The 2012 World Congress on
Advances in Civil, Environmental, and Materials Research (ACEM' 12)
Seoul, Korea, August 26-30, 2012

Numerical Modeling of Landslide Generated Impulse Waves

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Abstract

A huge water surface displacement can be generated by soil/structure failure in reservoir, snow avalanches into lakes, lavas or rock falls into the oceans or bays. A mesh-free particle method for such a multiphase soild-water system is developed. The model of this study is based on the Moving Particle Semi-Implicit (MPS) method (Koshiazuka and Oka, 1996). Sliding sand into water forms a two-phase system where the sand phase is treated as a non-Newtonian fluid. To validate the MPS multiphase model, the model was applied to the rigid box sliding down into the water first. The fluid motion of the numerical results is reasonably simulated when compare to the experimental results. The results show that the rheological effects on the water surface displacement have also been modeled well.

1. Introduction

A huge water surface displacement (tsunami) can be generated by soil/structure falls into reservoirs, lakes, ocean or bays. Tsunamis can be also generated by earthquakes, volcanic eruptions, or any under water mass movements. Massive waves generated by landslides in 1998 Papa New Guinea took approximately 2000 life (Bradet et al. 2003; Lynett et al. 2003). Waves generated by water volume displacement have potential to cause environmental disasters because of the massive possible run-up. As an example, a subarial rockslide was created by an Mw 8.3 earthquake in Lituy Bay, Alaska, which produced a maximum run-up of 524 m (Fritz et al. 2001). The modeling of any slide motion into the water and the generated wave can provide vital information for appropriate structural design of buildings, bridges, railways, roads, and any other infrastructure in coastal regions.

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Some experiments have been conducted on subarial or submerged landslide interactions with water and the associated wave propagation (Fritz 2002; Grilli and Watts 2005; Enet and Grilli 2007; Heller 2010). A number of Eulerian mesh-based numerical methods were developed to simulate the free surface problems including finite element method (Zhu and Randolph 2010), finite volume method (Serrano-Pachecod et al. 2009), Volume of Fluid method (Heinrich 1992), and Marker and Cell (Harlow 1964) method. However, special treatment is required to equations in numerical methods when free surface is encountered (Liu et al., 2005). As a result, a mesh free numerical model is more appropriated to free surface or interfacial problems such as waves generated by landslides in water.

The Moving Particle Semi-Implicit (MPS) method introduced by Koshiazuki and Oka (1996) is a weight averaging based mesh free particle method. Several free surface problems, such as braking waves (Koshizuka et al. 1998), flow over spillways (Shakibaeinia and Jin 2009), and hydraulic jump formation (Shakibaeinia and Jin 2010) were successfully simulated using the MPS method.

The present study aims to develop a mesh-free Lagrangian MPS model to reproduce the behaviour of a subarial landslide tsunami wave. The developed model is validated and evaluated using experimental measurements (Heller 2007) on a 2-D landslide problem. The numerical method of this study is presented first. The numerical model will be used and compared with experimental data.

2. The Model Methodology

Fluid flow governed by a continuity and momentum equation is based on a Lagrangian method can be expressed as:

$$\frac{D\rho}{Dt} + \rho(\nabla \cdot \mathbf{u}) = 0 \tag{1}$$

$$\rho \frac{D\mathbf{u}}{Dt} = -\nabla p + \nabla(\mu \nabla \cdot \mathbf{u}) + \mathbf{F} \tag{2}$$

where ρ, **u**, p, μ and **F** represent density, flow velocity, pressure, dynamic viscosity, and body forces, respectively. In the MPS method (Kashizuka and Oka 1996), position, velocity, and pressure are calculated for each particle in a mesh-free frame. There is no convection term in the momentum equation, and the movement of particles is simply calculated by D**r**/D*t*=**u**, with **r** being the position vector. The time integration is based on a fractional step method (Shakibaeinia and Jin 2010) where velocity for the target particle, *i*, is given as:

$$u_i^{k+1} = u_i^* + u_i' \tag{3}$$

in which, u^{k+1}_i is velocity at the new time step, (k+1); u'_i is the velocity correction term; and u^*_i is the velocity at the prediction step. The velocity prediction is given by:

$$u_i^* = u_i^k + \frac{\Delta t}{\rho_i}\left(F_i + \mu_{ij}\nabla^2 u_i^k\right) \quad (4)$$

$$r_i^* = u_i^* \Delta t \quad (5)$$

$$u = -\frac{\Delta t}{\rho_i}\nabla p_i^{k+1} \quad (6)$$

where Δt is the time step size and $\nabla^2 u_i$ can be approximated by using MPS technique as:

$$\nabla^2 u_i = \frac{2d}{\lambda n^o}\sum_{j \neq i}\left(\left(u_j - u_i\right)W\left(r_{ij}, r_e\right)\right) \quad (7)$$

in which n^o is the average value of initial particle number density (n).

