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A study of the flow field characteristics around star-shaped artificial reefs

Yan Liu [a], Yun-peng Zhao [a,*], Guo-hai Dong [a], Chang-tao Guan [b,c], Yong Cui [b,c], Tiao-Jian Xu [a]

[a] State Key Lab of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116024, China
[b] Qingdao Key Laboratory for Marine Fish Breeding and Biotechnology, Yellow Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences, Qingdao 266071, China
[c] Key Laboratory of Fishery Equipment and Engineering of Ministry of Agriculture, Fishery Machinery and Instrument Research Institute, Chinese Academy of Fishery Sciences, Shanghai 200092, China

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ABSTRACT

In this paper, a three-dimensional numerical model is devised to calculate the unsteady flow field around star-shaped artificial reefs. The model is based on Reynolds-averaged Navier–Stokes (RANS) equations embedded within a renormalization group (RNG) k–ε turbulence model. The RANS equations are solved using the finite volume method (FVM) with an unstructured tetrahedral mesh. The pressure and velocity coupling is solved at each time step with the SIMPLEC algorithm. Non-invasive particle image velocimetry (PIV) laboratory measurements are employed to verify the simulation results. Good agreement is found between the simulation and experimental results with respect to the major flow fields. Based on the flow-field verification, the influence of arrangement and spacing on the flow field of one and two artificial reefs are discussed in light of the numerical method. A large-scale slow flow region is obtained when the reef is arranged in the second form. In the parallel combination, a slight mutual effect exists between the two reefs when the spacing is larger than 3.0*L*. In the streamwise combination, the interaction of two reefs is at its strongest at spacings of 3.0*L* to 4.0*L*.

1. Introduction

An artificial reef is a type of artificial facility used to build marine ranches, to optimize marine ecological environments and to proliferate biological resources. The solid structures placed on the seabed to support offshore energy units create new habitats in areas dominated by soft bottoms and can be defined as artificial reefs (Langhamer et al., 2009). Generally speaking, fish have a variety of reactions to the surrounding aquatic environment. For example, certain fish prefer to reside in the shadows, while others prefer to gather in slow flow areas. Consequently, artificial reefs have been deployed in shallow waters to attract fish and enhance fish reproduction, while reducing beach erosion and protecting habitats (Miller, 2002; Powers, 2003). A series of research concerning artificial reefs has been carried out worldwide. A gill-net survey was performed by Santos and Monteiro (1998) over four and a half years to test the effectiveness of artificial reefs in attracting fish assemblages and enhancing fishing yield. Reynolds (2009) designed two studies to describe marine community utilization at the artificial reefs. The first study documented marine community colonization at the artificial reef relative to

* Corresponding author. Tel.: +86 411 8470 8950x8403; fax: +86 411 8470 8526.
E-mail address: Ypzhao@dlut.edu.cn (Y.-p. Zhao).

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that of natural communities. The second study used acoustic telemetry to document the residency and movements of rockfish and lingcod in artificial and natural reef habitats. Today, diverse types of artificial reefs exist with no unified division standard, and the differences in shape, material and layout have significant effects on the fish attracted to the artificial reefs. Dong et al. (2010) researched the differences associated with changing the material and color of the artificial reef and their effect on the attraction of fish. The relationship between production and reef pile size was analyzed using standing stocks of fishes surveyed at three established artificial reef habitats in the subtropical waters off the northern coast of Taiwan during April–August 1999 (Jan et al., 2003). Jordan et al. (2005) examined how varying the distance between patch reefs affects the reef fish assemblage structure; replicated concrete reef modules were deployed on a sand bottom near Ft. Lauderdale, Florida, USA.

Many studies have demonstrated the ecological effect of the proliferation of fishery resources from artificial reefs through flow field effects (Lin and Zhang, 2006). Zhang et al. (2001) discovered that when artificial reefs are constructed in the sea bed, significant local upwelling current fields and eddy current fields are generated at the front and the back of the artificial reef, respectively. Meanwhile, a geometric shaded area is distributed within and around the reef. Upwelling enhances the biological productivity, which feeds fisheries, thereby creating a habitat that is richer in nutrients. The nutrients fertilize phytoplankton in the mixed layer, and the phytoplankton are later eaten by zooplankton, which are eaten by small fish, which are subsequently eaten by larger fish, etc. (Liu et al., 2007). In engineering practice, the stability of artificial reefs is an important issue in preventing the failure of reef units due to wave and current actions. The stability of reefs and sediment erosion in the bottom of artificial reefs rely on the interactions among current-bottom material-reef systems. As a result, the study of flow field effects plays a leading role in enhancing recreational fishing and reducing beach erosion. Therefore, from a hydrodynamics aspect, it is an essential issue to study the flow field within and around the artificial reef to achieve optimal conditions for fish and to improve the performance of artificial reefs. Yu et al. (2004) simulated the hydrodynamics of artificial ship-reefs and determined how various patterns and scales affect the formation of upwelling currents, back vortices and the mixture and exchange between shallow- and deep-water layers. Su et al. (2007) conducted particle image velocimetry measurements to study the flow patterns in and around an artificial reef. The PIV results were then used to verify the numerical results obtained from the finite volume method (FVM) simulations of the same flow scenario. Liu et al. (2009) used wind tunnel experiments and numerical simulation methods to simulate the flow fields around solid artificial reef models with different shapes, including cubes, pyramids and triangular prisms. Waves are essential elements in the design of an artificial reef because the currents generated by waves breaking on the reef are significant with respect to reef stability; thus, the wave–current interaction must be considered. Cáceres et al. (2010) studied the response of wave and flow on the artificial surfing reef at three types of layouts using laboratory measurements.

This paper studies the flow field around single and binary combined star-shaped artificial reefs in combination with numerical models and laboratory measurements. In particular, the effect of arrangement on the flow field of a single reef and how spacing affects the flow field around the parallel and streamwise star-shaped artificial reef combinations are analyzed in detail. The numerical model is based on a solution of the equations governing conservation of mass and momentum for a Newtonian, incompressible fluid. A standard finite volume method (FVM) approach is utilized to calculate the Reynolds-averaged Navier–Stokes (RANS) equations, which are embedded within a renormalization group (RNG) k–ε turbulence model and a SIMPLEC algorithm. Non-intrusive flow visualization of images of tracer particles, particle image velocimetry (PIV), is used to validate the simulation results.

2. Materials and methods

2.1. Numerical simulations

The numerical simulation analysis of flow fields around the artificial reef is based on a dynamic, full 3-D model elaborated with the aid of FLUENT 6.3 commercial code. The FVM used in this study solves the three-dimensional Reynolds-averaged Navier–Stokes equations for incompressible flows. Turbulent flow can be modeled with several schemes. Huang et al. (2010) numerically investigated the characteristics of train-induced airflow in a subway tunnel with the RNG k–ε turbulence model. The two-dimensional TVD finite volume method can be used with the RNG turbulence model to determine the hydrodynamic forces, capturing well the vortex shedding characteristics (Wang, 2010). Hence, the RNG k–ε model is used in this study because it provides an option to account for the effects of swirl or rotation by modifying the turbulent viscosity appropriately (Pope, 2000).

2.1.1. Hypotheses

Several appropriate assumptions are introduced to decrease the complexity of numerical calculation for the three-dimensional turbulent flow fields around artificial reefs, detailed as follows:

(i) The water is an incompressible, viscous, Newtonian fluid.
(ii) Isothermal flows exist in the water, regardless of heat exchange.
(iii) The water surface is modeled as a “moving wall” with zero shear force and the same speed as the incoming fluid.
(iv) The flow is in a non-steady state.