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Engineering Evaluation of Break-away Links and Cascading Failure Risk for a Mussel Backbone System

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For: Ventura Shellfish Enterprise

Revision	Date	Originator	Description
0	11/2/2020	Tobias Dewhurst, PhD, PE	Final report
0.1	11/7/2020	Tobias Dewhurst, PhD, PE	Clarified example breaking strength for twine

1 Executive Summary

The purpose of this engineering evaluation was to mitigate structural failure and entanglement risks for the proposed mussel farm. The backbone-style mussel cultivation system considered was proposed by Ventura Shellfish Enterprise off the coast of southern California.

Kelson Marine Co. ("Kelson") calculated extreme current, wave, and wind conditions corresponding to a storm that would occur once every 100-years (the 100-year storm), based on nearby historical ocean observations. The 100-year significant wave height was calculated to be 5.91 m (19.4 ft).

To mitigate the risk of structural failure in extreme storms, key components of the backbone and mooring system must meet or exceed the required structural capacities reported in Table 5.

To mitigate the risk of animal entanglement, various break-away links have been proposed. Kelson Marine evaluated the strengths required for those links to maintain the structural integrity of the farm during various 100-year storm. Similarly, Kelson evaluated the strengths required to keep the fully-grown continuous mussel ropes attached to the backbone during 100-year storms.

Results showed that if 1700 lbf break-away links were used to attach the surface buoys to the backbone, they would provide a safety factor of 1.5. If 3400 lbf break-away links were used, they would provide a safety factor of 3.1.

If twine with an overall connection strength of 1100 lbf were used to connect the mussel droppers to the backbone, this connection would have a safety factor of 4.9.

Based on simulations of damaged conditions in which one surface buoy and one submerged buoy are detached from the backbone, the increase in loads on the remaining buoy attachments is negligible and the farm stays afloat. Thus, the structure is not at an appreciable risk of cascading failure due to damage to the buoy attachments.

2 Introduction

This report summarizes an engineering analysis of a mussel backbone system designed for the Ventura Shellfish Enterprise. The proposed site is 7 km (4.4 mi) from the coast of California, on the landward side of the Santa Barbara Channel.

The primary goal of this analysis was to determine the required capacities of the attachments connecting 1) the tethers connecting the surface buoys to the backbone, and 2) the continuous mussel dropper rope to the backbone.

3 Site Parameters and Extreme Metocean Conditions

3.1 Design Basis: Relevant Standards and Extreme Condition Return Period

Several industry and government standards exist for finfish aquaculture. Examples include:

- NS 9415: "Marine fish farms–Requirements for site survey, risk analyses, design, dimensioning, production, installation and operation" (Standards Norway, 2009).

- "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, 2012).
- "Design and analysis of station keeping systems for floating structures" (API, 2005)

NS9415 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 100-year storm condition was taken to be the design standard for the present study.

3.2 Currents

Based on previous analysis conducted for VSE, the current speeds shown in Table 1 were used for each return period.

Table 1. Extreme current speeds for various return periods.

Return Period, years	1	10	20	50	100
Speed, m/s	0.45	0.66	0.73	0.81	0.87

3.3 Waves

Based on previous analysis conducted for VSE, the significant wave heights and associated peak periods shown in Table 2were used for each return period.

Table 2. Extreme Significant Wave Heights (Hs) and associated Peak Wave Periods (Tp) for various return periods.

Return Period, years	**1**	**10**	**20**	**50**	**100**
Significant Wave Height, Hs (m)	3.89	4.94	5.23	5.62	5.91

3.4 Wind

Historical wind data was taken from NDBC station 46053. NOAA reports the maximum peak wind gust between 1998 and 2008 to be 54 knots (28 m/s). This 10-year return period wind speed was assumed to be aligned with the wave direction for all extreme loadcases.

3.5 Tidal Range

As per NOAA Tide Prediction station 9411189, Ventura CA, the maximum tidal amplitude near the site is 1.25 m.

4 Numerical Model of the Backbone System

4.1 Backbone dimensions

The backbone dimensions used for the present study proposed by VSE are shown in Table 3.

Table 3. Farm components, as analyzed. SI Units.

Component	Material	Qty	Length Each m	Net Buoyancy Total for material kg	Volume Each m^3
Mooring Line	Duradan	2	80.5	19	101.1E-3
Mooring Line Float	420L, LDPE	2	2.1	804.7	420.0E-3
Backbone	Duradan	1	175	21	220.2E-3
Surface Corner Float	300L, LDPE	2	1.51	535	300.0E-3
Corner Float Tether	Duradan	2	6.1	-5.4	7.7E-3
Submerged Backbone Float	120L, LDPE	30	1.1	3,229	120.0E-3
Backbone Float Tether	Duradan	30	0.1	-1.3	125.7E-6
Surface Backbone Float	300L, LDPE	10	1.5	2,875	300.0E-3
Surface Float Tether	Duradan	10	6.1	-27.2	7.7E-3
Mussel Dropper	Mussel Ropes	195	10.0	-5,717	574.9E-3

Table 4. Farm components, as analyzed. Customary Units.

Component	Material	Qty	Length Each ft	Net Buoyancy Total for material lbf	Volume Each ft^3
Mooring Line	Duradan	2	264.1	42	3.57
Mooring Line Float	420L, LDPE	2	6.9	1,774.1	14.83
Backbone	Duradan	1	575	46	7.78
Surface Corner Float	300L, LDPE	2	4.95	1,179	10.59
Corner Float Tether	Duradan	2	20.0	-12.0	0.27
Submerged Backbone Float	120L, LDPE	30	3.6	7,119	4.24
Backbone Float Tether	Duradan	30	0.3	-3.0	0.00
Surface Backbone Float	300L, LDPE	10	5.0	6,338	10.59
Surface Float Tether	Duradan	10	20.0	-60.0	0.27
Mussel Dropper	Mussel Ropes	195	33.0	-12,604	20.30

4.2 Numerical Modeling Approach

The proposed farm is located in an exposed ocean site subject to wind, waves, and currents. Since the cultivation 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 backbone system 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 mussel rope elements) is incorporated into the model using a Morison equation formulation (Morison, Johnson, & Schaaf, 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. Steady incident flow and wave forcing are specified by the user. For cases in which the angle between the current heading and the backbone axis was small (less than 10 degrees), the reduction in current speed along the length of the backbone was estimated by solving a one-dimensional momentum balance between the net horizontal drag force on the mussel droppers and fluid momentum associated with the current, using a simplified version of the method outlined by (Rosman, Monismith, Denny, & Koseff, 2010). Kelson has demonstrated the validity of this approach for exposed backbone cultivation systems for macroalgae. In this analysis, the pressure gradient due to the free surface gradient was neglected because the overall porosity of the farm (the ratio of volume occupied by water to volume occupied by farm structure) was small. The momentum balance was made one-dimensional by averaging the horizontal drag on the mussel droppers equal to the depth of the mussel droppers squared. This likely results in a conservative (high) estimate of total drag.

This analysis does not calculate the larger-scale reduction in current speeds or wave height throughout the farm. This results in a conservative (high) estimate of the required structural capacity for backbones that are not on the exposed edges of the farm.

The structural and hydrodynamic parameters of the mussel lines were taken from (Dewhurst, 2016) and (Dewhurst, Hallowell, & Newell, 2019). The diameter of the mussel ropes was set so that the dry weight of mussels was 12 kg/m (8 pounds per foot) of mussel rope, as specified by the client. This is a typical industry estimate of maximum growth. If higher growths are expected, this analysis should be repeated using the larger values. The net in-water weight of the mature mussel ropes was taken to be ¼ of the dry weight (Bonardelli, Kokaine, Ozolina, & Aigars, 2019). Each mussel dropper loop was combined into a single line of beam elements in the numerical model.

Since each backbone in the array has its own anchors and is independent of the other backbones, an individual backbone system was examined.

5 Results and Risk Mitigation

5.1 Mitigating the Risk of Structural Failure

5.1.1 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). For this project, the relevant permitting agencies requested the structure be designed withstand 100-year storms. Thus, 100-year current and wave magnitudes were combined with 10-year wave and current magnitudes, respectively. The 10-year wind speed was included in all load cases. Figure 1 shows a screenshot of the hydro-/structural dynamic FEA model of the backbone responding to a 100-year storm.

