Structural Design and Behavior of Aquaculture Installations

Design av bærestruktur og forankring for havbruksanlegg

Malin Bjørkøy

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Department of Marine Technology
Norwegian University of Science and Technology

NTNU Trondheim
Norges teknisk-naturvitenskapelige universitet
Institutt for marin teknikk

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Stud. tech. Malin Bjørkøy

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<u>Background</u>

The aquaculture industry has grown significantly the latest years and driven by increased use of advanced marine technology and competence. Extensive development and research projects have resulted in increased focus on safety and consistent structural design of the aquaculture installations.

At present, keywords such as larger installations in more exposed and tougher areas together with stricter design requirements have posed demanding challenges to the industry. A consequence is the demand for new and more optimal design of cage and mooring systems. At the same time, the risk of fish escape must be reduced. Hence, small scale model tests in combination with more advanced numerical simulations are required.

<u>Scope of Work</u>

1) Review relevant literature and describe state-of-art concepts and some of the new concepts for aquaculture installations like cage and mooring systems. In particular, relevant equipment and hardware components for the mooring system shall be described in detail.

2) Give an overview of the Norwegian rules and regulations, in particular the aspects in NS9415 that relates to structural design of cage and mooring system.

3) Familiarize with the simulation program AQWASIM and describe the theory that is relevant for design and behavior of cage and mooring systems.

4) Establish a AQWASIM model of a selected cage and mooring system. The selected concept to be agreed with the supervisor and the co-supervisor. Test case simulations shall be performed and experiences using AQWASIM shall be reported.

5) Conclusions and recommendations for further work.

General information

The work scope may change or prove to be larger than initially anticipated. Subject to approval from the supervisor, topics may be changed or reduced in extent.
In the project the candidate shall present her's/his personal contribution to the resolution of problems within the scope of work.
Theories and conclusions should be based on mathematical derivations and/or logic reasoning identifying the various steps in the deduction.
The candidates should utilise the existing possibilities for obtaining relevant literature.

Report/Delivery
The project report should be organised in a rational manner to give a clear exposition of results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.
The report shall be written in English and edited as a research report including literature survey, description of relevant mathematical models together with numerical simulation results, discussion, conclusions and proposal for further work. List of symbols and acronyms, references and (optional) appendices shall also be included. All figures, tables and equations shall be numerated.
The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

The report shall be submitted in two copies:
- Signed by the candidate
- The text defining the scope included
- In bound volume(s)
- Drawings and/or computer prints which cannot be bound should be organised in a separate folder.

Ownership
NTNU has according to the present rules the ownership of the project results. Any use of the project results has to be approved by NTNU (or external partner when this applies). The department has the right to use the results as if the work was carried out by a NTNU employee, if nothing else has been agreed in advance.

Thesis supervisor**:**
Prof. II Kjell Larsen, NTNU/Statoil
Co-supervisor :
CTO Martin Søreide, Aqualine AS

Deadline: December 16th, 2016

Trondheim, December 10th, 2016

Kjell Larsen (sign.)

Malin Bjørkøy (date and signature):

Preface

This report comprise the study of *Structural design and behavior of aquaculture installations*. The following presents the results of my Project Thesis, conducted at the Norwegian University of Science and Technology (NTNU) as a part of my Master of Science in Marine Technology.

I would like to express my gratitude to my supervisor Professor Kjell Larsen for valuable discussions, guidance and support through this process. He has helped me achieve a better understanding of complex structural design and contributed with valuable feedback. I would also like to acknowledge the cooperation with Aqualine AS, and especially co-supervisor Martin Søreide, CTO in Aqualine. Martin has contributed to this Thesis with an industry relevant topic, simulation model and valuable input from the industry's point of view. Mats Nåvik Hval, Marine Engineer in Aqualine, deserves acknowledgement for giving an introduction to the software AquaSim, and for answering questions regarding the software and technical standard throughout this project. Access to the software AquaSim was given to me by Aquastructures AS. Their support is acknowledged.

Malin Bjørkøy   Date

Summary

This project thesis focus on structural design and behavior of aquaculture installations, and has been conducted in cooperation with Aqualine AS. Different fish farm concepts, hardware components, and rules and regulations that apply for the aquaculture industry were studied. A simulation study of a single Aqualine Midgard® cage was conducted to examine the behavior of the mooring lines in static and dynamic environmental conditions, as well as to familiarize with the industry's "best practice" for dimensioning of equipment. Mooring analyses were conducted in the simulation and analysis software AquaSim to determine the response of the fish farm in different environmental conditions. The results from the dynamic analyses were used to conduct a design check to ensure that the mooring lines had sufficient strength in accordance with limit state design.

The aquaculture industry has developed rapidly over the recent years and new technology has made it possible to increase the size of the farming facilities. New installations must be designed to meet challenges such as more exposed sites, harsher environment and stricter rules and regulations, to reduce the risk of fish escape.

The main components of a typical fish farm concept are the floating collar, net cage and mooring system. The floating collar provides floatation and serve as a working platform, the net cage keeps the fish in place, while the mooring system maintains the fish farm at its desired position. Choice of fish farm concept is mainly dependent on the environmental conditions on its intended site. Circular collar fish farms are mainly applied for exposed sites, due to their high flexibility that provides good seakeeping performance in demanding environmental conditions.

NS9415 is the governing technical standard in Norwegian aquaculture. Its overall purpose is to prevent fish escape by ensuring sufficient structural integrity of the installations, and the integrity is controlled according to defined limit states. Two load combinations are assessed to control the installation in ultimate limit states; (i) 50 year current, 10 year waves and 10 year wind, and (ii) 10 year current, 50 year waves and 50 year wind. Additional controls for accidental limit state conditions must be conducted to ensure sufficient strength of the components.

The partial co-efficient method is used to define the limit states to which the installation can be exposed. It requires that the design load effect must be less than, or equal to, the strength of the component divided by a material factor. Safety factors are applied to account for uncertainties in load and response, as well as material properties.

Mooring analyses are performed in order to predict the response of the mooring system when it is exposed to waves, wind, and current, in compliance with the limit states. Dynamic analyses are conducted by solving the equation of motion in six degrees of freedom. Mass is provided by the mass of the structure, as well as the contribution from hydrodynamic mass. Stiffness is provided by the mooring system, while damping is provided by drag forces that act on the net cage. Waves and current are the governing excitation loads that act on a fish farm, and the environmental forces can be modelled by applying Morison's equation to screens and summarizing the individual load contributions.

Sammendrag

Denne prosjektoppgaven omhandler design av bærestruktur og forankring for havbruksanlegg, og er skrevet i samarbeid med Aqualine AS. Ulike konsepter for havbruksanlegg, systemkomponenter, og gjeldende regler og forskrifter er beskrevet i det følgende. Simulering av krefter på en enkel Aqualine Midgard® merd ble utført for å undersøke strukturens respons i ulike miljø.

Sjømatindustrien har vokst kraftig de siste årene, og installasjoner må designes for å møte nye utfordringer som mer eksponerte lokaliteter, hardere vær og strengere krav fra myndighetene, for å unngå rømning.

Type havbruksanlegg blir ofte valgt på grunnlag av miljøforholdene på lokaliteten. Merder med sirkulær flytekrage i plast brukes ofte på eksponerte lokaliteter på grunn av høy fleksibilitet som gir gode egenskaper i hard sjø. Et havbruksanlegg består først og fremst av flytekrage, not og forankringssystem. Flytekragen gir oppdrift og fungerer som arbeidsplattform. Nettet holder fisken på plass, og forankringssystemet sørger for at havbruksanlegget ligger i rett posisjon.

NS9415 er den tekniske standarden for flytende oppdrettsanlegg. Den stiller krav til lokalitetsundersøkelse, risikoanalyse, utforming, dimensjonering, utførelse, montering og drift. Overordnet mål med NS9415 er å forhindre rømning av fisk ved å sikre integriteten til installasjonen. To lastkombinasjoner må kontrolleres i henhold til bruksgrensetilstand.

Partielle koeffisienters metode definerer grensetilstandene som anlegget blir utsatt for og er basert på last- og materialfaktorer. Sikkerhetsfaktorene tar hensyn til usikkerhet i beregning av last og respons, samt materialegenskaper.

Forankringsanalyser utføres for å beregne respons på anlegget som følge av bølger, vind og strøm. Dynamiske analyser tar utgangspunkt i den dynamiske likevektsligningen i seks frihetsgrader. Forankringslinene gir stivhet til systemet, mens demping blir gitt av drag kreftene på nota. Bølger og strøm er de viktigste eksitasjonskreftene som virker på et anlegg, og disse kan beregnes ved å benytte Morsions ligning på notpaneler og deretter summere lastbidraget fra hvert panel.

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1 Introduction

Since modern commercial aquaculture begun in Norway in the early 1970's, the industry has experienced rapid development and growth. Marine fish farms are getting larger, the environmental conditions are tougher, and the farms are moved to more exposed sites. This entails stricter requirements for structural design to avoid fish escape, and increased use of advanced technology is essential to meet the new challenges in the industry.

To ensure high integrity of the installation and reduce the risk of fish escape, optimal design of cages and mooring systems are essential. The structure has to withstand loads from wind, waves and current, as well as additional loads from the system itself and the handling of it. The mooring systems must keep the aquaculture installation at its correct position for all possible loading conditions.

In the Norwegian aquaculture industry, NS9415 is the governing technical standard. The main purpose of this standard is to prevent fish escape due to technical failure and/or improper operation of the marine fish farm. The standard was drafted in 2003, and then revised in 2009. Since then, the industry has experienced rapid development, and it is essential that the technical standard meets the new challenges the industry opposes.

This Project Thesis will assess structural design and behavior of aquaculture installations. Concept design of aquaculture installations, in particular mooring systems, is described in chapter 3 and 5. Chapter 4 gives an overview of the rules and regulations that apply for the Norwegian aquaculture industry, with particular focus on the technical standard NS9415 and the parts that relates to structural design. Design and behavior of the fish farm and mooring system will be assessed in chapter 6, 7 and 8. A test case simulation was performed in the software AquaSim to study a single cage in different environmental conditions. The results from the simulation study are presented in chapter 9 and discussed in the end of this report, together with final conclusions and recommendations for further work.

The reader of this Project Thesis is expected to have basic knowledge about marine hydrodynamics, but no prior knowledge about structural design of aquaculture installations is required.

2 Method

To meet the objective of this Project Thesis and to ensure high quality results, a comprehensive literature study was performed. The results presented in this report were obtained from literature search within the Oria database, relevant web pages, lecture notes from NTNU courses, as well as personal communication with several experts in the field.

When performing a literature search, the information must be carefully evaluated. Four standard criteria that was used to evaluate the quality of the references were (VIKO, 2010):

- Credibility
- Objectivity
- Preciseness
- Suitability

Further, the source of information was considered in terms of who the author was, when the material was published, why it was published, as well as where it was published. The credibility of the author and publisher was important to assess to ensure that the literature search met the criteria stated above.

3 Aquaculture Installations

Large scale aquaculture is a relatively new industry in Norway, and the fish farming technology has experienced rapid development in recent years. The combination of new technology and competence has made it possible to increase the size of farming facilities and move the fish farms to more exposed sites. This has resulted in aquaculture being an important contributor to the Norwegian economy.

Today, several concepts for fish farms are available on the market. The most common construction is the *open fish farm*, which is characterized by free water flow through the plant. *Closed fish farms* is, as the name suggests, closed to the surrounding environment and needs its own water circulation system (Karlsen, 2015).

Fish farms can be located in the surface or be submerged, either partly or fully submerged. This Project Thesis will focus on open surface fish farms.

3.1 Fish Farm Design

The main objective when designing aquaculture installations is to ensure sufficient structural integrity to prevent fish escape. The fish farm must be able to withstand environmental loads, be operational, and ensure proper fish welfare (Fredheim, 2016).

Fish farms are designed and certified according to the technical requirements given in the Norwegian standard, NS9415, and all stages of design must coincide with the standard (Fredheim and Langan, 2009). The technical standard set requirements for individual components of the fish farm, as well as requirements for the functionality of the fish farm as a global installation. Rules and regulations will be further discussed in chapter 4.

The design process can be divided into three main steps (Søreide, 2016): (i) site survey and specification, (ii) analysis and testing, and (iii) report and planning. Each stage will be discussed briefly in the following sections.

3.1.1 Site Survey and Specification

In order to operate salmon farming, a licence must be issued by the relevant authorities. For the farmer to get a license to farm, a site survey must be carried out at the specific site intended for the installation. The aim of the site survey is to map the environmental parameters that will impact the installation in order to calculate environmental loads. Wind velocity, current velocity, and wave parameters can be determined from measurements, statistical data and/or calculations based on the site survey (Standard Norway, 2009).

The site survey must also include a description of water depth, bottom type and topography. This documentation is mainly used for the anchoring – and mooring analysis (Fredheim, 2016).

Specification of equipment is necessary to perform structural analyses of the installation and the main components shall be carefully documented. The technical standard require that calculations, material parameters, certificates for parts and traceability are documented for all structural components of the fish farm.

3.1.2 Analyses and Testing

Both structural and hydrodynamic analyses must be carried out for the specific components of the fish farm, as well as for the global installation. These analyses are based on the site survey and ensures that the structure meets the criteria stated in the standard.

In addition to analyses of loads and loading conditions, risk assessment must be carried out in the design process. Risk assessment includes risk analysis and risk evaluation, and must be performed to ensure the safety of people, fish, and the installation (Standard Norway, 2009). The risk analysis should map what can go wrong, estimate how likely it is that something goes wrong, as well as estimate the consequences of the event if something does go wrong. Risk evaluation is carried out to determine which risks that can be tolerated, and which risks that must be further assessed (Rausand, 2013).

Testing of equipment is performed to document the capacity of the installation and its components, and can be an alternative to analysis. Both model-tests and full-scale tests can be performed to ensure the safety of the installation. Testing can be used to (Standard Norway, 2009):

- Determine characteristics or breaking capacity of components
- Reduce uncertainty in analytical risk models
- Control the quality of construction parts
- Determine material characteristics
- Inspect fish farms after installation

3.1.3 Reporting and Planning

Reporting and documentation must be done according to the technical standard. Reporting is essential for safe and proper operation of the installations. Planning of the installation and operation of the fish farm is conducted to ensure safety of the people and environment (Søreide, 2016).

3.2 Fish Farm Concepts

Floating fish farms comes in various shapes and designs, and the choice of fish farm concept is often based on the amount of fish intended for the farm, as well as the environmental conditions on site.

The conditions on site can be defined according to degree of exposure. Sheltered sites are often deep in the fjords, protected from high waves and strong currents, while exposed sites have conditions more similar to those offshore. Exposed sites oppose challenges of harsh environmental conditions, such as strong currents, high waves, peak period and wave steepness. Also, longer duration of bad weather, as well as longer distance from shore makes it more challenging to operate aquaculture installations at exposed sites (Fredheim, 2016).

Fish farm cages can be categorized according to its structural properties and behavior in the ocean environment (Fredheim and Langan, 2009):

- Flexible systems
- Hinged connected bridges
- Rigid structures

Different concepts of floating fish farms are presented in the following sections.

3.2.1 Circular Collar Fish Farm

Circular high-density polyethylene (HDPE) collar cages are examples of flexible systems. This concept is illustrated in figure 3.1. The collar is made of plastic pipes that are welded together into preferred lengths and bent into circles with the desired ring size. Several rims, most often two, can be connected to ensure sufficient buoyancy and serve as a working platform. Circular plastic collars have high flexibility, which gives good seakeeping performance in demanding environmental conditions, and is often the preferred concept at exposed sites (Fredheim and Langan, 2009).

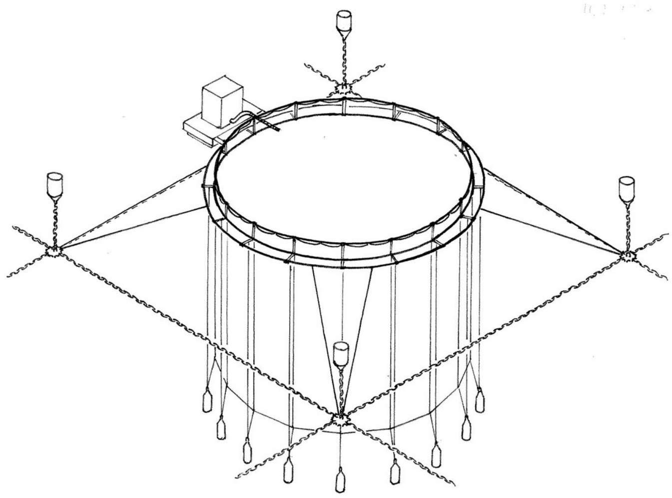


Figure 3.1: Circular collar fish farm (Illustration by SINTEF Fisheries and Aquaculture)

A typical floating fish farm consists of several cages and a global mooring system to keep the farm in position. Fish farms that consist of circular plastic collars ensures good water flow conditions due to optimal distance between the collars. This is an advantage concerning available oxygen for the salmon and for avoiding salmon lice. The main disadvantage of this concept is the working conditions. The working platform does not have room for extra storage, such that additional vessels with auxiliary equipment are needed to perform larger operations at the fish farm. Operational tasks are difficult to perform on the circular collar due to its flexibility, especially in bad weather (Fredheim and Langan, 2009).

3.2.2 Steel Fish Farm

Another fish farm concept is the interconnected hinged steel fish farms, where square cages are connected by bridges of steel. This is illustrated in figure 3.2. Polyester floatation is connected directly to the steel bridges and provides better flotation capabilities than the circular plastic collars. The interconnected hinged steel fish farms also have better working conditions due to larger and more stable working platforms. This makes the operation of the fish farm easier and safer. Lack of flexibility in the horizontal plane can cause structural problems when the fish farm is exposed to waves and ocean currents, and it is therefore more suitable for sheltered sites (Fredheim and Langan, 2009).

