Ocean Engineering 75 (2014) 90–111

Contents lists available at ScienceDirect

Ocean Engineering

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

Modeling of tsunami generation and propagation under the effect of stochastic submarine landslides and slumps spreading in two orthogonal directions

Khaled T. Ramadan *, M.A. Omar, Allam. A. Allam

Department of Basic and Applied Science, College of Engineering and Technology, Arab Academy for Science, Technology and Maritime Transport, P.O. Box 1029, Abu Quir Campus, Alexandria, Egypt

ARTICLE INFO

Article history:
Received 28 October 2012
Accepted 2 November 2013
Available online 3 December 2013

Keywords:
Tsunami modeling
Submarine landslides and slumps
Laplace and Fourier transforms
Stochastic process
Gaussian white noise
Itô integral

ABSTRACT

Tsunami generation and propagation caused by stochastic submarine landslides and slumps driven by a Gaussian white noise in the *x*-and *y*-direction are investigated. This model is used to study the tsunami amplitude amplification under the effect of the noise intensities, spreading velocities, length and width of sliding and times of the stochastic landslides and slumps in the two-dimensional movements. This study shows that focusing and amplification of tsunami amplitudes can occur in an arbitrary direction, determined by the velocities of spreading. Tsunami waveforms within the frame of the linearized shallow water theory for constant water depth are analyzed analytically by transform methods (Laplace in time and Fourier in space) for the stochastic source model. We derived and analyzed the mean and variance of the random tsunami waves in the two orthogonal directions as a function of the propagated uplift length and width, noise intensities of the stochastic source model and the average depth of the ocean along the generation and propagation path.

1. Introduction

Tsunamis are surface water waves caused by the impulsive perturbation of the sea. Apart from co-seismic sea bottom displacement due to earthquakes, landslides and slumps can also produce localized tsunamis with large and complex wave runup especially along the coasts of narrow bays and fjords. The massive destruction and loss of life associated with recent tsunamis (Indonesia, 2004; Papua New Guinea, 1998) has underscored the need to develop and implement tsunami hazard mitigation measures. In recent years, significant advances have been made in developing mathematical models to describe the entire process of generation and propagation of a tsunami event generated by seismic seafloor deformation (Abou-Dina and Hassan, 2006; Hassan, 2009; Zahibo et al., 2006).

Numerical models based on the nondispersive shallow water equations are often used to simulate tsunami propagation and runup (e.g. Hassan et al., 2010b; Titov and Synolakis, 1995). The propagation of these waves is strongly influenced by the shape of the bottom. The problem of tsunami source reconstruction is a key concern of tsunami research. Certainly, the best way to solve this problem is to measure tsunami waves in the open ocean near to the source area and far away from the distorting influence of the near-shore topography.

Tsunami waves arriving from the open ocean are generated by underwater earthquakes which cause an irregular topography of increasing or decreasing water depth. The estimation of the tsunami waves is a practical interest which attracts nowadays a lot of attention due in part to the intensive human activity in coastal areas. The evaluation of a local tsunami threat is useful to get a more effective measure for the tsunami warning system and for protection works to help mitigate the damage to life done by tsunamis.

The case of particular interest to this study is the mechanism of generation of tsunamis by submarine landslides and slumps. When a submarine landslide occurs the ocean-bottom morphology may be significantly altered, in turn displacing the overlying water. Waves are then generated as water gets pulled down to fill the area vacated by the landslide and to a lesser extent, by the force of the sliding mass. Submarine slides can generate large tsunami, and usually result in more localized effects than tsunami caused by earthquakes (Ben-Menahem and Rosenman, 1972). Determination of volume, deceleration, velocity and rise time of the slide motion makes modeling of tsunamis by submarine slides and slumps more complicated than simulation of seismic-generated tsunami.

---

* Corresponding author.
E-mail address: kramadan@aast.edu (K.T. Ramadan).

0029-8018/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.oceaneng.2013.11.013

Previous studies of tsunami generation have been concerned with the surface elevations induced by the impulsive motion of an impermeable rigid bottom resulting from an undersea earthquake in one direction (Hayir, 2006; Todorovska and Trifunac, 2001; Todorovska et al., 2002; Trifunac and Todorovska, 2002; Trifunac et al., 2003) and in two directions (Trifunac et al., 2002b). All these studies are took into account constant depth and used very simple kinematic source models represented by a Heaviside step functions for representing the generation and propagation of tsunami. Hence, we use a random submarine landslides and slumps spreading in two orthogonal directions in the form of a stochastic source model to measure the variability of tsunami amplitude related to different factors of the spreading of the stochastic source model.

In recent years, the results of numerical and analytical studies, simulating mechanism of tsunami caused by submarine landslides were discussed. Beisel et al. (2007) studied numerically the landslide mechanism of tsunami generation based on a complex of multi-parameters calculations with the help of algorithms. Lynett and Liu (2002) derived mathematically a full nonlinear model to describe the generation and propagation of water waves by a submarine landslide. The model consists of a depth-integrated continuity equation and momentum equations, in which the ground movement is the forcing function. This model is capable of describing wave propagation from relatively deep water to shallow water. They developed a numerical algorithm for the general fully nonlinear model. Jiang and LeBlond (1992) investigated coupling of a submarine slide and the surface water waves it generates. They found that the two major parameters that determine the interaction between the slide and the water waves are the density of sliding material and the depth of initiation of the slide. Rzadkiewicz et al. (1997) simulated an underwater landslide by introducing a two-phase description of sediment motion and using the volume of fluid (VOF) technique. Grilli and Watts (1999) simulated waves due to moving submerged body using a boundary element method. Ataie-Ashtiani and Shobeyri (2008) presented an incompressible-smoothed particle hydrodynamics (I-SPH) to simulate impulsive waves generated by landslides. Also, laboratory experimental studies on tsunami generation by a rigid solid body moving along the slope have been carried out by many researchers (see Ataie-Ashtiani and Jilani, 2007; François and Stéphan, 2007; Fritz et al., 2004; Najafi-Jilani and Ataie-Ashtiani, 2008; Watts, 1998; Watts and Grilli, 2003).

The speed at which the mass moves across the sea floor is critical for the wave heights attained. Very fast slides (debris-flows) generate tsunamis roughly as high as the slide is thick while very slow moving slides produce little or no tsunamis. However, where slides move at velocities close or equal to that of the tsunami being produced, they develop ‘in phase’, building the waves up to exceptional size (see Ward, 2001). The transient wave generation due to the coupling between the slide deformation and time variations in the moving velocity and the free surface has been considered by Trifunac et al. (2002a). They discussed the effect of variable speeds of spreading of submarine slumps and slides on the near-field tsunami amplitudes. They illustrated the nature and the extent of variations in the tsunami waveforms caused by simple time variations of the frontal velocity of spreading for two-dimensional kinematic models of slides and slumps and compared the results with those for slide spreading with constant velocity. They found that the overall nature of the near-field tsunami amplitudes depended on the overall average speed of slumping and sliding remains unchanged, with respect to their previous studies in Todorovska and Trifunac (2001), Todorovska et al. (2002), Trifunac and Todorovska (2002), and Trifunac et al. (2003) with constant velocities of spreading. Hayir (2003) investigated the motion of a submarine block slide with variable velocities and its effects on the near-field tsunami amplitudes. He found that the amplitudes generated by the slide are almost the same as those created by its average velocity. Both Trifunac et al. (2002a) and Hayir (2003) used very simple kinematic source models represented by a Heaviside step functions for representing the generation and propagation of tsunami.

The sea bottom deformation following an underwater earthquake is a complex phenomenon. This is why, for theoretical or experimental studies, researchers have often assumed uniform slip over the entire fault plane of the bottom. Most investigations of tsunami generation and propagation used integral solution (in space and time) for an arbitrary bed displacement based on a linearized description of wave motion in either a two- or three-dimensional fluid domain of uniform depth. Very few works used realistic curvilinear slide shape in order to represent the generation and propagation of tsunamis due to the complexity of the integral solutions developed from the linear theory. Ramadan et al. (2011) studied the nature of the tsunami build up and propagation during and after realistic curvilinear source models represented by a slowly uplift faulting and a spreading slip-fault model. They studied the tsunami amplitude amplification as a function of the spreading velocity and rise time. They also analyzed the normalized peak amplitude as a function of the propagated uplift length, width and the average depth of the ocean. Hassan et al. (2010a) investigated the tsunami evolution during its generation under the effect of the variable velocities of realistic submarine landslides based on a two-dimensional curvilinear slide model. They described the tsunami generation from submarine gravity mass flows in three stages: The first stage represented by a rapid curvilinear down and uplift faulting with rise time. The second stage represented by a unilateral propagation in the positive direction to a significant length to produce curvilinear two-dimensional models represented by a depression slump, and a displaced accumulation slide model. The last stage represented by the time variation in the velocity of the accumulation slide (block slide) by using transforms method.

The complexity of the integral solutions developed from the linear theory even for the simplest model of bed deformation prevented many authors from determining detailed wave behavior, especially near the source region.

We use a random submarine landslides and slumps on the form of stochastic source model to measure the variability of tsunami amplitude related solely to different factors of the spreading of the stochastic sea floor uplift. We discuss aspects of tsunami generation that should be considered in developing this model, as well as the propagation wave after the formation of the source model has been completed.

It is demonstrated that local tsunami amplitudes under the effect stochastic source model vary by as much as a factor of two or more, depending on the local bathymetry. If other earthquake source parameter such as focal depth is varied in addition to the slip distribution patterns, even greater uncertainty in local tsunami amplitude is expected.

It is becoming widely recognized that bottom topography is irregular and difficult to predict and its aspects are best revealed through a random source models which are more realistic, because sources of tsunamis are generally uncorrelated. Despite this, a few of the analytical and numerical studies considered a stochastic source models for the investigation of the generation and propagation of tsunami waves. This is due to the complexity in the mathematical modeling and analysis of the stochastic case compared to the deterministic case. The main complexity in the stochastic case arises from the difficulty in the derivation of the integral solution of the random profile. Probability of tsunami occurrence frequency on the coast of California was evaluated first by Wiegel (1970). Rascón and Villarreal (1975) worked a stochastic evaluation of possibility of tsunami hit on the Pacific coast of Mexico. Successively, similar studies have been undertaken to know the local property of the tsunami occurrence frequency. Nakamura (1986) considered an extended Poisson process in order to get a better fit