A new criterion for Multi-purpose platforms siting: fish endurance to wave motion within offshore farming cages

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Abstract

Early studies have described the existence of a critical speed in fish when challenged by unidirectional currents, often calculated as number of body length/second (BL/sec). In salmon farming, the criterion related to the disruption of normal swimming behaviour in cage and the consequent onset of intense aerobic challenging, marked by the start of ram ventilation, has recently been proposed with regard to unidirectional currents under tidal conditions. Unfortunately, this criterion appears only partially satisfactory within the specificity of the marine offshore environment, where wave motion dominates even at relevant depth, as in the case of long-lasting storms and associated waves in long wavelength, not uncommonly over 100 m of length.

In the present work, the orbital velocities generated by wave motion at different depths are proposed as additional criteria, besides critical speeds to unidirectional currents, to define the likely limits of exposure of fish stocks farmed in offshore environments and consequently, to set up a range of sea states compatible with fish welfare. This finding can support the definition of an acceptable sea state for the whole Multi-Purpose Platform (MPP) design, where the farmed fish are considered as the weakest link in the platform chain design.

Keywords

Multi-purpose offshore platform, Fish endurance, Wave motion, Offshore aquaculture, The Blue Growth Farm.

Highlights

Fish endurance to wave motion in offshore cages

Criteria for MPP siting

Fish welfare in offshore cages

Introduction

The onset of a new generation of Multi-purpose Platforms (MPPs) designed to operate in the open sea and combining wave and wind energy extracting devices with huge water volumes devoted to fish farming, has led to an unexpected technological challenge - the coupling of infrastructure for high energy sites with profitable fish culture units. Engineering Standards and Codes from the existing offshore industry provide references for platform design, validated to cope with all the expected sea states at the final installation site, although the association of living and mobile organisms with high-energy environments is not obvious.

Some authors (Zanuttigh et al., 2016), within the frame of the past EU FP7 project, have described a method to identify the best design solution for MPPs, including the technological features of either single- or multi-use platforms, to be selected for a given site. This method proposes a pre-screening phase, where the basic questions on the site potential are addressed, and a ranking phase where a value is associated to each envisaged technological solution. Although substantially based on engineering concepts, the method does not refer to any relationship between sea states and fishes' ability to withstand energetic environments.

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A number of methods have been applied to the study of swimming speed performance in fishes, from short-term intense current exposure trials to testing of maximum critical speed in incremental steps, up to trials evaluating fish long-term endurance to a fixed speed. Brett (1964) first developed the original concept of the critical swimming speed (***U_{crit}***), based on the measure of the swimming fish performance under increasing flow speeds. The ***U_{crit}*** values were correlated (Farlinger & Beamish, 1977; Willliams & Brett, 1987) with the current velocity and trial duration. ***U_{crit}*** estimations correlated with maximum prolonged swimming speed were provided by Wilson & Egginton (1994), Hammer (1995) and Plaut (2001). Several authors (Jones et al., 1974; Hartwell & Otto, 1991; Kolok, 1991; Hawkins & Quinn, 1996; Lowe, 1996; Myrick & Cech, 2000; Fisher, 2005) have used the ***U_{crit}*** of different fish species to investigate the correlation between fishes' swimming capabilities, their biological characteristics and the fundamental ecological variables, such as the local hydraulic environment. Videler (1993) demonstrated that prolonged swimming performance over daily times scales are of major importance in foraging activity and habitat exploitation in fish. The relationship between certain important ecological fish traits such as routine field speed and critical swimming speed was investigated by Plaut (2000), and Fisher & Bellwood (2003); the sustained speed and sprint speeds have also been investigated in a small number of fish taxa by Brett (1964), Fisher & Wilson (2004) and Reidy et al. (2000). Plaut (2001), considering the relevance of fish speeds to the fish biology and ecology, concluded that the ***U_{crit}*** represents a reliable measure of fish swimming speed capability.

