Engineering Challenges for Sustainable Coastal Cage Aquaculture

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Abstract: - As more than 71% of the Earth's surface is covered by water, aquaculture is considered as a formidable alternative to meet rising World population food needs. However, aquaculture is a multi-faceted economic activity requiring scientific expertise from multiple disciplines to bear its successful exploration. This paper deals with the main engineering challenges to be met for sustainable coastal cage aquaculture. In detail, a brief overview of the aquaculture practices is provided, coupled with the main engineering challenges as these apply for the coastal cage aquaculture. Finally, the case of a structured approach development to meet the needs of mooring scenario generation is presented as this applies for the Cyprus' South Coast aquaculture industry.

Key-Words: Coastal aquaculture, Aquaculture Mooring, Sustainable Aquaculture, Aquaculture Engineering.

1 Introduction

Current World population is 6.8 billion, and it is expected to pass through the 7 billion mark in 2012. According to the UN, the world population in 2050 will be 9.1 billion – a rise of over 6.6 billion in a 100 years since 1950 [1]. As more than 71% of the Earth's surface is covered by water, aquaculture is considered as a formidable alternative to meet rising World population food needs.

To this end, aquaculture continues to grow more rapidly than all other animal food-producing sectors, with an average global annual growth rate of 9% since 1970, compared with only 1% for capture fisheries and 3% for terrestrial farmed meat production systems. Today more than 30% of the global fish production comes from aquaculture and it is expected to continue growing during this century since marine aquaculture is probably the only animal-protein production system that does not depend on freshwater consumption [2].

However, in order to establish aquaculture sustainability and further expansion, key problems have to addressed, including among others, fish meal sustainability, wellbeing of surrounding marine environment and reliable engineering solutions to expand this economic activity to new breeding sites further away from the coast and in new operating Sea depths.

In addition, aquaculture is a multifaceted industry addressing multiple and often diverse issues. Successful aquaculture proliferation and sustainable development, needs coordinated efforts to address concurrently multiple arising issues.

To this end, this paper presents the main engineering challenges to be dealt with for sustainable coastal cage aquaculture. In detail, (a) a short overview of the diverse aquaculture practices is provided coupled by (b) a description of the multifaceted nature of this industry. Then, (c) the main engineering challenges for Coastal Cage aquaculture are presented followed by (d) a description of a structured approach for mooring scenarios development as this applies to Cyprus' coastal cage aquaculture.

2 Diverse Aquaculture Practices

Aquaculture, also known as aquafarming, is the farming of aquatic organisms such as fish, crustaceans, molluscs and aquatic plants. Aquaculture involves cultivating freshwater and saltwater populations under controlled conditions, and can be contrasted with commercial fishing,

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which is the harvesting of wild fish [3]. Particular kinds of aquaculture include fish farming, shrimp farming, oyster farming, algaculture (such as seaweed farming), and the cultivation of ornamental fish. In particular, in broad terms, the following aquaculture practices can be identified:

- **Mariculture:** This is the term used for the cultivation of marine organisms in seawater, usually in sheltered coastal waters. In particular, the farming of marine fish is an example of mariculture, and so also is the farming of marine crustaceans (such as shrimps), molluscs (such as oysters) and seaweed [3].
- **Fresh Water Aquaculture:** This is the term used for the cultivation of fresh water fish species, either in lakes, rivers or ponds.
- **Re-Circulation Aquaculture Systems (RASs):** These are systems in which water is (partially) re-used after undergoing treatment. These systems provide opportunities to reduce water usage and to improve waste management and nutrient recycling. RAS makes intensive fish production compatible with environmental sustainability [4].

3 Aquaculture: A Multi-Faceted Industry

As aforementioned, aquaculture is a multifaceted industry in need to address multiple issues from diverse scientific disciplines for its successful proliferation. The "European Aquaculture and Innovation Platform" has organized itself around eight (8) thematic areas, providing an overview of the scope of this industry [5]. In detail, these thematic areas (TAs) are as follows:

a) Product Quality, Consumer Safety and Health.
b) Technology and Systems
c) Managing the Biological Lifecycle
d) Sustainable Feed Production
e) Integration With The Environment
f) Knowledge Management
g) Aquatic Animal Health & Welfare
h) Socio-Economics and Management.

