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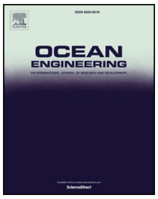

A SPH numerical wave flume with non-reflective open boundary conditions

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ABSTRACT

In this paper, a numerical wave flume with full functions of wave generation and absorption is proposed under the framework of Weakly Compressible Smoothed Particle Hydrodynamics (WCSPH). In contrast to the conventional SPH numerical wave flumes using wave paddles and sponge layers, the wave generation and absorption in this paper are implemented using non-reflective open boundary conditions, which are capable of generating multiple types of waves, including solitary waves, linear and second-order regular waves. Passive and active wave absorption are available for transmitting incident waves and preventing secondary reflections. Steady or unsteady flows can also be defined during wave generation and absorption to set up numerical wave-flow flumes. The results on a series of validation cases indicate that this SPH numerical wave flume not only performs satisfactorily in conventional wave generation and absorption and nonlinear wave-structure interaction simulations but also has the following three advantages: 1) It avoids using the sponge layers to shorten the flumes, which improves the efficiency; 2) it keeps the mean water level steady and prevents water level shifting; and 3) it implements steady/unsteady flow and wave-flow interactions to model a wider range of hydrodynamic problems.

1. Introduction

The numerical wave flume (NWF) is the expansion and application of the laboratory wave flume in the field of computational fluid dynamics. This powerful research tool has been used widely in hydrodynamics and coastal engineering in recent decades. As a promising mesh-free numerical method, Smoothed Particle Hydrodynamics (SPH) (Monaghan, 2005; Violeau, 2012; Zhang et al., 2017), is attracting increasing attention and has been adopted to implement numerical wave flumes and simulate highly nonlinear free surface flows (Violeau and Rogers, 2016), including unsteady flow interactions with complex structures and wave plunging and breaking.

Wave generation and wave absorption are two main functions for a NWF. The earliest and most direct way to generate waves (Monaghan, 1994) is to mimic the wave generation mechanism of a laboratory wave flume by forcing the water body to act in a targeted pattern through the mechanical movement of the wave generation equipment. Due to the SPH method's natural advantages in dealing with fluid-solid interactions and moving boundaries, this type of wave generation techniques is the most widely used in SPH NWFs. These techniques can be divided into piston-type (Altomare et al., 2017; Monaghan, 1994) and flap-type techniques (Altomare et al., 2014; Gomez-Gesteira et al., 2012; Shibata et al., 2011), according to the movement pattern of the wave generation equipment. All types of waves in laboratory wave flumes, including solitary waves (Monaghan and Kos, 1999; Pringgana et al., 2015), regular waves (Gao et al., 2012), irregular waves (Altomare et al., 2017), and even extreme waves (Dao et al., 2011), can also be generated in NWFs by adjusting the frequency and the amplitude of the equipment's movement. A good example was shown by a recent work of Altomare et al. (2017), which presented a fully comprehensive implementation of conventional wave generation and active wave absorption for second-order long-crested monochromatic and random waves in a WCSPH-based (Weakly Compressible Smoothed Particle Hydrodynamics) model.

Specific treatments were developed for the generation of non-periodic waves. For example, Li et al. (2012) and Lo and Shao (2002) generated solitary waves by initializing the water particles with analytical velocities and free surface elevations. Fu and Jin (2015) and Capone et al. (2010) simulated landslide waves as a sliding object interacting with steady water. Those wave generation techniques are only suitable for specific circumstances and cannot be generalized to periodic waves.

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Source generation is a rather common wave generation technique for grid-based NWFs (Brorsen and Larsen, 1987; Wei et al., 1999) but has not attracted much attention in particle-based NWFs. Ni and Feng (2013) first introduced the source generation technique into SPH NWF and successfully generated regular waves by modifying the velocities of the water particles inside the source zone. Later, Liu et al. (2015) provided a more complete theoretical derivation, implemented a momentum source in the framework of ISPH (Incomprehensible Smoothed Particle Hydrodynamics) and validated their NWF with a wave-breakwater interaction case. An additional sponge layer is usually needed behind the wave source to absorb the undesired waves, leading to an increase in the number of computational nodes in the system and a reduction of efficiency. Meanwhile, a qualified solitary wave cannot be generated in a particle-based NWF by modifying the momentum source without introducing mass momentum, i.e., adding or deleting particles. Similarly, this type of NWF cannot implement generalized free surface flow.

Except for the three abovementioned wave generation techniques, some research has also been carried out on the application of open boundary conditions (OBCs) in SPH NWFs. However, it is relatively difficult to implement an Euler-viewed OBC in a Lagrangian-characterized SPH model. First, a dynamic upload-unload algorithm for fluid particles should be carefully chosen to ensure the efficiency and robustness of the program. Second, the integral completion of the particles near open boundaries should be fully considered to guarantee the computational accuracy. Finally, it is also important to handle the exchange of both information (e.g., fluctuations of free surface elevations) and mass (e.g., fluid particles) between the inside and outside of the system, to prevent the side effects brought by the reflection and unphysical noise at open boundaries.

