Technical Memorandum NMFS-SER-9
https://doi.org/10.25923/r496-e668

Basis-of-Design Technical Guidance for Offshore Aquaculture Installations
In the Gulf of Mexico

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David W. Fredriksson, Ph.D.
Professor of Ocean Engineering
Dept. of Naval Architecture and Ocean Engineering
United States Naval Academy
Annapolis, Maryland

Jessica Beck-Stimpert, Ph.D.
Southeast Regional Aquaculture Coordinator
National Marine Fisheries Service, Southeast Regional Office
St. Petersburg, Florida

U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Southeast Regional Office
263 13th Avenue South
St. Petersburg, FL 33701

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Jessica Beck-Stimpert, Ph.D.
Southeast Regional Aquaculture Coordinator
NOAA Fisheries, Southeast Regional Office
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U.S. Department of Commerce
Wilbur L. Ross, Jr., Secretary

National Oceanic and Atmospheric Administration
Neil A. Jacobs, Ph.D., Administrator

National Marine Fisheries Service
Chris Oliver, Assistant Administrator for Fisheries

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https://doi.org/10.25923/r496-e668

NOTICE

Recommended citation:
Fredriksson, D.W. and J. Beck-Stimpert. 2019. Basis-of-Design Technical Guidance for Offshore Aquaculture Installations in the Gulf of Mexico U.S. Dept. of Commerce, NOAA. NOAA Technical Memorandum NMFS-SER-9: 27 p.

Copies of this report may be obtained from:
J. Beck-Stimpert
National Marine Fisheries Service
Southeast Regional Office
263 13th Avenue North
St. Petersburg, FL 33701

Or online at:
https://www.fisheries.noaa.gov/resources/all-publications

1. Introduction

The objective of this review is to provide a collection of ocean engineering guidance and material for the *Basis-of-Design* for aquaculture installations in the Gulf of Mexico. The guidance material focuses on offshore conditions within the Exclusive Economic Zone (EEZ) of the United States out to 200 nautical miles (370 km). A *Basis-of-Design* document is used to communicate the engineering criteria, techniques, reasoning and decisions employed to develop an aquaculture system in the offshore environment in a similar manner that is described in [1]. From an ocean engineering perspective, the *Basis-of-Design* document includes at a minimum, the following information:

- Site characteristics and environmental conditions.
- System analysis and loading.
- Design factors to address uncertainty.
- Replacement period and risk.
- Specification of components.
- System layout and technical drawings.
- Auxiliary equipment.
- Deployment and operational protocols.

This guidance provides a technical review of each of the topics listed above with associated references.

2. Site characteristics and environmental conditions

2.1. Permit site

The site perimeter is defined in Latitude and Longitude coordinates. The bottom seafloor area of the site is defined such that the three-dimensional shape of the containment and mooring system can fit into the volume of the space taking into consideration buoy watch circles and mooring system sweep. Surface buoys should also mark the permit site boundaries according to the *Notice-to-Mariners* guidance in [2].

2.2. Seafloor survey

The *Basis-of-Design* document should include bathymetric information of the aquaculture site defined with the data source referenced and depths relative to the Mean Lower Low Water (MLLW). Seafloor information can be assimilated from bathymetric datasets obtained by National Oceanic and Atmospheric Administration (NOAA) available at [3]. Gulf of Mexico datasets found at this source include multibeam bathymetric surveys, multibeam shaded relief imagery, trackline bathymetry density and National Ocean Service (NOS) survey information. Other bathymetric datasets are available, including the *General Bathymetric Chart of the Oceans* (GEBCO) found at [4].

2.3. Bottom sediment type

In addition to the bathymetric datasets, the bottom-type grain size distribution and cohesiveness [5] is needed to determine anchor-holding capacity (see Section 6.8) and for the environmental assessment of potential benthic community impact due to daily aquaculture operations. Bottom sediment samples can be obtained from a combination of field techniques depending upon the soil conditions. Techniques include bucket, clamshell, and grab samples, along with sediment core devices, penetrometers, and remotely operated vehicle/diver samples. The method, depth and spatial resolution of the samples should be sufficient to provide the necessary geotechnical data for design of the anticipated anchoring system. Geologic hazard characteristics such as slope instability, turbidity flows, or hard bottoms, which could influence the performance of the specified anchoring system, should also be considered in selecting the project site or in designing the facility.

2.4. Tide and surge water levels

Water level conditions including tides and storm surges are used for specifying mooring system geometry and as input for system analysis procedures (Section 3). For instance, system analyses under operational and extreme loads typically consider both maximum and minimum water levels. Water levels are referenced to a standard tidal or geodetic datum as described in the NOAA documents at [6] with reference to [7], [8] and [9]. In addition to the tides, storm surge should also be quantified. Some tidal amplitude and storm surge design values for hurricane conditions have been developed for specific regions of the Gulf of Mexico as described in the American Petroleum Institute (API) guidance document [10].

