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Research Article

Stress analysis of a submersible longline culture system through dynamic simulation

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ABSTRACT. This study analyzed the stresses on a submersible longline culture system subjected to both parallel and perpendicular oceanographic conditions of 0.5 and 1 m s^{-1} current velocity with 2 to 5 m wave height, using a dynamic simulation model based on the finite element method. Results indicated that when the culture system is submerged, the stress on mooring lines, the main line and whip lines decreases until a 55%. Additionally, changing the direction of the current and waves results in differences ranging from -59% to 312%. It was established that in an environment involving high-energy events, it is structurally possible to submerge the longline culture system in a direction parallel to oceanographic parameters, which could have positive implications for reducing the loss of cultivated biomass and improving productive conditions.

Keywords: mooring line, main line, whip line, farming, oceanographic parameters.

INTRODUCTION

In Chile, the Fisheries and Aquaculture Undersecretary (SUBPESCA) is promoting the productive diversification of the artisanal fishing sector, which has promoted the development of aquaculture activities in Management Areas (Áreas de Manejo y Explotación de Recursos Bentónicos - AMERB) as a complementary and compatible activity with benthic resource extraction (General Law of Fisheries and Aquaculture N°18.892, Art. 55 D). However, AMERBs face extreme environmental conditions (high waves and currents) and are exposed to tidal waves and tsunamis. Therefore, it is necessary to find alternatives for culture that are able to operate under these conditions, without endangering the safety of the operators or the crop. At the same time, the SUBPESCA argues that mussels, oysters and seaweed are the main species that should be cultivated. Culture systems are located in protected areas (González *et al*., 1999), which are limited in number, and represent the main limiting factor for the expansion and growth of this economic activity.

Longline culture systems are extensive and simple (composed of ropes, floats and culture units), involve reduced investment, are easy to operate and are applicable for the culture of scallops, oysters, mussels, algae and many other species. For these reasons, longline culture systems are presented as an alternative for the productive diversification of AMERBs. However, these systems were developed for use in protected areas, and it is therefore necessary to investigate alternative technologies allowing these systems to be adapted to exposed areas.

One alternative that would allow longline systems to operate in exposed areas is to submerge the structure, which would be favorable because it would result in better resistance to waves and current conditions under storm situations (Lee *et al*., 2009). Furthermore, it might be possible to avoid the harmful effects of toxic algal blooms (Drach *et al*., 2013). Lee *et al*. (2009) reported that submersible aquaculture systems have the highest survival rates, producing individuals of better quality. Adding that, submersible systems are also less vulnerable to structural damage, deformation and abrasion, in addition to reducing stress on the mooring systems, it reduces the probability of loss through system collapse. Jensen *et al*. (2007) reported that culture systems in exposed environments exhibit greater oxygen exchange through their culture units and more stable water temperatures.

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Moreover, there are tools based on the finite element method (FEM) that are applicable to the study of the hydrodynamic behavior of culture systems. Several authors have used this method to study the effect of currents and waves on the deformation and hydrodynamic resistance of these systems (Tsukrov *et al.*, 2000, 2002, 2005; Fredriksson *et al.*, 2003; Suhey *et al.*, 2005; Huang *et al.*, 2006)

Therefore, the objective of this study was to analyze the stresses on a submersible longline culture system subjected to the oceanographic conditions present in exposed areas, using dynamic simulation based on FEM.

MATERIALS AND METHODS

Dynamic simulation

A dynamic simulation of a longline-type culture system was carried out using the numerical analysis program AquaSim® (Aquastructures. Trondheim, Norway), based on FEM. This program performs a comprehensive analysis of the interactions of transmission forces between rigid and flexible components, in addition to calculating the local forces and stresses on each component, providing results such as the displacement, acceleration and deformation of the system (López *et al*., 2015).