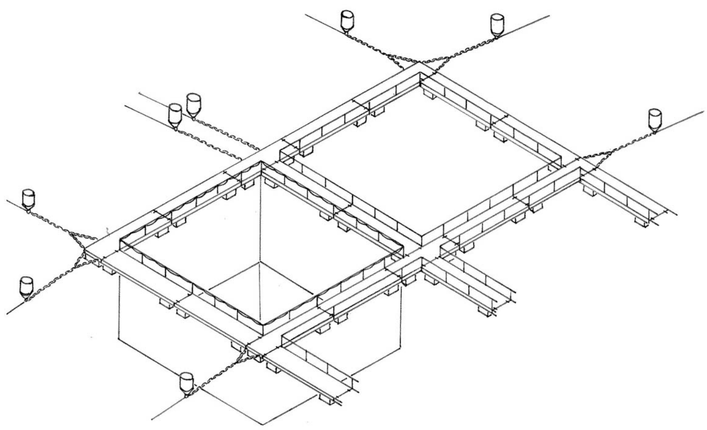


Figure 3.2: Steel fish farm (Illustration by SINTEF Fisheries and Aquaculture)

3.2.3 Catamaran Steel Fish Farm

Catamaran steel fish farms is another concept with hinged connected bridges, which consists of several steel hulls. The hulls provide flotation, while the hinges allow for rotation in the horizontal plane. The hulls are not in direct contact with water, and therefore they provide flotation only along one axis. This gives better resistance to displacement forces than the regular steel fish farms have. In contrast to circular collar fish farms, the catamaran fish farms also have the advantage of good working conditions, with large working platform area suitable both for storage and for performing daily operations (Fredheim and Langan, 2009). An illustration of the catamaran fish farm is shown in figure 3.3.

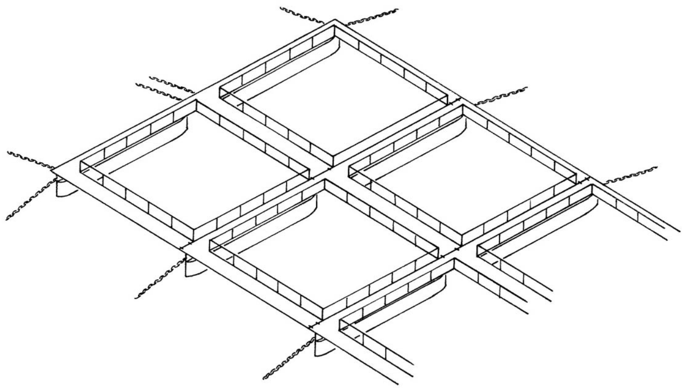


Figure 3.3: Catamaran fish farm (Illustration by SINTEF Fisheries and Aquaculture)

3.2.4 Rigid Steel Fish Farm

Rigid steel fish farm concepts vary within the category. The most common types consist primarily of steel pipes welded together into square collars. Wide working platforms gives good working conditions, in contrast to the circular collar farms. Because these systems are rigid, they are highly impacted by environmental loads and are not suitable for exposed sites (Fredheim and Langan, 2009).

3.3 Fish Farm Components

An aquaculture fish farm most often consists of several cages, and one farm usually range from 6 to 12 cages. The three main components of a typical fish cage are the floating collar, the net cage and mooring system. In addition, buoys and weights are needed to provide the necessary buoyancy and to ensure that the net cage remains its desired shape (Moe et al., 2007). Figure 3.4 illustrates a single cage and the following sections will describe the main components of a typical fish cage concept.

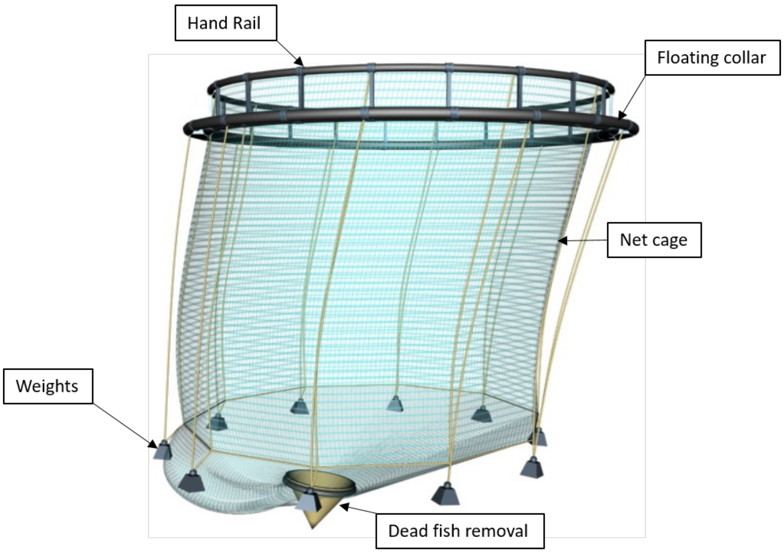


Figure 3.4: Single cage (Illustration by SINTEF Fisheries and Aquaculture)

3.3.1 Floating Collar

The floating collar serves as an attachment point for the net and integrates all parts of the floating fish farm. It provides buoyancy, distributes forces to the mooring system, and serves as a working platform for daily operations (Fredheim and Langan, 2009). According to NS9415, the floating collar shall absorb the forces imposed on it. This includes loads that directly affect the collar, but also loads that affect its adjacent parts, such as mooring system, net pen, feeding equipment etc. (Standard Norway, 2009).

3.3.2 Net Cage

The farmed fish is kept in place in a net cage connected to the floating collar. The net cage design aim to reduce the risk of fish escape, and ensure fish welfare. The net must also be able to withstand forces from waves and current, as well as manual handling (Karlsen, 2015).

Form and function of the net cage are determined by several parameters, such as shape of the floating collar, necessary net volume, depth and net materials. Depending on collar type, net cages can be circular or square, and they can have vertical or inclined sides. The bottom is usually cone shaped to collect dead fish in the bottom centre (Føre, 2016). A circular net cage provides the highest possible net cage volume compared to other shapes, and thus have higher fish capacity. High volume is also beneficial for increasing the efficiency of operational procedures such as feeding. On the other hand, increased net cage volume implies less control of the fish and increased consequences in the event of fish escape (Karlsen, 2015).

Weights are applied to the lower parts of the net to keep the desired shape of the net cage when it is under influence of environmental loads. For circular cages, a filled polyethylene ring, called sinker tube, or separate weights is used for maintaining the net shape in waves and current (Berstad et al., 2005).

A net cage consists of a system of ropes and netting, designed to transfer and carry forces through the ropes. The material used for netting can be produced of either *knotless netting*, which is knitted bundles of multifilaments, or *knotted netting*, which consists of twines of twisted multifilament bundles connected by knots. In Norwegian aquaculture, knotless netting is the most common type (Moe et al., 2007). The netting is usually made of synthetic fibre such as nylon, HDPE, polyethylen, polyester or Dyneema®. Synthetic fibre is suitable because of its distinct material properties; its rigidity ensures that the netting maintains the desired shape, while the flexibility provides resistance to environmental forces (Fredheim and Langan, 2009).

The mesh length is an important parameter for the net cage. Mesh length equals the distance between the centre of two opposing knots when the mesh is fully stretched out (Standard Norway, 2009). Choice of mesh length is mainly determined by the size of the fish that is kept in the net cage. Also, the mesh length must be small enough to avoid that wild fish swim into the net, while it must be large enough to ensure good water flow conditions through the net. Selection of mesh size influence the weight of the net cage and cost, as well as the effect of current loads (Karlsen, 2015).

3.3.3 Mooring

The purpose of the mooring system is to keep the fish farm at its desired position. The main components of the mooring system include ropes, floats and bottom attachments (Fredheim and Langan, 2009). The mooring system is described in chapter 5.

3.4 State of the Art

The aquaculture industry has developed rapidly in recent years. Today, several innovative concepts are being developed to meet new challenges such as more exposed sites, larger installations and stricter government requirements.

3.4.1 Innovation Liscences

In Norwegian aquaculture, there are strict regulations of the amount of fish allowed in a fish farm, as well as the amount of fish allowed in one single net cage. To produce farmed fish, the farmer needs a licence. The license constrain the maximum allowable production, called *maximum allowed biomass* (MAB), for each company as well as for the industry as a whole. MAB is implemented to regulate the produced volume of salmon. One MAB equals 780 metric ton, but several licenses can be granted for one site. In general, one farming site contain between 2340 and 4680 ton (Marine Harvest, 2015). The amount of fish in one single cage is also limited by regulations. One cage can only contain 25 kg fish per cubic meter of water to ensure fish welfare and for sanitary reasons (Fredheim, 2016).

The Directorate of Fisheries in Norway can grant special innovation licenses to concepts that have potential for innovation and significant investments. The purpose of the innovation licenses is to enhance technology developments that can contribute to solve challenges in the aquaculture industry. This license can grant permission to farm more than the general maximum allowable biomass for the industry, and the developers can apply for several licences for one concept (Fiskeridirektoratet, 2016).

3.4.2 Ocean Farm 1

Ocean Farm 1 is the first offshore aquaculture installation to be built. The technical solution is based on semi-submersible offshore concepts. Ocean Farm 1 is designed by Ocean Farming, which is a Research and Development company within the SalMar group. The offshore fish farm will be 250 000 cubic meters and can contain 6240 tonne salmon, which corresponds to 8 MAB licences (SalMar, 2016).

Ocean Farm 1 can be installed in areas with a water depth of 100 to 300 meters, which is beneficial both for production and operation. The offshore conditions provides good biological terms for the fish. The fish farm can be operated autonomously, which implies that heavy marine operations can be avoided. Ocean Farm 1 is the only concept that has been granted an innovation license yet, and will be tested offshore during the fall of 2017 (SalMar, 2016).

Figure 3.5: Ocean Farm 1 (SalMar, 2016)

3.4.3 Havfarm

The Norwegian company Nordlaks has proposed an aquaculture ship for farming salmon, called Havfarm. Havfarm is designed with a capacity of 10 000 tons of salmon, which corresponds to over 2 million fish, and shall withstand significant wave heights of up to 10 meters. The ship farm is planned to be 430 meters long and contain six net cages, each with a surface area of 2500 square meters and 60 meters depth (NSK Ship Design, 2016). The concept is designed by NSK Ship Design.

The facility will be equipped with thrusters to optimize the oxygen ratio for the salmon and to assist marine operations. Havfarm is intended to lay at one site for its lifetime of 25 years, and it shall be moored in the bow to provide weather vaning capabilities. This gives great advantages in rough sea. Also, by rotating the farm around the mooring point, the spreading area for waste products is increased (NSK Ship Design, 2016).

Figure 3.6: Havfarm (NSK Ship Design, 2016)

The Havfarm concept is still in the development phase, and an innovation license has not yet been granted (Fiskeridirektoratet, 2016).

4 Rules and Regulations

Rules and regulations are essential to ensure safe working environment and fish welfare in Norwegian aquaculture. Technical standards are an important part of Health, Safety and Environment (HSE) regulations, to protect the personnel and public from harm and reduce negative environmental impacts. The rules and regulations should also ensure safe and secure structures, and serve as guidelines for the farmers, suppliers, and manufacturers in the industry (Fredheim, 2016).

The overall objective of the rules and regulations applied in Norwegian aquaculture is to prevent fish escape by ensuring sufficient integrity of the installations (NYTEK, 2011). Operational integrity, design integrity, as well as technical integrity must be assessed in order to prevent escape. Fish escape is a threat to wild stock and nature. Interbreeding of farmed fish and wild stock can introduce new species that are not suited for wild life. Farmed fish claims food and space, and can possibly transfer pathogens and parasites to the wild stock (Fredheim, 2016).

Fish escape also results in economic losses for the farmer. Both loss of income due to escaped fish and the cost related to handling of the incident affects the total return, so it is of great interest for the farmer to avoid fish escape (Fredheim, 2016).

Marine fish farming in Norway are regulated by government regulations (NYTEK) and technical standards (NS9415).

4.1 NYTEK

NYTEK is the national regulation of technical standards for floating aquaculture installations issued by the Norwegian Ministry of Trade, Industry and Fisheries.

NYTEK includes regulations for certification and inspection of fish farms. For the farmers to get a licence to farm, documentation on the specific locality, mooring analyses and a site certificate is required. All main components, such as the cage, net and mooring system, must be controlled and verified by an independent third party inspection company (NYTEK, 2011). The purpose of the NYTEK certification is to reduce the risk of technical failure, and to ensure high reliability of the components.

NYTEK set requirements for all entities involved in the aquaculture industry; the farmers, the manufacturers and suppliers. The farmers are required to provide environmental data for the planned location of the fish farm to get a license, while manufacturers and suppliers is required to certify their products to be allowed to deliver products to the farmers. NYTEK refers to NS9415 for technical specifications.

4.2 NS9415

The Norwegian Standard, NS9415, outlines the technical requirements for design, dimensioning, production, installation and operation of a marine fish farm (Søreide, 2016). NS9415 is applicable to all main components of the farm, such as nets, floating collars, mooring systems and rafts. The standard was drafted in 2003, and then revised in 2009 (Standard Norway, 2009).

The specific design requirements include prerequisites for all main components of a fish farm, as well as requirements for the functionality of the global installation. This includes strength analysis, safety limits and lifetime analysis (Standard Norway, 2009). The standard also specifies which loads to include when dimensioning the equipment and how to calculate the specific loads.

As mentioned, the regulations state that a site survey must be performed in order to develop an aquaculture fish farm. The site survey shall provide the information needed to be able to determine the environmental loads on site. An overview of parameters such as wind, waves and current must be provided to indicate the conditions on site. These parameters will be used as a basis for the calculations of environmental loads that can affect the planned installation (Standard Norway, 2009).

NS9415 also include requirements for use and installation manuals. This is to ensure proper interaction between the main components of the fish farm (Fredheim, 2016).

5 Mooring System

Design and dimensioning of marine fish farms aim to reduce the risk of fish escape as a result of technical failure. All components of the fish farm must be designed in accordance with the requirements for the global installation. The purpose of the mooring system is to keep the installation at its correct position and ensure safe position-keeping at all times (Standard Norway, 2009).

5.1 Mooring Concepts

Choice of mooring concept is based on size and characteristics of the specific fish farm, as well as weather conditions and bottom topography at site. Mooring is usually done either by independent lines directly moored from the collar to the bottom, or by a grid mooring system. In the case of grid mooring, one or several collars are connected to a mooring frame which is independently attached to the seabed (Fredheim and Langan, 2009).

5.1.1 Independent Mooring

Independent mooring lines are usually applied for interconnected hinged bridge systems.

5.1.2 Frame Mooring

Frame mooring systems are applied for fish farms that consist of circular cages. The mooring frame intend to provide additional horizontal stiffness for the fish farm, since the plastic collars themselves have low horizontal stiffness (Fredheim and Langan, 2009).

The collars are connected to the mooring frame by bridles, such that each cage can move freely inside the frame, independent of the mooring grid. The main mooring frame consists of fiber ropes designed to withstand environmental loads. The mooring frame, bridles, mooring lines and frame buoys are connected by submerged connection plates (Karlsen, 2015).

The mooring frame itself is kept at sufficient depth, usually 5-10 meters, such that it wont affect marine operations. This avoids issues such as ropes coming into propellers and allows for boats to easily pass the installation site (Fredheim and Langan, 2009). An illustration of a frame mooring system and main components is shown in figure 5.1.

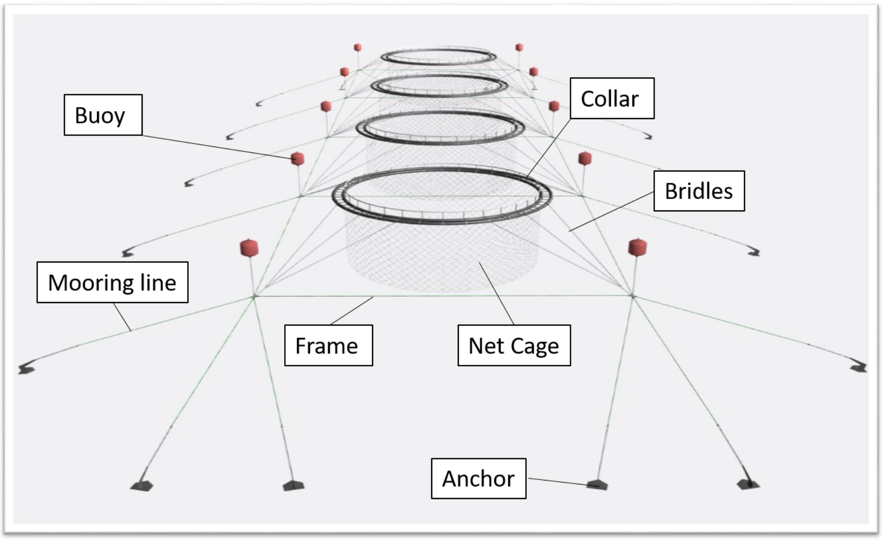


Figure 5.1: Frame Mooring Layout (Illustration by Aqualine)

5.2 Mooring Components

A general mooring system consists of several cables attached to the floating installation at different points with the lower ends of the cables anchored to the seabed (Faltinsen, 1990). The standard frame mooring system consists of synthetic ropes, long link chain, shackles, mooring plates, anchor chain and anchors (Søreide, 2016). The following sections focus on mooring components for a typical frame moored circular collar fish farm as the one shown in figure 5.1.

