Design considerations and loads on open ocean fish cages south of Iceland

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Abstract

The work presented in this thesis handles design considerations and loads on open ocean fish cages outside the southern shore of Iceland, in aquaculture of the Atlantic cod (*Gadus morhua*). The focus on the southern shore results from the fact that there growth conditions for the Atlantic cod are considered favorable all year round for all stages of the cods growth and maturity. However, environmental conditions are harsh.

A general overview of design considerations is provided, followed with special chapters devoted to most of the crucial aspects for a design and load-study of cages south of Iceland, and a few considerations for the Atlantic cod in relation to aquaculture in the open ocean.

Waves and currents are studied from some of the available data. It is concluded that the wave climate south of Iceland is extremely harsh, but noted that the distribution of waves is in such a way that only a small ratio of them reach significant heights above 12 m—a height which has been used for designs regarding some available open ocean cages.

Site evaluation follows and it is found that only a few places are available for operation of aquaculture south of Iceland where the ocean has favorable growth conditions for the Atlantic cod. Cage discussion is then carried out with a study of many presently available cages, and a few suggested designs. It is stated that none of those cages are designed to withstand a wave climate like the one south of Iceland, but noted that some arrangements could be made to reduce the loads on them.

Forces and loads are estimated, and it is found that by submersing cages deep enough, load conditions may reach similar characteristics to those that surface cages meet in sheltered sites.

The Atlantic cod is discussed in relation to aquaculture in harsh conditions. It is concluded that the cod will face great difficulties in thriving in cages in the wave and current climate south of Iceland, and besides that, various problems exist regarding the cods sexual maturity and resistance to long-term loads.

The assumption is finally made that offshore aquaculture of the Atlantic cod is probably not a viable option for the open ocean south of Iceland, in respect to environmental loads. Factors of uncertainty are many, and the information available indicates by most part that situations will be harder than what modern technology and designs are recommended for.

Contents

1

Introduction

The aim of this project is to estimate the possibilities of aquaculture of the Atlantic cod (*Gadus morhua*) of the coast of southern Iceland. General design considerations, estimation of loads, influence on fish and other factors will be analyzed and discussed.

The focus on the southern shore of Iceland results from the fact that the ocean temperature there is considered favorable for the Atlantic cod all year round, for all stages of its maturity [1, p.18]. This is severely important because high mortalities of fish are in many cases related to cold waters in aquaculture at given sites, for example of the Atlantic salmon (*Salmonidae salmo*) in culture west of Iceland [1, p.17-18]. Eliminating the risk of fish mortalities for that reason would be a huge advantage in site selection. Also, it seems the ocean south of Iceland has an average temperature closest to the optimal temperature of growth for the Atlantic cod [1, pp.17-19]. Therefore, two very important aspects are involved in operating aquaculture south of Iceland.

Figure 1.1 shows a map of Iceland and a few place names important to keep in mind for further reading.

The project is divided into three main parts:

1. **Study of current- and wave climate**, using existing wave and current data. Also a brief study of the wind climate south of Iceland. Chapters 4 and 5 mainly handle this discussion.

2. **Study of open ocean fish cages**, by studying design procedures, existing and proposed cages, and forces at hand. Also study the effects on fish inside cages under high stress. Chapters 3, 6, 7 and 8.

3. **Estimate whether or not a successful operation of aquaculture can be carried out south of Iceland**, by comparing the current- and wave climate with offshore fish cages and their design criteria.

The result of the project will be increased knowledge of the situation at hand from an engineering standpoint. An estimate is made on whether or not an installation of an aquaculture system is feasible outside the shores of southern Iceland, considering the environmental conditions at hand, and todays open ocean cages as well as proposed ones. No physical models are built as a part of this project.

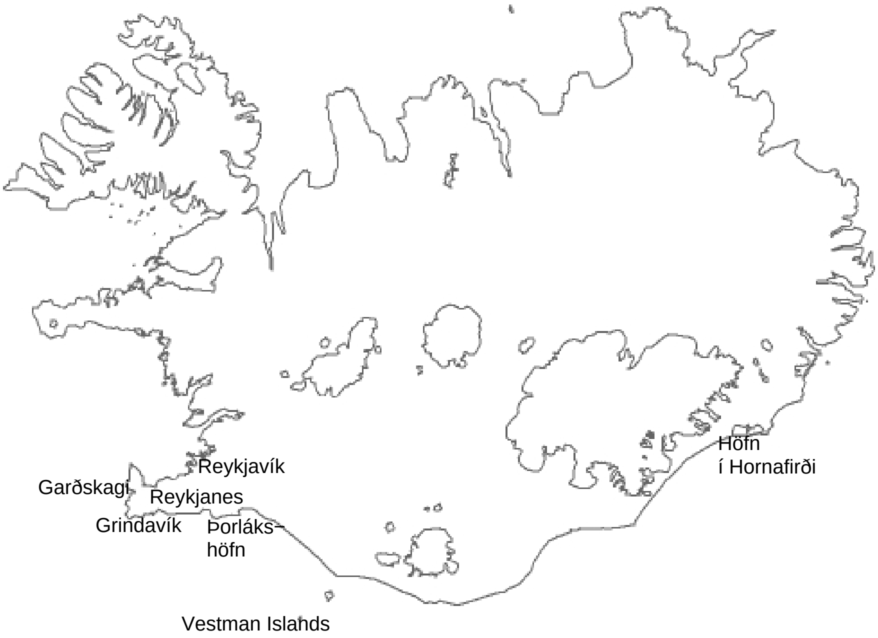

Figure 1.1: A map of Iceland showing a few important place names by the southern shore of Iceland (map: The National Land Survey of Iceland, **www.lmi.is**).

2

Background

Many different factors contribute to whether or not extensive aquaculture of Atlantic cod should be considered in Iceland. A few of them are experience with production, market prices, market acceptance and success in technology innovation and implementation. Others depend on local interests, environmental conditions and the ability to raise capital and start a viable business.

A few investigations have been made about possible cod-production in Iceland, one of the most extensive one published in 2002 on behalf of the Ministry of Fisheries in Iceland in co-operation with various members of interest [1]. Proposals for many different investigations, research and necessary preparation work were made. This project is a part of what has since followed.

2.1 Ocean fishing

Approximately 75% of the world-wide wild fish stocks are fully exploited, overexploited or not exploitable due to small size. Only an estimated 25% of the major marine fish stocks, for which information is available, are underexploited or moderately exploited [2, p.23]. However, demand for fish foods is rapidly increasing and is predicted to double in the next 15-20 years (estimated annual growth about 4.7% per year) [3]. Prices are expected to rise alongside this unless increased supplies of cultured or catched fish products are provided.

This reality is the main reason for increased interest in aquaculture for a wider variety of species, especially among the most expensive and most exploited ones. But with new species come new problems and the need for new technologies that could bring production cost down and prices and quality up.

2.2 Expansion of cod aquaculture

Many have started or are planning to start research and experimental culture of the Atlantic cod, for example in Norway, Canada and USA. Therefore, it can be expected that supplies of cultured cod will increase significantly over the next few years [1]. This goes hand in hand with the expansion of aquaculture as an industry. Its growth has been significant for the past few decades, and it is now the fastest growing animal food producing sector worldwide [2, p.26].

Culture of cod in Iceland is expected to increase dramatically in the next few years. The countries biggest fishing and fish processing companies show great interest in cultured cod production, and many have started or plan on starting experimental projects. This, along with extensive research and gain in experience, can be expected to result in considerable increase in cod aquaculture over the next few years in Iceland [1].

2.3 Site considerations

Coastal areas worldwide are valuable for many different reasons and are in many cases under great pressure. They are limited and competed for by various parties such as residents in search of high quality living space and industries in search of easy access to harbors and other transportation means [4, pp.227-234]. For aquaculture, this means that people are increasingly looking towards the open ocean for fish cage sites where competition for space is less. Other factors, such as pollution and public opinion, also encourage a further movement of aquaculture operations further into the open ocean.

Moving to offshore locations has its faults. Loads on structures from waves, currents and winds are higher, servicing the cages and the fish inside is more difficult, monitoring of the operation is troublesome and distances from harbor-facilities create extra cost and effort.

Moving to offshore locations also has great advantages. In many cases fish health considerations are more favorable [5], risks due to ship and boat traffic are less, and conflicts with other users of coastal areas are more rare. Pollution is also greatly reduced when distance from shore increases, due to faster regeneration of the water and ocean floor.

The southern shores of Iceland are exposed to harsh environmental conditions. Only a small part is inhabited or in use. Obtaining a license for a construction of an aquaculture site should therefore, by intuition, be readily obtained in this respect. In more sheltered sites north of the Reykjanes-peninsula demand for coastal areas is greater. This could cause difficulties in obtaining operating licenses, although some experiments with cage culture exists at these areas. In general though it is considered a complex process to obtain operating licences for aquaculture in Iceland, regardless of site [1, p.33].

In the ocean south of the Reykjanes-peninsula, in an area called Selvogsbanki, various environmental factors have measured more stable than in most other areas around

Iceland [6], and at least the ocean temperature is considered favorable for aquaculture of the Atlanic cod all year round [1].

2.4 Development of sea cages

With increased expansion of aquaculture to the open sea, a development of sea cages that can withstand the loads at hand is necessary. Many companies have realized this and today many sea cages for this application are available. Two examples are shown in Figure 2.1. The open ocean cages available today are recommended for open ocean aquaculture in general, but normally little more information is given. Pérez et al. [7] do not recommend any cages, surface or submerged, for situations where the significant wave height exceed 8-9 meters. According to Pérez et al. in the year 2000, nothing seems to be available for waves over 15 meters [5, pp.153-154]. Waves south of Iceland exceed this by far. Significant wave heights above 17 m have been measured in the open ocean [8]. This creates the need for new designs, or more robust designs of existing cages.

Feeding systems have to be studied with respect to the extreme scenarios likely to occur. For submerged cages these can be in the form of a buoy floating on the sea surface and connected to the sea cage itself through a feeding hose. Such a system is being tested at the University of New Hampshire, in a program called Open Ocean Aquaculture [9, 10]. Figure 2.2 shows an example of its configuration with the submerged cage.

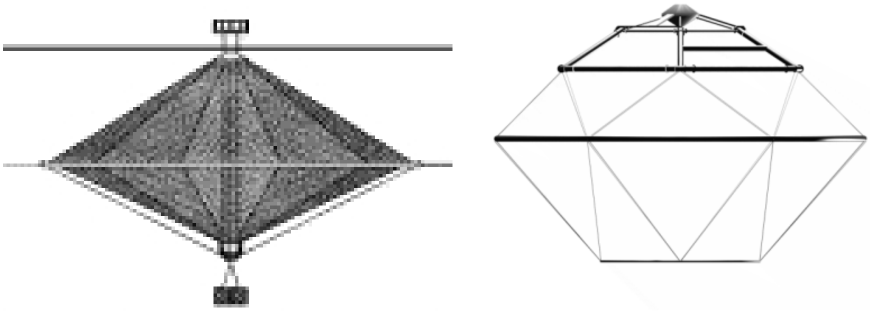

Figure 2.1: Two examples of submersible open ocean sea cages. On the left is the submersible Sea Station from Ocean Spar Technologies (picture: www.oceanspar.com). On the right is the Sadco-Shelf 4000 underwater cage (picture: www.sadco-shelf.sp.ru).

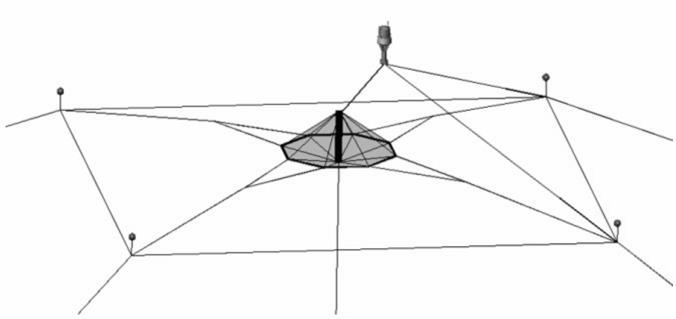

Figure 2.2: Compliant feed buoy mooring to surmerged fish cage (picture: **www.ooa.unh.edu**).

2.5 Impact on fish

The effects of loads from currents and waves on fish appear to be more or less unknown for many species, including the Atlantic cod. It has been speculated that even if a fish cage can withstand forces due to a certain wave climate, the fish may not [5]. If relative motion of fish compared to a cage is large, some descaling of fish might occur which is harmful and leads to high mortalities [5]. It is important that the fish cage itself, or its netting, does not harm the fish. Information about effects on fish in high-stress environments are not easily available and must be sought for or generated with more investigations and research.

The main assumption given in this project will be that if a fish cage can withstand a certain load, the fish in it should survive. This is not completely certain but the opposite probably is, that is, if a cage gives in to certain loads, the fish in it will not survive or be intact. Chapter 8 will cover various aspects regarding caged fish in more detail.

