SEAFISHER –A NOVEL FISH CAGE FOR OFFSHORE AQUACULTURE

Conference Paper · November 2024

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SEAFISHER – A NOVEL FISH CAGE FOR OFFSHORE AQUACULTURE

Chien Ming Wang[1,3], Yunil Chu[1,3], Joerg Baumeister[2], Mingyuan Ma[2], Hassan Karampour[2],
Hong Zhang[2], Martin Ziarmal[2] and Ugo Castellotti[4]

[1]*School of Civil Engineering, The University of Queensland, St Lucia, QLD 4072, Australia*
[2]*School of Engineering and Built Environment, Griffith University, Gold Coast, QLD 4222, Australia*
[3]*Blue Economy Cooperative Research Centre, Launceston, TAS 7248, Australia*
[4]*Maccaferri, 511, Blk G, Phileo Damansara 1, Petaling Jaya, Selangor, Malaysia*
(Corresponding Author's name and email: C.M. Wang, cm.wang@uq.edu.au)

ABSTRACT - Offshore aquaculture is rapidly gaining momentum, driven by the need to address environmental concerns associated with nearshore aquaculture and to mitigate conflicts over coastal water usage among local communities. This keynote paper introduces a novel offshore fish cage design called the SeaFisher. This fish cage is designed to overcome the challenges of fish farming in offshore environments, characterized by strong waves, deep waters, rapid currents, and high winds, especially in storm events. The SeaFisher consists of a 2 × n array of interlocking modular cubic fish cages. Each cubic cage frame is constructed from members formed by bundling four high-density polyethylene (HDPE) pipes, and stiffened by diagrid glass fibre reinforced (GFRP) rods. The HDPE pipes are secured by regularly spaced pipe bundling brackets and at the joints by connector pods. Supported by aluminium tubular frames, the pyramidal shaped top and bottom nets provide air space for salmon jumping and for easy removal of fish morts, respectively. Vertical aluminium ballast tubes, located at the top corners of each cage, allow the SeaFisher to submerge to avoid strong surface waves during storms and to resurface after the storm. The ballast tubes control filling ratio automatically to ensure hydrostability, including compensation for additional biofouling mass. Depth control buoys manage the cage's descent and maintain its submerged position. The SeaFisher is moored by a single mooring point (SPM) system, comprising a buoy, hawser, studlink chain and suction anchor. This system allows the SeaFisher to weathervane; reducing environmental loads and spreading fish waste over a wider water column. Presented herein are the design details of the SeaFisher, its modelling and hydroelastic analysis using the software package AquaSim. The SeaFisher is designed to operate in a significant wave height of 7.58m and current speed of 0.8m/s in the Storm Bay of Tasmania. With its resilient and cost-effective design, the SeaFisher is poised to revolutionize marine fish farming by facilitating the relocation of traditional nearshore farms to more expansive offshore enabling increased production of high-quality fish.

Keywords: Offshore Aquaculture; Submersible Fish Cage; HDPE Modular Cage; Hydroelastic Analysis; Single Point Mooring System.

1. INTRODUCTION

The global demand for sustainable seafood production is rising due to human population growth and improved living standards. Marine aquaculture has become essential in bridging the gap between wild capture seafood supply and growing demand. Farmed seafood production increased by 5.8 times, reaching 29 million tonnes annually from 1990 to 2020, and it is expected to grow to 74 million tonnes by 2050 (DNV, 2021).

Most marine aquaculture farms are traditionally located in sheltered nearshore waters for safe operation, ease of accessibility, power supply and transportation. However, recent opposition from the public and environmentalists highlights concerns over polluting of water, seabed and shoreline, as well as competition for valuable nearshore space for shipping, fishing, leisure, conservation, and tourism (Chu et al., 2020). As a result, obtaining new social licenses for nearshore farm sites has become increasingly challenging for fish farming operators. In response to these criticisms and constraints, there is growing shift towards relocating fish farms to offshore (exposed or open ocean) sites (Wang et al., 2019).

Moving aquaculture activities to offshore can significantly reduce habitat destruction and water pollution due to fish wastes and uneaten feed in the sensitive nearshore water. Offshore locations benefit from better water circulation and dilution from ocean waves and currents (Chu et al., 2020; Sanz-Lazaro et al., 2021). Additionally, the more spacious and pristine water column, cooler temperature, less pathogens and parasites promote healthier and faster fish growth and without the need for antibiotics (Morro et al., 2021; Tveteras et al., 2020).

Offshore aquaculture, however, poses several challenges, including navigating harsher sea conditions, managing an unpredictable marine environment, and addressing operational requirements related to worker safety and support vessels. Additionally, there is a lack of established experience and standards for designing offshore aquaculture farms (Chu et al., 2023). The most significant challenge is ensuring the survivability of farming infrastructure and the well-being of the fish during severe storms that are accompanied by huge surface waves, winds, and shear current actions.

In recent years, there has been a remarkable surge in research and development in offshore fish cages, driven by the advancements in cutting-edge technologies. This is evident from the design and construction of large and robust fish cage systems to withstand highly energetic offshore environments. Examples are Ocean Farm 1 with a height of 69m, a diameter of 110m that can accommodate 1.5 million fish (Zhao et al., 2019), and HavFarm 1 with a length of 380m, width of 59m and houses 10,000 tons of salmon (Li et al., 2017; Wang et al., 2022). However, these cages come with a substantial price tag, exceeding USD100 million each.

New submersible offshore fish cage concepts have attracted attention from fish farm operators due to their cost-effectiveness and potential for sustainable and profitable offshore aquaculture. By submerging the fish cage to an appropriate water depth, strong surface waves during storms can be avoided since the dynamic wave pressure decreases exponentially with depth. Moreover, submersible cages enable the use of offshore sites where floating open net cages are inappropriate due to intense surface waves or seasonal marine variations, or sea lice infestations. Examples of such submersible fish cages are SubFlex (Milich & Drimer, 2019), SeaStation (Loverich, 2010), Atlantis (AKVA group, 2024a) and Nautilus (AKVA group, 2024b).

