Ocean Engineering 104 (2015) 511–520

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Three-dimensional deformation of a large circular flexible sea cage in high currents: Field experiment and modeling

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ARTICLE INFO

Article history:
Received 18 September 2014
Accepted 19 April 2015
Available online 15 June 2015

Keywords:
Porous flexible structure
Current reduction
Fluid–structure interaction
In situ measurement
Eulerian current meters
3D dynamic super-element formulation
simulation

ABSTRACT

This paper presents the full-scale measurements of the deformation and current reduction of a large-scale fish sea cage submitted to high currents. Pressure tags were used to measure the cage deformation and the vertical displacement of the bottom ring, while an Acoustic Doppler Current Profiler (ADCP) and Acoustic Doppler Velocimeter (ADV) were used to measure the current reduction. The results show a reduction of 30% of the cage volume for current velocity above 0.6 m/s. The measured current reduction in the cage was 21.5%. A simulation model based on super-elements describing the cage shape was applied, and the results show good agreement with the cage deformations. Also the current flow measurements show the interaction between the sea cage and the bathymetry chart.

1. Introduction

The shift towards salmon farming at more exposed locations has been an industry-wide trend in Norway for the past decade. Moving fish farms to areas where high currents and waves exist can improve production through providing more stable temperatures and water quality and reducing the environmental impacts of modern fish farming (Holmer, 2010). However, exposed environments create challenges for salmon farming. If high currents and waves result in flows that exceed the typical swimming speeds of salmon, they may reduce the effectiveness of production. In addition, net deformation is often significant at exposed locations (Lader et al., 2008), which greatly reduces the space available for fish. Fish welfare is highly dependent on both the internal volume of the net structure and the hydrodynamic conditions. Thus, the synergistic effects of fast swimming in elevated flows generated by high waves and strong currents and reduced net volumes may prove particularly challenging for fish.

Nearly all cages in use for exposed farming in the Norwegian salmon industry are "gravity" type cages, according to the classification scheme proposed by Loverich and Gace (1998). These cages have a surface collar structure from which a net is hung within the water column. Gravity cages do not have rigid nets, and "bagging" deformation occurs during high currents, thereby decreasing the total cage volume. The force acting on the structure due to the fluid flow will affect the shape of the structure. Cages deform in current flow largely through lifting of the bottom netting and deformation of the front and back walls (Aarsnes et al., 1990; Løland, 1991, 1993). Current speeds of 0.13–0.35 m/s at two full-scale farms caused cage volume reductions of up to 20–40% and resulted in the cage bottom being pushed upwards (Lader et al., 2008). In extreme cases, where nets were severely deformed during storms that generated strong currents >1 m/s, mass mortalities of up to 40 tons of fish in a cage have occurred (Steine, 2004). Furthermore, in an aquaculture application, the internal volume of the net structure influences fish health and well-being, and therefore it is important to study how the volume reduction changes due to hydrodynamic force exposure. Flow through and around a cage is influenced by factors such as cage design, cage layout, fish movements, flow conditions at a site, and local topography (Klebert et al., 2013), but descriptions of these patterns and their correlations have not been field-tested. Simulations and lab-scale experiments have suggested that current speeds and net porosities can affect the internal hydrodynamics of sea cages (Shim et al., 2009; Gansel et al., 2008). The Norwegian government has introduced a new classification system (NAS, 2009) for fish farm sites using significant wave height and current speed (Table 1).

Current flows introduce loads that deform net cages, altering the available volume for fish and influencing their swimming and possibly feeding behaviors. Shim et al. (2009) performed simulations on a model scale to investigate flows through and around farms; a complex flow pattern existed with maximum drag at lowest net porosity. However, no tests have simulated flows on a full scale and

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http://dx.doi.org/10.1016/j.oceaneng.2015.04.045
0029-8018/© 2015 Published by Elsevier Ltd.

with flexible nets. This is due mainly to the limitations of the numerical models, which are mesh-based (Eulerian) approaches and require a large amount of memory to perform full-scale simulations. Other models (Lader and Enerhaug, 2005; Zhao et al., 2007) have been super-elements based and have focused only on the net structures without accounting for the current flow. Another numerical approach based on the joint use of the porous-media model and the lumped-mass model (Bi et al., 2014a, 2014b) has been used to simulate lab-scale experiments. In this article, field measurements of volume reduction in a large-scale fish cage and current reduction inside and behind the cage are presented as well as a numerical method based on these super-elements are presented and used in order to simulate the deformation undergone by the fish cage. The simulation results are then compared to the field measurements for validation of the method.

2. Material and methods

Measurements of current velocity and net deformation were conducted at a commercial marine salmon farm close to Torshavn in the Faroe Islands (61.99°N, 6.76°W) over a period of approximately 4 months. The farm itself had eight circular cages 41 m in diameter and two cages 50 m in diameter with a depth of 12 m to the bottom ring (Fig. 1).

Table 1
Norwegian aquaculture site classification scheme for waves and currents.