2.6 Other factors of concern

Many other factors contribute to necessary knowledge needed to manage a successful aquaculture of for example cod. An efficient method is still needed for hatching and growing smolt and further for growing of cod fingerlings. The procedure is expensive and has many technical difficulties [1, p.20]. Troubles are with cod's sexual maturity, but cod matures early in its lifetime and in spawning it looses up to 40% of its weight [1, p.23]. Market experiments for aquacultured fish have not been very extensive although first experience appears to be promising.

A lot of work regarding offshore aquaculture of cod and other finfish species has been done, especially over the past few years. Yet many difficulties exist and today it has not been established that such culture can pay off or provide reasonable outcome for the market or the demanding consumer [1].

3

Design considerations

Design considerations for an offshore aquaculture involve many different factors, such as access to harbor facilities and basic costs. Some of the most important factors involve waves. Their height and period, combined with effects from currents, determine the loads which cage structures, moorings and netting must withstand. Other factors involve cost, legal environment, site evaluation, etc.

3.1 Key terms and definitions

Cages for offshore fish farming are often classified into three main groups, depending on their layout in normal operating mode. The following classifications are adopted from Huguenin [11]:

- A **surface cage** (also called a gravity cage) most often consists of a floating circle or polygon from which a net enclosure is hung. Weights hold the cage shape and volume against current forces and other externally applied forces. Despite this, a serious reduction in cage volume will occur when currents are strong. Cages of this type are usually operated in sheltered sites.

- A **submersible cage** is a cage that can be lowered below surface for a certain period of time, usually during storms. Some types are in part under surface at all times. Maintenance and normal operation is done at surface, or close to it.

- A **submerged cage** is a cage fully operated and serviced below surface. For most, maintenance is done at surface.

Other classifications are also used [5, 12], but these are general. Each of these groups has various alternations with respect to moorings, size, shape, rigity, netting, etc.

Having a cage submerged in part or whole, for shorter or longer time, has many advantages and will eliminate many risk factors. Most of the wave forces are avoided when below surface and risk from boat traffic and floating objects is reduced. Thermal stability is better, biofouling is reduced and security from harassment is increased. But complications are some, especially due to servicing and operating of the system [11, p.169]. The focus will be on various types of submersible and submerged cages, since surface cages are not well suited for harsh conditions [7, 11].

A design procedure for a cage system structure must take into account many variables, both physical, such as wave heights, wave periods etc., and sociological, such as legal environment and public opinion. Key terms and definitions, mostly according to Turner [5], are:

- **Significant wave height**, H_s or $\overline{H}_{1/3}$: Defined as the average of the highest one third of the waves in a given wave height measurement data set (wave spectrum). Wave data is usually published as significant wave heights and corresponding wave periods [8]. See, for example, Kamphuis [4, p.57] for a more detailed discussion.

- **Orbital wave particle motions**: Waves propagate with a certain speed in the water but the individual water particles do not. They move in particle orbits. Close to surface their orbits are elliptical but with increased depth these orbits become circular in shape [4, 13].

- **Wave hindcasting** is an important process for determining wave climate from wind statistics, given some knowledge of wind systems and fetch lengths. For this project the wave climate and sea conditions are fairly well known so little wave hindcasting is necessary. Its purpose would only be to relate weather forecasted wind speeds to possible loads on cages due to wind generated waves.

- **Windspeed return period**: Defined as the probability of a certain windspeed event at any given year. Usually it is used in terms of the maximum windspeed for for example 20, 50 or 100 years. A related term is **wave height return period**. A structure is often designed in such a way that it can withstand forces do to a wave height with certain return period (probability of occurrence at any given year). See **design wave**.

- **Design wave** is defined as the highest wave for which a structure is designed to withstand. Its return period is estimated and the structures lifetime calculated with respect to that. It is to be noted that the biggest wave likely to occur is not necessarily the one that produces the most critical loading on offshore floating structures [7]. However, this will not be assumed for submerged structures and the design wave considered to be the highest one likely to occur.

These terms define most of the site conditions with respect to possible loadings on a structure due to waves. Both the moorings and the cages themselves have to be considered. Changes in, for example, cage orientation and net weighting affect the system's dynamic response, so physical knowledge of the ocean and wind conditions themselves isn't sufficient information, although it is necessary [5].

3.2 General design procedure

A design of coastal and ocean structures is highly dependant on wave and current conditions. Figure 3.1 shows a conceptual cage system structural design procedure, adopted from Huguenin [11] and adjusted to a situation where wave data is readily available. The focus is on wave and current loads and wind forces are therefore not included in the cages design procedure. In the case of surface cages this would not be the fact. Sarpkaya et al. [13] provide a similar procedure, with the focus on wave loading.

Several complications are involved in calculating forces on submerged cages and cage systems. Traditional methods for structural calculations in a moving fluid assume rigid structures, small deflections and solid or hard surfaces. Changes in wave or current conditions are not implemented and effects of many factors, such as biofouling on nets, are largely unknown [11].

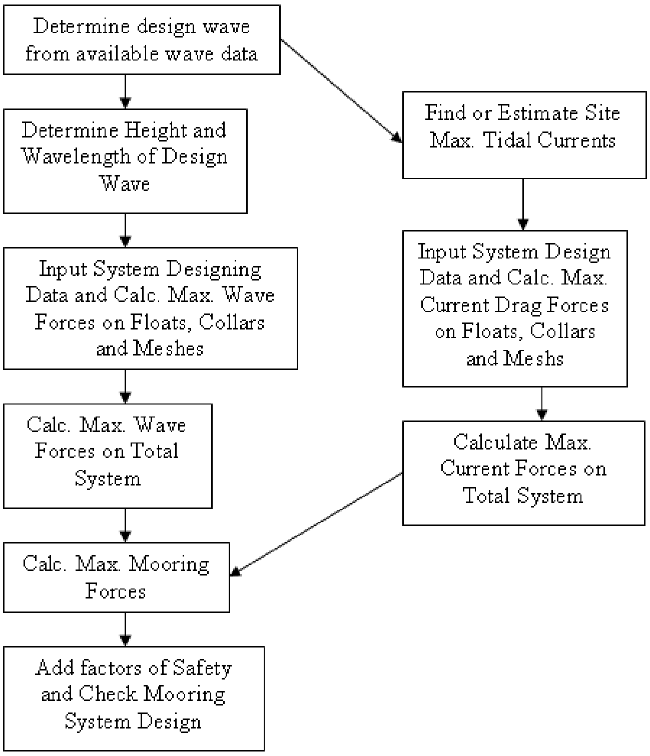

Figure 3.1: Design chart for a cage system structure, adopted from Huguenin [11]. For this project wind data is ignored for the design of the cage structure itself, and the focus put on wave and current data.

A fish cage with its moorings and cables, or a system of fish cages, will respond in a complex way to external loads from waves and currents, creating large forces in its various components. The problem is complex if no simplifications are made.

3.3 Wind and wave climate

Generally, wave conditions can be estimated from wind conditions [4, pp.103-104]. This is often the approach that engineers take since wave measurement data is usually scarce. However, this is not the case for the ocean surrounding Iceland. The Icelandic Maritime Administration has measurements of the weather and sea state for many measurement points all around the Icelandic coastline and they are readily available for use [8].

Although this is the case, the maximum windspeeds should not be neglected. Windspeeds are the parameters most frequently spoken of when sea conditions are discussed. A link between the maximum windspeeds and the maximum wave heights could be kept in mind to relate weather forecasted wind speeds to possible loads on cages due to wind generated waves.

3.4 Forces and loads

Estimating the force on a structure in a certain wave climate is a complex matter, and most often impossible when attempted analytically. Forces on a submerged structure depend on geometry, flow direction and pressure distribution and their calculation involves an integral over the entire surface of the structure [14].

Generally simplifications are made with calculations of forces and various loads. Informal studies and idea designs are also frequently being made; see for example Loverich and Gace [12].

More detailed studies are also available but in smaller numbers. Many of them are related to a project called Open Ocean Aquaculture, operated approximately 10 km from the New Hampshire coast, in the North-western Atlantic ocean, east of the United States. Among them are studies by Fredriksson, et al. from 2003 [15, 16, 17]. Their application is mostly regarding computer modelling of cages and netting using finite element analysis, calculations of loads on the cages and their moorings, and estimations of dynamic response of various components [9]. At SINTEF, Norway, models of net behavior due to waves and currents have been made [18].

Huguenin [11] lists some possibilities of accumulation and transmission of environmental forces on a nested cage system. See Table 3.1 for a short version of his list. Large open ocean cages at exposed sites are typically not kept in nested configurations [11]. Table 3.1 is adjusted with respect to that. Estimations in Table 3.1 also assume a submerged cage so winds don’t have any direct affects.

Table 3.1: Some possible failures of components of sea cages due to waves and currents, adopted from Huguenin [11] for a single cage. Accumulation and transmission of environmental forces are listed.

Cage component	Some possible failures due to waves and currents
Cage mesh	• Mesh old or worn. • Biofouling leads to overloads. • Stress concentrations on seams and corners. • Fretting of mesh. • Mesh chewed on by fish or seals, or weakened.
Cage collar, structure	• Floats loss buoyancy and sink. • Sinks due to weight of biofouling. • Collisions. • Corrosion. • Fails at joints.
Mooring system	• Fails at fittings due to corrosion or dynamic factors. • Fretting of lines.

3.5 Site and cage selection

Methods of site selection are in constant development, and many have been suggested [4, 7, 19]. Generally site selection depends on social, political, legal and economic aspects [11]. Other aspects are for example access to harbor-facilities, ocean temperatures and sea bottom landscape. However, from an engineering standpoint, the main factors are offshore and prevailing wave climate [5], as well as currents. These influence the forces exerted on structures and are the parameters needed for structural calculations that result from them.

Generally cages must meet many requirements regarding many factors—environmental loads must be withstood by the cage with as little cost and effort as possible, and without harm to fish inside it.

Turner [5] lists a number of key issues for practical operation of site and cage selection. See Table 3.2. Many of the issues in Table 3.2 are addressed in Chapters 5, 6 and 8. Most of the issues regarding fish, fish health and fish survival are neglected like described in Section 2.5.

Table 3.2: Key issues for practical operation when choosing sites and cages for aquaculture at a given site.

Factor	Issues
Survival: Fish, cages and moorings	• Is the cage site subject to breaking waves? • Will the fish survive the probable storms? • Would the fish survive partial cage failure? • What is its probability of survival? • What is the best orientation of the cage group? • How long will it last before requiring replacement?
Routine husbandry: Simplicity and cost	• What harbors are available for marine base if any? • What size and type of workboats will be required? • How many days of feeding and husbandry are likely to be lost through weather limitations? • After how long will the site need fallowing, if at all? • What are the capital, operational, maintenance and probable replacement costs?
Personnel and safety	• How safe are the cages for routine husbandry? • What training will be required for the routine tasks?

3.6 Concluding remarks

Clearly, a successful design of an open ocean aquaculture system with all its aspects involves a number of different factors. Most of them are routine for any kind of a coastal installation, like discussed by Kamphuis and others [4, 11]. What differs mainly with regard to open ocean aquaculture is the focus on very harsh wave and wind climate and its interaction with offshore fish cages and the fish inside, as well as maintenance and operation. The focus should be on the items in Table 3.3 which assumes the culture of Atlantic cod in submerged or submersible offshore cages.

Table 3.3: Design considerations to be put in focus for the design of an open ocean aquaculture, with respect to the Atlantic cod, assuming submerged or submersible cages.

Aspect	Discussion
Wind climate	Not of great concern for the cages. Feeding, maintenance and operation must be planned with respect to wave and wind climate.
Wave climate	Forces from waves decline fast with increased depth. Extreme conditions must be analyzed carefully in the cage design.
Fish considerations	Relative movement of cage compared to the fish inside should be kept to a minimum. Automatic feeding should be implemented.

4

Waves and Currents

Estimating loads on fish cages and their moorings involves an investigation of the waves and currents at hand. Wave and current parameters can be used to estimate forces and moments on ocean and coastal structures and give assumptions for engineering design.

4.1 Wave conditions

Extensive data is available for wave conditions in the ocean around the Icelandic coastline, mostly collected by the Icelandic Maritime Administration [8]. The data for the southern shore of Iceland indicates that waves can easily rise to great heights. Ten years of data include significant wave heights of over 17 m for one hour of measurements.

Generally the relation between the significant value of wave height is related to other wave height classifications by using the Rayleigh-distribution to fit given wave data with. Table 4.1, adopted from Kamphuis [4], shows the most commonly used wave height parameters in that respect. It shows, for example, that the average of the

Table 4.1: Commonly used wave parameters when relating wave occurrences to the significant wave height value H_s, using the Rayleigh-distribution.