Several swimming tunnel studies have reported the ***U_{crit}*** in salmonids. In adult reared Atlantic salmon (*Salmo salar*) the attained ***U_{crit}*** (weight 1.75 kg, fork length (L_f) = 51.3 cm, at 14°C) was 100 cm/sec (Remen et al., 2016). In adult wild *S. salar* (L_f = 55–60 cm) ***U_{crit}*** ranged between 176 cm/sec and 216 cm/sec at respectively 13°C and 18°C (Booth et al., 1997; Thorstad et al., 2008). Remen et al. (2016) demonstrated that ***U_{crit}*** value shifts with size from

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80.6 cm/sec in small post-smolts of approximately 80 g to 90.9 cm/sec in larger post-smolts (≈289 g) and 99.5 cm/sec in adults (≈1750 g). U_{crit}**,** when expressed as BL/sec, is inversely correlated with fork lengths, i.e. it is higher in smaller fish**.** In a push-cage experiment on reared specimens, the attained U_{crit} was 125 cm/sec (3.4 kg, L_f = 63 cm, 7-7.5°C, Hvas et al., 2017).

Basaran et al. (2007) studied the swimming performances of Gilthead seabream (*Sparus aurata*) in a current channel. Absolute U_{crit} performance, in wild and farmed fish, showed an increase with the fish length and the average U_{crit} of wild fish of wild was higher (0.86 m/sec) in a significant way compared to farmed fish (0.79 m/sec). The relative U_{crit} was also negatively correlated with the fish length (Figure 1) and significantly higher in wild fish (4.52 BL/sec) compared to farmed ones (4.21 BL/sec).

Seabass (*Dicentrarchus labrax*) U_{crit} was observed in a few studies. Carbonara et al. (2006) observed that U_{crit}**,** measured in tunnel, was lower than in seabream. The absolute U_{crit} ranged from 0.97 to 1.27 m/sec and relative U_{crit} ranged from 3.6 to 4.1 BL/sec. Different values were reported in the study of Luna-Acosta et al. (2011), ranging from 2.4 to 2.7 BL/sec, as standard length.

Remen et al. (2016) proposed marking the water velocity thresholds that indicate the safe welfare for salmon farming under exposed conditions, by using the U_{crit} as the limiting value. Beyond that value, a prolonged exposure would lead to physiological depletion, where the fish would no longer be able to move away from the rear closing grid in the experimental tunnel (Wood, 1991).

Recently Johansson et al. (2014) and Hvas et al. (2017), studied both endurance and swimming behaviour of Atlantic salmon in offshore cages at different current speeds. Below a current threshold of 20 cm/sec outside the cages (Johansson et al., 2007), *S. salar*

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maintained a swimming velocity independent from the current velocity outside the cage, and fish moved in circular schools swimming at speeds ranging from 0.3 to 1.1 BL/sec (Dempster et al., 2009; Stien et al., 2016).

On a commercial salmon farm in exposed conditions, at the increase in current speed from 20 cm/sec to 35 cm/sec and then to velocities over 47 cm/sec, the fish swimming pattern shifted from a circular ranging to a composition of circular movements with a part of the school facing the current, to end in a complete standing against the current of the entire school (Johannson et *al*., 2014). Swimming behaviour was as shown in Figure 2. At low current velocities the fish swam in a circle (Figure 2-A) and were distributed within the most of the cage volume. The authors assumed this normal schooling structure as marking the preferential fish velocity. At increasing current velocities, part of the school moved to face the current close to the net, while the rest of the school kept circling in an elliptic shape behind them (Figure 2-B). Fish swimming in circle maintained their behaviour up to the exposure of specimens' sides to the vivid current, when they gained a new position by drifting to the sheltered opposite side of the cage. With high current velocity, the circling pattern was completely disrupted and all fish appeared to swim in a dense group facing the current, abandoning the circling swimming pattern (Figure 2-C). After the disruption of circular swimming behaviour, the fish were therefore forced to swim at velocities imposed by the environmental energy acting inside the sea cages. Swimming in the wake of others against the current in a group has been reported to save energy (Herskin et al., 1998), in an attempt to optimize energetic consumption after current speed increase. The same swimming pattern was confirmed in the study of Hvas et al. (2017), where adult salmons in an offshore cage were exposed to strong currents. At flow speed ≈ 65 cm/sec, the onset of the ram ventilation was noticed, to become the dominating respiratory mode in the majority of fish above 100 cm/sec. In the presence of a prolonged swimming activity, ram ventilation thus

