# Using Finite Element Analysis for the Design of a Modular Offshore Macroalgae Farm

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**ABSTRACT**

A dynamic numerical modeling approach was used to inform the design process and economic analysis for an offshore kelp farm with a modular structure designed to scale to 1,000 hectares. This modeling approach incorporated finite-element representations of kelp aggregates and was implemented using the software OrcaFlex. A sequence of dynamic loading scenarios corresponding to extreme events observed in the Gulf of Maine (North Atlantic) was developed and implemented in numerical simulations. The simulations were used to predict the overall dynamic response of the considered modular offshore kelp farm and estimate the highest tensions in various farm components including the anchor lines. Both regular and random wave loadings were considered. It was shown that utilization of regular (monochromatic) wave model can lead to significant overprediction of expected tensions and overdesign of the structure under investigation. Identification of the appropriate worst-case loading scenarios allowed for the well justified specification of the farm components and a subsequent techno-economic analysis.

**Key Words:** macroalgae aquaculture, kelp farming, offshore aquaculture, finite element analysis

## NOMENCLATURE

$T_2$ Mean wave period [second]
$H_{1/3}$ Significant wave height [m]
$m_0$ Zeroth moment of a narrow banded wave spectrum [m]

FEM Finite Element Method

## 1. INTRODUCTION

The cultivation of macroalgae for use as food, fuel, and fodder has recently gained momentum in the US and Europe. Because macroalgae, such as kelp, do not require fresh water, fertilizers, or arable land for cultivation, kelp aquaculture has been identified as a route for increasing or replacing the production of essential human consumables without adding additional strain to overexploited resources. To reach this potential, technologies that enable minimal human input, high reliability, low capital investment, low ecological impact and high productivity must first be established. In the USA macroalgae cultivation systems must also be suitable for the offshore environment in order to avoid nearshore areas where the established uses by the fishing industry, shipping industry, coastal homeowners, or local military entities often bar new endeavors such as aquaculture. From an engineering perspective, the major challenge is the development of a low-cost structure that provides optimal conditions for kelp growth while being capable of sustaining the forces imposed by the offshore environment: waves, currents, and winds.

Numerical methods such as finite element analysis can be employed to evaluate structural performance of aquaculture structures in complex loading environments such as waves and currents. OrcaFlex (https://www.orcina.com/orcaflex/), a commercial FEM and multibody physics software package, specializes in evaluating loading and movement of rigid floating bodies moored by flexible anchor lines. OrcaFlex relies on Finite Element Analysis and multibody dynamics to simulate the hydrodynamic forces and response of marine structures subjected to waves, currents and winds. Marine structures are modelled as flexible and rigid elements in the form of lines, 6- or 3-degree-of-freedom buoys, and rigid body elements. Using steady hydrodynamic forces and catenary equations OrcaFlex's iterative solver determines equilibrium positions for preliminary static solutions. Using this static configuration as the initial condition, the dynamic simulation portion solves the equations of motion at progressive time steps, while accounting for large displacement using a nonlinear Lagrangian formulation. The nonlinear equations of motion are solved using either explicit or implicit integration schemes. The relative movement between structural elements and the surrounding fluid are applied to the Morison equation formulation in order to estimate the hydrodynamic loading on structural elements at each time step. The simulation accounts for penetration of the free-surface by truncating the buoyancy, drag and added mass of the affected element proportionally to the volumetric submergence of that element. OrcaFlex simulations allow for dynamic variation of added-mass and drag coefficients with change in relevant parameters such as Reynolds number at each time step. Current and wave fields are prescribed at the outset of the simulation and not modified by their interaction with the structure.

In 2018 the US Department of Energy ARPA-E program awarded 18 teams funds to pursue the development of technology that could help enable the cultivation of macroalgae at costs competitive with other biofuel feedstocks (https://arpa-e.energy.gov/technologies/programs/ mariner). This paper focuses on a portion of the engineering analysis for one of those projects titled “Continuous, High-Yield Kelp Production” which considered a potential deployment in the Gulf of Maine where ocean conditions are well suited for the cultivation of sugar kelp (*Saccharina latissima*).