Symbol	Description	Value
$\overline{H}_{0.01}$	Average of highest 1% of the waves	6.67σ
$H_{0.01}$	Height, exceeded by 1% of the waves	6.07σ
$\overline{H}_{0.10}$	Average of highest 10% of the waves	5.09σ
$H_{0.10}$	Height, exceeded by 10% of the waves	4.29σ
H_s	Significant wave height	4.0σ
$\overline{H}$	Average wave height	$\sqrt{2\pi}\sigma$
H_{mode}	Most probable wave height	2.0σ

highest 1% of the waves, $\overline{H}_{0.01}$, is related to the significant wave height, H_s, through the relation $\overline{H}_{0.01} = 6.67 \cdot H_s/4.0 \approx 1.67 \cdot H_s$. In other words, the average of the highest 1% of the waves is about 1.67 times the significant wave height value, or 67% higher.

Table 4.1 contains many parameters of concern besides the extreme values and the significant one. The most probable wave height, H_{mode}, is important when studying long-term resistance of an ocean structure to its average environmental conditions.

For this project, there are two sources of wave data:

- Twenty years of data accumulated by the European Center for Medium-Range Weather Forecasts (ECMWF) over the years 1979-1999 around the Icelandic coastline, made every 1.5° longitude and latitude [20]. Points at 63.0°N, 23.0°V and 63.0°N, 21.0°V were selected for investigation (both a few tens of kilometers outside the southern shore of Iceland).
- Ten years of data accumulated from January 1994 until April 2004, by the Icelandic Maritime Administration, at three sites by and close to the Reykjanes-peninsula. See Figure 4.1. Figure 4.2 shows a histogram of the data. Underlying values can be found in Appendix A.1, page 57.

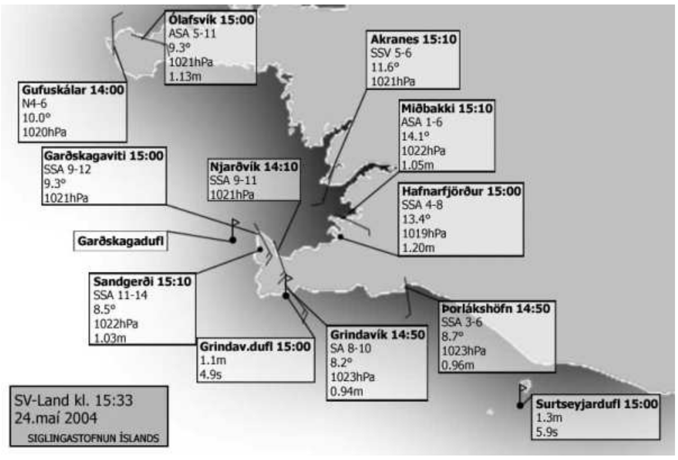

Figure 4.1: A slightly modified capture from the Icelandic's Maritime Administration's website (**www.sigling.is**), showing wave and wind measurements for several points outside the shores of the Reykjanes peninsula. Data from wave buoys at Garðskagadufl, Grindav.dufl and Surtsey are used in this project. They measure wave heights and wave periods and return values for one hour averages every one hour. Date of capture: 24th May 2004.

The distribution of the measurement points is not in such a way that they give a continuous picture of the wave climate south of Iceland. However, they give a clear picture of what can be expected.

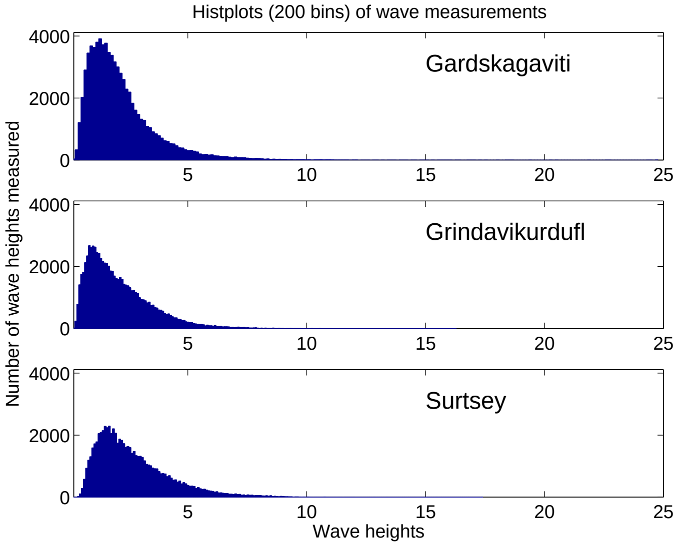

Figure 4.2: A histogram of 10 years of significant wave heights measurements data accumulated from January 1994 until April 2004, made by the Icelandic Maritime Administration, on two sites by the Reykjanes-peninsula—Garðskagadufl and Grindavíkurdufl—and one by Surtsey. See Figure 4.1, page 16, for a map.

4.2 Study of wave data

The measurement values from the Icelandic Maritime Administration discussed in the previous section are available in Tables A.1 and A.3 in Appendix A.1. Using statistical analysis methods, and prior to any structural design, they can be used to estimate the height of for example the 20, 50 and 100 year design wave [4, pp.93-99]. Turner [5] recommends 50 years. Also, by using the data, a relationship between wave height and wave period can be estimated using non-linear data fitting methods [4, pp.100-102].

Using pure statistical analyzes like this is relatively simple, but should be done with care. Ditlevsen [21] discusses a few problems in that respect. He notes that the non-linearity of large waves should be taken into account. The non-linearity influences the distribution of wave heights, and physical limits of wave heights before breaking are smaller than those that conventional statistical models predict, himself meaning a Gaussian process. Therefore, statistical analyses are conservative, showing more extreme values than can be expected in reality [21]. Fredriksson et al. [15] concur with that, stating that motions and loads in model predictions are usually higher relative to field observations.

Estimating the return period of a certain wave height is highly dependant on available data for a given site. Maximum values of available data will be the design param-

Table 4.2: Maximum and most probable significant wave heights (and their periods) from measurement data set from the Icelandic Maritime Administration, for the year 1994-2004. See Tables A.1-A.3 in Appendix A.1 for all values.

	Garðskagaviti	Grindavík	Surtsey
Maximum sign. waves	24.8 m (8.7 s)	16.3 m (10.3 s)	17.4 m (11.2 s)
Most probable waves	1.0-1.5 m (5-6 s)	1.0-1.5 m (5-6 s)	1.5-2.0 (5-6 s)

Table 4.3: Maximum and most probable significant wave heights (and their periods) from measurement data set from the European Center for Medium-Range Weather Forecasts (ECMWF), for the year 1979-1999 [20]. Values show measurements for December-February, when waves are generally the highest.

	63.0°N, 23.0°V	63.0°N, 21.0°V
Maximum sign. waves	15.5-16.0 (16-17 s)	15.5-16.0 m (15-16 s)
Most probable waves	3.0-3.5 m (9-10 s)	2.5-3.0 m (10-11 s)

eters for the most extreme conditions. For the engineer it is noted that the maximum values do not necessarily define the situation where failures of a structure occur. Long-term deterioration can occur for every day sized waves and corresponding periods [21]. See Tables 4.2-4.3 for a list of both maximum and most probable wave occurrences for a few sites south of Iceland.

4.3 Currents

Ocean currents can be a ruling factor in cage design when they are strong and persistent. Loverich et al. [12] state that currents cause the greatest loads on any type of sea cages. Some producers of offshore fish cages, such as Farmocean International AB, do not recommend fish farming in currents above 1.3 m/s [22]. In that respect, upper limits for currents of about 1.3 m/s have been made for the Farmocean-cages. At Ocean Spar Technologies, cages are being designed in such a way that strong currents cause them to sink, thus reducing the forces applied on them [12]. But despite this, currents are still a strong factor in cage design and cannot be neglected.

The concern with currents is mostly due to drag forces exerted on an object [5]. These forces depend on geometry and size of the objects at hand, and in the case of fish cages, the netting and its composition and physical behavior. Drag forces are quadruply related to current speed (see Chapter 7). This means that an increase of the current speed from 0.2 m/s to 0.8 m/s (fourfold increase) will result in a sixteen times greater drag force. Designs must therefore take closely into account the full range of current changes in order to account for load changes resulting from them.

The current climate outside the shores of southern Iceland is, in general, favorable for many offshore fish cages available to date. Currents measure up to 1 m/s near the coastline [23]. In many cases, existing designs seem to suffice in respect to the currents south of Iceland.

4.4 Important occurrences

Most of the important engineering design criteria arise when the so-called design storm is combined with site-specific conditions [11]. A certain composition of wave height, wave period and current speed at a given site will in most cases cause the maximum load on a structure, thus defining most of its design criteria. Normal conditions with respect to waves, currents, winds and debris in the ocean also give rise to engineering criteria.

One of the greatest contribution to a design storm is the maximum wave likely to occur at a given site. Other contributions include tidal currents and winds [11]. The maximum wave would be an indicator of the design wave for a structure at a site, since it would contribute to the creation the greatest single force exerted on a structure. Should a submerged structure survive the maximum waves effects it should survive the effects of other smaller waves. This should be kept in mind when wave measurements are analyzed to obtain engineering criteria. However, like stated previously, the biggest waves are not necessarily the cause of failure for floating structures. They will cause static failure, while the most common conditions will cause fatigue failure.

The design waves return period is normally estimated from some wind or wave dataset and a structures lifetime often calculated with respect to that. Normally this return period is in the magnitude of 20, 50 or 100 years. Using significant wave heights and realizing that the highest wave in a given wave spectrum can, statistically, be up to 67% higher than the significant wave, the wave data previously discussed implies maximum waves of over 30 m. Waves of that magnitude, with corresponding periods and some current velocities, have been used as extreme scenarios for modern designs for offshore fish cages [24].

Obviously, the larger the return period, the larger the wave under inspection, and the higher the cost of a structure designed in respect to the wave, or storm.

Table 4.4: Maximum and most probable significant wave heights (and their periods) from measurement data set from the European Center for Medium-Range Weather Forecasts (ECMWF), for the year 1979-1999 [20]. Values show measurements for both March-May and September-November.

	63.0°N, 23.0°V	63.0°N, 21.0°V
March-May		
Maximum sign. waves	15.0-15.5 (14-15 s)	13.0-13.5 m (15-16 s)
Most probable waves	1.5-2.0 m (7-8 s)	1.5-2.0 m (8-9 s)
Sept.-Nov.		
Maximum sign. waves	13.0-13.5 (13-14 s)	13.5-14.0 m (12-13 s)
Most probable waves	2.0-2.5 m (8-9 s)	1.5-2.0 m (8-9 s)

Two aspects of wave measurement data at a given site should be kept in mind for design purposes:

1. Maximum wave height and corresponding wave period—for ultimate failure resulting from the maximum wave force.
2. Most probable wave height and corresponding wave period—for fatigue failure resulting from deterioration because of every day situations.

Table 4.2 lists both scenarios for the measurements from Grindavík, Garðskagaviti, and Surtseyjardufl, made by the Icelandic Maritime Administration, and Table 4.3 for measurements made by the European Center for Medium-Range Weather Forecasts.

Both the extreme and the most probable values influence the design of an offshore cage system. Failure due to cracks on structural components, whether from weak long-term or strong short-term loads, are of concern [21, p.141]. Dynamic response of a cage system resulting from severe loads must be identified [16, p.242]. Important wave and current occurrences at a given site involve these factors.

Maximum waves heights change rapidly with time of year. Table 4.3 shows their range for two points during the period December-February. Table 4.4 shows the same kind of values for the periods March-May and September-November, and indicate that, on the average, both the maximum and most probable wave heights decrease outside the season of the most extreme values, and sometimes dramatically.

It should be noted that seasonal changes in wave heights are not a reliable factor in design. Wave heights of over 12 m are likely to occur most winter-months. Wave heights over 12 m have measured from August until May by Grindavík, and from November until March at Surtsey, during the years 1994-2004 [8]. The highest waves rise fairly seasonally, like displayed on Figure 4.3, but not in such a way that their occurrence can be predicted with certainty in structural design.

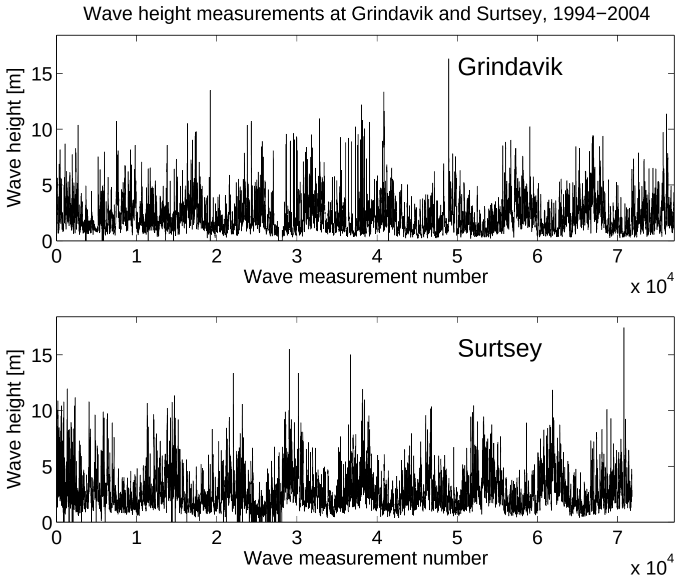

Figure 4.3: Wave height measurements at Grindavík and Surtsey during the years 1994-2004, made by the Icelandic Maritime Administration [8].

