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A two-layer granular landslide model for tsunami wave generation: Theory and computation

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ABSTRACT

We develop and test a new two-layer model for granular landslide motion and tsunami wave generation. The landslide is described as a saturated granular flow, accounting for intergranular stresses governed by Coulomb friction. Tsunami wave generation is simulated by the three-dimensional non-hydrostatic wave model NHWAVE, which is capable of capturing wave dispersion efficiently using a small number of discretized vertical levels. Depth-averaged governing equations for the granular landslide are derived in a slope-oriented coordinate system, taking into account the dynamic interaction between the lower-layer granular landslide and upper-layer water motion. The model is tested against an analytical solution for granular dam-break flow and 2D and 3D laboratory experiments on impulsive wave generation by subaerial granular landslides. Model results illustrate a complex interplay between the granular landslide and tsunami waves, and they reasonably predict not only the tsunami wave generation but also the granular landslide motion from initiation to deposition.

1. Introduction

Tsunamis can be generated by subaerial or submarine landslides in reservoirs, lakes, fjords, bays and oceans. Examples include tsunamis generated by subaerial landslides in Lituya Bay, Alaska in 1958 (Fritz et al., 2001, 2009; Weiss et al., 2009), Puerto Aysen, Chile in 2007 (Naranjo et al., 2009; Sepulveda and Serey, 2009), Tafjord, Norway in 1934 (Braathen et al., 2004; Harbitz et al., 1993), and by submarine landslides at Grand Banks, Newfoundland in 1929 (Fine et al., 2005), Papua New Guinea in 1998 (Synolakis et al., 2002; Tappin et al., 2001, 2002), Haiti in 2010 (Fritz et al., 2012) and Japan in 2011 (Tappin et al., 2014). The potential role played by large scale SMF's in tsunami climatology has been reviewed recently by Masson et al. (2006) and Harbitz et al. (2014). Compared to seismogenic tsunamis, landslide or submarine mass failure (SMF) tsunamis are normally characterized by relatively shorter wave lengths and stronger wave dispersion, and potentially may generate large wave amplitudes locally and high run-up along adjacent coastlines. Due to a complex interplay between the landslide and tsunami waves, accurate simulation of landslide motion as well as tsunami generation is a challenging task.

The development of models for landslide tsunami generation centers around two main focuses: choice of a physical model for landslide rheology, and choice of a level of approximation of the flow field and pressure field in the hydrodynamic model used to simulate the generation and propagation of resulting waves. The developer must also decide on the details of interaction between kinematics and dynamics of the landslide material and overlying water column. The hydrodynamics of landslide-induced tsunamis has been extensively studied using numerical models based on different levels of simplification. Examples, in increasing order of completeness in the underlying theory, include shallow water equations (Fine et al., 2005; Harbitz, 1992; Jiang and Leblond, 1992, 1993), Boussinesq equations (Fuhrman and Madsen, 2009; Lynett and Liu, 2003; Watts et al., 2003; Zhou and Teng, 2010), 3D non-hydrostatic models (Ma et al., 2013; 2012), fully nonlinear potential flow theory (Grilli et al., 2002; Grilli and Watts, 1999, 2005) and Navier–Stokes equations (Abadie et al., 2010; Ataie-Ashtiani and Shobeyri, 2008; Heinrich, 1992; Horrillo et al., 2013; Liu et al., 2005; Lovholt et al., 2008; Mader, 2004; Montagna et al., 2011; Quecedo et al., 2004; Yuk et al., 2006). Each of these approaches can provide useful information in suitable parameter ranges; however, full Navier–Stokes solvers are still numerically demanding. In the development below, we concentrate on further extensions to the non-hydrostatic modeling approach.

Most models of landslide or SMF tsunami generation consider the landslides as rigid blocks with prescribed landslide shape and behavior. Landslide motion is specified based on laboratory

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measurements or on an equation of motion based on the balance of forces acting on the sliding mass, including weight, buoyancy, friction, hydrodynamic drag and inertia forces (Enet and Grilli, 2007). This approach has been widely employed for estimating tsunami hazard (Grilli et al., 2015; Tappin et al., 2014). As discussed by Abadie et al., (2012, 2010), however, this methodology has severe limitations in application to real cases, where landslides may be deformable and have time-varying 3D geometry.

Another approach to simulating landslide-induced tsunamis is to consider both the landslide and the water as two different fluids. This approach allows the landslide to deform, and is capable of describing the two-way coupling between the landslide and surrounding water. Tremendous effort has been devoted to developing this type of model. For example, Jiang and Leblond (1992, 1993) developed a two-layer model in which the lower-layer landslide was treated as either a laminar incompressible viscous fluid or a Bingham visco-plastic fluid, with the deformable underwater landslide and associated tsunami waves dynamically coupled. This approach has been further developed by Fine et al. (2005) and Skvortsov and Bornhold (2007). Abadie et al. (2012) employed a 3D multi-fluid Navier–Stokes model THETIS to simulate tsunami waves generated by the potential collapse of the west flank of the Cumbre Vieja Volcano (CVV), Canary Islands, Spain. The landslide and water were considered as two immiscible fluids with different densities. The free surface as well as the landslide-water interface were captured using a volume of fluid (VOF) algorithm. A similar approach is employed by Horrillo et al. (2013). Assier-Rzadkiewicz et al. (1997) modeled the underwater landslide as sediment-water mixture, with rheology varying from linear fluid viscosity at low sediment concentration to Bingham visco-plastic rheology at high concentration. The model was applied to simulate a laboratory landslide and could reproduce the water waves generated by the landslide with reasonable accuracy. Heinrich et al. (1998) implemented the same approach in a 3D Navier–Stokes solver, and applied the model to study water waves generated by a potential debris avalanche in Montserrat, Lesser Antilles. This approach was also adopted and implemented by Ma et al. (2013) in the non-hydrostatic wave model NHWAVE, without inclusion of the Bingham visco-plastic behavior at high concentration. Their model was not able to capture landslide deposition.

