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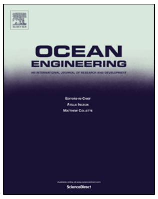

Laboratory and numerical study of the flow field of subaqueous block sliding on a slope

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ABSTRACT

Landslide induced waves have been the focus of attention in recent years. The majority of the research has mainly focused on wave generation but few investigations on the flow field. This paper examined the wave propagation and the corresponding flow fields in open channels caused by a wedge sliding along a slope to simulate a non-deformable landslide. A Weakly-Compressible Moving Particle Semi-Implicit (WC-MPS) method was used to simulate the impulse waves and velocity profiles. The MPS model was validated first with experimental data from the literature for water surfaces changes. To investigate the flow field, three releasing scenarios were considered; one under water, second was immediate beneath the water surface and the third, above the water surface. These three scenarios emulated a landslide on subaerial and in subaqueous conditions. The velocity measurement and water surface variation were collected using a Digital Particle Image Velocimetry (DPIV) system. The WC-MPS simulated results were compared with the experimental data for the velocity fields and water surface profiles. The results showed good agreement between the experimental data with the MPS model.

1. Introduction

Wave action caused by tsunami's have resulted in loss of life and extensive property damage (Schwaiger and Higman, 2007). Investigations of wave action has been completed in order to gain a better understanding of the flow dynamics and to improve prediction methodology. Previous studies included wave generation by wedge sliding on a slope (Heinrich, 1992; Watts, 1998; Fritz et al., 2004; Viroulet et al., 2013), sliding on deformable block (Ataie-Ashtiani and Nik-Khah, 2008; Heller et al., 2008; Heller and Hager, 2010), and dam break from saturated material along slopes (O'Donoghue et al., 2010; Kikkert et al., 2013). These investigations focused on the changes of the water surface and wave propagation. It also assessed the material of the sliding block, angle of the incline bed, slope of the sliding blocks, and the sliding speed, which can affect the accuracy of the prediction of the tsunami wave.

Mathematical studies have been developed to describe wave propagation, including empirical equation (Hungr et al., 2005), simplified analytical solutions (Didenkulova et al., 2010) and numerical modeling (Horrillo et al., 2013). Heller and Spinneken (2013) completed a series of physical model studies on impulse waves generated by mass movement along a slope and developed empirical equations to relate wave parameters with the front angle of the sliding block. Ataie-Ashtiani and Nik-Khah (2008) compared their laboratory results of impulsive waves caused by subaerial landslides to empirical equations. A wide range of effective parameters were considered in their experiments, including slide masses for rigid and deformable sliding object.

Recently, numerical studies have received attention through advances in computing software and hardware. Numerical simulation has been widely used and is an integral approach for solving engineering related problems in the past few decades. Because of the flexibility, efficiency and compatibility of numerical simulation, it has been applied in various engineering and science fields. These methods are capable of interpreting the natural phenomena and also offer an alternative way to study theories and experiments.

Earlier modeling studies on landslides using mesh-based methods like Finite Difference Method (FDM) was used to compute wave profile and velocity vector field for aerial landslide (Heinrich, 1992). The rheological model for the stress term was added to the fluid mechanics mixture model of Navier–Stokes equation for landslide model (Rzadkiewicz et al., 1997). Ataie-Ashtiani and Nik-Khah (2008) conducted serious laboratory tests on impulse waves caused by subaerial landslides.

A wide range of effective parameters were considered including slide masses for both rigid and deformable sliding object. Carvalho

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de and Carmo (2006) used volume-of-fluid method to study the wave generation and impact on downstream dams by different rigid block with different mass and size on two different slopes. Ghozlani et al. (2013) used control volume Finite Element Method (FEM) to study the dynamics of moving rigid body sliding into water body with un-prescribed speed of the plunging rigid body. Abadie et al. (2010) used a mixed Lagrangian and Eulerian multiphase model to include air–water–solid block movement. The solid block velocities and free surface deformations are accurately reproduced.

Due to the problem with mesh adaptability and connectivity, the application of the mesh-based methods for complicated phenomena has limitations if large deformations and fragmentations exist at the boundaries and interfaces (Liu and Liu, 2010), and the cells containing the free surface require complicated treatments (Koshizuka et al., 1998). In order to overcome the limitations of mesh-based methods, the mesh-free particle (Lagrangian) method becomes an attractive alternative for fluid flow simulation. Mesh free method represents the fluid domain by a set of particles moving in the Lagrangian system. The equation of the physical system is expressed by mass, momentum and energy conservation, and each particle possesses a set of field variables such as mass and momentum (Liu and Liu, 2003). Since no specific procedure for the capture or tracking of interfaces (e.g. free surface) is needed, and the position of fluid in this method is represented by particles, these methods are advantageous in simulating the boundary and interface.

Among all the particle methods, the Smooth Particle Hydrodynamics (SPH) method is one of the earliest and widely applied method (Gingold and Monaghan, 1977), which was originally developed to address astrophysical problems and later extended to solid and fluid mechanics applications (Dalrymple and Rogers, 2006).