4.5 Concluding remarks

The wave and wind climate south of Iceland is harsh. Waves south of Iceland can exceed 17 m in significant height, implying much larger values of some individual waves (statistically, a maximum height 67% higher, or roughly 28 m [4]). Like later discussed, wave heights of this magnitude are generally higher than todays cages have been designed to cope with.

However, the distribution of wave heights is in such a way that occurrences of wave exceeding for example 12 m are very rare. For measurements at Surtsey and Grindavík, only about 0.01-0.02% of the waves exceed 12 m (in significant height), and about 0.20-0.50% exceed 9 m. This means that for wave measurements made over every whole hour, only about one out of five to ten thousand measurement show a significant wave height of over 12 m, or one measurement every 30-59 weeks. If some preparations can be made to protect a submerged fish cage when the relatively rare occasion of waves exceeding 12 m occurs, then that wave height could possible be the design wave appropriate for the wave climate south of Iceland.

Finally it should be noted that the seasonal changes in both the maximum and most common values of the wave heights indicate that by somehow making special arrangements over the harshest season of the wave climate, a considerable decrease in environmental loads could be obtained—even with minimum efforts. Some cages are said to be easily towed, for example the Ocean Spars Sea Station [25], but that most likely only holds when they are empty, and may not be valid for many other types of ocean cages. An increased submersion is an arrangement which could be used to reduce forces, but only for those cages that can be submerged completely below surface.

5

Site evaluation

Selecting a suitable site for an aquaculture operation is an extremely important element in a successful commercial operation. Methods of site selection have been suggested by many. The following discussion will give an overview of the area south of Iceland and around the Reykjanes-peninsula regarding factors such as wave and wind climate, as well as available and necessary facilities for a practical operation of open ocean sea cages.

5.1 Focusing south of Iceland

Like stated earlier, two very important factors are governing when focusing on the shores south of Iceland, namely mortalities in aquaculture related to low ocean temperatures, and optimal growth temperature for the Atlantic cod [1, pp.17-19]. Although the environmental conditions are extremely harsh, these two factors are considered favorable enough to justify a consideration of aquaculture in this climate.

5.2 Data requirements

Data requirements for site evaluation are extensive, including for example meteorlogical, locational and biological factors. Table 5.1 is adjusted from Huguenin [11] to an open ocean aquaculture at an exposed site. Precipitation, humidity, sun-light and water quality are assumed adequate or acceptable. Soil factors are mostly neglected since they are not relevant for cage culture of cod at surface or mid-depths. The ocean temperature is assumed appropriate for culture of cod. Predators and parasites are neglected. Biological environment is assumed favorable, as well as amounts of toxic outfall and characteristics of seabed materials. Availability of interested and skilled personnel is taken for granted. Some other aspects are not listed, including social, political, legal and economical ones.

Turner [5] recommends the availability of various data apart from species and proposed tonnage, including maps of the area, lease area co-ordinates, initial concepts

Table 5.1: Some important site selection considerations for cage and hatchery locations in aquaculture, adopted from Huguenin [11]. Some factors originally listed by Huguenin are assumed adequate for this project.

Site factors	Description
Meteorological factors	• Winds - prevailing directions, velocities, seasonal variations, storm intensity and frequency. • Air and sea temperature and variations.
Locational factors	• Watershed characteristics - area gradients. (elevations and distances), ground cover, runoff, up-gradient activities. • Tides - ranges, rates, seasonal and storm variations, oscillations. • Waves - amplitude, wave length, direction, seasonal and storm variations, storm frequency, fetch lengths. • Hydrography - depths and bottom types. • Coastal currents - magnitude, direction and variations, exchange rates. • Existing facilities and characteristics. • Accessibility of site. • History of site - prior uses and experiences.
Biological environment	• Primary productivity - photosynthetic activity. • Local ecology - number of trophic levels, dominant species. • Wild populations of desired species - adults, sources of seed stocks. • Presence and concentrations of predators - land, water, airborne. • Endemic diseases, parasites and toxic algal blooms.

or cage types and numbers, and details of the working base to be used for the survey. Kamphuis also offers a list of data requirements for a coastal design in general [4, p.14]. For this project the most important aspects involve those of wave and wind climate, and currents.

5.3 Meteorological factors

The primary meteorological factors are wind climate and ocean temperature. Ocean temperature is assumed adequate all year round [1, p.18]. The wind climate affects wave climate. Extensive data is available for the wave climate so wave hindcasting using wind climate is not directly necessary.

Direct effects of winds are negligible for submerged structures. However, they affect servicing and maintenance of offshore structures, such as open ocean fish cages. A few decades of data for windspeeds at various places around and south of the Reykjanes-peninsula show monthly averages up to 11.3 m/s [26], obviously implying much higher maximum values. This creates difficulties in going to sea.

Number of days of rough sea conditions per year vary greatly. Figure 5.1 shows monthly averages of windspeed measurements at Eyrarbakki (see Figure 5.2, page 26), from January 1961 to December 2003. Overall, the monthly average is about 6.1 m/s. Over the winter months the winds are stronger, reaching a monthly average of about 7.1 m/s in February. Keeping in mind that the maximum values can be considerable higher than the average values, this wind climate could easily result in great difficulties when servicing offshore fish cages from Eyrarbakki and nearby harbors. Keflavik (see Figure 5.2) does not give lower values. For Keflavik-airport in February, monthly averages of windspeed measurements for the period 1961-2003 reach roughly 7.6 m/s.

The conclusion is that even if winds in many cases do not directly affect the loads on submerged offshore fish cages, they do have strong impact on the possibilities of servicing them, especially over the winter months. Small boats could face great problems in operations in this climate of consistently strong winds.

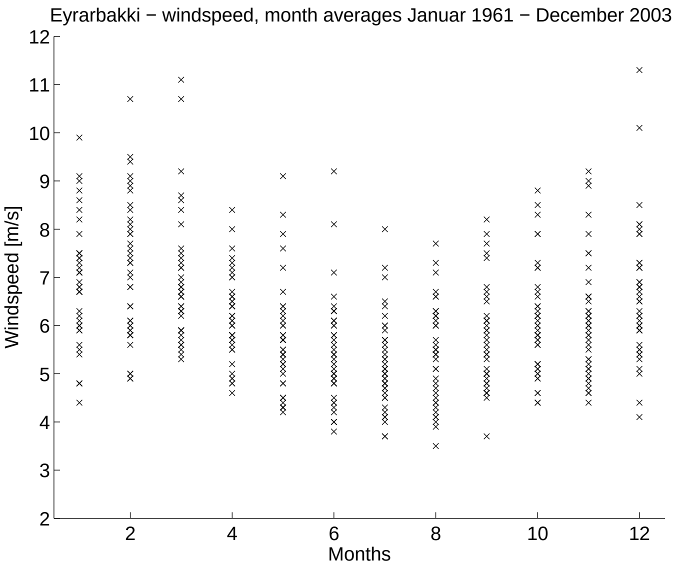

Figure 5.1: Monthly averages of windspeed measurements at Eyrarbakki (see map on Figure 5.2) from January 1961 to December 2003, obtained from the Icelandic Meteorological Office [26].

5.4 Locational factors

Of primary concern so far has been the influence of waves and currents, but many other factors determine the feasibility of a site regarding an aquaculture installation. Existing facilities, accessibility of sites and prior use and experience with sites come together in affecting ease of service, operation and maintenance of fish cages at sea.

Obviously, attempting to use existing facilities, by narrowing the site selection to areas in short range from harbors and populated coastal areas, will cut costs. In the case of southern Iceland this will narrow possible sites down to the ocean near a relatively few towns, since the coastline is very little habitated. Figure 5.2 shows a map of south and south-west of Iceland. All of the main towns where harbors exist with main facilities are marked on it. In south-east Iceland only Hornafjörður is inhabited by the coastline (see Figure 1.1, page 2). It should be noted that the Marine Research Institute in Iceland operates an experimental hatchery facility near the town of Grindavík which will most likely be an important provider of smolt and fingerlings for aquaculture installations south of Iceland [1]. Also, since access to warm ground-water is good on the Reykjanes-peninsula, that area is considered favorable for growing of smolt.

Figure 5.2: A map of south and south-west Iceland, showing major towns, most of which have harbors and many essential facilities for deploying boats or ships.

Site selection in relation to servicing facilities does not seem to follow any specific guidelines. In the Open Ocean Aquaculture-program at the University of New Hampshire, cages are kept at a site about ten kilometers from the coast of the mainland, at waters of depth of about 52 meters [10]. Some cages, like the Farmocean offshore cages (discussed in Chapter 6), can be installed in waters of up to one hundred meters in depth without special considerations [22].

Growth conditions at a given site are an important aspect in site selection. Environmental conditions in Selvogsbanki, south of the Reykjanes-peninsula, are more stable than in most other areas around Iceland [6], and considered favorable for the Atlantic cod [1]. Those conditions include factors such as ocean temperature, biomass of zooplankton and salinity. The ocean south of Reykjanes offers, in many aspects, optimal conditions for hatching and growth of the cod, the latter being crucial for operation of aquaculture in the area. Also, the favorable temperature of the area could help reduce production costs since the optimal temperature for food consumption for the Atlantic cod is lower than the optimal temperature for growth [1, p.28].

For this project the factor of wave transformation—a description of what happens when waves travel from deep water into shallow water—will be put to side. Wave transformation is highly site dependent and more detailed studies must be carried out when site selection has been narrowed down. The important factor is choosing a site where bottom types and hydrography are not in such a way that wave transformation exaggerates the loads from waves and currents, for example by wave breaking.

5.5 Concluding remarks

The final choice of a site for an open ocean aquaculture south of Iceland must take into account the aspects in Table 5.2. Given the scarcity of sites that have reasonable agreement with those aspects, the sites in Table 5.3 are most likely the only ones applicable for an operation of an open ocean aquaculture south of Iceland. Of those, Grindavík is probably the most viable option, especially due to the fact that there is a hatchery facility in the town today, besides a harbor and most other major facilities. Also, Þorlákshöfn could be considered a viable option. Both Grindavík and Þorlákshöfn enjoy the stable and favorable growth conditions described for Selvogsbanki south of Iceland, and both are exposed to the harsh environmental conditions of the area.

Table 5.2: Key aspects that a site evaluation must show agreement with in order to be looked at as viable for an operation of an offshore aquaculture.

Aspect	Discussion
Access to harbors	Servicing boats and facilities related to aquaculture should be as close from the cages themselves as possible.
Wind climate at site	Winds are strong south of Iceland. Reducing wind effects will ease all maintenance and servicing in the open ocean.
Wave climate at site	Wave climate is harsh. Ocean bottom types should be analyzed to find conditions where its effects are minimized.
Water aspects	Stable temperature. Favorable temperatures depending on species, maturity and resistance to cold and warm waters.

Table 5.3: Sites south of Iceland that fulfill the most requirements for an operation of an offshore aquaculture.

Site	Discussion
Grindavík	Has a harbor and many major facilities. Hatchery facility in town. Good access to warm ground-water for growing of smolt.
Vestman Islands	Has a harbor and many facilities.
Þorlákshöfn	Has a harbor and many facilities. Good access to warm ground-water for growing of smolt.
Reykjanes-peninsulas northern coastline	Has a few harbors and many facilities. The peninsula could provide shelter from strong winds from south.

6

Cage selection

The following is a list of a few demands that a cage must fulfill, among others:

- It must withstand the most extreme environmental conditions at a given site.
- It must withstand long-term effects of most common environmental conditions.
- It must not harm the fish inside it.
- It must keep out predators.
- It must be economical in initial cost, operation and maintenance.
- It must meet regulation standards and existing or suggested design codes, such as the one from the Norwegian Standards Association [27].

Cage selection for a given site is ultimately the decision that determines the success of an aquaculture project. The final choice is usually dependent on financial capabilities and site data [5], and operational and maintenance requirements also come strongly into play.

6.1 Present cages

A number of cages are available in the market today for open ocean aquaculture. They range from surface cages to submerged ones, and vary greatly in design, configuration and layout. Examples were provided in Figure 2.1, Section 2.4, but there are many more. Scott et al. [25] offer a short overview of many offshore cage systems. Their focus is on aquaculture in the Mediterranean. They conclude that none of the offshore cage designs currently on the market are fully effective in meeting target objectives for an open ocean aquaculture, including cost and endurance in the most severe conditions. However, they also conclude that the current generation of submersible and submerged cages may, by scaling up and testing newer designs and materials, offer improved and competitive opportunities [25].

6.2 Overview of offshore cages

The following overview is mostly adopted from Scott et al. [25] who studied offshore cage systems compared to situations in the Mediterranean. Their evaluation is mostly concerned with overall system characteristics, typical applications, approximate costs per unit of cage volume and essential advantages and disadvantages.

