Resonant Generation of Tsunami Waves by Submarine Landslides in Fjords

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ABSTRACT

Resonant generation of tsunami waves by submarine landslides in fjords is studied analytically within shallow-water theory. It is assumed that the landslide moves with a constant velocity in an inclined fjord and passes through the resonance. Three different types of fjord shape are considered: U-shaped, V-shaped and a fjord of rectangular cross-section. Dynamics of landslide generated waves in the three fjord types is investigated and compared. It is shown that waves of the largest amplitude are generated in a V-shaped fjord, while they remain hazardous longer in a fjord of a rectangular cross-section. Wave amplitude changes non-monotonically in time and space. Characteristics of resonant zone are studied in details.

KEY WORDS: tsunami, landslides, U-shaped bays, shallow water theory, resonant effects.

INTRODUCTION

The landslide motion is now recognized as an important source of tsunami wave generation. It is responsible for about 10% of all tsunami waves (Gusiakov, 2009). For example, an underwater landslide of 17 July 1998 caused a 15-meter tsunami which took more than 2200 lives in Papua New Guinea (McSaveney et al., 2000; Synolakis et al., 2001). It should also be noted that the largest world-known tsunami event of 9 July 1958 in the Lituya Bay, Alaska with 524-meter runup was also caused by the landslide (Fritz et al., 2009).

The number of analytical methods for analysis of tsunami wave generation by submarine landslides is limited even for the cases when the landslide moves with a constant speed and conserves its volume. 1D wave field generated by landslide moving with a constant speed in a basin of constant depth is computed in (Pelinovsky, 2003; Tinti and Bortolucci, 2000; Tinti et al., 2001; Okal and Synolakis, 2003). The 2D and 3D motion of a constant-speed landslide is studied analytically for shallow-water approximation in the framework of the potential theory in (Novikova and Ostrovsky, 1978; Pelinovsky and Poplavsky, 1997; Ward, 2001; Di Risio and Sammarco, 2008; Sammarco and Renzi, 2008). The landslide tsunami generation along a sloping beach in 1D and 2D cases is discussed in (Liu et al., 2003; Sammarco and Renzi, 2008).

In fjords and narrow bays landslide induced tsunamis also lead to the significant damage. For aerial and submarine landslides moving along the main fjord axis the effects of the wave spreading can be neglected and tsunami wave propagation can be studied in the framework of 1D shallow-water theory. Here we study generation of tsunami waves by landslides of constant shape moving with a constant speed along a U-shaped fjord of variable depth and focus on possible amplification of tsunami waves by resonant effects. It is natural that at some moment during landslide motion along the bed slope the speed of the landslide can become equal to the speed of long waves, which should lead to the resonant tsunami amplification. This passage through the resonance is studied here for three different fjord types: V-shaped, U-shaped and of rectangular cross-section. Various values of initial Froude number are considered, so the resonance may occur at different stages of the tsunami wave evolution.

MATHEMATICAL MODEL

Basic equations describing tsunami generation and propagation are shallow water equations. We will consider linearly inclined fjords opened to the sea with different cross-section described by the power law $z \sim y^m$, where $y$-axis is directed across the bay. Wave dynamics and runup in U-shaped bays has been studied in (Didenkulova and Pelinovsky, 2011) within 1D shallow water equations. In this case the linearized shallow water equations for landslide tsunami generation can be written in the following form:

$$\frac{\partial^2 \eta}{\partial t^2} = g \frac{\partial h}{\partial x} + gh \frac{\partial^2 \eta}{\partial x^2} - \frac{\partial z}{\partial x}, \quad \frac{q}{m} = \frac{m+1}{m}, \quad q = \frac{m+1}{m},$$

where $\eta$ is the wave elevation, $\eta$ is the volume of the landslide, $h$ is the depth of the water, $g$ is the acceleration due to gravity, and $z$ is the elevation of the bottom. The parameter $m$ is the exponent of the power law describing the depth of the fjord $z \sim y^m$.