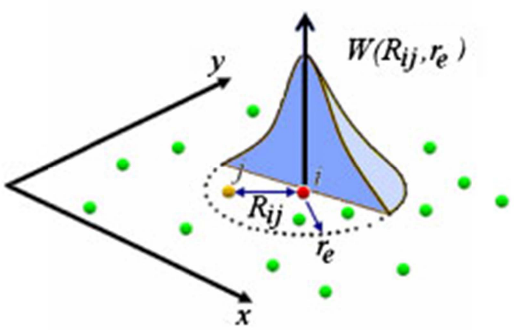

Fig. 1. Particle interaction conceptual model. (Shakibaeinia and Jin 2010)

The pressure calculation is based on the weakly compressible MPS (Shakibaeinia and Jin 2010):

$$p_i^{n+1} = \frac{\rho_i}{\gamma}c_o^2\left(\left(\frac{n_i^*}{n_o}\right)^\gamma - 1\right) \quad (8)$$

in which c_0 is the numerical sound speed and γ = 7 is considered to be a typical value in this simulation (Shakibaeinia and Jin 2010).

3. Subarial rigid box sliding down an incline into water

In this study, the experiment by Heller (2007) was selected for simulation. As shown in Fig. 2, a rigid box slide down along the wall and impacted the body water. The parameters used in the numerical model as shown in Table 1. The granular slide down with a box velocity of 3.25m/s (Fig. 2). To simulate the rigid body problem, the particle size is selected as 0.005m to obtain appropriate flow characteristics. Larger-sized particles will result in a less accurate wave profile. By applying the smaller particle size, more accurate water body deformation will result; however, the computational time will increase impractically. Based on the geometry of the problem and particle size, the total particle number is 79,240 including 1,641 wall (boundary) particles and 1,140 granular particles.

Table 1 Parameters of Granular Materials

still water depth	h	0.450 m	bulk slide porosity	n	40%
channel width	b	0.500m	grain diameter	d_g	5 mm
bulk slide density	ρ_s	623 kg/m^3	internal friction angle	ϕ'	27°
grain density	ρ_g	1038 (kg/m^3)	dynamic bed friction angle	δ	20°
relative grain diameter	D_g	0.011	relative slide mass	M	0.21

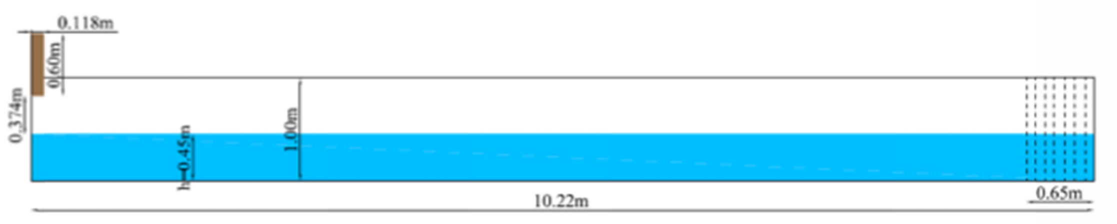

Fig. 2. Sketch of the experimental configuration of sliding box into the water

4. Discussion

Fig. 3 shows the fluid motion simulated by MPS method at the same sequence as the experimental results. The wave breaking of the MPS simulation at T_r= 0.93, 2.18, 3.42, and 4.67 s are similar to the experiment in the same sequence. The granular shapes are not modeled well as expected. The wave generated due to falling granular is illustrated well by the MPS simulation as compared to the experimental snapshot. The figure demonstrates that MPS simulates well on waves.

The water surface displacements of the experiment have been extracted from the experimental data with the same water depth (Heller 2007). The wave height of the numerical simulation results and experimental results have been plotted at six stations along the wave tank at different time steps. The wave height measurement stations are located at X=2.92, 5.72, 8.52, 11.32, 14.12, and 16.92. Fig. 4 illustrates the water displacement surface of the experimental and numerical results. As illustrated in Fig. 4, the wave breaking and water body motion of the MPS simulation for the rigid box slide generated a reasonable shape compared to the experiment.