6.2.1 Surface cages

Surface cages are in general not well suited for open ocean aquaculture [7, 11]. They can be classified into flexible and rigid types, depending on the nature of the structure holding the net [25]. The flexible cages are designed in such a way that they absorb wave forces by giving in to them to a certain extent. Models of those types are relatively inexpensive. The rigid cages are designed so that they withstand wave action rather than adjusting to it. With this comes extra cost in installation and operation, although they, unlike the flexible types, offer the possibility of servicing facilities being built on to the cages.

Both the flexible and rigid surface cages are very sensitive to strong currents, and are not at all suited for harsh wave climate. Depending on type, their installation cost and ease in operation can vary greatly. However, neither is of any importance when the environmental loads always exceed their design criteria.

6.2.2 Submersible cages

Submersible cages are those who can be lowered below surface for longer or shorter time, for example during storms. This characteristic has the potential advantage of making a cage lighter and simpler than surface cages designed to survive the impacts of extreme conditions, although being submersible may in many cases involve technical difficulties in operation, maintenance and routine husbandry.

Submersible cages can be divided into two categories; flexible and rigid. Figure 6.1 shows an example of a flexible submersible cage—the Refa tension leg cage. In normal conditions its top is at surface and accessible for normal operation, maintenance and even harvesting. When waves and winds increase in magnitude, the cage will give in to increased loads. Since loads from waves decrease fast with increased depth [11], this will result in decreased forces from waves and currents.

The design and behavior of the Refa tension leg cage is controversial. Loverich et al. [12] state that strong currents on the cage will result in extremely high anchoring loads and deformations [12]. The cages producer states that cage volume is reduced by no more than 30% in storms [28], and Scott et al. [25] concur with that, saying that volume reduction will be no greater than 25%. However, they point out that feeding

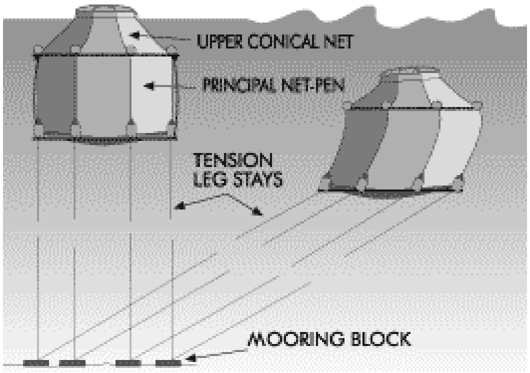

Figure 6.1: The Refa tension leg cage is a flexible submersible cage designed in such a way that when loads on it increase, it gives in and submerges, thus resulting in decreased forces from waves, winds and currents. The cage is fastened with mooring ropes to bottom blocks made of concrete (picture: Refa Med, **www.refamed.com**).

might be troublesome and installation more costly and difficult than with cages that rely on conventional anchors, instead of the mooring blocks.

Figure 6.2 shows two examples of submersible cages with rigid frameworks. Producers of both cages state that they are designed for open ocean aquaculture, without guaranteeing that they can withstand any specific conditions, except current speed of up to about 1.0-1.3 m/s for the Farmocean-cage [22] and about 0.8 m/s for the Sea Station [29]. In a current of 1 m/s, 90% of cage volume of the Sea Station has been recorded as retained [25]. Loverich et al. [12] state that rigid submersible cages show nearly 100% volumetric efficiency. Scott et al. [25] seem to lean more to the Farmocean-cages, stating that extensive experience with them has proven their capability to operate in harsh conditions. Also, their built-in feeding system offers the chance of automatic feeding for several days if access is denied due to bad weathers. However, since the Farmocean-cages can not be fully submerged unlike the Sea Station [25], they are in risk of becoming more vulnerable in very harsh wave and wind conditions.

Experience with the Ocean Spar Sea Station has been established in a few locations over the past few years, for example in relation to the Open Ocean Aquaculture program mentioned in Section 3.4. Mooring components have been designed using model simulations with a significant wave height input of 9 meters with a period of 8.8 seconds, and an average current of 1 m/s [9, 15]. The Ocean Spar Sea Station has proven well for the harsh wave climate east of the United States, where the significant wave heights reach up to 5 m [30]. The Sea Station has been installed elsewhere too, for example by Hawaii [31] and in Cyprus [25, p.86].

The overall experience with the Sea Station from Ocean Spar, independent of vol-

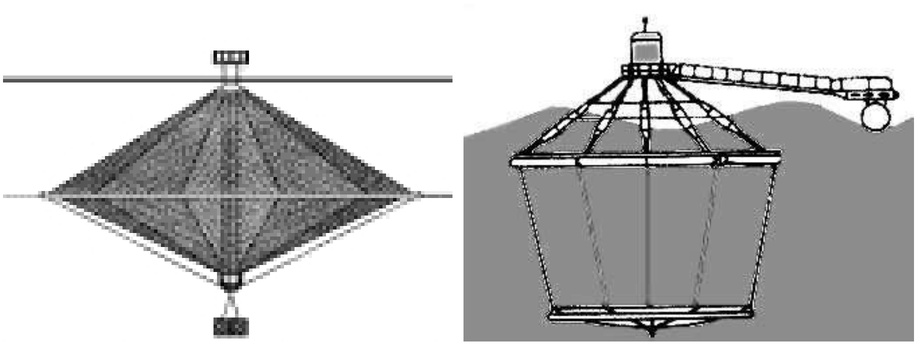

Figure 6.2: On the left is the submersible Sea Station from Ocean Spar Technologies (picture: **www.oceanspar.com**). On the right is a Farmocean cage from Farmocean International AB (picture: **www.farmocean.se**). Both cages have rigid frameworks and can be raised and lowered in sea to adjust to changing wind and wave conditions.

ume and model type, shows that it is well suited for relatively harsh conditions. Troubles are mainly related to initial cost [31], and a development of an effective, automatic feeding system is still underway [9, 25].

6.2.3 Submerged cages

In their analysis, Scott et al. [25] discuss three designs of fully submersible rigid cages—those from SADCO-SHELF Ltd., the Trident cage and the MII cage from Marine Industries and Investments. Of those three, the SADCO-design has gained most experience, for example in relation to the Open Ocean Aquaculture-program [9] and in deployment in the Caspian, Black and Mediterranean Seas [25]. The producer of the SADCO-cages states that the cages can withstand influence of maximum wave heights of up to 15 meters, current speeds of up to 1.5 m/s, and windspeeds of up to 35 m/s when underwater [32]. These values are unverified, but early models of the SADCO-cages have reportedly withstood storms including wave heights of up to 12 m [25].

The literature offers very little information about the Trident cage and the MII cage. Scott et al. [25] offer a brief description of both. The Trident cage is reported to have withstood windspeeds of 22-33 m/s and breaking waves of over 3.5 m, while 2/3 submerged [25]. The MII cage, likewise, has not received much attention in the literature but shows less promise than the Trident cage [25].

6.3 Cage improvements

It seems that todays choices of offshore fish cages of any kind are not sufficient for harsh conditions like those south of Iceland, although some designs look promising. Tradeoffs exist between difficulties in operation, labor and capital intensiveness and costs of maintenance [5]. Still, the problem of external loads likely to occur in the wave climate south of Iceland does not seem to be solved with the choices available to date.

Improvements can be made however, and radical ideas have been suggested [12]. Two examples can be seen in Figure 6.3—an ocean drifter and a rigid seabed bottom cage. The drifter is designed to reduce the effects of moving water by allowing the cage to drift with the ocean current. Drag forces are assumed to be non existent because it is stated that the velocity between cage and water will be reduced to zero [12]. The seabed cage is a submerged fish cages of very robust design. High costs are involved with cages like this, and even a cage of this type is not recommended for use when the significant height of waves exceeds 15 meters [5].

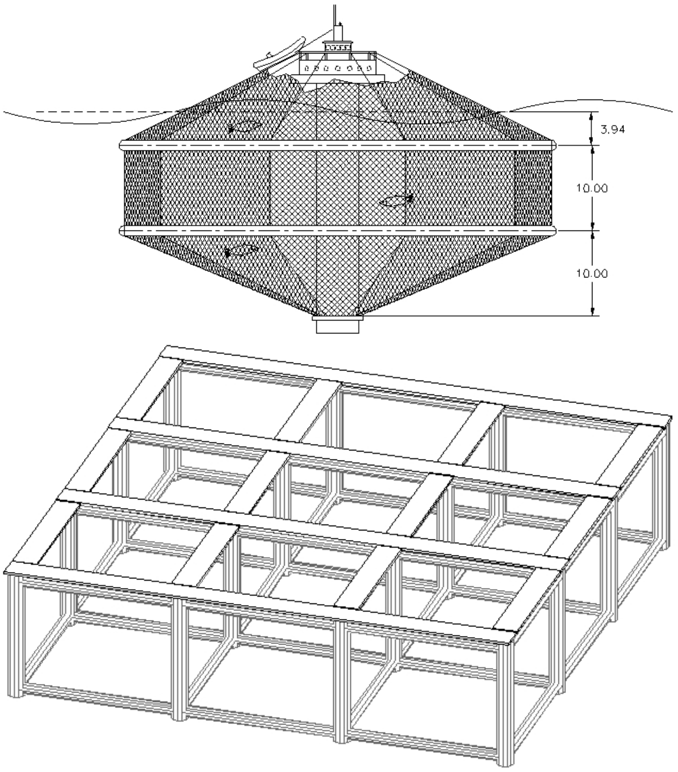

Figure 6.3: **Top picture:** Sea station ocean drifter (top) and a rigid seabed bottom cage (bottom)—two suggestions for future improvements and designs of open ocean fish cages. Pictures: Ocean Spar Technologies, **www.oceanspar.com**.

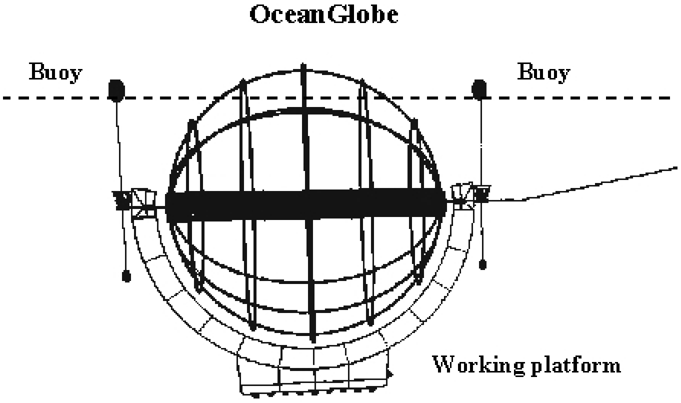

Figure 6.4: The OceanGlobe from Byks AS in Norway, in its submerged configuration. Its shape is sphere-like, and it is attached to the seafloor with a single anchor. So far its design is on experimental stage. Picture: **www.byks.no**.

In Norway, the generation of new designs is rapid. Figure 6.4 shows the so-called OceanGlobe from Byks AS in Norway in its submerged configuration. The OceanGlobe has a sphere geometry and is attached to the seafloor with a single anchor. So far its design is on experimental stage.

Other designs have been suggested, either by making improvements to present cage models or by making new ones from scratch. Great improvements have been made over the past years and with increased interest in open ocean aquaculture it is likely that building cages that can withstand the climate south of Iceland can be done with success. Understanding that climate in relation to open ocean cages is the focus of chapter 7.

6.4 Concluding remarks

Like discussed in Chapter 4, the wave climate south of Iceland includes maximum significant wave heights of over 17 m, which is considerably higher than the highest design waves of 9-12 m for the strongest of todays open ocean cages. The for mentioned idealistic OceanGlobe is designed with respect to extreme conditions with significant wave height of 14 m (and wave period 16 s), including waves with a total height of 30 m, and current velocities of up to 1.5 m/s [24]. Even those design parameters are not sufficient.

But, like also stated in Chapter 4, there is only a small fraction of the waves that exceed the design criteria of todays cages. On the average, about 0.01-0.02% of the waves exceed 12 m in significant height and about 0.20-0.50% exceed 9 m. This implies that cages designed for up to 12 m waves could suffice if special arrangements are made to count for the rare but extreme scenarios of higher waves, for example by not having the cages deployed for those times a year when they are likely to arise. However, that is an unlikely option since the Atlantic cod doesn't reach harvesting size until it is about two to three years old [1].

For cages that are said to withstand 15 m waves, the possibilities become even more favorable, although there are still considerable risks involved. Putting a cage with a 12 m design wave height into a wave climate with about 17 m maximum wave height implies a structural lifetime of only about one year, which could at best be feasible for experimental purposes.

Cages from Farmocean, Ocean Spar and SADCO are the most viable options today, but most likely not fit for the wave climate south of Iceland at its extreme. For them to do that, either they should not be deployed during times of year when waves exceed their design criteria, which is an unlikely option, or arrangements made so they can withstand the highest waves likely to rise at a given site. Largely increasing cage submersion, for example, will decrease wave forces considerably.

