Advances in Water Resources 92 (2016) 130–141

Contents lists available at ScienceDirect

Advances in Water Resources

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

Numerical simulation of landslide-generated waves using a soil–water coupling smoothed particle hydrodynamics model

Chuanqi Shi[a], Yi An[a], Qiang Wu[a], Qingquan Liu[a,*], Zhixian Cao[b]

[a] Key Laboratory for Mechanics in Fluid Solid Coupling Systems, Institute of mechanics, Chinese Academy of Sciences, Beijing, 100190, China
[b] State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China

A R T I C L E I N F O

Article history:
Received 30 November 2015
Revised 2 April 2016
Accepted 2 April 2016
Available online 7 April 2016

Keywords:
Landslide induced impulse waves
Smoothed particle hydrodynamics
Soil–water coupling
Elasto–plastic model
Dilatancy angle

A B S T R A C T

We simulate the generation of a landslide-induced impulse wave with a newly-developed soil–water coupling model in the smoothed particle hydrodynamics (SPH) framework. The model includes an elasto–plastic constitutive model for soil, a Navier–Stokes equation based model for water, and a bilateral coupling model at the interface. The model is tested with simulated waves induced by a slow and a fast landslide. Good agreement is obtained between simulation results and experimental data. The generated wave and the deformation of the landslide body can both be resolved satisfactorily. All parameters in our model have their physical meaning in soil mechanics and can be obtained from conventional soil mechanics experiments directly. The influence of the dilatancy angle of soil shows that the non-associated flow rule must be selected, and the value of the dilatancy angle should not be chosen arbitrarily, if it is not determined with relative experiments.

1. Introduction

Subaerial landslides may generate large impulse waves in lakes or reservoirs, which have a high potential to cause direct damage to the reservoir buildings and residents, and even result in the loss of life. The accurate estimation of the landslide-induced wave hazard is still an open problem because of its complexity. Numerical simulation of this process often faces the following three difficulties, which are essential in this problem: (1) accurate simulation of the large deformation of the slide and the free surface; (2) implementing the bilateral coupling of the slide and the water; and (3) dealing with deformation and movement of the slide and the water in one numerical framework.

Focusing on the last two problems, many numerical studies that ignore the landslide deformation have been developed to simulate landslide-generated waves. In simulations by Heinrich (1992), Monaghan et al. (2003), Ataie-Ashtiani and Shobeyri (2008), Xu (2012), Viroulet et al. (2013) and Serrano-Pacheco et al. (2009) (Table 1), landslides are considered as rigid blocks while the interaction between water and the slide is generally well proposed. Different numerical methods, including smoothed particle hydrodynamics (SPH), coupled Euler–Lagrange, and the finite volume method with a volume of fraction two-phase model, have been used for the simulations and different parameters have also been analyzed. The assumption of non-deformable landslide, which is reasonable for rock-dominated landslides, is very helpful in understanding the influence of the essential parameters, such as the still water depth, volume of the slide, and impact velocity.

However, most landslides in nature consist of soil or other deformable granular material, which will have a large deformation because of the interaction with water or boundaries, or both. In this situation, the rigid block model will not be valid. Fritz et al. (2003) found in experiments that the granular slide will deform notably and thus result in a wave different from that of the rigid body. In fact, two different main influences can be summarized by comparing experimental observations. First, the rigid block will either be stopped (Heinrich, 1992) or continue moving along with a smoothly curved track (Walder et al., 2003) when it reaches the bottom of the channel, whereas the granular material landslide will generally deposit in the corner. Second, the granular slide thickness and front angle will continually change during the penetration (Viroulet et al., 2013; Fritz et al., 2001; Fritz et al., 2003) because of the interaction with water, whereas the rigid block will not experience this complex phenomenon. The relative slide thickness will heavily influence wave characteristics, such as the maximum wave amplitude, based on the study of Fritz et al. (2004) on granular slide and Heller and Spinneken (2013) on block slide. Therefore, the deformation of the landslide must be considered in the simulation of landslide-generated waves.

Numerical studies that have considered the effect of slide deformation in landslides impacting water have been carried out

* Corresponding author: Tel.: +861082544202; fax: +860162561284.
E-mail address: qqliu@imech.ac.cn (Q. Liu).

http://dx.doi.org/10.1016/j.advwatres.2016.04.002
0309-1708/

Table 1
Rigid block model for a landslide.

Reference	Simulation method	Impact angle	Landslide shape	Landslide initial position
Heinrich (1992)	VOF	45°	Triangle	SM
Monaghan et al. (2003)	SPH	10°	Rectangle	SA
Ataie-Ashtiani and Shobeyri (2008)	ISPH	45°, 90°	Triangle, Rectangle	SM
Xu (2012)	CEL	45°	Triangle	SM
Viroulet et al. (2013)	SPH, FVM	35°	Trapezoid	SM, PSM
Serrano-Pacheco et al. (2009)	FVM	30.7°	Polygon	SA

SM: submerged; SA: subaerial; PSM: partially submerged.

Table 2
Non-Newtonian fluid model for a landslide.