2.5. Wind speed, direction and fetch

Surface-wind related loads can be significant if the system deployed has containment components above the water line. Wind data is also needed if wave climatology estimates are being developed with Coastal Engineering Manual techniques [11]. For both design applications, detailed wind information required includes speed, gust, direction, fetch and recurrence interval. The wind speed dataset may also need to be adjusted according to the 10 meter standard elevation and plotted in a wind-rose format. Wind speed magnitudes estimated for extreme return periods associated with hurricanes in the Gulf of Mexico can be obtained from [10]. Site-specific datasets can also be used if existing datasets or techniques are not suitable.

2.6. Wave conditions

2.6.1. Overview

In the design process, system analyses (Section 3) are conducted for both operational (2.6.2) and extreme (2.6.3) wave conditions. Wave conditions are typically characterized by the *significant* wave height (H_{m0}, H_s, $H_{1/3}$), the peak wave period (T_p) or frequency (f_p), and the direction of propagation (θ_{mean}). Irregular sea-states are represented as a frequency spectrum as described in [12]. The spectral shape can be estimated from datasets available at the NOAA, National Data Buoy Center (NDBC) website [13], with climatic summary plots available for many locations in the Gulf of Mexico. Data set details are described in the *Basis-of-Design* document. Techniques to estimate wave conditions and corresponding return periods are described in [14]. In addition, wave hindcast datasets for many locations within the Gulf of Mexico are available at the U.S. Army Corps of Engineers (USACE) - Wave Information Study (WIS) website [15]. Additional information is found in the API guidance document [10] for extreme events associated with hurricanes in the Gulf of Mexico. Commercial vendors also provide various wave data products, but the basis for using these products should be explained.

2.6.2. Operational wave conditions

Operational wave conditions can include data without storm events or include storms with return periods of 1- or 2-years. The operational wave spectral shape is characterized by specific H_{m0}, T_p (or f_p) and θ_{mean} and wave frequency range values. Operational wave conditions are used with extreme wave conditions (Section 2.6.3) to assess cyclical loading characteristics to determine component replacement period (Section 5).

2.6.3. Extreme wave conditions

Extreme wave conditions have return periods typically between 25- and 100-years (e.g. "the 25- or 100-year storm") depending upon design philosophy. These sea states are used in developing the design conditions to specify the strength/stress specification of system components. The wave spectral shape is characterized for a return period by specific H_{m0}, T_p and θ_{mean} and wave frequency range values. Wave height values for extreme design conditions can be extrapolated from long-term measurements for extended return periods by considering certain probability distributions (e.g. Weibull). Descriptions of multiple techniques are provided in [12] and [14] where assumptions, different distributions and confidence levels are discussed. Values for regions in the Gulf of Mexico are also described in the API guidance document [10] and at the WIS website [15], with datasets and climatic summaries at the NDBC website [13].

2.7. Offshore current velocity conditions

In addition to the wave conditions, knowledge of the offshore current velocities is critical for design. Current velocity components are related to tides, site-specific circulation patterns, winds, and internal waves and are assimilated into design conditions. Offshore current velocities can be analyzed as a distribution (e.g. Weibull) from which design values can be extrapolated as described in [12], [14] and [16]. Similar to the wind datasets, current velocity magnitudes, frequency and direction are represented in a current-rose format.

Existing datasets are available for the Gulf of Mexico. For example, the Louisiana-Texas Project (LATEX) had 81 deployed current meters at 34 locations across the Texas-Louisiana Shelf from 1992-1994. Other datasets have been obtained from the Texas Automated Buoy System (TABS). These datasets may help in the analysis of tidal currents and how they interact with the effects of loop circulation and corresponding eddies [17] in the western regions of the Gulf of Mexico.

Resulting values can have design implications since according to [18], the loop current can have magnitudes of 0.8 m/s. Datasets are also available from the Physical Oceanographic Division of NOAA [19]. Design values specific for the Gulf of Mexico have also been develop by the API as described in the [10]. If existing datasets are not available, measurements should be obtained considering the appropriate location of the site, instrument position in the water column, sampling rate and dataset duration.

3. System analysis and loading

3.1. Overview

As discussed in Section 2, one of the primary design steps is to quantify both the operating and extreme environmental conditions representative of the site. With the operating and extreme conditions, analysis of an offshore aquaculture system with a mooring is necessary to specify components to minimize failure and subsequent escape of cultured animals. Analysis procedures include quantifying hydrostatic stability, static tensioning of the mooring, and dynamic response of the entire system. Accidental and deployment loads should also be considered. Analysis procedures for these applications can be found in [20] and [21].

