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ENVIRONMENTAL DESCRIPTION IN THE DESIGN OF FISH FARMS AT EXPOSED LOCATIONS

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ABSTRACT

This paper addresses the description of exposure from waves and currents in coastal regions for design of marine fish farms. Representative descriptions of environmental conditions are important inputs to the design and dimensioning of reliable fish farm structures. A trend with moving production to more exposed sites and introduction of new and novel fish farm structures increase the need for more precise descriptions of the marine environment to keep control of uncertainties in design. Dedicated field measurements at two exposed aquaculture sites from February to December 2016 are presented. Results from statistical analyses of the measurement data demonstrate that common practice for characterization of exposure in design of fish farms has several deficiencies that should be improved to reduce uncertainties in design.

INTRODUCTION

Farming of Atlantic salmon has become a large industry in Norway, with annual production reaching 1.3 million metric tons in 2015 (ssb.no). The on-growth stage in sea is performed in floating gravity cages. These are flexible net-based structures anchored to the seabed at a given site. A large industry scale fish farm may consist of 15 cages and be more than 1 km of length. Each cage may contain up to 200 000 fish distributed over an un-deformed cage volume of 40 000 m3. Fish escapes due to structural or operational failure has been one of the main challenges for sustainable production and considered a threat to the wild salmon due to possible genetic pollution from crossbreeding. This motivated the development of a technical standard for the design and operation of marine fish farms, NS 9415 [1], that was first introduced in 2003. Implementation of this standard has resulted in a decrease in numbers of reported fish escapes from Norwegian fish farms, due to more reliable structures and systems. However, the problem of fish escapes is still not solved.

Moving production to more exposed sites, motivated by more favourable water quality and conditions for production, put higher demands on the structure to avoid fish escape and to ensure safe and healthy working conditions for personnel. Representative descriptions of environment conditions are important for the design and dimensioning of reliable marine fish farms. Challenges introduced by moving salmon aquaculture in Norway to more exposed locations is not only a matter of survivability of the structure, it is also a matter of being able to perform the necessary operations associated with the production, that is, to find

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sufficient weather windows [2]. Daily operations involve feeding, removal of dead fish, inspections and control of structural integrity. Other frequent operations are cleaning of net cages from biofouling, treatment of fish against sea lice. Further, some operations imply that large vessels connect to the farm structure. Examples are fish transportation by wellboat, feed supplies by bulk carriers, cleaning operations with dedicated service vessels. The various operations have different requirements to weather windows, depending on the complexity and potential consequence of failure of the operation. One risk factor is associated with the health and safety of the personnel, suggesting limits for the wave induced accelerations and relative motions of the working platform and equipment [3]. Another risk factor is associated with the fish health and welfare. Some operations, like harvesting, require the cage volume to be reduced. Increasing the stocking density by controlled cage volume reduction can be critical for the fish. If the stocking density become too high, the fish health and welfare can be affected by induced stress, while lack of oxygen can lead to increased mortality. Uncontrolled reduction of the cage volume can occur when the cage is subjected to strong currents. The current speed itself can also make the fish stressed, as the fish will have to swim faster and spend more energy to avoid contact with the net enclosure and other fishes [4].

Fish-farm structures for exposed locations should not only be designed to survive and withstand the physical loading from wind, waves and current at the site, the seakeeping characteristics of the structure should also be designed to allow for sufficient weather windows for safe operation in the given environment conditions. One design method gaining interest in design of fish-farms for exposed locations is limit state design. Use of limit state design in aquaculture requires extended definitions of exposure and more detailed description of environmental parameters. The limit states are typically separated into ultimate limit states (ULS), fatigue limit states (FLS), accident limit states (ALS) and serviceability limit states (SLS) [5]. Hence, there is a need for a detailed description of the physical environment at the site to be used as input in structural design of the fish farm. Site surveys are required before a fish farm can be installed a given site. This includes measurement campaigns of waves and current to obtain the dimensioning conditions. Requirements for how to perform such site surveys are given in NS 9415:2009 [1], however, the approach described has several deficiencies that can lead to insufficient and unreliable descriptions of the physical environment.

This paper addresses the description of exposure from waves and current to be used in design of fish farms for Atlantic salmon. The paper is organized as follows. After the introduction, state-of-the-art characterization of exposure at Norwegian fish farm sites are described, before a new and dedicated field measurement campaign is presented. Statistical treatment of the measurement data and the implications of results for design of fish farms are discussed.

EXPOSURE AT NORWEGIAN FISH FARMS

Norwegian fish farms are typically located at near-shore locations, more or less sheltered from the open ocean. However, tidal currents and local effects of bathymetry often yields complex conditions for waves and currents at the site. According to the Norwegian standard NS 9415:2009 [1], the degree of exposure for a given site should be surveyed and the results of the survey should be used as input in design and dimensioning of the fish farm. The standard focuses on four components of exposure that should be documented in the site survey. Those are current velocity, waves, wind and ice/icing. The main focus in the characterization and quantification of these components is the implications for survivability of the fish farm.

Exposure According To NS 9415:2009

Traditionally, the characterization of wave exposure at Norwegian fish farms has been based on a coarse range distribution of significant wave heights H_s and peak wave periods T_p. A similar classification exist to describe exposure from current at the site. This classification of wave- and current exposure does not provide a sufficient description of the physical environment for design of reliable fish farm structures. The probability of occurrence of the physical conditions is important in design analysis of fatigue damage, serviceability and operability.