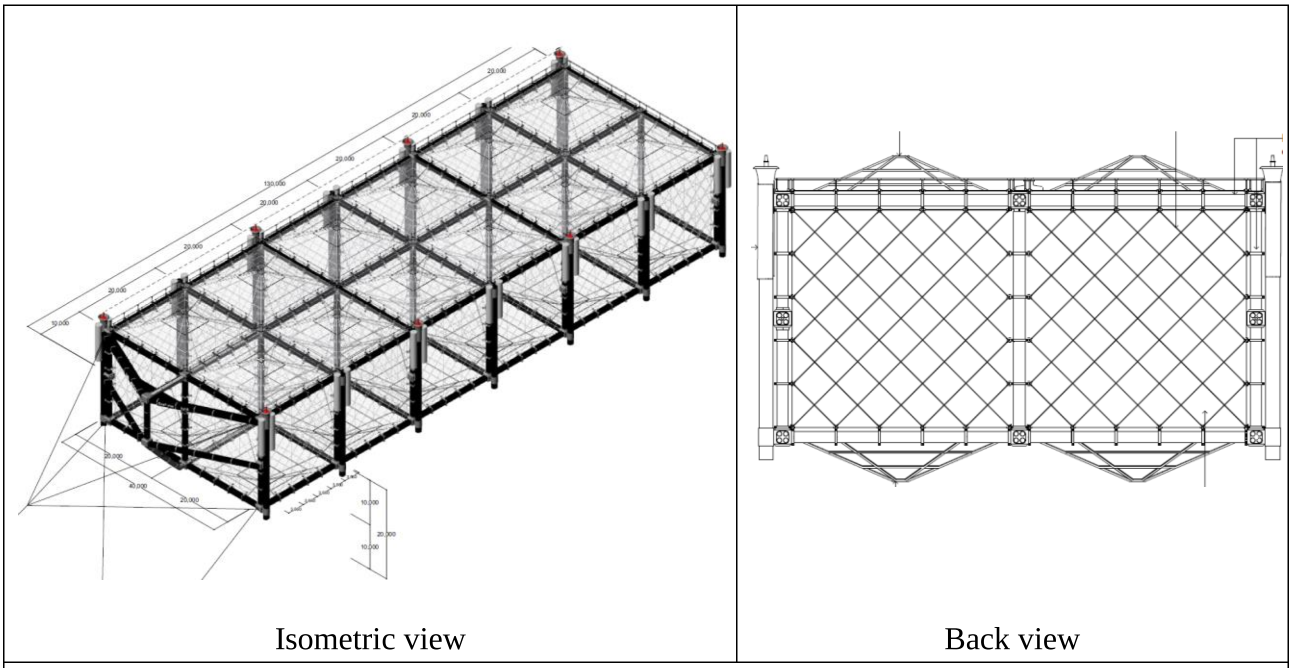
This paper introduces the SeaFisher which is a submersible offshore fish cage developed as part of a Blue Economy CRC research project that is focused on developing innovative offshore aquaculture solutions (Wang et al., 2023). In Section 2, a detailed description of the SeaFisher design and its various components are presented. Section 3 furnishes the hydroelastic responses of the SeaFisher and mooring forces under wave and current actions. Section 4 presents future research activities towards the commercialization of the SeaFisher.

2. DESCRIPTON OF SEAFISHER DESIGN

This SeaFisher is designed to tackle the challenges faced by farming fish in high-energy ocean environments that are characterized by deep waters, strong waves, fast currents, and high winds, especially during storms. The design features a 2 × *n* array of interlocking modular cubic fish cages, each measuring 20m × 20m × 20m. So, if *n* is 6, the SeaFisher measures 120m long, 40m wide and 20m high as illustrated in Figure 1.

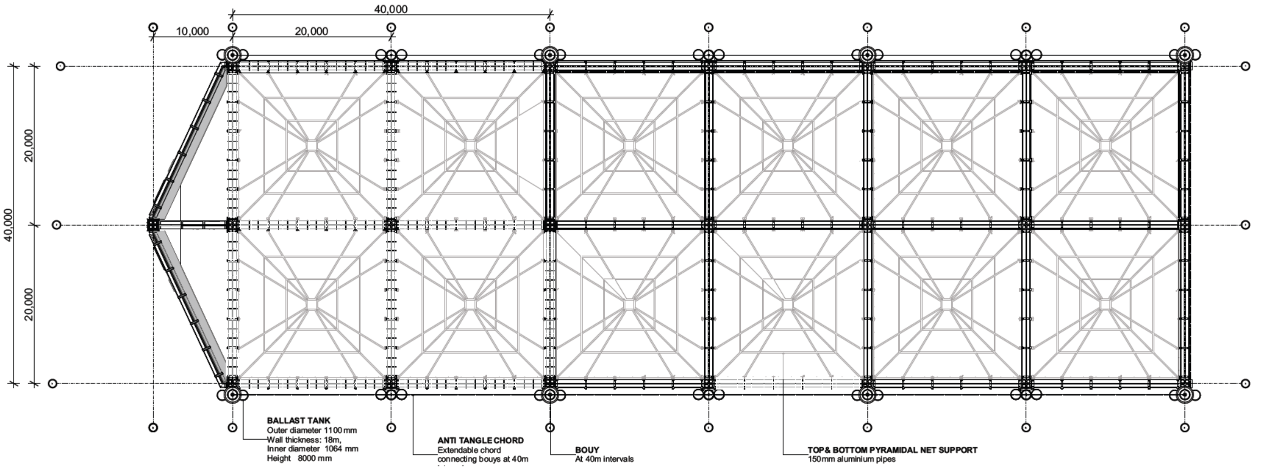
The frame structural member is constructed from bundling four High-Density Polyethylene (HDPE) pipe, each pipe with a 0.5m diameter, secured by custom-made brackets and connector pods, as shown in Figure 2. HDPE is chosen for its resistance to rotting and weathering, ease in construction of diverse structural forms, superior antibiofouling properties compared to other materials, and cost-effectiveness when procured in large quantities (Goudey et al., 2001). The bundled pipes are wrapped with thin HDPE sheets to create a protective smooth outer skin which prevents biofouling within the narrow spaces between pipes, helps reduce drag forces, and facilitates cleaning. The HDPE sheets can be bent by thermoforming and be extrusion welded to make the final closed shape. The protective skin will be welded onto the intermediate pipe bundling brackets to seal any gaps.

Given that HDPE has slightly lower density than seawater, it is necessary to fill the pipes with seawater and the bottom pipes with sand to keep the SeaFisher in the water with a freeboard of 0.5m. To stiffen the flexible HDPE frame structure, diagrid glass fibre reinforced (GFRP) rods are installed in all square cage panels except for top and bottom panels. The top surface panel of each cubic cage has a square pyramidal net supported by aluminium tubular frame (as shown in Figure 1) with its apex position at 4m above the water surface. This design provides sufficient space for fish (such as salmon) to access air and jump out of the water for better health (Oppedal et al., 2020). Additionally, the top third of the pyramidal net covered with a tarpaulin can serve as an air dome when the SeaFisher is submerged. Likewise, the bottom panels have a truncated square pyramidal aluminium frame-net to facilitate the collection of fish morts at the base. L-shaped zippers are incorporated in the top and bottom nets for easy access to the fish and fish morts removal. An HDPE shield barrier is positioned at the bow of the SeaFisher to protect the SeaFisher from floating debris and strong surface waves.

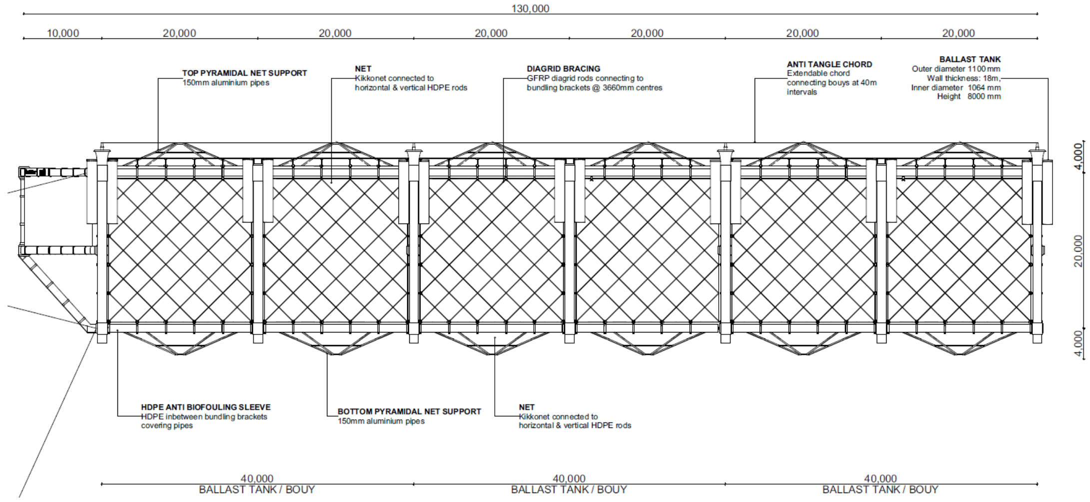


Isometric view

Back view



Plan view



Side view

Figure 1: Engineering drawings of SeaFisher

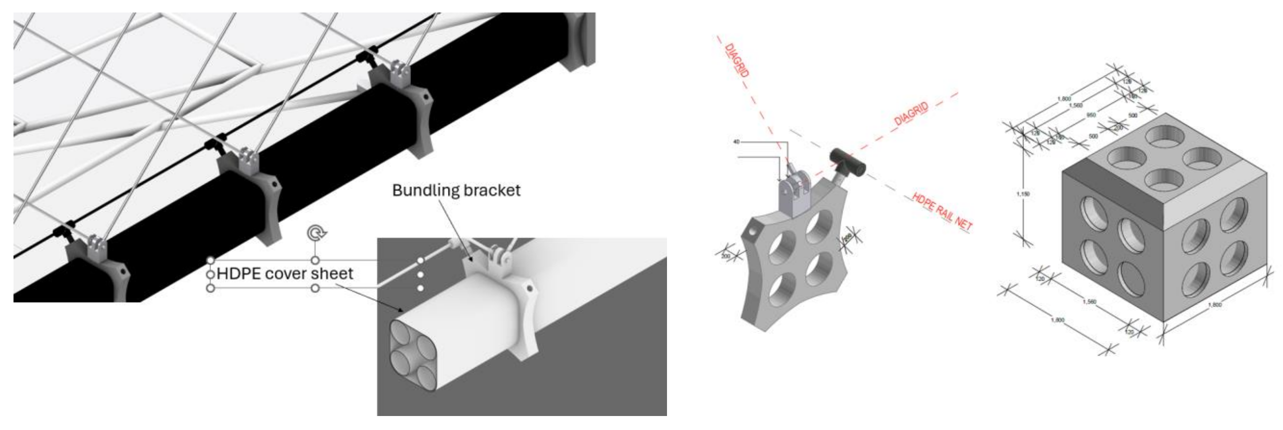


Figure 2: Pipe bundling brackets, HDPE cover sheet and connector pods

Maccaferri’s Kikkonet fish containment net, made from PET, is adopted as the SeaFisher cage net due to its superior strength and stiffness when compared to commonly used nylon nets. Moreover, its knotless and smooth monofilament design is effective against biofouling. Autonomous cleaning robots, such as the ones manufactured by AquaRobotics AS (AquaRobotics AS, 2024), may be deployed to clean the Kikkonet from biofouling organisms.