5.2.1 Mooring Line

Mooring lines are used to attach the installation to the seabed, and to connect the separate cages in a frame moored fish farm. The lines can consist of chain, fibre ropes, or a combination of both. Choice of mooring line material depends on its application, but a combination of chain and fibre rope is the most common option. The mooring frame itself usually consist of fibre rope.

Chain

Chains come in different diameters and with different grades, and choice of chain is based on the strength requirements determined in the dimensioning analysis. Chain has very good abrasion characteristics and provide high geometric stiffness due to weight (Larsen, 2016). This will be further discussed in chapter 7.

Chain links can be either studlink or studless. The studless chain links are most common for permanent mooring (Vryof Anchors, 2010). The bottom attachment is usually made of heavy studless chain to provide good dynamic capabilities and a flexible mooring system. In other parts of the mooring system, lighter chain is usually used (Standard Norway, 2009).

Synthetic fiber ropes

Synthetic fibre ropes has the advantage of high elasticity and low weight. Polyester and polyethylene, which are the most common materials, is close to nylon in strength, but stretches very little. They provide good damping effects and have highly elastic properties (Bai and Bai, 2012). Synthetic mooring lines are easy to handle and install, but does not have as good abrasion characteristics as chain links (Larsen, 2016).

5.2.2 Connectors

Connectors are applied to ensure safe and reliable connection between the different mooring components.

Shackles

Shackles are used to connect chains to the anchors, or as a connection between the chain segment and polyester segment of the mooring lines. They consists of a bow that is closed with a pin, and functions as a locking mechanism (Vryof Anchors, 2010). The Norwegian Standard NS9415 states that shackles must be doubly secured and be made of corrosion-resistant material. An example of a shackle can be seen in figure 5.2a.

Mooring Plate

The mooring plate is the connection point between the mooring frame, mooring lines, bridles and buoy. It is the most important part of the mooring system, and aim to ensure safe position keeping of the global installation. All ropes are connected to the mooring plate at the mooring frame depth, well below propeller depth, to ensure safe transport around the fish farm. The coupling plate must be designed such that the first yield occurs in a mooring line attachment point rather than in the plate itself (Standard Norway, 2009). A typical mooring plate configuration is shown in figure 5.2b. The buoy is attached in the middle of the plate, while the mooring lines and mooring frame ropes are evenly distributed and connected to the plate by shackles.

(a) Shackle (b) Mooring Plate

Figure 5.2: Connectors (Illustrations by Aqualine)

5.2.3 Bottom Attachment

The bottom attachment transfer loads from the mooring system to the seabed. Choice of bottom attachment type mainly depends on the bottom conditions on site. For rock bottom, rock pins are used, while for sand and clay bottom, anchors are the preferred type of bottom attachment.

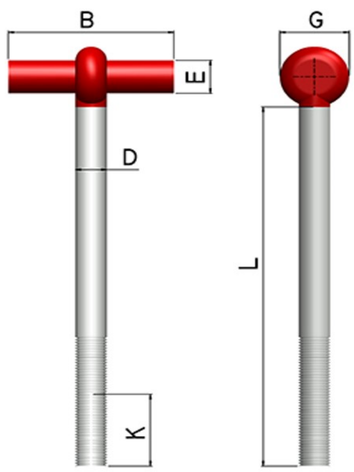
Rock Pins

Rock pins are hollow steel pipes that can penetrate through rock. Two types of rock pins are used for anchoring; T-pins and eye-pins. T-pins have a T-configuration on top of the pin and shackles can be connected around the bolt stem, while for eye-pins, shackles are connected through a hole at the top of the pin. The rock pin is installed by a piling hammer or vibrator, and it is fastened to the soil either by expanding the steel on the bottom of the pile, or by grout, which makes the pile stick to the rock. A combination of the two fastening methods is usually applied. The holding capacity of the rock pin depends on the strength of the steel, how good attachment it gets with the soil, as well as the strength of the soil itself (SINTEF et al., 2010). A typical T-pin configuration is shown in figure 5.3a.

Anchors

Dimensioning of the anchor must correlate to the geological conditions on site. The anchor holding power must meet the requirements in the mooring analysis.

Fluke anchors are the most common type of anchor used for mooring of fish farms. These anchors have the benefit of high holding capacity to weight ratio. The holding capacity depends on the amount of soil that is displaced by the anchor and the ability of the soil to hold together. This implies that anchors with large fluke and deep penetration gives the highest holding capacity. The penetration is dependent on soil conditions, and must be adapted to the specific site (Vryof Anchors, 2010). An example of a fluke anchor is shown in figure 5.3b.



(a) Rock pin

(b) Fluke anchor

Figure 5.3: Bottom attachment (Illustrations by Aqualine)

6 Design Considerations

When designing a marine fish farm, rules and regulations needs to be assessed in all stages of the design process. The technical standard set restrictions for all main components of an installation, and specifies design limit states for the individual components, as well as for the global installation. To ensure safe design of the structure, determination of loads, load effects and resistance to the load effects needs to be assessed. This should be done in accordance with defined limit states.

6.1 Limit State Design

In early stages of design, it is difficult to predict the loads that will act on the structure during its intended lifetime. Limit state design is a method for enabling more accurate safety factors by considering the possible loads separately (Curtin et al., 2008). The method is applied to verify that no structural limits can be exceeded due to loads and response, improper material properties, inaccurate geometrical data or product properties (Fredheim, 2016).

Design limit states are determined to ensure that the construction meets the specific design criteria that are necessary to avoid technical failure. The limit states define the load criteria the structure must be able to withstand (Standard Norway, 2009).

According to NS9415, dimensioning of a construction, or part of a construction, should be done in relation to two limit states:

- Ultimate Limit State (ULS)
- Serviceability Limit State (SLS)

Fatigue and accident situations should be seen in regard to the ULS condition (Standard Norway, 2009).

6.1.1 Ultimate Limit State (ULS)

The ultimate limit state (ULS) aim to ensure that the structure, or a specific part of the structure, have sufficient strength when exposed to extreme environmental loads. ULS is usually set equal to the maximum load that the components can withstand without structural failure. The ultimate limit state shall ensure the safety of people and the safety of the structure itself (Standard Norway, 2009).

6.1.2 Serviceability Limit State (SLS)

The serviceability limit state (SLS) is the limit state for when a structure, or part of a structure, no longer meets the requirements for normal use. This limit state assess the comfort of the people handling and operating the installation (Standard Norway, 2009).

6.1.3 Accidental Limit State (ALS)

The accidental limit state (ALS) is the limit state for when a structure, or part of a structure, is exposed to an accidental load (Standard Norway, 2009). ALS aim to ensure that the system has enough reserve capacity in accident situations. Accidental loads can arise from accidental events, such as collisions, or operational failure, such as improper pretension in mooring lines (Brown, 2005).

6.1.4 Fatigue Limit State (FLS)

The fatigue limit state (FLS) is the limit state for when a structure, or part of a structure, is exposed to repeated loads during its intended lifetime (Standard Norway, 2009). FLS aim to ensure that the system has enough reserve capacity when the equipment is exposed to cyclic loading. Fatigue depends on load variations over time, and for mooring lines it is especially important to asses loads that vary with wave frequency (Brown, 2005).

6.2 Load and load combinations

All possible loads that might affect the structure must be evaluated to ensure structural integrity of the installation. The load evaluation must be done in accordance with the limit states. Different loads and load combinations occur over the indented lifetime of the marine fish farm, and dimensioning must be supported by load calculations and proper documentation of the load effects.

According to NS9415, loads that can influence the marine fish farm can be divided into different categories. *Permanent loads* include the weight of the fish farm itself, the weight of fixed equipment, as well as static buoyancy forces. *Variable function loads* are maximum loads which is not permanent, and which can be removed. This can include, but is not limited to, personnel, variable ballast, movable equipment, and stored goods such as feed. *Deformation loads* occur during forced deformation of the structure. Deformation could be a result of the fish farm's function and its interaction with the environment, such as pre-tensionig, mooring, or the effect of temperature variations. *Environmental loads* include loads from wind, waves, and current. *Accidental loads* is more difficult to assess, but NS9415 require that accidental conditions such as breaks in mooring lines and loss of buoyancy must be evaluated (Standard Norway, 2009).

In addition to the different load categories mentioned above, possible combinations of loads needs to be assessed when designing a marine fish farm. Structural integrity is achieved by determining the correct characteristic loads and load combinations. Table 6.1 indicates the combinations of current, wind and waves that is controlled in ultimate limit states, given in return period.

Table 6.1: Combinations of environmental loads (Standard Norway, 2009)

Combination	Current	Wind	Wave
1	50	10	10
2	10	50	50

Load combination 1 implies that the response of the structure under influence of 50 year current, 10 year wind, and 10 year waves, must be controlled in ULS (Standard

Norway, 2009). The most unfavorable of the two load combinations are used as basis for determining characteristic load. This will be assessed in section 6.3. In addition, accidental limit states must be controlled under stress from the most unfavorable load combination. Which load combination that gives the most unfavorable response must be evaluated separately for each accidental event (Standard Norway, 2009).

6.3 Partial Co-efficient Method

The partial co-efficient method is applied to define the limit states to which the installation can be exposed. It incorporates safety factors to ensure that the structure meets the design requirements that are necessary to avoid technical failure. The partial co-efficient method is based on requiring that the design load effect, must be less than or equal to the strength of the component, divided by a material factor (Standard Norway, 2009):

$$S_f \leq \frac{R}{\gamma_m} \tag{1}$$

where

S_f	is the design load effect (characteristic load F_C times load factor γ_f)
R	is the strength of the component
γ_m	is the material factor

The characteristic capacity for resistance, R, is usually determined by equipment testing, and is most often set equal to the breaking strength of the component. The characteristic load, F_C, is determined from analyses based on the limit states.

The concept of the partial co-efficient method is illustrated in figure 6.1. The curve to the left illustrates the distribution of load, and the right curve illustrate the distribution of capacity. The objective of equation 1 is to ensure that the characteristic load does not exceed the strength of the component with sufficient probability. The probability of failure is indicated on the figure by the grey shaded area where the two distribution curves overlap.

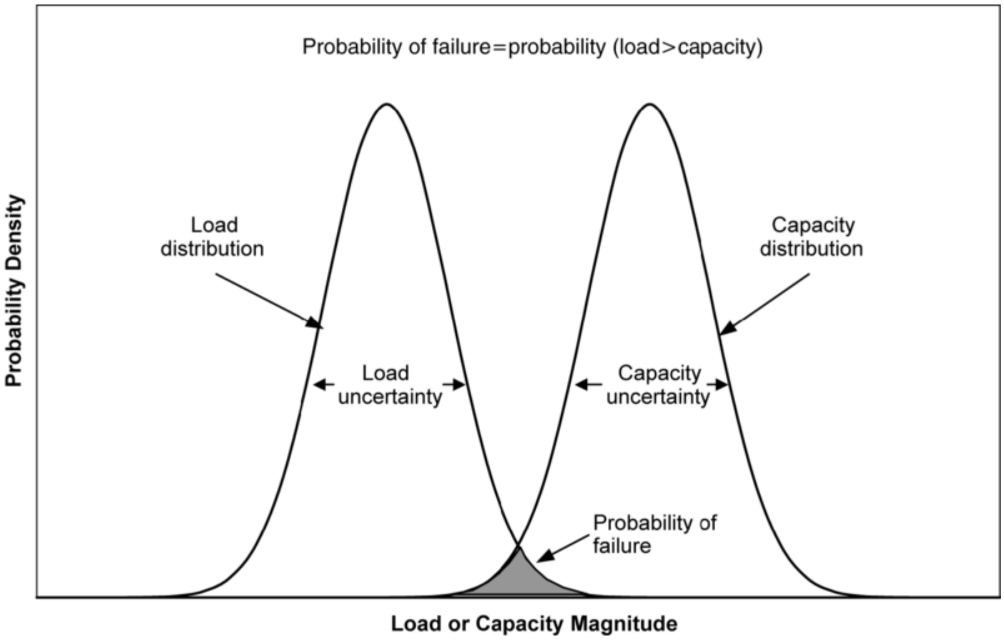


Figure 6.1: Load and resistance distributions (SPE International, 2016)

6.3.1 Safety Factors

The safety factors shall account for uncertainty in loads and response, as well as material properties (Standard Norway, 2009). Safety factors are applied to ensure that the possible loads imposed on the fish farm do not exceed the capacity of the different components with sufficient probability, i.e. that the grey shaded area in figure 6.1 is sufficiently small.

The load factor, γ_f, accounts for uncertainty in loads. Which load factor to apply depends on the type of analysis conducted. The load factor considers the following (Standard Norway, 2009):

- The possibility of loads deviating from the theoretical values
- The reduced probability of loads acting at the same time
- Uncertainties in modelling and analyses of loads

The material factor, γ_m, accounts for uncertainty in material properties. NS9415 provide material factors for all the main components of a marine fish farm. The material factor considers the following (Standard Norway, 2009):

- The possibility of material strength deviating from the theoretical values
- The possibility that the total material strength for the global installation is less than the material strength for each individual component
- Uncertainties in modelling of strength

6.3.2 Design Load

When designing a marine fish farm, the most important aspect is to ensure that equation 1 is valid. To determine the design load effect, S_f, wave distribution and environmental conditions at the locality is examined. The site survey provides the basis for determining the characteristic load, F_C. The environmental parameters in the site survey includes significant wave height, H_S, peak period, T_p, and current velocity, U_c. The parameters used for dimensioning purposes represents the maximum values measured during the measurement period at the site.

In the aquaculture industry, the characteristic load is most often determined by regular wave analyses. For regular waves, maximum wave height shall be assumed equal to

$$H_{max} = 1.9\ H_S \tag{2}$$

where

H_S	is the significant wave height

In the case of irregular waves, a JONSWAP spectrum with $\gamma = 2.5$ for wind sea and $\gamma = 6.0$ for swells shall be applied (Standard Norway, 2009).

The dimensioning current velocity is also based on the site survey. Maximum current velocity can be determined in three ways; (i) measurement of current for one year and use of long-term statistics, (ii) measurement of current for one month and multiplication factors, or (iii) use of previous current measurements (Standard Norway, 2009).

Characteristic load must be determined according to the load combinations presented in table 6.1. The extreme values of significant wave height and period is determined by calculations based on effective fetch length or long-term statistics. Concerning effective fetch length, 50 year significant wave height should be calculated from the site's measured 50 year wind (Standard Norway, 2009). Extreme values of current velocity are determined by applying the multiplication factors presented in table 6.2.

Table 6.2: Multiplication factor (Standard Norway, 2009)

Return period	Multiplication factor
10	1.65
50	1.85

6.4 Design of Mooring Systems

Mooring system design is based on assessing the environmental conditions provided in the site survey and the specifications provided by the producer of the floating collar and net cage. The mooring system must account for the deformations and additional loads that may arise from the fish farm's interaction with the environment. Mooring lines provide restoring forces to the installation, and the loads from the mooring system on the collar must be in accordance with the limitations provided by the manufacturer of the floating collar (Standard Norway, 2009).

Limit state design also apply for the mooring system, and the system must be controlled in ultimate limit states by assessing the load combinations presented in table 6.1. Also, accidental limit states must be assessed in accordance with NS9415.

6.4.1 Functional Requirements

The horizontal offset of the net cage should be limited to a minimum, such that the integrity of the installation is maintained. The mooring system should not affect the cage in any way that may increase the risk of fish escape. This means that the system must be designed to withstand the environmental conditions from waves, wind and current, as well as to meet the structural requirements of the installation as a whole. The mooring system must (Standard Norway, 2009):

- Withstand all expected loads and deformations without breaking
- Meet the requirements from environmental conditions at the locality
- Tolerate unexpected events that could harm the installation
- Withstand destructive effects such as corrosion or oxidation that could affect the mooring system over time

6.4.2 Load Factor

Mooring lines must be designed in accordance with the load factors provided in NS9415. The load factors depend on the type of mooring analysis that is performed and is presented in table 6.3. The certification company that performs the mooring analyses decide which type of analysis they will base the calculations on. The chosen load factor is applied in the partial co-efficient method to determine the design load effect of the installation.

Table 6.3: Load factors for mooring lines (Standard Norway, 2009)

Type of analysis	Load factor, γ_f
Static analysis	1.6
Quasi-static analysis	$1.15 \times$ DAF
Dynamic analysis	1.15
Accident limit (break in mooring line)	1.0
Spring flood	1.0

6.4.3 Material Factor

Material factors are applied in the partial co-efficient method to account for uncertainties regarding strength of the mooring lines. The specific material factor depends on the type of materials and/or components that is applied to the system. The mooring line material factors are presented in table 6.4.

Table 6.4: Material factors for mooring lines (Standard Norway, 2009)

Type	Material factor, γ_m
Synthetic rope	3.0
Synthetic rope with knots	5.0
Chains and chain components	2.0
Used chain	5.0
Coupling disks	1.5
Shackles	2.0
Rock bolts and other bottom attachments	3.0

As seen, synthetic rope has a material factor of 3.0, while chain has a material factor of 2.0. Chain has lower material factor due to its good abrasion characteristics, compared to synthetic fibre. The material that is going to be used must be in accordance with the documentation provided by the supplier of the mooring lines, and the material properties must be documented by proper testing (Standard Norway, 2009).

