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Time-dependent reliability analysis of mooring lines for fish cage under corrosion effect

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ABSTRACT

Moored fish cage structures are forced to move into the offshore area due to the shrinking availability of sheltered near-shore sites and increasing environmental impacts of aquaculture, and this provokes a significant challenge for the reliability design of mooring system. The uncertainties involved in the predictions of applied loads and structural strength are analyzed for calculating the reliability level of mooring system. In this study, a probability corrosion model is used to describe the uncertainty of corrosion depth and the joint probability density of significant wave height and spectral peak period is selected to depict the randomness of sea states. The non-linear finite element model is developed to investigate the minimum breaking strength of mooring chains and is validated through comparing with the formulas providing by the International Association of Classification Societies (IACS) Unified Requirements concerning for Materials and Welding. A validated numerical model is applied to calculate the tension force of mooring system for both the single-cage system and the multi-cage system at several sea states, and the response surface method is utilized to display the limit state function to calculate the reliability level in terms of the uncertain metocean variables. The results indicate that the reliability level decreases significantly with the increasing corrosion depth and the correlation of corrosion model for mooring chains has a remarkable impact on the failure probability of mooring system. In addition, the failure probability of mooring system for the four-cage system is much higher than that for the single-cage system.

1. Introduction

Aquaculture remains a growing, vibrant and important production sector for high-protein food and is set to play a key role in meeting the rising demand for fishery products (FAO 2010). However, the fish farm is forced to move into the offshore area, and thus the fish cage system has to withstand rigorous environmental loads. Failure of the mooring system for the fish cage system in the open sea could result in fish escape with the potential to cause serious economical damage and significant environmental consequences, which requires an appropriate engineering design method for evaluating the failure probability of mooring lines for the fish farm system.

To our knowledge, numerous researches were carried out to analyze the hydrodynamic response of fish cage in waves and current, including physical model test and field measurements, numerical simulation. Lader et al. (2007) conducted a series of experiments to investigate the interaction between waves and netting at a narrow wave flume facility. Balash et al. (2009) measured the hydrodynamic loads on net samples of differing mesh geometry in steady and oscillating currents. Kitazawa et al. (2011) carried out tank model testing to examine the inclination and floating velocity of proposed fish-cage floatation/submersion system. Fu et al. (2014) investigated the hydrodynamic characteristics of a floater-net system in oscillatory flows through oscillation experiments in a towing tank. Kristiansen and Faltinsen (2015) performed a dedicated model test to obtain benchmark data for investigating the mooring loads on net cage. Moe-Føre et al. (2016) conducted model tests of net cylinders with various solidities in a flume tank in high uniform flow. Lader et al. (2008) conducted a full-scale field measurement of net deformations under various flow conditions. Gansel et al. (2011) investigated the effects of biofouling and fish behavior on the flow patterns around and through stocked fish cages. DeCew et al. (2013) utilized an acoustic method to monitor the deformation of a small-scale fish cage in strong currents within Portsmouth Harbor. Rasmussen et al. (2015) conducted Boat-mounted Acoustic Doppler Current Profiler measures

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to visualize the flow field and predicted the velocity reduction at a full scale salmon farm. Klebert et al. (2015) presented the full-scale measurements of the deformation related to flow around a large-scale fish cages at a commercial marine salmon farm in Faroe Islands. Lee et al. (2008) developed a mass-spring model to analyze the performance of fish cage system influenced by currents and waves. Xu et al. (2013) investigated the hydrodynamic behavior of multi-cage and mooring system by lumped-mass model under the action of waves combined with current. Li et al. (2013) analyzed the nonlinear hydro-elastic response by finite element model of a deep-water gravity cage in irregular waves. Kim et al. (2014) analyzed the flow field characteristics within the abalone containment structure with computational fluid dynamic software and investigated the hydrodynamic response of the moored containment structure with a Morison equation type finite element model. Ito et al. (2014) investigated the hydrodynamic behaviors of a cubic shaped elastic net structure and estimated the mooring forces and mooring displacements. Yao et al. (2016) proposed a hybrid volume approach to add the resistance force of the net cage into the flow field for coupling the fluid and net. Huang et al. (2016) developed a finite element model to investigate the elastic deformations and mooring line tensions of floating collar in waves.

