

Numerical analysis of ship–feed barge interaction during side-by-side operations

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Abstract

This work analyzes the increase in axial forces in the mooring system and connecting mooring ropes of a feed barge and support vessel during side-by-side operations, using a coupled analysis in the FEM software AquaSim. Through this analysis, it is possible to verify the compliance of the materials used in the mooring system of the feed barge when subjected to a load increase due to the support vessel's operations, as well as assessing the program's capability to conduct this type of analysis under regular and irregular wave conditions. The study was conducted using environmental data recorded at an actual fish farm in southern Chile, along with the geometry of an existing feed barge. This data was used to create a numerical model, to which a combination of environmental loads was applied in eight cardinal directions. The impact on the mooring system was then evaluated when a ship connects to the feed barge, both on the port and starboard side. The results show that the mooring system distributes loads homogeneously when isolated, but significant imbalances occur in side-by-side operations. Additionally, a mooring maneuver performed on the starboard side of the feed barge, in this case, leads to significantly higher axial loads compared to maneuvers performed on the port side of the barge. However, these increases remain below the material limit and within safety factors established by local regulations.

Key words: AquaSim, floating structures, impact, mooring lines, mooring system, feed barge, fish farm, numerical analysis, Ship-feed, side-by-side operations

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Introduction

In the last decade, aquaculture has positioned itself as one of the most important activities for Chile. Its success rank Chile as the second-largest salmon producer worldwide, second to Norway. According to the FAO (Food and Agriculture Organization of the United Nations), Chile ranked as the eighth-largest global producer of cultured fish between 2003 and 2018 (FAO, 2024). The vast coastline extending throughout the country and the perfect environmental conditions enable the development of this ever-growing activity.

Alongside this economic growth, new technologies and studies have emerged to make this activity more efficient and safer, considering massive structures in Norway (Yu, et al., 2019), leaving a gap of knowledge on the response of flexible square steel cages typically used in Chile, Canada and other locations. Given the location of fish farms, which are often exposed to adverse environmental conditions, it is crucial to conduct an in-depth study of the area and carry out detailed mooring calculations of these structures, particularly during operations that could induce collision between floating constructions and service vessels (Vestbo, 2022). This ensures the determination of the tensions affecting the mooring system. The materials of these lines must withstand the maximum environmental loads in the area, always considering the worst-case scenario to guarantee the safety of the crew on board.

This study analyzes the increase in axial loads on the mooring system of a feed barge during ship-feed barge side-by-side maneuvers using the commercial software AquaSim, a time domain analysis software based of the Finite Element Method which includes net and membrane elements crucial for the calculation of forces on fish farms. There are multiple commercial codes for time domain analysis to study ship-platform interactions where a combination of environmental conditions can be applied such as OrcaFlex,

OpenFAST, Aqwa, Flecom, MOSER, ProteusDS, SeaFEM and DeepC. Up to date, there is no field data of such analysis; therefore, the use of numerical simulations represents the best design and verification tool for ship-barge side-by-side maneuvers.

Regulation

The regulatory body for fishing and aquaculture activities in Chile is called "Subsecretaría de Pesca y Acuicultura" (Undersecretariat of Fisheries and Aquaculture or SUBPESCA, as per its Spanish acronym), which is responsible for establishing policies, standards, and management procedures for the fishing and aquaculture sectors, based on available scientific information.

SUBPESCA Resolution No. 1821 establishes the methodology for data collection, processing, and calculations in the engineering study of mooring systems and structures for fish farming (SUBPESCA, 2020). It details criteria for the measurement of currents, wind studies, wave studies, seabed quality, and bathymetry, in addition to standards for the construction of fish farms and the calculation of mooring systems.

The mooring calculation report must contain technical information supporting the design and layout of the aquaculture structures to be installed, considering the most extreme environmental conditions recorded in the area. One of the requirements is the calculation of utilization factor (K), which value must be less than 1 (SUBPESCA, 2020).

$$k = \frac{\sigma_{max} \cdot F_{amb} \cdot F_{mat} \cdot F_{ana}}{\sigma_{cri}} \quad (1)$$

Where:

- σ_{max} : estimated tension in N
- F_{amb} : safety factor applied to the environmental load = 1.3
- F_{mat} : safety factor applied to the material (2 for chains and 3 for ropes).
- F_{ana} : safety factor applied to the type of

- analysis = 1.15 for dynamic analysis
- σ_{cri} : minimum breaking load in N

Use of AquaSim for mooring calculations

AquaSim is a FEM software developed by AquaStructures AS. AquaSim can perform coupled mooring analysis, linear structural analysis and solve forces and deformations on net systems. With this software, a global study of force transmission between rigid and flexible components can be conducted, calculating local forces and stresses in each component. The simulations allow the user to find the maximum tension on mooring lines under each of the evaluated scenarios. The AquaSim package includes four sub-

programs: AquaEdit, AquaTool, AquaView, and AquaHarmony. For mooring calculations, AquaEdit and AquaView are the main modules (Aquastructures, 2023).