Open-bottom aluminium ballast tubes are positioned at the top corners of the cubic cages, both side of the housings for depth control buoys and adjacent to the vertical HDPE frames. These ballast tubes enable to add or remove buoyancy, allowing the SeaFisher to submerge during storms to avoid strong surface waves and to resurface afterwards (see Figure 3). To submerge, compressed air is released from the ballast tubes through pressure sensitive valves, allowing seawater to enter the tubes. To resurface, compressed air is pumped into the tubes to displace the seawater. The ballast tubes also ensure that the SeaFisher is always at an even keel and have sufficient buoyancy, compensating for additional weight due to biofouling.

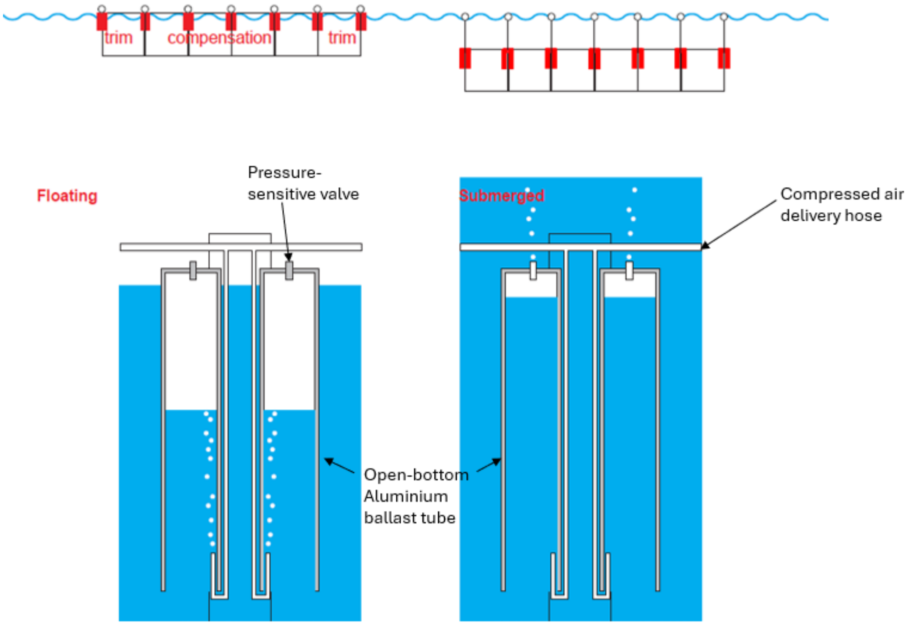


Figure 3: SeaFisher ballasting system

There is a diving support system consisting of depth control buoys and bottom weights, spaced 40m apart along both side corners of the SeaFisher. This system acts like a stopper during submersion, ensuring that the SeaFisher remains at its designated submerged position. The depth control buoys, and bottom weights are connected vertically by extensible polyester cords. Additionally, the depth control buoys are interconnected longitudinally by inextensible Dyneema (Ultra-High Molecular Weight Polyethylene) cords to prevent entanglement and maintain the buoys in equal spacing for enhancing overall safety of diving and refloating operations as illustrated in Figure 4.