6.4.4 Accidental Conditions

Design and dimensioning of mooring lines must also be done in accordance with accidental limit states, and controlled for the most unfavorable load combination in the event of an accident. In regard to the the accidental limit state for mooring, a floating fish farm must be evaluated for possible breaks in mooring lines. The following accidental conditions must be assessed and documented (Standard Norway, 2009):

- Break in mooring line with the largest load

- Break in mooring line that is critical with respect to the integrity of the floating fish farm
- Break in connection points
- Break in mooring line that is critical with respect to the possibility of impacting nearby structures

In addition to tolerate breaks in mooring lines, the fish farm shall tolerate an increased water level of 1.0 meter. In ALS condition, the material factor from table 6.4 is divided by a factor of 1.5 (Standard Norway, 2009).

7 Fish Farm Analysis

Aquaculture net cages are highly flexible structures that experience large deformations when exposed to waves and current, and fish farms will behave differently in its environment compared to rigid installations. The different loads that affect the behavior of a marine fish farm must be analyzed such that the effect of interaction between the different components of the farm is accounted for. The combination of stiff and soft parts impose a challenge for analyzing the fish farm as an integrated coupled system. All components will move and behave under mutual influence, and hydroelastic analyses is required to account for structural deflection.

The flexibility of the net and floating collar allows the cage to change shape when it is exposed to waves and current. The permeability of the net allows for part of the flow field to flow through the net cage, while the rest of the fluid will flow around the fish farm. For a fish farm with multiple cages, the presence of downstream cages will alter the flow field, and this must be accounted for when analyzing a marine fish farm. This effect is illustrated in figure 7.1.

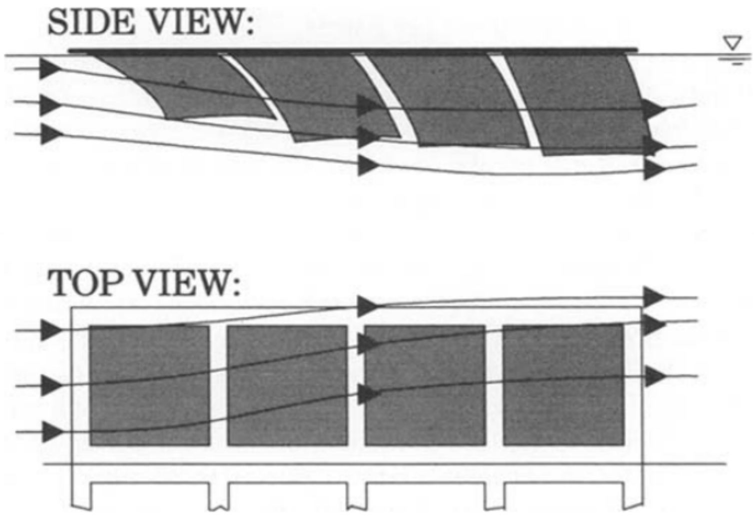


Figure 7.1: Flow through a system of net cages (Illustration by Løland (1993))

7.1 Equation of Motion

The equation of motion can be used to describe the system behaviour as a function of time. To determine the motions that act on a floating fish farm, the equation of motion in six degrees of freedom needs to be solved (Larsen, 2016):

$$(M + A(w))\ \ddot{x} + C(w)\ \dot{x} + D_l\ \dot{x} + D_q\ \dot{x}|\dot{x}| + K(x)\ x = Q(t, x, \dot{x}) \tag{3}$$

where

M	mass matrix
$A(w)$	frequency-dependent added mass matrix
x	position vector
$C(w)$	frequency-dependent potential damping matrix
D_l	linear damping matrix
D_q	quadratic damping matrix
$K(x)$	stiffness matrix
$Q(t, x, \dot{x})$	excitation force vector

For an aquaculture net cage, the equation of motion can be used to describe its horizontal movement, i.e. movement in x-direction. The excitation forces correspond to the environmental forces; wind, waves, and ocean current. The mass term includes the mass of the structure, as well as hydrodynamic mass. Damping is mainly provided by the net. Stiffness for a single cage, as well as an entire fish farm, is provided by the mooring system.

7.1.1 Mass

The mass term in the equation of motion includes the mass of the floating structure and the hydrodynamic mass (added mass). The net cage itself has low weight in water, thus the mass will mainly be provided by the weight of the collar and sinker tube. The installation will have an added mass contribution from the effect of fluid inside the net (Kristiansen and Faltinsen, 2012).

7.1.2 Damping

Damping denotes the structure's ability to dissipate kinetic energy, that is, its ability to transform kinetic energy into other types of energy (Langen and Sigbjörnsson, 1999). Submerged structures have larger damping forces than those in air, mainly due to viscous forces (Larsen, 2014). The damping forces on fish farms are provided primarily by drag forces on the net cage, and viscous effects are the most important contribution to damping. Different damping scenarios are presented in figure 7.2. For an overdamped system, the installation returns to equilibrium without oscillating, while underdamped systems oscillate with gradually decreasing amplitude. Critically damped systems return to equilibrium as quickly as possible without oscillating. A net cage in a fish farm will be overdamped in heave, surge and sway, due to the viscous damping from the net (Søreide, 2016).

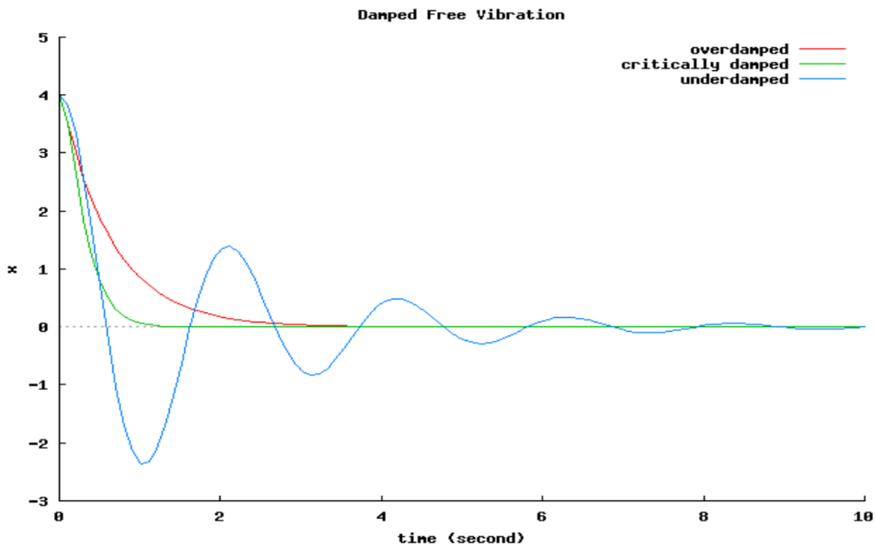


Figure 7.2: Damping scenarios (Søreide, 2016)

7.1.3 Stiffness

Stiffness of the aquaculture installation is provided by the mooring system. The effective stiffness is composed of *geometric* and *elastic* stiffness. Geometric stiffness is provided by line weight, and is the governing stiffness contribution from chains. Elastic stiffness is provided by line axial elongation, due to material characteristics and cross section properties of the mooring lines. For synthetic mooring lines, elastic stiffness is the dominating contribution (Faltinsen, 1990).

A floating fish farm is moored by pre-tensioned mooring lines, which implies that there is a certain tension in the lines when the farm is in its equilibrium position. When the structure moves in response to environmental forces, the geometry of the mooring lines change, which, in turn affects the tension. The offset of the structure will not be constant, but rather oscillate around a mean position, due to the installation's motion in waves. Mooring lines will thus impose a spring effect on the fish farm that depends on the stiffness of the system (Faltinsen, 1990).

For spread mooring systems, several pre-tensioned mooring lines are anchored around the fish farm to keep it at its desired position. The tension that restrains the farm from moving is provided by weight and/or elastic properties of the mooring lines. The segmented mooring lines that consist of both chain and synthetic fibres provides stiffness by both weight and elasticity (Faltinsen, 1990).

Total stiffness, k_{tot}, can be calculated by summarizing the inverse of the geometric and elastic stiffness:

$$\frac{1}{k_{tot}} = \frac{1}{k_G} + \frac{1}{k_E} \tag{4}$$

where

k_G	geometric stiffness
k_E	elastic stiffness

The horizontal stiffness contribution from one mooring line is determined by the mooring line characteristics. This will be discussed more closely in section 8.1.

7.1.4 Excitation Loads

Excitation forces are mainly provided by environmental loads, which corresponds to waves, wind, and current. Wind act on the parts of the fish farm that lies above surface, such as bird nets and hand rails. Wave forces act on the floating collar and the upper parts of the net cage. Current forces act mainly on the net cage, but mooring lines, the floating collar and floatation is also influenced by current (Fredheim and Langan, 2009).

Wind

The response of the structure due to wind is usually small, since wind only acts on the parts of the structure that lie above water. Only a small part of the fish farm is above surface, which means the wind loads can be neglected (Fredheim and Langan, 2009).

Waves

When performing structural analyses of floating installations, it is beneficial to characterize the structural members by their size compared to wave height and wave length (Fredheim and Langan, 2009). For *large-volume structures*, diffraction loads are the governing loads. Diffraction loads refer to loads induced by incident waves and their modification due to the presence of the structure. *Small-volume structures*, on the other hand, does not affect the incident waves, and long-wave approximation can be applied. The long-wave approximation implies that the wave loads can be modelled as if the body was not present in the fluid. Small-volume structures can be subdivided into drag dominated and inertia dominated structures (Faltinsen, 1990).

To classify the structure as large – or small-volume, it is beneficial to study a cylinder with diameter D in regular waves, with wave length λ, and wave height H. If $\frac{\lambda}{D} < 5$, the structure is classified as large-volume, while if $\frac{\lambda}{D} > 5$, the structure is considered small-volume. The proposed limits between large– and small-volume structures only serve as guidelines, and the classification of the structure will also depend on environmental conditions and the specific phenomenon that is studied (Pettersen, 2007).

Whether small-volume structures are drag dominated *or* inertia dominated depends on a range of factors. Drag dominated loads can be hard to determine due to the uncertainties connected to viscous effects. A rough estimate is that the structure can be considered to be drag dominated when $\frac{H}{D} > 4\pi$ (Pettersen, 2007).

Floating fish farms are complex systems since the differences in length scales makes such installations a combination of large – and small-volume bodies (Kristiansen and Faltinsen, 2015). For the components of a fish farm that are small compared to wavelength, Morison's equation can be applied to derive the wave loads. Morison's equation is used to calculate wave forces on circular cross-sections, and the horizontal force, dF, on a strip, dz, can be determined by (Morison et al., 1950):

$$dF = \underbrace{\rho\pi\frac{D^2}{4}C_M a_1 dz}_{Inertiaforce} + \underbrace{\frac{\rho}{2}C_D D|u|udz}_{Dragforce} \tag{5}$$

where

ρ	density of water
D	cylinder diameter
C_M	mass coefficient
C_D	drag coefficient
a	particle acceleration
u	particle velocity

The contribution from inertia forces is small compared to the drag forces, due to low particle acceleration, and drag loads are the governing forces when studying wave loads on a net cage. The drag term in Morison's equation is quadratic with respect to relative velocity between the fluid and the structure, which gives an exponential increase in drag force with increasing relative velocity. The drag coefficient is determined from empirical formulas (Kristiansen and Faltinsen, 2012).

For larger components of the fish farm, such as barges and live fish carriers, diffraction theory is applied to determine the wave loads (Berstad et al., 2014). Diffraction theory is based on considering the forces, F_i, on the body that arise when the structure is restrained from oscillating. These forces are composed of Froude-Kriloff and diffraction forces. The two contributions are obtained by integrating the incident-wave dynamic pressure and the diffraction dynamic pressure along the mean wetted surface of the structure, respectively (Faltinsen, 1990):

$$F_i = \underbrace{-\iint_S pn_i \, ds}_{Froude-Kriloff} + \underbrace{A_{i1}a_1 + A_{i2}a_2 + A_{i3}a_3}_{Diffraction} \tag{6}$$

where

p	hydrodynamic pressure on the submerged structure
A_{ij}	added mass coefficient
a_{ij}	acceleration

The wave forces decrease rapidly with depth, which means they are most critical with respect to the floater. For the net cage, current will have larger influence on the loads. Calculation of wave and current loads will be discussed in the following section.

Current

Current forces act on the submerged parts of the structure and are most often the governing environmental forces on a floating fish farm. When a net cage is placed in current, it will alter the flow field. A part of the flow will go around the net, while the rest will flow through the net cage with increased velocity due to the presence of the net. The increase in flow velocity is highly dependent on the area covered by twines, which is expressed by the solidity of the net. Solidity ratio, S_n, can be defined as the ratio between the area covered by twines and the total net area. Simplified solidity ratio can be calculated as (Løland, 1993):

$$S_n = \frac{2 \times d}{\lambda} \tag{7}$$

where

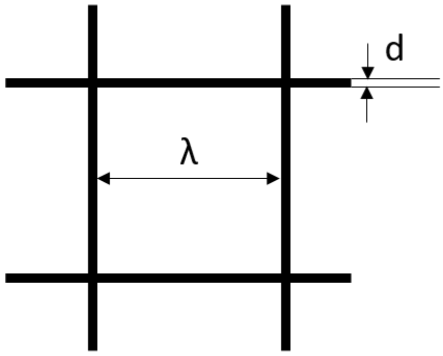
d	twine diameter
λ	mesh length

and the increased velocity, U_s, can be determined as a function of inflow velocity, U_∞, and solidity ratio, S_n,

$$U_s = \frac{U_\infty}{1 - S_n} \tag{8}$$

Figure 7.3a illustrates a simple net structure, while figure 7.3b shows basic definitions used to determine the solidity ratio.

(a) Typical net structure (Berstad et al., 2014)



(b) Mesh

Figure 7.3: Illustrations of net

Current and wave loads can be modelled by a hydrodynamic force model based on the Morison equation. A simplified approach for calculation of wave and current forces is to apply the Morison equation to each twine in the net, by assuming cylindrical twines with constant diameter. However, this method overpredicts the drag force for large inflow angles and does not account for the interaction effects between the twines (Kristiansen and Faltinsen, 2012).

Another option is to divide the net cage into a set of net panels, or screens, as illustrated in figure 7.4.

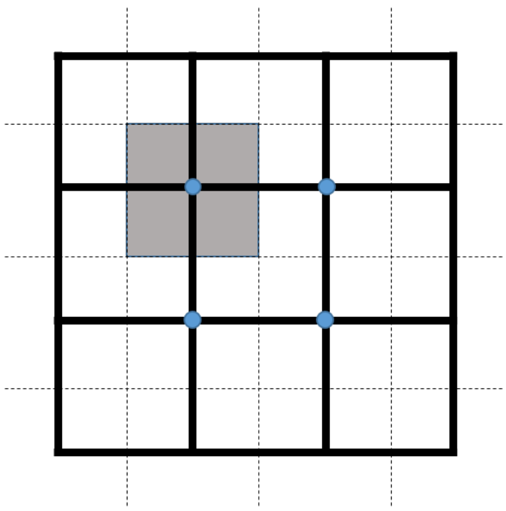


Figure 7.4: Net panel used for calculation of wave and current forces

The number of panels needed to determine hydrodynamic forces depends on the shape of the net cage. Morison's equation is also applied to each twine in this model, but each net panel now accounts for the effect of inflow angle and the shadow effect due to interaction between twines. The inflow angle is assumed to be equal for all twines in one screen.

The hydrodynamic force can then be decomposed into drag– and lift components for each twine in the net panel

$$dF_D = \frac{\rho}{2}\, C_D(\theta, S_n, Re)\ D\ |u|u\ dz \tag{9}$$

$$dF_L = \frac{\rho}{2}\, C_L(\theta, S_n, Re)\ D\ |u|u\ dz \tag{10}$$

respectively. The drag – and lift coefficients depends on the solidity of the net, inflow angle on the net panel, as well as Reynolds number (Kristiansen and Faltinsen, 2012). The current force on each screen is then calculated as a function of local current velocity, inflow angle and weight of sinkers. The total drag force on the cage can be found by summarizing the force contributions from each individual net panel (Løland, 1991). This method is also applicable for calculating current forces on a system of multiple cages.

The squared velocity term in Morison's equation implies that the total force on the system will behave quadratically with inflow velocity. This is only true for structures that does not deform when exposed to environmental loads. However, for fish farms, the geometry of the net cage will change due to its flexibility, and thus the total drag load will be lower than for a rigid structure.

7.2 Model Testing

Model testing is performed to investigate the behavior of a structure in its true environment, as well as non-linear effects. Hydrodynamic model testing aims to (Steen, 2014):

- Verify performance of actual concepts
- Verify theoretical methods and numerical models

- Obtain a better understanding of physical behaviour

Model tests can also be used to investigate the effects of simplifications used in numerical or analytical models.

For aquaculture fish farms it is essential to examine the non-linear effects on the installation. Mooring forces strongly depend on non-linear forces from the current and wave loads on the net cage. Also, if the fish farms are going to be moved to more exposed sites, proper documentation and qualification is essential to ensure sufficient structural integrity of the installations. This can be achieved through model testing (Søreide, 2016).

8 Mooring Analysis

To perform analyses of the mooring system, the floating fish farm has to be examined as a global system. The excitation loads that act on the fish farm will affect the tension and forces imposed on the mooring lines, such that the interaction effects between the different parts of the installation must also be assessed in a complete mooring analysis.

A certified mooring analysis is required by NYTEK for all fish farming sites. To perform an analysis of a complete mooring system, it is essential to have prior knowledge about the specific site where the system is going to be deployed. The site survey includes information about water depth, bottom type and topography, providing the basis for the mooring analyses. NS9415 requires that a sketch of the facility including the mooring system is contained in the documentation of the system. The documentation shall include the intended laying pattern, attachment points, line lengths and depths. An example of a mooring lay-out is shown in figure 8.1.

