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Improved SPH simulation of spilled oil contained by flexible floating boom under wave–current coupling condition

Yang Shi [a], Shaowu Li [a,*], Hanbao Chen [b], Ming He [a], Songdong Shao [c]

[a] State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China
[b] Tianjin Research Institute for Water Transport Engineering, Ministry of Transport of China, Tianjin 300456, China
[c] Department of Civil and Structural Engineering, University of Sheffield, Sheffield S1 3JD, United Kingdom

HIGHLIGHTS

- Modified solid boundary treatment is proposed to improve the model accuracy.
- Multi-phase SPH model is validated against physical test for the wedge entry process.
- The numerical wave–current flume is established and validated against physical test.
- The hydraulic performance of boom and oil containment process are investigated.
- Hydraulic and containment performances of flexible boom are compared with rigid one.

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ABSTRACT

A multi-phase Smoothed Particle Hydrodynamics (SPH) method is developed to model the failure process of a flexible oil boom. An algorithm is proposed based on the dynamic boundary particles (DBPs) for preventing particle disorders of multi-phase fluid particle movement around solid boundary. The improved multi-phase SPH model is firstly validated by the experimental data of a wedge falling into a two-layer oil–water fluid. Then a numerical wave–current flume is established with a piston-type active absorbing wave generator and a circulating current system. The model reliability is validated against the measured vertical profiles of velocity. Simulation of the flexible floating boom movement is implemented by introducing a Rigid Module and Flexible Connector (RMFC) multi-body system. The model is finally applied to the simulation of movement of a flexible floating boom in containing industrial gear oil under the action of combined waves and currents. Good agreements are obtained between the SPH modeling results and the experimental data in terms of the ambient wave–current field, hydrodynamic responses of the floating body and evolution process of the oil slick for the flexible boom. The hydrodynamic responses and containment performances of the flexible floating boom are also compared with those of the rigid one. It is found from both the experimental and numerical results that two vortices of the water phase exist in the front and rear of the boom skirt and the size of the front vortex decreases with increase of the current velocity while the wake vortex is reversed. It is also found that the skirt of the flexible boom has a larger magnitude of swaying and rolling than the rigid one and the maximum quantity of escaped oil of a flexible boom within one wave cycle is about 5% more than a rigid one under the present test conditions.

* Corresponding author.
E-mail address: lishaowu@tju.edu.cn (S. Li).

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1. Introduction

Oil spills, e.g. the Deepwater Horizon oil spill event in Gulf of Mexico on 20 April, 2010, can bring serious disasters on the marine and coastal environment as a result of both physical smothering and toxic effects. Floating oil booms are commonly used in concentrating spilled oil and preventing oil from spreading. Performances of a floating boom to contain spilled oil affected not only by the characteristics of itself, e.g. the floater diameter, skirt length, buoyancy/weight (B/W) ratio and boom flexibility, but also by the contained oil properties, e.g. the spilled volume, its viscosity and density. The failure modes of oil containment, such as oil splash-over, boom submergence and overturning, mainly depend on the hydrodynamic responses of the floating oil boom, while the failure modes of drainage (Cross and Hoult, 1971; Wilkinson, 1972), entrainment (Wicks III, 1969) and critical accumulation (Delvigne, 1989; Johnston et al., 1993) mainly happen during the evolution process of the oil–water interface in the front of boom.

