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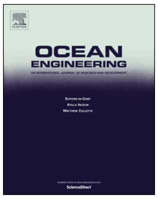

Efficiency, tranquillity and stability indices to evaluate performance in the artificial reef wake region

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ABSTRACT

The wake region of an artificial reef (AR) is defined as the space consisting of the recirculating water flow immediately behind the AR. This study proposes three performance indices to evaluate the wake region and pinpoints how to determine the indices for ARs. First, we established dimensionless performance indices, such as the so-called wake region efficiency index, tranquillity index and stability index. Second, we considered these three indices with respect to two ARs (AR1 and AR2) and determined wake volumes using the element-based finite volume method. AR2 was found to have better efficiency and tranquillity indices than AR1 because of its size and complexity. The AR1 stability index was slightly better than that of AR2. Overall, AR2 (box type with a steel box inside) showed better wake region performance, mainly because of a higher efficiency index (9.55) compared with that of AR1 (2.00). The results show that performance indices can be used to evaluate efficiency, tranquillity and stability of wake regions in ARs.

1. Introduction

To promote a common understanding of artificial reefs (ARs), the United Nations Environment Program (London Convention and Protocol/UNEP, 2009) defines an AR as a submerged structure deliberately constructed or placed on the seabed to emulate some functions of a natural reef such as protecting, regenerating, concentrating, and/or enhancing populations of living marine resources. The program also promotes the protection, restoration, and generation of aquatic habitats, as well as research, recreational opportunities, and educational use of the area. Consequently, artificial reefs provide several different kinds of benefits: environmental (biodiversity or ecosystem management, restoration, water quality management, etc.), living marine resources (attraction, enhancement, production and protection), promotion of tourism and leisure activities (angling, SCUBA diving, surfing, boating, etc.), scientific research and education, and multi-purpose structures.

Many studies have focused on ARs, including ecological interactions of ARs with marine resources (e.g., attraction vs. production (De Troch et al., 2013)); designs to maximise intended objectives (e.g., wake region (Kim et al., 2014b)); material selections (e.g., environmentally friendly (Huang et al., 2016)); reef stability (e.g., scour and settlement (Yoon et al., 2016)); economic or efficiency analyses (e.g., bioeconomic analysis (Udumyan, 2011)); construction and management guidelines (e.g., pre- and post-monitoring (Wilding and Sayer, 2002)); multi-purpose structures (e.g., rigs-to-reefs program (Ajemian et al., 2015); and artificial reef effects in offshore windfarms (Langhamer, 2012)). This extensive body of research is beyond the scope of the discussion here, but two critical issues are particularly relevant.

First, the attraction/production conflict is one central issue related to the effects of artificial reefs (Lindberg, 1997; Hunter and Sayer, 2009; De Troch et al., 2013). The attraction argument predicts that ARs simply attract fish away from natural reefs, and accordingly redistribute fish without augmenting production; the production argument predicts that ARs increase fish production by providing new habitats in an otherwise saturated demersal environment (Wilson et al., 2001). Several solutions have been suggested, such as no-take zones or protected reefs (Pitcher and Seaman, 2000), and marine protected areas (Claudet and Pelletier, 2004). As a result, today it is widely acknowledged that ARs involve both attraction and production (Broughton, 2012).

The second issue involves an important physical characteristic of any AR: the wake region formed by interaction of the reef with prevailing currents or water flows (Wolanski and Hamner, 1988). Wake regions have a high probability of attracting marine species such as fish because they facilitate energy saving zones for marine species (Liao et al., 2003; Beal et al., 2006; Hockley et al., 2013) and deposition of sediments, nutrients, and bio-deposits (Sawaragi, 1995; Miller et al., 2002; Falcão et al., 2007; Prairie et al., 2012). In general, the wake region of an AR is defined as the space consisting

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of the recirculating water flow immediately behind the AR (Sheng, 2000; Oh et al., 2011). The wake region provides shelter, feeding grounds, spawning grounds, rest areas, and a temporary stopover for marine species (Sheng, 2000).

Performance of a wake region can be classified in several ways. The first way is by size, which is related to its efficiency. This performance evaluation factor was mentioned by Nakamura (1985), Oh et al. (2011), and Sawaragi (1995), who suggested the concept of wake length, and was evaluated in 24 Korean ARs by Kim et al. (2014b). However, wake length depends on selecting a reference plane. In theory, an infinite number of ways exist to determine wake length for a specific reef; in practice, size, shape, and structure of the AR are important to determine the representative wake length. Kim et al. (2014a) proposed the wake volume concept. To avoid the need to capture all of the features of a wake region distribution, they used the element-based finite volume method to determine the finite volume with recirculating water velocity, which was applied to obtain total wake volume by summing the finite volumes. However, their wake region definition is somewhat different from that proposed by Nakamura (1985), Oh et al. (2011), and Sawaragi (1995). Rather than using the recirculating flow profile immediately behind the AR, Kim et al. (2014a) also considered the recirculating flow around the AR, including the inside profile, to quantitatively measure the entire wake volume.