The most frequently used OBC for the SPH method was proposed by Lastiwka et al. (2009). The integral completion of particles is guaranteed by deploying a buffer zone beside the open boundary, and the information and mass can be exchanged through the movement of buffer particles. This technique has already been applied in simulating multiple types of hydrodynamic phenomena based on the Navier-Stokes equations, including pipe flows (Khorasanizade and Sousa, 2016; Lastiwka et al., 2009), jets (Aristodemo et al., 2015), open-channel flows (Meister et al., 2014) and hydraulic jumps (Federico et al., 2012), as well as free surface flow problems based on the Shallow Water Equations (SWEs), such as the Okushiri tsunami in Japan and flood inundations from a hypothetical dyke breach at Thamesmead in the United Kingdom (Vacondio et al., 2012). It is worth mentioning that Ni et al. (2016) implemented non-reflective OBCs in an SWE-based SPH free surface flow model for the first time based on the OBC treatment from conventional ocean circulation models. This non-reflective OBC treatment ensures the unhindered transmission of internal fluctuations out of the system without reflections at open boundaries when inputting external signal simultaneously. It provides a theoretical basis for the wave generation and absorption technique in this paper.

Leroy et al. (2016) and Ferrand et al. (2017) investigated and introduced another kind of OBCs, named Unified Semi-Analytical Open Boundary Conditions (USAOBCs) in their ISPH and WCSPH based numerical models, respectively. It is an extension of the Unified Semi-Analytical Wall Boundary Conditions (Ferrand et al., 2013; Leroy et al., 2014). The most intriguing feature of this new method was that the OBCs analytically reconstructed the integral domain of particles near the open boundaries using open-boundary nodes and particles nearby, instead of using buffer particles. Solitary waves and regular waves were generated by a true mass source, i.e., creating and destroying fluid particles through the OBCs. A passive OBC was also implemented based on the Riemann invariants near the open boundary, and no reflection was observed when solitary waves propagated outwards. Leroy et al. (2016) used the USAOBC to simulate a Creager weir flow and a 3-D circular pipe flow. Their work associated with Ferrand et al. (2017)'s trial on WCSPH both proved the high accuracy and stability of the USAOBC. However, it remains to be studied whether this OBC can be used to construct an active OBC, i.e., transmitting fluctuation outwards while receiving external signals simultaneously, which is the key technique for Active Wave Absorption (AWA) in NWFs.

Wave absorption is also an essential function for NWFs to eliminate undesired free surface fluctuations or implement a semi-infinite NWF. The simplest and most direct approach is to mimic the wave absorption strategy in the laboratory wave flume by deploying a mild slope at one end of the flume, where waves will be dissipated after running up and breaking. However, this strategy is rarely utilized in SPH NWFs because of the poor absorption effectiveness and the low computational efficiency. The most widely used wave absorption technique in SPH NWFs is sponge layers (Altomare et al., 2017; Molteni et al., 2013; Ni and Feng, 2013), which originate from grid-based NWFs. By enhancing the resistance force against particles' movements, a sponge layer is able to dissipate wave energy within a relatively short distance (1–3 times the wavelength). It should be mentioned that one of the intrinsic disadvantages of sponge layers is that they generally cannot exist with flow at the same time and will fail to absorb waves when there are wave-flow interactions.

Shibata et al. (2011) calculated the amplitudes and phases of the incident waves using Fourier transform and implemented regular wave absorption by creating/deleting open boundary particles (OBPs) and modifying particle velocities analytically. This technique will certainly reduce the CPU time due to the absence of sponge layers. However, further study is required on whether it is capable of dealing with irregular waves and general unsteady flows.

After the incident waves interact with the structures in the flume, the reflected waves will propagate backwards to the wave generation side. A secondary reflected wave will then be triggered by the conventional wave generation equipment, e.g., wave paddles or virtual wave generation zones. Gradually, accumulated wave energy will lead to much larger waves and have a destructive influence on the experimental or simulation results. Researchers (Altomare et al., 2017; Didier and Neves, 2012) have solved this *secondary reflection* problem by mimicking the AWA technique from the laboratory flumes: 1) monitor the water elevation in front of the wave paddle in every step and obtain a modification signal by comparing the measured elevation with the targeted elevation and 2) add the modification signal to the original wave generation signal, and a compensated wave with the same amplitude and staggered phase will be generated to counteract the reflected waves.

In this paper, a numerical wave flume with full wave generation and absorption functionalities is proposed based on non-reflective open boundary conditions under the WCSPH framework. This NWF is capable of generating solitary waves and regular waves. Both passive and active wave absorption with high efficiency are available to transmit different types of waves and prevent secondary reflection. Steady and unsteady flows can also be added to the wave generation and absorption process to implement a numerical wave-flow flume. The paper is structured as follows: A summary and discussion of NWF, especially the development of SPH NWF, is provided in Section One. Section Two briefly reviews the SPH mathematical theory and numerical model, as well as the algorithms for piston wave generation and sponge-layer wave absorption. The SPH non-reflective open boundary condition and its extension to wave generation and absorption are introduced in Section Three. Multiple numerical tests are adopted to validate the performance of this new NWF in Section Four, including a wave absorption benchmark test for non-reflective OBC, regular wave generation and passive absorption tests with various wave periods, standing wave tests for regular wave active absorption, regular wave runup on a beach and regular wave interaction with submerged breakwater. Sections Five and Six present the conclusions and acknowledgements, respectively.