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SPH modeling of dynamic impact of tsunami bore on bridge piers

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ABSTRACT

The Smoothed Particle Hydrodynamics (SPH) method is applied to investigate the impact of a tsunami bore on simplified bridge piers in this study. This work was motivated by observations of bridge damage during several recent tsunami events, and its aim is to further the understanding of the dynamic interaction between a tsunami bore and a bridge pier. This study is carried out by simulating a well-conducted physical experiment on a tsunami bore impingement on vertical columns with an SPH model, GPUSPH. The influences of bridge pier shape and orientation on free surface evolution and hydrodynamic loading are carefully examined. Furthermore, the unsteady flow field that is around and in the wake of the bridge pier is analyzed. Finally, GPUSPH is applied to explore the hydrodynamic force caused by the bridge pier blockage, the wave impact on structures, and the bed shear stress around a bridge pier due to a strong tsunami bore.

1. Introduction

A tsunami disaster is one of the most devastating natural hazards; it not only causes loss of life, but also destroys infrastructure such as buildings and bridges. There were more than 300 bridges washed away during the 2011 Great East Japan Tsunami (Kawashima et al., 2011), and a field investigation in Indonesia after the December 2004 Great Indian Ocean Tsunami also shows that the tsunami caused the collapse of a number of bridges (Saatcioglu et al., 2006). Several modes of bridge failure, e.g., uplift due to buoyancy, washing of superstructures (Kawashima et al., 2011), movement of the abutments and piers, and scouring of foundations (Kawashima and Buckle, 2013), have been observed. Clearly the hydrodynamic loading of tsunamis on bridges, and the dynamic interaction between tsunamis and bridge structures are important for bridge design.

A tsunami is generated by displacement of a substantial volume of water, which then propagates in the form of a long wave in the deep ocean. Once it approaches the shallow water, it undergoes shoaling and may eventually break into a series of bores (e.g., Bryant, 2014). The fluid velocity of tsunami bores during the 2011 Great East Japan Tsunami reached to 7 m/s (Kawashima et al., 2011; Kawashima and Buckle, 2013). Considering the high-speed flows run over irregular and complex topographies, strong tsunami bores are unsteady in nature.

Owing to the infrequent nature of a tsunami event, it is difficult to conduct experiments in the field, so most of studies on tsunamis interaction with coastal structures utilize physical experiments and numerical simulations. In the laboratory, a solitary wave is often used as a convenient approximation to a tsunami. To further the understanding of physical parameters involved in three-dimensional (3D) tsunami run-up, a series of large-scale physical experiments involving solitary wave run-up a vertical wall and a conical island were conducted at USACE Waterways Experiment Station during 1992 and 1995 (Briggs et al., 1995, 1996). Titov and Synolakis (1995) reported a solitary wave with wave height $A/h = 0.3$ (where A is the solitary wave height, and h is the still water depth) run-up a plane slope. Due to the simple geometry considered in aforementioned experiments, they have been widely used for numerical wave model validation (see, e.g., Weiss et al., 2010; Wei and Jia, 2014; Shadloo et al., 2015). In recent years, complicated laboratory topographies have also been used to study more challenging nearshore tsunami processes, such as tsunami attack of an island (Matsuyama and Tanaka, 2001), tsunami breaking over a 3D shallow reef (Swigler, 2009), and tsunami–debris interaction (Rueben et al., 2014). It is noted that most of these experiments only measure the free surface evolution and time-series of velocity at a

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fixed number of gages, and few of them consider the hydrodynamic loading of a tsunami on structures (e.g., hydrodynamic pressure and wave forces).

Ramsden and Raichlen (1990) generated a solitary wave and measured the impact force on a vertical wall. Arnason et al. (2009) measured the hydrodynamic force of a tsunami bore on different configurations (e.g., shape and orientation) of vertical columns; they also collected velocity profiles around/in the wake of structures. It should be pointed out that this set of experiments resembles well a real-life tsunami bore impact on bridge piers, since (1), the generated flow field is unsteady, as observed in real-life tsunami events (e.g., Kawashima et al., 2011); and (2), the ratio of the approaching bore height over the width of vertical columns is close to unity. In reality, this dimensional ratio of tsunami bores over bridge piers was similar to or even larger than unity when the bridge superstructures were washed away by tsunamis (e.g., Kawashima and Buckle, 2013).

In this study, the Smoothed Particle Hydrodynamics (SPH) method is applied to simulate the experiment of Arnason et al. (2009) including the dynamic impact of a tsunami bore on bridge piers. In the past decade, the mesh-free method of SPH has gained popularity for modeling free surface flows, and it has become an alternative to traditional mesh-based methods for modeling coastal waves. Owing to the Lagrangian nature of the SPH method, there is no need to deal with the free surface when it is applied to simulate free surface flows, especially when the surface tension is not important. This property makes it particularly attractive to modeling water waves, e.g., wave propagation over beaches (e.g., Dalrymple and Knio, 2000; Monaghan and Kos, 1999), wave–structure interaction (e.g., Dalrymple and Rogers, 2006; Gómez-Gesteira and Dalrymple, 2004), nearshore rip–current system (Farahani et al., 2013), and turbulent vortical structures due to broken solitary waves (Farahani and Dalrymple, 2014). Furthermore, the SPH method is able to compute the dynamic force on structures directly (see, e.g., Gómez-Gesteira and Dalrymple, 2004). In terms of modeling tsunamis, SPH models have been applied to simulate landslide-generated tsunami (Capone et al., 2010; Rogers and Dalrymple, 2008), and tsunami inundation and run-up (Shadloo et al., 2015; Weiss et al., 2010). Recently, St-Germain et al. (2014) conducted a physical experiment similar to that of Arnason et al. (2009) to measure the hydrodynamic force of a tsunami bore exerted on a square column, and further computed the hydrodynamic force by an SPH model. Although St-Germain et al. (2014) have shown an SPH model has great potential to investigate a tsunami bore impact on a square bridge pier, the coarse particle size that they used (compared with the size used in the current study) is not fine enough to present an accurate and quantitative free surface evolution.