3.2. Hydrostatic analysis

Hydrostatic analysis and stability calculations are done for containment systems in both surface and submerged configurations whether on station or being towed. Hydrostatic calculations include weight, flotation and reserve buoyancy. If a system is deployed at the surface with substantial displacement characteristics, the appropriate transverse and longitudinal metacentric heights (GM_T and GM_L) must be positive. If deployed in the submerged configuration, the transverse and longitudinal (if not symmetric) center of buoyancy values (CB_T and CB_L, respectively) must be located at a position higher than the transverse or longitudinal center of gravity values (CG_T and CG_L). If tensioned moorings are incorporated into the system design, then appropriate hydrostatic analysis must be performed with specification of flotation buoys, especially if incorporated with chain in a mooring leg configuration. If the buoys are being used at the surface, the waterline and reserve buoyancy are calculated (Section 6.4). It also may be necessary to quantify the effects of biofouling into the calculations, especially with respect to specifying reserve buoyancy. Hydrostatic analysis procedures are fully described in the *Basis-of-Design* document.

3.3. Static tension configuration

Mooring systems for containment structures can include catenary, taut leg, single point or spread line configurations. In the design process, one of the first steps is to determine the static configuration (e.g. without environmental loads) of the system to be deployed at the site related to the hydrostatic characteristics described in Section 3.2. Often pre-tensioning is employed to minimize dynamic snap-loads that can occur due to slack components in response to winds, waves and currents. Pre-tensioning calculations are done as a balance between surface/submerged flotation, weights and mooring system geometry. Wet cordage characteristics along creep can influence a mooring system static configuration. Effective pre-tensioning with compliance can also be done by utilizing chain catenary configurations in the mooring legs where chain weight is specified with flotation and system geometry. The mooring leg geometry should be predetermined and related to the deployment process where anchors are spread out pulling floats down and lifting chain off the seafloor.

3.4. Dynamic load assessment

3.4.1. Overview

Aquaculture systems are inherently compliant consisting of flexible components such as chain, rope and net. In the offshore environment, waves and currents create dynamic forces inducing movements that can have large displacements and rotations. Forces due to waves, however, can be reduced if gear is submerged since wave velocities and accelerations that create drag and inertia, respectively, attenuate with depth. Wave velocities and accelerations oscillate with time and are 90 degrees out of phase. Drag induced by steady currents combines in a nonlinear fashion with wave velocities. Gear component movements also exhibit relative velocities and accelerations. With these dynamic implications, it is difficult to obtain accurate global force distributions through analytical procedures. Therefore, *Basis-of-Design* documents should define the analysis technique employed to assess dynamic loads. Dynamic load assessment is typically done with time-domain (Section 3.4.2), frequency-domain (Section 3.4.3) or quasi-static analysis procedures (Section

3.4.4). Depending on the technique chosen, the set of design factors should address uncertainty (Section 4).

3.4.2. Time-domain dynamic analysis

For containment structures, time-domain dynamic analysis uses numerical modeling routines that incorporate a Morison equation approach [22]. In this application, Morison equation can be modified such that

$$\frac{\partial \vec{F}}{\partial l} = \frac{1}{2}\rho_w D C_n |U_{Rn}| \vec{U}_{Rn} + C_t \vec{U}_{Rt} + \rho_w A \vec{\dot{U}}_n + \rho_w A C_m \vec{\dot{U}}_{Rn} \, , \qquad (1)$$

for small diameter components relative to the wavelength. As shown in equation (1), $\partial \vec{F} / \partial l$ is the fluid force per unit length, $\vec{U}_{Rn}$ and $\vec{U}_{Rt}$ are the normal and tangential components of the fluid particle velocity relative to the element velocity. These relative velocity parameters should include both the wave orbital and offshore current components. Also in equation (1), $\vec{\dot{U}}_n$ is the normal component of absolute fluid particle acceleration, $\vec{\dot{U}}_{Rn}$ is the normal component of the fluid particle acceleration relative to element acceleration, ρ_w is the water density, A is the external cross-sectional area, C_n is the normal drag coefficient and C_m is the added mass coefficient. In this form, tangential drag is represented as $C_t \vec{U}_{Rt}$ where C_t has units of viscosity. If the tangential drag of the object modeled is cylindrical and is a function of $|\vec{U}_{Rt}| \, \vec{U}_{Rt}$, then $C_t = \frac{1}{2} C_f \rho \pi |\vec{U}_{Rt}|$ with C_f as a friction coefficient.

