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Engineering analysis of a submersible abalone aquaculture cage system for deployment in exposed marine environments

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ABSTRACT

Great potential may exist in the development of abalone aquaculture in underutilized, exposed marine environments. Abalone is a shellfish that feeds on kelp and as a product, can often render high market value. In this study, the development of a commercial-size, submersible abalone cage grow-out system with a modular box structure is described. The flow field characteristics within the abalone containment structure were analyzed with computational fluid dynamic software. The hydrodynamic response of the moored containment structure was investigated with a Morison equation type finite element model that simulates fluid-structure interaction. Environmental forcing input to the model consisted of loading conditions representing combinations of currents with a magnitude of 1.0 m/s and irregular seas with a significant wave height of 8.01 m and peak period of 12.52 s. Simulations were performed with the abalone cage model in both surface and submerged configurations. From the simulations, the attachment loads were determined and used in a structural model to calculate local stresses. Structural analysis of the deployment and recovery operation was also investigated. The results indicate the importance of including a combination of detailed structural/hydrodynamic/flow analyses into the design framework to avoid catastrophic failures of abalone farming systems.

1. Introduction

As the worldwide exploitation rate of capture fisheries continues, the development of sustainable aquaculture practices is increasing. These practices must consider not only minimizing impact on the environment, but also be economically viable. The aquaculture of shellfish is often viewed as a logical area of development, since aspects of production minimize environmental impact. Carnivorous fishes, on the other hand, have nutritional needs that often require protein and fats that have, in the past, been acquired by fishing. Even though the feed development process for finfish is evolving to include more sustainable ingredients (see for example, Allan et al., 2000; Carter and Hauler, 2000; Turchini et al., 2010), shellfishes do not have this need.

Many shellfishes are filter feeders that remove waterborne particles, including phytoplankton. Abalone, on the other hand, feed on macro-algae (kelp). Kelp use water column nutrients and sunlight to produce growth and oxygen. Sustainable harvesting or farming of kelp can be considered as a potential benefit to mitigate excessive nutrient levels as part of a broad coastal management plan (Chopin et al., 1990). In the process, two valuable products can be developed, where kelp grown in nutrient rich waters can have environmental benefits and then be converted to high-value abalone meat when used as feed. Furthermore, abalone meat is considered a delicacy with a high market value.

A demand for abalone meat exists in southern Korea where coastal harvesting of wild animals has increased from 2062 MT in 2005 to 6228 MT in 2010 (FAO, 2012). Abalones are also cultured in southern Korea, particularly in the coastal waters of the Jeonnam provinces, where *Haliotis discus hannai* is the most common species. Korean coastal waters, however, have been polluted by many anthropogenic sources that affect dissolved oxygen (DO) levels. For instance, it has been shown by Choi et al. (2013) that

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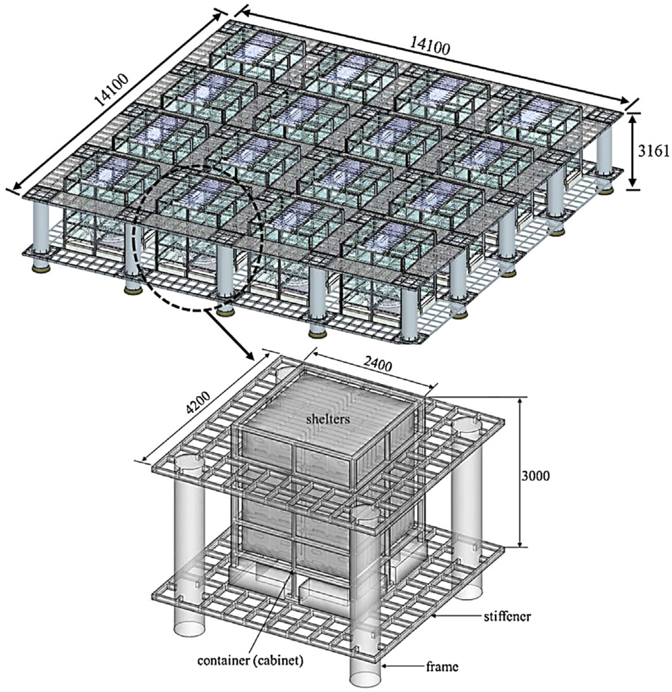

Fig. 1. The entire rigid cage abalone system has modular components that can be combined in groups of four containers to make an open ocean farm (unit: mm).