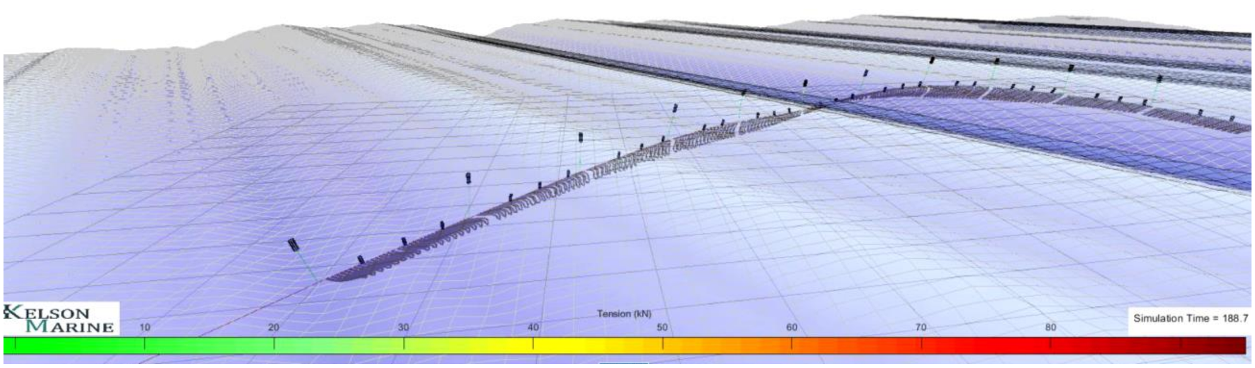

Figure 1. Dynamic model of backbone system in a 100-year, wave-dominated storm.

5.1.2 Calculation of Required Structural Capacity

For each load case, the maximum expected tensions and forces in a three-hour storm, F_{max}, were calculated assuming a Rayleigh distribution of the maximum loads. That is,

$$F_{max} = F_{mean} + \sqrt{2\log(3 * 3600/T_{pk})}\sigma_F,$$

where T_{pk} is the peak wave period and σ_F is the standard deviation of the force time series

Kelson calculated the minimum breaking strength of the structural lines and the minimum holding power of the anchors required to achieve safety factors recommended by ABS and API for offshore structures. The American Bureau of Shipping (ABS) recommends a safety factor of 1.82 on synthetic ropes (ABS, 2012). API requires a safety factor of 2.0 on vertical loading of pile anchors (API, 2005). In the present analysis, this safety factor of 2.0 was applied to both the vertical and horizontal forces on the helical anchor.

Taking into account the required safety factors, Kelson computed the minimum allowable capacity (e.g. breaking strength) of major structural components based on the results of the dynamic simulations of the fully-stocked backbone system in the 100-year storm conditions. These required capacities include the recommended safety factors. Since no industry-standard safety factors exist for breakaway links, the required capacities are shown in Table 5 and Table 6 with a safety factor of unity, which corresponds to failure in the 100-year storm condition. In practice, safety factors on weak links must be higher than this.

Table 5. Minimum allowable capacity (e.g. minimum breaking strength) of major structural components in extreme storm conditions. Recommended safety factors are included. When purchasing ropes, the breaking strength must equal or exceed the requirements shown below. The definition of minimum breaking strength of selected ropes must include reductions in strength due to knots or splicing. SI Units

		Mooring Line and con-nections, Minimum Breaking Load	Backbone and con-nections, Minimum Breaking Load	Mussel dropper con-nections, Minimum Breaking Load	Backbone surface float con-nections, Minimum Breaking Load	Backbone submerged float con-nections, Minimum Breaking Load	Anchor--Horizontal capacity	Anchor--Vertical capacity
	Safety Factor	1.82	1.82	1.82	1	1	2	2
Case	Storm direction, deg.	kN	kN	kN	kN	kN	kN	kN
10 year waves, 100-year current, 10-year wind	1	78	74	1.0	4.6	1.5	82	26
	23	227	225	**1.8**	4.8	2.0	246	46
	45	206	204	1.3	4.7	1.6	223	44
	68	176	174	0.9	4.6	1.3	190	40
	90	143	140	0.7	4.6	1.2	153	36
100 year waves, 10-year current, 10-year wind	1	76	72	1.1	4.7	1.6	79	25
	23	195	193	1.7	**4.9**	**2.0**	210	42
	45	178	176	1.2	4.9	1.6	192	40
	68	152	150	0.8	4.7	1.4	163	37
	90	123	121	0.6	4.7	1.3	132	34