Fluid particle velocity and acceleration fields are typically calculated using linear wave theory as described in [23], though nonlinear wave formulations can also be incorporated to represent other wave conditions. Basic hydrodynamic coefficients can be found in [21] with containment net specific approaches described in [24], [25] and [26]. Numerical routines developed for *time-domain dynamic analysis* typically include wave kinematics such that velocities and accelerations attenuate with depth. For the case of irregular seas, the wave field can be approximated in the model using a superposition of waves, so that the water surface elevation is given by

$$\eta(x,t) = \sum_{i=1}^{N} \frac{H_i}{2} cos(k_i x - \omega_i t + \epsilon_i), \qquad (2)$$

where H_i are the wave heights, k_i are the wave numbers, x is the horizontal position in the direction of wave propagation, ω_i are the wave radian frequencies and ε_i are the random phase components.

These parameters can be decomposed from the spectral wave characteristics described in Section 2.6 with procedures provided in [27]. The wave frequency components should then be used to create a nonrepeating, surface elevation time-series that includes the largest expected wave characteristic of the storm condition.

If time-domain analysis is conducted, details are included in the *Basis-of-Design* document. These details include the design load-cases model input parameters such as the (1) geometric properties, (2) material properties, (3) drag coefficients and (4) added mass coefficients for each element of the system. In the analysis procedure, the solidity of the containment structure with influence of the maximum expected biofouling should be documented for global load distribution assessment (Section 3.5.1). In addition to the load on a specific containment structure, the flow reduction characteristics throughout an array of structures should also be provided. A body of work exists to estimate flow reduction through containment structures that has been obtained using physical model tests, field measurements and numerical approaches including Computational Fluid Dynamics, e.g. [28] - [31].

An extensive amount of work has also been conducted to assess the validity of various time-domain modeling procedures as described in [32] - [38]. Most of the time-domain modeling work has been compared to physical model tests with some field measurements. With the extensive body of work available, the time-domain analysis approach to assess dynamic system loads on the proposed containment system can be done with a high level of confidence. However, if a large unmanned displacement vessel is incorporated as part of the aquaculture structure, modifications to the approach will need to be applied to represent vessel dynamic response and system interactions.

3.4.3. Frequency-domain dynamic

A *frequency-domain dynamic analysis* approach can also be done to calculate representative dynamic responses. Frequency-domain dynamic analysis involves the linear combination of mean, low frequency and wave frequency components of forcing and response and can be in the form of Response Amplitude Operators. Techniques are described in [20]. These methods, however, typically do not include nonlinear interactions since the processes are decoupled. It has been shown that the nonlinear wave-current interaction effects for containment structures can represent a significant loading component when applied to these systems [33]. Therefore, if frequency-domain analyses are applied to assess dynamic loads, design factors (Section 4) should be explained in the *Basis-of-Design* document to consider nonlinear interactions and other uncertainties.

3.4.4. Quasi-static analysis

The *quasi-static analysis* approach applies a static force magnitude on the aquaculture system structure in the horizontal direction, where vertical dynamics are not considered. A Dynamic Amplification Factor is typically applied to the quasi-static results to account for dynamic influences. If this approach is considered, procedures should be documented with detail in the *Basis-of-Desig*n document and sufficient design factors provided.

3.5. Other loading considerations

3.5.1. Influence of biofouling

Biofouling on aquaculture system components, especially on the nets, can influence both drag and mass characteristics (see [39] and [40]). A biofouling assessment for the deployment period of the proposed gear should be included in the *Basis-of-Design* document. The assessment should incorporate a discussion on how biofouling will affect the choice of flotation elements and how the global force calculations are made.

3.5.2. Accidental loads

Accidental loads are incurred through a variety of situations such as (1) failure of the flotation element(s), (2) collision with service or other vessels, (3) failure of mooring lines and (4) connector breakage. An evaluation of potential accidental loads should be described in the *Basis-of-Design* document. It can also be included as part of the development of design factors (Section 4).

3.5.3. Deployment loads

Loads incurred during the deployment process also need to be considered. These loads include (1) lifting components into the air, (2) towing a system out to a site, and (3) spreading of the mooring system during pre-tensioning operations. An evaluation of deployment loads should be described.

4. Design factors to address uncertainty

4.1. Overview

Design factors are used to account for uncertainties with the engineering process and typically include the allowable-stress or the load- and resistance-factor design approaches. The *Basis-of-Design* document should describe the use of the design factors chosen in the specification of system components.

4.2. Allowable-stress design

Specification can be done with the deterministic, allowable-stress design approach where system analysis results (Section 3.4) are evaluated for each component for a set of specific return-period conditions (Section 2) to find the *design response* (e.g. tension, load, stress). The calculated value is then compared to the corresponding *component failure capacity* (e.g. tension, load, stress) to satisfy a safety-factor such that the

$$Safety\ Factor = \frac{Component\ Failure\ Capacity}{Design\ Response} \geq 1 \tag{3}$$

The design response with the safety factor from equation (3) is also used to find component replacement period and risk (Section 5) associated with fatigue limits. This design approach is described in [20]. If the allowable-stress design approach is applied, the basis for safety factor values should be explained in the *Basis-of-Design* document.