The simulation software calculates drag force according to the Morison equation (Morison *et al*., 1950):

$$F_d = \left[0.5*\left(C_d*\mathrm{D}*\mathrm{A}*\mathrm{V}^2\right)\right]/\mathrm{g}$$

where the terms of the equation are as follows: Cd: drag coefficient; D: density of sea water (kg m^{-3}); A: solid area normal to the flow (m^2); g: acceleration due to gravity equal to 9.8 m s^{-1} and V: velocity of the incident current (m s^{-1}).

Additionally, the software incorporates a reduction coefficient for the current velocity (R) due to the hydrodynamic resistance generated by the panels (Loland, 1991), which corresponds to the following relationship:

$$R = 1.0\text{-}0.46*C_d$$

where C_d is the drag coefficient, which depends on both the strength of the net (S_n), and the existing angle between the current and the panel (α), as shown in the following relationship:

$$C_d = 0.04+\left(\text{-}0.04+0.33*S_n+6.54*S_n^{\ 2}\text{-}4.88*S_n^{\ 3}\right)*\cos(\alpha)$$

Characteristics of the culture system

The culture system evaluated in this study is one type of longline system for the culture of scallops, with a main line of 20 m and 18 lanterns as culture units. The lanterns are composed of a 4 mm diameter steel wire structure covered with polyamide (PA) panels with a 2 mm thread diameter and a 21 mm mesh size. Each lantern has 10 levels, each having a height of 0.2 m and diameter of 0.35 m. Near the top, 8 ropes are attached to steel wires, which are attached to each other at their ends, thus terminating in a single rope known as a "whip line", which is attached to the main line (Fig. 1, Table 1).

The mooring system is composed of a 24 mm-diameter polypropylene (PP) mooring line with a length of 60.8 m, 24 mm-diameter PP main line, and 18 midwater buoys of 50 kg each, which are attached to the main line by a 12 mm-diameter PP rope, and two 1 m^3 marker buoys attached to each end of the main line and the mooring line by a 12 mm-diameter PP rope.

The weight of the oysters on the lanterns was incorporated in the model, considering 40 individuals of 60 g each one per floor. This incorporation was carried out including two *beam* elements evenly distributed on each floor, for a total weight of 2,400 g.

In the numerical model, the net panels were modeled as *membrane* elements, the structural lantern wires as *beam* elements and all of the ropes as *truss* elements. The midwater buoys were modeled as a point force on the positive Z axis with a magnitude of 294 (N), and the marker buoys were modeled as *springs*.

The system modeled is of a smaller dimension than the real systems (*i.e.*, main line length and number of culture units) due to limited data processing capacity of the available traditional computing hardware.

Variables

To assess the effects of submerging the longline system, two operating conditions were used and referred as "surface" and "submerged". Surface operation consists of the culture system being submerged to the point at which the main line reaches a depth of 7 m (operating conditions commonly used for this aquaculture system). While the submerged system operates with the main line submerged to a depth of 15 m. Each system was simulated under the following oceanographic conditions: water current velocity of 0.5 m s^{-1} and 1 m s^{-1} and wave height of 2 and 5 m with 10 s period, considering that the system faces these conditions in a perpendicular or parallel direction with respect to its main line. Such environ-mental conditions were categorized according to Norway Standard "Marine fish farms - Requirements for design, dimensioning, production, installation and operation" NS 9415 (Table 2).

Specifically, the percent change in the stress on the three components analyzed (*i.e.*, main line, mooring line and whip line) was determined as a difference from

