	1.67 %	0.97 %	0.11 %	0.03 %	0.00 %	0.00 %	0.00 %	100.00 %
NOV	54.40 %	21.72 %	12.76 %	5.46 %	3.15 %	1.69 %	0.56 %	0.11 %	0.11 %	0.03 %	0.00 %	100.00 %
DES	40.95 %	22.54 %	13.17 %	8.88 %	6.26 %	4.14 %	2.82 %	0.98 %	0.15 %	0.07 %	0.03 %	100.00 %
Total	61.85 %	21.17 %	8.94 %	4.18 %	1.99 %	1.04 %	0.50 %	0.21 %	0.07 %	0.05 %	0.00 %	100.00 %

Figure 43 Second results presented in a pivot table generated in the excel file "Availability and weather window analysis"

All the occurring significant wave height measured for one month over 10 years are analysed against six intervals. If we take January as an example, based on the 10-year recordings of significant wave height during January month, 46% can be found in the interval 0.0 < Hs < 0.4. 91% of the recorded significant wave heights this month has a value between 0.0 and 1.6 meters. Based on the 10-year wave data significant wave heights seldom find themselves in the vicinity of or over 2.4 meters, which were the identified threshold value derived from hydrodynamical analysis. But may occur. From the same wave data, a scatter diagram for the location has been generated in excel and can be found in the excel attached excel file "availability and weather window analysis".

Table 36 Scatter diagram relevant for the specific location

T_z [s] / H_s [m]	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	14-15	Tot.
0-0.4	18434	7210	*6154*	8359	5685	5416	3681	655			413	56007
0.4-0.8	2690	1127	2061	6059	1882	2049	2951	343	4			19166
0.8-1.2		827	86	3016	2106	832	1147	75	6	3		8098
1.2-1.6		80	122	779	1389	842	495	58	10	6		3781
1.6-2.0		3	89	57	484	716	397	39	14	3		1802
2.0-2.4		1	82	14	122	354	324	38	6			941
2.4-2.8			6		36	153	226	32	1			454
2.8-3.2			6		1	26	141	14	5			193
3.2-3.6						10	46	11				67
3.6-4.0							36	5				41
4.0-4.4							2					2
Tot.	21124	9248	8606	18284	11705	10398	9446	1270	46	12	413	90552

With the scatter diagram we can calculate the probability of the different significant wave height intervals occurring simultaneous with the different zero-up-crossing intervals. An example on how we can use such scatter diagrams to find the probability of different sea states is provided for the usage in the risk analysis. So let us look at the probability that the established limiting criteria in table 31 occurs. Again, wind is not accounted for.

1. Calculate the probability of $2.0 \leq H_s \leq 2.4$ and $5.0 \leq T_z \leq 6.0$
   a. Event A: $2.0 \leq H_s \leq 2.4$
   b. Event B: $5.0 \leq T_z \leq 6.0$

- $P(B|A) = \frac{P(A \cap B)}{P(A)}$
- Where $(A \cap B)$ is number of observations where A and B occurs simultaneous
  - 82 (red number in table 34)
- And $P(A)$ is total number of observations of event A.
  - 941 (red number in table 34)

$$P(B|A) = \frac{favorable\ outcomes}{possible\ outcomes} = \frac{82}{90552} = 0.0009$$

$$P(A) = \frac{favorable\ outcomes}{possible\ outcomes} = \frac{941}{90552} = 0.0104$$

$$P(B|A) = \frac{P(A \cap B)}{P(A)} = \frac{0,0009}{0,0104} = 8.7\%$$

The established operational criteria we calculated using hydrodynamical analysis software have been calculated to have a small chance of occurring based on wave data from a 10-year period (≈ 9%).

7.1.2 Execution

An arbitrary period is chosen for the execution of an operations which demands assistance from a large service vessel like the modelled service vessel in this thesis. The chosen period is one week in February month, year 2020. We assume that this period is forecasted weather data and we will use this to evaluate the potential weather windows. The weather windows where the wave parameter is below the operational limiting criteria is denoted “calm period”, and the weather windows where the wave parameter is above the operational limiting criteria is denoted “Storm periods” [14].

The operation involves delousing all the four modelled enclosures. The last weather forecast is assumed issued on Sunday 2300 hours by two independent forecasters. At 0000 hours on Monday the vessels and crew are ready for transfer from port to the aquaculture fish farm. The operation is considered as rather standard, meaning that the maximum contingency time (T_c) is assumed equal to the planned operation time (T_{POP}). The operation is now divided into phases and listed in table 37.

Table 37 Operation phases

Phase		T_{POP}	H_s	T_p	U_{ref}	Reason
1	Transfer to the fish farm	0.5 hours	2.4 [m]	5.5 [s]	12 [m/s]	calculations
2	Delousing operation of four enclosures	10 hours	2.4 [m]	5.5 [s]	12 [m/s]	calculations
3	Transfer back to port	0.5 hours	2.4 [m]	5.5 [s]	12 [m/s]	calculations
	Total operation time	11 hours				

For the first part of the operation, phase 1, transfer time is the estimated time it takes for the vessel to sail from port to the aquaculture fish farm. The second phase is the estimated time it takes to delouse four enclosures. This phase includes the time it takes to moor the vessel, finish the delousing operation, cut the moorings, and then move on to the next enclosure.

The alpha-factor method will be used as described in chapter 4.5. Step one: defining operational limiting criteria ($OP_{lim,D)}$ has already been performed and are based on the results from the hydrodynamical analysis in chapter 6.4. We will now move on to step two: define operation reference period, T_R. T_R is calculated using equation (4.25). The contingency time (T_C) has not been assessed and therefore set to equal to planned operation period (T_{POP}) and based on the results we get the alpha factor. These alpha factors are relevant for waves in the North Sea, so they may be conservative.

Table 38 Estimations of adjusted operational limiting criteria (H_s)

Phase		T_{POP}	T_C	T_R	$\propto_{factor}$	H_s
1.0	Transfer to the fish farm	0.5 hours	0.5 hours	1.0 hours	0.76	1.7 m
1.1	Delousing operation of four enclosures	10 hours	10 hours	20 hours	0.71	1.7 m
1.2	Transfer back to port	0.5 hours	0.5 hours	1.0 hours	0.76	1.7 m
	Total operation time	11 hours	11 hours	22 hours		

We now have calculated T_R to be 22 hours and the relevant alpha factors are obtained from table 5. We can now start the evaluation of the forecasted weather against the reference period, planned operational period and significant wave height criteria. An excel file has been created by the writer for this purpose and the results are snapshots of the results.

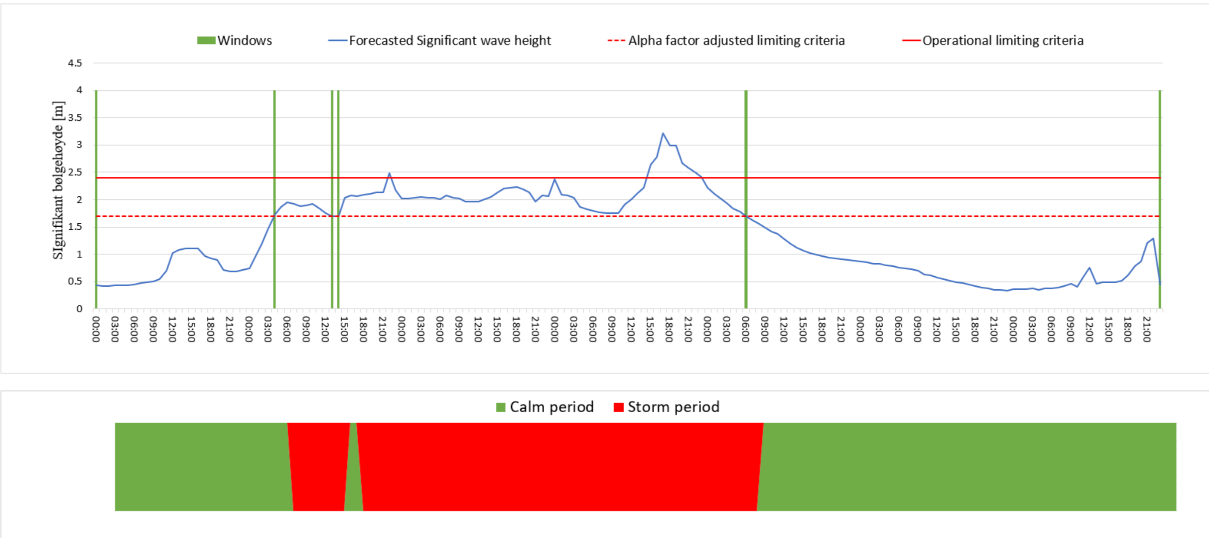

Figure 44 Weather window analysis for one week in February month, year 2020.

The blue line illustrates the change in significant wave height every hour for the next seven days. The red dotted line illustrates the alpha factor adjusted limiting criteria, and the red line illustrate the predetermined operational limiting design criteria. The vertical axis shows the significant wave height and the horizontal axis show the time. The green bars indicate the windows present during these seven days in February month, year 2020. The second graph visualises the calm and storm periods throughout the week, where the green area represents the calm periods, and the red area represents the storm periods.