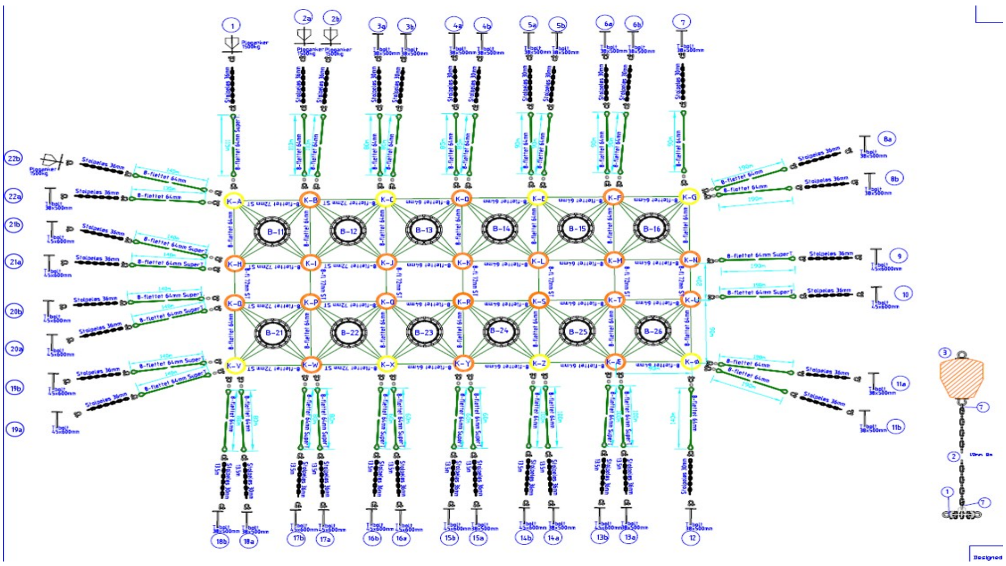


Figure 8.1: Mooring lay-out (Illustration by Aqualine)

The supplier of the mooring system must provide sufficient documentation to prove that the system is suitable for the specific site. The documentation describes the specifications of each mooring line, the expected limit states, design working life, etc., and the documentation must be supported by calculations and dimensioning (Standard Norway, 2009).

Installation of the mooring system takes place in accordance with a lay-out plan. After the system is installed, a new mooring analysis is performed to control that the requirements in the standard are met. If the actual lay-out deviate from the lay-out plan, proper documentation must be provided to ensure that the change has not led to weakening of the system (Standard Norway, 2009).

8.1 Static Analysis of Mooring Lines

When performing static analyses, the dynamic effects are neglected, and only the stiffness term and the excitation loads are considered. The equation of motion is then simplified to

$$K(x)\ x = Q(t, x, \dot{x}) \tag{11}$$

where,

x	position vector
$K(x)$	stiffness matrix
$Q(t, x, \dot{x})$	excitation force vector

The objective of a static analysis is to determine the stiffness contribution from the mooring lines to the total system. The following sections explain how to perform a static analysis of a mooring line, both for inelastic and elastic lines, and then how the equations can be generalized for a frame mooring system. The description of static analysis is based on Faltinsen (Faltinsen, 1990).

8.1.1 Static Analysis Model

When analyzing a mooring system, it is convenient to look at the load effects in one separate mooring line, and then generalize the case for spread moored systems. A typical mooring analysis consist of summarizing the load effects from all individual mooring lines to determine the global effect of the mooring system.

A simplified model of a mooring line is shown in figure 8.2. h equals the water depth, x indicates the horizontal distance from the anchor to the structure, while s equals the length of the catenary. In this model, it is assumed that the seabed is horizontal and the mooring line is considered to be in the vertical plane. The position where the mooring line touch the seabed is called the touch down point. The behavior of a mooring line can be described by the catenary equations, which is based on neglecting the bending stiffness effect. This is a good approximation for chains, but for synthetic fibre ropes, the bending stiffness has to be accounted for. This will be discussed in section 8.1.3.

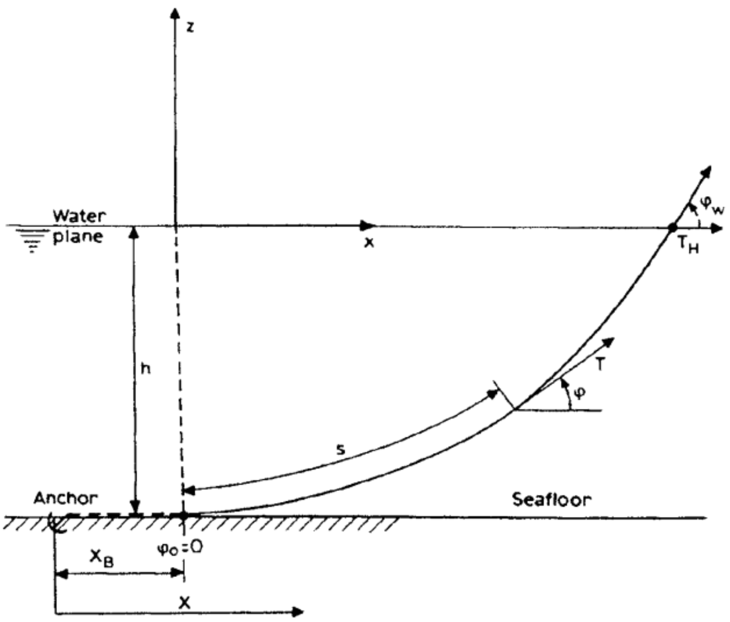


Figure 8.2: Mooring line with symbols (Brown, 2005)

Static analysis of a mooring line is conducted by inspecting an infinitesimal element of the line. Forces acting on the element is shown in figure 8.3. F and D are hydrodynamic external forces, mainly current forces, acting on the mooring line in the tangential and normal direction, respectively. w is the weight of the mooring line per unit length in water. The weight will not be evenly distributed over the element due to deviation in buoyancy at the two ends, but this effect will be neglected in the following sections.

Mooring line properties are described by E, which is the elastic modulus of the line, and A, which is the cross-sectional area of the mooring line. T represents the tension in the mooring line.

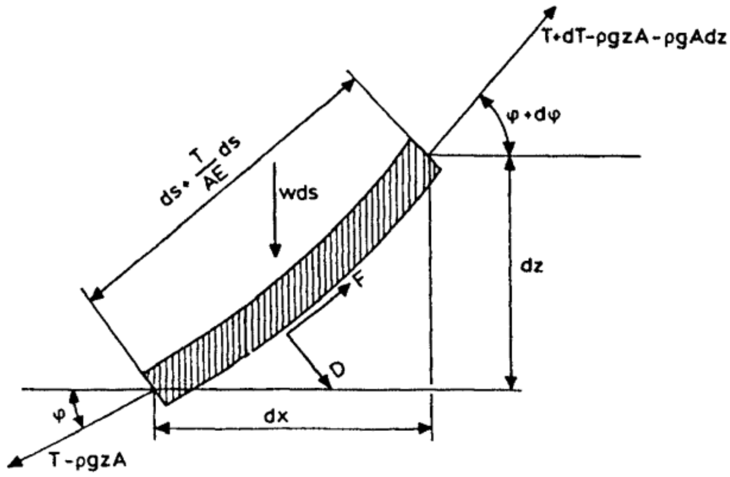


Figure 8.3: Forces acting on an infinitesimal element of the mooring line (Brown, 2005)

From figure 8.3, it can be seen that the static equilibrium of the element is given by

$$dT = [wsin(\phi) - F(1 + \frac{T}{EA})]ds \tag{12}$$

$$Td\phi = [wcos(\phi) + D(1 + \frac{T}{EA})]ds \tag{13}$$

in tangential and normal direction, respectively. These equations are non-linear, and a explicit solution can not be found. To solve the above equations, the following assumptions are introduced:

- Current loads (D and F) are neglected. For fish farms, current forces on mooring lines will in most cases be insignificant compared to the loads on the net cage, and can therefore be neglected (Fredheim and Langan, 2009).

- The tension is much less than the axial stiffness for normal mooring line components, and effect of elasticity is neglected for simplicity. In extreme conditions, such as high tension, very long mooring lines or elastic segments (synthetic fibre) the elasticity must be accounted for.

8.1.2 Inelastic Mooring Line (Catenary Equation)

By neglecting elasticity and current loads, equation 12 and 13 are simplified to

$$dT = w\sin(\phi)\ ds \tag{14}$$

$$Td\phi = w\cos(\phi)\ ds \tag{15}$$

The catenary length, s, equals the length from the attachment point of the mooring line to the touch down point, and can then be expressed as

$$s = \frac{T_H}{w}\ \sinh(\frac{wx}{T_H}) \tag{16}$$

and the vertical distance from the installation to the seabed (depth) is expressed by

$$h = \frac{T_H}{w}\ [\cosh(\frac{wx}{T_H}) - 1] \tag{17}$$

By combining equation 16 and 17, the top tension in the mooring line, T_H, can be expressed in terms of depth and catenary length

$$T_H = (s^2 - h^2)\ \frac{w}{2h} \tag{18}$$

To determine the mean position of the installation in wind, waves and current, it is beneficial to look at the top tension in relation to the horizontal offset of the floater, called line-characteristics. The catenary length, s, increase when the floater move away from the anchor, and it is thus appropriate to select the anchor point as reference.

Line characteristics can then be expressed as

$$X = l - s + x \tag{19}$$

By using equation 16 to express s, and equation 17 to express the horizontal distance from the floater to the touch down point, x, the following relation between top tension and the horizontal distance between the anchor and anchor line attachment point is determined

$$X = l - h\sqrt{(1 + \frac{2w}{T_H h})} + a\cosh^{-1}(1 + \frac{hw}{T_H}) \tag{20}$$

8.1.3 Elastic Mooring Line

As discussed, the elasticity of the mooring line has to be accounted for in extreme conditions. For fish farms, polyethylene ropes are often used for mooring, and these have high elasticity, which means elasticity has to be included in a static analysis. By introducing elasticity, the distance from the structure to the seabed, h, becomes

$$h = \frac{T_H}{w}(\frac{1}{\cos(\phi_w)} - 1) + \frac{1}{2}\frac{w}{EA}s^2 \tag{21}$$

and the catenary length, s, is now expressed in terms of the vertical component of the top tension, T_Z,

$$s = \frac{T_Z}{w} \tag{22}$$

By expressing the top angle, ϕ_w, at the mooring line attachment point in terms of tension, the horizontal top tension can be determined from

$$T_H = \frac{T_Z^2 - (wh - \frac{1}{2}\frac{w}{EA}s^2)^2}{2\ (wh - \frac{1}{2}\frac{w}{EA}s^2)} \tag{23}$$

To determine the line characteristics similar to equation 19, the distance from the attachment point to the touch down point, x, needs to be determined. For elastic mooring lines, x can be expressed in terms of horizontal and vertical top tension as

$$x = \frac{T_H}{w}\ \sinh^{-1}(\frac{T_Z}{T_H}) + \frac{T_H}{EA}s \tag{24}$$

and finally, the horizontal displacement can be calculated as

$$X = (l - s)(1 + \frac{T_H}{EA}) + x \tag{25}$$

These equations give approximate solutions. If mooring line characteristics for a given horizontal top tension, T_H, is going to be determined, x has to be calculated by assuming different values of vertical top tension, T_Z, and then interpolate the data.

The horizontal distance between the anchor and the floater can be plotted against horizontal tension in the mooring line to examine the displacement of the structure due to static loads. Figure 8.4 illustrates the line characteristics for one elastic line and one inelastic line, with the same pretension and length. Line characteristics of the synthetic mooring line, with high elasticity and low weight in water, is linear. For the inelastic line, the horizontal tension also increase for increasing displacement, but as the distance gets larger, the tension increase more rapidly.

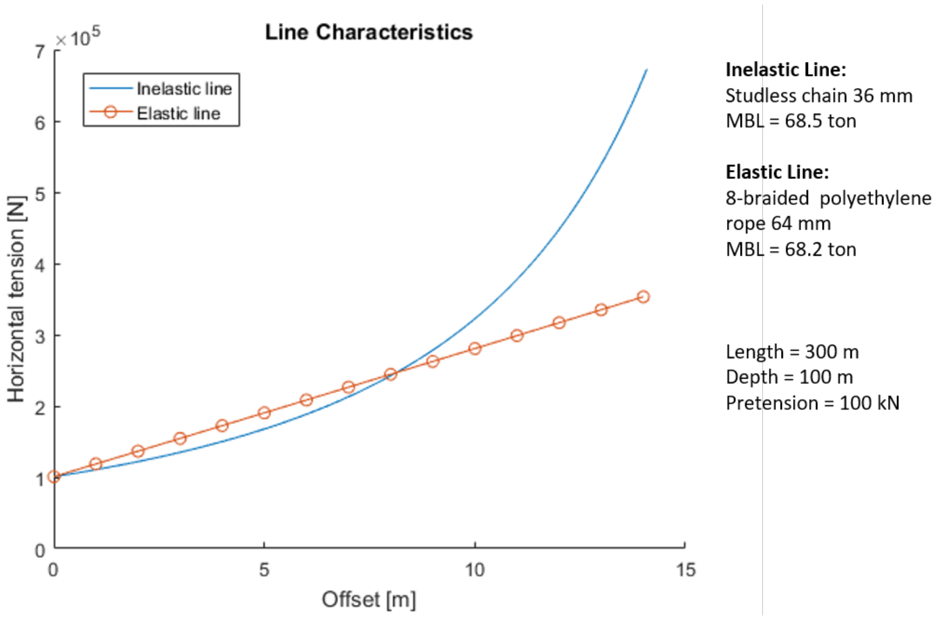


Figure 8.4: Line characteristics for chain and synthetic mooring lines

8.1.4 Analysis of Frame Mooring System

The procedure presented above can be generalized to a spread mooring system that consist of several mooring lines. The relationship between the mooring line tension and horizontal position of the fish farm can be determined by summarizing the tension contribution from each line separately (Faltinsen, 1990).

The horizontal forces in surge and sway, and the yaw moment from the mooring lines can be determined by

$$F_1^M = \sum_{i=1}^{n} T_{Hi}\cos(\psi)_i \tag{26}$$

$$F_2^M = \sum_{i=1}^{n} T_{Hi}\sin(\psi)_i \tag{27}$$

$$F_6^M = \sum_{i=1}^{n} T_{Hi}[x_i\sin(\psi) - y_i\cos(\psi)_i] \tag{28}$$

where

T_{Hi}	horizontal force from mooring line number i
x_i	x-coordinate of attachment point of the mooring line
y_i	y-coordinate of attachment point of the mooring line
ψ_i	angle between x-axis and mooring line

For the fish farm to be in equilibrium, the horizontal tension in the mooring line must balance the mean environmental forces. The restoring force of the system can be determined by studying the horizontal tension in all mooring lines simultaneously. Figure 8.5 illustrates horizontal tension as a function of the structure's horizontal offset for two mooring lines.

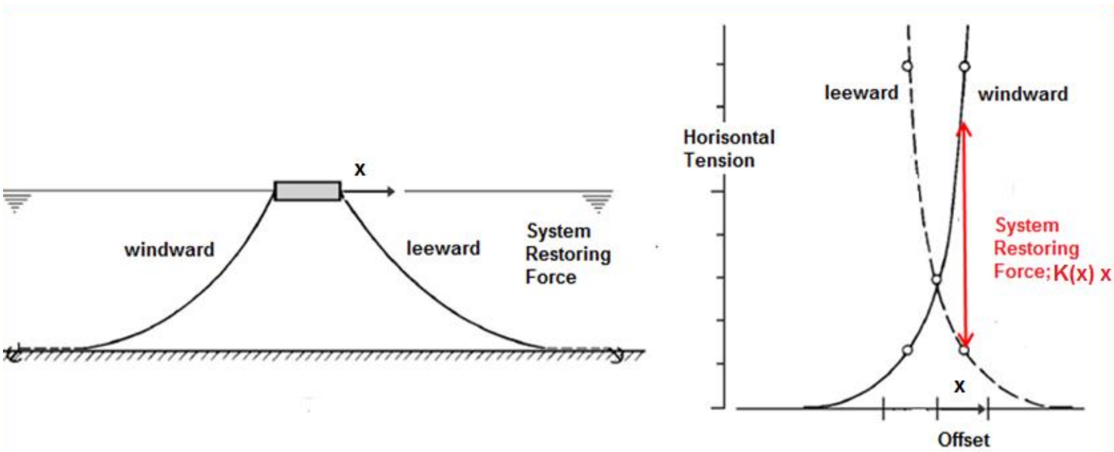


Figure 8.5: System restoring force (Larsen, 2016)

The tension in the leeward line decrease with increasing offset of the structure. Accordingly, the tension in the windward line increase with increasing offset. The system restoring force can be determined as the difference between the tension in the two lines at a given offset, as shown in the right part of figure 8.5.

Figure 8.6 also illustrates the result of a static analysis of two mooring lines. The objective of the static analysis is to determine the restoring effect of the mooring lines in the equation of motion. The slope of the restoring curve at the specific offset, gives an equivalent linear stiffness, K.