Waves are separated into swell, wind-generated waves, ship generated waves and wave-scatter due to nearby topography. Hence, wave conditions at near-shore aquaculture sites can be quite complex. There can also be large spatial variations at the site, causing different exposure at different parts of the structure.

There are several physical effects causing currents at near-shore sites. Relevant current components that should be considered in site surveys are tidal current, wind-driven surface currents, outbreak from the coastal current and spring flood due to ice- and snow melting [1]. In practice, it is difficult to separate the various components of currents from field measurements only, although some reasoning can be made by analysing the frequency spectrum of the measurement data and correlations between measurements of current profile and wind.

FIELD MEASUREMENTS AT TWO NORWEGIAN FISH FARMS

Physical conditions of waves, wind and current at coastal and near-shore locations for salmon farming can be significantly different from conditions offshore. Small islands, reefs and local bathymetry affect the local wave conditions at near-shore sites through refraction, diffraction and scatter effects, which can make the wave conditions vary considerably within the site. Local bathymetry is also important for the current conditions, where tidal currents typically are more pronounced than for the open ocean where the coastal current dominates. In this section, the results from a field measurement campaign with aim to describe physical conditions of waves currents and wind at possible future exposed salmon sites are presented.

Measurement campaign

Two exposed locations, Munkskjæra and Salatskjæra, have been monitored with wave, wind and current measurements since February 2016. Measurements are still ongoing by December 2016. Both locations are outside the island of Frøya in Central Norway, see Figs. 1-3. Oceanographic buoys of type SEAWATCH Midi 185 Buoy by Fugro OCEANOR were installed at the two sites. The buoys are equipped with sensors to measure current velocity profile, directional waves and wind. A number of additional quantities such as temperature and salinity are also measured. Current measurements are made with an acoustic profiler (ADCP) of type Nortek Aquadopp 400kHz, where the current speed and direction are measured at 20 different depth levels. The speed range of measurement is 0 - 300 cm/s discretized by 256 points, yielding an accuracy of 1.2 cm/s. Current measurement is performed with sample rate 1 Hz, and 1024 samples is taken to obtain 17 min time averaged values of current speed and direction, which is sufficient to obtain reliable mean current velocities in tidal currents and large eddy currents [6].

Directional waves are measured with FOAS Wavesense 3m in terms of wave elevation, wave period and wave propagation direction. Based on measurement sequence of 17 min duration per hour, corresponding to 2048 samples and 2 Hz sample rate, wave parameters like significant wave height, maximum wave height and zero crossing period are calculated. According to [7], this is a common approach. All measurements are logged once every clock hour to limit the power consumption of the buoy, which is mainly due to data transfer to shore.

The Munkskjæra site (63.82227 N, 8.38422 E) is located west of the island Sula (Fig. 1). The bathymetry map (Fig. 2) suggests an apparent strong exposure of waves coming from the open sea to the West/South-West, but also wind-generated waves coming from the East due to long fetch. The main direction of current is expected to be aligned with an East-West axis. The water depth at the site is about 80 m.

The Salatskjæra site (63.91995 N, 8.59277 E) is located north of Mausund (Fig. 1), in a remote area of quite complex bathymetry (Fig. 3). The area is characterized by myriads of underwater rocks and skerries, likely to provide shelter from ocean waves, but not from wind exposure. The water depth at the buoy location is about 40 m.

Current

Current measurements obtained from February 2016 (Munkskjæra) and March 2016 (Salatskjæra) to January 2017 (both sites) are analyzed in the following. Distribution of the measured current speed and directions (“going to”) at depth level 4 m for the two sites are plotted in polar diagram in Figs. 4 and 5, showing that directional current at the Munkskjæra site is mainly aligned with the East-West axis, while that for the Salatskjæra site is mainly aligned with the North-South axis. The strongest current was measured at the Munkskjæra site, where the largest value recorded was 63 cm/s at depth level 4 m on September 3rd. The highest current speed at the Salatskjæra site was 54 cm/s at

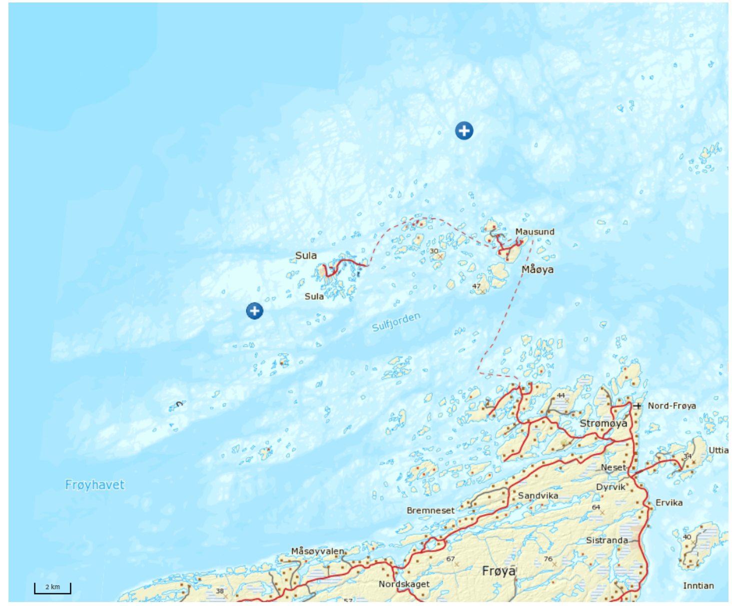

FIGURE 1: MAP OF THE TWO MEASURING SITES, MUNKSKJÆRA (LOWER LEFT) AND SALATSKJÆRA (UPPER RIGHT), OFF THE ISLAND FRØYA IN TRØNDELAG, NORWAY.