Environmental conditions

The operational area for the analysis was set at the Jorge 742 fish farm, located in the Bynon Channel, northwest of Jorge Island, Cisnes Province in the Aysén Region (Aex Group SpA, 2023). All environmental data was obtained through studies conducted by AEX Group, pursuant to current regulations. The following are the current, wind, and wave data recorded in the area.

Fig. 1. Current velocity [knots].

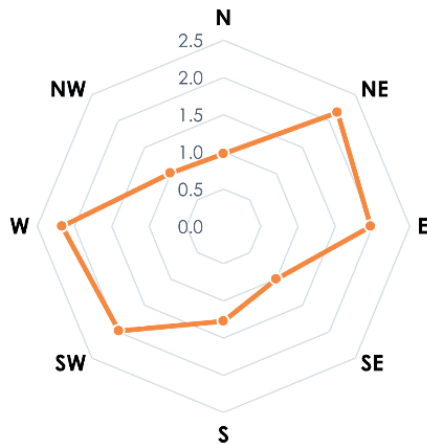


Fig. 2. Wind velocity [knots].

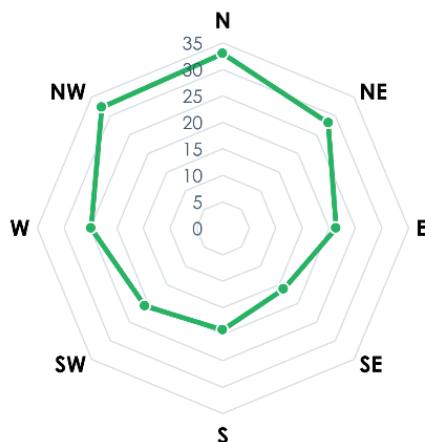


Table 1. Maximum current velocity.

Direction	[knots]	[m/s]
North to South	0,98	0,50
Northeast to Southwest	2,16	1,11
East to West	1,98	1,02
Southeast to Northwest	1,00	0,52
South to North	1,27	0,65
Southwest to Northeast	1,99	1,02
West to East	2,16	1,11
Northwest to Southeast	1,01	0,52

Table 2. Maximum wind velocity.

Direction	[knots]	[m/s]
North to South	32,98	16,96
Northeast to Southwest	28,14	14,48
East to West	21,33	10,97
Southeast to Northwest	16,26	8,36
South to North	19,21	9,88
Southwest to Northeast	20,76	10,68
West to East	24,90	12,81
Northwest to Southeast	32,30	16,61

Fig. 3. H_{M0} [m].

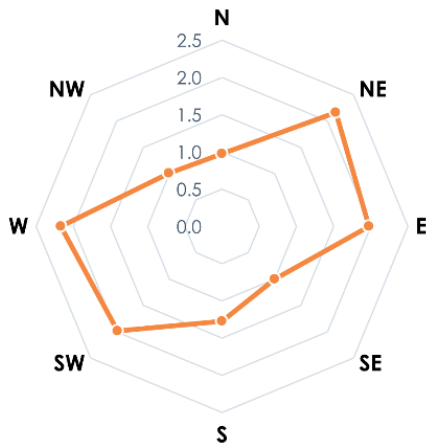


Table 3. Waves H_{M0}^* and T_p .

Direction	H_{M0} [m]	T_p [s]
North to South	0,68	2,81
Northeast to Southwest	0,97	3,73
East to West	0,25	1,56
Southeast to Northwest	0,10	0,91
South to North	0,15	0,96
Southwest to Northeast	0,20	1,27
West to East	0,84	3,36
Northwest to Southeast	0,71	2,90

$$H_{M0} = 4\sqrt{m_0}; m_0: \text{zeroth spectral moment}$$

Description of components

The numerical models are created in AquaEdit. Here, the models are represented by lines connected to components, to which a cross-section with specific properties is assigned. These components can be of the BEAM type, which can include hydrodynamics loads when representing ship hulls and general floaters or the TRUSS type for ropes, chains, or cables.

For each component representing a floating structure, it is necessary to create drag plates with negligible thickness that cover the stern and bow areas for hull components. The purpose of these plates is to receive the environmental loads on these areas and calculate the drag and inertia loads additionally to the load along the hull where strip theory is applied.

Furthermore, it is necessary to implement a virtual Dummy element, which will be an auxiliary component without volume or weight properties. It will be used to connect the different nodes of the components, thus providing rigidity to the model. This helps to avoid nonconvergence issues in simulations.

Feed barge

The feed barge operating at the Jorge 742 center has a feed cargo capacity of up to 200 tons, a water tank capacity of 20,000 liters and a fuel capacity of 30,000 liters (Aex Group SpA, 2023).

In Fig. 4, the components of the hull and superstructure of the feed barge are shown in wireframe form, and in Fig. 5, the components are displayed in 3D within the AquaSim software environment.

Fig. 4. Wireframe components of the hull and superstructure of the feed barge.

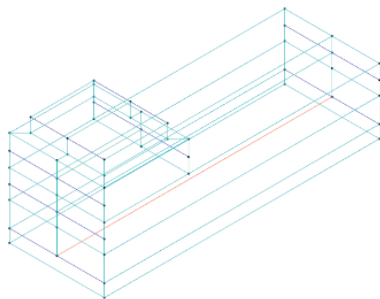


Fig. 5. 3D components of the hull and superstructure of the feed barge.

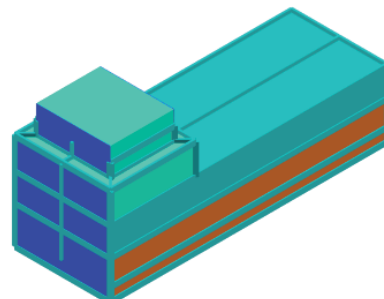


Table 4. Main feed barge characteristics.

Parameter	Value
Total length [m]	26,13
Hull beam [m]	9,00
Maximum beam [m]	12,00
Depth [m]	3,50
Design draft [m]	1,00
Displacement [ton]	241,00

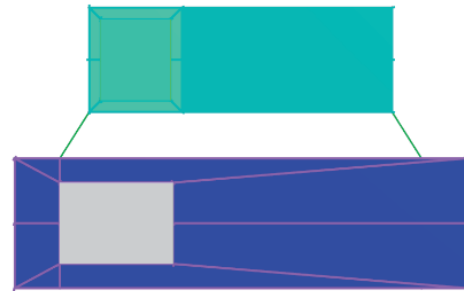
Vessel

The vessel selected for the analysis is a landing craft hull with a length of 39 meters and is designed for transporting pellets used as food in the salmon farming industry (Parra, 2015). In the numerical model, the vessel's weight is distributed along its length in the hull component, while the superstructure components act as exposed areas for wind loads.

Table 5. Main characteristics of the ship.

Parameter	Value
Total length [m]	26,13
Hull beam [m]	9,00
Maximum beam [m]	12,00
Depth [m]	3,50
Design draft [m]	1,00
Displacement [ton]	241,00

Fig. 6. Ship connected to the feed barge in AquaSim.



Mooring system and connecting mooring ropes

The projection of the mooring lines was carried out by AEX Group in their mooring calculation report for the Yadrán 4 feed barge (Aex Group SpA, 2023).

The feed barge has 8 mooring lines composed of elements such as ropes, chains, shackles, etc. Each mooring line is divided into three different segments. The first segment is 13,75 meters long across all lines and is made of 28-mm diameter chain. The second segment varies in length depending on the mooring line (see Table 6) and is made of 1 1/4-inch diameter cable. The third segment is 27,5 meters long for all lines and uses the same chain as the first segment. Finally, all lines are anchored with a 20-ton gravity anchor. Table 6 shows the length and the angle relative to the horizontal for all the mooring lines.

Fig. 7. Mooring system materials.