Up till now, quite a number of numerical models have been proposed for revealing the relation between the capacity and behavior of oil containment of an oil boom and its mechanical characteristics under the action of combined waves and currents. An et al. (1996) and Goodman et al. (1996) investigated the oil–water flow around a stationary boom by using the commercial CFD software package FLUENT and the three typical containment failure modes were successfully reproduced in their simulations, namely the drainage failure, droplet entrainment and critical accumulation. The simulated results show satisfactory agreement with the experimental data of Brown et al. (1996) in terms of the length and thickness profiles of the oil slick. Fang and Johnston (2001) developed a more comprehensive non-hydrostatic flow model to simulate oil contained by a stationary boom under the action of waves, currents and winds. It is found that the oil–water interface is more unstable at the upstream end of the oil slick than near the boom under the action of waves and that the boom fluctuations are positively correlated with the wave height. The fluctuation of the oil–water interface induced by waves can be suppressed due to the presence of current. The effect of winds on the oil containment is similar to that of the currents and can be regarded as an additional current velocity (about 1∼6% of the wind velocity). Violeau et al. (2007) and Yang and Liu (2013) applied the SPH model to simulating a movable oil boom interaction with oil slick, however only heave movement of the boom was considered in their simulations and the roll and sway motions as well as the effect of flexibility of the boom were ignored. With regard to the boom flexibility, Amini et al. (2005) developed a numerical coupling model for fluid–structure interaction based on FLUENT to assess the containment process of oil boom and indicated that a flexible skirt could significantly change the pressure on the boom skirt and accordingly affect the oil containment process. Recently, Amini and Schleiss (2009) found that the wake vortex could spread over quite a wide range of area behind the rigid boom than the flexible one under the current condition. Nevertheless, the use of a rigid-lid CFD model and simplification of the boom as a thin baffle in their simulations may impose some limitation on revealing more practical mechanisms.

Comparatively, the Lagrangian meshless methods, such as the Smoothed Particle Hydrodynamics (SPH), have clear advantages in modeling the complex problems of fluid–structure interaction (FSI) with multi-interfaces through explicitly tracking (Yang et al., 2014; Liu and Li, 2016). A number of documented works were reported on modeling the interaction of multiphase fluids with structure using the SPH method. Colagrossi and Landrini (2003) proposed a two-phase SPH model to simulate the violent fluid–structure interactions with air entrapment, in which large surface tension was incorporated in the lower-density phase for the purpose to enhance the interface stability. Hu and Adams (2006, 2007) developed a multi-phase SPH method that can handle the density discontinuities across the phase interface automatically, and applied the model to non-free surface flows. Based on the works of Colagrossi and Landrini (2003) and Hu and Adams (2006), Grenier et al. (2009) derived a Hamiltonian interface SPH formulation that can simulate both interface and free surface flows. Considering the enormous computation cost for determining the volume distributions of particles in Grenier et al. (2009), Monaghan and Rafiee (2013) later proposed a relatively simpler algorithm for the multi-fluid flow with high density ratios. They found that the velocity smoothing and artificial surface tension used by Colagrossi and Landrini (2003), the number density concept adopted by Hu and Adams (2006), and the compensating functions used by Grenier et al. (2009) are not a necessity.

This paper presents a weakly compressible Smoothed Particle Hydrodynamic (WCSPH) model for the multiphase flows with complex interfaces, which is similar to that used by Monaghan and Rafiee (2013) in dealing with flow of multiphase fluids with different density. Improvement is made by introducing an algorithm based on the concept of the dynamic boundary particles (Dalrymple and Knio, 2001) to remove the spurious pressure oscillations near the interface of multi-fluids and the solid body. It is then combined with a Rigid Module and Flexible Connector (RMFC) approach of multi-body system (Riggs and Ertekin, 1993) to treat the flexible floating boom. Simulation of boom movement under the action of coupled wave–current is performed in consideration of three degrees of freedom including the heave, sway and roll.

The paper is organized as follows. After the introduction section, the methodology of the numerical model is presented, which includes the governing equations of the WCSPH model, the solid boundary treatment, the equations of motion of the rigid body and multi-body system, and the solution algorithm. In Section 3, the numerical model is validated against the data collected from the wave–current flume and wedge entry into a two-layer water–oil fluid. In Section 4, extensive discussions are performed in terms of the optimization of elastic coefficient of mooring line and the multi-body system, the simulation of interaction of floating boom with waves, and the hydrodynamic characteristics of the floating boom with different flexibilities. In Section 5, combined effects of current, wave and boom flexibility on the oil containment failures are investigated by using the improved WCSPH model. Finally, in Section 6 the conclusions are summarized.