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Study on the influence of cut-opening ratio, cut-opening shape, and cut-opening number on the flow field of a cubic artificial reef

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ABSTRACT

Upwelling and back eddy are usually selected as obvious indices to study the characteristics of the flow field of artificial reefs. The influences of cut-opening ratio (OR), cut-opening shape (OS), and cut-opening number (ON) on the flow field of a cubic artificial reef were investigated. A Reynolds-averaged Navier–Stokes equation was established to solve the flow field of an artificial reef. Based on the finite volume method, the standard k-ε model was used to discretize the Reynolds-averaged Navier–Stokes equation. Flume model experiments were carried out to validate the accuracy of the numerical simulation. A multivariate analysis of variance was used to analyze the diversities of the OR, OS, and ON. The results showed that the upwelling velocities, including the maximum upwelling velocity and the volume-weighted average velocity, changed less with the above three factors. The ON and OR had prominent effects on the volume of upwelling and back eddy, while the OS had the least effect. A reasonable arrangement of ON and OR can enhance the field of upwelling and back eddy while an excessive OR or ON can weaken them. This study provided a scientific reference for the optimal design of cubic artificial reefs.

1. Introduction

Globally, coastal ecosystems are suffering from global climate change, marine environmental pollution, natural habitat degradation, and overfishing. It has been reported that some coastal ecosystems are no longer suitable for fishing activities, and many fish populations have been overexploited or fully exploited in recent decades (FAO, 2014; García and Leiva Moreno, 2003; Garcia and Newton, 1994; Lundin and Lindén, 1993; Myers and Worm, 2003; Pauly et al., 2002, 2005). To prevent this situation, marine ranching and the development of artificial reefs are important measures to alleviate the decline of fishery resources, improve the ecological environment of coastal waters, and provide a natural shelter for marine organisms (Collins et al., 1990; Jensen et al., 1994; Steimle et al., 2002; Seaman and Sprague, 2013; Fang et al., 2013).

An artificial reef is a submerged structure deployed on the seabed to emulate some features of a natural reef such as protecting, concentrating and enhancing populations of living marine organisms (London Convention and Protocol/UNEP, 2009; Kim et al., 2016). After putting reefs on the seabed, an optical shadow is created around the reefs, forming a dark area in the water and changing the original light and shade distribution in the area (He and Shi, 1995). The presence of artificial reefs affects the spatial distribution of seawater. When the reefs are put in combination on the seabed, they have a great influence on the seafloor space and will directly change the seafloor topographic conditions (Baine, 2001). In addition, the main function of an artificial reef is to alter the water flow field and circulate the water column much better. The flow is separated by the reef blockage, and the separated part of water flows upwards to form an upwelling, which helps to promote the exchange layer of sea water, increase the bottom and surface water nutrient transport and enhance the effect of bait diffusion around reef area (Haro et al., 2004; Lan et al., 2004). Accordingly, upwelling region has obvious effects in attracting fish. On the other hand, part of the separated flow will cross the reef to bring in a series of flow field changes such as vortex and sediment flow, which accelerates the frequency of seawater exchange in the whole seabed area. Furthermore, behind the reef, there is a small velocity swirl zone that vortex flow speed is slow and stable. Many studies have indicated that fish tend to group around reefs because the back-eddy flow provides the fish with favorable conditions (Bohnsack and Sutherland, 1985; Collins

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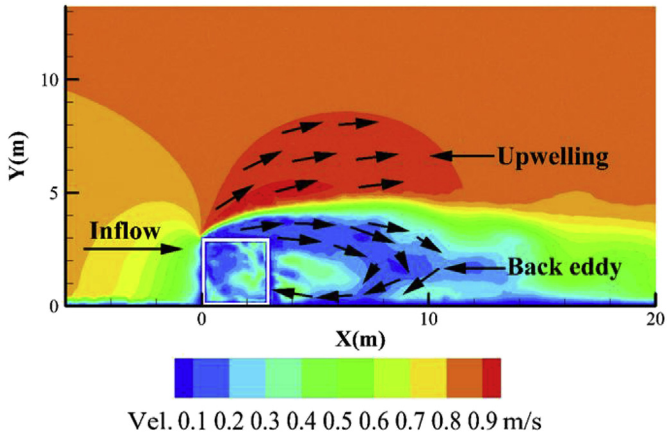

Fig. 1. Schematic diagram of flow-field velocity effect around artificial reef (m/s).

et al., 1990; Godoy et al., 2002), the characteristics of back eddy around the reef is stable and tranquil compared with turbulent flow. From the structure perspective, porous reef structures are natural breeding habitats to repair the marine ecosystem as well as to conserve the fisheries resources. As shown in Fig. 1, complex back eddies and upwelling are formed when currents encounter an artificial reef.