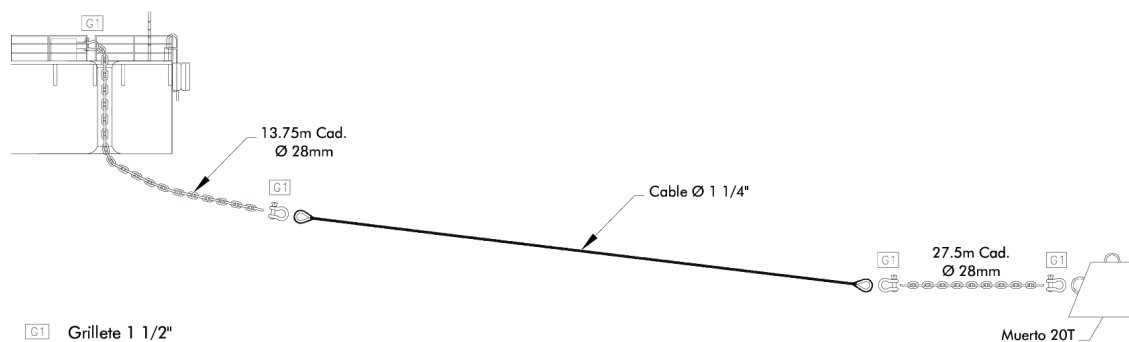


Table 6. Length and angle of the lines.

Item	Length section 1 (m)	Length section 2 (m)	Length section 3 (m)	Total length (m)	Angle (°)
LF 1	13,75	109,27	27,50	150,52	22,20
LF 2	13,75	100,69	27,50	141,94	22,64
LF 3	13,75	29,96	27,50	71,21	23,18
LF 4	13,75	22,91	27,50	64,16	22,74
LF 5	13,75	23,21	27,50	64,46	22,91
LF 6	13,75	25,18	27,50	66,43	23,22
LF 7	13,75	89,56	27,50	130,81	23,67
LF 8	13,75	90,00	27,50	131,25	24,54

Table 7. Properties of the materials used in the mooring system and mooring ropes.

Item	Section 1	Section 2	Section 3	MR
Type	Chain	Rope	Chain	Rope
Material	Steel	Steel	Steel	Polypropylene
Diameter (mm)	28	31,75	28	48
Breaking Strength (tonf)	34,09	60,9	34,09	48
Mass per Length (kg/m)	17,85	3,50	17,85	1,15
Young's Modulus (GPa)	110	110	110	2,1
Type	Chain	Rope	Chain	Rope

The connecting mooring ropes between the ship and the feed barge have a length of 4,76 meters from one bollard to another. They are made of polypropylene. In Fig. 9, the diagram of mooring rope designations is presented.

Fig. 8. General mooring system diagram.

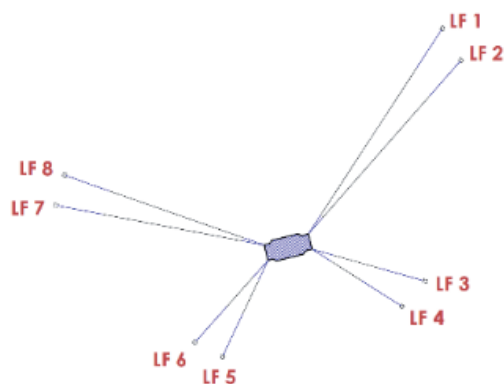


Fig. 9. Connecting mooring ropes between the feed barge and the ship.



The line at the feed barge's bow will be identified as Mooring Rope 1 or MR1, and the one at the stern will be identified as Mooring Rope 2 or MR2. The properties of the materials implemented in the mooring system and the connecting mooring ropes are shown in Table 7.

Analysis scenarios

Three analysis scenarios were considered for this study. An initial scenario where only the feed barge is present, which will be referred to as the Isolated System (see Fig. 8). And two scenarios where the ship performs the mooring maneuver, one over the port side and another over the starboard side of the feed barge, referred to as the Port-Side Moored System or PSM system (Fig. 10) and Starboard-Side Moored System or SSM system (Fig. 11). These scenarios will be subjected to 8 collinear load combinations of currents, winds, and waves. The environmental data previously presented, corresponding to the maximum recorded loads in the 8 cardinal directions, are arranged to form the 8 environmental conditions that will be used in the analysis (see Table 8).

Fig. 10. Port-Side Moored System (PSM).

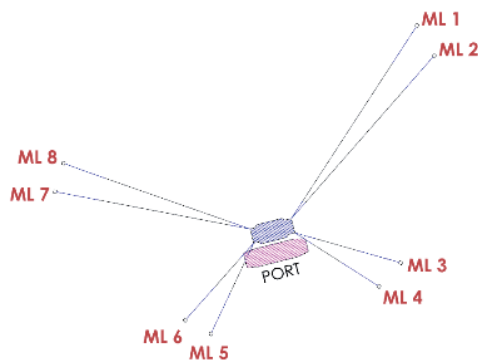
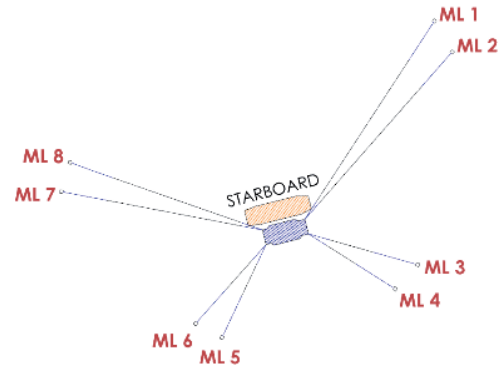


Fig. 11. Starboard-Side Moored System (SSM).



In summary, there are 3 analysis scenarios that will be evaluated in both regular and irregular waves. In addition, each scenario will be simulated in the 8 described conditions, so in total, there are 48 cases to be simulated.

Results and discussion

Tensions in the mooring system

The following are the maximum tensions recorded in the mooring system for each environmental condition under regular and irregular waves. Additionally, a table is laid out showing the utilization factor calculated with these results.

Table 8. Environmental conditions.

N°	Direction (From)	H_{m0} [m]	Tp [s]	Wind W_{max} [knots]	Current V_{max} [knots]
C1	N	0,68	2,81	32,98	0,98
C2	NE	0,97	3,73	28,14	2,16
C3	E	0,25	1,56	21,33	1,98
C4	SE	0,10	0,91	16,26	1,00
C5	S	0,15	0,96	19,21	1,27
C6	SW	0,20	1,27	20,76	1,99
C7	W	0,84	3,36	24,90	2,16
C8	NW	0,71	2,90	32,30	1,01

Fig. 12. Maximum tensions in the mooring system under regular wave conditions (Tonf).

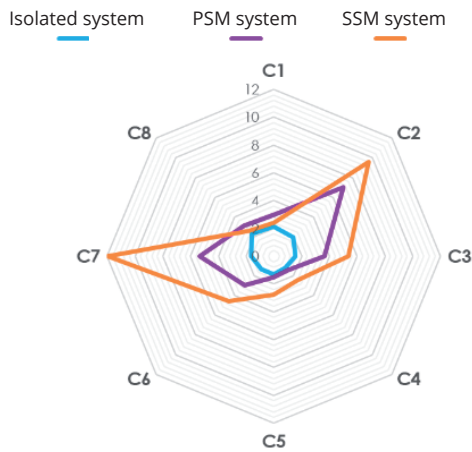


Table 9. Maximum tensions (Tonf) and percentage variation in the mooring system under regular wave conditions.

Cond.	Isolated sys.	PSM sys.	SSM sys.	PSM Var.	SSM Var.
1	2,13	2,98	2,38	40%	12%
2	1,93	7,04	9,63	265%	399%
3	1,52	3,63	5,35	139%	252%
4	1,16	1,42	2,42	22%	109%
5	1,32	1,50	2,75	14%	108%
6	1,30	2,98	4,57	129%	252%
7	1,66	5,35	11,96	222%	620%
8	2,26	3,07	2,56	36%	13%

Fig. 13. Maximum tensions in the mooring system under irregular wave conditions (Tonf).

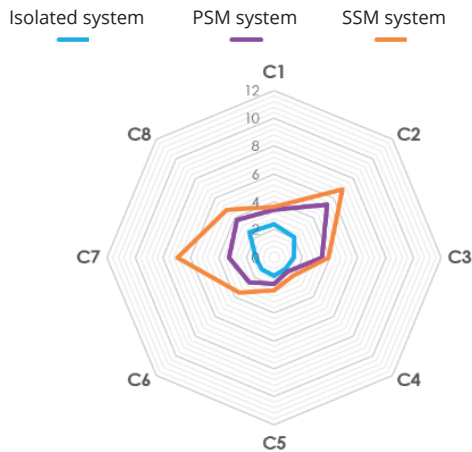


Table 10. Maximum tensions (Tonf) and percentage variation in the mooring system under irregular wave conditions.