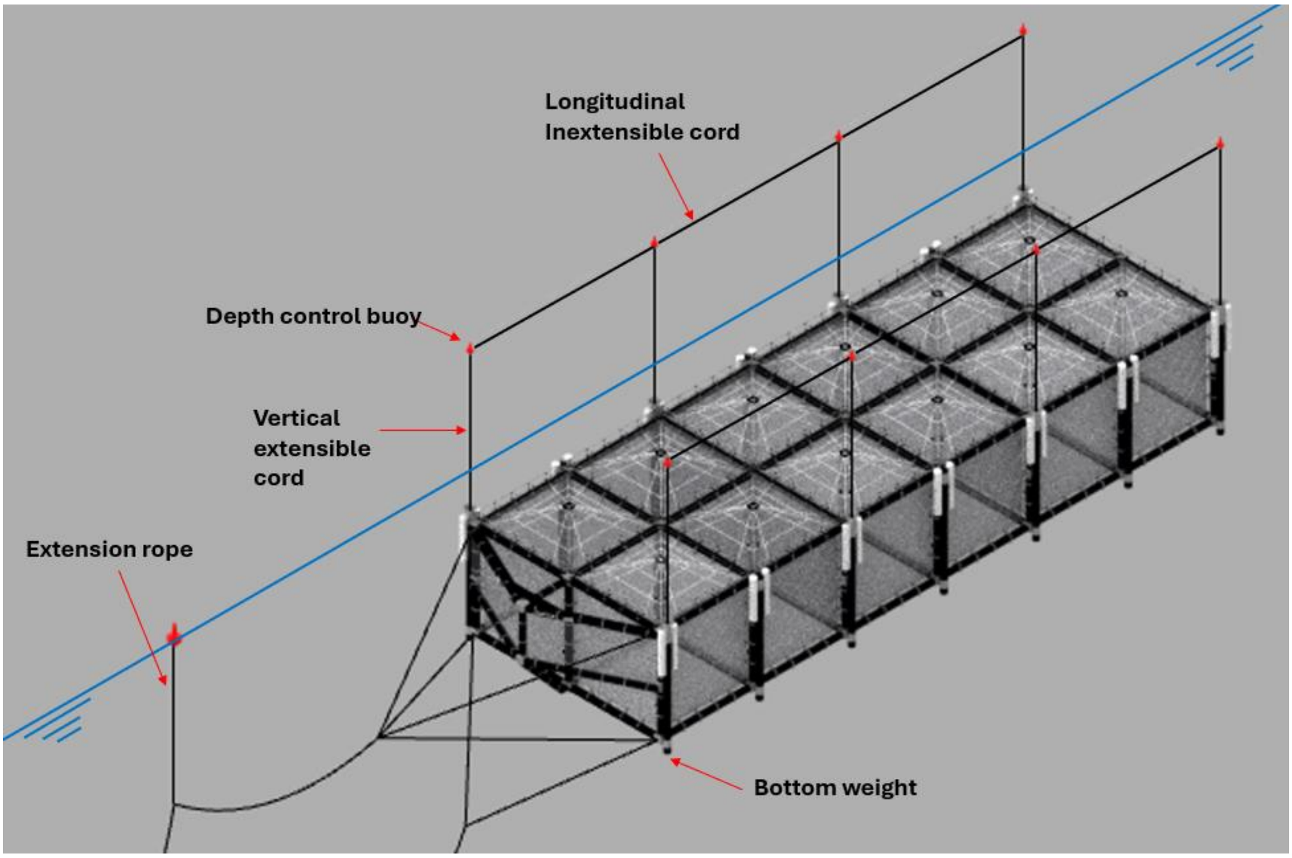


Figure 4: Illustration of diving support system

The SeaFisher is kept in position by a single mooring point (SPM) system comprising a centre buoy, a hawser, studlink chains, and a suction anchor. The hawser used in this study is constructed with two bundled nylon sheaths over a braided hollow core, each has 32 core strands and 64 sheath strands. There is an additional identical hawser (long and loose secondary hawser) to hold the SeaFisher in case the primary hawser fails. The hawser is attached to a connecting plate that spreads the mooring force to the SeaFisher structure via cables as shown in Figure 5. This SPM system allows the SeaFisher to weathervane, reducing environmental loads on the fish cage (Wang et al., 2022) and dispersing fish waste and uneaten feed over a wider water column.