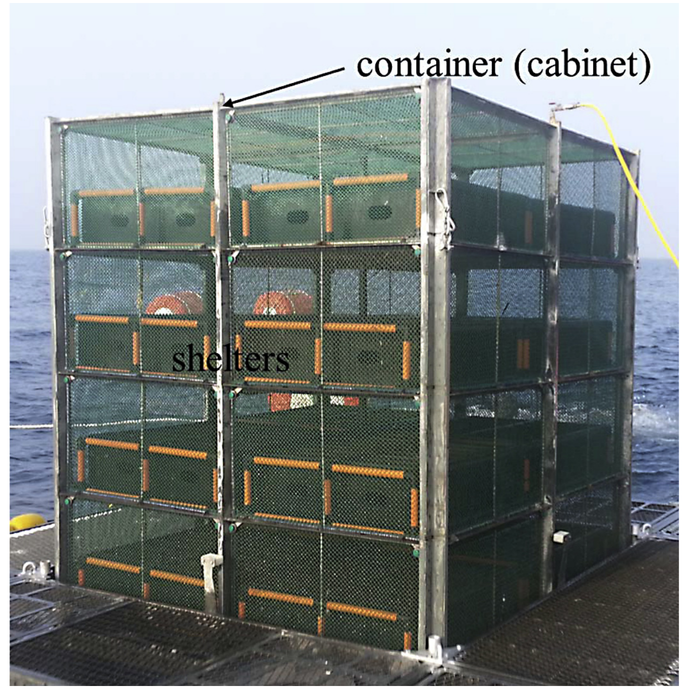

Fig. 2. Container (cabinet) for 16 shelters in abalone cage.

DO levels within a near shore abalone farm can drop as low as 40% of saturation (4.0 mg/L). Therefore, to expand abalone aquaculture operations, one option is to consider more exposed, often underutilized sites where DO exchange is better. These sites, however, can be subjected to high energy conditions that include strong oceanic currents and irregular seas, especially those related to typhoon events. Moving the existing structures to the more exposed sites is not recommended because most of the existing abalone cage systems utilize net cages mounted to raft-type structures, which maintain buoyancy with Styrofoam billets mounted under polyethylene (PE) pipe square frames. These cage systems are fragile and most have been destroyed by typhoons with high waves and strong currents in 2011 and 2012. Thus, a rigorous engineering approach needs to be taken to design an abalone cage system for exposed environments.

In this study, the development of a novel abalone farm structure is described and analyzed using advanced computer modeling techniques. The use of "off-the-shelf" computer modeling tools is becoming more prevalent for the design and analysis of marine aquaculture structures. Perhaps one of the first applications was done by Gignoux and Messier (1999) using a version of ABAQUS that introduced the concept of mapping coefficients with beam elements to represent dense net meshes with fewer elements. Helsley and Kim (2005) performed computational fluid dynamics (CFD) simulations with a finite difference code called FLOW3D with downstream diffusion of a bi-conical rigid cage system. The results indicated that even at small tilt angles, enhanced mixing occurred. Fredriksson et al. (2007a) applied structural analysis techniques using MSC.MARC finite element modeling (FEM) software to evaluate high-density polyethylene plastic pipe for marine applications. To investigate potential design procedures for marine-deployed closed-containment aquaculture systems, Fredriksson et al. (2008) used CFD (FLUENT) for closely spaced solid cylinders. They also utilized MSC.MARC to investigate the structural characteristics of a potential system design. Patursson et al. (2010) applied a porous media model for flow through net panels also using the FLUENT software package. A submersible sea cucumber cage structure was analyzed with two separate FEM software products in Oh et al. (2012). Zhao et al. (2013) performed a numerical simulation of the flow field inside and around gravity cages. Kim et al. (2014b) investigated dissolved oxygen and animal survival and growth in co-culture cage systems for grow-out of juvenile abalone, *Haliotis discus hannai*, with juvenile sea cucumber, *Apostichopus japonicas* (Selenka), with CFD analysis and indoor seawater tanks.

In this study, the design of a commercial-size submersible abalone cage grow-out system with a modular box structure is

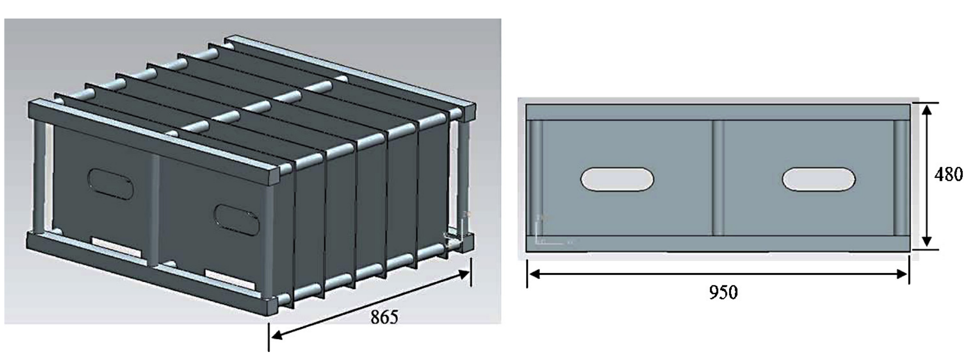

Fig. 3. Geometries of plate type shelter for abalone grow-out (unit: mm).