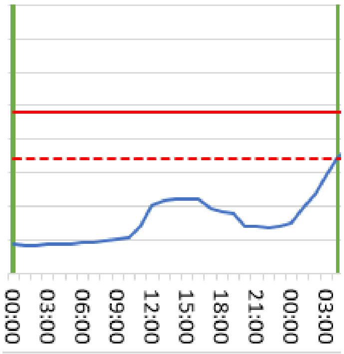

Figure 45 First weather opening in the scheduled week

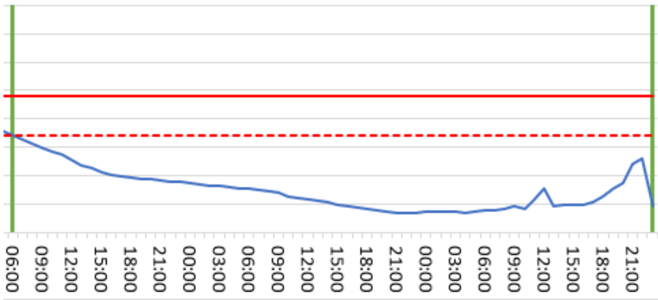

Figure 46 Second opening for that scheduled week

With a calculated reference period of 22 hours and the adjusted operational limiting criteria for significant wave height being 1.7 m after accounting for the determined alpha factor we see that the operation must be finished between 0000 hours and 0300 hours (Monday/Tuesday) (figure 45) or the crew and vessel must wait for 75 hours before re-attempting the operation, where they will have 63 hours to complete the operation.

Chapter 8 Risk assessment results

In chapter 4.4 some bullet points where listed. One of these bullet points mentioned that the new revised NS9415:2021 demands a risk assessment and that the simplifications, assumptions and prerequisites are stated before conduction such an analysis. The simplifications for this risk assessment are:

- simplified models are used to calculate the vessel motions and therefore may differ from full scale vessels.
- Regular 50-year waves are used to identify the axial forces in the mooring lines, meaning that the results will be conservative.
- The estimated design waves are based on a simple method using fetch length and fetch width and does not include swell waves, bottom effects, interference, and reflection from steep hillsides.

The assumptions made are:

- The sea states are assumed to be like the critical sea state used in the operational analysis and therefore the probability for chosen unwanted incidents are higher than for calm waters. The probability of the calculated critical sea state has been calculated to be 9% (approximately once every fifth year and once every 10th year).

	Probaility	Consequence	
expected	6		
very likely	5	1	harmless
more likely	4	2	a certain danger
likely	3	3	dangerous
less unlikely	2	4	critical
very unlikely	1	5	disastrous

Figure 47 Probability and consequence ranking

Risk matrix						
Consequence		1	2	3	4	5
Probability	6					
	5		1			
	4		1			
	3			1	1	
	2		3	2		2
	1					

Figure 48 Number of occurrences. probability and consequence

Risk Assesment

Prosject: Master thesis | Created by: Martin R. Vestbø | Updated: 18.05.2022

						Initial risik (without measures)				Residual Risik (after mesures)		
Analyse object	#	HAZARD	Cause	Consequence (description)	Consequence (hazard type/loss)	Probability	Consequence	Risk acceptance	Risk reducing measures	Residual probability	Residual consequence	Risk acceptance
vessel	1	Roll motion exceeding NORDFORSK	Environmental conditions exceeding operational limiting criteria	loose equipment roaming freely on deck	Life and helth	2	3	Moderate	Sea fastening of equipment, keeping your back cleared	1	2	acceptable
			Environmental conditions exceeding operational limiting criteria	man over board	Life and helth	2	5	critical	JSA before operations start, personal safety equipments, lifewest	1	4	Moderate
			Environmental conditions exceeding operational limiting criteria	loss of balance	Life and helth	2	3	Moderate	Hands on railings, personel safety equipment	1	4	Moderate
			Environmental conditions exceeding operational limiting criteria	snap loads in vessel moorings, bridle ropes, buoy strap	Operation, production and service	2	2	acceptable	visual check of vessel mooring lines, right mooringline dimension	1	2	acceptable

Figure 49 Risk assessment results 1

vessel	2	Lateral accelerations exceeding NORDFORSK	Environmental conditions exceeding operational limiting criteria	Breakage in buoy strap used for vessel mooring	Operation, production and service	2	2	acceptable	moving the vessel to a more suitable position	1	2	acceptable
			Environmental conditions exceeding operational limiting criteria	Sea sickness	Life and helth	5	2	Moderate	hydration breaks	3	2	acceptable
			Environmental conditions exceeding operational limiting criteria	delousing tube moving from enclosure to sea.	Fish escape	3	4	critical	Sea fastening of delousing tube	2	3	Moderate
			Environmental conditions exceeding operational limiting criteria	personell caught between floater and boat due to loss of balance	Life and helth	2	5	critical	firm sea fastening of vessel to floater. Risk assesment	3	3	Moderate

Figure 50 Risk assessment results 2

vessel	3	Pitch motions exceeding NORDFORSK	Environmental conditions exceeding operational limiting criteria	slamming	economic and material values	2	2	acceptable	Identifying critical sea states for pitch motions	4	1	acceptable
			Environmental conditions exceeding operational limiting criteria	wear and tear of equipment	economic and material values	4	2	Moderate	adequente sea fastening of equipment	3	2	acceptable
			Environmental conditions exceeding operational limiting criteria	Failure in vessel mooring lines fra vessel to floater	Operation, production and service	3	3	Moderate	making sure that the mooring lines posesses adequent MBL	2	3	Moderate

Figure 51 Risk assessment results 3

A risk assessment would have been more valuable if performed by a team consisting of personnel with different background and subject of expertise. The objective of this risk assessment was to show how one can identify hazards, evaluate the risk acceptance criteria, and based on this implement mitigating measurements to reduce the risk and increase the safety onboard vessels. The risk assessment setup can be viewed attachment under the name “Risk assessment master thesis”.

Chapter 9 Discussion

After the introduction and research questions the main components in an aquaculture fish farm was described. These where enclosure, floater, mooring system, and barge. The barge was neglected because the thesis does not include the barge in the analysis, and it is not part of the scope of the project. Although the barge is one of four main components it can be viewed as a separate system since it has its own mooring system and are not in direct contact with the enclosure, floater, and mooring system.

After describing three out of the four main components, the thesis moves on to a description of the surrounding environment. The location chosen is the fjord system outside my bedroom window and was found to be an appropriate location because of its specific characteristics. The fjord system has four distinct main directions, hence the name «the cross fjord». We measured the fetch lengths of these four main directions using google maps. For an even more detailed measurement of these distances an Olex-plot could have been used. These detailed maps are often used on vessels in the industry. The fetch lengths were then used to estimate the 50-year significant wave heights based on a 50-year reference wind relevant for the county where site A is located. This parameter could have been obtained using a more detailed method, such as 10 minutes measurements taken at a height of 10 meters over the water surface over a three-month period at the exact location or used wind data over the last 50 years.

The fetch length method used in this thesis is a simplified approach and does not account for water depth, steep hillsides (reflection), swell waves, bottom effects, or interference. According to NS9415:2009, when using the fetch length method, calculations of significant wave heights should be calculated for eight sectors where the size of the sectors is $\pm 12°$, with one fetch length every 1 to 3 degrees [6]. For this thesis, the greatest fetch length for each direction is used and thereby the possible highest significant wave height calculated.

In chapter four an attempt to describe the wave theories and how the external forces due to waves, wind and currents generate movements in a floating object is presented. The assumptions and approximations are described. As mentioned, the scope of the thesis is not to show the reader how the equations and methods are derived, but to give the reader some basic knowledge on how the analysis software calculate external and internal forces in and on the modelled elements. The criteria for convergence were achieved for all the analysis completed, and apart from the simplifications made, the results may be viewed as valid.

When the theoretical chapter is completed, the modelling phase is explained. The modelled aquaculture fish farm is inspired from the design of one of many aquaculture fish farms located in the fjord system. We could have used other shapes and sizes for the enclosure and floater or used longer and deeper mooring lines, but to answer the research questions and to dig deeper into the procedure on how to model such structures in AquaSim this design was chosen to be sufficient. With aid from the

AquaSim training course tutorial manual, the modelling of the aquaculture fish farm was a straightforward process. The modelling of vessels proved to be much more challenging and time consuming. As mentioned, the structures in AquaSim are modelled either as trusses or beam elements. If one chooses the beam elements, we can give the element a cross section, material properties and choose which load model we intend to calculate the forces with. It proved to be a challenging task to model a vessel as realistically as possible, and I would not recommend using AquaSim for this task. There are some procedures on how we can model barges in AquaSim found on the Aquastructures website, but not how to model ships. Because of this, it proved to be a time-consuming task, modelling the service vessel. When all comes to all, I am quite satisfied with the result, although it would have been interesting to model a couple more vessels with the same main dimensions but with different hull shapes to investigate the difference in vessel movements, and if a more simplified or more detailed model would have given the same results.

The procedure chosen to investigate the RQs was to set up six cases, one for each of the analyse phases. We started with a static analysis to determine the necessary buoy sizes and to validate the modelled aquaculture fish farm models floating capability. The second case involved investigating the axial force in the mooring lines without a moored service vessel present. For the third case we merged the modelled vessel design together with the modelled aquaculture fish farm and investigated the axial force in the mooring lines to answer the first RQ. After comparing case 2 and case 3 we moved on to analyse the impact on the mooring lines when the most utilized mooring lines went to failure (the ALS analysis). For another thesis it would be interesting to vary the draught of the vessel and to analyse the impact this would have on the mooring lines. It should also be mentioned that we kept the vessel at one position throughout the entire analysis and therefore narrowing the results.