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represents an effective adaptation to higher oxygen requirements. As a consequence, swimming at sustained speeds causing a prolonged ram ventilation would physiologically challenge fish and possibly impair their growth (Hvas et al., 2017). In the wild, Blanchet et al. (2008) reported that the growth of Atlantic salmon was improved by the lower swimming costs sustained at low flow velocities, when compared to swimming costs at intermediate flow speeds. In farming practice, *S. salar* post-smolts grew at significantly higher rates at a current of 0.8 BL/sec compared to 1.5 BL/sec (Solstorm et al., 2015).

Wave motion is considered to be one of the most powerful structuring forces in marine communities, and extreme wave events have been reported to cause mass fish stranding (Follet, 1970). Bodkin et al. (1987) reported a mass mortality of kelp-forest associated fish community, after a series of extreme events due to waves of high amplitude and heights of 8–10 m, capable of exceeding the fishes' capacity of maintaining their position. Lassig (1982, 1983) reported a large number of fish wounded after a tropical cyclone, likely caused by substratum abrasion, and also a displacement of a number of individuals from their usual habitats. At the same time, Cheal et al. (2002) argued that the majority of fish populations is either able to encompass the effects of these short-lasting wave extremes, or quickly recolonize habitats from sheltered locations after intense wave disturbances. In some cases, extreme wave events can completely remove individuals from their habitats and hence wave disturbance is able to modify the composition and diversity of local fish communities (Connell, 1997; Hughes & Connell, 1999). Jordaan (2010) found that fish community composition was correlated with exposure to waves along the coast of Maine, reflecting a combination of physical factors and physiological barriers.

In freshwaters (Gabel et al., 2011), waves can provide an advantage to predatory fish with body shapes adapted to extreme hydraulic environments. The increase of swimming activity

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recorded in breams was also interpreted as a manoeuvre to escape the wave exposed area. Weihs (1993) reported that posture stability is directly correlated with fish swimming velocity and fish of substantial body sizes have the chance of a larger momentum when caught by waves (Webb, 2002). Stoll and Fischer (2010) found juvenile cyprinids with increased metabolic rates and reduced somatic growth, suggesting a larger energy allocation to swimming activity in the presence of an intense wave action. Moreover, benthic prey availability was related to orbital velocity. Fischer & Eckmann (1997) reported that breams moved from the shallow littoral zone to deeper bottoms when their shape shifted to deep-bodied.

Wave energy is also affecting the fish community of coral and rocky reefs (Ebeling & Hixon, 1991). Fulton et al. (2001) found a significant correlation between the swimming performance and the distribution and abundance at different wave exposure of labrid fishes (Bellwood & Wainwright, 2001). Fulton & Bellwood (2004) correlated the distribution of temperate labrids at different wave exposures and their swimming performances. Reef fishes' distribution patterns varied within different wave exposures and was correlated with the fish swimming capabilities (Fulton, 2005).

Early authors (Blake, 1983; Webb, 1984; Weihs, 1989), demonstrated how the body fish shape is an indicator of swimming capabilities, where fusiform shapes are favoured in fast continuous swimming, and laterally compressed shapes are associated with stability and manoeuvrability at low speeds. Environmental flow velocity has a direct linear relationship with the swimming speed performances of fishes in nearby communities. Fulton (2005) reported how chaetodontiform and subcarangiform body shapes of reef fishes were either completely absent or in low abundance in reef flat habitats swept by the most intense waves and where water flow speeds were close to the upper limit swimming speed of these fish

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groups. Denny & Gaylord (2002) measured the wave-induced water velocities within rocky intertidal habitats, up to speeds of 2.5 m/sec, and argued that the energy demand for living in such habitats imposes a substantial physical challenge on marine organisms.

