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Simulation of wave overtopping using an improved SPH method

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ABSTRACT

An improved Smoothed Particle Hydrodynamics (SPH) method is used to study wave overtopping for different coastal structures. Simulated wave overtopping is too sensitive to the particle movements near the free surface boundary; however, the calculated flow acceleration by means of common SPH methods is not free of errors at this boundary due to the truncation of kernel function and contribution of fewer particles in solving the governing equations. In this paper, this problem is solved by modifying the viscosity of surface particles based on the concept of surface viscosity originally introduced by Xu (2010). By means of the introduced modification, unrealistic particle fluctuation at free surface boundary can be decreased significantly while keeping the model accuracy. This improvement can be used for both Incompressible and Weakly Compressible SPH methods and its implementation is easy and computationally efficient too. Different cases including dam break, solitary wave breaking and wave overtopping at vertical and sloping seawalls are simulated with the modified model and the new model is validated via comparing the results with several experimental and numerical data. Based on this study, free surface boundary can be simulated more accurately by means of the introduced modification and as a result, the predicted values particularly the calculated wave-overtopping rate become more reliable.

1. Introduction

Design the geometry of most coastal structures such as breakwaters and seawalls depends on the wave parameters near the coastlines. For example, crest elevation of the breakwater is determined based on the predicted wave-overtopping rate and wave run-up. Therefore, it is desirable for coastal engineers to have a reliable numerical tool for modeling the free surface flows accurately. Free surface profile can be easily traced via using the Smoothed Particle Hydrodynamics (SPH) method which is a Lagrangian particle based method originally developed by Monaghan (1992) for the astrophysics. Lagrangian particle approach has more advantages over Eulerian grid approach in simulating large deformations in free surface flows because there is no numerical diffusion in this method as a result of direct calculation of advection term. SPH methods have been widely used in the field of coastal engineering for modeling wave breaking, run-up and overtopping (Khayyer et al., 2008; Akbari and Namin, 2013; Shadloo et al., 2015) and for modeling wave interactions with several coastal structures such as vertical seawall, perforated and submerged porous breakwaters (Altomare et al., 2015; Meringolo et al., 2015; Akbari, 2014; Ren et al., 2016). Some other applications of SPH methods in addition to recent achievements for ISPH methods have been categorized by Gotoh and Khayyer (2016) in a good review article. They addressed several enhancements in stability, accuracy, computational efficiency and boundary conditions of SPH methods too.

At first, SPH method was applied to fluid mechanics as Weakly Compressible SPH (WCSPH) method (Monaghan and Kos, 1999) and afterward, Shao and Lo (2003) developed Incompressible SPH (ISPH) method based on a semi-implicit projection procedure. Lee et al. (2008) and later, Lee et al. (2010) showed the efficiency of ISPH method particularly in improving the pressure field in comparison with WCSPH method. In addition, ISPH benefits from a rigorous mathematical framework and it provides better results not only in terms of pressure field, but also in volume conservation (as highlighted by Gotoh and Khayyer, 2016). However, Szewc et al. (2012) reported that ISPH methods suffer from the density error accumulation in their original formulation. Although performance of these methods have been compared in several studies (Shadloo et al., 2012; Zheng et al., 2014), there is not yet a global agreement about the superiority of one method as reported by Gomez-Gesteira et al. (2010a,b). The main drawback of WCSPH methods was the noisy pressures calculated from a sensitive equation of state. To overcome this problem, several attempts have been done including earlier methods such as X-SPH or density reinitializing methods (Monaghan, 1989; Colagrossi and Landrini, 2003) and later ones such as iteration methods, grid scheme, utilizing a modified pressure term and particle shifting (Fatehi and Manzari, 2012; Violeau and

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Rogers, 2016; Sun et al., 2017). This problem can be solved by making use of ISPH method and its improvements such as shifting the particles (Lind et al., 2012; Khayyer et al., 2017) or utilizing a modified Poisson pressure equation (PPE) (Khayyer and Gotoh, 2010). In spite of these improvements, instabilities occur yet due to the truncated kernel at the free surface boundary as discussed by Lind et al. (2012). This numerical error arises in both WCSPH and ISPH methods and may decrease the accuracy of the results especially near free surface boundaries. On the other hand, particle movements at free surface boundary are too important in calculating a reliable wave-overtopping rate over coastal structures.