4.3. Load- and resistance-factor design

Specification can also be done with the load- and resistance- factor design approach. This partial-coefficient approach incorporates load (γ_l) and resistance factors (γ_r) into the process according to

$$(Design\ Response)(\gamma_i) \leq \frac{Component\ Failure\ Capacity}{\gamma_r}, \tag{4}$$

The load factor (γ_l) in equation (4) can be intended to account for limitations of available environmental datasets, probability of exceeding prescribed conditions and uncertainties in the modeling and analysis of the structure. The resistance (sometimes called the material) factor (γ_r) can account for component variability in the construction process, modifications associated with fastening (e.g. knots, splices) and time related degradation (e.g. wear, UV exposure). Further information regarding this design approach is described in [41]– [43]. If the load- and resistance-factor design approach is applied, the use of these factor values should be explained in the *Basis-of-Design* document.

5. Replacement period and risk

5.1. Fatigue and component replacement period

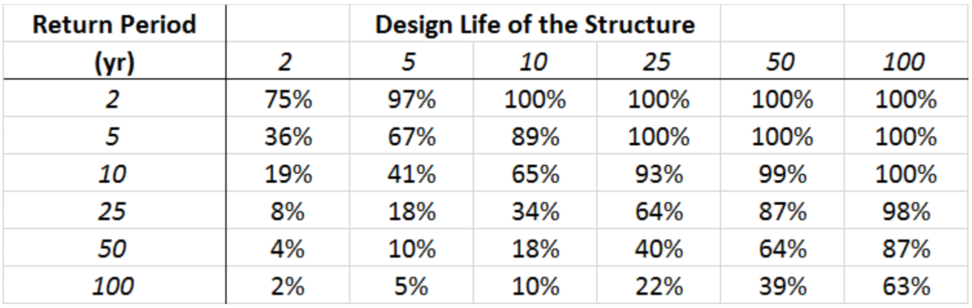
Fatigue of the containment structure and mooring system components should be assessed and described in the *Basis-of-Design* document. Fatigue is typically characterized as the Tension- or Stress- as a function of the number of cycles and is used to determine component replacement period based on operational and extreme conditions. An example is described in [44] with marine rope fatigue behavior reviewed in [45]. Procedures are also described in [46] and [47]. The replacement period for the entire system individual components should be explained in the *Basis-of-Design* document. Replacement period characteristics can be adjusted depending upon the values of the design factors employed.

5.2. Encounter probability

An estimate of the encounter probability that a specified extreme condition will occur during the design life of the system [14], should be described in the *Basis-of-Design* document. The encounter probability is defined (P_e) as

$$P_e = 1 - \left(1 - \frac{1}{T_R}\right)^n, \qquad (5)$$

where T_R is the storm return period and n is the design life of the component. The Table below provides the results for equation (5) where the percentage values represent the probability of a design condition occurring during the component design life (or replacement period) related to the design factors chosen.



Return Period		Design Life of the Structure				
(yr)	*2*	*5*	*10*	*25*	*50*	*100*
2	75%	97%	100%	100%	100%	100%
5	36%	67%	89%	100%	100%	100%
10	19%	41%	65%	93%	99%	100%
25	8%	18%	34%	64%	87%	98%
50	4%	10%	18%	40%	64%	87%
100	2%	5%	10%	22%	39%	63%

For instance, if the components of an entire system are to be designed for a 50-yr storm condition and the useful life is specified at 10 years, the probability of the 50-year design condition occurring during the useful life is 18%.

5.3. Risk analysis

Risk analysis should be performed to assess potential component failure and reported in the *Basis-of-Design* document. An example for aquaculture systems is described in [44]. Risk is typically estimated by comparing the probability of environmental extreme and operational loading with the probability characteristics of the material response. An environmental loading probability density function can be estimated from a series of system analysis results (Section 3.4) with design condition input that describes the operational and extreme wave probability conditions. The material response is described by the strength probability function typically provided by the manufacturer as a normal distribution with mean and standard deviation values. Failure occurs when the strength of the component is less than that experienced from the environmental loading. The risk of failure is calculated as the area associated with the intersection between the loading and strength probability density functions. The amount of probability density function overlap (risk) can be reduced by choosing a component capacity higher than the value calculated at the design condition. This can be done by applying a safety factor or by adjusting the probability density functions with load and resistance factor as described in Sections 4. Fatigue should be considered by adjusting the mean strength values (new) with a residual breaking strength value calculated as a function of years of operation related to the number of cycles.

6. Specifications of components

6.1. Overview

Equipment specification should be made so that the components have sufficient capabilities to exceed ultimate stress conditions and permanent deformation strain, and reserve strength to account for fatigue through cycling. Loading values are obtained from the techniques described in Section 3 with appropriate design factors described in Section 4.