Sites selected for aquaculture installations in offshore areas are often associated with a relevant wave energy and intense water currents, compared to coastal locations selected for fish farming; several papers (Castro et al., 2013; Davidson, 1997; Gallagher et al., 2001; Huntingford, 2010; Palstra et al., 2015; Palstra & Planas, 2011; Solstorm et al., 2015) explored how fish farmed in offshore cages would physiologically react in exposed environments in terms of growth, stress levels, behaviour and welfare. Wave motions, currents and platform motions can interact with fish living in a confined environment, like the water volume inside a cage net, whose walls and bottom prevent fish from fleeing away to reach a suitable environment, from the point of view of their energetic expenditure and endurance capability. Hence, the exposure of large fish batches to intense wave motion and its possible influence on fish welfare (Ashley, 2007; FEAP Code of Conduct, 2008; Segner et al., 2019) should not be neglected during processes of MPP design and appropriate installation site assessment.

The objective of the present study is therefore to establish a design criterion for offshore farming facilities that encompasses the fish capability of coping with harsh hydraulic conditions, within an acceptable welfare. With this aim, the similarity between fish endurance in unidirectional currents and that under the orbital movements generated by storm waves will be discussed, and the rationale behind the fish welfare status related to U_{crit} and the welfare due to wave movements exposition will then be investigated.

The three species (seabass, gilthead seabream and Atlantic salmon) suitable for farming within the Blue Growth Farm platform (BGF, **www.thebluegrowthfarm.eu)** were chosen on

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the basis of several considerations, including optimal temperature range, value and market share. Only these species are focused on here, as a useful paradigm for establishing a MPP design criterion including fish endurance, although the concept may be widely extended to offshore cage farming. While Atlantic salmon is the most farmed fish species in cold waters, seabass and gilthead seabream well represent Mediterranean fish mariculture; moreover, several other species suitable for offshore aquaculture may be investigated in the future.

Material and methods

To assess a fish sustainable wave motion, the orbital water speed within a wave cycle has been taken into account along the water column, at a step of 1 m, from the surface to the maximum depth where an offshore cage bottom (-35 m) is commonly located.

The orbital particle velocity U_{wav}, at increasing depth steps of 1 m, has been calculated based on the formulas in Mosetti (1979).

The X and Z semi-axes of the wave particles orbits are:

$$X = a\,(\cosh(2\pi(z-h)/\lambda) / (\sinh(2\pi h/\lambda))) \quad (1)$$

$$Z = a\,(\sinh(2\pi(z-h)/\lambda) / (\sinh(2\pi h/\lambda))) \quad (2)$$

Where:

a: wave amplitude, m

z: depth where orbit is calculated, m

h: bottom depth, m

λ: wavelength, m

The orbital particle velocity has been derived from the formula for ellipse perimeter

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calculations, as:

$$\boldsymbol{S = 2 \pi \sqrt{((X^2+Z^2)/2)}} \quad \textbf{(3)}$$

Representing the distance covered by the water particles within the period T;

Orbital velocity is then obtained as ***S / T.***

$$\boldsymbol{S / T = U_{wav}} \qquad \textbf{(4)}$$

Wave parameters have been calculated using formulas for the JONSWAP spectrum (Hasselmann et al., 1973), as in Boccotti (2004). This spectrum, although not completely fitting the shorter Mediterranean wavelengths (Mosetti, 1979), has been chosen for its general validity.

Peak period, $\boldsymbol{T_p}$, has been calculated as:

$$\boldsymbol{T_p = 8.5 \pi \sqrt{(H_s/4g)}} \qquad \textbf{(5)}$$

Where:

$\boldsymbol{H_s}$ is the significant wave, m

$\boldsymbol{g}$ the gravity acceleration, m/s^2

$\boldsymbol{T_p}$ has then been multiplied by 0.95 to obtain a good estimate of $\boldsymbol{T_s}$, the significant period, used in further waveform calculations

$$\boldsymbol{T_p * 0.95 = T_s} \quad \textbf{(6)}$$

The wavelength $\boldsymbol{\lambda}$ has been calculated from the formula:

$$\boldsymbol{\lambda = (T_s)^2 g / 2\pi} \quad \textbf{(7)}$$

Under the simplified hypothesis of a sinusoidal wave.