The second performance index is the speed of the recirculating water flow, which is related to tranquillity in the wake region. This index is important because low recirculating water velocity in a wake region helps marine species settle and optimise their net energy expense (Beal et al., 2006; Bradford and Heinonen, 2008; Hockley et al., 2013). Similar assessments have been carried out by Al-Bourae et al. (2013), Liu and Su (2013), Liu et al. (2013), and Nakamura (1985), but their studies were limited. The first three studies focused on the reef flow field around the AR but did not establish a performance evaluation index. Nakamura (1985) proposed a formula for calculating current speed in the reef lee, but a formula was not determined to evaluate performance. Thus, no study has investigated the tranquillity index associated with the wake region.

The third performance index is the bottom profile of the wake region. Reef stability as it relates to waves and currents is critical because the high horizontal component of the hydrodynamic forces can cause overturn or slide (Takeuchi, 1991; Sohn et al., 2011; Yoon et al., 2016). The stability number (N_s) proposed by Hudson et al. (1979) and the stability coefficient (K_D) established by CERC (1984) are adaptable. However, these parameters do not consider the bottom profile of the wake region. Because high flow velocity and a large wake distribution at the seabed can cause partial settlement due to scour, and thereby threaten reef stability, it is important to determine flow velocity and the size of the bottom profile. However, to date no stability index that considers the bottom wake region profile has been documented.

Here, we propose three performance indices to evaluate the wake region. First, we establish three dimensionless performance indices: the wake region efficiency index, tranquillity index, and stability index. Second, we demonstrate how to quantitatively measure the indices considering two different ARs. A computational fluid dynamics tool, called the element-based finite volume method (EbFVM), was used for the quantitative measures. In this method, the region of interest is divided into sub-regions, and the governing equations are discretised to solve them iteratively over each sub-region; hence, the value of each variable is obtained at nodal points over the domain (Marcondes and Sepehrnoori, 2010; dos Santos et al., 2013; Woo et al., 2014). The ANSYS-CFX general purpose software package (ANSYS Inc., 2009) was used to facilitate the tool.

The following assumptions were followed in this study. First, wake volume proposed by Kim et al. (2014a) was used, and the wake regions covering recirculating water flow immediately behind the reef and the surrounding regions including inside the reef were considered. Second, water depth was assumed to be deep enough so that waves were not considered hydrodynamic forces. In other words, we only considered currents (water flow) for the flow analyses. Third, the assumption was made that the target marine species were limited to types A and B, as mentioned by Nakamura (1985). Thus, we did not consider fish (type C) that tend to hover above the reef while remaining in the middle and upper parts of the water column. We do not discuss the effect of upwelling flow due to reef height on fish production. Fourth, some studies have shown that scour provides more available space for invertebrates and fish (Kruer and Causey, 1992; Sherman et al., 1999), but the benefit of scour was not considered here because we were interested in reef stability and scour causes partial reef settlement. Finally, the assumption was made that well-targeted AR designs increase biomass and species productivity (Bohnsack et al., 1994; Charbonnel et al., 2002; Brickhill et al., 2005; Granneman and Steele, 2014; Smith et al., 2015), although some studies claim that ARs do not necessarily attract or increase the biomass of desired species or retain them for long periods (Osenberg et al., 2002; Powers et al., 2003; Brochier et al., 2015). The ‘attraction vs. production’ debate has been resolved in fisheries societies (Pitcher and Seaman, 2000; Bortone, 2011), but this study only focused on evaluating the wake region, assuming a positive effect. As we concentrated on the described indices, the details and verification of numerical studies were neither considered nor included.

2. Materials and methods

2.1. Target artificial reefs (ARs)

Two ARs are selected, as shown in Fig. 1. The AR in Fig. 1a is a concrete box-type AR (AR1), and the one in Fig. 1b is a concrete box-type reef with a steel box inside (AR2). These ARs are included in the general Korean AR inventory, which is approved by the Central Artificial Committee, a governmental authority in South Korea. The geometric dimensions of each AR are given in Fig. 1.

2.2. Flow domains and boundary conditions

The flow domain ($L=20$ m, $B=20$ m, and $H=10$ m) of AR1 is established as shown in Fig. 2. The AR2 flow domain is also established as in Fig. 2, except the domain size is $L=35$ m, $B=20$ m, and $H=20$ m. This change is made to consider the different sizes of the ARs. Here, the boundary conditions are the following: (1) an inlet at the front face (Fig. 2a) to facilitate a steady flow of 2 m/s (the general Korean practice for ARs); (2) an outlet at the rear face (Fig. 2b) to allow water to flow out by assigning zero pressure gradient; (3) symmetric boundary conditions at the left, right, and top faces (Fig. 2c) to reduce the effect of the limited dimensions on flow analyses; (4) a no-slip boundary condition at the bottom face (Figs. 2d); and (5) smooth walls on the ARs.

2.3. Analysis method and hypotheses

The EbFVM has been used widely as a computational fluid dynamic tool for flow analyses of automobiles, subsea pipes, artificial reefs, and other structures (Marcondes and Sepehrnoori, 2010; Woo et al., 2014; Kim et al., 2014a, 2014b) because it allows powerful mesh generation and wake volume adaptation. The method discretises the analysis domain into sub-regions, and the governing equation is converted into algebraic equations and then iteratively applied to find a solution (Finnegan and Goggins, 2012).

In the flow analysis, the water in the domain was assumed to be incompressible, viscous, Newtonian, and steady flow. The governing