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Numerical study on interaction of a solitary wave with the submerged obstacle

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ABSTRACT

The extremely nonlinear interaction between waves and marine structures is one of most challenging problems in ocean engineering. In this study, the propagation of a solitary wave over a submerged vertical obstacle is investigated by a developed two-dimensional multi-phase viscous model. The constrained interpolation profile (CIP) based on Cartesian grid method is introduced to solve the Navier-Stokes equations, and free surface is captured accurately by the Tangent of Hyperbola for INterface Capturing (THINC) scheme. First, the free surface motions and velocity fields of a solitary wave interacting with a submerged obstacle are simulated. The present calculations fit fairly well with the measurements through whole wave propagation over the submerged obstacle. Second, the corresponding vorticity fields are calculated to illustrate characteristics of vortex generation and evolution. Third, wave forces acting on the submerged obstacle are calculated, and the results agree well with existing computations. Finally, the effectiveness of the submerged obstacle as a targeted breakwater is estimated by evaluating the reflection and transmission coefficients. The presented computations confirm that the CIP-based Cartesian grid method is capable of reproducing strongly nonlinear interaction of a solitary wave with the submerged obstacle and performing predictions of comprehensive flow-field information accurately.

1. Introduction

The propagation of waves over an obstacle usually experiences complicated hydrodynamic behaviors, including vortex generation and violent free-surface flow, which can dissipate the energy of incident waves and reduce the height of transmitted waves effectively. Many types of offshore structures have been studied to find the suitable breakwaters in ocean engineering. Among them, submerged-type structures attract numerous attentions in these years due to its environmental advantage, and many studies on the interaction between waves and submerged structures have been carried out. Model experiment is still the dominating method for these studies, although it has the limits of high cost and scale effect in most cases. The numerical model being capable of providing comprehensive flow information and capturing strongly nonlinear phenomena accurately, therefore, is highly desirable for the design and construction of marine breakwaters.

Earlier studies of wave transmission over submerged obstacles, including partially and fully submerged structures, mostly focused on periodical incident waves, such as Losada et al. (1992, 1993). However, few of these studies considered the wave propagation over a submerged obstacle induced by a solitary wave. It is well-known that the solitary wave is a desirable alternative to simulate tsunami-type wave. Many studies have employed solitary wave to investigate the interaction of extreme wave with marine structures. Considerable amount of these studies focused on transmission properties of solitary waves propagating over obstacles. Seabra-Santos et al. (1987) studied the propagation of solitary wave over an obstacle by both numerical and experimental methods. Similar studies also include experimental and numerical works conducted by Lynett et al. (2000), Chang et al. (2001) and Lin (2004). Shao (2005) employed the smoothed particle hydrodynamics (SPH) method to examine the characteristics of solitary wave reflection and transmission after impacts on a partially immersed breakwater. Lately, solitary wave impinging on porous breakwaters was numerically investigated to determine the wave transmission properties by Lin and Karunarathna (2007). Most of these studies primarily focused on the effectiveness of breakwater with different structural forms and different wave conditions.

Moreover, vortex shedding and evolution induced by a solitary wave propagating over submerged obstacles have attracted considerable attentions in recent days due to improvement of measured facilities and

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Nomenclature

P	Pressure (Pa)
u_i	Velocity component (m/s)
f_i	Body force (N)
ρ	Density of fluid (kg/m^3)
μ	Fluid dynamic viscosity (N·s/m^2)
Δx	Grid spacing in x-direction (mm)
Δy	Grid spacing in y-direction (mm)
Δt	Time step (s)
φ	Density function
τ	Duration of paddle motion (s)
K	Outskirts decay coefficient
a	Wave height (m)
h	Water depth (m)
ζ	Wave elevation (m)
λ	Physical property
c	Wave celerity (m/s)
W_G	Position of wave gauge (m)
W	Width of breakwater (m)
H	Height of breakwater (m)
Cr	Reflection coefficient
Ct	Transmission coefficient
x	Horizontal position along x-axis (m)
y	Vertical position along y-axis (m)
t	Time (s)
$X(t)$	Displacement of wavemaker (m)
$X'(t)$	Velocity of wavemaker (m/s)
SWL	Still water level
PIV	Particle Image Velocimetry
F_{xmax}	Maximum horizontal wave force (N)
F_{ymax}	Maximum vertical wave force (N)
F_x	Total horizontal wave forces impacting on the structure (N)
F_{sx}	Horizontal wave forces impacting on single side of the structure (N)

