Ocean Engineering 109 (2015) 34–59

Contents lists available at ScienceDirect

Ocean Engineering

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

Near- and far-field tsunami amplitudes by a moving curvilinear stochastic submarine slide shape based on linearized water wave theory

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ARTICLE INFO

Article history:
Received 2 September 2014
Accepted 27 August 2015

Keywords:
Near- and far-field tsunami amplitudes
Linear wave theory
Submarine slump and slide
Laplace and Fourier transforms
Gaussian white noise
Itô integral

ABSTRACT

The process of tsunami generation caused by a moving curvilinear stochastic submarine landslide with constant and variable velocity, driven by two Gaussian white noise processes in the x- and y-directions is investigated. Generation of tsunami is described initially by a rapid curvilinear down and uplift faulting, then propagating to a significant length to produce curvilinear stochastic three-dimensional model represented by a depression slump, and a displaced accumulation slide model and finally represented by the movement of the accumulation block slide. The moving curvilinear stochastic block slide acts to reduce wave focusing. This model is used to study the tsunami amplitude under the effect of the noise intensities and times of the curvilinear stochastic source model. The increase of the normalized noise intensities leads to an increase in oscillations and amplitude in the free surface elevation. Tsunami waveforms using linearized water wave theory for uniform water depth are analyzed analytically by transform methods (Laplace in time and Fourier in space). The normalized peak amplitude is analyzed as a function of the propagation length, width, noise intensities of the source model and the water depth. Tsunami propagation waveform is demonstrated after the slide stops moving at different propagation times.

1. Introduction

A tsunami can be generated by any disturbance that displaces a large water mass from its equilibrium position. In the case of earthquake-generated tsunamis, the water column is disturbed by the uplift or subsidence of the sea floor.

Significant advances have been made in developing mathematical models to describe the entire process of tsunami event generated by seismic seafloor deformation caused by an underwater earthquake, see Abou-Dina and Hassan (2006), Zahibo et al. (2006).

Submarine landslides, which often accompany large earthquakes, as well as collapses of volcanic edifices, also disturb the overlying water column as sediment and rock slump down slope and are redistributed across the sea floor. For many coastal areas, underwater landslides represent one of the most dangerous mechanisms for tsunami generation. Thus, the mechanism of generation of tsunami by underwater landslides is the particular interest in this study. Underwater landslides can generate surface water waves that have a high potential to cause damage and loss of life in coastal areas. Predicting the damage of these waves is of importance when assessing risk and magnitude of flooding in these areas.

Recent catastrophic tsunami events at Flores Island 1992 (Bardet et al., 2003; Tinti and Bortolucci, 2000), Swagway 1994 (Murty, 2003; Watts et al., 2005), Papua New Guinea 1998 (Tappin et al., 2001), and Turkey 1999 (Watts et al., 2005;Wright and Rathje, 2003) caused widespread damage and loss of life and hence have significantly increased an interest in studying landslide generated tsunamis. Modeling of tsunami generation caused by submarine slumps and slides is a much more complicated problem than simulation of seismic-generated tsunami as the characteristics of a tsunami generated by submarine landslides are mainly determined by the volume, deceleration, velocity, and time of the slide motion as well as the water depth.

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http://dx.doi.org/10.1016/j.oceaneng.2015.08.064

Hundreds of submarine landslides have been discovered and studied worldwide (e.g. Moore et al., 1994; McAdoo et al., 2000; Tinti et al., 2004; Papadopoulos et al., 2007; Tappin et al., 2007; Berndt et al., 2009; Brune et al., 2010).

Laboratory experimental studies on tsunami generation by a rigid solid body moving along the slope have been carried out by many researchers. Sue et al. (2011) described an idealized two-dimensional laboratory model of tsunamis generated by submarine landslides. Najafi-Jilani and Ataie-Ashtiani (2008) performed 84 laboratory experiments to study the impulse wave caused by underwater sliding. Ataie-Ashtiani and Nik-Kha (2008) investigated impulsive waves caused by subaerial landslides. They performed laboratory tests to study the effects of bed slope angle, water depth, slide impact velocity, geometry, shape and deformation on the impulse wave characteristics. A comprehensive review on the experimental and numerical study about landslide waves has been provided by Ataie-Ashtiani and Najafi-Jilani (2007). They provided an applied approach to predict the amplitude of initial impulse wave caused by underwater landslide based on numerical investigations. Enet and Grilli (2007) performed three dimensional large scale laboratory experiments by rigid underwater landslides. They used a smooth solid underwater body of Gaussian shape made of aluminum, located at an initial submergence depth and then released.

Fritz et al. (2009) rebuilt a cross section of Gilbert Inlet at 1:675 scale in a two dimensional physical laboratory model based on the generalized Froude similarity of the Lituya Bay 1958 event included landslide impact, tsunami generation, propagation and runup on headland. Mohammed and Fritz (2012, 2013) modeled physically tsunamis generated by three-dimensional deformable granular landslides based on the generalized Froude similarity.

Sælevik et al. (2009) performed two-dimensional experiments of wave generation from the possible Âkneset rock slide using solid block modules.

In recent years, the results of numerical and analytical studies, simulating mechanism of tsunami caused by submarine landslides were discussed. Weiss et al. (2009) studied the mega-tsunami runup with a hybrid modeling approach applying physical and numerical models of slide processes of deformable bodies into a U-shaped trench similar to the geometry found at Lituya Bay. Fritz et al. (2013) measured tsunami flow depths and runup heights along coastlines in the Gulf of Gonâve and along Hispaniola's south coast and recorded tsunami dataset in Haiti and the Dominican Republic by the International Tsunami Survey Team (ITST) from 3 to 7 February 2010. Fritz et al. (2003a) focused on the landslide impact induced water displacement volumes and rates extracted from the instantaneous velocity vector fields obtained by particle image velocimetry (PIV). Fritz et al. (2003b) applied digital particle image velocimetry (PIV) to the landslide impact and wave generation. They highlighted on applicability of PIV at large scale as well as to flows with large velocity gradients. Fritz et al. (2004) focus on the observed wave types, major near field wave characteristics of landslide generated impulse waves and slide energy conversion.

Ma et al. (2013) simulated numerically tsunami waves generated by deformable submarine landslides using a combined finite volume/finite difference approach with a Godunov-type shock-capturing scheme. Beisel et al. (2007) determined the dependences of the process of wave formation on length and width of landslide, on the depth of its bedding, on the law of motion and on the bottom slope angle. Agustinus (2008) developed a numerical method to simulate the wave propagation in shallow water with nonlinear friction on the sloping bottom. Wijaya et al. (2008) used the characteristic-based split method for the solution of the shallow water equations to simulate tsunami propagation on the open sea. Trifunac and Todorovska (2002) reviewed the differences between submarine slumps and slides on one side and earthquakes on the other side, as sources of tsunami to further understanding of the nature of tsunami waveforms near the source. Todorovska et al. (2002) described generation of tsunami by submarine slumps and slides using elementary forward source models of rectangular or sloping blocks spreading laterally with assumed velocities, see also their works, Trifunac et al. (2002a, 2002b). 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. Trifunac et al. (2002a, 2002b), Hayir, (2003, 2006) used very simple kinematic source models represented by a Heaviside step functions either spreading in one or two directions to model the generation of tsunami caused by submarine landslides and slumps. In reality the sea bottom deformation following an underwater landslides are characterized by some rugosity.

Submarine landslides have high hazard potential to coastal communities. An effective local tsunami early warning system requires the derivation of source parameters already during tsunami excitation, Brune et al. (2009). They proposed a method to assess location, volume and velocity of submarine landslides using a tiltmeter array. They illustrated their method by applying it to the Storegga event and discuss its accuracy with respect to tsunami prediction.

In practice, the available data about the geometries of the source model are always subject to some uncertainties. The missing information can be modeled by the inclusion of random effects. These circumstances have led several authors to consider water wave propagation in random media, de Bouard et al. (2008), Nachbin (2010). In this paper, a curvilinear stochastic model is proposed to describe the underwater landslide irregularity and its effect on the generation of the tsunami waves. It has become widely recognized that sources of tsunamis are irregular and generally uncorrelated and difficult to predict. The best way to reveal their aspects is through random source models which are more realistic. Nevertheless, few analytical and numerical studies considered stochastic source models for the investigation of tsunami generation and propagation waves. This is due to the complexity of the mathematical modeling and analysis of the stochastic case compared to the deterministic case. The main complexity arises from the difficulty in the derivation of the integral solution of the random profile in the stochastic case.

Wiegel (1970) evaluated the probability of tsunami occurrence frequency on the coast of California. Rasćon and Villarreal (1975) carried out a statistical study on the tsunamis that have reached the Mexican Pacific coast in order to evaluate probabilities of exceedance of the maximum wave height during tsunamis. Nakamura (1986) estimated the exceedance probability of tsunami occurrence in the eastern Pacific as an extended Poisson process. Geist (2002) studied the local tsunami wave field under the effect of stochastic source model by way of different slip distribution patterns. Omar et al. (2012) studied the tsunami generation and propagation by a unilateral spreading of a stochastic source model driven by a Gaussian white noise. Ramadan et al. (2014) investigated the tsunami generation and propagation caused by stochastic submarine landslides and slumps spreading in two orthogonal directions. Allam et al. (2014) investigated the tsunami generation and propagation caused by stochastic seismic fault driven by additive two Gaussian white noises in the x- and y-directions. They derived and analyzed the mean and variance of the random tsunami waves as a function of the propagated uplift length, noise intensities, and the average depth of the ocean along the generation and propagation path. Omar et al. (2014) illustrated the tsunami