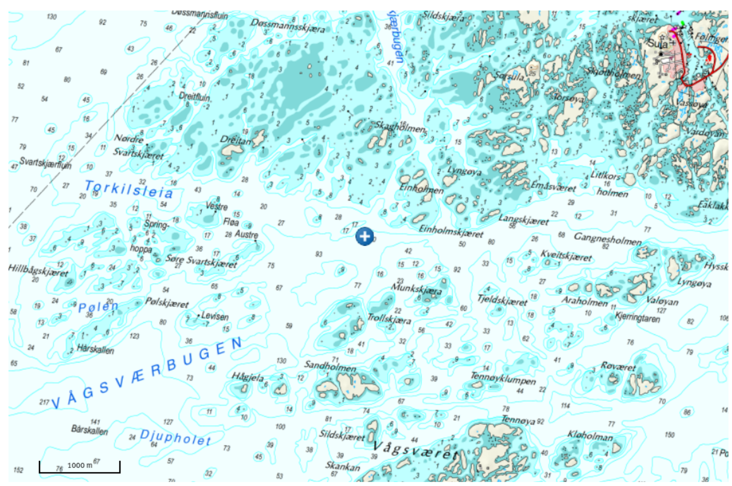

FIGURE 2: BATHYMETRY AT MUNKSKJÆRA.

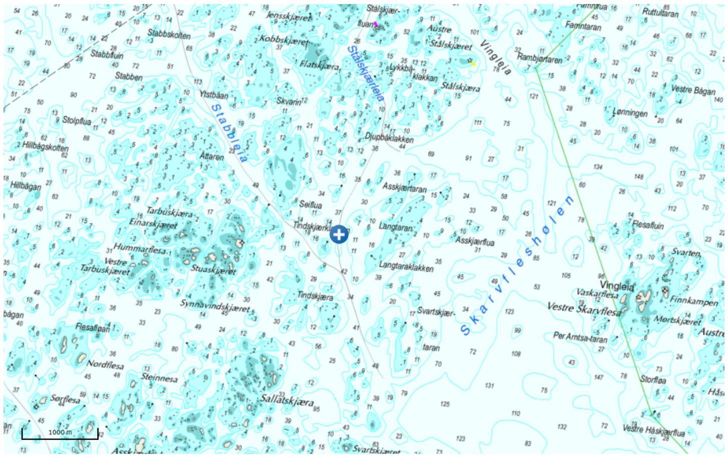

FIGURE 3: BATHYMETRY AT SALATSKJÆRA.

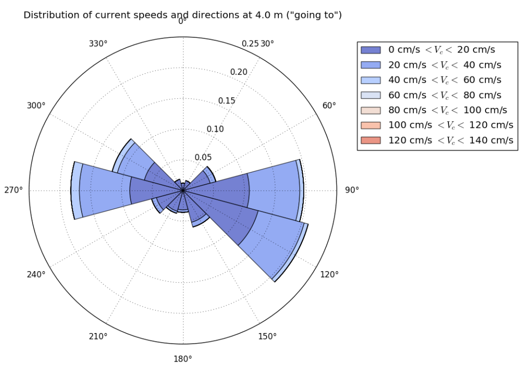

FIGURE 4: CURRENT DISTRIBUTION AT MUNKSKJÆRA.

depth level 4 m measured on August 2nd.

The depth of floating aquaculture net-cages used in salmon farming are typically around 30 m, and the current velocity at typical salmon sites is likely to vary over the depth. Due to this, the current speed at various depths should be considered in the design and dimensioning of such structures. In the standard NS 9415 [1], the current speed at depths 5 m, 15 m and 20 m are suggested as a minimum to describe the current profile. The present measurements are taken at 20 depth levels ranging from 4 m with increment of 3 m. The flow direction for the strongest current events at Munkskjæra appear to be rather uniform with depth, either going to the East or to the West. However, some of the current profiles are characterized by significant shear.

According to NS 9415 [1], extreme values of the current speed corresponding to 10 years and 50 years return period should be used in design of fish farms and suggests at least 1 month measurements to obtain these values. However, the standard does not describe statistical treatment of measurement data to obtain these extreme values. Hence, basic distributions for calculation of extreme values are applied and fitted to the empirical distribution of the measured current speeds from February to December 2016. As the highest current speeds were measured at the top of the water column, we consider the measured time-series of the current speed at depth level 4 m in the following. The three-parameter Generalized Extreme Value (GEV) distribution, which has the cumulative distribution

