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Summary of an Engineering Evaluation and Design of Loch Melfort Aquaculture System for Open Climate Solutions

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For: Open Climate Solutions

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1.0	02/27/2023	Nate Baker, Sam Rickerich	Dewhurst	Dewhurst	Released for Public Viewing

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1 Executive Summary

The purpose of this engineering evaluation was to mitigate the risk of structural failure and maximize performance and operability in the proposed aquaculture farm system.

Kelson Marine Co. ("Kelson") calculated extreme current, wave, and wind conditions corresponding to a storm that would occur once every 50-years (the 50-year storm). Kelson constructed a numerical model of the farm and simulated a series of characteristic loadcases to determine the proposed system's response to the current, wave, wind, and tidal variations. Observed challenges with the proposed design were mitigated by iterative design improvements.

2 Introduction

This report summarizes an engineering design analysis for the proposed aquaculture farm in a variety of design current, wind, and wave conditions.

The primary goal of this engineering design work was to design and evaluate an aquaculture farm structure suited for semi-exposed sites in Scotland.

These goals were achieved through the completion of the following tasks:

1. Determine Environmental Design Conditions
2. Quantify Structural Response and Performance
3. Assess Required Component Capacities

3 Design Basis: Design Requirements and Relevant Standards

3.1 Relevant Standards

Environmental loads on open ocean structures are driven by currents, waves, water levels, and wind (DNV, 2010). Kelson's characterization of these metocean variables and their extreme values conforms to NS 9415:2021, *Floating aquaculture farms Site survey, design, execution and use,* as much as possible (Standards Norway, 2022). Additional relevant guidance includes:

- "A Technical Standard for Scottish Finfish Aquaculture" (Ministerial Group for Sustainable Aquaculture's Scottish Technical Standard Steering Group, 2015)
- "Basis-of-Design Technical Guidance for Offshore Aquaculture Installations in the Gulf of Mexico" by the U.S. Dept. of Commerce's National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Southeast Regional Office. (Fredriksson & Beck-Stimpert, 2019)
- "Guidance Notes on the Application of Fiber Rope for Offshore Mooring" (ABS, 1999).
- "Guide for Position Mooring Systems" (ABS, 2018).
- "Design and analysis of station keeping systems for floating structures" (ABS, 1999)

NS 9415 and the Scottish standard mandate that structures be designed to withstand 50-year storms. No agreed-upon standard exists for non-finfish aquaculture and its relatively lower associated risks compared to finfish systems. To ensure a conservative analysis, and to comply with guidance from the relevant permitting agencies for this project, the 50-year storm condition was taken to be the design standard for the present study.

For the present study, Kelson compared design capacities from safety factors in NS9415 and ABS "Position Mooring Systems". Kelson also applied a 15% additional model validation factor to the ABS safety factors, and an additional adjustment to drag anchor holding factor to account for uplift.

4 Site Parameters and Extreme Meteorological Ocean Conditions

4.1 Location

The Project Site is located on the West Coast of Scotland in Loch Melfort, in Kilchean Bay ~100 m to the west of Eilean Coltair (Figure 1 and Figure 2). The proposed cultivation array is contained within permit area of the coordinates in Table 1.