Cond.	Isolated sys.	PSM sys.	SSM sys.	PSM Var.	SSM Var.
1	2,38	3,41	3,65	43%	53%
2	2,03	5,40	6,92	166%	241%
3	1,42	3,42	3,91	141%	175%
4	1,14	1,41	1,90	24%	67%
5	1,31	1,92	2,39	47%	82%
6	1,24	2,51	3,56	102%	187%
7	1,30	3,27	6,97	152%	436%
8	2,53	3,80	4,83	50%	91%

Table 11. Utilization factor for each analysis scenario.

System	Section 1	Section 2	Section 3
Isolated system	0,22	0,19	0,22
PSM system	0,47	0,40	0,47
SSM system	0,61	0,51	0,61

In Table 9 and Table 10, 'PSM variation' and 'SSM variation' are the percentage variations of the tensions with respect to the isolated system.

The results show a good distribution of axial forces in the isolated system, but a significant increase and imbalance when the ship is moored to the feed barge. In the PSM system, axial forces intensify at C2 and C7; this imbalance is even more pronounced in the SSM system. In the case of irregular waves, the same phenomenon is observed, but to a lesser extent. This notable increase in tensions in C2 and C7 is expected due to the higher wind and wave loads displayed in these conditions. The most unfavorable condition in general was C7, with the SSM system resulting in axial force increases of up to 620% in regular waves, and 436% in irregular waves. While these increases

are relatively high, the materials used in the mooring lines meet the safety requirements established by the regulations, maintaining a utilization factor below 1 (see Table 11).

Tensions in the mooring system

The following are the maximum tensions recorded in the connecting mooring ropes for each environmental condition under regular and irregular waves.

As with the loads recorded in the mooring system, the tensions in the connecting mooring ropes evince a significant increment

in C2 and C7 for both regular and irregular waves. Whether the ship is moored on the port or starboard side, tensions will reach up to 13,9 tons in regular waves and 11,7 tons in irregular waves. However, this magnitude of axial force is below the 48-ton breaking tension of the mooring rope material.

Software performance

AquaSim is a well-regarded program primarily used for hydrodynamic analysis of elements like nets, membranes and mooring lines. It is known for its intuitive interface, which makes it user-friendly. However, its simplicity also

Fig. 14. Maximum tensions in MR1 under regular wave conditions (Tonf).

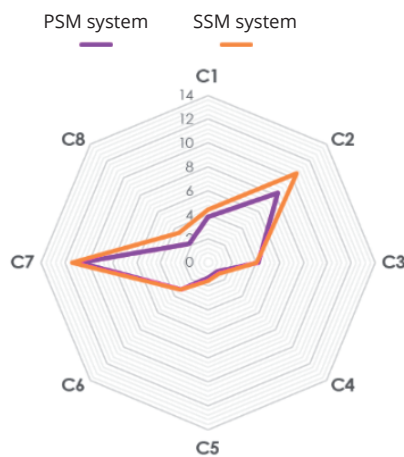


Table 12. Maximum tensions (Tonf) and percentage variation in MR1 under regular wave conditions.

Cond.	PSM system	SSM system	Variation
1	3,78	4,43	17%
2	8,24	10,52	28%
3	4,17	4,09	-2%
4	1,10	1,29	17%
5	1,32	1,53	16%
6	3,21	3,26	2%
7	10,77	11,41	6%
8	2,22	3,49	57%

Fig. 15. Maximum tensions in MR1 under regular wave conditions (Tonf).

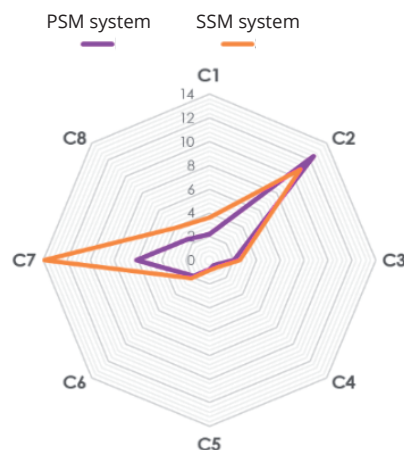


Table 13. Maximum tensions (Tonf) and percentage variation in MR2 under regular wave conditions.

Cond.	PSM system	SSM system	Variation
1	2,21	3,63	64%
2	12,44	10,84	-13%
3	2,11	2,58	22%
4	0,56	0,87	54%
5	0,77	0,86	12%
6	1,89	2,10	11%
7	6,14	13,91	127%
8	2,55	3,94	55%

Fig. 16. Maximum tensions in MR1 under irregular wave conditions (Tonf).

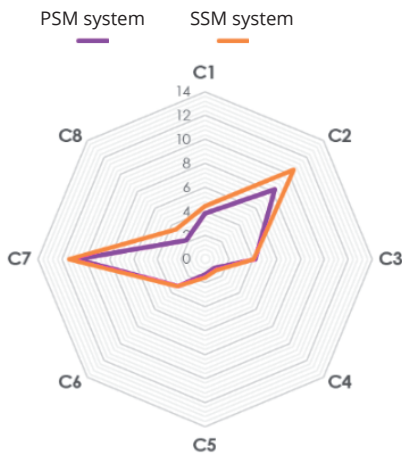


Table 14. Maximum tensions (Tonf) and percentage variation in MR1 under irregular wave conditions.

Cond.	PSM system	SSM system	Variation
1	6,11	3,95	-35%
2	11,03	11,70	6%
3	3,78	3,57	-6%
4	1,02	1,06	4%
5	1,35	1,39	3%
6	3,14	3,22	3%
7	8,69	8,72	0%
8	7,70	3,15	-59%

Fig. 17. Maximum tensions in MR2 under irregular wave conditions (Tonf).

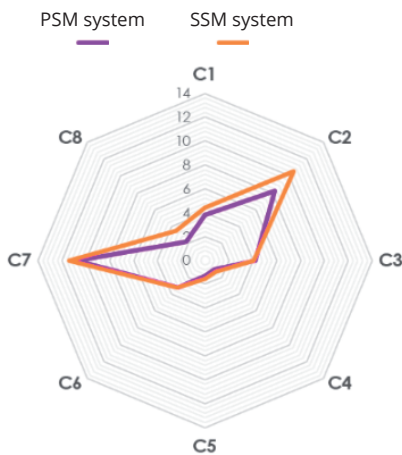


Table 15. Maximum tensions (Tonf) and percentage variation in MR2 under irregular wave conditions.

Cond.	PSM system	SSM system	Variation
1	4,43	4,03	-9%
2	10,93	7,17	-34%
3	1,44	1,72	19%
4	0,31	0,53	71%
5	0,51	0,65	27%
6	1,78	2,31	30%
7	4,13	9,11	121%
8	5,00	3,67	-27%

limits its capabilities, especially for detailed modeling of ships and feed barges, where approximations in geometry and properties are necessary. The program demonstrates poor performance when analyzing coupled structures, and convergence errors often occur when running simulations. Many dummy element designs were tested to model the hulls, as well as different connecting mooring rope designs to achieve a behavior as close to reality as possible and, through trial and error, all simulations were

conducted with the design presented in this work, but with only 100 wave components to avoid convergence problems. For irregular wave generation, it is important to be cautious with the input parameters, as the environmental conditions table indicates H_s (significant wave height), but the value that should be entered is the wave amplitude multiplied by 1,05. It is recommended that the wave elevation graph in AquaEdit be checked to ensure that the generated wave height is correct.

Conclusions

A coupled analysis was conducted using numerical modeling in AquaSim to estimate the increase in axial loads on the mooring lines of a feed barge during side-by-side ship operations. The mooring system designed for this feed barge proves to be quite efficient when applying external loads. The loads are evenly distributed in the case of the isolated system. However, during side-by-side operations, both on the port and starboard side, a noticeable imbalance and a high increase of stress in specific lines occur. Despite this, the materials remain within the safety range stipulated by the regulations. Environmental conditions C2 and C7 were the most unfavorable in the analyses conducted. This study focused on a specific case of an existing aquaculture farm in southern Chile. Future research could be conducted to achieve a complete 3-hour simulation in irregular waves. Additionally, an accidental limit state analysis, consisting of a further mooring analysis where the line under the maximum tension load is cut, would complement the mooring study even further, allowing for the distribution of tensions in that condition to be observed. Likewise, further development in the numerical modeling method of ship and feed barge components would enable a more realistic behavior in simulations.

Contributions

- Diego Aguilar: Writing – original draft, Validation, Investigation, Conceptualization
- Cristian Cifuentes: Writing – original draft, Writing – review & editing, Validation, Supervision, Investigation, Conceptualization
- Richard Luco: Writing – original draft, Writing – review & editing, Supervision, Investigation
- Marcos Salas: Writing – original draft, Writing – review & editing, Supervision, Investigation

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