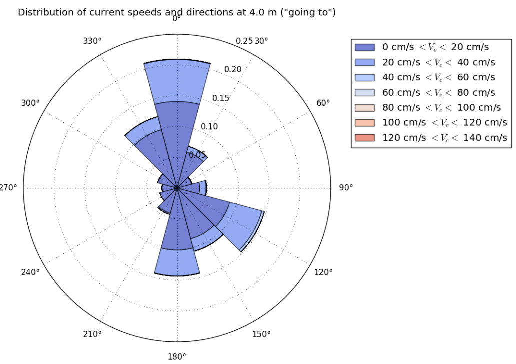

FIGURE 5: CURRENT DISTRIBUTION AT SALATSKJÆRA.

$$F_u(x;\mu,\sigma,\xi) = \exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\xi}\right\} \qquad (1)$$

was fitted to the empirical data, where the location parameter (μ), the scale parameter (σ) and the shape parameter (ξ) are determined by maximizing a log-likelihood function [8]. However, the fitted GEV distribution deviates from the empirical distribution at the tail and may seem to give very conservative estimates of the 10 years and 50 years current maxima (Fig. 6). Parametric bootstrapping [9] was applied to estimate the uncertainty at the tail of the fitted distribution, by performing 100 replications with 100 random samples drawn from the fitted distribution. The resulting uncertainty of the predicted maxima is shown in Fig. 6 in terms of 95% confidence interval, calculated according to the Student-t confidence limits [9].

To better capture the trend of the tail of the empirical distribution, the Generalized Pareto Distribution (GPD) was applied, which has the cumulative distribution function

$$F_\xi(x) = \begin{cases} 1-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\xi} & \text{for } \xi \neq 0 \\ 1-\exp\left\{-\frac{x-\mu}{\sigma}\right\} & \text{for } \xi = 0 \end{cases} \qquad (2)$$

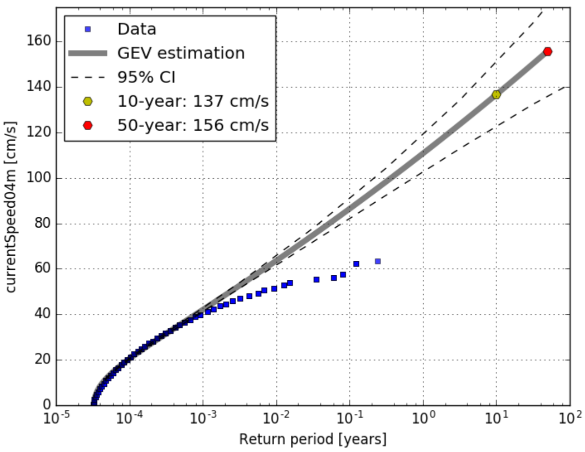

FIGURE 6: PROBABILITY OF EXCEEDANCE BY GEV FIT OF MEASURED CURRENT SPEEDS AT DEPTH 4 M FROM FEB. TO DEC. FOR THE MUNKSKJÆRA SITE.

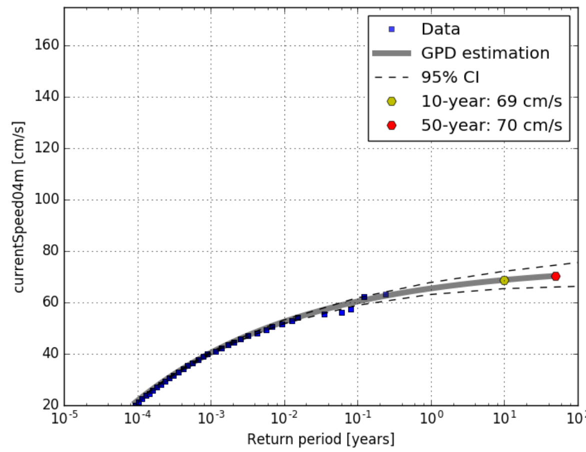

FIGURE 7: PROBABILITY OF EXCEEDANCE BY GPD FIT OF MEASURED CURRENT SPEEDS AT DEPTH 4 M FROM FEB. TO DEC. FOR THE MUNKSKJÆRA SITE.

TABLE 1: ESTIMATED 50-YEARS RETURN LEVEL OF CURRENT SPEED [cm/s] BASED ON MEASUREMENT DATA FROM A SINGLE MONTH.

		$U_{max} \times 1.85$	GEV	GPD
Munkskjæra	March	89	85	78
	August	117	234	86
Sallatskjæra	March	67	61	42
	August	93	129	60

The location parameter (μ), the shape (ξ) and the scale parameter (σ) are determined by maximizing a log-likelihood function [8], considering only the maxima exceeding the threshold value here taken as 20 cm/s. Then, only the samples over a given threshold value is considered. Although the GPD fit seems to follow the tail of the measured data, the estimates of 10 years and 50 years current maxima might be non-conservative (Fig. 7). Further, the fit of the distribution was found to be sensitive to the choice of threshold value. Similar as for the GEV fit, parametric bootstrapping was applied to give estimates of the uncertainty. Based on the fitted GEV and GPD distributions to specific months of the data-set, return levels of the maximum current speed corresponding to 50-years return period were computed, which are presented in Tab. 1. The obtained return levels of the maximum current speed are sensitive to the choice of month considered, as well as on the choice of distribution used for the extrapolation.

To see how the temporal variations of the current is distributed over frequencies, the Fast Fourier Transform (FFT) of the measured time series are computed for given depth levels. The obtained frequency spectra clearly indicate strong components of tidal currents. Main tidal current frequencies are associated with the semidiurnal and diurnal periods, which are 6 hrs 13 min and 12 hrs 25 min, respectively, while Fourier amplitudes with frequencies corresponding to the lunar month (29.5 days) are also observed to matter. The lunar month is the time it takes for the Moon to revolve around the Earth with respect to the Sun.