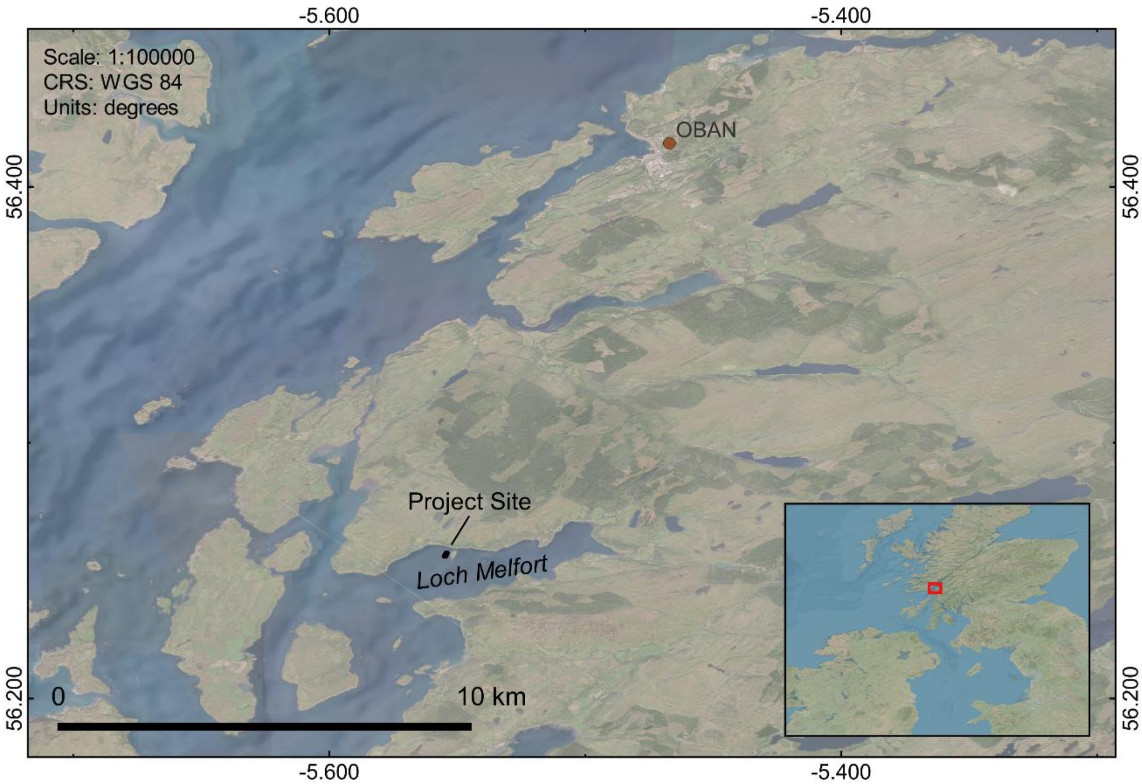

Figure 1: Location of the Project Site in Loch Melfort.

Table 1: Coordinates of the permit area that define the Project Site, as specified by the Client. Coordinates of a yellow marker buoy are given as well.

ID	Longitude (WGS 84)	Latitude (WGS 84)
Block A	5°33.278'W	56°15.437'N
Block B	5°33.330'W	56°15.329'N
Block C	5°33.204'W	56°15.428'N
Block D	5°33.257'W	56°15.315'N
Yellow Special Marker Buoy	5°33.364'W	56°15.313'N