As it can be realised multiple scientific disciplines need to work in a synergistic manner to provide prosperous future for the aquaculture industry. Such scientific disciplines, can be among others, marine biology, marine genetics, marine environment, mechanical/ ocean/ electrical/ electronic/ engineering, agricultural economics/ management and many more.

4 Engineering Challenges for Coastal Cage Aquaculture

Coastal Cage Aquaculture applications currently represent a major proportion, if not the overwhelming majority, of aquaculture production on a Global scale. However, its future proliferation heavily depends on new engineering solutions due to competing claims by other economic activities and/or environmental concerns for shallow coastal waters utilization. Thus, future coastal aquaculture installations will be positioned further away from the coast in greater operating sea depths. This fact has brought the following engineering challenges to aquaculture engineering professionals and academic community:

- **Cage designs:** Recent advances in this scientific discipline include larger Cages. In addition, it includes advances in submersible Cages and feeding automations.
- **Cage mooring solutions:** Operating in depths greater than 70m will create issues relating to mooring setting, since divers will find it increasingly difficult to operate in such depths. If considerable automation is required for this purpose, related costs will increase substantially.
- **Aquaculture Stock monitoring:** As Menicou and Vassiliou [1] describe, larger aquaculture installations, operating even further from the Coast will create the need for remote monitoring.
- **Powering automation/ remote monitoring:** Similar to the aforementioned issue, Menicou and Vassiliou [1] describe the need for Renewable Energy Sources deployment and customization to power increased needs in automation and remote monitoring.
- **Operations Management/ Logistics:** Moving further away from the Coast will create the need for larger aquafarms to compensate for the increased needs in engineering infrastructure. Thus, arising issues will have to be dealt with relating to operations management and production/ distribution logistics.
- **Staff Health and Safety:** Operating further away from the Coast will inevitably create increased staff health and safety precautions and more complicated operating procedures.
- **Fish Processing Plants' Procedures:** Operating with larger fish stocks will create the need for more efficient fish processing plants' procedures to ensure product quality and consumers' health and safety.

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5 A Structured Approach for Coastal Cage Mooring Design

5.1 Problem Definition

The Cyprus Department of Fisheries and Marine Research (DFMR) latest report states that seven companies conducted operations in Cyprus in the field of Cage-based Coastal aquaculture during 2010. Their product mix consists primarily sea bass (*Dicentrarchus labrax*) and sea bream (*Sparus aurata*), even though blue fin tuna (*Thunnus thynnus*) is also cultured on a commercial basis in addition to small quantities of sharp snout bream (*Puntazzo puntazzo*), red porgy (*Pagrus pagrus*), pandora (*Pagellus erythrinus*), and rabbit fish (*Siganus rivulatus*) [6]. The majority of fish stock produced is consumed in the local market, even though extensive exports have been achieved to the nearby Israeli market.

In Cyprus, there is extensive tourist Industry and subsequently there is fierce competition for Coastal space. Subsequently, six out these seven companies are licensed to operate in the Vasiliko bay located in Southern Cyprus, where the bulk of Cyprus' marine industrial activities takes place (see figure 1).

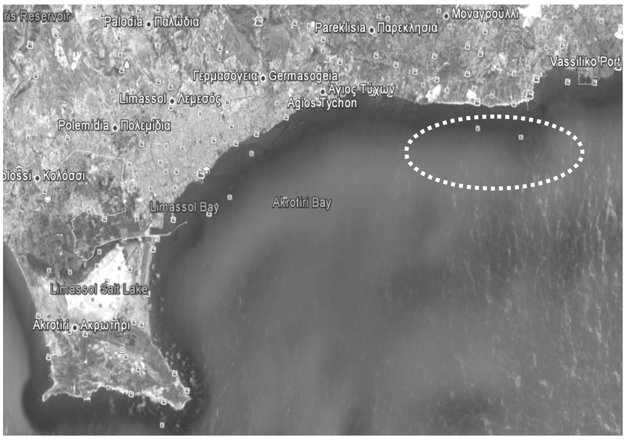

Fig. 1. Vasiliko Bay, Southern Cyprus, location of most of the Island's Coastal Aquaculture activities

On average the installations are located at a distance of 1 to 4 km from the coast, at water depths ranging from 18 - 70 meters at a distance of about 2 km between each other [6]. Almost a decade ago there were also offshore aquaculture installations at the southwest part of Cyprus, offshore the city of Paphos. However, after a high intensity storm the majority of the aquaculture cages were destroyed due to failure of their mooring lines that left them ungoverned at the mercy of the rough sea waves.

Almost all Cypriot fish farms utilize surface grid arrays as their mooring system. As stated by Tsukov and DeCew [7], surface grid arrays are the predominant mooring system in the aquaculture industry worldwide and are part of a group of five different types, the rest being (a) submerged grid array; (b) single point moorings; (c) tension leg platforms; (e) multipoint anchor arrays. Surface grid arrays consist of a series of anchor legs supported by floats, interconnected by lines, shackles and connection plates. They are mostly utilized with plastic gravity-type net pens. The mooring grid is located at depths of approximately five meters below surface and is held up off the bottom with cylindrical of spherical floating elements on each anchor leg. The anchor legs are made up of chain and rope and extend down to the bottom beneath the floats and the grid to plow embedment or dead-weight anchors [7].

5.2 Current Mooring Practices

After extensive interview sessions between the research teams and the major coastal aquaculture companies, the conclusion was reached that the current mooring design approach, as this applies for the majority of the Cypriot Coastal aquaculture fish farms is based on the "trial and error" method for deploying surface grid arrays. The mooring design approach typically addresses the issues basic anchoring tension calculations and anchors' positioning. Critical environmental loading parameters present at the area of deployment are omitted, apart from the case of sea basin's depth. Overall, a "do-it-yourself" approach governs the deployment of fish farms mooring coupled with practical knowledge of experienced divers which usual leads to over sizing system components and connections. Apart from the cage's parts which are purchased from Industry suppliers, the type, dimensions, material, physical properties etc for the rest of the mooring parts' are decided on a 'trial and error" basis and bought from local hardware stores.

In particular, as sated by Vassiliou et al. [8] a typical fish farm's anchoring is achieved either with 10 to 12 tones cement blocks and/or anchors; the floating cages are of approximately 20m diameter created with double high density polyethylene (HDPE) tubes of 250mm diameter passed through brackets of an inverse Greek gamma shape on which net pens and net pen tension weights of 20 to 50Kg are connected that provide a restoring force to help resist net deformation and volume loss in waves and currents; the connecting elements are shackles, mooring lines of 3-strand rope or 8-plaite with a

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45mm or 40mm diameter, stud-link chains of approximately 30m length and iron rope rings; finally, the floating devices utilized are plastic, foam-filed cone-shaped floating buoys of 1000L [9]. Fig. 2 provides a bird's eye-view of a typical cage arrangement, as well as the orientation of the Coastal aquaculture farm towards the predominant wind, while Fig. 3 gives a graphical side view of the whole system and its components.

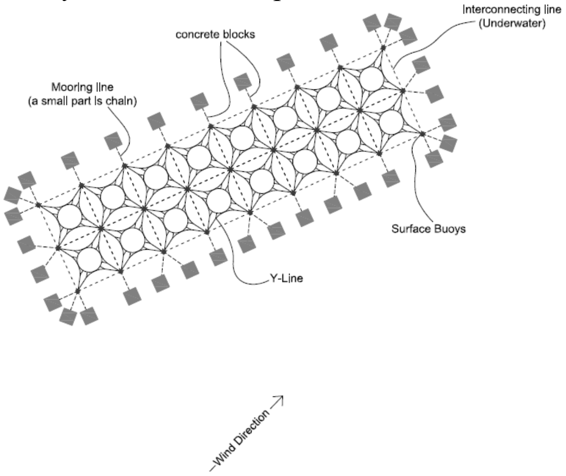

Fig. 2. Bird's eye view of aquaculture array [8]

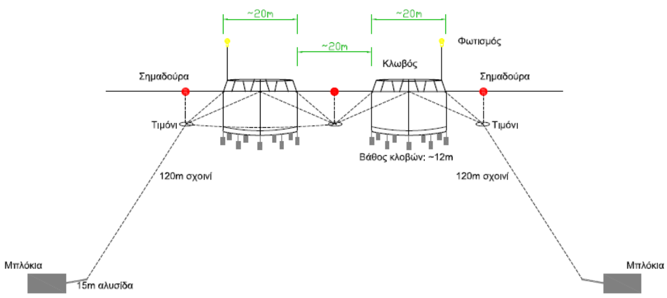

Fig. 3. Side-view of mooring system [8]

This approach has numerous limitations leading to numerous catastrophic events peaking with the December 2001 event during which Sagro Aquaculture fish farm near Paphos International airport suffered a decisive catastrophic event and ceased operations. In particular, during this event mooring lines failed and the supported grid arrays were left unanchored. In the aftermath of the destruction undersized mooring line's diameter and inconsistent maintenance practices were blamed [10].

5.3 Proposed Mooring Design Methodology

Following the aforementioned event, a research project was funded by Cyprus' Research Promotion Foundation to address the issue, supporting a project titled: "A structured approach development for Cyprus' offshore aquaculture mooring requirements investigation and mooring scenario development". To address this challenging task, a consortium of three organizations has been setup, consisting Frederick Research Centre (Cyprus), the University of New Hampshire (USA), and Seawave Fisheries Ltd (Cyprus).

In brief, the proposed structured approach consists of (a) recording the environmental loading parameters at the area of interest; (b) assessing alternative mooring scenarios and employing numerical analysis to predict their structural integrity under extreme environmental loading conditions; (c) field monitoring procedures; and finally (d) validation of the models with in-situ data.

Commencing with the environment loading parameters, it is a fact that although the design of mooring systems can easily be grouped and analyzed, based on their similarities, as described in Section 5.2, the environmental conditions and their understanding are essentially unique and location specific. In fact the primary forcing mechanism on aquaculture installations are waves and currents hence it is of paramount importance to quantify the level of exposure as this is characterized by the current velocity (velocity profiles of tidal, wind and pressure driven currents) and wave height (prevailing wave spectra, and 25 or 50 year significant wave height and period). Accurate identification of operational (daily) and extreme (storm events) environmental load cases for design purposes will help develop more accurate numerical models thus extract more reliable results. Current profiles are typically measured with Doppler instruments whereas the local wave climate can be either measured with deployed instrumentation or estimated from meteorological stations' wind data, weather buoys and other sources.

Following environmental loading recording, numerical models are developed that provide insight into system dynamics, mooring tensions, and possible system resonance. Scaled physical modelling were crossed out since they require significant infrastructure such as wave tanks and flumes and are also far more time consuming. The numerical technique chosen is that of finite element analysis procedures. Validation of the models with in-situ data and field monitoring procedures, have an iterative nature and are the last stages of the methodology [8].

5.4 Preliminary Results

Within the context of the aforementioned research project, numerical models of candidate mooring scenarios, tailored to the needs of a typical Cypriot fish farm were developed, employing the University of New Hampshire's Aqua-FE software package. The software employs the finite element analysis approach most recently described by Tsukrov et al. [11]. Aqua-FE can simulate waves and currents on marine structures such as fish cages and moorings and output selected component motion and tension values.

Additional piece of work includes (a) a state-of-the-art review of alternative mooring scenarios available and their respective merits for the Cyprus' case and (b) a cost-benefit analysis under Cyprus' operating conditions.

The preliminary assembled Aqua-FE mooring model developed, described a typical Cyprus fish farm consisting of a surface grid array securing 18 fish cages as depicted in Fig. 4. The 40 meter long grid lines are suspended 5 meters below the surface by thirty float and chain assemblies, each having a 1000 liter float and 14 mm diameter chain. Twenty-six anchor legs, consisting of 110 meters of 45 mm nylon line, 27 meters of 42 mm diameter chain and a 12 tone deadweight anchor secure the mooring to the seafloor. Note that in the numerical simulations, the anchor positions were fixed.