Waves

Wave measurements from the same period as above are analysed for both sites. The directional distribution of the significant wave height at the two sites are shown in Figs. 8 and 9. As expected from the maps in Figs. 2 and 3, the main wave directions are aligned in the East-West direction at Munkskjæra, while most of the waves come from North and East at Salatskjæra.

The largest significant wave height measured at Salatskjæra was 2.0 m on December 31th, 2016, while 3.5 m was measure at Munkskjæra on December 26th, 2016. In the design of marine structures it is often beneficial with more robust estimates of the expected wave heights at a site, than what is obtained using sample maxima. Extreme value distributions are usually fitted to the measurements of the significant wave height in order to obtain estimates corresponding to return periods of for instance 1 year and 50 years. There are no guidelines for statistical treatment of wave measurements in NS 9415:2009 [1]. However, DNV-RP-C205 [6] recommends various methods for long term statistical

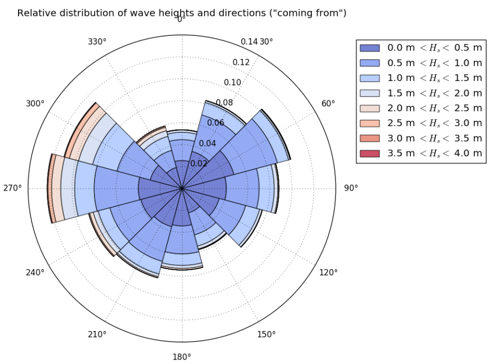

FIGURE 8: DIRECTIONAL DISTRIBUTION OF SIGNIFICANT WAVE HEIGHT AT MUNKSKJÆRA.

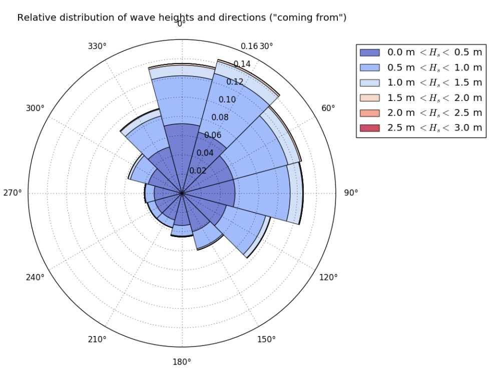

FIGURE 9: DIRECTIONAL DISTRIBUTION OF SIGNIFICANT WAVE HEIGHT AT SALATSKJÆRA.

analysis of wave measurements. A 3-parameter Weibull distribution may be used as marginal distribution for the significant wave height H_s

$$F_{H_s}(h) = 1 - \exp\left[-\left(\frac{h-\gamma}{\alpha}\right)^{\beta}\right], \qquad (3)$$

where γ, α and β are location, scale and shape parameters, respectively. Figure 10 shows a fitted marginal distribution of the significant wave height at Munkskjæra. The 95 % confidence band has been estimated using parametric bootstrapping (see e.g. [9]). Figures 10 and 11 show that the significant wave height correnponding to a 1 year return period is estimated to be slightly large than the sample maximum for Munkskjæra and slightly lower at Salatskjæra. More interesting is the statistical uncertainty in the estimates.

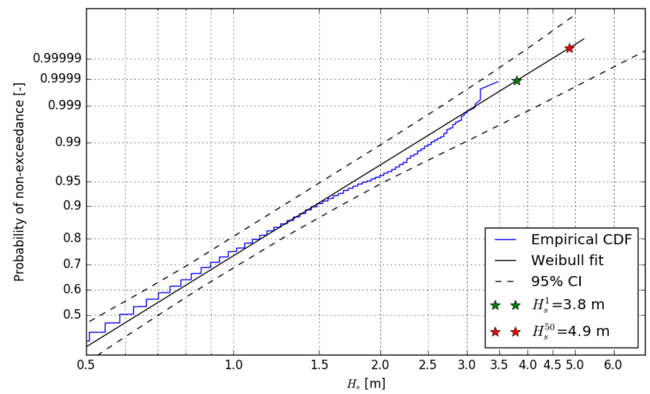

FIGURE 10: CUMULATIVE DISTRIBUTION OF SIGNIFICANT WAVE HEIGHT AT MUNKSKJÆRA, WEIBULL FIT AND 95 % CONFIDENCE BAND.

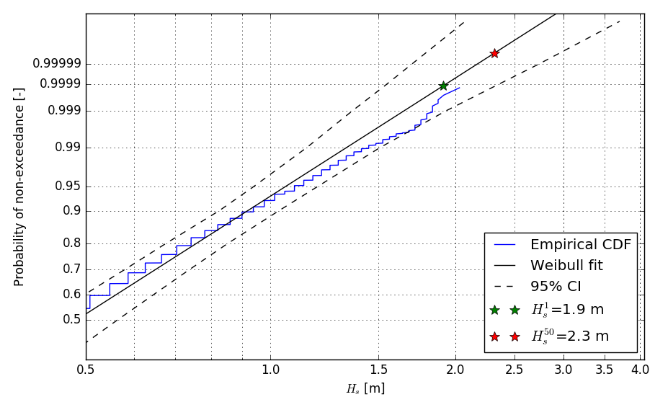

FIGURE 11: CUMULATIVE DISTRIBUTION OF SIGNIFICANT WAVE HEIGHT AT SALATSKJÆRA, WEIBULL FIT AND 95 % CONFIDENCE BAND.