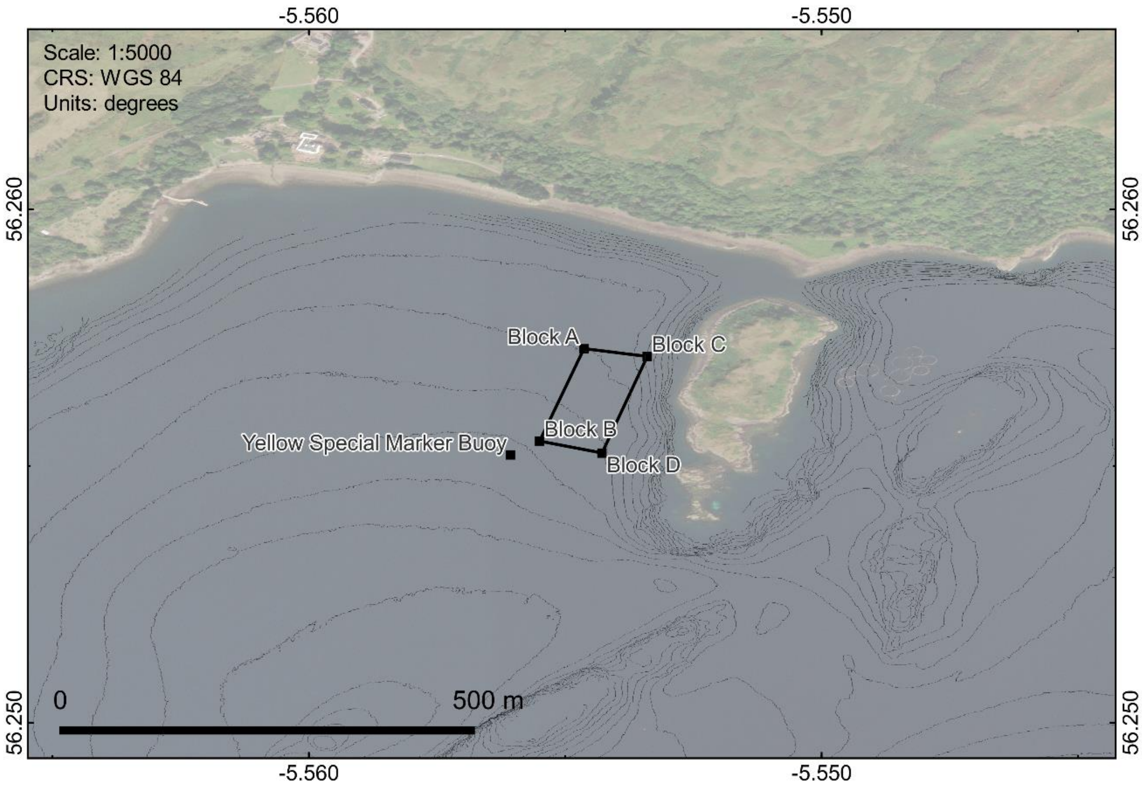

Figure 2: Project Site lease boundary and location of the Yellow Special Marker Buoy. Bathymetry 2 m contours are shown from data from Section 4.2. Eilean Coltair is the small island to the east of the Project Site.

4.2 Bathymetry

Depths in the Project Site range from 25.52 to 17.86 m LAT, with a mean depth of 23.13 m LAT (Figure 2).

4.3 Summary of Metocean Conditions

Kelson conducted a full analysis of the currents, wind, and waves of the site to identify the extreme percentile and return-period associated extreme values for 8 directional bins. The maximum direction-agnostic metocean values with a 50-yr return period are shown in Table 2.

The site outlined in Figure 2 is sheltered by the islands to the east and by its location within the loch. The extreme loads that this site experiences are likely to be less than those that other nearby potential sites would experience. The extreme 50-yr return period metocean values in Table 2 apply to this site only. These values should not be assumed to be characteristic of any other site.

Table 2: Metocean Conditions, 50-yr Return Period, Direction Agnostic

	Surface Current Speed	**10m Wind Speed**	**Significant Wave height**	**Peak Period**
Units	m/sec	m/sec	m	sec
50-yr Return Period Values	0.22	35.1	0.6	2.3

4.4 Biomass

The primary species to be cultivated is *saccharina latissima* at a maximum average biomass of 9 kg/m of cultivation line.

5 Engineering Design and Evaluation

5.1 Numerical Modeling Approach

The proposed farm is located in an exposed ocean site subject to wind, waves, and currents. Since the aquaculture system is comprised of flexible components subject to nonlinear wave and current forces, static analysis of the structure was not sufficient for determining the required structural capacity. Therefore, Kelson Marine Co. ("Kelson") developed a numerical model of the proposed structure using a Hydro-/Structural Dynamic Finite Element Analysis approach (HS-DFEA). This HS-DFEA approach solves the equations of motion at each time step using a nonlinear Lagrangian method to accommodate the large displacements of structural elements, as described in NOAA's Basis-of-Design Technical Guidance for Offshore Aquaculture Installations in the Gulf of Mexico (Fredriksson & Beck-Stimpert, 2019). Wave and current loading on buoy and line elements (including biomass elements) is incorporated into the model using a Morison equation formulation (Morison et al., 1950) modified to include relative motion between the structural element and the surrounding fluid. For elements intersecting the free surface, buoyancy, drag, and added mass forces are multiplied by the fraction of the element's volume that is submerged. Wave forcing and steady incident flow are specified by the user, and reduction in current speed through the farm is accounted for. The hydrodynamics of the macroalgae were incorporated using the modeling techniques developed by Kelson Marine, the U.S. Naval Academy, the University of New England, and collaborators under the U.S. Dept. of Energy Advanced Research Projects Agency-energy (ARPA-e) MARINER project. Kelson and collaborators have demonstrated the validity of this approach by comparing model predictions against measurements of line tension in a full-scale exposed *saccharina latissima* cultivation backbone at an open-ocean site in the Gulf of Maine, which were found to be within 15% of predicted values on average.