AquaSim proves to be a fantastic software when it comes to mooring analysis. The program is easy to use, and it has an initiative interface (AquaEdit) and gives us great visualisation possibilities of the results in AquaView. I have used other analysis software such as SESAM by DNVGL, and opensource programs like OpenFOAM, but when it comes to mooring analysis, AquaSim proves more valuable than either of them. That being said, if the sole purpose is to perform hydrodynamical analysis and modelling of floating vessels AquaSim has a long way to go compared to SESAM by DNVGL.

For the vessel movements the RMS values for lateral- and vertical acceleration and roll motions were used as reference. The mooring analysis was done using regular waves, while for the analysis of vessel motion we used a JONSWAP wave spectrum (irregular waves). The analysis involved varying the significant wave height and wave period for three wave headings. These headings were 89°, 135° and 175°. Heading 89° and 135° corresponds to east and south-east directions and was identified as the two greatest fetch lengths and therefore chosen to investigate. Waves coming from 175 was to induce enough movements in the vessel so that the RMS in roll was exceeded.

After establishing three operational limiting sea states we continued to the operational analysis. Here we used available hindcast wave data (10 years) to evaluate the availability of an aquaculture location and how to use the alpha factor method to execute operations based on the threshold values established in case 5 and case 6. We only used the significant wave height as the limiting factor, leaving the wave period and wind velocity out. The results from the hydrodynamical analysis shows that the wave period plays an important part in vessel movements, and therefore should be included when performing availability and weather window analysis.

One of the most rewarding parts of the thesis was for me working with the availability and weather window analysis especially the part involving the scatter diagram. From previous work I have found working with risk assessments to be challenging when deciding the probability of certain incidents, but if there is enough data available to generate a scatter diagram, one can easily calculate the probability of different sea state combinations and use these probabilities in the risk assessment analysis.

Chapter 10 Conclusion and further work

10.1 Conclusion

The fetch length method proved to be simple procedure on estimating the significant wave heights and corresponding wave periods. From the four main directions of the chosen fjord system, we calculated the environmental conditions to be:

Environmental conditions

$Heading$	F_L [km]	F_W [km]	$\frac{F_W}{F_L}$	$\frac{F_e}{F}$	F_e [km]	U_{ref} [m/s]	U_A [m/s]	H_s [m]	T_p [s]	T_z [s]
NE (36°	7	1.9	0.3	0.51	3.57	24	24.85	0.76	2.78	1.98
E (89°)	19.5	4.5	0.2	0.4	7.8	24	35.39	1.60	4.06	2.88
SE (135°)	20	4.2	0.2	0.4	8.0	24	46.57	2.13	4.49	3.19
SV (222°)	12.5	2.1	0.2	0.4	5.0	24	46.57	1.68	3.84	2.72

Although NS9415:2009 deem the method sufficient, the method is very simplified and does not account for several factors which may challenge the validity of the results. If an actual aquaculture fish farm were to be dimensioned these parameters should be evaluated and assessed.

The results of the mooring analysis with and without a moored vessel alongside the floater with the most utilized mooring lines shows that there is an overall minor increase in the mooring elements when comparing case 2 and case 3. The increase in percentage of each of the identified most utilized mooring lines with and without the moored vessel was:

	Case 2	Case 3	Difference
Component:	Axial tension load	Axial tension force	Axial tension force
name	[tonnes]	[tonnes]	%
Bridle rope	12	14	13.9
Grid rope A4-A5	25	25	0.3
Mooring line 15	19	19	0.3
Mooring line 16	18	18	1.1
Mooring line 17	20	22	7.7
Mooring line 18	22	23	7.0
Anchor chain	22	23	7.0
Buoy line	9	11	15.8

The biggest increase in axial tension force is in the buoy line. This is the rope of the buoys used for station keeping of the vessel. With this we can conclude that although an increase in the axial tension forces the increase is not major. It should also be mentioned that the load factor and material factor intended to account for any inaccuracies in the environmental loads and inaccuracies when testing the material, is not accounted for. Nevertheless, when dimensioning a mooring system, it would be wise to keep in mind that large service vessel most likely will at some point be moored to the floaters and that although small, the mooring lines, hen foot ropes and buoy straps may experience an increase in axial force, which may lead to line break if not accounted for. It is also concluded with that vessel mooring lines should be visually checked before delousing operations during sea states close to calculated operational limiting design criteria.

The results from the ALS analysis shows that the axial force is absorbed by the bridle rope when grid rope A4-A5 goes to failure. The increase in axial force were calculated to 146%. When mooring line 18 went to failure the loads were more spread over the remaining mooring lines, grid ropes and bridle ropes.

The AquaSim analysis software proved to be a great tool when performing mooring analysis and modelling of the aquaculture fish farm, but not so much when it comes to modelling detailed vessels. The interface in AquaEdit is intuitive and easy to use, and the visualization of the results were great.

The results from case 5 and 6 show that the operational limiting design criteria for the three assessed sea state directions the significant wave height operational limiting design criteria were:

$OP_{lim,O}$	89°	135°	175°
OP_{lim,O,H_s}	2.0 [m]	2.0 [m]	2.4 [m]

The results from case 5 and case 6 were used to evaluate an arbitrary aquaculture fish farm location using wave data from a 10-year period (2010-2020). The results show that for this location the predetermined threshold values (operational limiting criteria) are very unlikely to be exceeded. The total number of hours of significant wave heights below 2.4 meters were for each month during a 10-year period:

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Okt	Nov	Des
8007	7328	8172	7920	7426	7197	7440	7438	7156	7430	7142	7139

And as percentage of the total hours with significant wave heights under 2.4 meters in each month:

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Okt	Nov	Des
97.84 %	98.18 %	99.85 %	100 %	99.81 %	99.96 %	100 %	99.97 %	99.39 %	99.87 %	99.19 %	95.95 %

Based on the same time period and data a scatter diagram was generated in excel and with this scatter diagram the probability that wave periods between 5 and 6 seconds and significant wave height between 2.0 and 2.4 occurred at the same time were calculated to be 9%.

Although a small likelihood that the critical sea state could occur a weather window analysis where performed. The results showed that by using the alpha factor method the arbitrary week under investigation contained two possible calm periods possible to perform the predetermined sub-operations.

10.2 Further work

The modelling of the service vessel proved to be a time-consuming and challenging task and still could be more detailed to mirror the full scaled vessel. Further work on the vessel model could provide more realistically results.

In this thesis only the one vessel where under investigation, and thus gives a narrow image of the fleet involved in aquaculture operations. It is relevant to use the biggest vessel involved in aquaculture operations when investigating the impact it has on the mooring system, but these operations are also accompanied of smaller monohulls and catamarans. In a real-life situation, when evaluating the weather windows, the limiting factor must be based on the limiting factor of the smallest ships needed in the operation. It would be interesting to model a couple more vessels with different sizes and shapes and then performed the same hydrodynamical and operational analysis.

It should also be mentioned that the vessel where only investigated when moored to one floater and three wave headings. Further work should include hydrodynamical analysis when the vessel is moored alongside every floater, a larger amount of wave headings, and more sea states. I see now that the master thesis could have narrowed the scope more and investigated in more detail of each of the predetermined RQs. Further work could be to dig deeper into how we can use relevant availability and weather window analysis methods and produce a procedure on how we can use the methods used in the oil and gas and offshore wind industry to improve the operation efficiency and safety of aquaculture operations now that the structures are getting bigger, and the surrounding environment are getting harsher.