For structures sensitive to period and/or wave steepness, the zero crossing period T_z or the spectral peak period T_p should be taken into account. The distribution of wave heights and periods can be described by scatter tables, or by the environmental contour method. The latter is based on estimating a joint probability density function of H_s and T_z (or T_p)

$$f_{H_s,T_z}(h,t) = f_{H_s}(h) f_{T_z|H_s}(t|h), \qquad (4)$$

where $f_{H_s}(h)$ is the probability density function for significant wave height and $f_{T_z|H_s}(t|h)$ the conditional distribution of the zero crossing period given significant wave height. The method by Haver and Nyhus [10] was applied, using a lognormal distribution

$$f_{T_z|H_s}(t|h) = \frac{1}{\sigma t\sqrt{2\pi}} \exp\left[-\frac{(\ln t-\mu)^2}{2\sigma^2}\right], \tag{5}$$

where

$$\mu = \mathrm{E}(\ln T_z) = a_0 + a_1 h^{a_2} \tag{6}$$

$$\sigma^2 = \mathrm{Var}(\ln T_z) = b_0 + b_1 e^{-b_2 h^{b_3}} \tag{7}$$

and the coefficients a_i and b_i are fitted to the data. It was difficult to fit Eq. 7 to the data, and the following expression was applied instead

$$\sigma^2 = \mathrm{Var}(\ln T_z) = \frac{b_0}{hb_1\sqrt{2\pi}} \exp\left(-\frac{(\log h - b_2)^2}{2b_1^2}\right), \tag{8}$$

which is simply a scaled lognormal density function. The inverse first order reliability method (IFORM) can be applied to obtain contour lines for given return periods [11]. The joint distribution is then mapped into standard Gaussian variables, and the contour lines becomes circles of radius $\beta = -\Phi^{-1}\left(\frac{\tau}{365\cdot 24\cdot T_R}\right)$, where Φ is the cumulative Gaussian distribution function, τ is the sampling interval in hours and T_R is the return period in years. The contour line in H_s-T_z space is then found as $h_s = F_{H_s}^{-1}(\Phi(u_1))$ and $t_z = F_{T_z|H_s}^{-1}(\Phi(u_2))$, where u_1 and u_2 are points on the circle with radius $\beta = \sqrt{u_1^2+u_2^2}$. Figure 12 shows measured data from Munkskjæra and contour lines for return periods 1, 10 and 50 years. The modification of the model by Haver and Nyhus seems to fit reasonably well for higher wind driven sea states, but does not capture swell adequately (Fig. 12).

Figures 13 and 14 show the how often periods of duration of at least 12 hours with significant wave height less than some limiting value occur at both sites. Operations of duration up to 12 hours limited by a significant wave height of 0.5 m seems to be realistic to perform at both sites in the extended summer season, but not during winter time. At Salatskjæra one may expect long periods with significant wave height less then 1.5 m all year, while for Munkskjæra this can only be expected from May to October.

DISCUSSION

Measurements

Characterization of the physical environment at weather-exposed aquaculture sites by means of field measurements is a challenging task. Seasonal and spatial variations of the wave and current conditions at the site implies that the duration of the measurements as well as the location of the measurement buoy must be chosen carefully to obtain representative statistics for the site. The present study demonstrates that measurements with one month duration at a single location is not sufficient to obtain representative statistics of the wave and current conditions (cf. Tab. 1). Spatial variations is expected to be significant due to local bathymetry at the two sites considered. We are not confident that the actual location of the measurement buoys correspond to the location where the most extreme conditions occur. The spatial and also temporal variability at the site should be investigated numerically using oceanographic software tools, e.g. SINMOD [12]. To minimize uncertainty of measurements, mea-

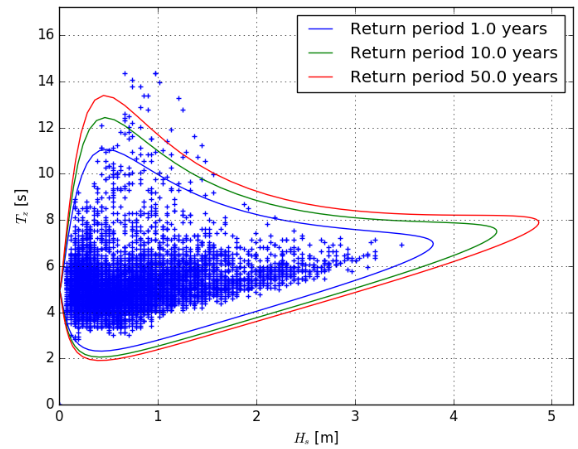

FIGURE 12: MEASURED WAVE DATA FROM MUNKSKJÆRA AND ESTIMATED CONTOUR LINES FOR VARIOUS RETURN PERIODS.

