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Numerical study on three-dimensional waves produced by a bottom jet

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ABSTRACT

The eruption of an underwater volcano can initiate the disturbances of the sea surface and subsequently generate a group of outward-propagating tsunamis. The theme of this study is to introduce a three-dimensional (3D) fully nonlinear wave model for the simulation of wave motions induced by a bottom jet. A boundary-fitted coordinate system is utilized to conveniently adjust grids according to the transient moving free surface. The governing Laplace equation of the velocity potential is solved by an implicit finite-difference scheme while a mixed explicit/implicit iteration procedure is applied to solve the free-surface boundary conditions. In addition, a set of generalized Boussinesq equations are solved for comparison with the fully nonlinear model. Good agreements in comparisons with the existing numerical and analytical solutions are achieved for cases investigated. Waves induced by three types of bottom jets: namely (1) sudden eruption, (2) initial transient, and (3) periodic transient are discussed in this paper. For the case of sudden erupted jet, a system of 3D outgoing waves as the cylindrical wave pattern are presented and discussed. For the initial transient types, it shows the transition in the incipient stage has a great influence on the initial rising of the water surface and the induced leading waves. Furthermore, an interesting up-down phenomenon in the center of disturbed free surface due to the type of periodic jet is revealed.

1. Introduction

Submerged jet flows are frequently observed in engineering application and in our daily life. Examples include the disposal of wastewater through vertical diffusers at the coastal bottom; the discharge of water from a pipe bursts with a strong jetting velocity in a shallow water, and the underwater fountain in a leisure pond. Furthermore, eruptions of undersea volcanoes are other naturally occurred examples. As a result of a jet eruption, the free surface is stirred up to form an impulsive wave evolving into a series of outward propagating waves. In the past, more attentions have been paid on the studies of horizontal buoyant turbulent jet flow (e.g. [7,14]). For the vertical jet, Maurel et al. [12] conducted a series of jet experiments to observe the two-dimensional hump phenomenon in free surface with a small setup of equipment.

Water waves can be generated by any kinds of external forcings in water. The vertical forcing of submerged jets observed in water column may be a result of underwater explosion or volcano eruption. The induced huge disturbance in water surface has a tendency to generate large waves. For example, the undersea earthquake, volcano eruption, and landslide, are commonly known for the formation of tsunami [10]. Certainly, earthquake, landslide, and volcano eruption may sometimes occur in connection. According to a statistical survey of tsunami during the period from 1790 to 1990 by Imamura in 1998 (cited in Kawamata et al. [9]), 3.3% (22 events) and 6.4% (43 events) were generated mainly by landslides and volcanic eruptions respectively. As reflected by the fact that the liquid water covers 70% of the earth surface, geologists have identified more than 5000 active underwater volcanoes [5]. The number is still increasing through searches by the scientists. The so called volcanogenic tsunami occurred due to the eruption of an underwater volcano, have been investigated by many researchers (such as [4,11,20,23]). It was known the volcanogenic tsunami may be generated by the vertical eruption, lateral eruption and the crater avalanche. Although there is only 6.4% tsunami formed by the volcano eruption [9], however, once the volcanogenic tsunami is produced, the severe disaster may be followed. Historically, about 3600 years ago, a huge tsunami generated by an underwater-volcano eruption was evidenced from its deposits on the island of Thera, in Aegean Sea [13]. In the 18th century, one well known occurrence of tsunami was reported in 1883 in Indonesia. An underwater volcano in Krakatoa Island erupted and created an almost 40 m tsunami attacking Java and Sumatra. About 36,000 people have died in that tsunami event (Levin, and Nosov [10]). Another similar case happened in 1741, a tsunami caused by the volcanic eruption of Oshima-Oshima resulted in the maximum

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runup of 13 m or more and about 2000 people died (Satake [18]). Later, in 1792, a huge tsunami generated by the collapse of Mt. Mayuyama during the volcanic activity attacked the coast around Ariake Sea (Kyushu in Japan). The landslide and tsunami killed nearly 15,000 people, one of the Japan's major historical volcanic disaster (Miyamoto [16]). The 1994 Rabaul eruption series were one of the most recent eruptive events that were accompanied by significant tsunamis. In the south of Rabaul, the largest tsunami wave invaded 100–200 m inland [17]. It is worth to study the mechanism of such non-seismic tsunamis to further comprehension of these disasters. Those tsunamis were mostly initiated from small disturbances of free surface, but the waves are long and can transmit their energy over longer distances. Kawamata et al. [9] applied the improved two-layer model to simulate the 1741 Oshima-Oshima tsunami and attempted to reproduce actual tsunami heights along the Hokkaido coast and the Korean Peninsula in the Japan Sea. In this study, for simplification of one layer model we assume the produced jet has the same property as the water.