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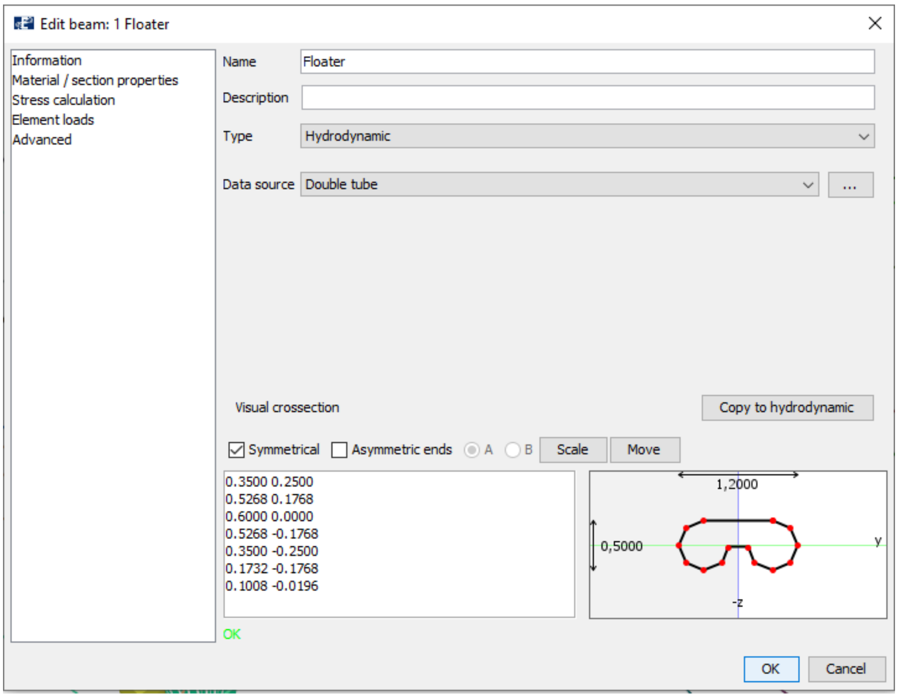
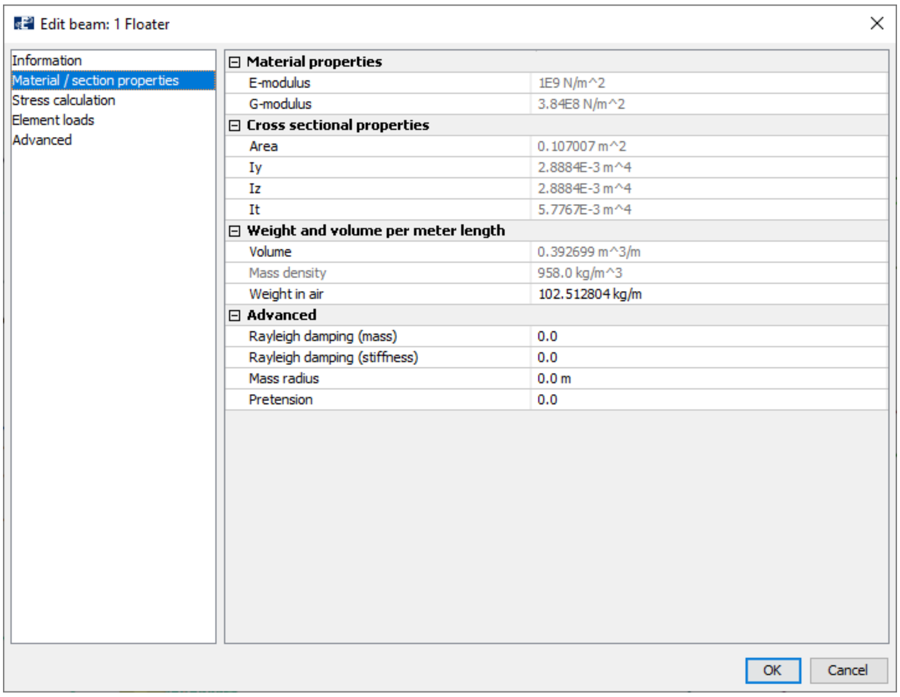
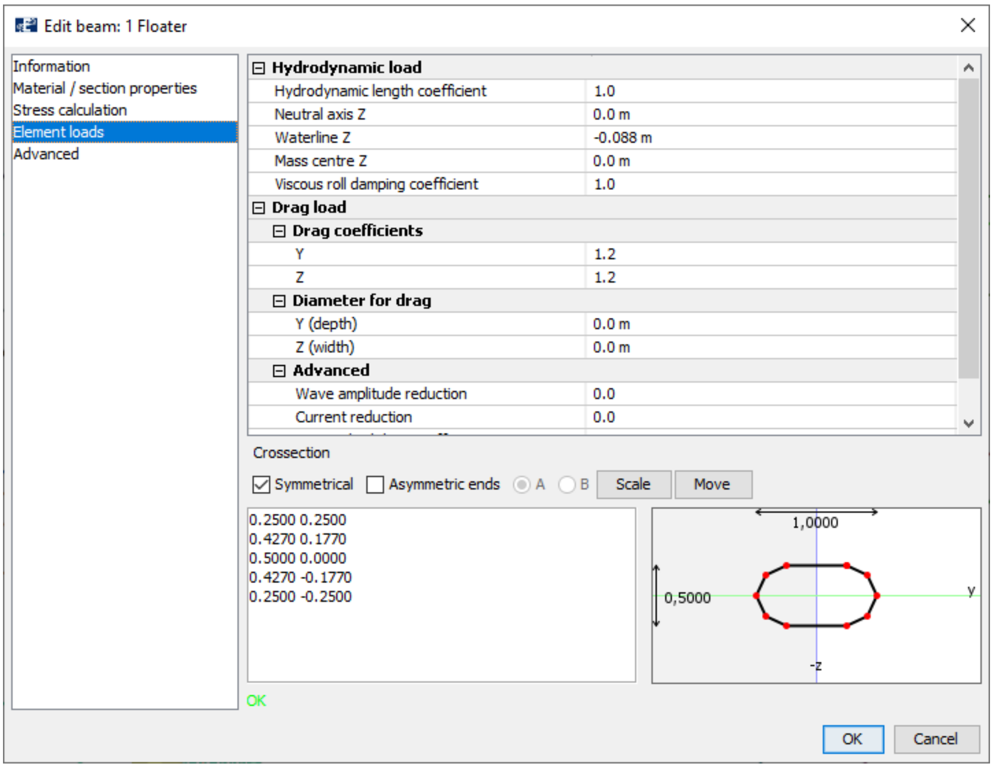
Appendix A – model inputs fish farm model

In this appendix the information, material/section properties and element load relevant for the aquaculture fish farm model is presented.

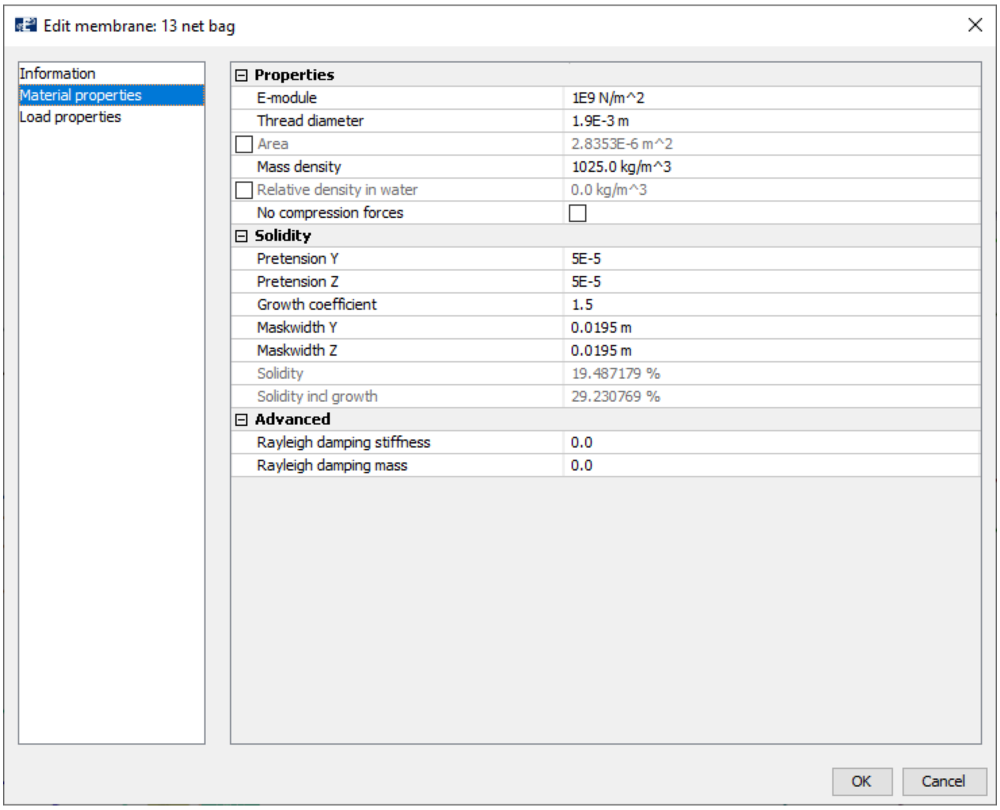
Floater:



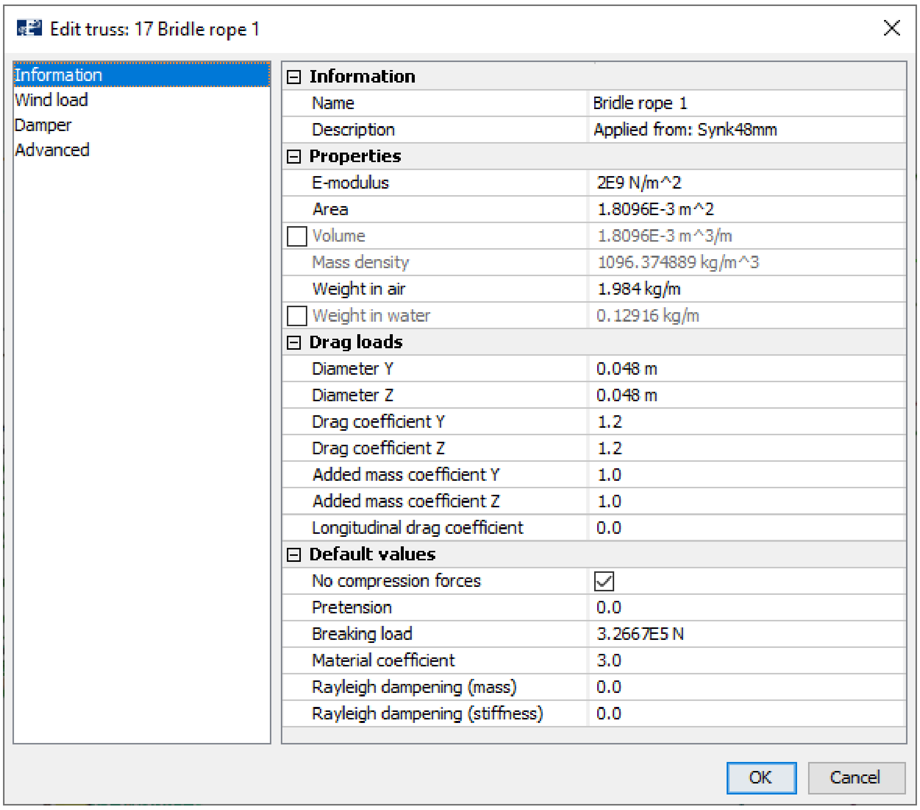




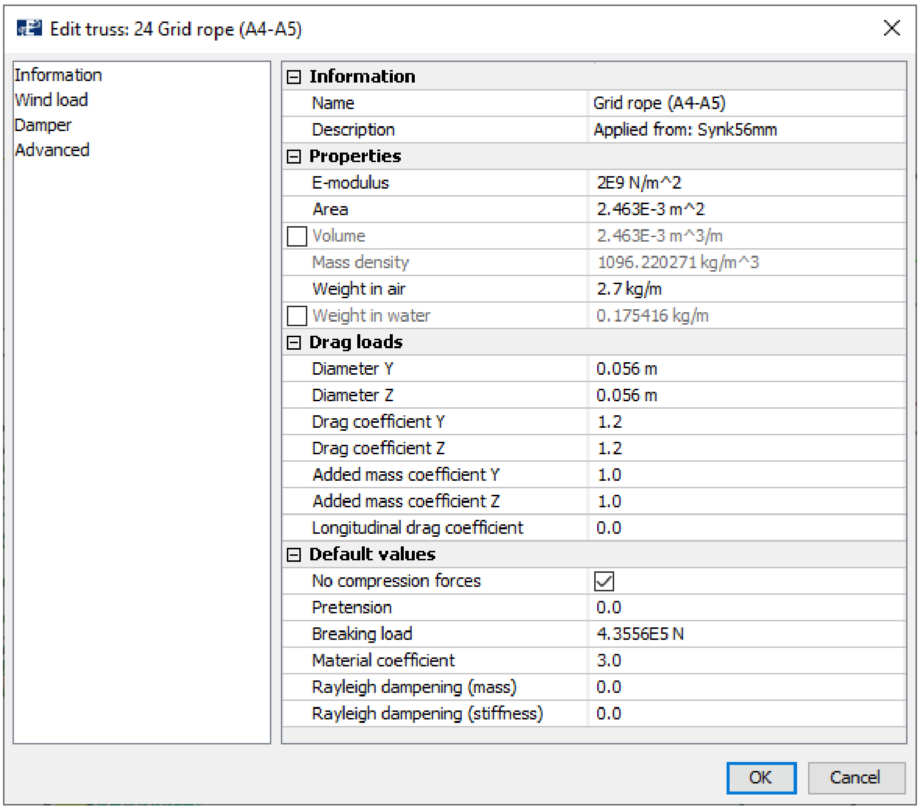
Spaghetti net:



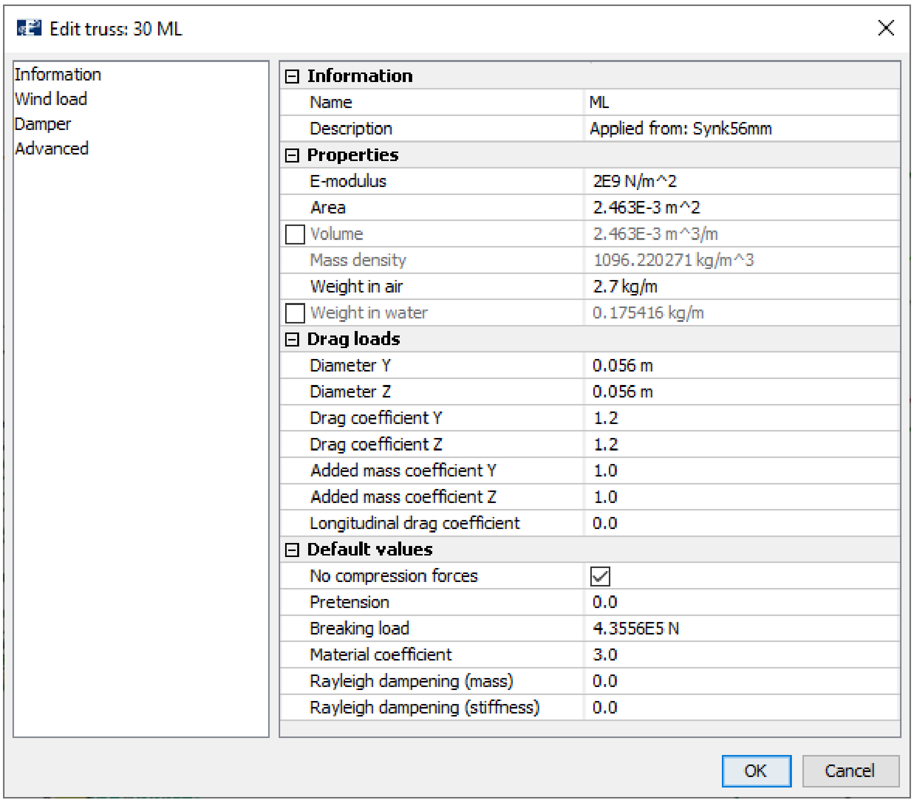
Bridle ropes:



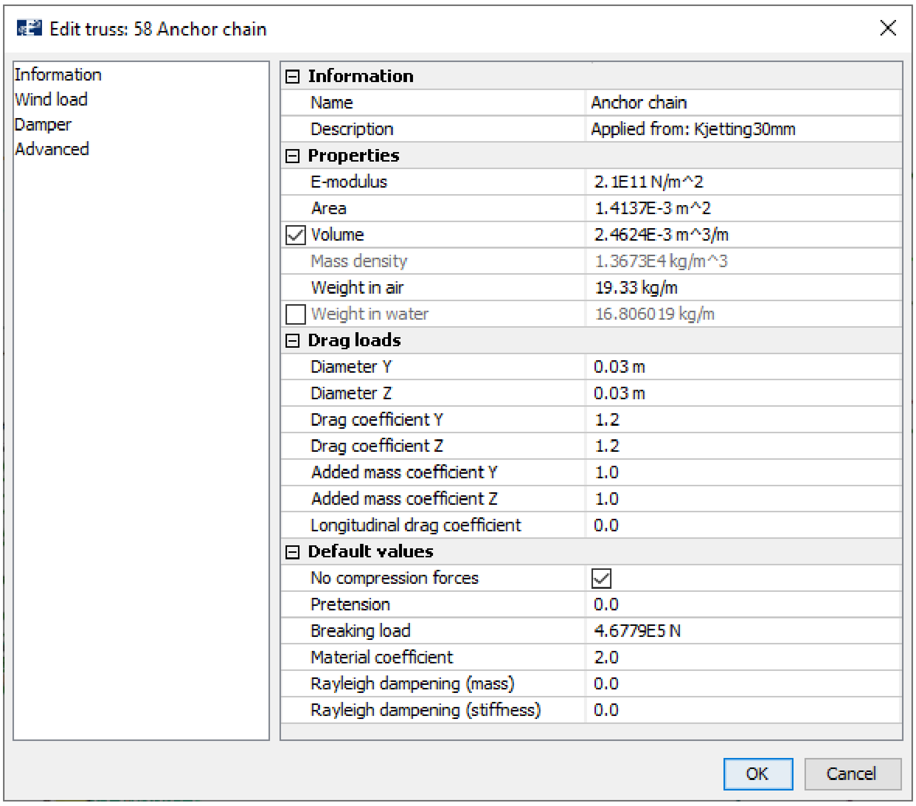
Grid ropes:



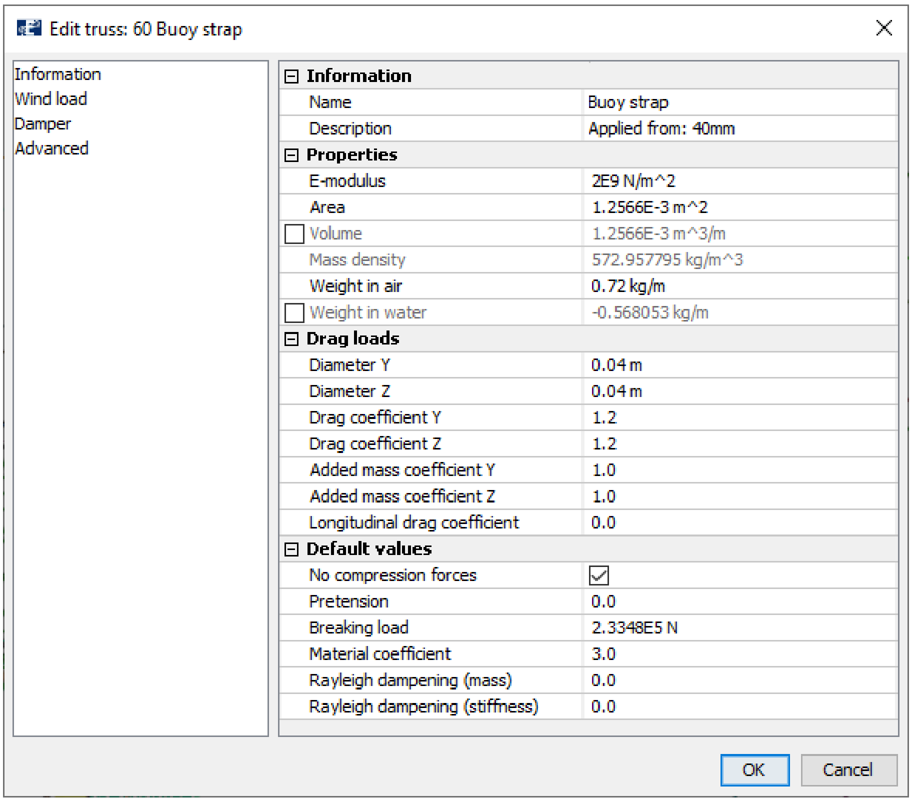
Mooring lines



Anchor chains:



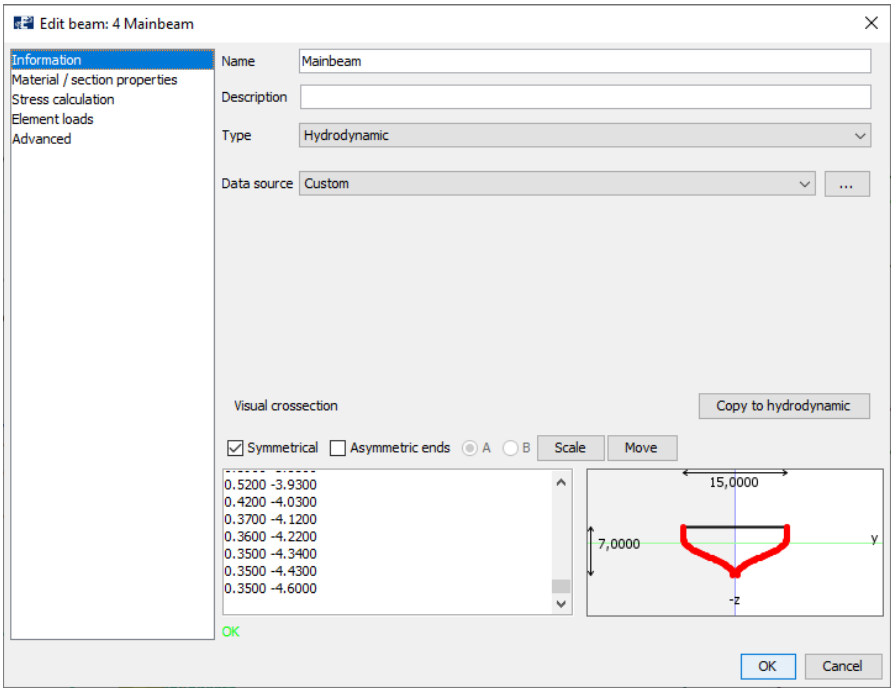
Buoy straps:

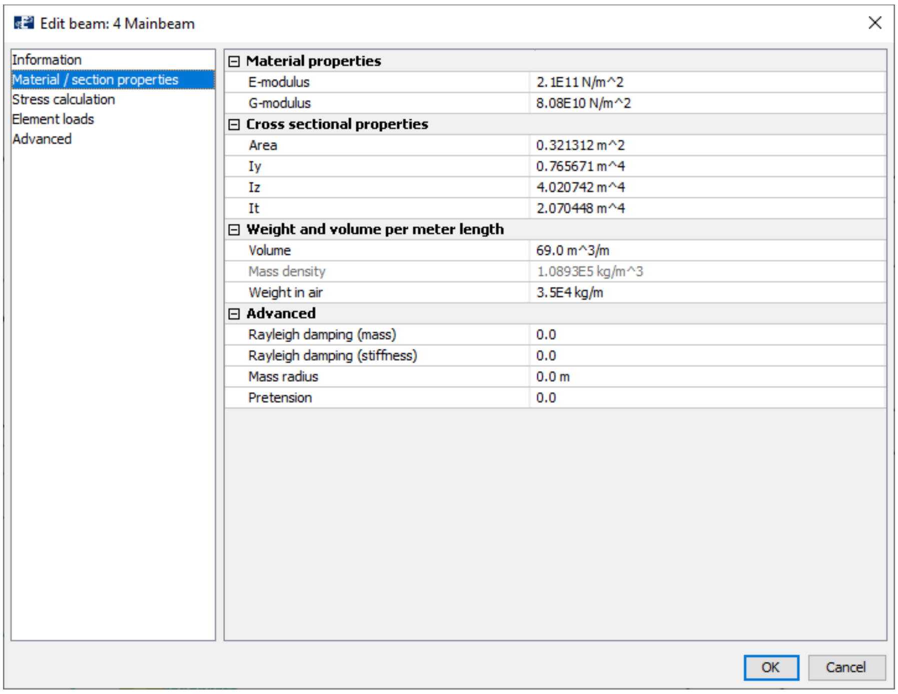

Edit truss: 60 Buoy strap
Information
Wind load
Damper
Advanced
Information
Name
Buoy strap
Description
Applied from: 40mm
Properties
E-modulus
2E9 N/m^2
Area
1.2566E-3 m^2
Volume
1.2566E-3 m^3/m
Mass density
572.957795 kg/m^3
Weight in air
0.72 kg/m
Weight in water
-0.568053 kg/m
Drag loads
Diameter Y
0.04 m
Diameter Z
0.04 m
Drag coefficient Y
1.2
Drag coefficient Z
1.2
Added mass coefficient Y
1.0
Added mass coefficient Z
1.0
Longitudinal drag coefficient
0.0
Default values
No compression forces
Pretension
0.0
Breaking load
2.3348E5 N
Material coefficient
3.0
Rayleigh dampening (mass)
0.0
Rayleigh dampening (stiffness)
0.0
OK
Cancel

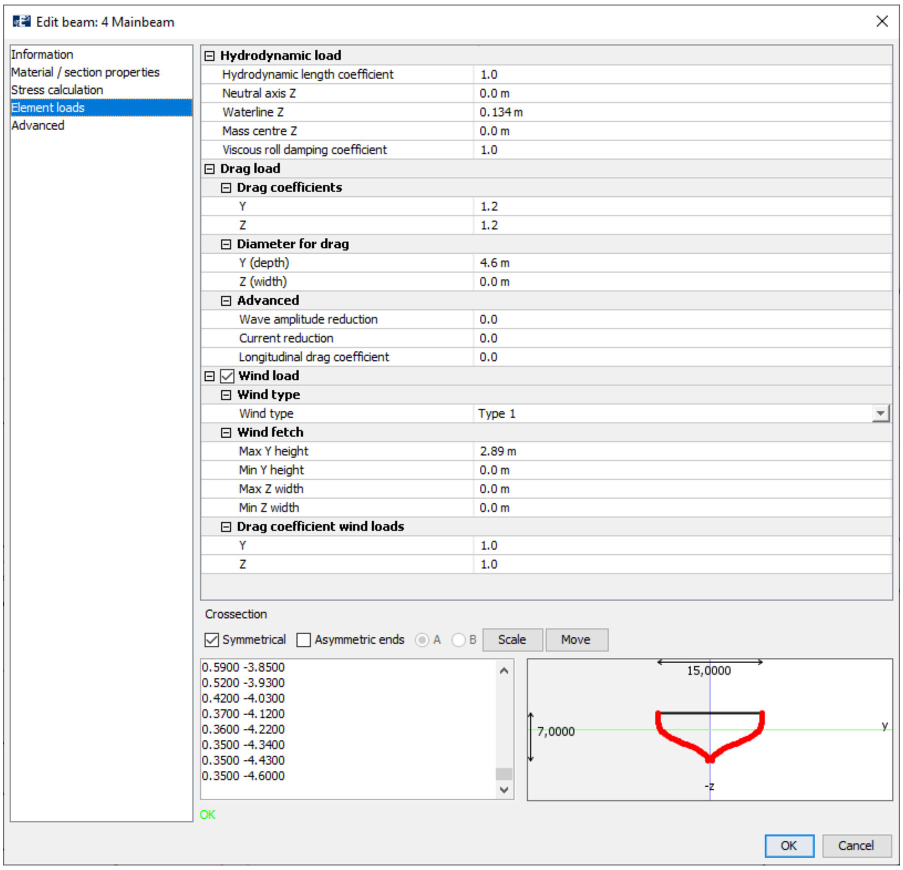
Appendix B – model inputs service vessel

In this appendix the information, material/section properties and element load relevant for the service vessel model is presented.