5.2 Design Results

The farm configuration resulting from design iterations is shown in Figure 3.

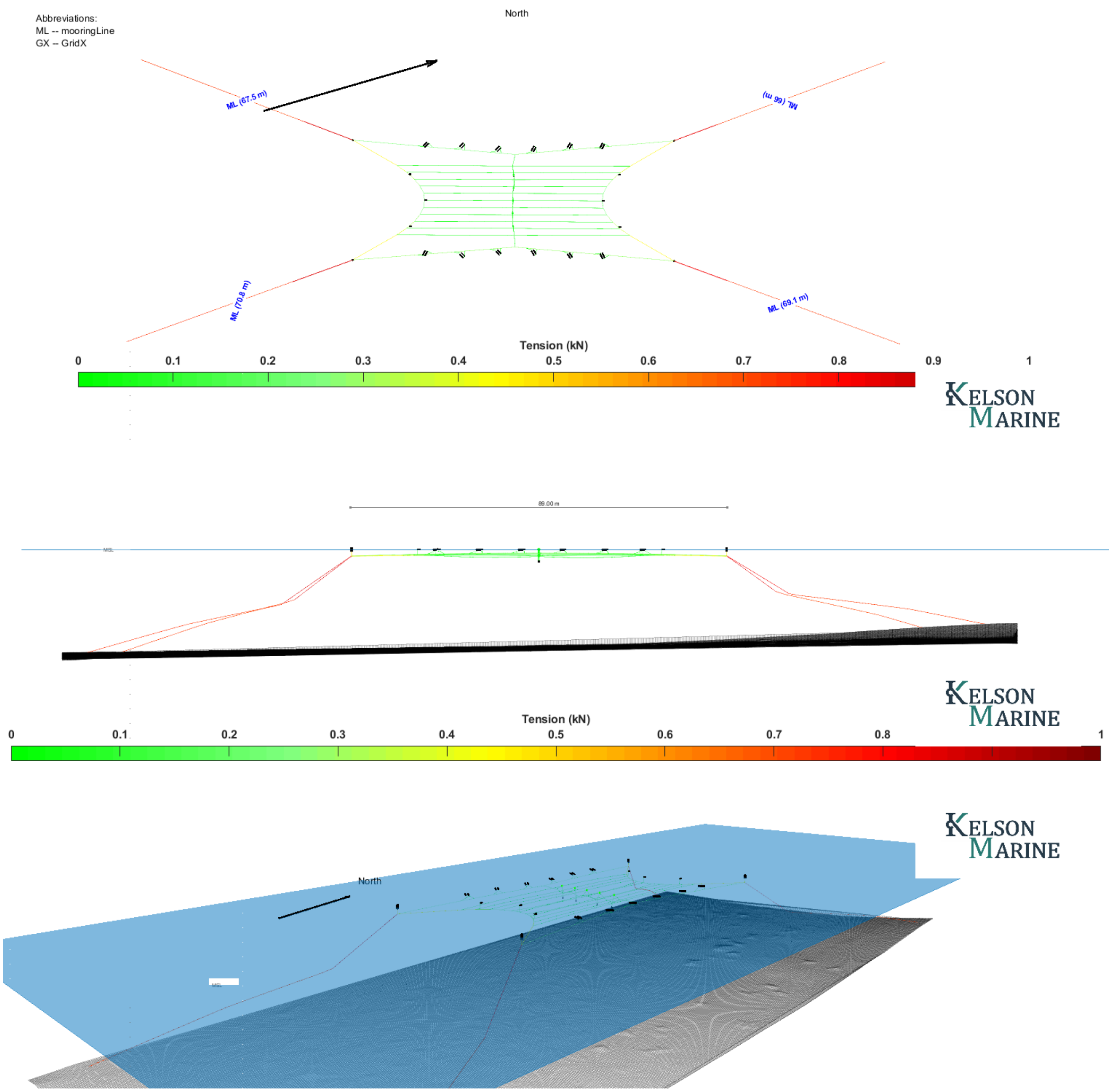

Figure 3. Final farm design, top, side, and perspective views.