Reference	Soil model	Simulation method	Impact angle	Landslide initial position	μ_B $(Pa \cdot s)$	τ_B (Pa)
Quecedo et al. (2004)	Generalized viscoplastic fluid model	CBG	45°	SA	48	1000
Cremonesi et al. (2011)	Changed BM	PFEM	45°	SA	75	35
Rzadkiewicz et al. (1997)	BM	VOF	45°	SM	0	200
					0	1000
Capone et al. (2010)	Changed BM	SPH	45°	SM	1	1000
Ataie-Ashtiani and Shobeyri (2008)	BM and Cross model	ISPH	45°	SM	0.1	250
					0.15	750
Mariotti and Heinrich (1999)	BM	VOF	45°	SM	0	Update

SM: submerged; SA: subaerial; PSM: partially submerged; BM: Bingham model.

recently. Using rheological theory, a non-Newtonian fluid model was used to describe the deformation and movement of landslides by Quecedo et al. (2004), Cremonesi et al. (2011), Rzadkiewicz et al. (1997), Capone et al. (2010), Ataie-Ashtiani and Shobeyri (2008), Mariotti and Heinrich (1999) (Table 2), and Manenti et al. (2015). Simple governing equations and fluid-fluid interaction for the coupling process in this model will reduce the simulated difficulties. The non-Newtonian fluid model can describe some features during the slope deformation; however, it generally overestimates the deformation. In fact, the landslides are mainly composed of granular material and are better described as an elasto–plastic soil model. In this paper, we introduce an elasto–plastic soil model for the slide and the bilateral interaction between soil and water in the simulation to overcome the above shortcomings in the SPH method.

SPH is a mesh-free method in which continuum or dispersed material is discretized into a set of disordered particles (Monaghan, 2005). These particles will carry field variables, such as mass, density, and stress tensor, and move with the material velocity. No fixed connection between particles or meshes exists, avoiding the inaccuracy from the distorted mesh when dealing with a large deformation and post failure movement of the landslides (Huang et al., 2009). The SPH method has already been used for simulating waves generated by landslides by simplifying the landslide in to a rigid body (Shi et al., 2015; Vacondio et al., 2013) or a non-Newtonian fluid model (Ataie-Ashtiani and Shobeyri, 2008; Capone et al., 2010). Because of its Lagrangian and mesh free characteristics, the SPH method avoids the issue of the simplified treatment of materials' interface in the Euler mesh. As a result, this has the advantage of dealing with the complicated soil–water coupling problem.

In this paper, a novel soil–water coupling model in SPH framework is introduced to simulate the landslide-induced impulse wave problem. The elasto–plastic soil constitutive model is employed to describe the large deformation and post-failure movement of landslides, the traditional weak compressible SPH method is used to simulate the free surface flow of water, and a bilateral coupling of soil and water is designed to consider the interaction between flow and slide. This method can therefore fulfill the three conditions mentioned above to accurately simulate the landslide-induced impulse wave problem. Two experiments (waves generated by a slow and a fast landslide) have been simulated to test the validity of the model and good agreement with experiments is obtained. We present a comparison between our model and a non-Newtonian fluid model to show the model' characteristics in simulating the landslide generated waves. Finally, the influence of the dilatancy angle of soil, which has been ignored in previous studies, is presented and discussed.

2. Numerical model

2.1. Model for water

The governing equations for fluid flow are the Naiver–Stokes equations, in which the conservation of mass and momentum can be written in SPH Lagrangian form (Liu and Liu, 2004) as:

$$\frac{D\rho_i}{D_t} = \sum_{j=1}^{N} m_j (v_i - v_j) \cdot \nabla_i W_{ij} \tag{1}$$

$$\frac{Dv_i{}^\alpha}{Dt} = -\sum_{j=1}^{N} m_j \left(\frac{P_i}{\rho_i{}^2} + \frac{P_j}{\rho_j{}^2} + \Pi_{ij} \right) \cdot \nabla_i W_{ij} + g^\alpha \tag{2}$$

where α is the superscript used to denote the coordinate directions, N represents the total particles in the support domain, and m and ρ are the mass and the density of particles, respectively. v^α is the velocity vector, g^α is the gravitational acceleration, and P is the pressure. W is the kernel function, which takes the form of the cubic spline function in this study (Liu and Liu, 2004):

$$W(r,h) = \alpha_D \begin{cases} 1 - \frac{3}{2}q^2 + \frac{3}{4}q^3 & 0 \le q \le 1 \\ \frac{1}{4}(2-q)^3 & 1 \le q \le 2 \\ 0 & q \ge 2 \end{cases} \tag{3}$$

where $q = r / h$, r is the distance between particles i and j, h is the smoothing length, and α_D is $10/7\pi h^2$ in two dimensions.

In the SPH simulation, to represent viscosity and to prevent the unphysical penetration of particles, artificial viscosity Π_{ij} has been introduced to the momentum equation. Viroulet et al. (2013) tested three viscosity models for landslide induced wave problem, which are the artificial viscosity, the laminar viscosity, and a sub-particle scale (SPS) approach. In their study, good agreement with experiments is observed for all three models, especially the artificial viscosity model. In our model, one of the most widely used types of