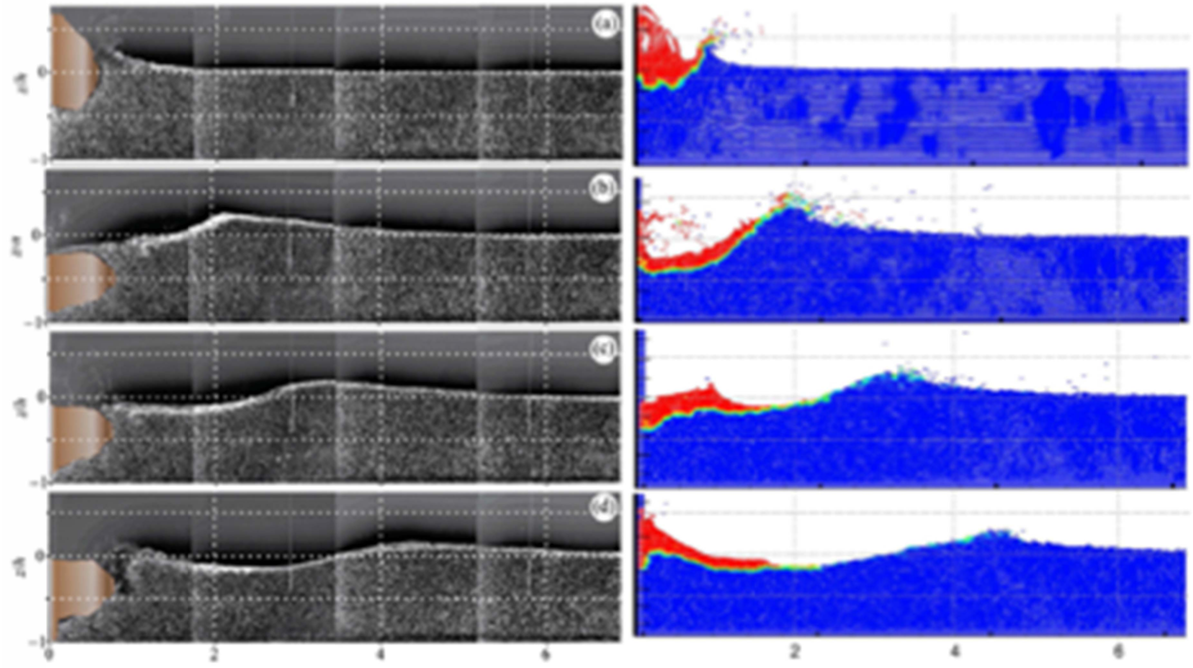

Fig. 3. Snapshot of the particle configuration simulated by MPS model compared with the experimental snapshot for *Tr* =(a) 0.93, (b) 2.18, (c) 3.42, and (d) 4.67 after slide impact and for the same sequences.

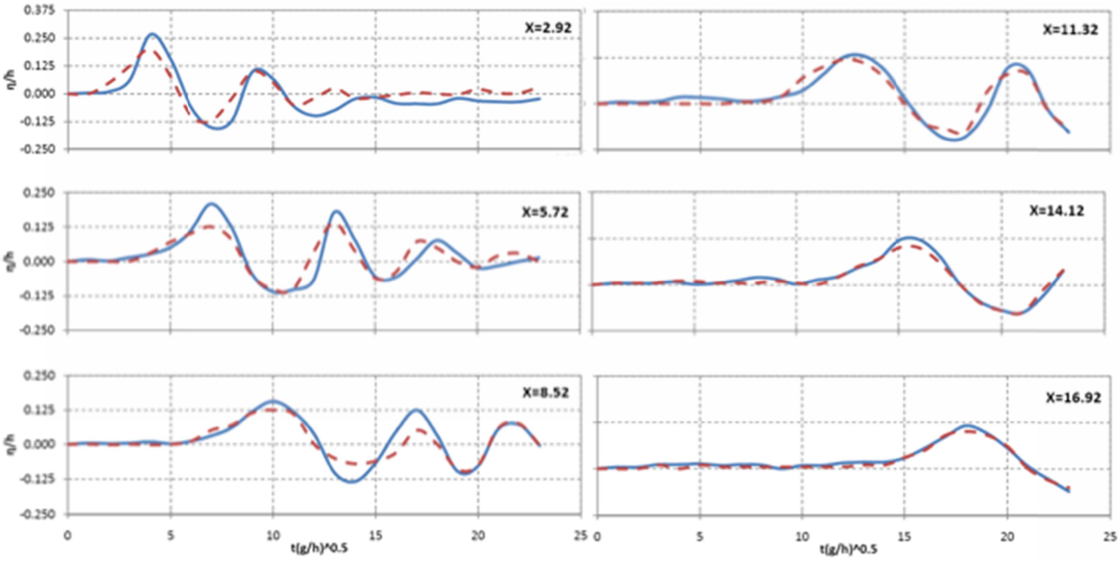

Fig. 4. Wave profile (water surface displacement/depth) comparison between MPS simulation and experimental data

5. Conclusion

In conclusion, recent research has been aimed at forecasting destructive coastal occurrences such as tsunamis. Landslides are a considerable cause of high waves and run-up at shorelines. In this research, Moving Particle Semi–Implicit method (Shakibaeinia and Jin 2010) was applied to simulate a subarial rigid box sliding down into water body along a defined slope. The experimental data from Heller (2007) was used for this simulation. The water body motions and wave breakdowns of the MPS method with reasonable accuracy when compared to the experimental results. Consequently, the results verify that the MPS numerical model is appropriately capable of simulating a subarial landslide into water. The present study can be developed to predict the results of non-rigid subarial landslides such as soil failures or snow avalanches in future research.

Acknowledgments

This research was supported by the Natural Science and Engineering Research Council of Canada.

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