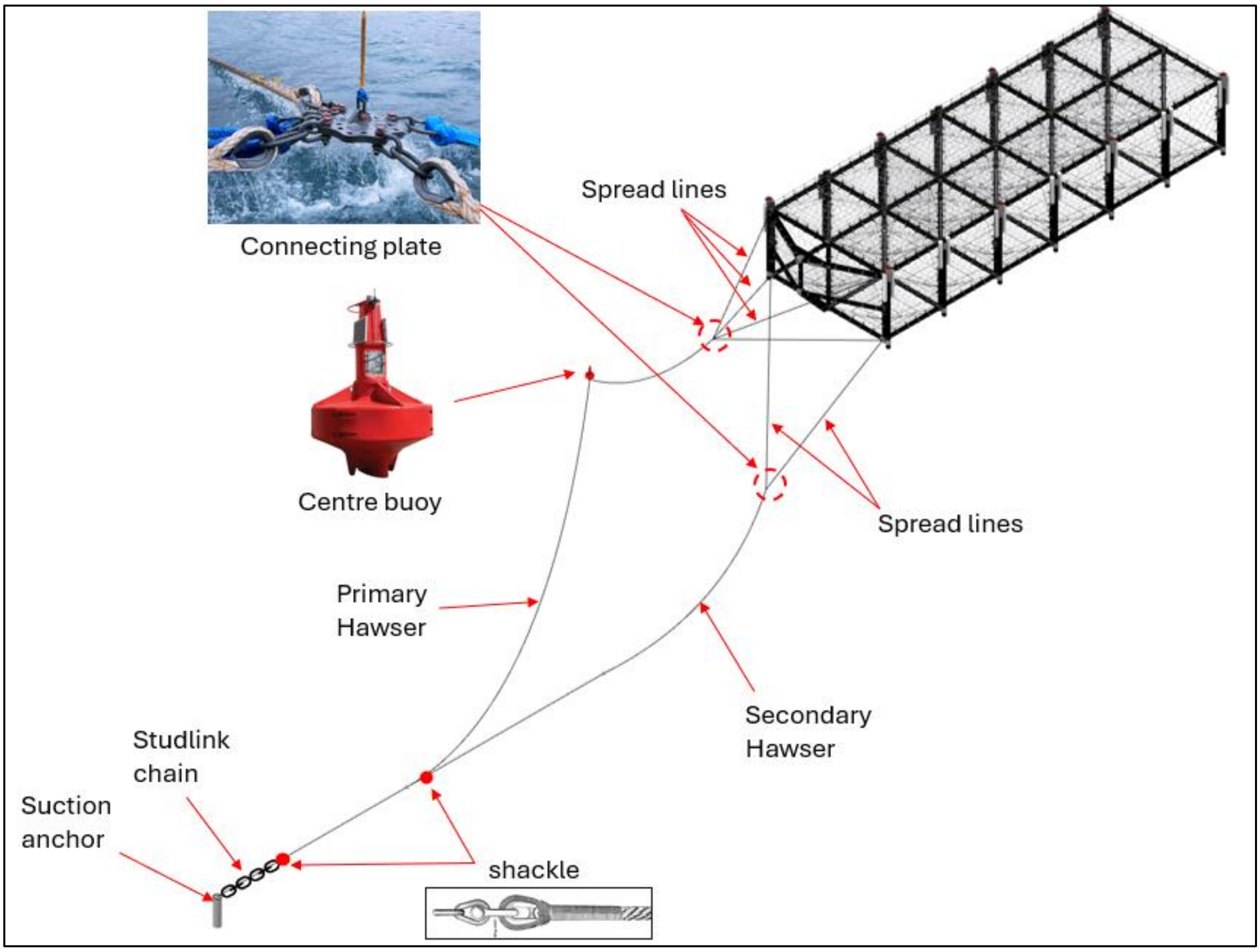


Figure 5: Mooring arrangement

Table 1 and Table 2 present the selected materials and properties for the SeaFisher's fish cage pipes and Kikkonet, respectively. Table 3 and Table 4 summarize the material and geometrical properties of the mooring system components, as well as the diagrid rod used for reinforcing the fish cage frames, the extensible and inextensible cords connecting between the depth control buoys and the bottom weights, and aluminium tube for top and bottom net frames. The material properties of hawser, studlink chain, diagrid rod, and aluminium tube were taken from Lankhorst (2024), DNV (2011, 2015), Khan et al. (2015), and ASM International (ASM International, 1984) respectively. The Young's modulus of GFRP was taken from compression testing results of a GFRP rod obtained by Khan et al. (2015), which is lower than tensile testing results, to be conservative. Table 5 shows hydrostatic parameters for the bundled HDPE fish cage frame and ballast tubes of the SeaFisher.

Table 1: Material properties of fish cage HDPE pipes for frames and connectors

Material	Applied Components	Mass Density	Young's Modulus	Shear Modulus	Poisson's Ratio
HDPE	frames, connectors	958 kg/m³	1.0 GPa	0.384 GPa	0.30

Table 2: Monofilament properties of Kikkonet (supplied by Maccaferri)

Thread Diameter	Tensile Strength	Elongation at Break	Mesh Size
2.5 mm	230 MPa	20 mm	35 mm

Table 3: Material and geometrical properties of mooring system

Properties	Primary Hawser	Secondary Hawser	Studlink Chain	Spread Line primary / secondary
Material	Nylon	Nylon	Steel	Nylon
Number of lines	2 (bundled)	2 (bundled)	1	4 / 2
Line diameter (mm)	168	168	122	168
Young's modulus (GPa)	2.7	2.7	56	2.7
Weight in air (kg/m)	17.47	17.47	196.6	17.47
Breaking strength (kN)	6235	6235	9990	6235

Table 4: Material and geometrical properties of diagrid rod, extensible, inextensible cord and top and bottom net frames

Properties	Diagrid Rod	Extensible Cord	Inextensible Cord	Top/bottom net frame (thickness)
Material	GFRP	Polyester	Dyneema	Aluminium
Diameter (mm)	27	30	30	150 (6)
Young's modulus (GPa)	42	22	120	68
Weight in air (kg/m)	1.76	0.62	0.97	7.3
Breaking strength (kN)	1000	818	1000	651

Table 5: Component dimensions, ballasting, and permanent filler in pipes

Component	Dimensions	Material	Filler	Density of Filler
			Full/ Partial/ Ballast	kg/m³
Top longitudinal and transverse pipes	- Outer diameter: 500mm - Wall thickness: 45mm - Length: 20m per unit fish cage - Number of pipes: 128	HDPE	Partial (bottom two pipes only)	1024 (seawater)
Vertical pipes	- Outer diameter: 500mm - Wall thickness: 45mm - Length: 20m per unit fish cage - Number of pipes: 88	HDPE	Full	1024 (seawater)
Bottom longitudinal and transverse pipes	- Outer diameter: 500mm - Wall thickness: 45mm - Length: 20m per unit fish cage - Number of pipes: 128	HDPE	Full	1535 (sand)
Ballast tubes with open bottom	- Outer diameter: 1100mm - Wall thickness: 18mm - Length: 8m per tube - Number of tubes: 28	Aluminium	Ballast	-

Based on the hydrostatic analysis, it is found that the filler density required for the bottom pipes is equivalent to that of sand (between 1520 to 1680 kg/m^3), which is a good filler material due to its fine particles. Table 6 presents different displacement masses (i.e., buoyant mass) of the SeaFisher at surface and at 30 m submerged state. When the SeaFisher is fully submerged, the entire section of the top frame is assumed to contributes to buoyancy, whereas only half of the top frame section contributes to buoyancy when the SeaFisher floats at the water surface. In contrast, the ballast tubes contribute to buoyancy when the SeaFisher floats at the water surface, while they do not contribute to buoyancy when the SeaFisher submerged. Given the assumptions, the SeaFisher will remain in a neutral buoyant condition when it floats at the surface, while it will be slightly negative buoyant condition when submerged. However, the negative buoyant force resulting from submersion will be compensated by the additional positive buoyant force provided by the 8 depth control buoys, each with a diameter of 1.4m and height of 2.7m, that can supply the appropriate displacement mass when immerged to one-third of their height.

Table 6: Hydrostatic calculation of SeaFisher at surface and submerged states

States	Structure mass (a)	Moorings, net and diagrid Mass (b)	Total mass (A = a + b)	HDPE pipes displacement mass (c)	Ballast tubes displacement mass (d)	Total displacement mass (B = c+d)	B − A
	Tonnes	Tonnes	Tonnes	Tonnes	Tonnes	Tonnes	Tonnes
Surface	1526	50	1576	1358 (half section)	218	1576	0
Submerged 30m	1526	50	1576	1564 (full section)	0	1564	-12

Note that the structure mass in Table 6 accounts for filler masses.

3. HYDROELASTIC RESPONSE OF SEAFISHER UNDER WAVES AND CURRENTS

For the modelling and hydroelastic analysis, we utilise the AquaSim software package (Berstad, 2024). AquaSim performs hydroelastic analysis in a time domain which is tailored for assessing aquaculture infrastructure under wave, current and wind actions with consideration for nonlinear behaviour of coupled flexible structures.