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Calculations of the orbital velocities at increasing depth, at step of 1 m, were carried out for:

Sea bottom depth: 100 m; 40 m;

Significant wave H_s of: 4 m; 5 m; 6 m; 7 m; 8 m;

The above values have been assumed as representative of the range of depths commonly exploited by offshore cages and of waves related to severe sea states, possibly representing an operative limit capable of discouraging the farming activities in offshore environments.

In Atlantic salmon, Johansson et al. (2014) inferred that a current speed of approximately 0.7 BL/sec, indicating the onset of disruption of the voluntary swimming pattern, may be considered the preferential fish speed when free to choose its preferred position in a circling shoal. Keeping the fish a circular structure (with one semi-circle favouring the current and the other against it), they proposed to set at twice this speed (1.4 BL/sec, approximately 0.66 U_{crit}) the upper limit of current speed marking the range of water velocities that salmon can withstand without impairing their welfare and growing capability under acceptable farming conditions.

The welfare critical speed for salmon U_{welf}, has been here considered as:

$$0.66 * U_{crit} = U_{welf} \quad (8)$$

Similarly, the orbital velocity U_{wav} will be considered here as in relationship with the U_{welf} for the same multiplying factor:

$$0.66 * U_{wav} = U_{welf} \quad (9)$$

In the present study, the reference wave is the significant wave H_s, defined as the average of the highest third of the waves in a given sea state; commonly considered as the design wave, its value well represents (together with the associated significant period T_s) the mean of the

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worst part of a storm episode. As it is an average, it does not account for the extreme wave heights during a storm, of critical importance for fish restrained in cages due to the associated orbital speeds; the $\boldsymbol{H_s}$ is here chosen as reference value under the assumption that peak waves have a limited temporal extension, and the $\boldsymbol{U_{welf}}$ setting at 66% of the $\boldsymbol{U_{wav}}$ may ensure a safety margin to fish endurance.

Results

The criterion established for salmon as the threshold for an acceptable welfare in challenging hydraulic environments is extended here to seabream and seabass under farming conditions. In the absence of experimental data on current velocity leading to circling behaviour disruption for seabass and seabream confined within sea cages, the same value of 0.66 $\boldsymbol{U_{crit}}$ is used here, with the aim of maintaining an acceptable safety margin between their experimental $\boldsymbol{U_{crit}}$ and the welfare environmental velocity $\boldsymbol{U_{welf}}$ for these species. Following Basaran et al. (2007) and Carbonara et al. (2006), the $\boldsymbol{U_{welf}}$ values would then be set at 2.7 BL/sec for seabream and 2.5 BL/sec for seabass, considering their average $\boldsymbol{U_{crit}}$ of 4.2 and 3.85 respectively.

Table 1: Proposed values (cm/sec) of sustainable environmental speeds (66% U_{crit} = U_{welf}) for species and size at 20 °C for seabass and seabream, derived from equations in Basaran et al. (2007) and in Carbonara et al. (2006). In salmon for smolt (small and large) at 14°C, and for adult at 7°C, derived from data in Remen et al. (2016) and Hvas et al. (2017)

Species/size (cm)	**5**	**10**	**20**	**30**	**50**	**60**
Seabream	20	35	55	58		
Seabass	17	32	58	76		

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Salmon small smolt		47	53			
Salmon large smolt				59		
Adult salmon					71	77

While $\boldsymbol{U_{crit}}$ values were experimentally derived in tunnel experiments and for salmon in cages under an approximately unidirectional current, the recent scientific literature does not report data on fish endurance under wave movements in a confined environment such as a fish cage.