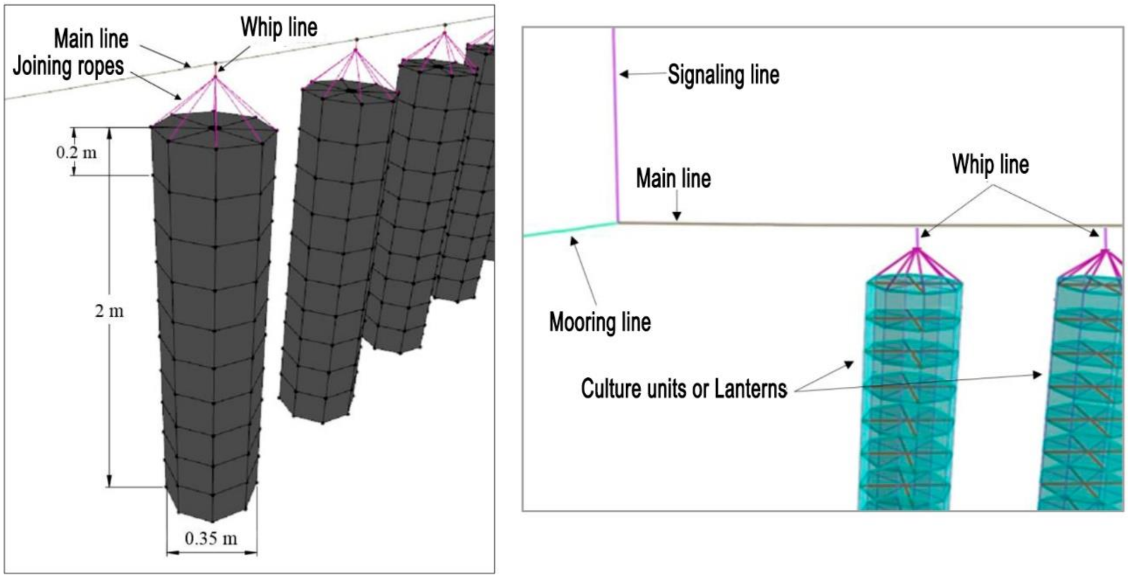

Figure 1. Components and dimensions of the culture unit (lantern).

Table 1. Technical specifications of the main components of the longline culture system used in the simulation. *T#: mesh size.

Item	Characteristic	Element type
Lantern		
Panel	Square mesh *T# 21 mm (PA ϕ 2 mm)	Membrane
Structure	Standard steel wire (ϕ 4 mm)	Beam
Joining ropes	PP ϕ 10 mm	Truss
Whip line	PP ϕ 10 mm	Truss
Anchor		
Mooring line	PP ϕ 24 mm	Truss
Main line	PP ϕ 24 mm	Truss
Midwater buoy ropes	PP ϕ 12 mm	Truss
Marker buoy ropes	PP ϕ 12 mm	Truss

surface and submerged operating conditions and from changes in the direction of the oceanographic variables (parallel or perpendicular).

RESULTS

Main line stresses

Stress magnitudes obtained from the main line indicate that increasing energy in the environment increases stress in this element, except for the cases where it goes from a condition of 1 m s^{-1} and 2 m (category Cc) to 0.5 m s^{-1} and 5 m (Eb) of current velocity and wave height respectively in perpendicularly direction, decreasing 1,853 to 1,549 kg for the case where the longline system operates surface and 1,752 to 1,213 kg for case where it operates submerged (Fig. 2).

Under the submerged operating condition, results obtained showed a lower stress in the main line when the direction of water current and wave are parallel to the longline system as compared with perpendicular direction. In addition a maximum difference was observed in main line stress under 1 m s^{-1} water current velocity and 2 m wave height conditions, reaching a 59% decrease in stress magnitude (Table 3).

Under surface operating condition, a similar change was observed when modeling low energy environmental conditions (0.5 m s^{-1} and 2 m, 1 m s^{-1} and 2 m, current velocity and wave height, respectively). When modeling higher environmental energy conditions (current velocity of 0.5 m s^{-1} and 5 m) an increase in stress from 1,549 to 2,153 kg for a high wave was observed. While a high environmental energy condition of current velocity of 1 m s^{-1} and 5 m wave height,

Table 2. Environmental classification based on current velocity and wave height according to Norway Standard NS 9415. Cb, Cc, Eb and Ec: Name of location class assigned by Norway Standard to different ranges of oceanographic parameters.