numerical analysis tools. Chang et al. (2001) conducted a series of numerical and experimental tests to investigate the vortex evolution induced by solitary waves passing over a submerged rectangular obstacle. Further studies on vortex shedding and evolution after solitary waves impinge on submerged obstacles were performed by Huang and Dong (2001), Lin et al. (2006), Lin and Huang (2010). More recently, the vortex generation and evolution during a solitary wave propagating over a bottom-mounted barrier were investigated both experimentally and numerically by Wu et al. (2012). Zarruk et al. (2015) conducted a variety of experimental and numerical investigations to examine the shedding and evolution of vortices induced by a solitary wave passing over a submerged cylindrical structure. Zaghian et al. (2017) investigated experimentally the interaction of a solitary wave with a submerged thin plate with the consideration of installed angles, in which the velocities and vortices near the submerged structure were measured using PIV technique. The majority of the above experimental and numerical studies mainly emphasized on the characteristics of velocity and vorticity fields near the targeted structure without the consideration of wave forces.

The constrained interpolation profile (CIP) method was firstly proposed to solve the hyperbolic-type equations by Takewaki et al. (1985), which was named as the cubic-interpolated pseudo-particle method originally. This semi-Lagrangian scheme mainly applied in the fields of physics and electromagnetism was further developed by Takewaki and Yabe (1987), Yabe and Takei (1988), Yabe and Aoki (1991), Yabe et al. (1991), Yabe et al. (2001). Then, Hu and Kashiwagi (2004, 2009) employed the CIP method to predict violent free-surface flow and strongly nonlinear wave-structure interaction. After that, the CIP method was extensively validated by a series of wave-body interaction studies, such as He et al. (2011), Zhao and Hu (2012), He (2013), Liao and Hu (2013), Zhao et al. (2014), Zhao et al. (2015), Zhao et al. (2016), Ji et al. (2017). In this study, a submerged structure in form of vertical and thin obstacle (height-width ratio > 1) was investigated using the CIP-based model. Such structure is easy to design and construct as an alternative of breakwater, as well as it has a small influence on environment.

The primary goal of this study is to develop a CIP-based numerical model to investigate a solitary wave propagating over a submerged obstacle. Violent free-surface motions and corresponding nonlinear phenomena were simulated and analyzed. The wave forces acting on the submerged obstacle were calculated by integrating pressure along the structure surface. In addition, the velocity and vorticity fields were evaluated to determine the characteristics of vortex generation and evolution. The numerical results including free surface profiles, velocity distribution, and vorticity fields were compared with the published experimental data in good agreement. Finally, transmission properties of the solitary wave impinging on the structure with different widths and heights were systematically studied by this well-validated model.

2. Numerical model

2.1. Numerical methods

A two-dimensional computational model based on the CIP method with non-uniform and staggered Cartesian grid was developed in the study. The model solves an unsteady, viscous and incompressible flow, which is governed by the following continuity and Navier-Stokes equations:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_j\frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{1}{\rho}\frac{\partial}{\partial x_j}(2\mu S_{ij}) + f_i \tag{2}$$

where u_i is the velocity component; ρ and μ are density and dynamic viscosity, respectively; p is the pressure and f_i denotes the body force including the gravity; $S_{ij} = (\partial u_i/\partial x_j + \partial u_j/\partial x_i)/2$.

The multi-phase flow was adopted in the model, which includes the liquid phase (water), gas phase (air) and solid phase (structure). The interfaces between the different phases should be captured accurately in the computations. More specially, the free surface and solid boundary need to be determined in each time step.

We define a density function φ_{m} ($m = 1, 2, 3$ denotes liquid, gas, solid phase, respectively) to recognize different phases, which satisfies the following equation:

$$\frac{\partial \varphi_m}{\partial t} + u_i\frac{\partial \varphi_m}{\partial x_i} = 0 \tag{3}$$

In addition, the density functions in each computational cell have the following relation:

$$\sum \varphi_m = 1.0 \tag{4}$$

The structure in the study is assumed to be rigid, and a direct method was used to calculate the φ_3. The φ_1 was obtained by solution of Eq. (3). Then, the density function for air phase φ_2 was calculated via algebraic relation of Eq. (4). Once the density functions are determined, physical information in each computational cell can be obtained: