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Simulation of a laboratory-scale experiment for wave propagation and interaction with a structure of undersea topography near a nuclear power plant using a divergence-free SPH

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ABSTRACT

The Divergence-Free SPH (DFSPH) method is a recently proposed novel incompressible Smoothed Particle Hydrodynamics (SPH) method. The DFSPH method enforces incompressibility via two iterative solvers: the Divergence-Free (DF) solver and the Constant-Density (CD) solver. In this study, the DFSPH algorithm is implemented into the SOPHIA Plus framework to simulate a set of wave propagation under the same geometry and conditions of a laboratory-scale experiment. The experiments are conducted for wave propagation and interaction with a structure of scaled-down undersea topography near the Kori nuclear power plant in South Korea. This study compares the free surface propagation and the wave height with the experimental measurements for three test cases: low/medium/high frequency waves. Overall, the simulation shows good agreement with the experiment both qualitatively and quantitatively. However, according to the sensitivity study, more realistic water splashing behaviors are captured as the particle size is reduced. The predicted wave heights at three different locations are also in fairly good agreement with the experimental measurement. Slight differences are observed after the wave collides with the structure because of the low energy dissipation in the simulation. However, the differences are not significant.

1. Introduction

After the Fukushima accident, interest in the impact of tsunami on nuclear power plants has increased. Tsunami is a long high sea wave caused by an earthquake, submarine landslide, or other significant disturbance. The behavior of a tsunami depends on various parameters, such as seismic activity, submarine topography, and coastal structures. When a tsunami occurs near the nuclear power plant site, the major potential issues are flooding, failure of drains, inability to intake water and physical damage on the building structures; these issues may lead to station-black-out and eventually severe accident conditions. Therefore, it is important to accurately predict tsunami propagation and behavior and to understand the potential risk to individual power plant sites exposed to different environments in order to ensure plant safety.

Many numerical techniques have been developed to simulate free surface problems including tidal wave and tsunami. Typically, there are two numerical approaches: The Eulerian method and Lagrangian method. The Eulerian method uses an interface tracking technique to recognize a surface of fluid, such as a void fraction, in a fixed mesh (Laadhari and Székely, 2017). Currently, the mesh adaptation technique is applied in the Eulerian method in order to resolve the complicated shape or large displacement of the interface that changes with time (Apsley and Wei, 2003; Laadhari and Székely, 2017). An adaptive mesh refinement allows a more accurate free surface simulation, but it has been challenged to employing it in three-dimensional problems because of high computational cost. The Lagrangian method is based on a meshless method, in which the mesh is not fixed but moves according to the fluid motion. Therefore, moving mesh itself is identified as the fluid region (Nakayama and Mori, 1996). In the Lagragian formulation, it is simple and easy to simulate the three-dimensional problems, since the momentum equation has no non-linear advection

Abbreviations: CD, Constant Density; DF, Divergence Free; DFSPH, Divergence Free Smoothed Particle Hydrodynamics; EOS, Equation of State; IISPH, Implicit Incompressible Smoothed Particle Hydrodynamics; ISPH, Incompressible Smoothed Particle Hydrodynamics; NPP, Nuclear Power Plant; PCISPH, Predictive Corrective Incompressible Smoothed Particle Hydrodynamics; PPE, Pressure Poisson Equation; SPH, Smoothed Particle Hydrodynamics; WCSPH, Weakly Compressible Smoothed Particle Hydrodynamics.

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Nomenclature

W	Kernel function	x_{ij}	Particle distance, m
c	Speed of sound, m/s	α	Constant coefficient of artificial viscous force
f	Force or acceleration term of momentum equation m/s^2	β	Constant coefficient of artificial viscous force
$\mathbf{g}$	Gravity acceleration, m/s^2	γ	Stiffness parameter of EOS
h	smoothing length, m	δ	Stiffness coefficient of DFSPH
k	k-th iteration step of Divergence Free solver	ϵ	Coefficient of XSPH method
l	l-th iteration step of Constant Density solver	κ	Stiffness parameter of DFSPH
m	mass, kg	μ	Dynamic viscosity, Pa $\cdot$ s
p	Pressure, Pa	ν	Kinematic viscosity, m^2/s
t	Time, s	ρ	density, kg/m^3
$\mathbf{u}$	Particle velocity vector,m/s	ρ_0	Reference density, kg/m^3
$\mathbf{x}$	particle position vector		

term. Although the required mesh resolution is much higher than that of grid-based Eulerian method, it is complemented by improving the computational performance through parallelization.