Operating condition	Direction of currents and waves	Current velocity	Wave height (m)	Location class according to NS 9415
Surface	Parallel Perpendicular	0.5 m s^{-1}	2	Cb
	Parallel Perpendicular	1 m s^{-1}		Cc
	Parallel Perpendicular	0.5 m s^{-1}	5	Eb
	Parallel Perpendicular	1 m s^{-1}		Ec
Submerged	Parallel Perpendicular	0.5 m s^{-1}	2	Cb
	Parallel Perpendicular	1 m s^{-1}		Cc
	Parallel Perpendicular	0.5 m s^{-1}	5	Eb
	Parallel Perpendicular	1 m s^{-1}		Ec

showed no incidence of the direction of the oceanographic variables on the stress in the main line (Fig. 2).

Results obtained showed that independently of the oceanographic variables direction and environmental energy levels considered, stresses in main line are always lower in submerged operating conditions than under surface operating conditions (Fig. 2).

Stresses on the mooring line

Stress magnitudes obtained from the mooring line indicate that increasing energy in the environment increases stress in this element, except for cases where it goes from a condition of 1 m s^{-1} and 2 m (category Cc) to 0.5 m s^{-1} and 5 m (Eb) of current velocity and wave height respectively in perpendicularly direction, decreasing 1,858 to 1,562 kg for the case where the longline system operates surface and 1,757 to 1,221 kg for case where it operates submerged (Fig. 3).

Under the submerged operating condition, results obtained showed a lower stress in the mooring line when the direction of water current and wave are parallel to the longline system as compared with perpendicular direction. In addition a maximum difference was observed in mooring line stress under 1 m s^{-1} water current velocity and 2 m wave height conditions, reaching a 59% decrease in stress magnitude (Table 4).

Under surface operating condition, a similar change was observed when modeling low energy environmental conditions (0.5 m s^{-1} and 2 m, 1 m s^{-1} and 2 m, current velocity and wave height, respectively). When modeling higher environmental energy conditions (current velocity of 0.5 m s^{-1} and 5 m high wave) an increase in stress from 1,562 to 2,217 kg was observed. While a high environmental energy condition of current velocity of 1 m s^{-1} and 5 m wave height, showed no incidence of the direction of the oceanographic variables on the stress in the mooring line (Fig. 3).

Results obtained showed, as well as in the main line, that in submerged operating condition always observed lower stress than under surface operating conditions, independently of the oceanographic variables direction and environmental energy levels. (Fig. 3).

Stress on the whip line

The stresses experienced by the whip line indicate that greater forces are experienced when the direction of the current and waves is parallel to the main line, rather than perpendicular (Fig. 4), resulting in an increase of 312% when the system is at the surface and a decrease of 120% when submerged, both under location class category Cc (Table 5).

Moreover, there is evidence that whenever the system is submerged, stress on the whip line decreases (Fig. 4), with the greatest decrease being 17% (53 to 45 kg) when the current and waves are perpendicular, versus 55% (219 to 99 kg) when the current and waves are parallel to the main line (Table 5).

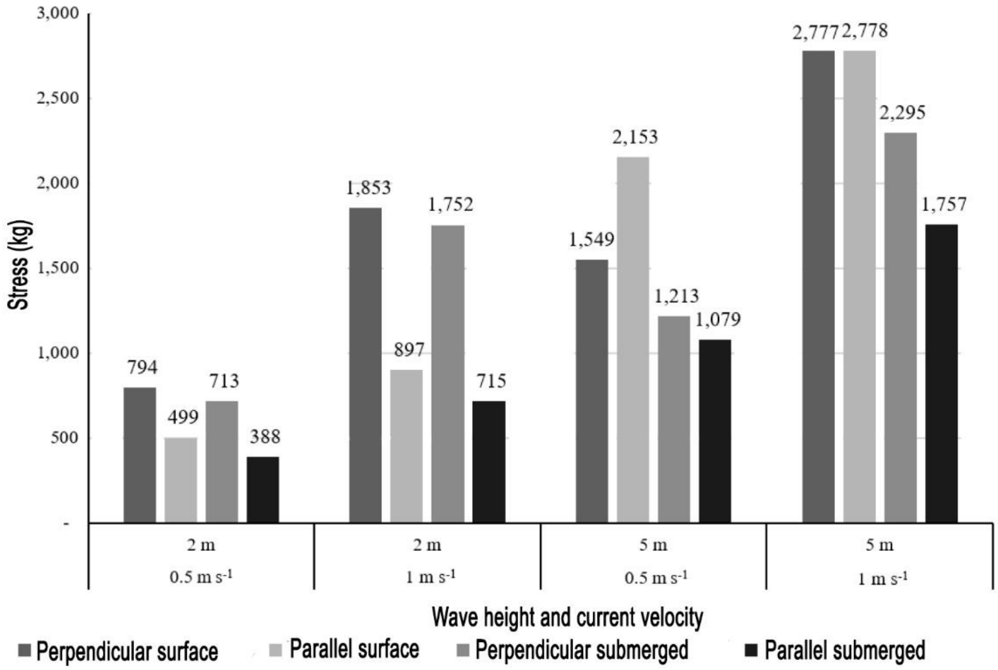

Figure 2. Main line stresses under two operating conditions and different oceanographic variables.

Table 3. Percent change in main line stresses upon submerging the longline system (effect submerge) and upon changing the direction of the current and waves (effect to the direction of oceanographic variables). DOV: direction oceanographic variables, OC: operating condition.

Location class	Current speed and wave height	Submergence effect (7 to 15 m depth)		Effect of the direction of oceanographic parameters (perpendicular 90º to parallel 0º)	
		DOV: Perpendicular	DOV: Parallel	OC: Surface	OC: Submerged
Cb	0.5 m s^{-1} and 2 m	-10	-22	-37	-46
Cc	1 m s^{-1} and 2 m	-5	-20	-52	-59
Eb	0.5 m s^{-1} and 5 m	-22	-50	39	-11
Ec	1 m s^{-1} and 5 m	-17	-37	0	-23

DISCUSSION

This study showed that modifying a traditional longline culture system to allow its submergence is an alternative that helps to minimize the effect of the environment on the culture system, which according to Lee *et al*. (2009) could allow this system to be used in exposed areas. This would permit local fishermen operating in management areas in exposed areas to incorporate the culture of aquatic species such as scallops, mussels and algae as a productive activity, thus also contributing to the objective proposed by the for Fisheries and Aquaculture Undersecretary in Chile.

Although this study was based on a longline system with lanterns used mainly for scallop aquaculture, these results can be extrapolated to mussel, algae, abalone or similar species where aquaculture system stress performance will be the same despite differences in their culture units.

In terms of the effect of submerging the longline system, stress on the three components analyzed (main line, mooring line and whip line) was decreased by submergence under all of the evaluated oceanographic parameters. This effect has also been observed in simulations of rafts of submersible fish cages, which resulted in a decrease of the stress on the mooring lines of 64% (Lee *et al.*, 2009).

The resulting stress on the main line and mooring line under submerged conditions decreases when the oceanographic parameters change direction from perpendicular to parallel for all combinations of current velocity and wave height. This finding can be explained by the fact that all of the culture units (lanterns) are affected by the current and waves at the same intensity