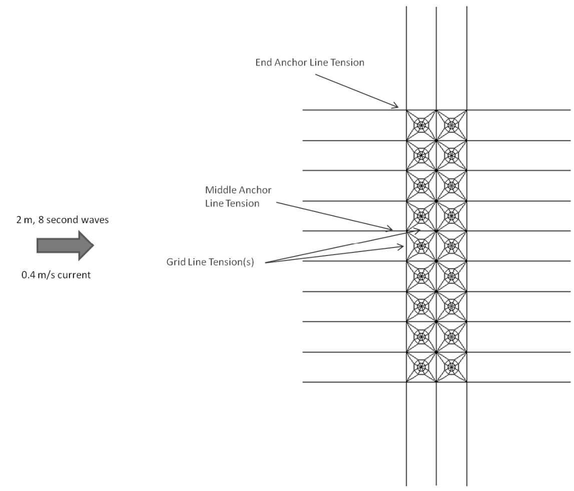

Fig. 4. Surface grid array arrangement and current and wave parameters

Each grid bay contains a 20 meter diameter gravity-type fish cage. The cages consist of floating superstructure of 2 high density polyethylene (HDPE) pipes, 25 brackets, and a handrail. The buoyant rim supports a 10 meter deep net chamber and 16 concrete weights. For this analysis, the net had a twine diameter of 1.8 mm and a mesh spacing of 8 mm. This high solidity (34.8%) grow-out net is typically used during initial fish stocking / grow-out and represents a worst case design condition due to the increased drag of the net. The net chamber typically dominates the drag of fish cages, as documented by [12]. The entire cage and mooring system model was constructed using 1659 nodes and 2522 elements.

The development of the current profile of the area of investigation is achieved through the purchase and deployment of RDP600 instrument from AANDERAA Data Instruments. RDP600 is a medium range, 600kHz self-recording Doppler current profiler that can be configured to deal with several profiles simultaneously for optimum flexibility [13], as shown in Fig. 5.

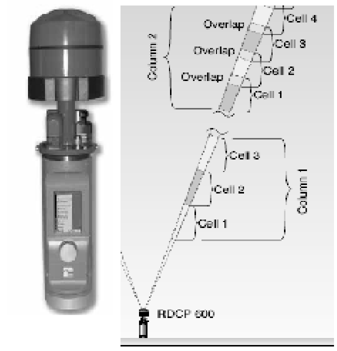

Fig. 5. RDCP600 Doppler current profiler

In contrast, historical wave data for the extraction of the load conditions were not available. Thus, as described in [8], records of the wind speed and direction will be used to predict the wave conditions. The methodology to develop the wave environmental load cases was as follows: Wind speed and direction data were purchased from local meteorological stations near the coast of Cyprus. The wind data were then processed to determine the relationship between the wind speeds, direction, duration and fetch. Average and maximum values were then utilized to generate a spectrum based, for example, on the Pierson-Moskowitz approach described in [14]. Note that this approach is only one of the possible approaches, and its usage has to be validated. Using wind speeds corrected to 19.5 meters above the water surface, the spectral energy of the sea, *S*, significant wave height, H_{mo}, and dominant wave frequency, f_p, can be calculated using the following Eg. (1)-(3), where $\boldsymbol{\alpha}$ is a shaping factor, $\boldsymbol{g}$ is gravity, $\boldsymbol{f}$ is the wave frequency, and *U* is the wind speed.

$$S(f) = \frac{ag^2}{(2\pi)^4 f^5} e^{-0.74\left(\frac{g}{2\pi U f}\right)^4} \qquad (1)$$

$$f_p = \frac{0.87g}{2\pi U} \quad (2)$$

$$H_{mo} = \frac{0.21U^2}{g} \quad (3)$$

For the purposes of the initial investigation regular waves, having a height of 2 meters and period of 8 seconds, and a co-linear, constant with depth, 0.4 m/s current, were applied to the system as shown in Fig. 4.

The model was run for 180 seconds, allowing the system to enter a cyclic steady state response and the results of the analysis showed that anchor and grid lines have maximum tensions of 47 kN and 37 kN, respectively. These values are significantly lower than the minimum breaking load of the line (306 kN) [15]. However, it is important to note that this analysis is preliminary. The wave characteristics and current profile were estimated and might not represent the actual extreme loading conditions at the site. In addition, the system was oriented perpendicular to the loading, which is only one of the possible arrangements in the field. A more thorough investigation will be performed on various scenarios once all parameters are recorded and categorized.

6 Conclusions

Marine aquaculture can provide food for the World population, which has reached unprecedented levels. However, a key scientific discipline necessary to enable such aquaculture advance is robust engineering solutions to safeguard the product, the investment, the workers, and the customer.

Within this context, this paper provides a short overview of the engineering challenges as these apply for the Coastal Cage aquaculture. In addition, it provides a comprehensive case-study during which a structured approach was developed to record cage mooring requirements and develop alternative mooring scenarios.

7 Acknowledgements

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