Considering the deployment of SeaFisher in the Storm Bay, Tasmania, Australia, the design irregular wave condition is characterised by a significant wave height (H_s) of 7.58m and a zero-crossing wave period (T_z) of 9.87s, with a 100-year return period based on the JONSWAP spectrum. This 100-year return period wave data was derived from the extrapolation of 35 years of metocean records at the deployment site. For a conservative and simplified approach, a constant current speed of 0.8m/s, representing the 100-year return period current, is assumed to coincide with the direction of the irregular waves. Assuming the Rayleigh distribution for the wave height, the maximum wave height is 1.9 times of the significant wave height for irregular waves modelled by JONSWAP (Norwegian Standard, 2021). To capture this maximum wave height, 50 random wave cycles were found to be sufficient to generate at least one maximum wave height of 14.4m as shown in Figure 6.

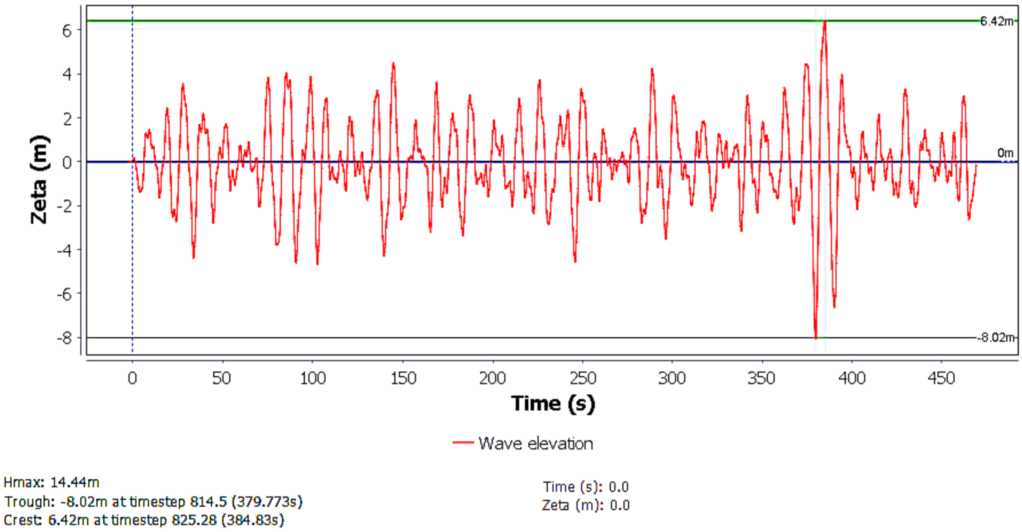


Figure 6: Irregular waves generated from JONSWAP spectrum capturing the maximum wave height of 14.4m

In the analysis models (see Figure 7), the HDPE pipes, aluminium ballast tubes, and top and bottom net frames were modelled using beam elements. The GFRP rods were modelled as truss elements, while the Kikkonet net was modelled using membrane elements, accounting for its drag efficiency based on the thread diameter and mesh length in Table 2. The centre buoy was modelled with a node-to-spring element, reflecting the waterplane stiffness of a standard 5m marine buoy. The node-to-spring element was removed from the submerged model, as the buoy is designed to have an extended connecting line (see Figure 4) to the hawser to prevent any possible intervention with the submerged SeaFisher. Both the hawser and studlink chains were modelled as truss elements. The last four truss elements of the studlink chain are fixed at one end, which is assumed to be securely anchored to the seabed by a suction anchor. The vertical extensible and horizontal inextensible cords and their dynamic effects were not incorporated in the hydrostatic and hydroelastic analyses as the diving support system was treated as a separate system that did not directly affect the overall mass and buoyancy of the SeaFisher.

Hydroelastic analyses were performed for various sea state conditions; however, due to space limitation, only the results for 3 specific conditions are presented: SeaFisher at the surface with H_s = 5m, T_z = 8.02s; at the surface with H_s = 7.58m, T_z = 9.87s; and submerged at 30m with H_s = 7.58m, T_z = 9.87s. In all cases, a current speed of 0.8m/s in the same direction as waves was considered.