Furthermore, the corrosion of chains which is an important phenomenon affecting the risk of failure of mooring lines has been analyzed extensively in previous research. Gao et al. (2005) estimated the service lifetime of mooring lines using probabilistic approaches with a uniform corrosion rate to predict strength degradation. However, Melchers et al. (2007) indicated that the corrosion of steel in seawater is a function of many factors including water temperature, salinity, water velocity, and surface roughness. For chains subject to (semi-) continuous 'working', both interlink abrasion and corrosion can occur, and thus the interlink zone will suffer higher material loss than elsewhere on the chain links. Lardier et al. (2008) estimated a reliability-based formulation for assessing mooring chains under the deterioration due to combined fatigue cracking and corrosion wastage. Melchers (2012) proposed a model to predict long term corrosion of steels in seawater based on extensive reviews of in-situ data and on corrosion science principles. The corrosion of steels immersed in seawaters can be accelerated, under certain circumstances, by the effect of microbiologically influenced corrosion (MIC). Fontaine et al. (2014) indicated that MIC may also be involved in the corrosion of mooring chain, and the periodic wear in the interlink zone could have a negative influence on the possibility of occurrence of MIC. Melchers (2014) analyzed quantitatively the effect of concentration of dissolved inorganic nitrogen (DIN) on long-term seawater immersion corrosion loss of structural steels in terms of the data from a variety of field exposure programs. Steenkiste et al. (2011) analyzed the wear mechanism acting on a link chain at the touch-down area of mooring lines where the sands may be entrapped between the chain links or the chain links are in contact with the seabed. De Pauw et al. (2013) designed a full-scale test rig to analyze the wear in a single shackle chains in presence of seawater and sand, which reveals the wear mechanism as abrasive wear. Yaghin and Melchers (2015) analyzed the rate of wear of model (i.e. small-scale) mooring chains through laboratory experiments, in which various axial loadings and specific angular displacement were used with testing under either dry or wet conditions. The results show that tensile force has a significant but non-linear effect on the inter-link wear.

The net cage system in the open sea is anchored to the sea bed by a series of mooring lines, including the anchor lines, the bridle lines and the grid lines. Based on the above analysis, the whole mooring system is very complicated, especially for the multi-cage system. However, the reliability analysis of mooring lines for the net cage system is very limited, and thus the aim of this study is to develop a statistical approach to evaluate the reliability index of mooring system for fish cage and to extend the knowledge of the effect of corrosion on the reliability analysis of mooring lines for fish farms. As shown in Fig. 1, a self-developed numerical model of net cage and mooring system is applied to analyze the tension force on mooring lines, and then the finite element method is adopted to calculate the minimum breaking strength of mooring chains with consideration of corrosion, after that the time variant reliability analysis is performed to investigate the reliability index of mooring lines for the single-cage system and the multi-cage system.

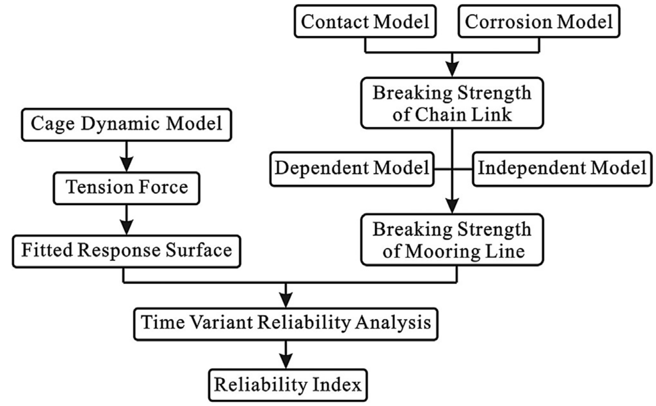

Fig. 1. The flow chart of the time variant reliability analysis model.

2. Numerical model of fish cage in waves

The self-developed numerical model (Xu et al., 2011) based on the lumped-mass method and rigid body kinematics principle was adopted to analyze the tension force on mooring lines for fish cage. The numerical model has been validated by physical model test in our previous research. A brief description of numerical model is given here.

2.1. Fish cage and mooring system

In this study a single fish cage with grid mooring system installed in 20 m water depth is analyzed. The fish cage and mooring system analyzed here includes a gravity cage and a submerged mooring grid, as shown in Fig. 2. The gravity cage consists of a float collar, net pen and sinker. The detailed parameters of the fish cage and mooring system are given in Table 1. The cage net is made of PE with a mass density of 953 kg/m^3. There are 1800 meshes in the circumferential direction and 240 in the depth direction. The net is knotless, with a mesh size of 46.8 mm and a twine thickness of 1.44 mm. When mounted as diamond meshes, the net forms an open vertical cylinder with a diameter of 15.92 m and a height of 9 m. The diameter of floating pipe is 0.25 m (referring to Fredriksson, 2001).

The mooring system is composed of a submerged (4 m below the surface), pre-tensioned squared grid (40 m × 40 m in plane). The mooring system consists of bridle lines, grid lines and anchor lines. Gravity cage is located at the center of each grid square. It is connected to the submerged mooring grid by four bridle lines. The grid is anchored to the bottom using eight anchor lines. The mooring chains are located at the lower part of the anchor line to maintain the pretension of the mooring system and to avoid the decrease in the strength due to excessive friction with the sea floor. The material of the man-made fiber rope and the mooring chain is Polyethylene (PE) and steel, respectively. The elasticity of the mooring line is $T = 670(\Delta S/S)^{1.132}$, where T is the tension of mooring line with the unit of kN, ΔS is the elongation of the mooring line and S is the initial length of mooring line. The pretension force on the anchor line is provided by the bottom chain located at the lower