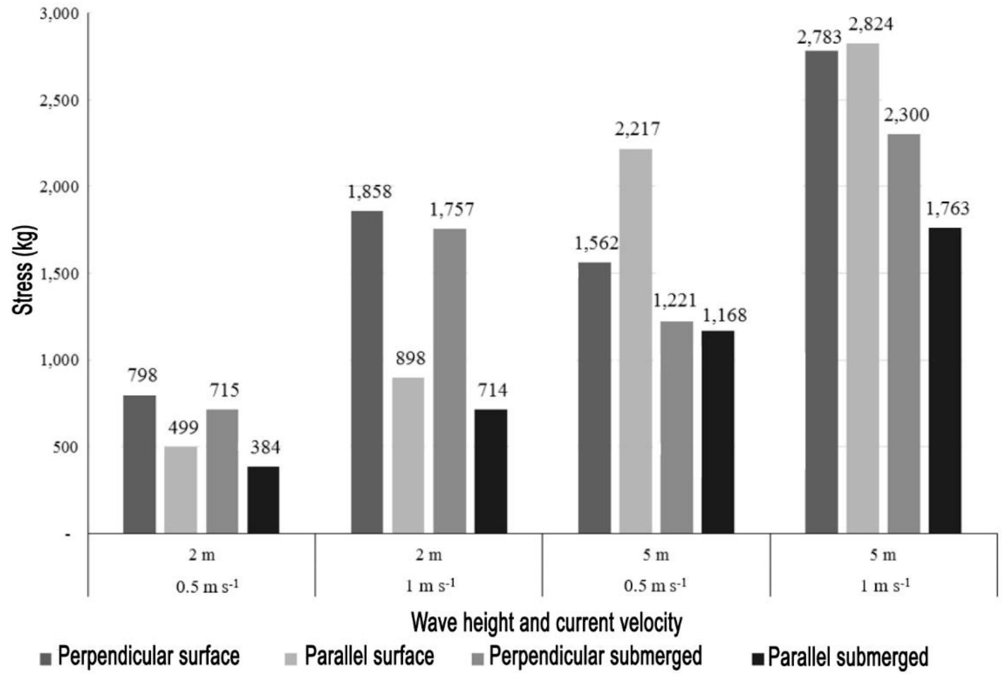

Figure 3. Stress on the mooring line under two operating conditions and different oceanographic variables.

Table 4. Percent change in mooring line stresses upon submerging the longline system (effect submerge) and upon changing the direction of the current and waves (effect to the direction of oceanographic variables). DOV: direction oceanographic variables, OC: operating condition.

Location class	Current speed and wave height	Submergence effect (7 to 15 m depth)		Effect of the direction of oceanographic parameters (perpendicular 90º to parallel 0º)	
		DOV: Perpendicular	DOV: Parallel	OC: Surface	OC: Submerged
Cb	0.5 m s^{-1} and 2 m	-11	-23	-38	-46
Cc	1 m s^{-1} and 2 m	-5	-21	-52	-59
Eb	0.5 m s^{-1} and 5 m	-22	-47	32	-4
Ec	1 m s^{-1} and 5 m	-17	-38	2	-23

when these environmental parameters arrive perpendicularly, whereas when they occur in a parallel direction, the current velocity along the main line decreases (Loland, 1991), which reduces the drag force that each culture unit adds to the system, resulting in a smaller overall drag force for the system. This effect is reflected as a decrease in the stress on the main and mooring line.

Under surface conditions, stress decreases only when the direction of the current and waves changes from perpendicular to parallel under oceanographic parameters in lower energy categories (Cb and Cc). The opposite effect occurs under oceanographic parameters in categories Eb and Ec. This could explain the high energy level to which the longline is exposed as well as the drag force of the system concentrated on a single mooring line and at only one end of the main line when the oceanographic parameters are parallel, leading the maximum force on these components to increase significantly (forces located at the top of the longline system) compared with what occurs when the direction is perpendicular.

At the same time, the whip lines transmit greater stress (maximum) when the direction of the currents and waves is parallel to the main line. However, the greatest stress is recorded on the whip lines of the culture units located in front, which are most affected by the oceanographic parameters, as the current velocity along the main line decreases as the water flow passes through each lantern (Loland, 1991), gradually decreasing the drag force that each lantern adds to the system, resulting in a progressive decrease in the stress recorded for each whip line along the main line. The stress recorded on the whip lines is understood as an indicator of the level of agitation that the culture unit endures. Thus, it can be inferred that due to changes in the forces exerted upon the whip line during short time