The jet free-surface problems in linear wave theory with cylindrical domain have been studied analytically in literatures [4,10]. Recently, due to the fast advancements in computational capability, the development of 3D simulation model becomes increasingly common in the field of computational fluid dynamics. The importance of 3D simulations is related to the realization in practice. For shallow-water wave problems, the scale in vertical direction is smaller than that of the horizontal directions. Thus the depth-averaged wave models (such as Boussinesq-like equations) have been derived to simulate wave propagation in quasi-3D situations. The computational efforts can be saved when comparing to fully 3D models. The advantages of shallow-water wave models are reflected with their simplification and computational efficiency to easily extend their applications [25]. Researchers were also interested in developing the Quasi-3D models including higher-order terms to maintain higher accuracy in equations [1]. However, the Quasi 3D models in some cases are limited to tackle some of the wave problems, such as the strong waves with high nonlinearities, domains with the step-like or complex bottom topography, or the submerged obstacles suspending in water [3]. Those problems cannot be properly solved with depth-averaged models. Hence, the development of complete 3D nonlinear wave models becomes necessary in solving some of the practical but complicated problems. An increasing number of researchers have invested the efforts in three-dimensional fully-nonlinear studies, such as [2,6,8,3]. Here we extend the study to investigate the performance differences between the Quasi-3D model using generalized Boussinesq (gB) equations and the fully-nonlinear potential flow model introduced in this study for the problem of modeling nonlinear waves produced by a submerged jet. It is assumed that the eruption jet takes place from an underwater source (e.g. a volcano) with a specified vertical velocity. A fully 3D hydrodynamic model developed by Chang and Wang [3] is extended to simulate the jet induced wave motion in water surface. Here, we use the fully-nonlinear model to discuss various Froude numbers (defined based on the jet velocity and still water depth) ranging from 0.4 to 1.2. The results under the strong-velocity flow conditions are presented to highlight the wave generation phenomena. We believe that understanding this fundamental but idealized wave generation issue will help in the near future to explore more complex problems. Although the flow scales are modeled theoretically, the results are expected be useful for learning the basic mechanism of bottom jet induced surface waves.

2. Problem formulations

As depicted in the sketch of water wave generation over a bottom round jet in Fig. 1, let a round jet launch at the speed V^* on the sea bottom with uniform depth H^*. The physical variables are normalized into dimensionless quantities using the characteristic velocity, characteristic length, and time scale as defined by $\sqrt{gH^*}$, H^*, and $\sqrt{H^*/g}$, respectively. The variables with superscript "*" denote the dimensional variables. In other words, all variables described below without superscript "*" are dimensionless variables. For the fluid domain, the z-axis points upward and the (x,y)-plane lies on the undisturbed free surface. The center of the bottom jet with diameter D is located at $(x,y) = (0,0)$. Under the assumption of incompressible, inviscid, and irrotational flow, the wave motion described by the velocity potential $\phi(x,y,z,t)$ satisfies the Laplace equation

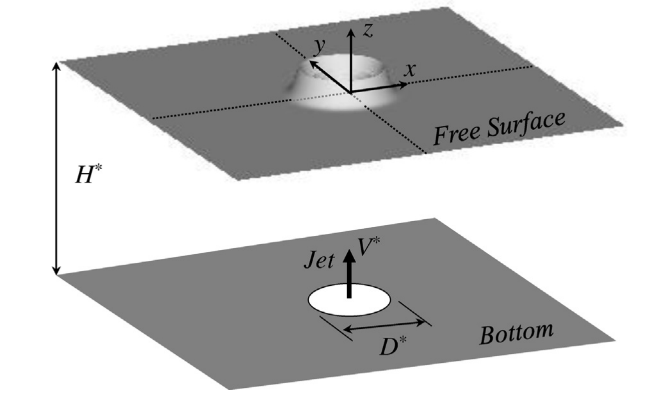

Fig. 1. Schematic diagram showing a bottom jet and induced free-surface waves.

$$\phi_{xx} + \phi_{yy} + \phi_{zz} = 0 \tag{1}$$

The subscripts denote partial differentiation. Initially, the water region is undisturbed, that is $\zeta = \phi = 0$. Here $\zeta(x,y;\ t)$ is the free-surface displacement and the 3D velocity vector is defined as $(u,v,w) = (\phi_x,\phi_y,\phi_z)$. The kinematic and dynamic free-surface conditions are

$$w = \zeta_t + u\zeta_x + v\zeta_y \tag{2}$$

$$\phi_t + (u^2 + v^2 + w^2)/2 + \zeta + p_a = 0 \tag{3}$$

where p_a is the atmospheric pressure on the free surface and is set as zero in this study. The simulation domain is bounded in the region of $x \in [x_{\min}, x_{\max}]$ and $y \in [y_{\min}, y_{\max}]$. A set of simple wave equations are chosen as the open boundary conditions to radiate all primary waves out of the lateral boundaries. They are

$$x \to x_{\max}, x_{\min} : \phi_t \pm \sqrt{(1+\zeta)}\phi_x = 0; \quad \zeta_t \pm \sqrt{(1+\zeta)}\zeta_x = 0 \tag{4a,b}$$

$$y \to y_{\max}, y_{\min} : \phi_t \pm \sqrt{(1+\zeta)}\phi_y = 0; \quad \zeta_t \pm \sqrt{(1+\zeta)}\zeta_y = 0 \tag{4c,d}$$

in which, the "+" sign is used for treating the boundaries of $x_{\max}$ and $y_{\max}$ and "−"sign for the $x_{\min}$ and $y_{\min}$ boundaries. On the bottom, the region within the circular jet with diameter D is subjected to a dimensionless upward velocity described by $F = V*/\sqrt{gH*}$ (Froude number) and elsewhere is impermeable. The dimensionless bottom vertical velocity (w_b) expressed with the relationship of F appears in the bottom boundary condition as:

$$\begin{cases} \dfrac{\partial \phi}{\partial z} = w_b = F, & \text{if } \sqrt{x^2+y^2} \le (D/2) \\ \dfrac{\partial \phi}{\partial z} = w_b == 0, & \text{otherwise} \end{cases} \tag{5}$$

3. Numerical method

Here we introduce two numerical models to solve the three-dimensional bottom jet problems. One is the fully nonlinear wave