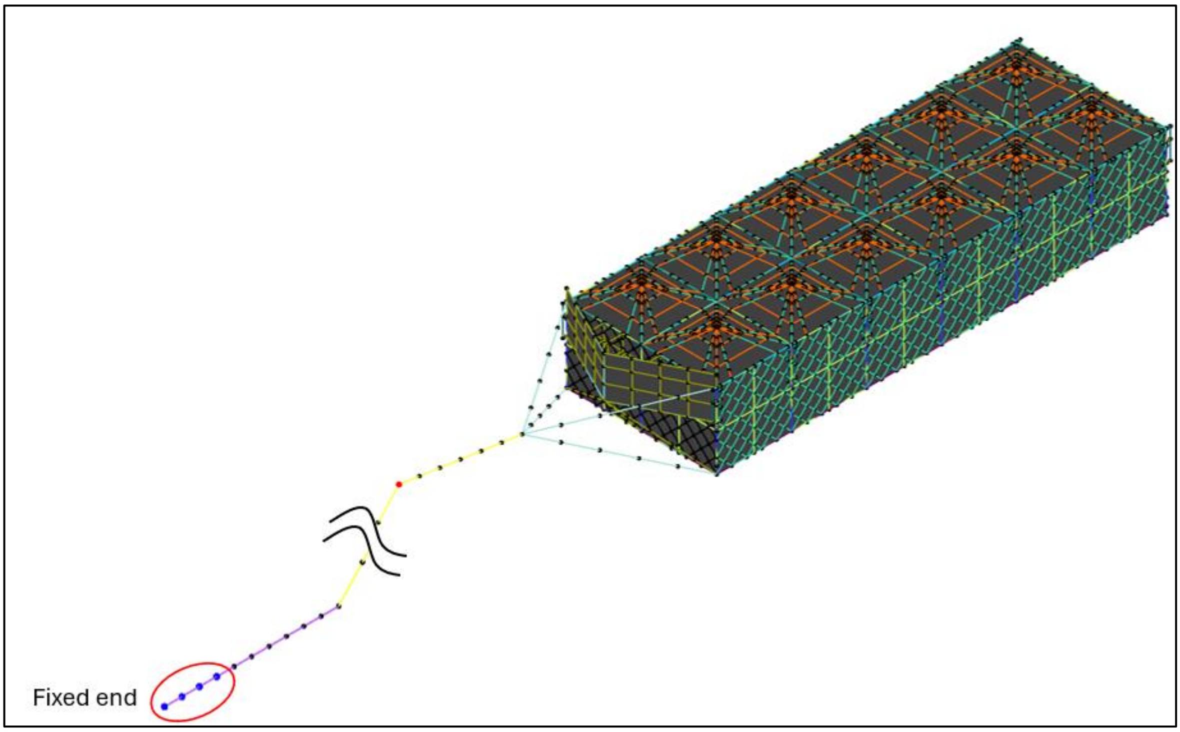


Figure 7: Hydroelastic analysis model for SeaFisher

Table 7 compares the maximum values of deflection, stress and force obtained from the analysis against the design permissible values for the key components of SeaFisher. These design permissible limits were specified by the Norwegian Standard for Fish Farms (Norwegian Standard, 2021), which is widely recognized for assessing HDPE fish cages (Chu et al., 2023), the technical guidance (ASM International, 1984; DNV, 2011, 2015), manufacturer brochure ((Lankhorst, 2024) and experimental test results from (Bureau of Engineering city of Los Angeles, 2023; Han, 2017; Khan et al., 2015; Wu and Zhang, 2017).

It can be seen that the maximum deflections of the SeaFisher structural members are at mid-span and they are relatively small because of the stiffening effect provided by the diagrid GFRP rods (see Table 7).

When the SeaFisher is at the surface under the high sea state with H_s = 7.58m, the safety margins for von Mises stress in some HDPE structural members, tension forces in the hawser and studlink, and compressive force in some aluminium frame tubes are violated (indicated by the red-coloured safety margins in brackets in Table 7). However, when the SeaFisher is submerged 30m below the water surface, all the maximum values of structural responses have adequate design safety margins. Note that the safety margins for all structural responses have to be above unity, while the safety margins for the hawser and studlink have to be at least 2.1 in a single-point mooring system (Chu et al., 2023; DNV, 2015). However, the safety margins are satisfied when the SeaFisher is at the surface with a sea state with H_s = 5.00m (having a maximum wave height of 9.5m) and T_z = 8.02s. This sea state condition will be adopted as the limit sea condition for SeaFisher to remain at the water surface. Beyond this sea state limit, the SeaFisher will be submerged at 30m below water surface.

Table 7: Design permissible limits and maximum values due to current (speed of 0.8m/s) and irregular waves

Structural Response	Unit	Design Permissible Value	Maximum value (Safety Margin=permissible value / maximum value)		
			Surface, H_s = 5m, T_z = 8.02s	Surface, H_s = 7.58m, T_z = 9.87s	Submerged, H_s = 7.58m T_z = 9.87s
Vertical mid-span deflection in centre longitudinal HDPE pipes (check for strength)	m	1.5 i.e. 7.5% of length (Han, 2017)	0.07	0.08	0.05
von Mises stress in HDPE pipes (check for strength)	MPa	13 (Norwegian Standard, 2021)	10.42 (1.25)	18.21 (0.72)	8.55 (1.53)
Tension force in HDPE pipes (check for strength)	kN	5911 (PE100+Association, 2018)	1188 (4.98)	2192 (2.70)	763 (7.75)
Compression force in HDPE pipes (check for buckling)	kN	2038 (PE100+Association, 2018)	912 (2.24)	1538 (1.33)	623 (3.28)
Axial force in GFRP diagrid rod (check for strength)	kN	1000 (Khan et al., 2015)	200 (5.00)	354 (2.83)	188 (5.32)
Tension force in aluminium frame (check for strength)	kN	651 (ASM International, 1984)	289 (2.26)	545 (1.20)	203 (3.21)
Compression force in aluminium frame (check for buckling)	kN	426 (Euler buckling)	418 (1.02)	451 (0.95)	234 (1.83)
Tension force in hawser (check for strength)	kN	6235 (Lankhorst, 2024)	2147 (2.91)	3336 (1.87)	1243 (5.02)
Tension force in studlink chain (check for strength)	kN	9990 (DNV, 2011)	4262 (2.35)	6635 (1.51)	2485 (4.03)

4. FUTURE RESEARCH ACTIVITIES FOR SEAFISHER DEVELOPMENT

Currently, the SeaFisher design is at Technology Readiness Level (TRL) 3. The next phase of development involves conducting physical model tests in a towing tank and wave basin to calibrate and validate the mathematical models and assumptions used in the static and hydroelastic analyses. This phase will also help to identify any physical phenomenon not captured in the analysis. Different scale models (e.g., 1:50 and 1:25) will be utilised in the tests to examine the scale effects. Additionally, tests will be carried out on the new HDPE connector system, diagrid GFRP rods, top/bottom net frames and Kikkonet net to ensure the safety of the SeaFisher design against stresses and fatigue. Successful completion of the next phase of the project will advance the SeaFisher design to TRL 4 or TRL 5. For this novel fish pen design, enabling technologies such as digital twins and autonomous ROVs for cleaning, monitoring and repair have to be developed as well.

5. ACKNOWLEDGEMENTS

The authors acknowledge the financial support of the Blue Economy Cooperative Research Centre (CRC), established and supported under the Australian Government's CRC Program, grant number CRC-20180101. The authors would like to thank Aquastructures AS for granting access to their amazing software AquaSim.

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