Wave	H_s (m)	T_p (s)	Degree of exposure	Current	V_c (m/s)	Degree of Exposure
A	0.0–0.5	0.0–2.0	Small	a	0.0–0.3	Small
B	0.5–1.0	1.6–3.2	Moderate	b	0.3–0.5	Moderate
C	1.0–2.0	2.5–5.1	Medium	c	0.5–1.0	Medium
D	2.0–3.0	4.0–6.7	High	d	1.0–1.5	High
E	> 3.0	5.3–18.0	Extreme	e	> 1.5	Extreme

H_s: wave height; T_p: wave period; V_c: current speed.

The depth of the site is 20–30 m, with the shallower part on the side towards the land, and the total biomass at the site was 1320 tons. The net cage (solidity $Sn = 0.225$) that was used for these experiments had a diameter of 41 m and a lower depth of 12 m; it is a gravity plastic cage with a bottom weight ring of 50 tons Tables 2 and 3.

The site has 10 cages organized in a mooring grid, as shown in Fig. 1. The depth of the mooring grid is 6 m. In Fig. 2, a farm layout is shown. The current is dominated by tidal currents with a maximum speed of around 80 cm/s. The current moves in both directions along the mooring grid and is approximately constant with the depth. During the days with the strongest tidal current, the peaks were around 65 cm/s, and during the days with the weakest current speed, the peaks were around 40 cm/s.

2.1. Current measurements: ADV and ADCP

The current measurements were conducted with three current profilers, two 600 kHz Workhorse Sentinels from RD Instruments that measured the average current speed close to the cage, and a 600 kHz AWAC from Nortek placed around 250 m in front of the cage in order to measure the reference current velocity. In addition, two Vector Acoustic Dopler Velocimeters (ADV) from Nortek were located inside the cage at a depth of 6 m.

All current profilers were set up similarly with a time interval between each profiling of 120 s and a bin height of 2 m. The profilers sampled for 60 s for each ensemble. The time interval between the measurements for the ADVs was set to 240 s.

The profiler data were processed using the same time intervals as the ADVs and pressure sensors. Data points were used only when cleared by the standard processing routines of the profiler data, and spikes were removed from the data in each interval when data points were more than twice the standard deviation away from the mean of the sample in the intervals. The interval averages were used only when the maximum difference between data points in each interval was less than 0.2 m/s, more than 50% of the data points were good, all the profilers had accepted means at all depths, and the difference in speed between the three uppermost bins in the reference and the up-current profilers was less than 0.1 m/s. In addition, only data sets with a minimum current of 0.15 m/s in the northerly direction were used.

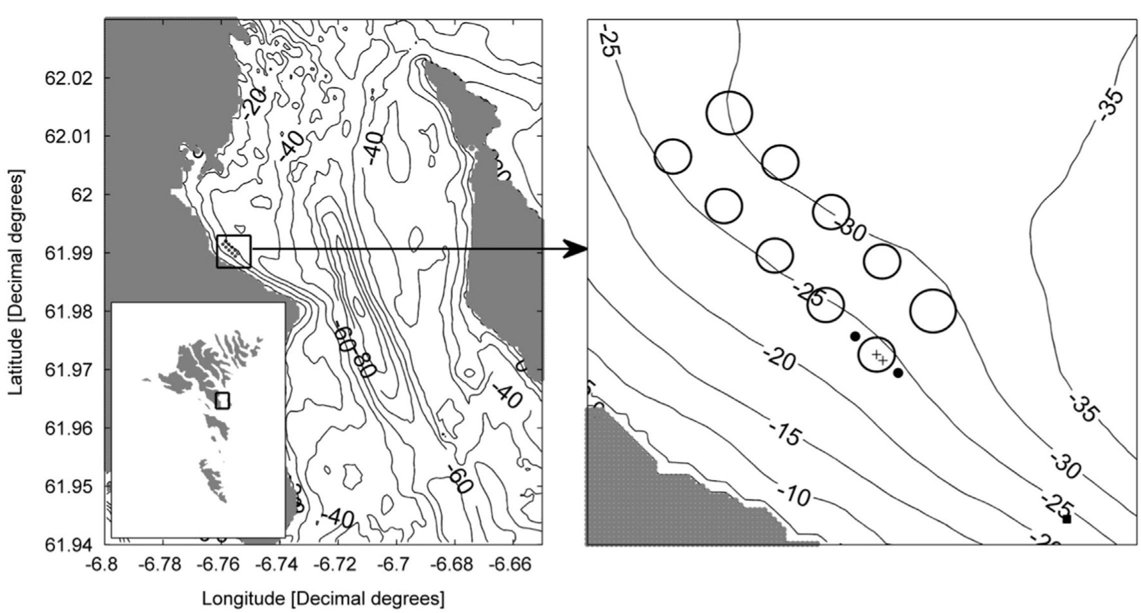

Fig. 1. Location of the farm in the Faroes.