The two-fluid models described above can be reasonably successful in predicting tsunami wave generation. However, they often fail to correctly simulate landslide motion from initiation to deposition. Underwater landslides are gravity-driven flows of dense grain-fluid mixture. Fluid or visco-plastic continuum rheologies typically are not sufficient to explain details of landslide behavior, from initiation of motion from a quasi-equilibrium initial static state, through dynamics of the evolving slide, to final arrest of motion and landslide deposition (Iverson and George, 2014). It is necessary to consider the intergranular stresses and pore fluid pressure in the landslide model. Initial steps towards development of granular flow-based models for landslide behavior have usually been based on depth-integrated models pioneered by Iverson (1997); Savage and Hutter (1989) and others. These models were initially developed for application to shallow subaerial debris flows. Pioneering work to implement these formulations as models for submarine landslides were carried out by Kelfoun et al. (2010) and Giachetti et al. (2011), among others. In their model, the landslide was simulated by a depth-averaged granular flow model, in which the intergranular stresses were modeled by Coulomb friction. Tsunami wave generation was simulated using a shallow-water equation model based on the assumption that the landslide-induced tsunamis are long waves, as in the previous two-fluid models of Jiang and Leblond (1992, 1993), Fine et al. (2005) and Skvortsov and Bornhold (2007). The model was used to examine the consistency of run-up predictions with patterns of sediment deposition which are hypothesized to be the result of tsunami inundation. Their model, however, contains several critical limitations. The Coulomb frictional retarding stress was assumed to be constant over the whole domain. Wave dispersion was not captured due to the shallow-water assumption.

In this paper, we establish a numerical model for the generation and propagation of tsunami waves by granular landslides. A discrete two-layer landslide-induced tsunami generation model is developed and validated using analytical solutions and laboratory measurements. The landslide is described as a granular flow accounting for intergranular stresses governed by Coulomb friction, following the theoretical framework described by Savage and Hutter (1989) and Iverson (1997). Tsunami wave generation is simulated using the 3D non-hydrostatic wave model NHWAVE, which is fully nonlinear and is capable of efficiently capturing wave dispersion using 3–5 discretized vertical levels and simulating wave breaking and associated wave energy dissipation by a shock-capturing scheme. The governing equations for the granular landslide and tsunami waves are coupled dynamically and solved using a Godunov-type finite volume TVD scheme.

The remainder of the paper is organized as follows. Section 2 presents the theoretical basis for the two-layer granular landslide and tsunami wave model. The formulation for the lower-layer granular landslide is derived. The interactions between the landslide and surrounding water as well as the numerical schemes employed to solve the granular flow equations are also discussed. The granular landslide model is first validated in Section 3 using an analytical solution for dam-break flow developed by Mangeney et al. (2000). The model is then applied to study waves generated by a 2D granular landslide in Section 4 and a 3D granular landslide in Section 5. Conclusions and avenues of future model improvement are presented in Section 6.

2. Two-layer Granular landslide and tsunami model

In this section, we derive the formulations for the two-layer granular landslide and tsunami model. In this model, the landslide motion and tsunami wave generation are simulated by separate model components. The lower-layer landslide movement is simulated by a granular flow model, while the upper-layer tsunami wave motion is simulated by the three-dimensional Non-Hydrostatic WAVE model NHWAVE (Ma et al., 2012). The lower layer landslide and upper layer water interact at each time step, maintaining a fully-coupled kinematic and dynamic connection between the layers.

2.1. Lower-layer granular landslide

In this study, we simulate the landslide as a saturated granular debris flow. The details of the derivation follow from Iverson and Denlinger (2001) unless otherwise noted. Following Iverson (1997) and Iverson and Denlinger (2001), we adopt a slope-oriented coordinate system as shown in Fig. 1, with x' oriented down-slope, y' along slope and z' oriented upwards and perpendicular to the slope. Mass and momentum conservation equations from continuum mixture theory are given by

$$\nabla' \cdot \mathbf{v} = 0 \tag{1}$$

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla'\mathbf{v}\right) = -\nabla'\cdot\mathbf{T} + \rho\mathbf{g} \tag{2}$$

Here, $\rho = \rho_s\gamma_s + \rho_f\gamma_f$ is mixture density, ρ_s and ρ_f are the densities of solid and fluid, respectively, and γ_s and γ_f are volume fractions of solid and fluid, respectively. $\mathbf{v} = (v_{x'}, v_{y'}, v_{z'})$ is the mixture velocity, given by $\mathbf{v} = (\rho_s\gamma_s\mathbf{v}_s + \rho_f\gamma_f\mathbf{v}_f)/\rho$, with $\mathbf{v}_s$ and $\mathbf{v}_f$ being the velocities for solid and fluid phases. $\mathbf{T} = \mathbf{T}_s + \mathbf{T}_f$ is the total stress tensor for the mixture and consists of contributions from the fluid and solid