6.2. Loads specific to containment structures

The internal structural capacity of the proposed containment structures should be specified for the offshore conditions in the Gulf of Mexico. In this process, it may be necessary to characterize the containment structures since the construction will determine the type of analysis needed to assess internal component stress distribution. According to [48], existing containment structures (e.g., cages) can be classified into the following categories.

- Class 1: Gravity cages that rely on buoyancy and weight to hold their shape and volume against environmental forces.
- Class 2: Cages that rely on the anchor tension to keep shape and volume.
- Class 3: Self-supporting cages that rely on a combination of compression in rigid elements and tension in flexible elements to keep the system in position so the shape and volume are maintained.
- Class 4: Self-supporting cages that rely on rigid constructions such as beams and joint components to keep shape and volume.

The class type will determine the appropriate procedures for analyzing the proposed containment structure. If a novel containment structure is being considered, it should be described in the *Basis-of-Design* document. In general, global loading on an entire aquaculture installation is predominantly due to the containment component. Storm environmental loads induced on the nets and/or containment structure are transferred through the attachment connections to the mooring system. The attachment locations can serve as boundary conditions in the analysis to perform internal stress analysis of the containment structure [49]. As the environmental loads are distributed through the containment structure, the stress distribution and component specification should be quantified so breakage and escapement is prevented. This process should be described in the *Basis-of-Design* document by providing the containment structure details from a reputable manufacturer.

6.3. Containment structure materials

Details on how the containment structure is fabricated corresponding to the classes described in Section 6.2 should also be provided. Most containment structures include nets that are often fabricated in parts and connected through a series of seams and can be made from a variety of fiber types. The fibers are made of filaments and should be made from synthetic material that includes polyamide (PA) or nylon, polyester (PES), polypropylene (PP), Polyethylene (PE), high-modulus PE such as Spectra^{TM} or Dyneema^{TM}, aramid, vectran and zylon. Fibers can also be combined, such as PE and PP, to form a co-polymer rope. The fiber should be treated against UV so that it will maintain its structural integrity for at least three years. The net manufacturer should provide the applicant strength test information in elongation according to [50]. The net manufacturer should also provide details regarding net mesh strength testing. If a net treatment is being proposed, the effect of the treatment on the net mesh strength should also be documented.

Many net construction characteristics incorporate vertical rope members (“down-ropes”) that connect to surface flotation with a weight assembly at the bottom of the net. The down ropes and weights should be evenly distributed around the circumference of the net as clumps or a continuous ring. The vertical ropes should be sized to withstand both static and dynamic loading conditions. The net may also include an integrated horizontal rope around the circumference at various depths. Both the vertical and horizontal rope should be configured to transfer the loads on the net to the flotation at the surface, transferring to the bridle lines that connect the containment structure to the mooring system.

Details should be described on how the seams and net ropes are connected to the nets. Since the net ropes transfer the loads, attachment details between the net ropes and the floaters should also be provided in the *Basis-of-Design* document. Net and net rope locations that will be exposed to abrasion should be identified and suitable chafing gear employed.

Some containment structures can incorporate other types of mesh material. For instance, copper-alloys have been used in this application and can be constructed as chain-link, expanded, welded and crimped mesh construction types. Examples of copper-alloy mesh applications are described in [51]. Mesh types can also include polyethylene terephthalate (PET) and polyvinyl chloride (PVC) coated wire mesh. For these specific cases, the global load distribution within the containment system should be documented. Details regarding load members and attachments should be included with appropriate design factors.

It is important to note that the design guidance procedures described here do not apply to containment structures incorporating solid or semi-impermeable membrane components (e.g. closed-containment).

6.4. Buoyancy components

The specification of all buoyancy components should be described in the *Basis-of-Design* document. Maintaining effective static and reserve buoyancy is critical in mooring system design to prevent components from sinking, for pre-tensioning purposes and for dynamic loading compensation. Buoys are typically made of UV stabilized polyethylene filled with closed cell foam with either galvanized or stainless steel hardware. Hardware configurations include threaded rod with a swivel eye-nut secured with locking nut or through pipe assembly enabling for the pass through of chain or cable. Buoy hardware components should be specified to withstand attachment loads verifiable from a reputable manufacturer. Hydrostatic analysis should be performed to show that the appropriate buoy is stable at the surface or submerged depending upon the application (Sections 3.2 and 3.3). Documentation regarding depth specification should also be provided. If buoys being proposed are to be made from other materials, such as steel spheres, plastics or composites, then the material characteristics, depth limitation, attachment configurations and anti-corrosion practices should be specified.