In Table 2, the proposed welfare velocities due to the orbital speeds for some significant waves are reported. In the calculation, the sea bottom has been set at -100 m, and orbits are mostly circular down to the cage bottom (-35 m). Safe welfare velocities are attained at significant depth.

Table 2: Depth of welfare orbital velocity for seabream at various sizes, for significant waves of 4-5-6-7-8 m; sea bottom depth = 100 m

Seabream size (cm)	5	10	20	30
$\boldsymbol{U_{welf}}$ **(m/sec)**	0.2	0.35	0.55	0.58
$\boldsymbol{U_{welf}}$ depth at $\boldsymbol{H_s}$ = 4 m	33 m	25 m	17 m	16 m
$\boldsymbol{U_{welf}}$ depth at $\boldsymbol{H_s}$ = 5 m	>35 m	33 m	24 m	23 m
$\boldsymbol{U_{welf}}$ depth at $\boldsymbol{H_s}$ = 6 m	>35 m	>35 m	31 m	29 m
$\boldsymbol{U_{welf}}$ depth at $\boldsymbol{H_s}$ = 7 m	>35 m	>35 m	>35 m	>35 m
$\boldsymbol{U_{welf}}$ depth at $\boldsymbol{H_s}$ = 8 m	>35 m	>35 m	>35 m	>35 m

In Table 3, sea bottom has been set to -40 m, thus within half of the wavelength, ranging from 102 to 204 m. Orbits become quickly elliptical, with the major axis on the X, and safe depth is deeper than previously. Velocity on the X direction becomes dominant.

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Table 3: Depth of welfare orbital velocity for seabream at various sizes, for significant waves of 4-5-6-7-8 m; sea bottom depth = 40 m

Seabream size (cm)	5	10	20	30
U_{welf} **(m/sec)**	0.2	0.35	0.55	0.58
U_{welf} depth at H_s = 4 m	>35 m	25 m	17 m	17 m
U_{welf} depth at H_s = 5 m	>35 m	>35 m	25 m	23 m
U_{welf} depth at H_s = 6 m	>35 m	>35 m	>35 m	34 m
U_{welf} depth at H_s = 7 m	>35 m	>35 m	>35 m	>35 m
U_{welf} depth at H_s = 8 m	>35 m	>35 m	>35 m	>35 m

In Table 4, the different critical speeds for seabass led to a different pattern in safe depths for each wave compared to seabream, at sea bottom of -100 m. Seabass of 30 cm in length are safe from 12 m to the cage bottom, with all the wave range up to 8 m H_s in the JONSWAP spectrum.

Table 4: Depth of welfare orbital velocity for seabass at various sizes, for significant waves of 4-5-6-7-8 m; sea bottom depth = 100 m

Seabass size (cm)	5	10	20	30
U_{welf} **(m/sec)**	0.17	0.32	0.58	0.76
U_{welf} depth at H_s = 4 m,	>35 m	26 m	16 m	12 m
U_{welf} depth at H_s = 5 m	>35 m	35 m	23 m	17 m
U_{welf} depth at H_s = 6 m	>35 m	>35 m	29 m	29 m
U_{welf} depth at H_s = 7 m	>35 m	>35 m	>35 m	29 m
U_{welf} depth at H_s = 8 m	>35 m	>35 m	>35 m	35

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At a sea bottom of -40 m (Table 5), adult seabass (30 cm length) are in safety up to a H_s of 6 m that provides a further 10 m (from -25 to the cage bottom) of safe shelter.

Table 5: Depth of welfare orbital velocity for seabass at various sizes, for significant waves of 4-5-6-7-8 m; sea bottom depth = 40 m

Seabass size (cm)	5	10	20	30
U_{welf} **(m/sec)**	0.17	0.32	0.58	0.76
U_{welf} depth at H_s = 4 m	>35 m	26 m	17 m	12 m
U_{welf} depth at H_s = 5 m	>35 m	>35 m	23 m	18 m
U_{welf} depth at H_s = 6 m	>35 m	>35 m	34 m	25 m
U_{welf} depth at H_s = 7 m	>35 m	>35 m	>35 m	>35 m
U_{welf} depth at H_s = 8 m	>35 m	>35 m	>35 m	>35 m

Atlantic salmon is able to exploit a relevant part of cage depth under JONSWAP stormy waves at -100 m (Table 6). At shallower depth (-40 m, Table 7), the cage becomes unsuitable for adult farming under an acceptable welfare at waves greater than 6 m.