Smoothed Particle Hydrodynamics (SPH) is a Lagrangian particle-based method for fluid simulation. In SPH, a whole system is represented by a set of particles, each of which possesses physical properties, such as density and pressure. These particles move according to the governing equations, which are approximated using the summation interpolant with the neighboring particles. Because the SPH is a Lagrangian method, it can easily handle free surface, multi-phase, and large deformation with complicated geometries (Liu and Liu, 2003). Because of these advantages, the SPH is widely used in various research areas, including ocean science, mechanical engineering, chemical engineering, bioengineering and nuclear engineering. In particular, free surface flow, such as that of a tsunami, is one of the most actively applied and studied areas of the SPH method (Liu and Liu, 2003; Wei, 2016).

The most typically used SPH method is the Weakly Compressible Smoothed Particle Hydrodynamics (WCSPH) method, which accounts for the compressibility of a liquid to some extent (Liu and Liu, 2003; Becker and Teschner, 2007). The WCSPH method uses the Equation of State (EOS) that considers the pressure as being proportional to the density variation. This approach is easy to be implemented and has been successfully used in various applications. However, the EOS function should be very stiff for the incompressible liquids, resulting in the following drawbacks: 1) even a small density variation induces the drastic pressure fluctuation with high frequency pressure noise; 2) the time steps are restricted to accommodate these sharp pressure changes; 3) the small time steps degrade the overall computational performance (Lee, 2008a; Morris et al., 1997; Xu et al., 2009). To address these issues, several incompressible SPH (ISPH) methods have been developed in recent years. (Hu and Adams, 2007; Lee, 2008b)

ISPH methods are classified into two methods: one is the projection method, and the other is the iterative correction method. Table 1 shows the key features of various ISPH methods. The projection method was proposed by Cummins and Rudman (Cummins and Rudman, 1999). This method enforces incompressibility by solving the Pressure Poisson Equation (PPE) instead of the EOS which means projecting the velocity field onto a divergence-free state. Ihmsen et al. (Ihmsen, 2014) proposed an Implicit ISPH (IISPH) technique to avoid the inverse matrix calculation of the projection method. The IISPH method implements relaxed Jacobi scheme to solve the matrix-free system, resulting in speed up and high convergence rate of the simulation. The iterative correction methods enforce incompressibility through computing pressure forces iteratively until it resolves the compression induced by non-pressure forces. The Predictive-Corrective Incompressible SPH (PCISPH) method, which was proposed by Solenthaler and Pajarola (Solenthaler, 2009), satisfies incompressibility by low density variation. Most recently, Bender et al. (Bender and Koschier, 2015) proposed the Divergence Free SPH (DFSPH) method, which satisfies both density invariant and divergence-free velocity conditions by using two solvers that iteratively calculate pressure forces. To sum up, the DFSPH method has the advantages of 1) strictly ensuring the incompressibility of the fluid, 2) having superior computational performance than the previous methods and 3) efficient parallelization on GPUs. Therefore, we applied the DFSPH method for the present work.

Table 1
Summary of key features of various ISPH methods.

ISPH method	Key features
Projection (Cummins and Rudman, 1999)	• Enforces incompressibility by solving Pressure Poisson Equation (PPE). • Requires an inverse matrix solver for PPE. • Demands high computational cost.
IISPH (Ihmsen, 2014)	• Discretizes the Laplacian term of the PPE to avoid inverse matrix calculation. • Improves the convergence of PPE solver. • Speeds up the simulation by implementing relaxed-Jacobi scheme.
PCISPH (Solenthaler, 2009)	• Satisfies incompressibility by repetitive correction of the particle position. • Enforces the low density variation under 1% volume compression. • Enhances computational performance than the projection method.
DFSPH (Bender and Koschier, 2015; Bender and Koschier, 2017)	• Enforces both density invariant and divergence-free velocity using two iteration solvers. • Ensures low density variation at the same level as that of PCISPH and IISPH method. • Allows larger time steps than PCISPH method. • Enhances the convergence and stability of the simulation.

In this paper, the DFSPH algorithm was implemented in the SOPHIA-plus framework (Jo et al., 2017) to realize fully incompressible flow features in large-scale wave-propagation simulations. Next, the simulations were compared with a set of laboratory-scale wave-propagation experiments following the topography near the Kori Nuclear Power Plant in South Korea. In Section 1, the background of this study is described. In Section 2, the fundamentals of the SPH and DFSPH methods are briefly