7

Forces and loads

Analysis of loads on ocean structures due to waves and currents range from estimations using quasi-static methods to the use of more detailed computer models simulating for example netting deflections [11, p.182]. For this project the forces at hand will be studied on a global scale with respect to waves and currents—loads on individual cage and mooring components, netting twines etc. are neglected and the focus put on the magnitudes of forces at hand. Forces from other sources, such as ice and debris, are neglected.

7.1 Wave forces

Generally, wave forces on objects in sea depend on many different variables, such as wave height, wave length, water depth, particle velocity and the geometry of the object in question [33]. Huguenin [11] notes that before environmental forces on an object can be estimated, all dimensions and detailed system parameters have to be known. Kamphuis [4] notes that simplifications are generally involved in coastal design. Locational factors are of importance, like discussed in Section 5.4. Watershed characteristics and hydrography will not be considered to be of complex nature, and water transformation not counted for.

7.1.1 Wave characteristics

Since wave measurements generally come in pairs of wave heights and wave periods at sites with certains water depths [8], the wave length has to be calculated. For small wave heights and periods in certain proportions to water depth, linear methods apply. With increasing wave heights and periods, methods for wave length calculations become more complex, and factors such as wave breaking become important. When watershed characteristics and hydrography increase in complexity, refraction and diffraction become increasingly important parameters; see Section 5.4.

The Small Amplitude Wave Theory (SAWT) is a simple linear method to describe waves by calculating various parameters from pairs of wave height and wave period measurements [4]. For linear wave theories, the main assumptions are [4, p.30]:

- The water (fluid) is ideal—that is, continuous and frictionless.
- Wave height is infinitesimally small compared to wave length, water depth and other defining lengths—wave amplitudes are small and depths great.
- Wave transformation is not in the scale that is sufficient to cause breaking of waves.

Kamphuis [4, p.28] states that despite these narrow conditions, it has been found over the years that SAWT is appliciable for most problems, so that the use of more complicated wave theory is not necessary—more complex wave theories have been developed, but their application is normally regarding research and very complex designs. The Icelandic Maritime Administration publishes wave lengths that are calculated linearly from wave measurements, regardless of wave height and period [8]. Hughes et al. [33] note that although linear wave theory provides a nice closed-form solution for forces and moments on slender cylindrical piles, in practice, the hydrodynamics associated with the steeper design wave conditions will not be well predicted by linear wave theory.

An overview of the SAWT can be found in Kamphuis [4] and Sarpkaya et al. [13]. A short summary from those discussions now follows.

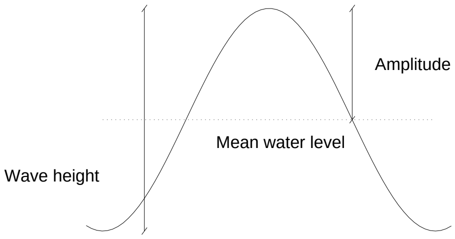

Figure 7.1: Wave shape according to SAWT, where the wave height is double the amplitude of the wave.

Linear wave theory: Small Amplitude Wave Theory.
SAWT assumes perfecly linear shapes of the waves, like shown on Figure 7.1, where the wave height is assumed to be double the wave amplitude. SAWT requires the following inputs:

- Wave height, H.
- Wave period, T.
- Total water depth, d.

First, the so-called deep water approximation, L_0, is calculated.

$$L_0 = \frac{gT^2}{2\pi} \tag{7.1}$$

The constant g is the gravitational acceleration. The dispersion equation

$$\omega^2 = gk \tanh(kd) \tag{7.2}$$

where the parameter $k = 2\pi/L$ is the wave number, L is the wave length, and $\omega = 2\pi/T$ is the angular wave frequency, can be rewritten as

$$C = \frac{\omega}{k} = \frac{L}{T} = \frac{gT}{2\pi} \tanh(kd) \tag{7.3}$$

to find the velocity of wave propagation, C.

Equation 7.4 is an approximation of the Newton-Raphson root finding technique to calculate C—one of many available [4],

$$\frac{C^2}{gd} = \left(y_0 + \frac{1}{1 + 0.6522y_0 + 0.4622y_0^2 + 0.0864y_0^4 + 0.0675y_0^5} \right)^{-1} \tag{7.4}$$

where

$$y_0 = \frac{2\pi d}{L_0} \tag{7.5}$$

The wave length L is now available as $L = TC$.

Individual water particles do not propagate like the waves. They are assumed to travel in orbital paths in the water, which become circular with increased depths. For a given submersion depth z below surface, the horizontal and vertical displacements of the water particles orbital velocities can be calculated according to the relations,

$$\Delta x = -\frac{H}{2}\frac{\cosh(k(d-z))}{\sinh(kd)}\sin(\theta) \text{ (horizontal displacement)} \tag{7.6}$$

$$\Delta y = \frac{H}{2}\frac{\sinh(k(d-z))}{\sinh(kd)}\cos(\theta) \text{ (vertical displacement)} \tag{7.7}$$

where $\theta = kx - \omega t$ is the wave phase angle [13] which describes the position of the water particle on its orbital path. The horizontal and vertical components of the water particles orbital velocities can be calculated according to the relations,

$$u = \frac{\pi H}{T}\frac{\cosh(k(d-z))}{\sinh(kd)}\cos(\theta) \text{ (horizontal component)} \tag{7.8}$$

$$w = \frac{\pi H}{T}\frac{\sinh(k(d-z))}{\sinh(kd)}\sin(\theta) \text{ (vertical component)} \tag{7.9}$$

The maximum values of the orbital velocities are reached when $\cos(\theta) = 1$ (eq. 7.8) and $\sin(\theta) = 1$ (eq. 7.9) respectively. The corresponding water particle accelerations are [13]

$$\frac{\delta u}{\delta t} = \dot{u} = \frac{2\pi^2 H}{T^2}\frac{\cosh(k(d-z))}{\sinh(kd)}\sin(\theta) \tag{7.10}$$

$$\frac{\delta w}{\delta t} = \dot{w} = \frac{2\pi^2 H}{T^2}\frac{\sinh(k(d-z))}{\sinh(kd)}\cos(\theta) \tag{7.11}$$

Other parameters are sometimes of interest. Among them are: Maximum oribital velocity of water particles, pressure, energy density, wave power and mass transport at bottom, all discussed by Kamphuis [4] and Sarpkaya et al. [13, p.159].

Higher order wave theory does not estimate the perfecly sinusodial wave pattern like SAWT does, where the wave height is double the amplitude (Figure 7.1). Instead it estimates that the wave crests are higher and the wave troughs are shallower [4, p.39].

Chang et al. [34] discuss an explicit approximation to wave length of non-linear waves, and a number of other suggestions for wave length calculations. The reader is referred to his work for further detail.

7.1.2 Wave force estimation

When the wave conditions have been described sufficiently and the design and geometry of the structure at hand has been decided, an estimation of forces can be carried out. Of special interest are the maximum forces likely to arise.

Silvester [35] provides formulas for estimating the maximum horizontal force from waves on the center-point of objects of large dimensions of various geometry. They are analytical and depend on wave height, wave length, water depth and object geometry [35, p.408-415].

Because of the complex nature of wave forces, approximations have been made. The most common one is Morison's Equation which is generally applied to slender offshore structures [33].

$$F = \underbrace{(m_{11} + \rho\forall)\dot{u}}_{inertiaforce} + \underbrace{\frac{1}{2}\rho l^2 C_D u|u|}_{dragforce} \tag{7.12}$$

or

$$F = \rho C_M \forall \dot{u} + \frac{1}{2}\rho l^2 C_D u|u| \tag{7.13}$$

with the following parameters: Specific mass of water ρ and object length l, added mass, m_{11} (effective mass of the fluid that surrounds the object), displaced volume of fluid, $\forall$, fluid acceleration $\dot{u}$, apparant damping coefficient C_D (also called drag hydrodynamic force coefficient, or simply the drag coefficient [33]—usually determined experimentally), inertia or mass hydrodynamic force coefficient C_M (another way of interpreting the added mass—usually determined experimentally), and squared fluid velocity $u^2 = u|u|$ so that the drag force acts in the same direction as the fluid velocity.

The first term of Morison's Equation, the inertia force, is the force required to hold the object in place subject to a constant free stream acceleration. The second term, the drag force, is the force required to hold the object in place subject to a stream of certain velocity.

A few cages have geometries that can be approximated as spheres; see Chapter 6. They will encounter oscillations. Netting deflection will be neglected since most submersible, rigid cages show very little volume reduction against external loads [12]. The distribution of force over the objects surface will be neglected, and also possible un-even mass distribution of fish inside the cage. The influence of drag and inertia forces is highly dependant on the size of the object in the ocean compared to the wave characteristics [14].

7.2 Current forces and other forces

7.2.1 Current characteristics

Currents have relatively simple characteristics compared to waves. They may be considered uniform with depth close to surface [35, p.237-238], and divide into two main categories:

- Currents with long fetch resulting from deep-sea flow. Low velocities.
- Currents due to tides, for example in bays and channels. High velocities.

In the open ocean south of Iceland there will be no concern for the second category. Measurements show that currents reach velocities of up to $U_c = 1$ m/s [23]. The current direction can be considered the same as the direction of wave propagation.

7.2.2 Current forces

Like wave forces, current forces are subject to a number of parameters of various complexity. Currents can have significant influence on loads on an object in the ocean, for example by increasing the amplitudes of forces from wave action [36], and by effecting wave lengths and direction of wave propagation [35, p.237-240]. The currents effects will be included in the overall wave loading by superposition, which is the conventional way and applicable for most circumstances [13, pp.319-323].

7.2.3 Forces from other sources

Forces from ice are usually of great concern in aquaculture around Iceland and other countries by cold waters [1, 30], and analyses of them is often of great importance. Hughes et al. [33, VI-5-279], Kamphuis [4] and others offer many approaced to study ice forces when they exist. However, temperatures south of Iceland raraly offer any conditions for which ice can form on coastal and offshore structures, so effects of ice can be neglected here.

Another issue of concern is debris, but its effects are highly unpredictable since they completely depend on what kind of objects form the debris. Also, since cages south of Iceland will most likely have to be submerged for great periods of time, the risk of debris collisions is greatly reduced, and its effects therefore negligible.

7.3 Application

7.3.1 Assumptions

An example in the use of Morison's Equation (eq. 7.12) is now provided. The forces at hand will be estimated on a relative scale. The two following scenarios are proposed, following an explanation of their use:

- An open ocean wave climate with extreme wave heights in deep waters.
- A sheltered wave climate with small waves in shallow water.

The following assumptions are made:

- Linear methods apply for both sceanarios.
- The maximum forces likely to arise are the most important ones in engineering design.
- A submerged fish cage is more or less fixed in the water despite heavy loads being exerted on it, and at some fixed time interval, will not face oscillations and heave respones.
- The cage is submerged in the open ocean wave climate so wave breaking is not of concern.
- The bathymetry of the sea floor is of simple nature so the effects of wave transformation are negligible.

It is known that forces on submerged objects decrease rapidly with increase submergence [11]. The idea is to see for how much submersion in an open ocean wave climate a cage will face similar loads than if it were at surface in a sheltered wave climate. The following parameters are used for the open ocean wave climate:

- Wave height $H = 16.3$ m, wave period $T = 10.3$ s (maximum wave height and corresponding wave period for Grindavík), water depth $d = 100$ m (maximum depth recommended for for example the Farmocean cages [22], and describing for the ocean depths south of the Reykjanes-peninsula).
- Current velocity $U_c = 1$ m/s.

The following parameters are used for the sheltered wave climate:

- Wave height $H = 3$ m, wave period $T = 8$ s, water depth $d = 30$ m.
- Current velocity $U_c = 0.1$ m/s (greatly underestimated for narrow bays since cages in such locations often experience large tidal currents, but applicable for open, sheltered areas).

For both scenarios the following entities are used:

- Ocean waters specific density, $\rho = 1035$ kg/m^3.
- Gravitational acceleration $g = 9.81$ m/s^2.
- Cage volume $V = 3000$ m^3 (comparable with a model of the Sea Station from Ocean Spar Technologies with a 25 m diameter, Figure 6.2 [29]).

The effects from currents are incorporated by superposition. The current profiles will be uniform for about half of the water depth, and decrease hyperbolically from there to a zero velocity at bottom [35, pp.237-240].

7.3.2 Coefficients

The evaluation of the drag coefficient, C_D, is a matter of great discussion in the literature, and a higly complicated matter. Sarpkaya [13], Silvester [35], Hughes et al. [33] and many others offer a number of suggestions, mostly in relation to slender, horizontal cylinders. Fredriksson et al. [15, 16] suggest a use of a modified version of the Morison's Equation to account for relative motion between the structural elements and the surrounding fluids, and coefficients of drag and added mass (inertia) respectively.