6.5. Rope

Various types of rope are used throughout a marine aquaculture system including the mooring system, containment components and nets. Like netting, rope filaments should be made from synthetic fibers that include polyamide (PA) or nylon, polyester (PES), polypropylene (PP), Polyethylene (PE), high-modulus PE such as Spectra^{TM} or Dyneema^{TM}, aramid, vectran and zylon. Fibers can also be combined, such as PE and PP, to form a co-polymer rope. Rope is typically constructed in either a twisted or a braided configuration. Rope specifications should include diameter, construction, mass density, minimum breaking strength, elongation at break and UV resistance. Characteristics should consider both wet and dry conditions. The appropriate design factors should also be described and these characteristics included in the *Basis-of-Design* document.

6.6. Steel chain

Steel chain is utilized in many aspects of marine aquaculture including the mooring system as ground tackle and to connect buoys within the mooring system. Steel chain is also used during deployment and rigging operations. The American Society of Testing and Materials (ASTM) specification standards describe five types of chain that could potentially be used for aquaculture operations for both in and out of water. The applications and the specific ASTM standards are summarized below.

- Grade 30: Grade 30 is a general purpose, welded, carbon-steel utility chain typically used in various industrial and agricultural applications. It is often referred to as *proof coil chain* and has an ultimate breaking strength of 30 N/mm^2. More details are provided in the standard, [52]. For marine purposes, it should be hot-dipped galvanized to reduce corrosion and not be used for lifting.
- Grade 43: Grade 43 type chain has an ultimate strength of 43 N/mm^2 and is referred to as *high test chain*. It is used in logging, towing and marine applications. In marine application it is hot-dipped galvanized to reduce corrosion effects. This type of chain is also described in the ASTM standard [52] and should not be used for lifting.
- Grade 70: Grade 70 chain has an ultimate strength of 70 N/mm^2 and is used for transport purposes and load securement purposes. It is also described in [52]. As with Grade 30 and 43, this chain should not be used for overhead lifting. It is also not typically used for marine applications.
- Grade 80: Grade 80 is a high quality, heat-treated alloy chain used in sling rigging, tie down and overhead lifting applications, such as loading equipment on a flatbed trailer or service vessel. It has an ultimate breaking strength of 80 N/mm^2. The standard specification for Grade 80 alloy steel chain is described in [53].

- Grade 100: Grade 100 is the highest quality lifting chain with an ultimate strength of 100 N/mm^2. It consists of the highest strength, heat-treated alloy. The standard specification for Grade 100 alloy steel chain is described in [54].

For mooring applications, hot-dip galvanized Grade 30 or 43 should be specified with wire diameters considering the appropriate design factors. For additional weight, the U.S. Coast Guard uses open-link chain for mooring aids to navigation buoys in both coastal and inland waterways [55]. Open-link (also called "long-link") also has the advantage of being large enough to fit the pin of the same size shackle into the link. The moorings of large ships often utilize stud-link chain to achieve heavier weight. The standards for stud-link chain are described in [56].

Chain considered as a component of the mooring system or lifting operation should be identified by its grade and application in the *Basis-of-Design* document and have strength test certificates from the manufacturer. Use of actual diameters should be provided for strength characterization, especially if used chain is considered. Proof testing certificates should also be done post galvanization.

6.7. Mooring connectors

A wide range of mooring system connectors and combinations are available depending upon the application. Connections in mooring systems are typically made from anchors to chain, chain to mooring lines, mooring lines to the grid, grid to cage attachment line (e.g. bridle) and cage attachment line to the cage. The following is a summary of various mooring system connector types.

- Shackles: Shackles are the most common connection component used in a mooring system. Shackles can be acquired in two shapes, anchor (or bow) shackle, or a chain D-shackle. Anchor shackles have a larger "O" shape enabling the shackle to orientate itself in the direction of the load and accommodate more components. Chain shackles have a narrower "D" shape, which are stronger than anchor shackles but tend to rack with side loads. Both shackle types can be secured with either a clevis screw-pin or bolt. Screw-pin shackles need to be seized with wire made of a material to minimize galvanic corrosion. Bolt-type shackles can also be seized with wire or cotter pin. All shackles should be specified from manufacturer provided information according to design loads with appropriate design factors and be hot-dipped galvanized.

- Thimbles: Thimbles are used at the termination of mooring component line (or wire), are incorporated as part of an eye-splice and are used at connections with shackles or lashings to prevent abrasion. Once the splice is made tight over the thimble, binding should be applied in two locations to prevent the thimble from rotating. Thimbles are sized to match that of the rope specified for the particular mooring component.
- Corner plates or rings: In mooring systems that included horizontal grids, like a typical multi-pen salmon farm [57], corner plates or rings facilitate the connection of anchor, grid and bridle lines. These are critical components and therefore should have documentation showing rigorous engineering analyses with derived global loads and motions with material factors. The same approach applies to various ring, ellipses and pear links.
- Lashings and knots: Shackles and other hard components can be connected to rope using multiple wraps of a smaller lashing material. Care needs to be taken on how the lashing ends are terminated. Knots are another option, however, the strength of rope is greatly reduced for every knot used.