5.3 Mitigating the Risk of Structural Failure

5.3.1 Load Cases Considered

NS9415 and the Scottish finfish standard mandate that structures be designed to withstand 50-year storms. They stipulate that two 50-year events should be examined: A) 50-year wave conditions combined with 10-year current conditions (the wave-dominated case) and B) 50-year current conditions combined with 10-year wave conditions (the current-dominated case). Wind speeds with the same return period as wave conditions were included in all load cases. Additionally, still-water loadcases were evaluated at Lowest Astronomical Tide (LAST), Mean Water Level (MWL), and Highest Astronomical Tide (HAST), both with and without biomass. To simulate the structure's response to a mooring failure, loadcases were constructed where the upstream mooring line most aligned with the loading direction was detached from the seabed.

5.3.2 Calculation of Required Structural Capacity

Through simulations of the proposed structure in extreme loading conditions, maximum loads and tensions were determined for each component of the farm. The minimum required capacity for synthetic lines was then determined with the inclusion of an NS-specified safety factor.

6 Discussion and Conclusion

6.1 Summary of Design Decisions in Correspondence

Multiple design decisions were communicated between Kelson and OCS via email correspondence. They are listed here.

- To achieve uniform mooring tension and work within the specified anchor positions, the dimensions of the farm are 89m by 33m, as measured from the corner buoys in static, midtide conditions.
- Unstretched line lengths for specific components are defined in Table 4.
- Angel weights will consist of three links of chain for a total mass of 39 kg.
- The three buoys attached to the header line will be attached at 18.2m, 26.7m, and 35.2m along the arclength of the line. These distances result in each buoy supporting one third of the total number of longlines.
- Stopper knots in conjunction with spinners will be used to secure and connect lines.
- Additional weights of 13kg will be added underneath the header buoys.
- Set line buoys will be attached to the set line with two lines, forming a "V" shaped bridle.
- Header and setline buoys must have at least 40kg of net buoyancy. Polyform A3's are recommended.
- Weight attachment lines will be spliced into the header with the shortest possible tag line length, about 1m.
- Corner float freeboard values and corresponding values of tension in lines during still-water conditions at three tidal levels are displayed in Table 5 and Table 6.

6.2 Applicability of Engineering Evaluation and the Effects of Operational Adjustments to the Structure

The sensitivity of loads to various design parameters is an area that is being investigated by the aquaculture engineering research community. However, in conducting this analysis, Kelson expects the following parameters to vary over time and within the farm. Changes to these parameters would not require additional engineering evaluation:

- Changing rope types or buoy construction
- Adjusting lengths of lines to tension the grid system.

- Adjusting weight and buoyancy on the growlines throughout the growing season.

The following changes would require additional engineering evaluation:
- Increasing the number or length of cultivation lines.
- Changing the location or orientation of the farm.
- Changing the geometry of the mooring and structural lines.

Specified minimum required component capacities are specific to the metocean conditions of the site outlined in Figure 2. If the characteristic metocean conditions are greater than those of this site (50-yr return values provided in Table 2), then component requirements must be quantified by an appropriate engineering evaluation.

6.3 Observations

The following safety factors were computed based on the specified synthetic lines used by OCS. For line groups consisting of multiple objects (e.g. buoy tethers), the computed safety factor was computed along with the minimum required capacity.

Table 3: NS 9415 Computed Safety Factors for Maximum Simulated Loads on OCS-Specified Components.

Structural Object	Example Material and Diameter	Min. NS 9415 Req. Capacity [N]	Calculated Safety Factor
Mooring Lines	3-strand polysteel, 28mm	21.9E+3	17.43
Cultivation Lines (9 of 11 total)	3-strand polysteel, 12mm	5.6E+3	12.53
Cultivation Lines (2 of 11 total)	Polyester, 12mm	6.1E+3	4.64
Headers	3-strand polysteel, 18mm	12.7E+3	10.58
Oyster Lines	3-strand polysteel, 18mm	12.0E+3	12.95
Set Line	3-strand polysteel, 18mm	7.8E+3	17.39
Set Line Buoy and Weight Tethers	3-strand polysteel, 18mm	3.4E+3	20.31
Header Buoy and Weight Tethers	3-strand polysteel, 18mm	3.8E+3	21.15
Oyster Cage Tethers	3-strand polysteel, 12mm	10.3E+3	7.79
Spinner (2.5 tonne capacity)	Nylon	21.9E+3	3.22

6.4 Summary

The synthetic lines and buoys in Table 3 as specified by Open Climate Solutions exceed the minimum required capacities as specified by NS 9415.