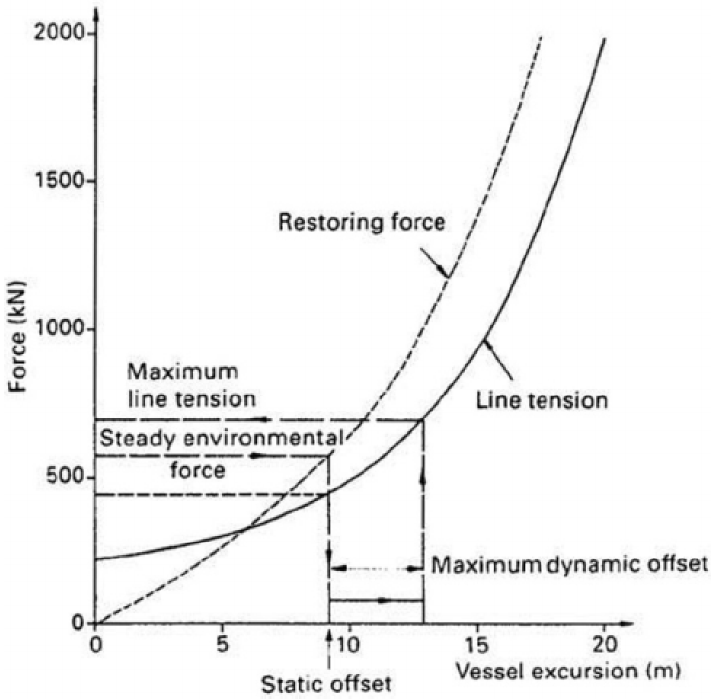


Figure 8.6: Restoring force and line tension vs offset (Brown, 2005)

By examining the steady environmental forces from wind, current and wave drift on the vertical axis in figure 8.6, the static offset can be obtained from the horizontal axis. The slope of the restoring force curve at this offset equals the linear stiffness of the mooring system in the equation of motion. The maximum dynamic offset due to wave and drift frequency effects can be estimated by inspecting maximum line tension (Brown, 2005).

8.2 Dynamic Analysis of Mooring Lines

When performing static analyses, the environmental forces is considered to be unidirectional, and large safety factors must be applied to account for uncertainties, as seen in table 6.3. Also, by using this method, important dynamic features are ignored (Brown, 2005).

Dynamic analysis account for all environmental forces, both static and dynamic loads, that act on the structure. It also accounts for mass, damping and rigidity of the construction, as well as accelerations as a result of wave movements (Standard Norway, 2009). In a dynamic analysis, all parts of the equation of motion, presented in section 7.1, must be included.

9 Simulation Study

A simulation study was performed in the simulation and analysis software AquaSim to examine the behaviour of the fish farm in static and dynamic environmental conditions. A state of the art mooring analysis was conducted by applying the load combinations required by NS9415 to a single net cage, to ensure that the strength of the mooring lines were sufficient.

9.1 AquaSim

Marine fish farms are complex structures that can experience large deformations when exposed to wind, waves and current. To analyze these types of structures, it is important to apply simulation tools that can handle deformation of highly flexible structures.

AquaSim is an analysis and simulation tool owned and developed by Aquastructures. AquaSim is based on the finite element method (FEM) and is used to perform static and dynamic analyses in time-domain. The software can be used for real-time simulation and calculations of structural response of slender and flexible structures (Berstad et al., 2014). It provides visual simulation of the displacements and deformations that occur when the structure is exposed to environmental forces, and calculates the displacement and stresses in structural components of the fish farm (Aquastructures, 2016). AquaSim can account for reduction in current velocity in the case of multiple subsequent net panels, which is an essential feature in analyses of marine fish farms with multiple cages.

The AquaSim software consists of four subpackages. AquaEdit is the 3D drawing toolkit where the model is drawn. AquaBase is the pre-processor in AquaSim where the model is prepared for export. Material characteristics, loads and environmental variables is applied to the model in AquaBase. AquaSim is the simulation engine of the software. AquaView and AquaTools are used to present the results of the simulation. AquaView visualize the results in 3D, while AquaTools presents the results in diagrams and tables (Aquastructures, 2016).

9.1.1 Theoretical Basis

AquaSim is based on the finite element method (FEM), which is a numerical procedure for analyzing complex structures. In FEM analyses, the structure is modelled as an assemblage of small elements. The benefits of this approach is that the simple geometry of each element is easy to analyze, compared to the global structure (Moan, 2003).

AquaSim can implement environmental forces such as waves, wind and current, as well as impulse loads, resonance and operational conditions. The software accounts for non-linear effects, such as varying cross-sectional area, and hydro-elasticity. AquaSim can also handle global analyses of the entire fish farm, as well as the interaction between flexible and stiff components (Berstad et al., 2014).

AquaSim uses the basis of FEM to establish equilibrium between the external loads, R_{ext}, that are acting on the structure and the internal reaction forces, R_{int}:

$$\sum F = R_{ext} + R_{int} = 0 \tag{29}$$

First, AquaSim conduct a static analysis to establish equilibrium. Then, current loads are applied, followed by wind - and wave loads. The first wave builds up the wave amplitude for the dynamic analysis, and AquaSim can be used to simulate both regular and irregular waves. The response of the structure is determined from dynamic analyses (Berstad et al., 2014).

9.1.2 Elements

Elements are single parts of the model and several element types are available for building a model in AquaSim. *Beams* are structural elements that can resist bending loads, and floating collars are usually modelled as beams. *Membrane* elements are used to model the net cage. *Truss* elements are applied when the element forces are either tensile or compressive, and trusses are used to model ropes (Aquastructures, 2016).

9.1.3 Modelling

AquaSim can be used to model both small– and large-volume structures. Wave loads are derived either by applying the Morison equation, or by diffraction theory. For structural components that are small compared to the wave length, the Morison formula is applied, while for larger components, diffraction theory is used to determine the wave loads (Berstad et al., 2014).

Diffraction theory can be applied to both beam – and truss elements. The diffraction theory that is used by AquaSim is a form of strip theory (Berstad et al., 2014). Strip theory is based on dividing the structure in strips of equal length and then estimating the load effect for each strip, separately. The resulting load is determined by summarizing the load contribution from each strip (Faltinsen, 1990). Morison theory is used to calculate wave forces on the floater and net cage. In AquaSim, wave forces that act on beam and truss elements are calculated by using the cross-flow principle (Berstad et al., 2014). The cross-flow principle is based on assuming that the flow separates due to cross-flow past the structure (Faltinsen, 1990). The added-mass term in the Morison equation is non-linear, due to large deflections when the structure is exposed to waves. Morison's equation is also used to estimate drag – and lift forces on membrane elements. Equation 9 and 10 is applied to net screens by assuming that each twine in the screen can be simplified to cylinders with constant diameter, and that the inflow angle is equal for all twines in one screen (Berstad et al., 2012).

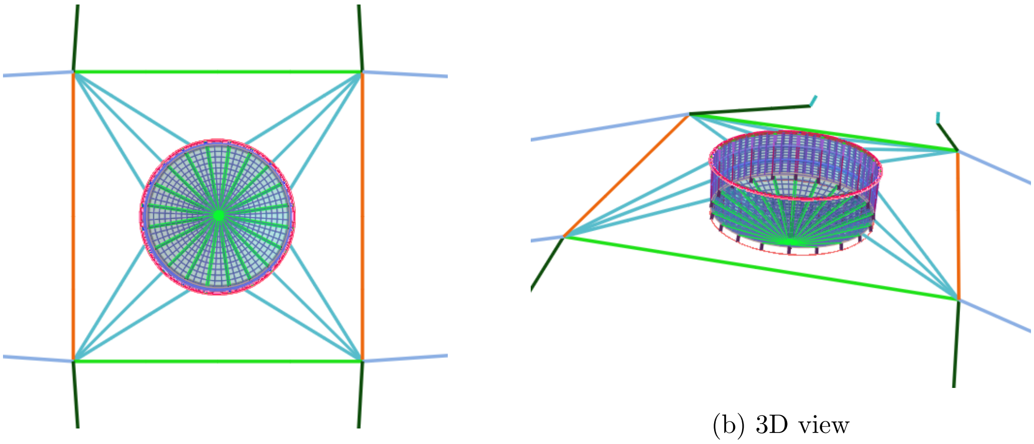
9.1.4 Applications

AquaSim is widely used for analyses and calculations of the structural integrity of fish farms. It has the ability to model and simulate the combination of stiff and soft components, as well as the interaction between components such as the fish farm, feed barges and live fish carriers. In addition, AquaSim can be used to conduct mooring analyses (Aquastructures, 2016).

AquaSim can also be applied to a wide range of offshore applications, such as marine operations, mooring analyses of offshore units, towing procedures and installation of equipment (Berstad et al., 2014).

9.2 Simulation Model

The simulation model that was used to study the behavior of the cage in different environmental conditions was provided by Aqualine. A single Aqualine Midgard® cylindrical cage was used for the simplified analyses. The Aqualine Midgard® system is an integrated net cage and distension system that consist of circular collar floaters, a net cage with cone-shaped bottom, and a submerged sinker tube to maintain the shape of the cage. The cage itself is connected to the mooring frame by three bridles in each corner, and the total system is moored to the seabed by eight mooring lines. Figure 9.1 shows illustrations of the model from AquaBase.



(a) Top view

(b) 3D view

Figure 9.1: Aqualine Midgard® model

The floaters are modelled as beams, divided into 60 elements each. The net cage is modelled as membrane elements, while all ropes, including both elastic and inelastic elements, are modelled as trusses. The provided simulation model is a standard model that is mainly used for mooring analyses and dimensioning purposes. Table 9.1 present some key parameters of the simulation model.

Table 9.1: Model Characteristics

Property	Symbol	Value	Unit
Floating collar diameter	D	0.5	m
Floater circumference	O	157	m
Net depth	h_{net}	30	m
Mooring Frame depth	h_f	8	m
Frame area	A_{frame}	1000	m^2
Mooring line length	l	341.29	m
Water depth	h	100	m

The mooring lines consist of segments of polyethylene and chain. The polyethylene part consist of 8-braided rope with a diameter of 64 mm. In addition to fibre rope, the mooring lines incorporates anchor chain at the bottom segment. This model use studless chain with a diameter of 64 mm. Chain provides stiffness by weight, while the synthetic fibre provides stiffness by elasticity. The combination of elasticity in the synthetic fibre ropes and the weight of the anchor chain gives the mooring line optimized behaviour when opposed to environmental loads (Aqualine, 2016). Table 9.2 presents the key characteristics of the polyethylene and chain segments of the mooring lines. The mooring frame itself consist of the same elastic ropes as the mooring lines. The complete mooring data of the model is presented in appendix A.

Table 9.2: Mooring line characteristics

Property	Symbol	Polyethylene	Chain	Unit
Elastic Modulus	E	1.87×10^9	1.1×10^{11}	$\frac{N}{m^2}$
Cross-sectional Area	A	3.22×10^{-3}	2.0357×10^{-3}	m^2
Weight in air	w_{air}	3.1878	15.8789	$\frac{kg}{m}$
Weight in water	w_w	0.101937	27.499	$\frac{kg}{m}$
Segment length	l	313.79	27.5	m
Breaking strength	R	6.6904×10^5	6.723×10^5	N

9.3 Simulation

Different environmental conditions were simulated to study the resulting axial force of the mooring lines in static and dynamic conditions. A static analysis was carried out by applying current only. The relationship between current velocity and axial force, as well as axial force and displacement of the element, was compared with the theoretical static behavior of mooring lines.

In the dynamic analysis, both current and regular waves were applied to the structure. Systematic variation of combined current and wave conditions were carried out to investigate the dynamic load contribution to the axial force in the mooring lines. Both load combinations required by NS9415 were assessed to ensure that the strength of the mooring lines were sufficient.

9.3.1 Load Combinations

The load combinations that were used in the simulation study was provided with the model. The tested 50 – and 10 year environmental combinations are presented in table 9.3. These combinations of environmental loads represent extreme conditions, and is mainly used for dimensioning purposes.

Table 9.3: Tested combinations of environmental loads

Combination	V_C [m/s]	V_{wind} [m/s]	H_S [m]	T_P [s]
1	1.38	32.0	4.3	8.4
2	1.23	34.0	4.5	8.6

9.3.2 Site Classification

In addition, the behavior of the structure in different degrees of exposure was examined to determine the significance of the static and dynamic loads. NS9415 provides site classification based on wave classes and current classes. These are presented in table 9.4 and 9.5. The wave classes at site are decided by dimensioning, significant wave height and wave period, while the current classes are based on current velocity of the midcurrent (Standard Norway, 2009).

Table 9.4: Wave classes at the site (Standard Norway, 2009)

Wave Class	H_S [m]	T_P [s]	Designation
A	0.0 – 0.5	0.0 – 0.2	Little exposure
B	0.5 – 1-0	1.6 – 3.2	Moderate exposure
C	1.0 – 2.0	2.5 – 5.2	Substantial exposure
D	2.0 – 3.0	4.0 – 6.7	High exposure
E	> 3.0	3.0 – 18.0	Extreme exposure

Table 9.5: Current classes at the site (Standard Norway, 2009)

Current Class	V_C [m/s]	Designation
a	0.0 – 0.3	Little exposure
b	0.3 – 0.5	Moderate exposure
c	0.5 – 1.0	Substantial exposure
d	1.0 – 1.5	High exposure
e	> 1.5	Extreme exposure

By comparing the site classifications with the tested load combinations in table 9.3, it can be seen that the regular waves in both load combination 1 and 2 correspond to wave class E, which is designated as "extreme exposure". Current velocity for both combinations correspond to current class d, which is designated as "high exposure".

9.4 Results

The aim of the analyses performed in AquaSim were to study the axial force in the mooring lines in different environmental conditions. Since the model is symmetrical, one of the mooring lines in windward direction was used as a basis for all analyses. The specific mooring line is highlighted in figure 9.2.

Three different wave – and current directions were studied to determine which heading was the most critical with respect to axial force in the mooring lines. The environmental loads normal to the mooring frame gave the highest load contribution on the windward mooring lines in both static and dynamic conditions. Hence, this direction was used as a basis for all other analyses. The load direction is also indicated in figure 9.2.

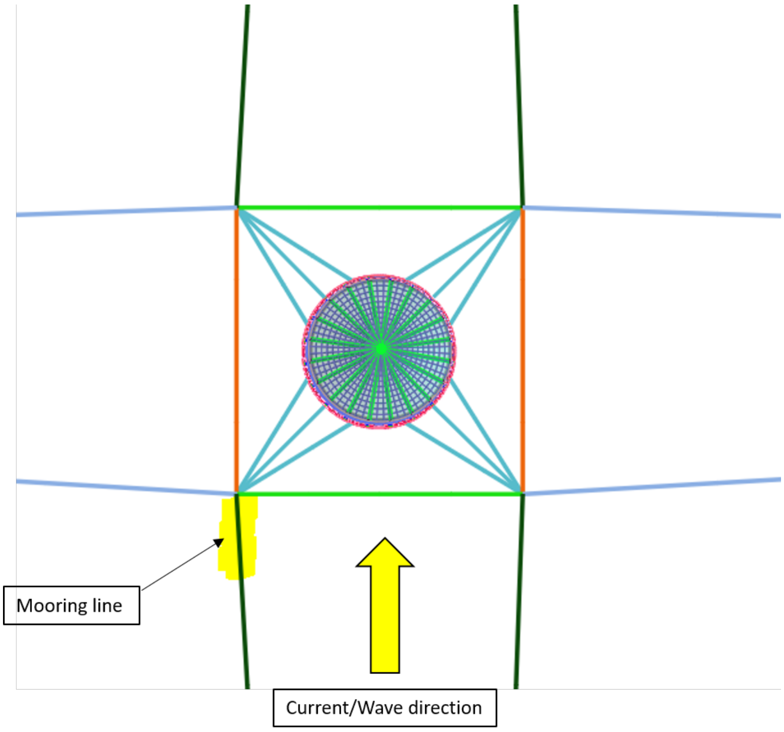


Figure 9.2: Mooring line element and load direction

9.4.1 Static Analysis

In static analyses, current velocity from each current class in table 9.5, as well as 50 – and 10 year values from table 9.3, were applied to the installation to study the variations of axial force in the mooring line. Figure 9.3 presents the variation of axial force in the mooring line element for various current velocities plotted together with a quadratic trendline. The specific element is highlighted in the right corner of the figure.

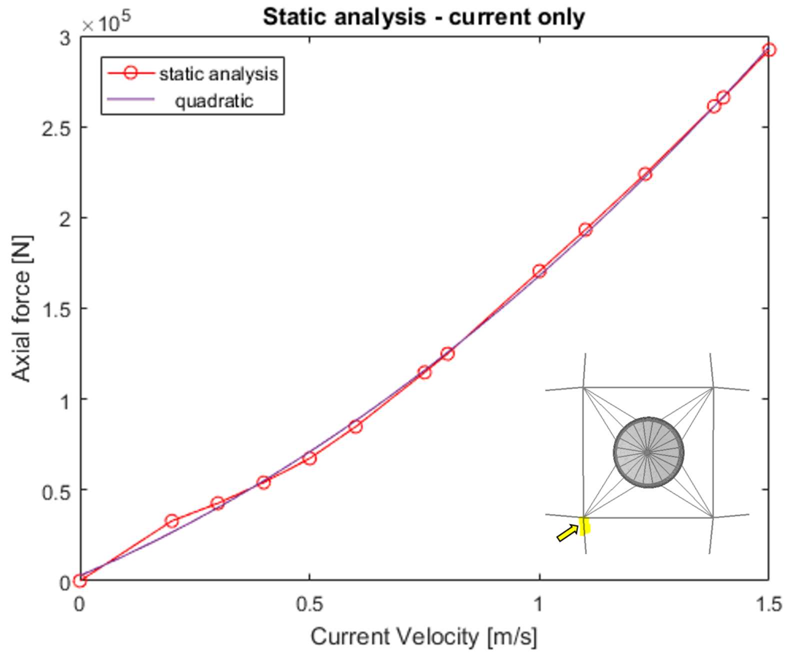
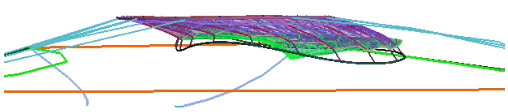
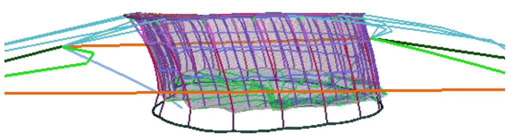


Figure 9.3: Static analysis of mooring line tension

The velocity term in the linear Morison equation is quadratic. The deviation from the quadratic trend line in figure 9.3 is a result of the deformation of the net cage when it was exposed to current loads. The degree of deformation is highly influenced by the weight of the sinker tube or bottom weights. Figure 9.4a illustrates the deformation of the net cage under influence by "high exposure" current for a standard sinker tube with weight of 80 kg/m. Figure 9.4b illustrates the deformation of the net cage exposed to the same current velocity, but with a sinker tube with weight of 1000 kg/m.



