Applied Ocean Research 63 (2017) 36–48

Contents lists available at ScienceDirect

Applied Ocean Research

journal homepage: www.elsevier.com/locate/apor

Numerical investigation of tsunami-like wave hydrodynamic characteristics and its comparison with solitary wave

K. Qu[a], X.Y. Ren[b,*], S. Kraatz[a]

[a] Department of Civil Engineering, City College, The City University of New York, New York 10031, USA
[b] College of Civil Engineering and Architecture, Hainan University, Haikou 570228, China

ARTICLE INFO

Article history:
Received 5 August 2016
Received in revised form 3 December 2016
Accepted 4 January 2017

Keywords:
N-wave
Solitary wave
Wave run-up
Breakwater
Navier-stokes equations
Volume of fluid

ABSTRACT

Solitary waves have been commonly used as an initial condition in the experimental and numerical modelling of tsunamis for decades. However, the main component of a tsunami waves acts at completely different spatial and temporal scales than solitary waves. Thus, use of solitary waves as approximation of a tsunami wave may not yield realistic model results, especially in the coastal region where the shoaling effect restrains the development of the tsunami wave. Alternatively, N-shaped waves may be used to give a more realistic approximation of the tsunami wave profile. Based on the superposition of the $\text{sech}^2(*)$ waves, the observed tsunami wave profile could be approximated with the N-shaped wave method, and this paper presents numerical simulation results based on the tsunami-like wave generated based on the observed tsunami wave profile measured in the Tohoku tsunami. This tsunami-like wave was numerically generated with an internal wave source method based on the two-phase incompressible flow model with a Volume of Fluid (VOF) method to capture the free surface, and a finite volume scheme was used to solve all the governing equations. The model is first validated for the case of a solitary wave propagating within a straight channel, by comparing its analytical solutions to model results. Further, model comparisons between the solitary and tsunami-like wave are then made for (a) the simulation of wave run-up on shore and (b) wave transport over breakwater. Comparisons show that use of these largely different waveform shapes as inputs produces significant differences in overall wave evolution, hydrodynamic load characteristics as well as velocity and vortex fields. Further, it was found that the solitary wave uses underestimated the total energy and hence underestimated the run-up distance.

1. Introduction

Tsunamis typically are long waves of small steepness triggered by impulsive geophysical events of the seafloor and of the coastlines, such as earthquakes, submarine and aerial mass failures, volcanic eruptions and asteroid impacts (Synolakis and Bernard [1]). Along with its evolution over continental shelf, tsunamis can cause severe and massive devastation in coastal regions. Generally, the energy of tsunamis will focus inside narrow bays, moving a vast volume of water in process. The lifted water is then able to easily move further inland overtopping protective structures such as sand banks and levees, often resulting in significant economic and environmental impacts. Synolakis et al. [2] summarized tsunami impacts of events resulting in 3000 or more fatalities between years 1992–2002. The tsunami of December 26th 2004, originating in the India Ocean, resulted in an estimated final death toll of more than 230,000. As reported by Yalciner et al. [3], 22,626 people are presumed dead during the Tohoku tsunami on the March 11th 2011, and ultimately caused the meltdown of three reactors within the Fukushima Daiichi Nuclear Power Plant complex in Japan. As reported, most of the fatalities were attributed to overland flow. Meanwhile, if the tsunami originates nearby or early detection equipment is not in place, there is not enough time to seek refuge from a tsunami (Cho et al. [4]). Therefore, understanding of the characteristics during the tsunami wave run-up process is important for emergency preparedness.

In order to save human lives and enhance the safety and intactness of the coastal infrastructures, the generating mechanisms of the tsunami flows have been extensively studied. Tsunami earthquakes were originally identified by Kanamori [5] as kind of earthquake which has an anomalous tsunami excitation relative to short period body and surface seismic waves. Pelayo and Wiens [6] summarized the factors of the tsunami earthquake that may induce anomalous tsunami excitation including shallow dip of the source

---

* Corresponding author.
E-mail address: renxingyue@gmail.com (X.Y. Ren).

http://dx.doi.org/10.1016/j.apor.2017.01.003

mechanism, shallow source depth and low rigidity at the source. The source effects on the generation and propagation of tsunami were investigated by Geist and Yoshioka [7] and the shallowness of the source and the amount of slip were reported as the most significant factor, and the directivity of the tsunami will be affected by the orientation of the slip.

Although the generation mechanisms of tsunamis have been generally understood (Synolkis [8]), there is still a knowledge gap on numerical prediction of tsunami flows with acceptable resolution and accuracy due to the complexities of coastline formations, the moving free surface and the strong local turbulence near the free surface. So far, numerical models for tsunami wave run-up simulations were mainly carried out based on the depth-integrated and three-dimensional Navier-Stokes equations. In most cases, solitary waves were used to represent a tsunami wave. For instance, using the solitary wave, Cho et al. [4] numerically investigated run-up heights of nearshore tsunamis in the vicinity of a circular island through a numerical model based on the nonlinear shallow-water equations and quadtree grid system. Liang et al. [9] studied the solitary wave run-up on coast with a Boussinesq type wave model based on the depth-integrated equations. Ha et al. [10] developed a three-dimensional model based on the Navier-Stokes equations and successfully reproduced the solitary wave run-up and rundown on a slope. A three dimensional numerical approach based on IHFOAM was applied to study the interaction of tsunami waves with mangrove forest by means of solitary waves (Maza et al. [11]). The major shortcoming of the depth-integrated equations based models is that they are unable to capture flow structures in detail during tsunami frontal breaking or the complex interactions with coastal infrastructure. A fully three-dimensional model is essential for tsunami wave investigations. Here we present a wave model based on the three-dimensional Navier-Stokes equations, developed and applied to numerically study the complex flow phenomena induced by tsunami-like wave run-up on a plane beach and over a rectangular wave breaker which is a common infrastructures implemented in the coastal area.