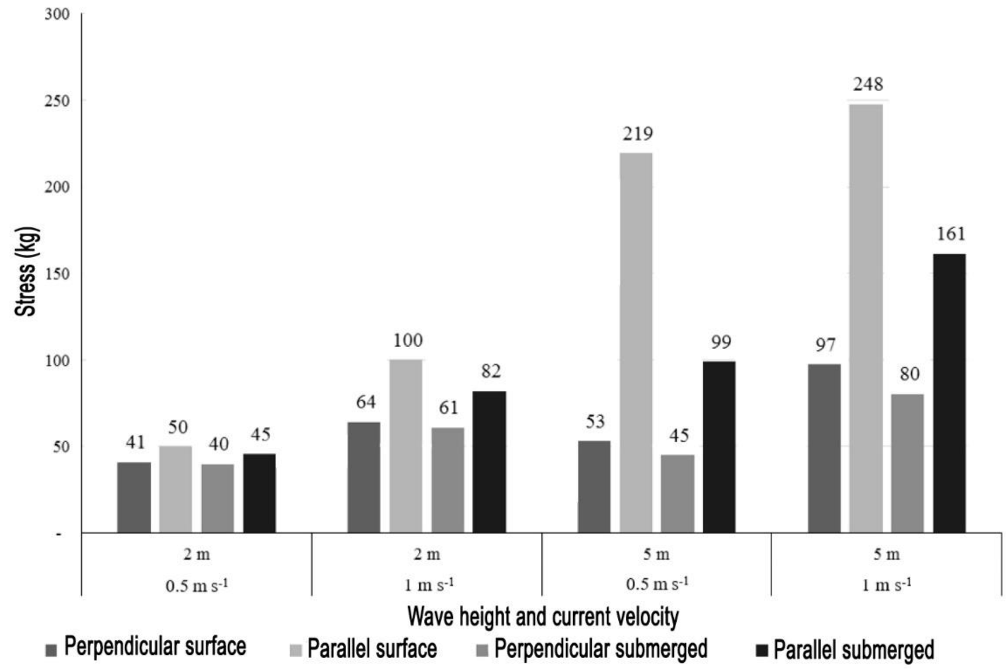

Figure 4. Stresses on the whip lines under two operating conditions and different oceanographic variables.

Table 5. Percent change in whip line stresses upon submerging the longline system (effect submerge) and upon changing the direction of the current and waves (effect to the direction of oceanographic variables). DOV: direction oceanographic variables, OC: operating condition.

Location class	Current speed and wave height	Submergence effect (7 to 15 m depth)		Effect of the direction of oceanographic parameters (perpendicular 90º to parallel 0º)	
		DOV: Perpendicular	DOV: Parallel	OC: Surface	OC: Submerged
Cb	0.5 m s^{-1} and 2 m	-3	-9	22	14
Cc	1 m s^{-1} and 2 m	-5	-18	56	34
Eb	0.5 m s^{-1} and 5 m	-16	-55	312	120
Ec	1 m s^{-1} and 5 m	-17	-35	155	101

periods, explained by the period of the wave, vertical acceleration increases at the surface relative to the submerged position, resulting in greater agitation due to the displacement produced along this axis (Chakrabarti, 1987). These effects should impact the growth and mortality rate of oysters (Pereira, 1995). In the case of culture of mussels or algae in the longline system, such effects could result in loss of biomass due to the displacement of individuals.

In general, the case of the mooring and main line the drag force is higher when the culture system is perpendicular to oceanographic variables. This as the velocity of the current facing each lantern is the same and this does not happen when oceanographic conditions are parallel to the culture system. The above is explained by the fact that the effect of reducing flow velocity decreases the drag force and at the same time the tension in the mooring line.

Nonetheless, the above is not the case when the system operates in surface with high energy (Eb and Ec) what could be explained by the larger wave effect when the culture system is parallel rather than perpendicular to the oceanographic conditions. Given the above findings, further studies in the field will be necessary to evaluate the level of impact that a submersible longline system would have on productive factors such as growth rates and mortality as well as losses through detachment and stress associated with the energy of the environment.

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