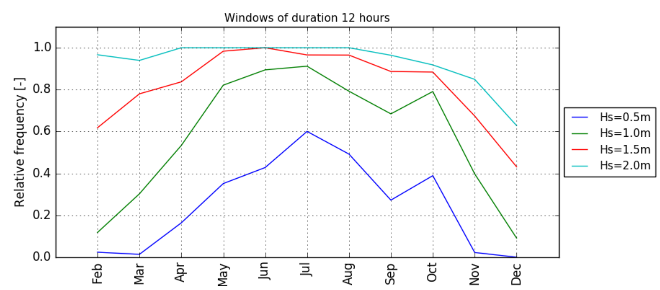

FIGURE 13: RELATIVE FREQUENCY OF CONTINUOUS TIME PERIODS OF DURATION MORE THAN 12 HOURS WITH SIGNIFICANT WAVE HEIGHT LOWER THAN VARIOUS THRESHOLDS AT MUNKSKJÆRA.

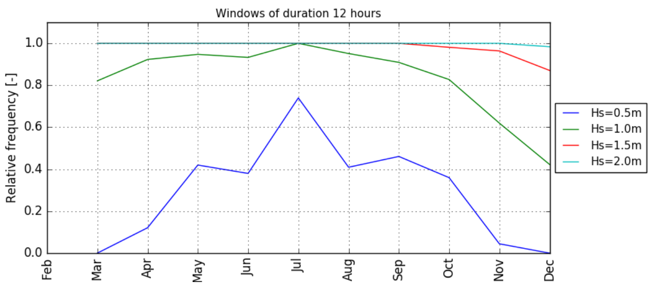

FIGURE 14: RELATIVE FREQUENCY OF CONTINUOUS TIME PERIODS OF DURATION MORE THAN 12 HOURS WITH SIGNIFICANT WAVE HEIGHT LOWER THAN VARIOUS THRESHOLDS AT SALATSKJÆRA.

surement buoys should be located where the spatial variations are expected to be small. Numerical simulations of the physical conditions at the site could then be used as decision support for location of the buoy.

Statistical analysis

Estimation of the dimensioning waves and current conditions rely on distribution of extreme values, i.e. the statistic behaviour of rare events. Hence, long time-series are needed to obtain representative statistics of the extremes. However, time-consuming measurement campaigns are impractical for the development of new aquaculture sites. This favour the use of numerical simulation tools to obtain the necessary long-term statistics. Significant components of current due to tidal effects at coastal sites complicates the estimation of dimensioning current speeds from measurement data, which is typically performed by extrapolation from probability distribution functions fitted to the measurement data. For GEV, the challenge remains to estimate the distribution parameters with very limited duration of data, relative to the 50 year time scale prediction. A key requirement of the GEV theory is that only one value (maximum) from each observation period (epoch) is used in the model. This is often an inefficient use of data set, which becomes particularly significant when historic data is limited. One modification of the GEV approach is to use a Peak-Over-Threshold (POT) method. This approach is based on GPD and makes use of each data point above a specified threshold. In this way, more information can be extracted from the limited data set, than when only the epoch maximum is used [8]. Present results shows that the GEV distribution does not follow the tail of the measurement data such that extrapolation at the tail becomes uncertain (Fig. 6). This could be due to the combination of harmonic components from tidal effects and components of more stochastic nature which makes the direct use of standard distribution functions like the GEV distribution inappropriate. The GPD distribution is found to provide better fit to the tail of the data (Fig. 7), but is sensitive to the choice of threshold. A further investigation of the different current components is needed to improve the estimates of the dimensioning current condition.

Design considerations

Relevant and prepresentative descriptions of the physical environment are important input to design of fisih farms. However, what is a relevant description of the physical environment depend on the design considerations in question. In limit state design, the structures performance at different limit states are controlled, where different limit states require different descriptions of the exposure.

Survivability Design against failure in critical components is discussed in NS 9415:2009 [1]. Typical net based fish cages are dominated by current forces. Hence, it is important with a reliable estimate of the dimensioning current speed as well as the resulting current forces on the net cage. A common practice is to perform current measurements for one month and then multiply the maximum current sample speed by 1.85 to obtain a current speed with a return period of 50 years, which is used in the design calculations. Based on the measurements presented above, it is obvious that the current practice gives large variations in design current speed, due to seasonal variations. As seen in Tab. 1, the 50 years design current speed at the Sallatskjæra site based on measurements from August is 39 % larger than if it is based on measurements from March. As current induced pressure forces in general are proportional to the current speed squared, an increase of 39 % in current speed will give an increase of 92 % in current induced force. This has direct consequences for instance for the dimensioning of the mooring system and may lead to either over dimensioned and costly mooring systems or under dimensioned systems, which may fail at lower sea states than expected. The estimates of the design current speed should be improved or the mentioned uncertainty should be accounted for in safety factors. However, current induced forces on flexible net-cage structures does not follow a quadratic relationship with the incident current speed as flexible deformations will reduce the projected area in the direction of the current and hence reduce the exposure [13]. On the other hand, flexible deformations of the net cages will cause a reduction of the cage volume, leading to an increase of the effective stocking density within the cage with possible negative consequences for the fish health and welfare. An interesting observation from the field measurements of current at the Sallatskjæra site is the events of extreme current going to the East, which is one of the directions with lowest frequency of occurranse for local current speed maxima, according to Fig. 5. This means that although the main directions of the current at the site is North and South, the other directions cannot be ruled out from a design and dimensioning point of view.