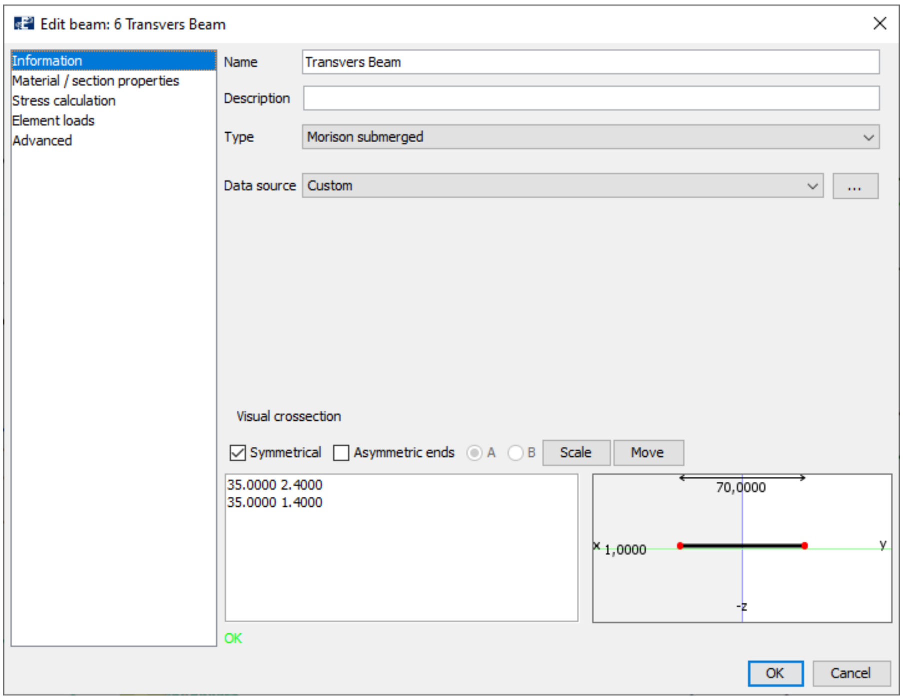
Main beam:

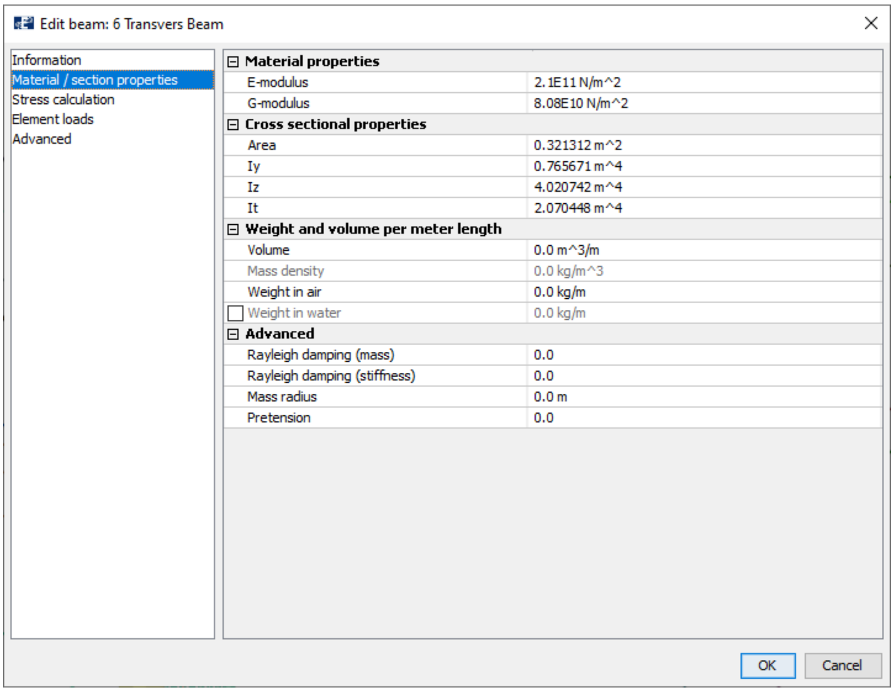


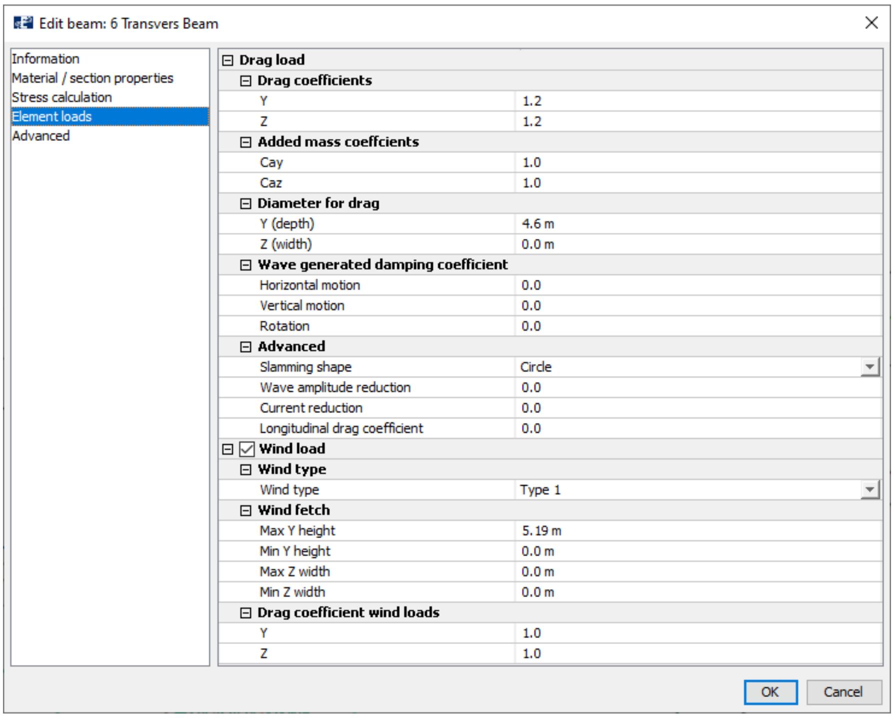




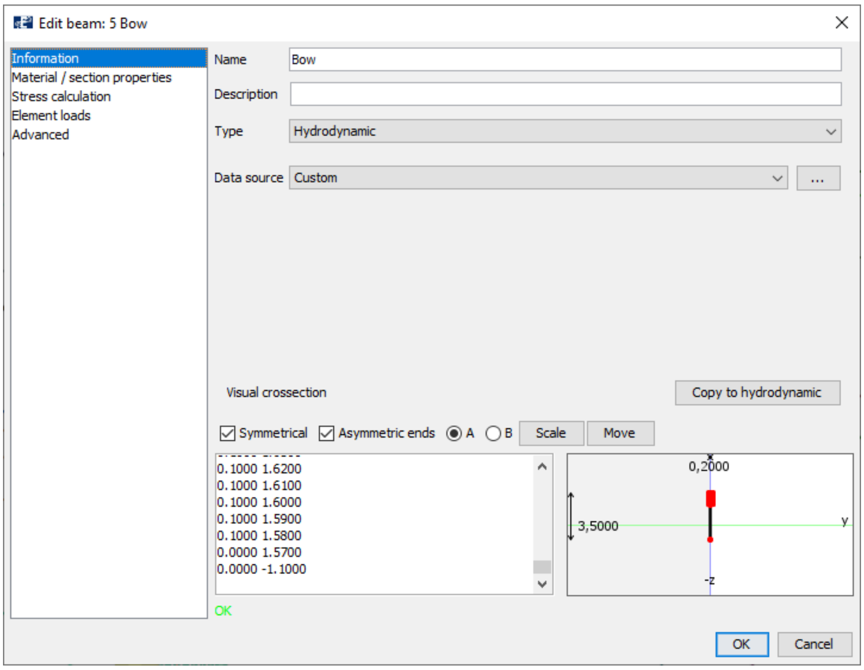
Transverse beam:

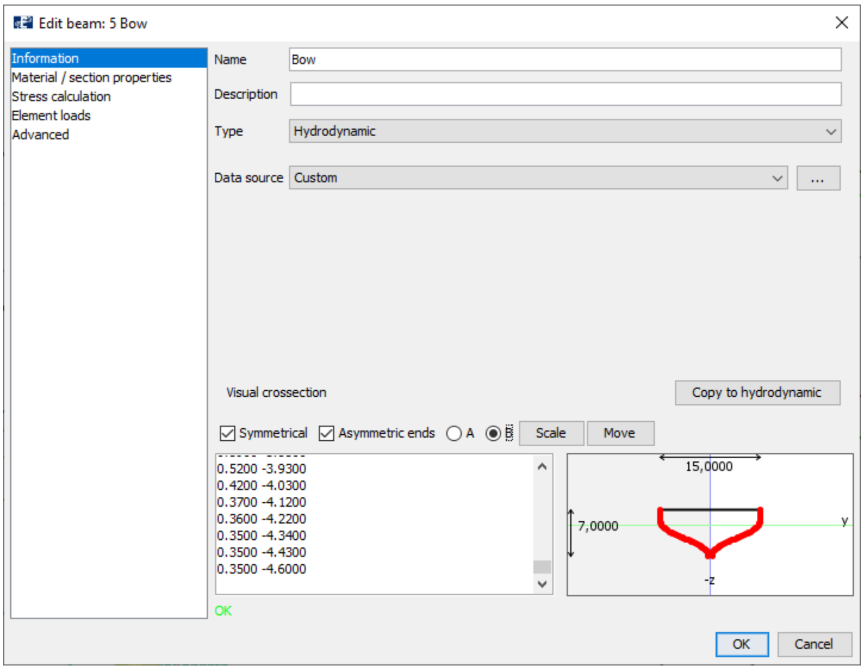


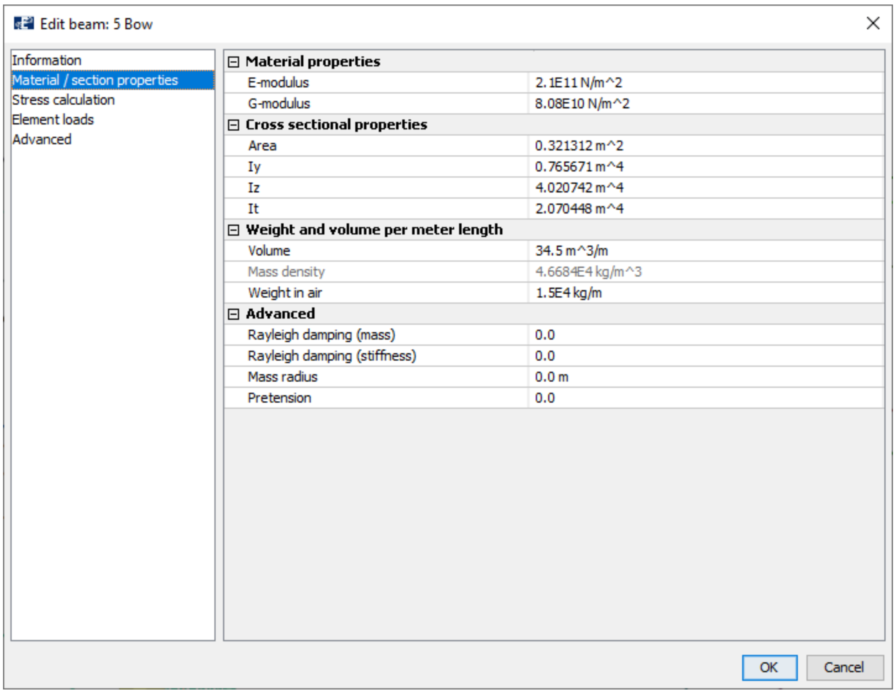

Edit beam: 6 Transvers Beam
Information
Material / section properties
Stress calculation
Element loads
Advanced
Material properties
E-modulus 2.1E11 N/m^2
G-modulus 8.08E10 N/m^2
Cross sectional properties
Area 0.321312 m^2
Iy 0.765671 m^4
Iz 4.020742 m^4
It 2.070448 m^4
Weight and volume per meter length
Volume 0.0 m^3/m
Mass density 0.0 kg/m^3
Weight in air 0.0 kg/m
Weight in water 0.0 kg/m
Advanced
Rayleigh damping (mass) 0.0
Rayleigh damping (stiffness) 0.0
Mass radius 0.0 m
Pretension 0.0
OK
Cancel

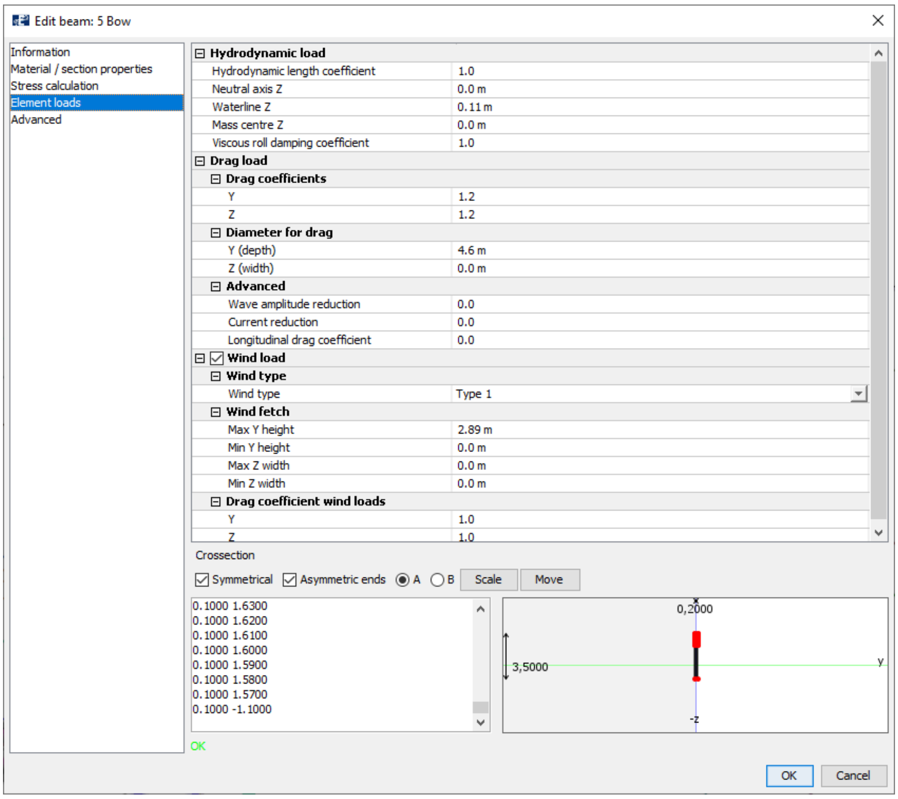

Edit beam: 6 Transvers Beam
Information
Material / section properties
Stress calculation
Element loads
Advanced
Drag load
Drag coefficients
Y 1.2
Z 1.2
Added mass coeffcients
Cay 1.0
Caz 1.0
Diameter for drag
Y (depth) 4.6 m
Z (width) 0.0 m
Wave generated damping coefficient
Horizontal motion 0.0
Vertical motion 0.0
Rotation 0.0
Advanced
Slamming shape Circle
Wave amplitude reduction 0.0
Current reduction 0.0
Longitudinal drag coefficient 0.0
Wind load
Wind type
Wind type Type 1
Wind fetch
Max Y height 5.19 m
Min Y height 0.0 m
Max Z width 0.0 m
Min Z width 0.0 m
Drag coefficient wind loads
Y 1.0
Z 1.0
OK
Cancel

Bow:


Edit beam: 5 Bow
Information
Material / section properties
Stress calculation
Element loads
Advanced
Name
Bow
Description
Type
Hydrodynamic
Data source
Custom
Visual crossection
Copy to hydrodynamic
Symmetrical
Asymmetric ends
A
B
Scale
Move
0.1000 1.6200
0.1000 1.6100
0.1000 1.6000
0.1000 1.5900
0.1000 1.5800
0.0000 1.5700
0.0000 -1.1000
0,2000
3,5000
y
-z
OK
OK
Cancel


Edit beam: 5 Bow
Information
Material / section properties
Stress calculation
Element loads
Advanced
Name
Bow
Description
Type
Hydrodynamic
Data source
Custom
Visual crossection
Copy to hydrodynamic
Symmetrical
Asymmetric ends
A
B
Scale
Move
0.5200 -3.9300
0.4200 -4.0300
0.3700 -4.1200
0.3600 -4.2200
0.3500 -4.3400
0.3500 -4.4300
0.3500 -4.6000
15,0000
7,0000
y
-z
OK
OK
Cancel


Edit beam: 5 Bow
Information
Material / section properties
Stress calculation
Element loads
Advanced
Material properties
E-modulus 2.1E11 N/m^2
G-modulus 8.08E10 N/m^2
Cross sectional properties
Area 0.321312 m^2
Iy 0.765671 m^4
Iz 4.020742 m^4
It 2.070448 m^4
Weight and volume per meter length
Volume 34.5 m^3/m
Mass density 4.6684E4 kg/m^3
Weight in air 1.5E4 kg/m
Advanced
Rayleigh damping (mass) 0.0
Rayleigh damping (stiffness) 0.0
Mass radius 0.0 m
Pretension 0.0
OK
Cancel


Edit beam: 5 Bow
Information
Material / section properties
Stress calculation
Element loads
Advanced
Hydrodynamic load
Hydrodynamic length coefficient 1.0
Neutral axis Z 0.0 m
Waterline Z 0.11 m
Mass centre Z 0.0 m
Viscous roll damping coefficient 1.0
Drag load
Drag coefficients
Y 1.2
Z 1.2
Diameter for drag
Y (depth) 4.6 m
Z (width) 0.0 m
Advanced
Wave amplitude reduction 0.0
Current reduction 0.0
Longitudinal drag coefficient 0.0
Wind load
Wind type
Wind type Type 1
Wind fetch
Max Y height 2.89 m
Min Y height 0.0 m
Max Z width 0.0 m
Min Z width 0.0 m
Drag coefficient wind loads
Y 1.0
Z 1.0
Crossection
Symmetrical
Asymmetric ends
A
B
Scale
Move
0.1000 1.6300
0.1000 1.6200
0.1000 1.6100
0.1000 1.6000
0.1000 1.5900
0.1000 1.5800
0.1000 1.5700
0.1000 -1.1000
0,2000
3,5000
y
-z
OK
OK
Cancel

Appendix C – NORDFORSK, 1987

NORDFORSK (1987) - Seakeeping Criteria

General Operability Limiting Criteria for Ships

(NORDFORSK, 1987)

Description	Merchant Ships	Navy Vessels	Fast Small Craft
RMS of vertical acceleration at FP	0.275 g ($L \leq$ 100 m) 0.050 g ($L \geq$ 330 m)	0.275 g	0.65 g
RMS of vertical acceleration at Bridge	0.15 g	0.20 g	0.275 g
RMS of lateral acceleration at Bridge	0.12 g	0.10 g	0.10 g
RMS of Roll	6.0 deg	4.0 deg	4.0 deg
Probability of Slamming	0.03 ($L \leq$ 100 m) 0.01 ($L \geq$ 300 m)	0.03	0.03
Probability of Deck Wetness	0.05	0.05	0.05

General Operability Limiting Criteria for Ships (NORDFORSK, 1987).

Criteria for Accelerations and Roll

(NORDFORSK, 1987)

Description	RMS Vertical Acceleration	RMS Lateral Acceleration	RMS Roll Motion
Light Manual Work	0.20 g	0.10 g	6.0°
Heavy Manual Work	0.15 g	0.07 g	4.0°
Intellectual Work	0.10 g	0.05 g	3.0°
Transit Passengers	0.05 g	0.04 g	2.5°
Cruise Liner	0.02 g	0.03 g	2.0°

Seakeeping performance criteria for human effectiveness - Limiting Criteria with regard to accelerations (vertical and lateral) and roll motion (NORDFORSK, 1987).