Monaghan and Kos (1999) reproduced the block motion, wave height and features of complex free surface flow close to the solid with SPH model. SPH is also used to simulate non-linear waves due to landslide with the air to obtain an accurate numerical predication of propagation and generation of such waves (Qiu, 2008). Ataie-Ashtiani and Shobeyri (2008) used Incompressible-Smoothed Particle Hydrodynamics (ISPH) model to simulate the impulsive waves generated by landslides of a submerged mass sliding along an inclined plane. Viroulet et al. (2013) combined the SPH and finite volume method to predict subaerial landslide-generated tsunamis. Wang et al. (2016) used the Discontinuous Deformation Analysis (DDA) coupled with SPH method to study the solid–fluid interaction and validated the numerical results with experimental data taken from existing literature. Lin et al. (2015) reported simulation of surge waves induced by submarine and aerial landslides using a coupled ISPH model. The solid particles are treated as fluid by adding the rheology model in the meshless model to simulated landslide deformation and wave propagation (Capone et al., 2009).

The Moving Particle Semi-implicit (MPS) method (Koshizuka and Oka, 1996) is another particle method originally developed for fluid mechanic applications. In MPS, the spatial gradients and Laplacians are calculated by the weighted average of gradients or Laplacians of a physical quantity between the particle of interest and its neighboring particles. The contributions of each particle to a quantity are weighted by a kernel function according to their distance from the particle of interest. Huang and Zhu (2014) used Bingham constitutive model with the Mohr–Coulomb yield criterion to create a modified MPS flow model for the dynamic characteristics of flow slide. To decrease the computation time, the Poisson equation is replaced by the equation of state if the fluid is assumed to be weakly compressible. However, it required that the density variation of fluid is less than 1% of the reference density (Dalrymple and Rogers, 2006). Xie et al. (2014) studied the non-Newtonian dam break flow with the rheology model by using the Weakly Compressibility Moving Particle Semi-implicit method (WC-MPS). Recently, Fu and Jin (2015) studied both non-deformable and deformable landslides under submerged and non-submerged conditions with a multiphase WC-MPS model. Good agreement was obtained between the numerical and the experimental results. However, the flow field was not studied due to the lack of information.

Although many numerical studies have been conducted and verified with experimental data on the waves, there has been a lack of investigations on the flow fields. Specifically, the velocity distributions are not obtained due to the difficulty in measuring the unsteady flow field. In order to study the flow field around the sliding block, a Digital Particle Image Velocimetry (DPIV) system is used to capture the water surface profile and velocity distribution (Willert and Gharib, 1991; Chen et al., 2013) by using the PIVlab software. The numerical model of this study is based on the WC-MPS.

The aim of this study is to exam the capabilities of the MPS method in simulating the impulse wave caused by sliding structures, including the shape and the height of the wave, and the velocity field around the structures. The data collected in the experiments are used to compare with the MPS simulation.

2. Governing equations and MPS formulation

2.1. Governing equations

The motion of an incompressible viscous fluid flow is described by the continuity and momentum equations. In the Lagrangian system, the vector form of continuity equation reads

$$\frac{\mathrm{D}\rho}{\mathrm{D}t}+\rho(\nabla\bullet\mathbf{u})=0, \tag{1}$$

and the momentum equation is given by

$$\rho\frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t}=-\nabla p+\mu\nabla^2\mathbf{u}+\rho\mathbf{f}, \tag{2}$$

where $\mathbf{u}$ denotes the flow velocity, ρ is the density, p is the pressure, μ is the dynamic viscosity, and $\mathbf{f}$ represents the body forces (per unit volume). In the Lagrangian system, there is no convective acceleration term in the left hand side of the momentum equation. The movement of each particle is monitored by the position vector $\mathbf{r}$ which evolves with respect to $\mathrm{D}\mathbf{r}/\mathrm{D}t$.

2.2. MPS discretization

The spatial derivatives, gradient and divergence, in the governing equations are determined by the introduction of the kernel function W and the inter-relationship between particles, cf. Fig. 1. Letting $\mathbf{r}_i$ and $\mathbf{r}_j$ be the position vectors of particle i and j, respectively, the kernel function $W(r_{ij}, r_e)$ of particle i is given by (Shakibaeinia and Jin, 2010)

$$W(r_{ij}, r_e)=\begin{cases}\left(1-\dfrac{r_{ij}}{r_e}\right)^3 & 0\le\dfrac{r_{ij}}{r_e}<1\\ 0 & \dfrac{r_{ij}}{r_e}\ge 1\end{cases} \tag{3}$$

with $r_{ij}=\left|\mathbf{r}_j-\mathbf{r}_i\right|$ the distance between particles and r_e the radius of the interaction area around each particle. With the kernel function (3), the gradient for any physical quantity $\varnothing$ and divergence of vector $\mathbf{v}$ of particle i are determined by (Koshizuka et al., 1995),

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