Lader et al. [18] suggest drag and lift coefficients (C_D and C_L) for modeling of a simple net exposed to waves and currents in three dimensions. Their approach will be used here. They use the following drag and lift coefficients on a net subject to uniform current:

$$\begin{aligned} C_D &= 0.04 + (-0.04 + S_n - 1.24S_n^2 + 13.7S_n^3)\cos(\alpha) \\ C_L &= (0.57S_n - 3.54S_n^2 + 10.1S_n^3)\sin(2\alpha) \end{aligned}$$

where α is the angle of attack and S_n is the solidity of the net (the ratio between the projected area of the net and the total area enclosed by the net). The drag force is parallel to the flow direction and dependant on the horizontal particle velocities (and the current). The lift force is perpendicular to the flow direction and dependant on the vertical particle velocities. Both the lift and drag force are calculated using the second term of Morison's Equation (eq. 7.12). For an angle of attack $\alpha = 45°$ (on the average, and keeping in mind the shape of Ocean Spars Sea Station on Figure 6.2, page 32). Here the maximum net solidity recommended, $S_n = 0.35$ [18], is used, since nettings on open ocean cages generally have great density, for example so they can keep predators out and increase the nettings strength. Now the following coefficients are obtained:

$$\begin{aligned} C_D &= 0.6 \\ C_L &= 0.2 \end{aligned}$$

General recommendations for the drag coefficient are in the range 0.6-1.0 [13, pp.312-317], and the value obtained here shows agreement with that. The contribution of the lift force is sometimes omitted [16, 37], and it is found here that its contribution is negligible.

The choice of value for the inertia coefficient is made from the work of Frediksson et al. [16], obtained from field tests for a model of the Ocean Spar Sea Station, namely

$$C_M = 2.9$$

Another option is to use the theoretical value of the addess mass m_{11} for a sphere, $m_{11} = \frac{2}{3}\rho\pi R^3$, where R is the spheres radius [13]. The radius of a sphere with volume $V = 3000$ m^3 is about 9 m, the added mass about 19.4 m^3, and a translation into an inertia coefficient yiels

$$C_M = (m_{11} + \rho\cancel{V})/\rho\cancel{V} \simeq 1.0 \tag{7.14}$$

Since a general range of recommendations for the inertia coefficient are in the range of 1.5-2 [13, pp.312-317], and since inertia forces are likely to have great effects on large objects (compared to water depth and wave amplitude) [35], this approach is not used.

The customary way to incorporate a steady current U_c into the hydrodynamical forces resulting from wave action is by superposition [13]. According to Sarpkaya et al. [13], the acceleration to be used in the calculation of the inertial force should be written as

$$a_x = \dot{u} + u\frac{\delta u}{\delta x} + U_c\frac{\delta u}{\delta x} \tag{7.15}$$

where $\dot{u} = \delta u/\delta t$ is the horizontal particle acceleration previosly obtained in the absence of current, u is the horizontal particle velocity and

$$\frac{\delta u}{\delta x} = \frac{\Delta u}{\Delta x} = -\frac{2\pi}{T}\frac{1}{\tan(\theta)} \tag{7.16}$$

obtained from the horizontal particle displacement (eq. 7.6) and velocity (eq. 7.8). The current is given a decreasing profile like described earlier.

7.3.3 Force comparisons

A comparison of extreme open ocean conditions of waves and currents compared to values for the sea south of Iceland, and sheltered site conditions of low waves and weak currents is displayed on Figure 7.2. The figure indicates that a submersion in the open ocean of about 51 m will result in loads comparable with those at surface at a sheltered site.

In the absence of currents, this value reduces to about 31 m—see Figure 7.3. Reducing the open ocean water depth to 70 m results in less than 1 m decrease in the intersection depth of open ocean and sheltered site force. Increasing the depth of the sheltered site water to 40 m, keeping the open ocean depth at 100 m, reduced the intersection depth to about 47 m. Clearly depth changes have small effects in the present wave climate comparison. Two related conclusions can be made from these submersion values:

- A fish cage that can be submerged to the depths indicated here, or generally depths of a few tens of meters, can, by a reasonable approximation, find themselves in load conditions similar to those found at surface in sheltered sites, where cages are generally not built to resist heavy loads.
- Cages that can not reach the submersion indicated here will, in general, have to be designed to resist much larger forces that todays conventional surface cages, without stating in detail what conditions those might be. This would imply for example the Farmocean cages and the experimental OceanGlobe, both discussed in Chapter 6.

Still unmentioned, for the purpose of fish considerations, are the currents likely to exist inside the cage. A reduction factor, γ, is provided by Lee et al. [37] for the current velocity flowing through a net, defined as

$$\gamma = 1.0 - 0.46C_D \tag{7.17}$$

where C_D is, like before, the drag coefficient. With $C_D = 0.6$ a reduction factor $\gamma = 0.74$ is obtained, indicating that the current velocity is reduced to about 74% of

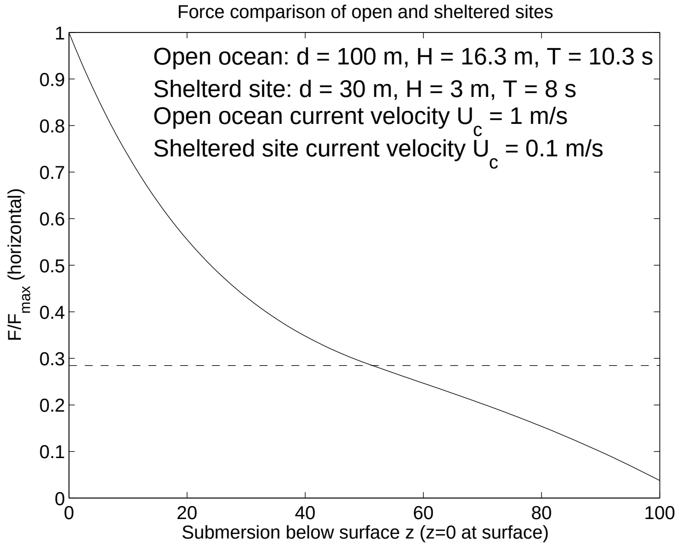

Figure 7.2: A comparison of an extreme open ocean conditions of waves and currents (compared to values for the ocean south of Iceland), and sheltered site conditions of low waves and weak currents, using Equation 7.12 (page 41).

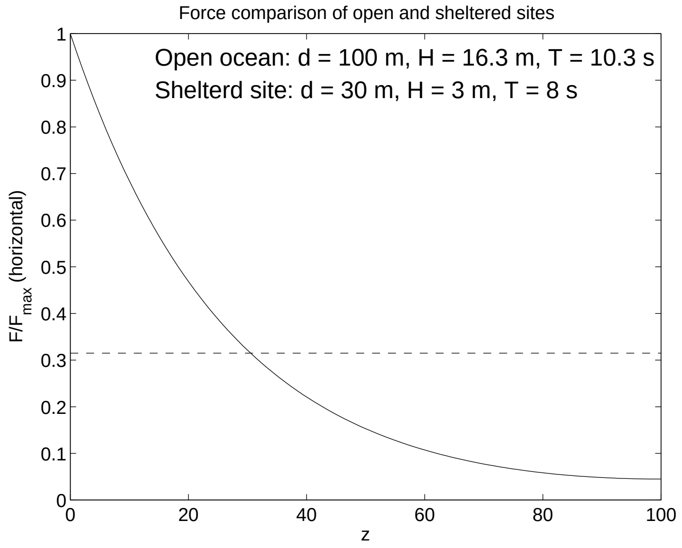

Figure 7.3: A comparison of an extreme open ocean conditions of waves and sheltered site conditions in the absense of currents, using Equation 7.12 (page 7.12). The figure indicates that a submersion in the open ocean of about 31 m will result in loads comparable with those at surface at a sheltered site.

its original value when the water flows through the net. This means that cages facing a current with velocity 1 m/s could experience currents of about 0.7-0.8 m/s inside them, which is considerably higher than recommended for fish species like the Atlanic cod.

7.3.4 Some issues for consideration.

Pressure is not included in the force analyses. Pressure increases with depth and depends on water depth and wave characteristics [13, pp.156-157]. It will affect forces exerted on a submerged cage and, if not accounted for, can result in various failures on the cage structure, or even of the structure itself. However, it has not been found that pressure is incorporated into estimations of forces from waves and currents on offshore cages. It is therefore assumed that the cages are designed to withstand considerable submersion before pressure becomes a defining factor in force calculations. This holds for submersion of at least about 15 m [9].

Submergence does not only lead to a decrease in loads due to wave action. It has also been found that with increased submergence of a sphere, a decrease of both heave and surge occurs [38]. In other words, the object or cage stabilizes in the ocean with increased submersion, which leads to lower stresses on moorings and anchors, as well as improved living-conditions for fish inside.

Although submersion might decrease the loads on the fish cage itself, all possible feeding and mooring components at surface would still have to face direct loads from waves. This will put a lot of stress on all mooring lines, cables, fastenings and feeding hoses. Also, since many open ocean fish cages are not designed to submerge to depths of a few tens of meters, they would still face heavy loads in extreme wave conditions.

8

The Atlantic cod

The subject of loads from currents and waves is not only a study of the cages themselves, but also involves taking into account the fish inside them. However, this subject is clouded with a number uncertainties, especially for the Atlantic cod. Further research on the matter is planned, but results so far are scarce and inconclusive. However, some information is available and assumptions can be made regarding several factors of importance.

Although concrete knowledge of the behavior and resistance of Atlantic cod inside ocean cages subject to large environmental loads is scarce, assumptions are often provided, and speculations made. A few are now listed:

- Even if a cage can withstand extreme load conditions, the fish inside it may not [5].

- Large relative motion of cage compared to the fish inside it may result in large descaling of fish [5].

- Feeding of the Atlantic cod must take place regularly, for example because of high risk of cannibalism if fish in a cage grows at un-even rate [1]. A suggested frequency of every other day at least has been made when the fish exceeds 500 grams [39, p.18].

- The aspects of water quality, pollution, biofouling of nets and disease in fish are generally favorable for open ocean aquaculture compared to culture in sheltered, nearshore sites, thereby resulting in better general fish health [5, p.154]. However, environmental conditions are tougher.

The question is: Can the Atlantic cod survive in cages under high loads and times of low or no food-intake?

8.1 Effects on the Atlantic cod

The subject of high level stress and its effects on caged cod hasn't received much attention in the literature, thereby increasing all uncertainties in that relation. For the Atlantic salmon, a large growth reduction has been related to acute stress over a certain period of time [40]. The issue of stress on the Atlantic cod in general has been researched, especially in relation to reproduction capabilities [41]. It has been stated that on the whole, the Atlantic cod shows resilience to stress. However, it also appears that the effects of stress is cumulative in fish so that long-term low-level stress will create long-term difficulties for it during spawning. When fish is stressed the probability of a high ratio of deformed offsprings increases [41].

An open ocean fish cage is designed for harsh conditions of strong external loads from various sources. The cage should be designed in such a way that relative motion compared to the fish inside is as small as possible. In order to do so, the cage should move to some degree with the the water. By doing so, the cage will experience harmonic motion and possible resonant oscillations [16]. The cage will face irregular ocean currents and effects of unsteady wave motion. Forces are exerted on the cage and the fish inside. The combined effects of all this for different scenarios of storms and ocean movement is largely unknown for the Atlantic cod.

Indications are that the Atlantic cod does not favor swimming against currents. It has been found that in the wild it moves with currents and uses them for transport during its shoreward feeding migration during its spawning season [42]. Also it has been speculated that the cod should be kept in conditions where the steady current speed is below 0.2 m/s, and that a few days must go by before the fish recovers and regains full acceptance for food after heavy cage movements during strong weathers [43]. Finally, it is known that cod fingerlings are very vulnerable to strong currents and heavy water movements [1, p.23], and small cods seem to face high mortalities when they encounter resistance, for example in towing in nets [43].

The Atlantic cod is sensitive to strong currents and should be protected from them as much as possible, especially during its smolt and fingerling stages of growth (weight less than 500 grams) [43]. The cod is a weak swimmer in the sense that it prefers to move with currents rather than swim against them [42]. Recommendations have been made about its feeding [39], and special considerations have to be made regarding its early sexual maturity [39].

Table 8.1 is a proposal for considerations regarding the Atlantic cod in an open ocean aquaculture.

Table 8.1: Suggested considerations for the aquaculture of the Atlantic cod in an open ocean environment.

Aspect	Considerations
Feeding	For bigger fish; at summer any day or every other day. At winter about three times a week. For smolt and fingerlings; once or more often every day.
Sexual maturity	Delay as much as possible, for example by using special light-manipulation methods.
Currents	Cod seems to drift with currents rather than swim against them. Full-grown cod not recommended in currents exceeding 0.2 m/s, and smolt and fingerlings should be sheltered to very little or almost no exposure to currents.
Cage design	Cage should show minimum relative movement compared to fish inside. Tradeoffs exist between that and oscillations of the cage because of wave loadings, with seemingly unknown effects on the fish.

9

Conclusions

A few speculations have already been made in the preceding discussion which indicate that a year-round offshore aquaculture south of Iceland could face a large number of difficulties unless some special considerations are made. An overview of that discussion will now be provided, and additions to it made.