(a) Standard sinker tube



(b) Heavy sinker tube

Figure 9.4: Deformation of net cage under influence by current

It can be seen that with a heavy sinker tube, the cage will behave similar to rigid structures when exposed to current – there is almost no deformation. This implies that the resulting axial force in the mooring lines will be proportional to the current velocity squared, due to the squared velocity term in the Morison equation. However, for standard sinker tubes, the axial force curve will be slightly S-shaped, due to large deformations of the net cage. This can be recognized from figure 9.3.

Figure 9.5 presents the line characteristics of the mooring line. The resulting axial force in the mooring line is plotted for displacement of the element, together with a linear trendline. The specific element is indicated in the right corner of the figure.

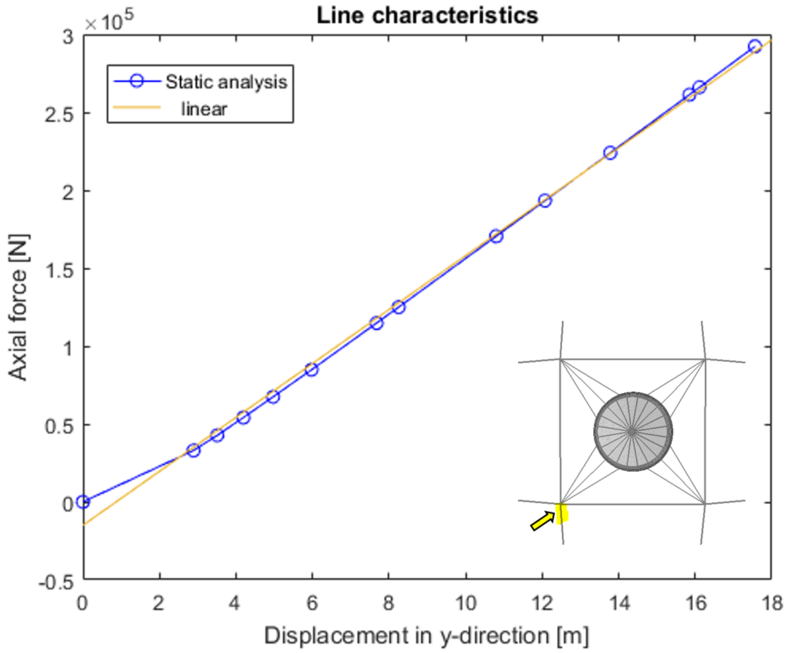


Figure 9.5: Line characteristics

No pretension of the mooring lines was applied in the simulation study. Figure 9.5 shows that the axial force increase almost linearly with element displacement. This correlates with theoretical behavior of elastic mooring lines presented in section 8.1.3. The linear behavior is a result of the high elasticity of the mooring line. The small deviation from linearity is caused by the bottom chain segment of the mooring line, due to its high weight.

9.4.2 Dynamic Analysis

A dynamic analysis was conducted by applying current and regular waves to the installation. Environmental load combinations were studied to determine the characteristic load in the partial co-efficient method, and different wave heights and current velocities were combined to examine the dynamic and static contribution to the total loads.

The resulting axial force in the mooring line due to impact from the two environmental load combinations presented in table 9.3 is shown in figure 9.6. Maximum axial force in all components are included in appendix C. Simulation of the extreme environmental conditions was performed with two design waves since this is how mooring analyses are conducted in the industry today. One wave is used to build up the energy, while wave number two is considered fully developed. By simulating two design waves, the peak-values that act on the installation can be determined.

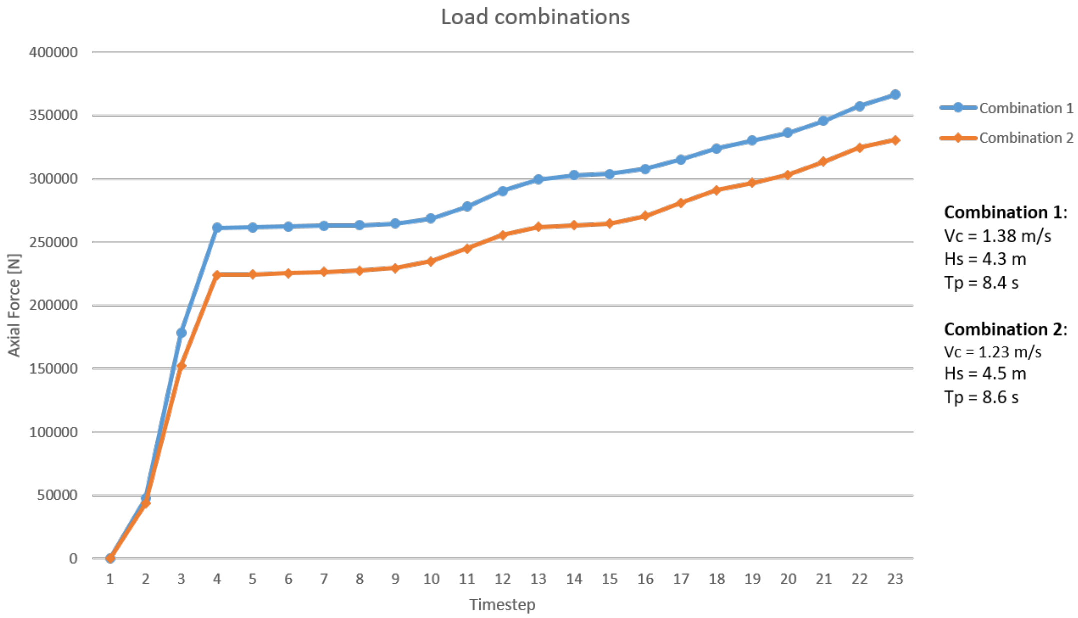


Figure 9.6: Environmental load combinations

As seen in figure 9.6, load combination 1, which corresponds to 50 year current, 10 year waves and – wind, gave the maximum resulting axial force in the mooring line.

This implies that the peak value that arise from load combination 1 shall be used as characteristic load in the partial co-efficient method described in section 6.3.

Further, the contribution from the static and dynamic loads were investigated in regular seastates. Figure 9.7 presents the mooring line response in current only, waves only, as well as a combination of current and waves. Current velocity and wave height corresponding to load combination 1 was applied in this analysis.

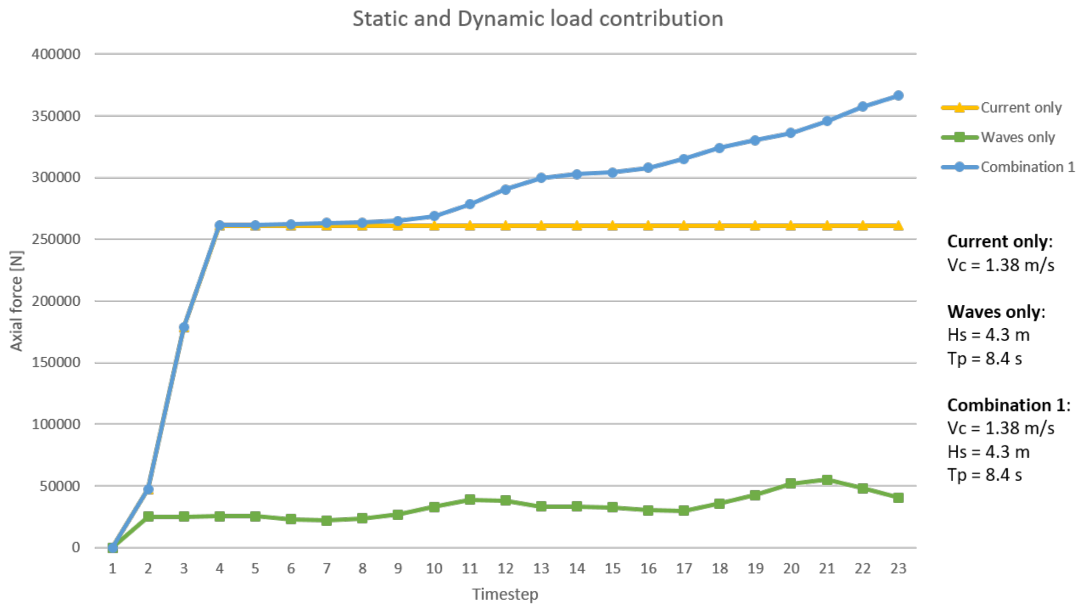


Figure 9.7: Static and dynamic load contributions

As seen from figure 9.7, the static contribution to the axial force is high compared to the dynamic contribution in a "high exposure" site. To examine whether this was the governing trend, a systematic variation of regular wave and current combinations according to the site classifications were applied. First, wave height and peak period from all wave classes were applied, while current velocity was kept constant at "substantial exposure" equal to $V_C = 0.5\ m/s$. Secondly, current velocity from all current classes was combined with regular waves of $H_S = 2\ m$ and $T_P = 5.0\ s$. The tested combinations are presented in table 9.6 below.

Table 9.6: Tested environmental conditions based on site classification

Class		V_C [m/s]	$H_S[m]$	$T_p[s]$
Wave class	A	0.3	0.1	0.2
	B	0.5	1.0	3.2
	C	0.5	2.0	5.1
	D	0.5	3.0	6.7
	E	0.5	5.0	9.0
Current class	a	0.3	2.0	5.1
	b	0.5	2.0	5.1
	c	1.0	2.0	5.1
	d	1.5	2.0	5.1
	e	1.7	2.0	5.1

All simulations were conducted with two design waves, and the results are presented in figure 9.8.

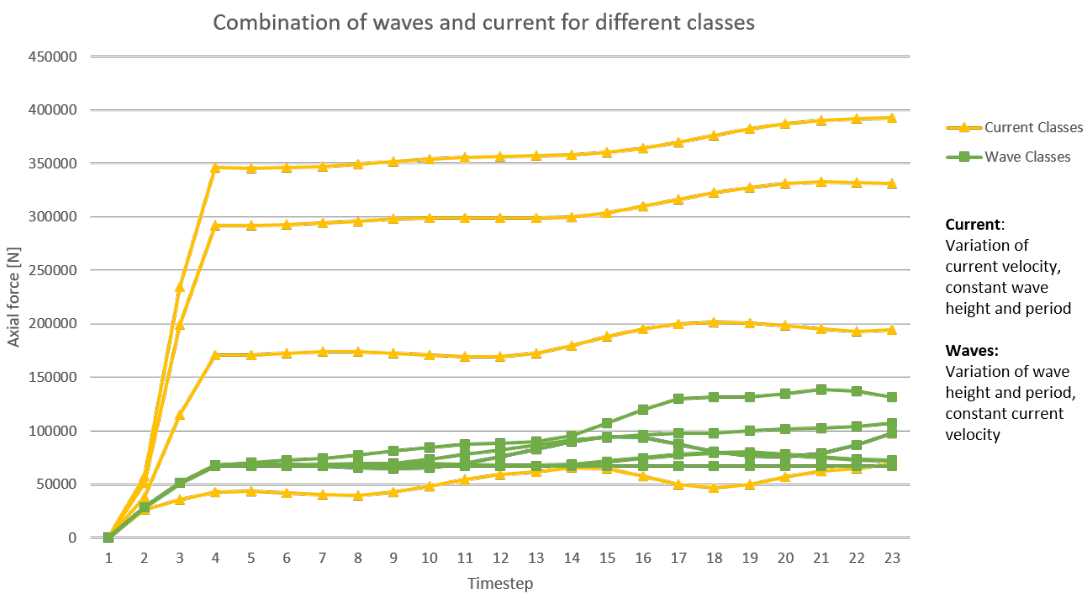


Figure 9.8: Environmental combinations based on site classification

As seen from the figure, current has a large impact on the axial force in the mooring line, and is the governing load contribution for current velocities above 1 m/s. For lower current velocities, the dynamic contribution from waves is more dominant for the axial force in the mooring line. For the different current classes the axial force in the mooring line range from 69 kN for current class a, to 392 kN for class e, while for the wave classes, the axial force range from 67 kN for wave class A, to 138 kN for class E.

9.4.3 Design Check

A design check was performed according to "best practice" in the industry to ensure that the strength of the equipment was not exceeded when the structure was exposed to wind, waves, and current. The design check was performed by requiring that the design load effect should be less than the strength of the component divided by material factor:

$$S_f \leq \frac{R}{\gamma_m} \tag{30}$$

or

$$R \geq \underbrace{F_C \times \gamma_f \times \gamma_m}_{Load\ effect} \tag{31}$$

The design check was conducted for an element in top of the polyethylene mooring line. The applied material factor corresponded to the material factor for synthetic rope mooring lines provided in NS9415. The load factor was selected according to type of analysis, and load factor for dynamic analysis was applied. The breaking strength of the 8-braided 64 mm mooring line was provided with the model.

$$\begin{aligned} \gamma_f &= 1.15 \\ \gamma_m &= 3.0 \\ R &= 68.2\ ton \end{aligned}$$

The characteristic loading, F_C, was determined from the simulation studies, by examining the maximum axial force that occurred during simulation of two design waves. The design load effect was calculated for all previously tested environmental conditions and compared to the breaking strength of the synthetic mooring line. Figure 9.9 presents the results of the design check. The different load effects were sorted in ascending order to determine which environmental conditions that could possibly exceed the breaking strength of the mooring line. The environments are indicated with a letter or number above each bar in the bar chart, corresponding to site classification or load combination 1 and 2, respectively. The breaking strength of the mooring line is indicated on the figure.

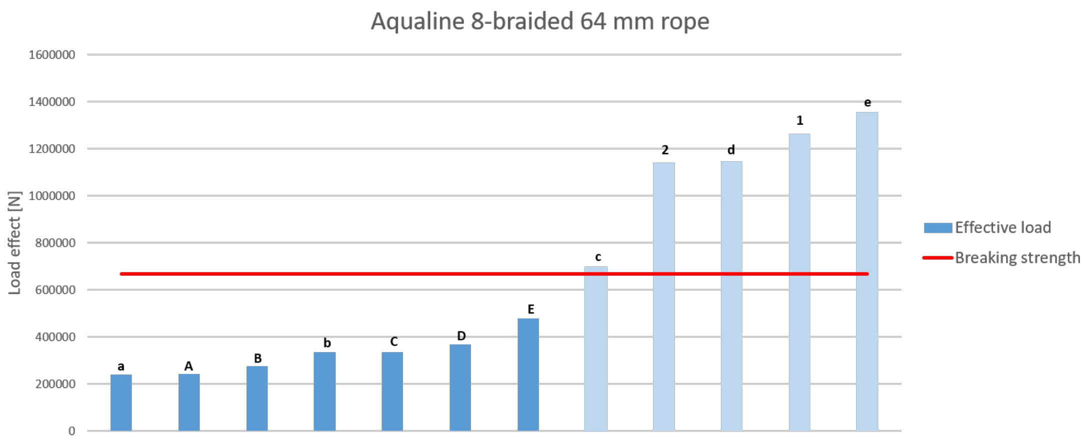


Figure 9.9: Design check for different environmental conditions

The resulting characteristic load and calculation of load effect for all simulations are presented in appendix D. As seen from figure 9.9, the breaking load was exceeded for the most extreme environmental conditions with high current velocity. Current class c to e, as well as load combination 1 and 2, gave resulting load effects that exceeded the breaking strength of the mooring line. This means that the dimensions of the mooring lines must be increased in order to provide sufficient strength for these environmental conditions. Dimensioning is an iterative process, and new analyses must be conducted each time the dimensions of the mooring lines are changed.

Additional simulations were performed with increased dimensions of the rope, and a new design check was conducted to control that the new dimensions met the criteria of the two load combinations. All mooring lines and the mooring frame was adjusted to 8-braided Aqualine Super Tech 80 mm ropes, with breaking strength of 129.9 *ton*. Figure 9.10 shows the resulting load effects from the two load combinations.