Table 6. Minimum allowable capacity (e.g. minimum breaking strength) of major structural components in extreme storm conditions. Recommended safety factors are included. **When purchasing ropes, the breaking strength must equal or exceed the requirements shown below. The definition of minimum breaking strength of selected ropes must include reductions in strength due to knots or splicing. US customary units.**

		Mooring Line and con-nections, Minimum Breaking Load	Backbone and con-nections, Minimum Breaking Load	Mussel dropper con-nections, Minimum Breaking Load	Backbone surface float con-nections, Minimum Breaking Load	Backbone submerged float con-nections, Minimum Breaking Load	Anchor--Horizontal capacity	Anchor--Vertical capacity
	Safety Factor	1.82	1.82	1.82	1*	1	2	2
Case	Storm direction, deg.	kip	kip	kip	Kip	kip	kip	kip
10 year waves, 100-year current, 10-year wind	1	17	17	0.235	1.0	0.333	18	6
	23	51	51	**0.405**	1.1	0.440	55	10
	45	46	46	0.301	1.1	0.358	50	10
	68	40	39	0.208	1.0	0.299	43	9
	90	32	31	0.148	1.0	0.281	34	8
100 year waves, 10-year current, 10-year wind	1	17	16	0.242	1.1	0.357	18	6
	23	44	43	0.379	1.1	**0.447**	47	9
	45	40	39	0.270	1.1	0.370	43	9
	68	34	34	0.188	1.1	0.306	37	8
	90	28	27	0.136	1.0	0.296	30	8

Note: 1 kip is 1,000 pounds force.

Table 6 shows that surface floats would detach from the backbone in a 100-year storm if 1100 pound-force (1.1 kip) break-away links were used. If 1700 lbf break-away links were used, they would provide a safety factor of 1.5. If 3400 lbf break-away links were used, they would provide a safety factor of 3.1. Additional design options for mitigating entanglement risks while maintaining structural integrity can also be explored.

The minimum strength required for mussel dropper attachments to the backbone is 405 lbf. This assumes there is one connection at each end of a loop in a continuous dropper configuration. Unlike the results for break-away links, these results include a safety factor of 1.82, which is standard for synthetic lines. If twine were used to form a connection that had an overall breaking strength of 1100 lbf (when including strength lost to abrasion, knots, etc.), this connection would have a safety factor of 4.9.

5.1.3 Risk of Cascading Failure

Accidental damage to one component in a structure has the potential to increase the loads on nearby components. If the increased loads on the intact components cause those components to fail, this can result in a cascading, catastrophic failure in which components fail one after another until the structure is destroyed. The proposed backbone structure was evaluated to mitigate the risk of cascading failure.

The risk of cascading failure was investigated using the 100-year storm loadcases described above. For each loadcase, the highest-loaded surface buoy attachment and the highest-loaded submerged buoy attachment were identified. Then, Kelson simulated the same 100-year storm events with these attachments broken. In every loadcase, the forces on the other buoy attachments increased by less than 2%, and the system stayed afloat. Thus, the structure is not at an appreciable risk of cascading failure due to damage to the buoy attachments.

6 Conclusion

To mitigate the risk of structural failure in extreme storms, key components of the backbone and mooring system must meet or exceed the required structural capacities reported in Table 5.

If 1700 lbf break-away links were used to attach the surface buoys to the backbone, they would provide a safety factor of 1.5. If 3400 lbf break-away links were used, they would provide a safety factor of 3.1.

If twine were used to connect the mussel droppers to the backbone with an overall connection strength of 1100 lbf, this connection would have a safety factor of 4.9.

Based on simulations of damaged conditions in which one surface buoy and one submerged buoy are detached from the backbone, the increase in loads on the remaining buoy attachments is negligible and the farm stays afloat. Thus, the structure is not at an appreciable risk of cascading failure due to damage to the buoy attachments.

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