Wave loads are important for the dynamic response of today's fish cages and their mooring systems and will probably be even more important for feed barges and several novel types structures. More exposed locations will also bring larger waves and wave actions. As mentioned earlier, there is limited information about how to treat waves in NS 9415:2009 [1]. The standard largely relies on fetch analysis, which is a simplified and useful method to estimate wave height based on wind speed and fetch length, but with clear limitations [14], as the method is limited to wind driven waves and does not take bathymetry into account. As seen from Figs. 10 and 11 it was challenging to establish reasonable estimates for the 50 year return period of the significant wave height, mainly due to a short period of observation. The estimated confidence interval indicates that the uncertainty is rather large. As for current, this uncertainty is transferred into the response analysis and hence to the dimensioning of components in the fish farm.

There are three main design approaches for structures in waves; the design wave approach, the short term approach and the long term approach. Regular waves are applied in the design wave approach, where the dimensioning wave height is often taken as $H_{\max} = 1.9H_s$. For dynamic systems it is common to apply irregular waves and short or long term design approaches. Both of these methods rely on joint distributions of significant wave height and peak period/zero crossing period, sometimes conditional on propagation direction and/or month. A common method for establishing such distributions for offshore locations was outlined above, see Fig. 12. In the short term design approach one is sampling sea states from the desired contour line, while for the long term approach, "all" sea states described by the joint distribution are simulated and the design value for the response in question is establish based on long term statistics. The long term approach is considered more correct [5].

More effort should be put into understanding of the applicability of the environmental contour method in coastal regions. The present analysis indicates that the model by Haver and Nyhus, originally developed for open ocean, may not fit coastal sites. Local conditions have strong impact on the waves at the site, and it may not be possible to generalize as in the North Sea and the Norwegian Sea. A larger data set from observation and/or numerical simulations is necessary before conclusions on this matter can be drawn.

Fatigue damage Design against fatigue failure can be important for mooring systems of fish cages and feed barges, as well as for cage systems in steel and steel details on flexible cages. Fatigue is also relevant for several new fish farming concepts under development. As the Norwegian fish farming industry is aiming at more exposed locations, the importance of fatigue is likely to increase, due to increased cyclic loads from waves.

As fatigue damage is normally calculated as a weighted sum of fatigue damage in individual sea states, it is necessary with a representative description of the dominating wave conditions at the site, in addition to adequate methods to calculate fatigue damage for each sea state. Scatter tables are commonly applied to describe the relative occurrence of combinations of wave height, wave period and wave propagation direction. Scatter tables can be based on measurements. There will be uncertainty associated with the use of measurements, also for fatigue damage assessments, but not as severe as for extreme value calculations. Fatigue damage is often caused by quite frequent sea states (common events), so scatter tables should be possible to establish based on a relatively short period of measurements.

Fatigue damage is addressed by NS 9415:2009 [1], but the standard lacks methodology for how to describe waves for this purpose. There are several options for obtaining suitable wave data. Measurements, as discussed above, will provide reasonable scatter tables given a sufficiently long measurement period. In addition to being time consuming, such measurements are quite costly and need to be planned well in advance. Hindcast data is commonly applied in design and operation of offshore structures, by running numerical simulations based on measurements, and thereby obtaining long term wave statistics, see [15]. The same methodology may be applied in coastal regions using numerical simulation tools for wave propagation at the coast, e.g. SWAN [16, 17]. However, complex bathymetry, shallow water and boundary conditions makes this challenging, and calibration/validation of the numerical model with measurements will probably be necessary [7].

Operations Operational aspects are maybe the largest obstacles in moving to more exposed locations [2]. Effort is put into redesigning aquaculture operations in order to allow for farming at more exposed locations. This includes new types of structures allowing other types of operations, minimizing the amount of manual work [3]. However, there will still be operations to be performed, such as crane operations, launch and recovery of ROVs and operations involving interaction between vessels and structures.

For the purpose of planning of operations it is beneficial to establish statistical estimates for the probability of success, using operational windows. Limits for safe operation in critical operations should be established. Such operational limits can be for instance be defined in terms of accelerations, responses and forces. Numerical simulations can then be applied to find the operational limits in terms of environment (wind, waves and current). A long term statistical model of the environment can then be used to plan when to perform operations, given the operational limits.

As an example, consider an operation where the operational limit corresponds to a significant wave height of 1 m and where a time window of 12 hours is needed in order to complete the operation. Figures 13 and 14 show the probability of having a long enough time window with significant wave height below some limit for various months based on measurements. These figures illustrate how metocean data can be applied for planning of operations, but such considerations should rather be based on a statistical model than on direct measurements as done here. The discussion regarding improvements of metocean data, wave data in particular, for fatigue analysis of structures in coastal regions also applies to operations.

CONCLUSIONS

Description of exposure from waves and current for design of fish farms at exposed coastal sites is presented. Common practice for estimation of dimensioning wave and current conditions based on field measurements, as described in the technical standard NS 9415:2009 [1], is found to be insufficient. It is demonstrated that approaches from offshore engineering for description of exposure at the open sea do not apply to coastal sites relevant for farming of Atlantic salmon. We suggest that numerical simulation tools for calculation of waves and current conditions at coastal aquaculture sites should be utilized to supplement field measurements and improve the long-term statistics used as input in design of future fish farms for exposed locations.

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