To control unwanted particle fluctuations at free surface and preserve the angular momentum, Khayyer et al. (2008) used a modified gradient of kernel function. Xu et al. (2009) increased the stability of ISPH method by moving the particles slightly through streamlines and later, Xu (2010) utilized an extra artificial diffusion around free surface boundary to decrease the errors due to the truncated kernel. Marrone et al. (2010) proposed an algorithm to detect the free surface particles for both 2D and 3D simulations. They introduced a level set function and validated their technique by simulating a dam break and evaluating flow impact on a tall structure. Rafiee et al. (2012) used modified Riemann solver and Shao et al. (2012) utilized a modified kernel gradient and density correction to improve the accuracy of SPH methods. Asai et al. (2012) simulated a dam break with and without turbulent viscosity and concluded that a smoother surface profile and a smoother pressure distribution could be obtained after implementing an additional turbulence viscosity. They applied a relaxed density-invariance scheme to overcome extra fluctuations in their simulations. Shadloo et al. (2012) shifted non-uniform particles at the end of each time step by introducing an artificial displacement and compared their modified WCSPH method with ISPH method. It is desirable to keep uniformity of particles during simulation of an incompressible fluid. However, a non-uniform particle distribution occurs due to the errors associated with the truncated kernel function as reported by Lind et al. (2012) and due to the large deformations at free surface boundary as reported by Skillen et al. (2013). These researchers calculated the gradient of particle densities and moved disordered particles from a high concentration area to a low concentration area based on the Fick's law of diffusion. Lind et al. (2012) validate their model via simulating dam break and regular wave propagation and obtained acceptable results in comparison with experimental data. Later, Lind et al. (2016) coupled incompressible and compressible phases and simulated the interface between compressible air and incompressible water domains. They applied Fick's law to the incompressible phase to improve simulated pressure field and utilized an equation of state to calculate pressure field in the compressible phase. Recently, Khayyer et al. (2017) modified Fick's law at interfaces and introduced an optimized particle shifting method to enhance modeling of free-surface and vicinity particles. In another study, Nair and Tomar (2014) introduced a semi-analytical approach to impose zero pressures to the particles located at free surface boundary. For this purpose, they applied a modified approximation of PPE to the particles with a kernel sum less than 0.95. Liu et al. (2014) used a more accurate criterion for assessing surface particles based on the concept of symmetry of inner particles originally introduced by Khayyer et al. (2009). They applied weight function in evaluating the symmetry condition and enhanced the simulated free surface profile particularly near mirror corners. Later, to conserve particle volume at free surface boundary, Tsuruta et al. (2015) presents a new PPE. Although many studies have been done to improve the SPH capability in modeling a free surface boundary, yet as reported by Gotoh and Khayyer (2016), the reliability of SPH methods for ocean engineering applications can be enhanced by developing more accurate, consistent free surface boundary conditions. In addition, it is desirable to reach a reliable approach with a low computational cost.

This study aims to enhance the accuracy and stability of SPH methods (both WCSPH and ISPH) and reduce the errors due to the truncated kernel function at free surface boundaries. To do this, an additional viscosity is introduced and applied to particles around the free surface boundary to keep them in a uniform distribution. In addition, the introduced method is computationally efficient and its implementation is simple. Different cases including dam break, solitary wave breaking and wave run-up and overtopping over vertical and sloping seawalls are studied and the results are compared with the results of other numerical and experimental studies. In the following sections, governing equations and modifications are presented and then the model performance is investigated in a dam break simulation. After that, overtopping at a vertical seawall is studied by making use of different surface viscosities and the results are compared with the experimental data by Gotoh et al. (2005). Finally, the model is verified by simulating two other cases: first, solitary wave breaking over a sloping bed, based on laboratory data presented by Grilli et al. (1997) and second, regular wave overtopping over seawalls with four different crest elevations, based on experimental data reported by Saville (1955). It has been shown that unrealistic particle fluctuations at free surface boundaries can be decreased with the introduced method and as a result, model accuracy especially in calculating overtopping rates improves significantly.

2. Governing equations

The governing equations in SPH method are Navier-Stokes (NS) equations. Continuity equations for compressible and incompressible fluid flow are:

$$\frac{1}{\rho_w}\frac{D\rho_w}{Dt} + \vec{\nabla}\cdot\vec{U}_f = 0 \tag{1}$$

$$\vec{\nabla}\cdot\vec{U}_f = 0 \tag{2}$$

where ρ_w and $\vec{U}_f$ are the fluid density and fluid particle velocity, respectively. The momentum equation for turbulent viscous flow in Lagrangian approach is:

$$\frac{D\vec{U}_f}{Dt} = \frac{-1}{\rho_w}\vec{\nabla}P + \upsilon_E\nabla^2\vec{U}_f + \vec{g} \tag{3}$$

The first term on the right hand side of Eq. (3) represents pressure force caused by pressure gradient. The second term denotes the viscous force and the last term in the momentum equation is representative of the gravitational acceleration vector. P and g are the total pressure and gravitational acceleration vector, respectively and $\upsilon_E = \upsilon_w + \upsilon_T$ is effective viscosity that is summation of the kinematic viscosity of the fluid υ_w (1.0 E-6 for water) and turbulent viscosity. Based on Sub-Particle Scale (SPS) turbulence model applied to MPS method by Gotoh et al. (2001), Smagorinsky turbulent viscosity υ_T is utilized as:

$$\upsilon_T = (C_S\cdot dr_0)^2\cdot\left|S(\overline{U}_f)\right| \tag{4}$$

dr_0 is initial particle spacing, C_S is the Smagorinsky constant that varies depending on the flow condition and its value is supposed as 0.1 in this study. It should be noted that no reliable equation has been introduced yet for determining an accurate value for this constant and as reported by Shao (2006), for any particular flow, the accuracy of the model calculations may be improved by adjusting the constants. $S(\overline{U}_f)$ is large-scale strain-rate tensor and it is a function of the velocity gradient as:

$$S(\overline{U}_f) = \frac{\nabla\vec{U}_f + \left(\nabla\vec{U}_f\right)^T}{2} \tag{5}$$

By making use of the turbulent viscosity and following Shao and Ji (2006), turbulence kinetic energy can be obtained as:

$$k_{sps} = \left(\frac{\upsilon_T}{0.08dr_0}\right)^2 \tag{6}$$