7 References

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Standards Norway. (2022). *NS 9415:2021 (en) Floating aquaculture farms Site survey, design, execution and use* (Issue 1.0, p. 140).

8 Appendix

8.1 Unstretched Line Lengths

Table 4: Unstretched Line Lengths and Material

Line Type	Example Material and Diameter	Unstretched Length [m]
Oyster Support (Grid)	28mm Polysteel (4 strand)	88.9
Header	28mm Polysteel (4 strand)	53.4
Setline	28mm Polysteel (4 strand)	32.9

Cultivation Line Number	Cultivation Line Unstretched Length [m]	Header Arclength Attachment [m]
1	64.55	13.95
2	59.17	17.21
3	54.93	20.04
4	51.84	22.50
5	49.95	24.68
6	49.31	26.70
7	49.95	28.72
8	51.84	30.90
9	54.93	33.36
10	59.17	36.19
11	64.55	39.45

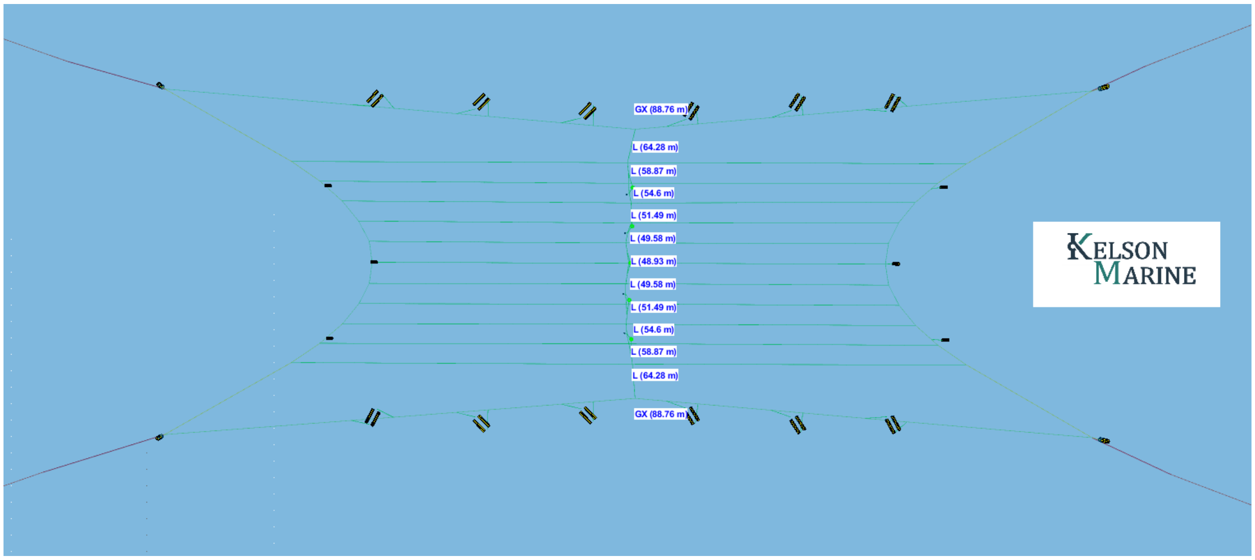

Figure 4. Growline sub-assembly lengths

8.2 Expected Buoy Freeboard and Line Tension in Still-Water Conditions at LAST, MWL, and HAST Tidal Levels

Table 5: Expected Buoy Freeboard in Still-Water Conditions at LAST, MWL, and HAST Tidal Levels

Corner Float Freeboard [m]

	A (NW)	B (SW)	C (NE)	D (SE)
LAST	0.45	0.44	0.45	0.43
MWL	0.36	0.34	0.39	0.36
HAST	0.17	0.11	0.26	0.17

Table 6: Expected Line Tensions in Still-Water Conditions at LAST, MWL, and HAST Tidal Levels

Approximate Tension in Lines [N]

	Oyster Line	Setline	Cultivation Line	Header
LAST	280	50	75	450
MWL	540	100	150	900
HAST	1100	175	300	1900