Table 6: Depth of welfare orbital velocity for Atlantic salmon at various sizes, for significant waves of 4-5-6-7-8 m; sea bottom depth = 100 m

Salmon size (cm)	10	20	30	50	60
U_{welf} **(m/sec)**	0.47	0.53	0.59	0.71	0.77
U_{welf} depth at H_s = 4 m	20 m	18 m	16 m	13m	12 m
U_{welf} depth at H_s = 5 m	27 m	24 m	22 m	19 m	17 m
U_{welf} depth at H_s = 6 m	34 m	31 m	29 m	24 m	22 m
U_{welf} depth at H_s = 7 m	>35 m	>35 m	>35 m	31 m	28 m
U_{welf} depth at H_s = 8 m	>35 m	>35 m	>35 m	>35 m	35 m

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Table 7: Depth of welfare orbital velocity for Atlantic salmon at various sizes, for significant waves of 4-5-6-7-8 m; sea bottom depth = 40 m

Salmon size (cm)	10	20	30	50	60
U_{welf} **(m/sec)**	0.47	0.53	0.59	0.71	0.77
U_{welf} depth at H_s = 4 m	20 m	18 m	16 m	13 m	12 m
U_{welf} depth at H_s = 5 m	28 m	25 m	23 m	19 m	17 m
U_{welf} depth at H_s = 6 m	>35 m	>35 m	33 m	27 m	24 m
U_{welf} depth at H_s = 7 m	>35 m	>35 m	>35 m	>35 m	>35 m
U_{welf} depth at H_s = 8 m	>35 m	>35 m	>35 m	>35 m	>35 m

Discussion

The Blue Growth Farm Project, running under a Horizon 2020 collaborative scheme, aims to design an offshore platform devoted to fish farming, equipped at the same time for a relevant wind and wave energy extraction, and combining different technologies with a high degree of environmental flexibility. During the site selection process, the capability of fish stocks to cope with extreme environmental conditions was raised as a concern, since farmed fish may be considered as the "weakest link" within an offshore platform's operational chain.

Under sea states characterized by long wavelengths (>100 m), the water motion can be relevant even at the depth of the cage bottom, ranging from 10 to 35 m in current offshore aquaculture practice. The water particles' orbits are at their maximum size at the surface, decreasing exponentially with depth. Therefore, within each wave cycle the fish is forced, in order to maintain its position, to sustain a swimming phase with a total length theoretically approaching the orbit perimeter at the depth where the fish is located, and the duration of

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movement is close to the wave period, at that depth. It may be argued that a similarity exists between the swimming phases of a circling shoal in a horizontal plane and the corresponding phases generated by the orbital movements of the incoming wave in a vertical plane, both characterized by an active (against current) and a passive phase (with current).

The orbital velocity at various depths can generate extreme motion levels, in some cases overcoming fish $\boldsymbol{U_{crit}}$, particularly within the superficial layers. Here we assume that, within the range of wave motion that a fish is able to withstand without being cast away to collide with the net walls or the cage bottom, the $\boldsymbol{U_{crit}}$ is not attained; at the onset of fish collisions against nettings, the $\boldsymbol{U_{crit}}$ is to be intended as surpassed. During storms, wave periods mostly range from 9 to 15 sec and duration can encompass several hours. Thus, fish may experience a huge number of cycles of swimming (e.g. for a 3 hours peak storm duration at T = 10 sec, a number of 1080 cycles is reached), which we assume to be no less energy-consuming than the effort sustained under continuous exercise of rather short duration (from 20 min to 1.5 h in tunnel experiments). As a consequence, the cyclical speed $\boldsymbol{U_{wav}}$ due to orbital motion should not exceed the $\boldsymbol{U_{crit}}$, and therefore not leading to fish exhaustion under a prolonged storm; to be compatible with an acceptable fish welfare, the $\boldsymbol{U_{welf}}$ is set at 66% of the calculated $\boldsymbol{U_{wav}}$, as for unidirectional currents (Johansson et al., 2014).