9.1 Environmental conditions and offshore cages

Waves south of Iceland reach significant wave heights for one hour measurements of over 17 m. This is far beyond the recommendations made for any available fish cage today, and even higher than any design ideas for which information is readily available today. For some cages it is claimed that up to 15 m wave heights are allowed. For offshore aquaculture, maximum significant wave height values of about 9-12 m are used in design of mooring systems and in force analyses, even though the maximum significant wave heights only measure about 5 m.

The ratio of waves south of Iceland that actually exceed for example 12 m is very small. Outside the period December-February, the waves, on the average, show quick reduction in height, indicating that for most part, the wave climate is by or under the design criteria for cages that are offered today, or are on experimental stage. To count for this, two methods are proposed:

- Operate an aquaculture operation outside the season of the most extreme wave heights, if possible.
- Make some arrangements during the season of the most extreme wave heights, for example by towing the cages into temporary shelter, or submersing them significantly.

An estimation of forces gives a little different picture. It is found that a cage in an open ocean wave and current climate (H = 16.3 m, T = 10.3 m/s, U = 1 m/s), submerged to about 51 m in water of depth 100 m, will face similar loads that a surface cage in a sheltered site wave climate experiences at surface (H = 3 m, T = 8 s, U = 0.1 m/s). Possibly this could mean that the design considerations for sheltered site surface cages, in respect to loads and general force conditions, could be used for designs of cages which have to endure extreme wave and current conditions, given that they can be submerged enough.

However, the point is repeated here that no cages exist or are being designed to account for a wave climate like the one south of Iceland. If an open ocean aquaculture were to take place there, some steps need to be taken for the season of highest waves and harshest weathers.

9.2 Currents

Many factors are important as well, when excluding the cages themselves. If currents reach velocities of 1 m/s, and reduce only to about 70% of their original value inside the cage, or to about 0.7-0.8 m/s, it is clear that they, and even half of them, exceed informal recommendations for caged Atlantic cod. Those recommendations are in the range 0.1-0.2 m/s. This, besides the effects of oscillations of cages and loading effects due to waves, could have significant impact on the cods acceptance to food, and reduce its growing rate considerably. However, it may well be possible that enough submergence can reduce this problem considerably. Current velocities reduce rapidly with submersion.

9.3 General conclusion

In general, more factors are against the feasibility of an open ocean aquaculture of the Atlantic cod south of Iceland, than are with it. Environmental loads are high and uncertainties regarding a number of important aspects are many. The favorable factors, like ocean temperature, rapid water regeneration and general interest, are not considered to weigh fully against the opposing ones.

It is clear that if for example an experimental installation of a cage or cage system is to be made, many special arrangements have to follow because of the large number of uncertain aspects. Many cages exist for harsh conditions, and designs are being made for even harsher ones, but the annual wave conditions that occur south of Iceland seem to be above all recommendations for any cage available today. Counteractions could be made, for example in regard to submersion of the cages, but those might result in increased costs for both the cages and the product itself—the fish.

Present technology and available information indicate that full-scale, year round aquaculture of Atlantic cod south of Iceland is, in the sense of environmental loads, probably not a feasible option. Present and proposed cages have yet to show that they can reduce or resist the large forces that result from the waves and currents south of Iceland. Also, a number of other factors seem to be unfavorable for aquaculture in the area under consideration. However, open ocean fish cages are being designed so they can be deployed in tougher and tougher environments. Whether or not they will ever meet the demands which the ocean south of Iceland makes will not be answered here.

Appendix A

Appendixes

A.1 Wave data values

The tables in this section show the number of waves measured with certain heights and certain periods.

T_z [s] H_s [m]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0.0 - 0.5	0	0	0	424	1071	711	632	289	47	3	1	1	2	0	0
0.5 - 1.0	0	0	0	1002	3216	3922	2967	1709	666	157	67	78	63	37	19
1.0 - 1.5	0	0	5	559	1947	4273	3937	2377	1017	305	151	97	53	22	17
1.5 - 2.0	0	0	0	240	839	2772	3401	2558	1121	500	190	32	3	1	1
2.0 - 2.5	0	0	0	133	224	1492	3030	2533	1235	489	183	44	4	3	0
2.5 - 3.0	0	0	0	98	121	587	2077	2414	1318	484	176	61	2	0	0
3.0 - 3.5	0	0	1	77	101	153	1141	1890	1272	471	149	72	17	1	1
3.5 - 4.0	0	0	0	58	56	82	484	1465	1080	482	143	62	26	5	0
4.0 - 4.5	0	0	3	32	40	33	154	863	877	466	116	29	22	5	0
4.5 - 5.0	0	0	0	16	16	14	47	357	665	405	125	33	7	10	3
5.0 - 5.5	0	0	0	0	8	9	15	168	374	335	106	22	12	3	1
5.5 - 6.0	0	0	0	0	5	5	7	40	231	258	103	17	8	7	2
6.0 - 6.5	0	0	0	1	4	1	5	30	102	174	119	28	9	0	1
6.5 - 7.0	0	0	0	0	1	0	1	6	61	120	98	28	5	1	0
7.0 - 7.5	0	0	0	0	0	0	3	9	24	91	76	33	3	3	2
7.5 - 8.0	0	0	0	1	0	0	0	9	13	32	75	23	3	2	0
8.0 - 8.5	0	0	0	0	0	0	2	4	5	15	39	21	5	1	0
8.5 - 9.0	0	0	0	0	0	0	0	12	6	16	21	12	0	1	0
9.0 - 9.5	0	0	0	0	0	0	0	3	7	8	12	8	3	0	0
9.5 - 10.0	0	0	0	0	0	0	0	1	2	4	6	8	1	0	0
10. - 10.5	0	0	0	0	0	0	0	1	2	1	2	5	2	0	0
10.5 - 11.0	0	0	0	0	0	0	0	1	2	1	3	6	4	0	0
11.0 - 11.5	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
11.5 - 12.0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
12.0 - 12.5	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
12.5 - 13.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13.0 - 13.5	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
13.5 - 14.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14.0 - 14.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14.5 - 15.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15.0 - 15.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15.5 - 16.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16.0 - 16.5	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
16.5 - 17.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A.1: Wave measurements made by Grindavík, south of the Reykjanes-peninsula, from December 1994 until April 2004.

T_z [s] H_s [m]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0.0 - 0.5	0	0	0	74	163	109	84	32	24	31	23	23	14	10	17
0.5 - 1.0	0	0	0	83	1638	2274	909	149	36	19	15	10	7	8	6
1.0 - 1.5	0	0	0	33	2324	4455	3235	947	139	42	9	12	4	5	6
1.5 - 2.0	0	0	0	1	1077	4815	4150	1910	398	103	22	10	5	7	3
2.0 - 2.5	0	0	0	0	137	2966	3783	2252	681	165	34	12	9	5	3
2.5 - 3.0	0	0	0	0	4	1034	3240	2567	1044	243	53	15	12	6	4
3.0 - 3.5	0	0	0	0	0	161	2104	2464	1305	334	74	10	2	4	5
3.5 - 4.0	0	0	0	1	0	11	1052	1962	1283	481	73	16	3	5	7
4.0 - 4.5	0	0	0	0	0	1	318	1459	1287	523	100	18	6	5	7
4.5 - 5.0	0	0	0	0	0	1	60	936	1014	540	123	24	7	3	1
5.0 - 5.5	0	0	0	0	0	0	29	364	807	479	167	41	11	3	0
5.5 - 6.0	0	0	0	1	0	0	11	125	501	504	150	49	14	4	2
6.0 - 6.5	0	0	0	0	0	0	8	35	288	397	157	29	11	2	1
6.5 - 7.0	0	0	0	0	0	0	1	13	132	294	136	30	5	7	2
7.0 - 7.5	0	0	0	0	0	0	0	8	50	227	125	35	7	7	6
7.5 - 8.0	0	0	0	0	0	0	0	1	13	131	151	39	16	7	1
8.0 - 8.5	0	0	0	0	0	0	0	0	4	50	133	70	13	0	0
8.5 - 9.0	0	0	0	0	0	0	1	0	3	23	76	46	8	3	0
9.0 - 9.5	0	0	0	0	0	0	0	0	1	5	50	32	12	3	0
9.5 - 10.0	0	0	0	0	0	0	0	0	0	1	15	32	1	2	0
10.0 - 10.5	0	0	0	0	0	0	0	0	0	1	5	15	6	0	0
10.5 - 11.0	0	0	0	0	0	0	0	0	0	0	1	12	2	1	1
11.0 - 11.5	0	0	0	0	0	0	0	0	0	0	0	10	3	0	0
11.5 - 12.0	0	0	0	0	0	0	0	0	0	0	0	2	4	0	1
12.0 - 12.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12.5 - 13.0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
13.0 - 13.5	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
13.5 - 14.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14.0 - 14.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14.5 - 15.0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
15.0 - 15.5	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
15.5 - 16.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16.0 - 16.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16.5 - 17.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17.0 - 17.5	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
17.5 - 18.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A.2: Wave measurements made by Surtsey in Vestman Islands, south of Iceland, from January 1994 until April 2004.

T_z [s] H_s [m]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0.0 - 0.5	0	0	0	264	596	569	234	63	10	11	8	9	11	6	5
0.5 - 1.0	0	0	0	904	4448	3730	2060	758	155	38	16	15	7	5	6
1.0 - 1.5	0	0	0	185	4993	5088	3178	1362	332	84	21	9	8	2	3
1.5 - 2.0	0	0	0	0	2443	5064	3516	1870	697	185	43	8	3	2	3
2.0 - 2.5	0	0	0	0	269	3720	3439	2123	855	262	83	16	2	0	0
2.5 - 3.0	0	0	0	0	17	1318	2478	2047	867	273	38	3	2	0	0
3.0 - 3.5	0	0	0	1	3	224	1409	1650	1031	351	66	9	1	1	2
3.5 - 4.0	0	0	0	1	1	29	489	1296	901	403	99	6	2	0	0
4.0 - 4.5	0	0	0	0	0	4	111	786	803	416	131	23	5	0	0
4.5 - 5.0	0	0	0	0	0	10	36	339	687	328	131	19	4	0	1
5.0 - 5.5	0	0	0	0	1	4	14	131	548	332	92	26	8	1	0
5.5 - 6.0	0	0	0	0	0	0	4	32	298	292	84	19	5	0	0
6.0 - 6.5	0	0	0	0	1	0	3	9	175	261	74	15	10	2	0
6.5 - 7.0	0	0	0	0	0	2	3	6	81	227	84	13	1	1	0
7.0 - 7.5	0	0	0	0	0	1	2	8	20	180	94	26	3	2	1
7.5 - 8.0	0	0	0	0	0	1	3	2	9	112	80	20	4	0	0
8.0 - 8.5	0	0	0	0	0	0	1	3	3	49	69	33	2	1	2
8.5 - 9.0	0	0	0	0	0	0	0	0	2	25	61	17	7	1	1
9.0 - 9.5	0	0	0	0	0	0	0	1	3	13	51	18	4	1	1
9.5 - 10.0	0	0	0	0	0	0	0	0	2	8	34	22	5	2	0
10.0 - 10.5	0	0	0	0	0	1	0	0	1	4	15	21	5	1	1
10.5 - 11.0	0	0	0	0	0	0	0	0	1	6	9	22	8	2	0
11.0 - 11.5	0	0	0	0	0	0	0	0	0	2	4	8	5	2	0
11.5 - 12.0	0	0	0	0	0	0	0	0	0	1	3	9	3	3	0
12.0 - 12.5	0	0	0	0	0	0	1	0	0	0	1	4	2	2	0
12.5 - 13.0	0	0	0	0	0	0	0	0	0	1	0	1	2	0	0
13.0 - 13.5	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0
13.5 - 14.0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	1
14.0 - 14.5	0	0	0	0	0	0	1	0	0	0	0	0	3	0	0
14.5 - 15.0	0	0	0	0	0	0	2	0	0	0	0	0	2	0	0
15.0 - 15.5	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0
15.5 - 16.0	0	0	0	0	0	0	0	1	0	0	0	0	2	3	0
16.0 - 16.5	0	0	0	0	0	0	0	0	0	0	0	1	0	1	2
16.5 - 17.0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	4
17.0 - 17.5	0	0	0	0	0	0	0	0	0	0	0	0	0	1	5
17.5 - 18.0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
18.0 - 18.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
18.5 - 19.0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0
19.0 - 19.5	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0
19.5 - 20.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20.0 - 20.5	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
20.5 - 21.0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
21.0 - 21.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21.5 - 22.0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
22.0 - 22.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22.5 - 23.0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0
23.0 - 23.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23.5 - 24.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.0 - 24.5	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0
24.5 - 25.0	0	0	0	0	0	0	1	2	1	1	0	0	0	0	0

Table A.3: Wave measurements made by Garðskagaviti, east of the Reykjanes-peninsula, from February 1994 until April 2004.

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