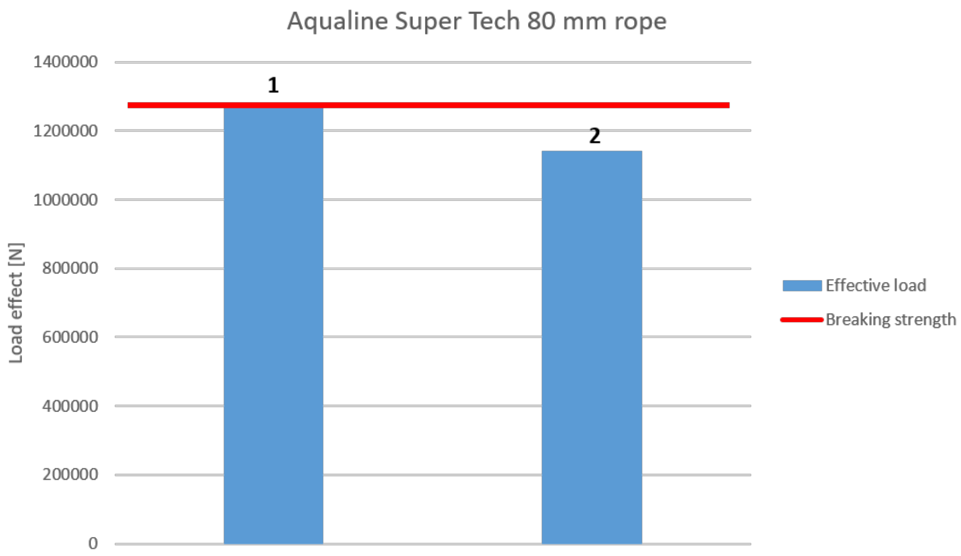
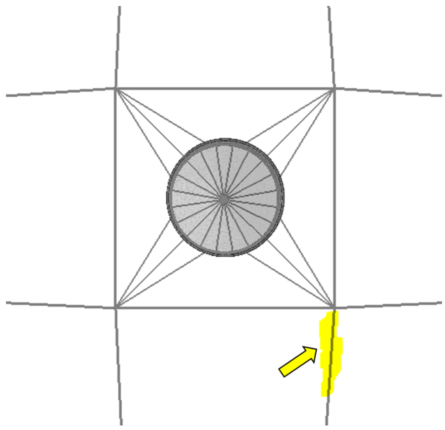


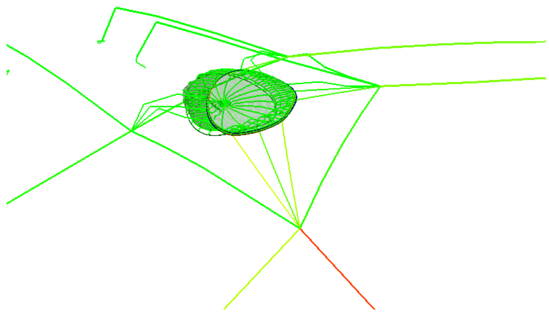
Figure 9.10: Design check with increased rope dimensions

As seen from the figure, the adjusted rope dimensions fulfilled the requirements for control in ultimate limit states. The design load effect did not exceed the strength of the ropes, and the chosen dimensions could be considered safe according to control in ULS.

In addition to the required control in ultimate limit states, NS9415 states that accidental limit states shall be controlled under stress from the most unfavorable load combination. Load combination 1 gave the highest load effect on the mooring line, and was further used for control in ALS. ALS conditions for breaks mooring lines was presented in section 6.4.4. Accordingly, a design check for breaks in the mooring line that carried the largest load was conducted. Due to symmetry, one line in windward direction, indicated in figure 9.11a, was assumed to carry the largest load. The ALS condition was modelled by removing the restrain on the bottom attachment node, which enabled the mooring line to move freely in all degrees of freedom. The deformation of the model in ALS condition is shown in figure 9.11b. Notice the high stress in the remaining windward mooring line.



(a) Broken mooring line



(b) Deformation in ALS condition

Figure 9.11: Accidental Limit State

The resulting load effect from simulation of the ALS condition is shown in figure 9.12. As seen, the load in the remaining mooring line exceeded the breaking strength of the line. This means that the rope dimensions should be further increased, and new design checks should be conducted. However, the tested current velocity can be considered extreme, and normally this rope strength would be sufficient.

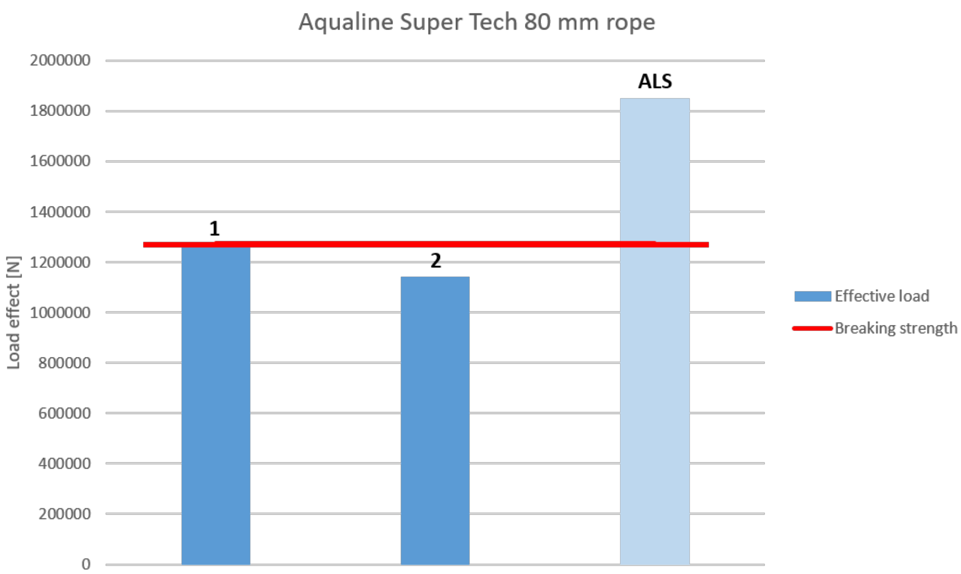


Figure 9.12: Design check in Accidental Limit States

9.5 Discussion

The presented simulation study was based on how the industry perform simulations and mooring analyses today. The following sections include a general discussion of the results and the industry's "best practice".

9.5.1 Regular Wave Analyses

In the Norwegian aquaculture industry, "best practice" is to determine characteristic load in the partial co-efficient method from analyses with *regular waves* only, i.e. *irregular* wave analyses are not required. In regular wave analyses, the load is deterministic, which means there is no randomness to consider. This implies that the uncertainty in load distribution is not assessed. The resulting load will not be represented by a distribution, but single values, as illustrated in the left part of figure 9.13.

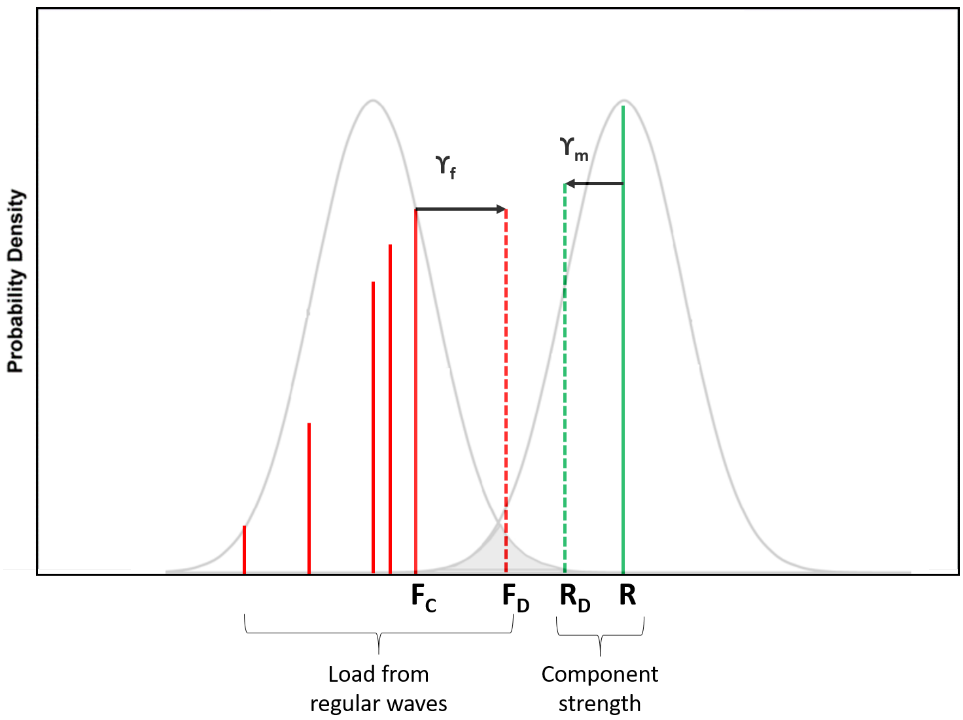


Figure 9.13: Load and resistance for regular waves

The characteristic load is determined from the environmental conditions that have the highest structural impact on the installation, denoted F_C in the illustration. This characteristic load is applied in the partial co-efficient method to ensure sufficient strength of the components.

The strength of the components are mainly determined by equipment testing. The distribution of the capacity is usually narrow, and the strength of the component can be determined as the mean value of the capacity distribution, denoted R in the illustration. This implies that in regular wave analyses, the characteristic design load, F_D, and design strength, R_D, is only determined by the load – and material factors, respectively, without accounting for uncertainty. The safety factors and component strength are constants, which means that the characteristic load, F_C, is the only variable that will change with varying environmental conditions.

When performing analyses with regular waves only, no statistical distribution is required, and extreme value statistics is not assessed in these types of analyses. This means that in theory, the dimensions of the mooring lines are only determined by the characteristic loading from (a) one of the load combinations, or (b) by the resulting accidental loads. However, the companies that conduct the mooring analyses are free to perform additional testing and analyses of their equipment, and risk assessment of the calculations must be performed. Aqualine spend a lot of resources and time internally to determine which regular waves that gives the highest load contributions. Also, they perform model testing in the ocean basin to ensure their installations can handle irregular loads as well.

9.5.2 Length of Timeseries

As "best practice" in the industry, mooring analyses performed in AquaSim are conducted with short timeseries, by assuming that the environment is fully developed after two design waves. The environmental loads will not be stable after two waves, but the uncertainty in the system damping makes analyses with several waves too conservative. The developers of AquaSim say that by including two design waves in the analyses, the user can be sure that there is enough energy included in the wave, without being too conservative.

In a realistic environment, there will not be several 50 year waves consecutively, which implies that it would be too conservative to determine the characteristic load from the stabilized environment. To avoid the effect of large fluctuations, the environment is considered fully developed after two design waves, and characteristic load is chosen as the highest value obtained after two regular design waves. The uncertainties in this method is considerable, but this is the governing industry standard today.

10 Conclusion

An aquaculture fish farm behaves different from rigid structures when it is exposed to wind, waves, and current. Fish cages are highly flexible structures that experience large deformations, and these deformations must be accounted for in dynamic analyses. In addition, fish farms consist of a combination of soft and stiff parts, and the interaction between the components impose a challenge for determining the response of the structure.

Wave forces mainly act on the floating collar and upper parts of the net. Current forces act on the submerged parts of the structure and are most often the governing environmental forces on a floating fish farm. Wave – and current forces can be modelled by applying Morison's equation to net panels by assuming cylindrical twines with constant diameter and inflow angle.

Dimensioning of components are based on the partial co-efficient method, by requiring that the design load effect must be less than, or equal to, the strength of the component divided by a material factor. This requirement ensures that the loads imposed on the fish farm does not exceed the strength of the different components. Safety factors are applied to account for uncertainties in load and response, as well as material properties.

The mooring analyses performed in the industry today are based on regular wave analyses. The simulation and analysis software AquaSim has limitations when it comes to modelling of system damping, and analyses are conducted with two design waves to avoid being too conservative. Simulations performed with only two design waves exclude the effects of loads over longer time periods, and time varying loads are not assessed in standard mooring analyses.

The simulations carried out in this project thesis were based on the industry's "best practice", and only regular wave analyses were conducted. As for recommendations for further work, analyses with longer time series and irregular waves should be conducted to study the behavior of fish farms in a realistic environment. The challenges that comes with more exposed sites must be modelled correctly to ensure that the installations are fit for harsher environmental conditions.

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A Simulation Model

Table A.1: Data for the mooring system of Aqualine Midgard®

Mooring System	Value	Unit
Mooring lines		
Number	8	#
Length polyethylene segment	313.79	m
Area polyethylene segment	3.22×10^{-3}	m^2
E-modulus polyethylene segment	1.87×10^{9}	N/m^2
Weight in water polyethylene segment	0.101937	kg/m
Breaking load polyethylene segment	6.6904×10^{5}	N
Length chain segment	27.5	m
Area chain segment	2.0357×10^{-3}	m^2
E-modulus chain segment	1.1×10^{11}	N/m^2
Weight in water chain segment	27.499	kg/m
Breaking load chain segment	6.723×10^{5}	N
Anchor depth	100	m
Spring stiffness of bottom attachment	2×10^{5}	N/m
Bridles		
Bridles at each corner	3	#
Length	48.73	m
Area	2.46×10^{-3}	m^2
E-modulus	1.87×10^{9}	N/m^2
Breaking load	4.7775×10^{5}	N
Mooring frame		
Length frame	100	m
Depth	8	m
Rope area	3.22×10^{-3}	m^2
E-modulus	1.87×10^{9}	N/m^2
Breaking load	6.6904×10^{5}	N
Buoys		
Number (one in each corner)	4	#
Buoyancy	2500	$litre$

B Simulation Test Runs

Table B.1: Static test runs - current only

#	Current class	V_C [m/s]	Current dir. [deg]
1	a	0.3	0.5
2	b	0.5	0.5
3	c	1.0	0.5
4	d	1.25	0.5
5	50 year	1.38	0.5
6	10 year	1.23	0.5

Table B.2: Dynamic test runs - regular waves and current

#	Site classification	H_S [m]	T_P [s]	V_C [m/s]	Wave dir. [deg]	Current dir. [deg]
1	Combination 1	4.3	8.4	1.38	180	0.5
2	Combination 2	4.5	8.6	1.23	180	0.5
3	50 year	4.5	8.6	-	180	-
4	10 year	4.3	8.4	-	180	-
5	A	0.5	2.0	0.5	180	0.5
6	B	1.0	3.2	0.5	180	0.5
7	C	2.0	5.1	0.5	180	0.5
8	D	3.0	6.7	0.5	180	0.5
9	E	5.0	9.0	0.5	180	0.5
10	a	2.0	5.1	0.5	180	0.5
11	b	2.0	5.1	0.5	180	0.5
12	c	2.0	5.1	1.0	180	0.5
13	d	5.1	2.0	0.5	180	0.5
14	e	5.1	2.0	0.5	180	0.5

C Maximum axial force

C.1 Load combination 1

Table C.1: Maximum axial force, load combination 1

Component Name	Component index	Max axial force	Timestep
Flytekrage - indre rør - 500mm	1	5.801E5	17
Flytekrage - ytre rør - 500mm	2	4.37E5	18
500 klammer - Fortøyning	3	89451.00	17
500 klammer - Standard	4	36402.00	18
Stolpe	5	3713.20	17
Bunnring - 400SDR11 - 80kg/m	6	2781.10	13
Sidepanel Uk24x15_5mmsq	7	N/A	0
Bunnpanel Uk24x15_5mmsq	8	N/A	0
Stag/Kjetting Flytekrage	9	75730.00	20
Hovedtau	10	12589.00	22
Bunntau	11	8502.60	12
Loftetau	12	36298.00	22
Sidetau	13	12661.00	16
Sidetau 5m	14	7454.30	20
Opphengskjetting	15	55610.00	22
Opphengstau	16	55609.00	22
Mageband 5m	17	16761.00	21
Mageband 10m	18	13734.00	22
Krysstau bunn	19	32106.00	21
Not-flytekrage løftetau	20	11050.00	19
Not-flytekrage sidetau	21	20157.00	16
Not-bunnring	22	13291.00	16
Ramme langs	23	54447.00	11
Ramme tvers	24	33035.00	21
Haneføtter	25	2.38E5	21
Forankringsline langs	26	1.571E5	17
Forankringsline tvers	27	3.664E5	22
Ankerkjetting	28	3.66E5	22

C.2 Load Combination 2

Table C.2: Maximum axial force, load combination 2

Component Name	Component index	Max axial force	Timestep
Flytekrage - indre rør - 500mm	1	5.429E5	17
Flytekrage - ytre rør - 500mm	2	4.172E5	17
500 klammer - Fortøyning	3	81996.00	16
500 klammer - Standard	4	34011.00	17
Stolpe	5	2540.60	17
Bunnring - 400SDR11 - 80kg/m	6	3568.40	21
Sidepanel Uk24x15_5mmsq	7	N/A	0
Bunnpanel Uk24x15_5mmsq	8	N/A	0
Stag/Kjetting Flytekrage	9	73617.00	20
Hovedtau	10	13025.00	22
Bunntau	11	6851.40	22
Loftetau	12	33140.00	22
Sidetau	13	11595.00	16
Sidetau 5m	14	8233.40	19
Opphengskjetting	15	50019.00	22
Opphengstau	16	50024.00	22
Mageband 5m	17	17375.00	20
Mageband 10m	18	12407.00	21
Krysstau bunn	19	26863.00	20
Not-flytekrage løftetau	20	12678.00	19
Not-flytekrage sidetau	21	18656.00	16
Not-bunnring	22	13034.00	17
Ramme langs	23	50011.00	19
Ramme tvers	24	33009.00	21
Haneføtter	25	2.204E5	20
Forankringsline langs	26	1.467E5	16
Forankringsline tvers	27	3.307E5	22
Ankerkjetting	28	3.303E5	22

D Design Check

To apply the partial co-efficient method, characteristic load needs to be determined from the analyses. Characteristic load is assumed equal to the peak-value achieved during analyses with two design waves. When characteristic loading is known, the load effect can be calculated according to

$$F = S_f \times \gamma_m = F_C \times \gamma_f \times \gamma_m \tag{32}$$

The calculated load effect for different environmental conditions is presented in table D.1.

Table D.1: Load effect from different environmental conditions

Environment	Characteristic load [N]	Load effect [N]
Combination 1	366 360	1 263 942
Combination 2	330 650	1 140 742
a	69 433	239 544
b	97 525	336 461
c	201 590	695 485
d	332 820	1 148 229
e	392 910	1 355 539
A	70 147	242 007
B	79 696	274 951
C	97 525	336 461
D	106 760	368 322
E	138 740	478 653