In this paper we will introduce the defining characteristics of this specific farm design (section 2). Section 3 describes the numerical model used to estimate the dynamic performance of the farm design. The development and application of loading cases are explained in section 4. In section 5 the results from the numerical model are presented. Conclusions are discussed in section 5.

## 2. DESCRIPTION OF THE MODULAR OFFSHORE MACROALGAE FARM

The offshore macroalgae farm considered in this paper is characterized by its mooring geometry, deemed a “lattice mooring grid”. The lattice moored grid concept features a grid of cultivation array “tiles” positioned between “nodes” from which four anchor legs, consisting of synthetic line, and a short section of chain connect to helical anchors that are centered below the adjacent cultivation arrays. In this way each anchor is connected to four nodes, and each node to four anchors creating an interconnected lattice (similar to a crystal lattice) of anchors lines in which nodes and anchors can serve multiple arrays simultaneously. Floats are tethered above each node to provide buoyant stationkeeping. Because any given anchor can be loaded in any of the four directions of the attached anchor lines, special considerations to the anchor design must be incorporated. Between the nodes equally spaced cultivation lines connect to “header lines” forming what has been deemed a “tile”. Figure 1 provides schematics of a 2x2 tile array. Because the hydrodynamic load from each tile is transferred directly to the seafloor, loads across a large array are not additive, preventing the need for large expensive mooring equipment typical for conventional aquaculture “mooring grids”. Sharing of anchors across multiple tiles allows for reduction of mooring cost, while also increasing redundancy and decreasing risk of catastrophic failure.