6.8. Anchors and ground tackle

Anchoring components used in offshore aquaculture installations primarily consist of one or a combination of the following types:

- Drag embedment,
- Deadweight (with and without shear keys),
- Pile, and
- Direct embedment.

Deadweight and drag embedment anchors are the most common used in marine aquaculture. The holding power of each anchor within the system depends upon the bottom sediment types (Section 2.3). The loading application magnitude and angle requirements are also different for each of the anchor types. For example, the optimal loading condition for a drag embedment anchor is horizontal and therefore typically include a chain catenary as part of the mooring leg (Section 3.3). Deadweight anchors can provide both horizontal (with friction) and vertical (weight) resistance, but require attention to construction materials and shape. Pile and direct embedment anchors, which are not as common in the aquaculture industry, typically resist vertical loads. Full detailed guidelines for seafloor anchor design can be found in [58], [20] and [46]. Anchoring and ground tackle specifications should be provided with appropriate design factors. Anchor systems should be proof-loaded prior to installation of the aquaculture facility.

7. System layout technical drawings

7.1. System technical drawings

System technical drawings of the system deployed at the site should be included in the *Basis-of-Design* document in both plan and profile views. The technical drawings should be labeled with pertinent dimensions, part components and locations including the containment system, buoyancy elements (e.g. floats, buoys), rope, fasteners, ground tackle and anchor position within the site.

7.2. Subassembly technical drawings

From the technical drawings described in Section 7.1, a detailed list of the individual components should be described specifying the subassemblies including the containment system, corner buoys, grid-lines, connection shackles, mooring lines, anchor, etc., with the manufacturer, working load specification, design factors and other applicable details. The basis for each component specification should also be provided as described in Section 6 once the analysis in Sections 4 and 5 are completed. Supplemental information from the manufacturer can also be provided in this Section.

8. Auxiliary equipment

8.1. Overview

The auxiliary equipment utilized can vary depending upon the type of aquaculture operation being proposed. Systems will typically require feeding and mortality (“morts”) collection equipment.

8.2. Near-shore feeding systems

Near-shore systems often employ large feed barges utilizing compressed air feed delivery through floating high-density polyethylene (HDPE) pipe. The floating HDPE connects the feed barge to each containment structure in an array. These types of feeding systems may be considered vessels and therefore would require registration with the U.S. Coast Guard.

8.3. Offshore feeding systems

In the offshore environment, automated feed systems have been designed to hold feed pellets within the hull of a surface vessel or buoy [59] and deliver feed through water pumping systems. Large feed system mooring systems need to be designed with components separate from the containment system. Depending upon the size of the floating system, dynamic loading analysis may need to be modified to incorporate specific motion response characteristics in both the typical and extreme loading conditions.

Feeding devices can also be integrated into the containment system. In this case, both the static and dynamic stability influence should be quantified in both full and empty configurations. Shifting feed, associated with the free-surface effect, should also be verified.

8.4. Mortality and net mesh cleaning systems

A strategy for removing mortalities should also be provided as part of the overall system design. Details should include how the system is attached to the containment system so that structural integrity is not compromised allowing cultured animals to escape. The same details should be provided for net mesh cleaning systems.

9. Deployment and operations protocols

9.1. Equipment and maintenance records

Each operator or responsible entity should maintain detailed documentation of the equipment deployed and a record of maintenance activities. Documentation should include a description of the site and all related information regarding the design of the system deployed. This should include the initial environmental datasets for system design, detailed design process and equipment specification details. Throughout the operation of the aquaculture installation, documentation should be updated as new information becomes available, replacement parts are incorporated and other operational changes are implemented. Operational and maintenance plan documentation should also be included in the record-keeping system. It is expected that documentation materials are to be maintained as an updated source of the gear deployed and should be available to both onsite operators in the field and management personnel onshore for daily decision-making purposes.

9.2. System deployment plan

Details regarding the installation of the aquaculture system should be described in the *Basis-of-Design* document. The plan should include the type and number of service vessels and contractor information as necessary. Details regarding the transportation, assembly and deployment of the mooring system should also be included. If system components are to be towed to the site, towing loads should be verified and appropriate equipment specified. Mooring of working vessels at the site should be independent of the containment and feed-system mooring systems.

9.3. System inspection

An inspection plan of system components at prescribed intervals immediately following installation should also be included in the *Basis-of-Design* document. The plan should also include inspection after storm events. Inspection results should be included in the equipment and maintenance documentation records.

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