Farmed fish ideally take advantage of all of the cage volume within normal farming conditions, and in the event of a stressing episode they may display a schooling behaviour leading to fish grouping in considerable densities, reaching 20 times more than normal (Oppedal et al., 2011). The water column within a farming cage can therefore offer a volume of different thickness depending on incident waves, where fish can stay in a comfortable hydraulic environment. Due to the specific fish $\boldsymbol{U_{crit}}$ at different sizes, this layer can be represented by a significant part of the original cage volume, or be restricted to the deeper cage part, where fish can attain a very high density. The calculations proposed above indicate

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that, in open marine areas under a severe wave regime, shallow cages may be unsuitable to guarantee an acceptable welfare mainly for juvenile stockings.

The need to ensure a sufficient vital volumes to fish stocks able to comply with their $\boldsymbol{U_{welf}}$, has driven the BGF design process towards a partial shelter to incoming waves provided by the platform immersed walls, and to the provision of a deep volume by the relevant depth of cage nets. In view of the future offshore aquaculture development, the present study supports the definition of the operational limits for offshore cages taking into the due account the fish endurance. Although an early author (Turner, 2000) pointed out the issue of fish surviving capability in offshore conditions, the current technological rush to offshore aquaculture has only so far been driven by the engineering challenges aimed at extending the capability of farming structures to operate and survive in extreme sea states. The fish stocks have received scant attention, even though they are sentient vertebrate animals that must be ensured of acceptable (from the fish point of view) farming conditions (see Council of Europe (2006), and Toni et al. (2019) for a review of EU Directives and recommendations on fish welfare). In high-energy offshore sites, production facilities should be able to offer an adequate shelter to fish stocks, either by defensive structures or by deeper cages, even when requesting an elevated degree of automation for husbandry practice, compared to common offshore cages.

The recent MPP design developments, supported by several FP7 (MERMAID, TROPOS and H2Ocean) and H2020 initiatives (Space@Sea and The Blue Growth Farm) have explored the possibility of joining aquaculture to offshore space and renewable exploitation. The challenges posed by the associated development of marine renewables, based on high-energy sites, and aquaculture, so far operating successfully in mild conditions, have not been sufficiently addressed since the very early conceptual elaborations, not adequately having taken into account the limits of fish welfare in exposed sites. On the basis of this study, the future MPPs

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design will be oriented towards structures able to support deep cages, either from a dynamic point of view than as operational needs.

The present study aims to contribute to a welfare-based design of MPPs and, more generally, of offshore aquaculture installations. At the same time, it offers a rationale for allocating offshore areas suitable for aquaculture, on the basis of specific wave climate knowledge, and when the fish endurance limits of a relevant number of species will be available in the future.

Conclusion

During the process of siting of MPP designed to support fish farming in offshore areas, the fish endurance to extreme sea states should not be overlooked and, as for engineering standards for offshore infrastructures, a criterion to set the limiting sea state conditions leading to acceptable fish welfare should be included in the design process, both to comply with the legal and ethical farming requirements and to provide an adequate production environment.

The orbital movements generated by waves are deemed capable of affecting fish welfare, in analogy with the unidirectional currents. The present study provides a new perspective on fish welfare, based on the environmental energy due to the orbital water motion, in offshore areas where wave movements dominate the hydraulic environment.

The acceptable limits of wave motion at various depths under different sea states are presented, for seabream, seabass and Atlantic salmon. For these species, the limiting wave orbital speed is set at a safety value with respect to their U_{crit}, as a threshold criterion for welfare in offshore cage farming.

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