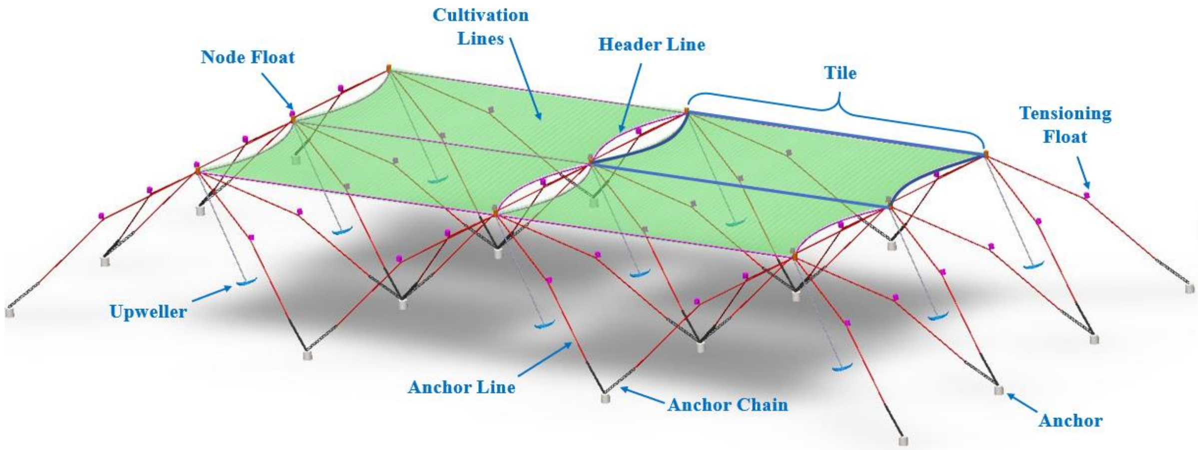


**Figure 1.** Modular kelp farm design schematics: 3D representation of a 2x2 “tile” array

While the cultivation lines provide substrate for the attachment of kelp holdfasts (analogous to a plant's root system), the header line allows for aggregation and transfer of load from the cultivation lines to the anchor lines via the nodes. By configuring the cultivation and header lines in a geometry similar to the natural deformed shape (a parabolic curve), discrepancies in the tension distribution across the array of cultivation lines can be minimized. This is similar to methods employed in suspension bridges, typical paragliding or kite bridle systems, and some other kelp cultivation systems such as those proposed by C.A. Goudey & Associates or Daniel Fedøy of Seaweed AS. Submerged "tensioning floats" provide extra buoyancy, maintain tension across tidal levels, and help prevent shock loading by allowing the anchor leg to elongate when subjected to high impulse loading. Simultaneously, the anchor lines are carefully pretensioned to create a semi-taut mooring system capable of resisting excessive deformation. Three "dropper" floats spaced evenly (at 35 m apart) are tethered 2 m above cultivation line in order to help maintain the cultivation line depth as biomass increases. Table 1 offers a summary of the key parameters (material choices or size) characterizing important components of the farm design.

The design includes wave actuated passive upwelling devices located under each node float. The movement of the node float in the waves is expected to pump a hydrofoil rotor in the lower water column providing upward momentum to deep nutrient rich water, bringing it closer to the surface. Upwelled water can provide essential nutrients for kelp growth that become seasonally scarce in offshore settings which often exhibit steep nutrient gradients with depth. Because the detailed design and dynamics of the upweller had not been finalized at the time of this effort, the upweller was represented as a constant vertical force for the purpose of simulations presented in this paper.

**Table 1**. Major parameters defining the cultivation structure design modelled in this study.

| | |
|---|---|
| **Tile dimensions** | 140 m x 70 m |
| **Overall farm footprint** | 560 m x 350 m |
| **Depth of cultivation lines** | 2 m |
| **Cultivation lines per tile** | 35 |
| **Water depth** | 50 m |
| **Anchor and header lines** | 8 Braid Copolymer Rope |
| **Cultivation lines** | 3 strand Copolymer Rope |
| **Anchor chain** | Studlink chain |
| **Node float** | 65 kN buoyancy |
| **Tension float** | 6.5 kN buoyancy |
| **Kelp weight** | 245 N per m of cultivation line |
| **Droppers** | 1.2 kN buoyancy |
| **Upweller** | 10 kN constant downward force |

## 3. DESCRIPTION OF MODEL

Figure 2 shows a numerical model of the 4 x 3 – tile array implemented in the OrcaFlex software. Ropes are approximated by linear elastic elements with a prescribed diameter, density and modulus of elasticity, and element length. Floats are defined as cylindrical rigid bodies with a given diameter, length, density, and center of gravity. Anchors are approximated as fixtures at the seafloor. The mechanical, geometric and physical properties of the farm's major components are provided in Table 2.

Modeling of the kelp was one of the significant challenges in the development of numerical model. Kelp was modeled with linear elastic elements. However, in order to reduce computing time, individual kelp fronds were aggregated according to a method suggested by Tsukrov et al. (2002) for approximating the individual twines of a finfish aquaculture net as aggregated elements. This method mitigates the issue that arises when scaling diameter for aggregated units and the associated discrepancy between drag related projected area and buoyancy and inertia related cross-section area. Since the drag and inertial terms are decoupled in the Morison equation, their coefficients can be modified such that the drag, buoyancy, and elastic forces on the element, as well as its inertia, can be reproduced independently. Every 5 m of cultivation line and associated kelp growth was aggregated. Furthermore, an aggregation ratio of 1:7 was applied to entire cultivation lines. This resulted in each equivalent kelp element representing 35 m of kelp covered cultivation line.

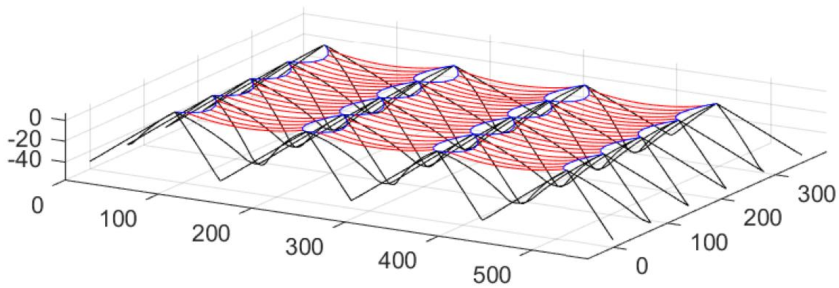


**Figure 2.** Numerical model of the farm in static conditions (no current or waves): mooring lines (black), header lines (blue), and cultivation lines (red). Floats and kelp are not shown. Dimensions are shown in meters.