Much research has focused on the effect of reef shape and structure on the hydrodynamics and flow field effects of reefs because of the extreme complications owing to different reef structures and shapes (Pickering and Whitmarsh, 1997). Because cubic artificial reefs have simple mechanical structures and low manufacturing costs, many investigations have been carried out on the flow field characteristics of cubic reefs by wind tunnel experiments, flume experiments, and numerical simulation technology based on computational fluid dynamics (CFD). Tang et al. (2007) studied the influence of the velocity of incoming currents at different angles on the flow field and the resistance of cubic reefs by the flume test and found that the resistance of reefs to incoming current at an angle of 45° was larger than that at an angle of 0°. Liu et al. (2012) concluded that the height and area of the upwelling regions changed less with various incoming velocities using the cubic artificial reef model. Liu and Su (2013) and Cui et al. (2011) analyzed the influence of different pitch arrangement on flow field around cubic reefs using CFD and a wind tunnel experiment and found that the optimum spacing adjustment between cubic reefs was about 1–1.5 times the length or width of a reef. Shao et al. (2014) and Huang et al. (2014) conducted numerical simulations on the influences of the cut-opening ratio (OR) and incoming velocity on the flow field of cubic reefs and found that the OR had a significant impact on the flow field and the incoming velocity seemed to have no effect on the flow field of reefs. Based on the results of a two-way analysis of variance, Fu et al. (2012) studied the influence of the OR and the shape of a reef on the flow field and showed that the effect of reef shape on the flow field was less significant than that of the OR. All of the aforementioned works provided important information for the optimal design and layout of cubic reefs.

It has been shown that variations of structure, including outline shape, cut-opening shape (OS), cut-opening ratio (OR), and cut-opening number (ON) of artificial reefs might have significant effects on the flow field around reefs, but related research is still lacking. OR is the ratio of the projected area of the cut-opening hole to the whole projected area of the reef surface in the direction perpendicular to the flow. In this study, a statistical method was employed to investigate the combined influences of cut-opening factors on the flow field of cubic artificial reefs based on numerical analysis results of CFD by ANSYS Fluent 15.0. Illuminating the influence of multi-structure factors on flow fields is instrumental in improving organizational efficiency of cut-openings with less expenditure by combining appropriate parameters of OR, OS, and ON. The aim of this study was to provide a scientific reference for the optimal design of cubic reefs.

In order to simplify this work, several hypotheses should be discussed before carrying out investigations on cut-openings and flow field. Firstly, the seafloor was assumed to be horizontal and infinity, without considering the existence of other marine organism on the seabed. Reefs fell on the seabed without being affected by other objects during the process of deploying. Secondly, we assumed that the flow velocity and direction of current in the reef area remained constant, so the effects of change of the current on the flow field around reefs are ignored. In reality, after the reefs deployed on the seabed, occasional stacking or burial around the reefs might occur in the reef area, forming reef sets or groups and enhancing the flow field effects around the reefs to some degree (Grove and Sonu, 1985; Yoon et al., 2016). Furthermore, stacking or burial around the reef might lead to the intervals or spaces around reefs, causing the change of effective usable volume or facilitate volume (Yoon et al., 2016). But study subject of this paper focused on impacts of cut-openings of single reef on the flow field, reef sets or groups were not included for the time being. Finally, considering the scope of this study, it was assumed that the reef kept stable after layout in current, although cut-openings of the reef caused the weight loss of the reef and consequently affected the stability of the reef for field engineers, such as rolling and slipping on the seabed. For this reason, it is suggested that the arrangement of cut-openings of reef should be symmetric as far as possible.

2. Materials and methods

2.1. Materials

In this study, a cubic artificial reef (3.0 m × 3.0 m × 3.0 m) without a top or bottom cover was used as the prototype design. The height, width, and length of the cubic reef model were 150 mm with a

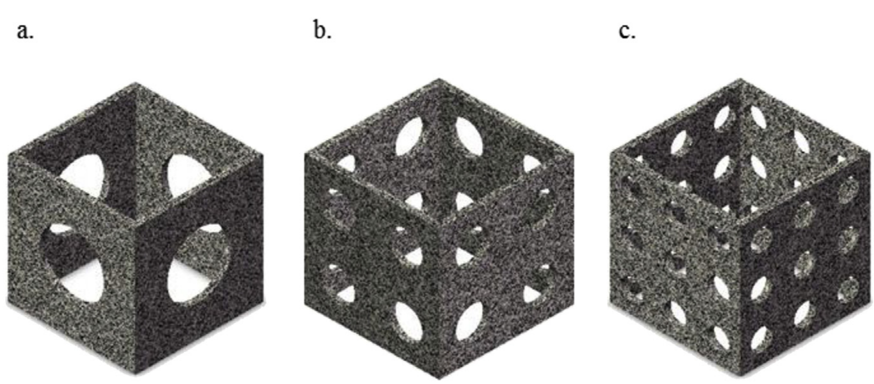

Fig. 2. Artificial reef models (OR 0.2, circular OS).