Since the 1970s, the solitary waves have been widely adopted to approximate the initial condition of the tsunami waves in numerical simulations (Cho et al. [4]; Liang et al. [9]; Maza et al. [11]; Hsiao [12]; Limura [13];) and experiments (Synolakis [8]; Gedik et al. [14]; Goseberg et al. [15];). However, the main tsunami wave develops at completely different time and space scale from that of solitary waves (Madsen et al. [16]; Madasen and Schäffer [17]). Madsen et al. [16] pointed out that the required evolutionary distance for an initial free surface hump into a solitary wave far exceeds the width of any ocean on Earth and that real word large scale tsunamis would not evolve into solitary waves on geophysical scale. Synolakis [8] first questioned the use of solitary wave as a landside initial situation for tsunami investigations in physical and numerical studies, and suggested that the solitary wave profile could has limited applicability in use as initial condition for the tsunami simulation. Moreover, the usefulness of this solitary wave model diminished remarkably when applied to study the effects of near-shore tsunamis. Observations from the field survey also supported the conclusion above. Tadepali and Synolakis [18] reported that tsunami waves were often preceded by a depression. This was also observed at the filed survey from the India Ocean and Tohoku tsunamis. In both cases, the tsunami waves caused nearby shorelines to first recede (drawdown of water) before advancing (flood wave). Further, based on tsunami wave records during the Tohoku tsunami event (Chan and Liu [19]), tsunami waves were found to have significantly longer wavelengths than solitary waves on the continental shelf. Therefore, there are many shortcomings that limit applicability of solitary waves in the representation of the tsunami main wave and a better alternative is needed.

In considering waveforms with leading-depression wave, Tadepali and Synolakis [18] introduced a concept of N-shaped solitary wave, which were composed of solitary or solitary-like waves and could be designed to be either leading depression N-wave or leading elevation N-wave. Their proposed N-waves incorporate the classical solitary wave tie between the wave number and nonlinearity, which are fundamentally inappropriate for geophysical tsunamis (Madsen et al. [16]). Madasen and Schäffer [17] proposed another form of N-wave composed of superposition of positive and negative single waves, whose wavelength is not linked to the wave nonlinearity as in solitary wave theory. Tadepali and Synolakis [20] presented the analytical discussions for the N-wave run-up on sloping beaches, which showed leading depression N-wave had larger maximum run-up height than solitary waves. This was also observed by Liang et al. [9], who used a Boussinesq type wave model to attribute the produced higher maximum run-up height to the steeper wave front of the main wave following the depression. Therefore, a good description of the profile of the leading tsunami wave could be sufficient to give a reasonable estimation of the maximum run-up height, as suggested by Chan and Liu [19]. In their study, based on the concept of N-wave, the temporal evolution of the tsunami wave recorded at Iwata South station during the 2011 Japan Tohoku tsunami was approximated with a combination of three $\mathrm{sech}^2(*)$ profiles which closely resembled the profile of the leading tsunami wave.

In this work, we numerically investigate the Tohoku tsunami wave implementing the N-wave model by solving the three dimensional Navier-Stokes equations with volume of fluid method to accurately resolve the interface between air and water. Results are then compared to those using a solitary wave to represent the tsunami wave. The tsunami-like wave profile is formulated by adapting the Tohoku tsunami wave parameters reported by Chan and Liu [19] to the wave generating model incorporated within our CFD model. Through adopting a more realistic and practical tsunami-wave model, this work intends to demonstrate the feasibility of numerically simulating tsunami-like waves with acceptable accuracy, and its potential use to study tsunami impacts on the coastal region.

2. Numerical model

2.1. Governing equations

The governing equations for the two immiscible fluids are the 3D Naiver-Stokes equations for incompressible flows, which can be written in the vector form as

$$\nabla \cdot \vec{U} = 0 \tag{1}$$

$$\frac{\partial \rho \vec{U}}{\partial t} + \nabla \cdot \left(\rho \vec{U} \vec{U}\right) - \nabla \cdot \left(\mu_{eff} \nabla \vec{U}\right) = \nabla \vec{U} \cdot \nabla \mu_{eff} - \nabla p + \left(\rho - \rho_{ref}\right) \cdot \vec{g} \tag{2}$$

where $\vec{\mathrm{U}}$ is the flow velocity, t is the time, P is the pressure, ρ is the density of air-water mixture, ρ_{ref} is the reference density, $\mu_{eff} = \mu_l + \mu_t$ is the effective viscosity including the laminar viscosity μ_{l} and turbulence viscosity μ_{t}, and $\vec{\mathrm{g}}$ is the acceleration of gravity. The reference density is used to eliminate the hydrostatic pressure accumulation in the gas phase region. The total pressure$p^* = p + \rho_{ref} \vec{r} \cdot \vec{g}$, where $\vec{\mathrm{r}}$ is the vector that starts from the reference point to the locations where the total pressure values are calculated.

The turbulent viscosity is determined using Smagorinsky model [21], and the turbulent viscosity is calculated as:

$$\mu_t = C_s^2 \Delta^2 \sqrt{2 S_{ij}^2} \tag{3}$$

where $\mathrm{C_s}$ is a coefficient between 0.1 and 0.2, and a constant value $\mathrm{C_s} = 0.2$ was used in the present model. The filtered strain rate ten-