**Table 2.** Numerical model parameters for farm components

| | Mass Density ($kg/m^3$) | Element Length (m) | Total Length (m) | Elastic Modulus (MPa) | Diameter (mm) |
|---|---|---|---|---|---|
| **Cultivation Lines** | 1530 | 1 max | 140 max | 186 | 27.1 |
| **Kelp** | 1100 | 0.8 | 2.5 | 37 | 384 |
| **Mooring lines** | 940 | 2 | 78.2 | 1,512 | 57 |
| **Anchor chain** | 7880 | 2 | 13.8 | 36,000 | 25 |
| **Header lines** | 940 | 1 | 80 | 1,539 | 59 |
| **Node float** | 142.7 | 3 | 3 | N/A | 1.75 |
| **Tensioning float** | 233.6 | 1 | 1 | N/A | 1 |
| **Dropper float** | 300 | 0.59 | 0.59 | N/A | 0.59 |

Cultivated kelp biomass is comprised of densely packed collections of flexible fronds constantly changing orientation as they interact with the surrounding fluid flow. Fluid movement across this complex geometric structure can typically be characterized as turbulent flow; Rosman et al. studied turbulence in wild kelp forests (Rosman et al. 2010). Turbulent flows are difficult to quantify, with few recognizable patterns between one turbulent flow to another (Davidson, 2015). Thus, parameters used to characterize these flows are usually empirically derived and validated for any given scenario. Fredriksson et al. (2020) used laboratory tests to estimate some key parameters for kelp grown on rope: normal drag coefficient and tangential drag coefficients. They also estimated mass densities and bending stiffness of typical kelp blades which were applied to the numerically modelled kelp. Table 3 provides the hydrodynamic parameters used in simulations. Drag diameter equals normal drag reference area per length, or tangential drag reference area per length multiplied by π.

**Table 3.** Hydrodynamic parameters of the model

| **Component** | **Normal Drag Coeff.** | **Tangential Drag Coeff.** | **Drag Diameter (m)** | **Added Mass Coeff.** |
|---|---|---|---|---|
| Kelp | 5 | 0.015 | 15.3 | 1 |
| Cultivation line | 1.2 | 0.008 | 0.01 | 1 |
| Header line | 1.2 | 0.008 | 0.059 | 1 |
| Anchor line | 1.2 | 0.008 | 0.057 | 1 |
| Tension float | 1.3 | 0 | 1 | 1 |
| Node float | 1.3 | 0 | 1.75 | 1 |
| Dropper Float | 1.2 | 0 | 0.594 | 1 |

Fluid momentum is lost when interacting with the kelp biomass and the farm structure. Friction with kelp blades, subsequent flow stagnation and eddy formation dissipate fluid kinetic energy. These effects are most dramatic in upstream portions of the structure. Consequently, the flow in and around the kelp is different from the free stream flow. Gaylord et al. (2007) studied the modification of fluid flow through natural *Macrocystis Pyrifera* (giant kelp) forests along the California coast. They found that within a few hundred meters of the leading edge of the forest, flow was reduced by up to 30%. Because the flow reduction across cultivated sugar kelp canopies is not well studied, Gaylord et al. studies were used to estimate average flow reduction in the model space. Because the flow cannot be modified based on fluid-structure interaction, the flow was reduced ubiquitously across the model space. "Shadowing coefficients" were defined for different flow regimes and applied as multipliers of ambient current velocity. The coefficients are detailed in Table 4.

**Table 4.** Current shadowing coefficients utilized in the model.

| **current (m/s)** | **0 - 0.3** | **0.3 - 0.6** | **0.6 - 0.9** | **0.9 - 1.2** |
|---|---|---|---|---|
| **parallel to cultivation lines** | 0.80 | 0.70 | 0.55 | 0.40 |
| **perpendicular to cultivation lines** | 0.90 | 0.80 | 0.70 | 0.60 |
| **diagonal to cultivation lines** | 0.85 | 0.75 | 0.63 | 0.50 |

## 4. ENVIRONMENTAL LOADING CASES FOR THE GULF OF MAINE

Extreme conditions for the potential deployment location in the Gulf of Maine were determined through statistical analysis of oceanographic data collected by the National Data Buoy Center, Station # 44027 (used for waves), and Station # 44034 (used for currents). These publicly available data represent decades of ocean wave, wind, and sometimes current magnitudes and directions. Using methods suggested by Goda (2000), return periods for extreme storm events (significant wave heights, and current magnitudes) were established by fitting extreme values from the long-term NDBC data sets to Weibull distributions. 50-year return period conditions were selected to define our design load cases. Aquaculture industry standards, such Norwegian standard NS 9415 (Standards Norway, 2009) typically suggest the application of waves or currents with a 50-year return period in design load cases for aquaculture structures. Dominant wave period was extrapolated via an exponential regression of historical dominant periods versus significant wave heights during steep wave events at NDBC station #44027.

Analysis of aquaculture structures in ocean conditions often involves exposure to monochromatic (regular) waves in numerical modelling space. However, rarely do real-world sea states actually resemble monochromatic wave fields, rather storm conditions are typically characterized by superposition of waves with many different periods, the full composition of which changes throughout a storm's duration. Comparative model simulations of a 4 x 3 tile array were run in order to discern the difference in effect of an irregular sea state versus a monochromatic wavefield on structural response. Because wind driven currents typically accompany storm conditions, current was included in all scenarios. The expected direction of regional extreme current and waves relative to the chosen orientation of the proposed farm are depicted in figure 3.

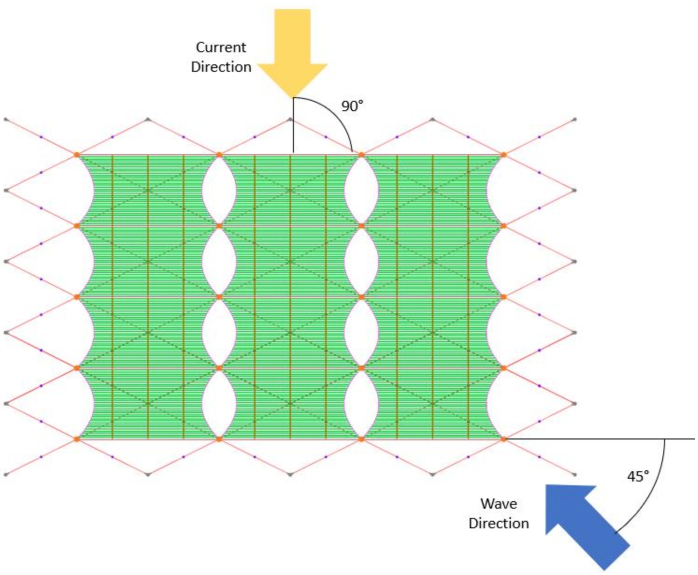


**Figure 3.** Plan view of the 4 x 3 tile farm with wave direction (blue) and current direction (yellow) indicated with respect to the farm orientation. Directions were prescribed according to the typical directions associated with extreme events identified in the NDBC data sets.

Monochromatic wave heights and periods were defined in such a way that they would approximate the passage of a wave with the statistical maximum height and peak period for 50-year return period storm conditions. Regular waves were run with a wave height equal to the largest expected wave in both a 1-hour and a 3-hour storm with the given significant wave height (8.5 m). Nonlinear (large amplitude) wave kinematics were based on the method proposed by Rienecker and Fenton (1981). The most probable largest single wave amplitude ($A_{max}$) was computed according to the following equation.

$$A_{max} = \left(2m_0 \ln \frac{t}{T_2}\right)^{\frac{1}{2}} \quad (1)$$

Here $t$ is the storm duration of interest and $T_2$ is the mean wave period. Furthermore, $m_0$ is the zeroth moment of a narrow-banded wave spectrum, such that significant wave height $H_{1/3} \approx 4\sqrt{m_0}$ (Faltinsen, 1990). The resulting wave heights are provided in Table 5.

Irregular waves fields can be characterized in the frequency spectrum. In OrcaFlex the user has the option to choose from among several methods to define the wave spectrum. For the modelling described in this paper, the ISSC method (a.k.a. Bretschneider or modified Peirson-Moskowitz spectrum) was applied. The spectra were calibrated around significant wave heights and dominant wave period estimate for the chosen 50-year return period. OrcaFlex creates an irregular wave field by assigning random phases (for a given "wave seed") to a user-defined number of wave components within a user-defined frequency range. Each wave component is characterized by a specific frequency and an equal portion of the total spectral energy centered around that frequency. Random wave seeds were selected to ensure that the maximum wave height in the simulation equaled the maximum expected wave in a 3-hour storm.

**Table 5.** Environmental loading cases used for regular vs. random wave comparison

| | **Wave Period (s)** | **Wave Height (m)** | **Duration (s)** | **Current Speed (m/s)** |
|---|---|---|---|---|
| **Regular Wave 1- hour storm** | 9.82 | 15.5 | 300 | 0.44 |
| **Regular Wave 3- hour storm** | 9.82 | 16.7 | 300 | 0.44 |
| **Random Wave** | 9.82[1] | 8.5[2] | 300 | 0.44 |

[1] *Dominant Wave Period*
[2] *Significant Wave Height*

## 5. SIMULATION RESULTS

A numerical representation of the modular offshore kelp farm was built in OrcaFlex and was subjected to the simulated ocean conditions described in section 4. Two regular wave simulations were run; each simulated 5 minutes of ocean conditions. One simulation subjected the structure to successive regular (monochromatic) waves with a height equal to the maximum wave height expected to occur during one hour of storm conditions with the given significant wave height (8.5 m). The other simulation applied wave heights equal to the maximum wave height expected to occur during 3 hours of peak storm conditions. Five random wave simulations were run, each with a duration of 5 minutes. Unique random wave seeds were used to generate the irregular seas applied in each simulation. In this way, the geometry of the largest wave generated in each simulation is also unique. Peak anchor line and header line loads were recorded for each simulation. The results are presented in Table 6. A snapshot of the graphical representation of the numerical model results is depicted in figure 4.