In this work, a high-fidelity SPH model, GPUSPH, is applied to study a tsunami bore impact on bridge piers in a thorough way. The influence of different configurations of bridge piers on free surface evolution and hydrodynamic loading are investigated, and the transient velocity field in the wake of a bridge pier is compared to the measurements of Arnason et al. (2009). Moreover several important issues, e.g., the blockage effect of the bridge pier, wave impingement on different shapes of piers, and the bed shear stress distribution under unsteady flows are analyzed. The rest of the paper is organized as follows. The governing equations of the SPH method and its numerical implementation, the GPUSPH model, are introduced in Section 2. Section 3 presents the physical experiment and the corresponding numerical setup. Section 4 compares the numerical results with the laboratory measurements including the free surface evolution, hydrodynamic force, and velocity. Then Section 5 discusses the blockage effects of different shapes of bridge piers, the influence of pier shape on wave impact, and the bed shear stress distribution around a bridge pier under the attack of a tsunami bore. Finally, the conclusions are in Section 6.

2. Numerical model

2.1. Governing equations of the SPH method

In an SPH model, the computation domain is discretized into a set of particles, which possess material properties, such as mass, velocity, density, and pressure. Under the framework of the large eddy simulation, the mass and momentum equations of particles are derived from the Navier–Stokes equations by using a spatial filter and written as follows:

$$\frac{\mathrm{D}\rho}{\mathrm{D}t} = -\rho \nabla \cdot \mathbf{u} \tag{1}$$

$$\frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} = -\frac{\nabla P}{\rho} + \mathbf{g} + \nu_0 \nabla^2 \mathbf{u} + \frac{1}{\rho} \nabla \cdot \tau \tag{2}$$

where t is time; ρ is fluid density; $\mathbf{u}$ is particle velocity; P is pressure; $\mathbf{g}$ is the gravitational acceleration; ν_0 is the laminar kinematic viscosity; and τ is turbulence stress tensor, which is approximated by the sub-particle scale (SPS) model (see, e.g., Dalrymple and Rogers, 2006):

$$\tau_{m,n} = \rho \nu_t \left(\frac{\partial u_m}{\partial x_n} + \frac{\partial u_n}{\partial x_m} - \frac{2}{3} \delta_{m,n} \sum_{k=1}^{3} \frac{\partial u_k}{\partial x_k} \right) - \frac{2}{3} \rho C_I \Delta^2 \delta_{m,n} \|S\|^2 \tag{3}$$

where the constant parameter $C_I = 0.0066$; Δ is the initial particle spacing $\delta_{m,n}$, is the Kronecker delta; and the shear stress component directions m and n follow the Einstein notation. The turbulent viscosity is determined by the Smagorinsky turbulent model (Smagorinsky, 1963):

$$\nu_t = \left(C_{\mathrm{smag}} \Delta \right)^2 \|S\| \tag{4}$$

where C_{smag} is the Smagorinsky constant, which is determined by calibration in this study. The strain rate tensor is $S_{m,n} = \frac{1}{2} \left(\frac{\partial u_m}{\partial x_n} + \frac{\partial u_n}{\partial x_m} \right)$ and its norm is defined by $||S|| = (2S_{m,n}S_{m,n})^{1/2}$, which is further expanded as

$$\|S\|^2 = 2 \sum_{m=1}^{3} \left(\frac{\partial u_m}{\partial x_m} \right)^2 + \sum_{m=1,n>m}^{3} \left(\frac{\partial u_m}{\partial x_n} + \frac{\partial u_n}{\partial x_m} \right)^2 \tag{5}$$

In this study, the fluid is assumed to be weakly compressible, then the pressure can be directly computed by using the equation of state (Monaghan, 1992) as follows

$$P = \beta \left[\left(\frac{\rho}{\rho_0} \right)^{\gamma} - 1 \right] \tag{6}$$

where ρ_0 is the initial density; γ is chosen to be 7; and the parameter β is calculated by

$$\beta = \frac{\rho_0 C_s^2}{\gamma} \tag{7}$$

where C_s is the speed of sound. The real speed of sound leads to a very small time step, which is not practical for numerical simulation. A good workaround is to set the ratio of $C_s/u_{max} \geq 10$ (where u_{max} is the maximum velocity in the simulation) by adjusting β. Although this practice gives a slight density fluctuation (that is < 1% as required by Monaghan (1994)), a very important gain is that the governing equations can be solved explicitly; this further allows numerical implementation to utilize the latest parallel computing techniques.