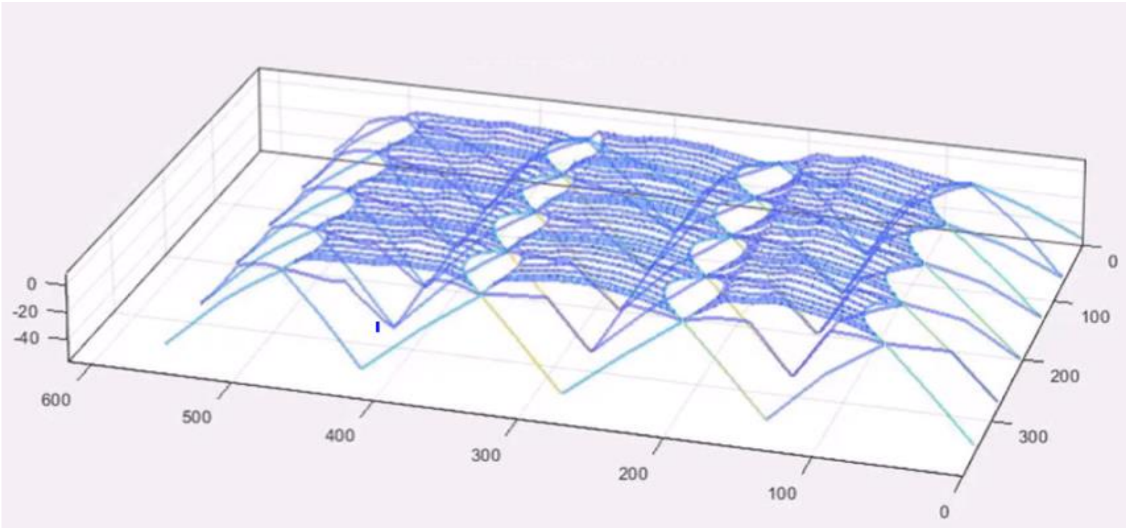


**Figure 4.** Graphical representation of the numerical model during irregular waves conditions. The deformation of the cultivation lines and anchor lines is evident.

**Table 6:** OrcaFlex simulation results

| | Mooring Line Tension (kN) | Header Line Tension (kN) |
|---|---|---|
| **Regular Waves** | | |
| 1 Hour Storm Peak | 333.7 | 340.7 |
| 3 Hour Storm Peak | 386.6 | 376.8 |
| **Irregular Waves** | | |
| Max Peak | 282.6 | 268.8 |
| Mean Peak | 243.3 | 238.2 |
| Standard Dev. | 29.9 | 23.6 |

The recorded tensions indicate mean peak values 59% higher in the anchor lines and 58% higher tensions in the header lines when the structure was subjected to 16.7 m regular (monochromatic) waves compared to random seas with a single maximum wave height of 16.7m. Anchor line and header line tensions were 37% and 40% higher respectively when comparing maximum peak tensions across regular and irregular seas.

## 6. CONCLUSIONS

The simulation results show that the regular wave representation resulted in the predicted peak tensions significantly higher than those obtained with the random sea approach. Given that real sea states can more accurately be defined by irregular waves, the significant discrepancy between model results indicates that the application of regular waves in a simulated design load case would result in significant overdesign of the offshore macroalgae farming structure under investigation.

The cultivation system described in this paper is characterized by large flexible interconnected moored structures with hydrodynamic drag-inducing bodies (kelp) distributed evenly throughout. This is a key difference when compared to finfish aquaculture net pens, where hydrodynamic loading bodies are concentrated at semi-rigid net-pen structures connected to a mooring network which is spread over significantly larger horizontal dimensions. Distributed hydrodynamic loads mean that aggregate loads on anchor lines are highly dependent on the dynamics of a given portion of the wave field, roughly outlined by a single tile. This is in contrast to a finfish net pen that may experience hydrodynamic forcing from a relatively small portion of a wave field, i.e., the flow under only the crest of a passing wave. This would result in a higher sensitivity to large waves, suggesting that monochromatic waves may better represent the peak loading conditions for highly concentrated system such as finfish net pens.

The peak loads experienced by aquaculture systems are also highly dependent on mooring response dynamics. Key drivers of this dynamic response are mooring geometry, elasticity, and buoyancy. These factors combine to define the compliance of the structure. Typically, more compliant structures can avoid intense shock loading, but risk high amplitude motion and loading if resonant behavior occurs with wave loading periods. Stiffer systems can avoid high amplitude regular motion and loading but are prone to violent shock loading.

A structure's relative position on the spectrum between compliant and stiff will play an important role in the suitability of regular or irregular waves to approximate storm loading conditions. Irregular wave fields can interrupt the regularity needed to exhibit resonance, while regular wave fields may not introduce the high contrast, steep waves needed to produce violent shock loads. Because regular waves produced higher loads on the system under investigation, it would suggest that the structures behaved closer to the compliant end of the spectrum: i.e., repeated high amplitude waves created dynamic motions that become amplified with regular periodicity.

Further work is needed to fully characterize the effect of regular versus irregular sea states on kelp aquaculture systems, including a sensitivity analysis of quantified mooring compliance and concentration of loading bodies (within the larger mooring structure). For now, the studies described in this paper were insightful to guide the further model-based design of the proposed kelp aquaculture structure for which irregular sea states were exclusively applied.

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