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3D ISPH erosion model for flow passing a vertical cylinder

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ABSTRACT

In this paper a 3D incompressible Smoothed Particle Hydrodynamics (ISPH) erosion model is proposed to simulate the scouring process around a large vertical cylinder. The erosion model is based on the turbidity water particle concept and the sediment motion is initiated when the fluid bottom shear stress exceeds the critical value. The previous 2D SPH sediment initiation model is expanded by combining the effects of both transverse and longitudinal sloping beds in a practical 3D situation. To validate the developed model, a laboratory flume experiment was carried out to study the clear water scouring around a vertical cylinder under unidirectional current, in which high-speed video cameras were used for the real-time monitoring of sediment movement. The 3D ISPH results are compared with the experimental data with good agreement in terms of the scouring patterns and scales. Besides, the computed flow velocity field suggests that both the horseshoe vortices and lee-wake flows around the cylinder have been realistically simulated.

1. Introduction

The non-cohesive sediment bed scouring initiated by the existence of an isolated structure is a popular topic widely investigated in both the fluvial and offshore environment. Dealing with the safety assessment of a structure placed on the riverbed (e.g. bridges, barrages etc.), the erosive action of the river stream must be reliably evaluated (Dordoni et al., 2010; Guandalini et al., 2012). Also, in the design of highly demanding marine structures, the scour around the foundations should be carefully considered (Petrini et al., 2010). Quite a few empirical formulas to predict the final scouring are available, but the phenomenon is time-dependent and it is affected by several uncertainties related to both the sediment and the flow characteristics. Most predictive formulas for scouring behind a vertical cylinder under either current or wave condition are established from the experimental observations on relatively small size of the cylinder. Using these formulas for field applications could suffer large error if the large cylinder diameter is encountered. Ettema et al. (2006) found that the intensity and frequency of vortices generated during a large cylinder scouring are much smaller than those generated during a smaller cylinder. Moreover, due to the differences in experimental conditions, there exist substantial divergences of the result among various empirical predictive methods. Early numerical studies in this field are attributed to Olsen and Melaaen (1993), Richardson and Panchan (1998), Olsen and Kjekkesvig (1998) and Roulund et al. (2005), in which only a small cylinder was used. Although Sheppard et al. (2004) investigated a large pier scouring with diameter of 0.914 m, the dynamic vortex

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evolutions were not observed. Generally speaking, there are plenty of documented works on the final size and shape during the cylinder scour, but there is limited information on the dynamic process.

The Smoothed Particle Hydrodynamics (SPH) method emerged as a promising tool for free surface flow simulations, which has the advantages in simulating large deformation of water surface and multi-phase interface. Compared with its popular applications in the coastal hydrodynamics, the SPH's versatility in simulating 3D sediment scouring behind a vertical cylinder has not been thoroughly explored. Most SPH works simply treated the cases of 2D configuration in order to save computational expenses. For example, Morris et al. (1997) carried out a pioneering SPH study on low Reynolds number flows passing a regular lattice of the cylinders and compared the results with finite element solutions. Yildiz et al. (2009) improved the SPH solid boundary treatment by using a multiple boundary tangent approach and studied the flow interactions with an obstacle with complex curved boundaries. Ellero and Adams (2011) considered very viscous flow of the Newtonian liquid passing through a linear array of the cylinders confined in a channel and disclosed the mixing of shear and extensional behaviors. Omidvar et al. (2012) developed a variable mass SPH to investigate water waves generated by a heaving cylinder and water wave scattering by a fixed cylinder. Marrone et al. (2013) adopted a ghost-fluid technique, which led to a more accurate enforcement of the solid boundary. Their model was used to study the evolution of a viscous flow around a blunt body for different Reynolds numbers. Nestor and Quinlan (2013) presented a Finite Volume Particle approach using the pressure projection for fully incompressible flow interacting with a rigid body. The developed model was applied to the Vortex-Induced Vibration (VIV) of a circular cylinder in laminar cross-flow. By adopting a parallel SPH model, Wen et al. (2016) proposed 3D numerical wave basin to study the wave impact on a vertical cylinder. Their OpenMP programming technology, combined with an existing MPI program contained in the parallel version of SPHysics code, was implemented to enable the simulation of several hundred million particles. The latest work in this field was reported by Bouscasse et al. (2017) for viscous flow past a circular cylinder interacting with free surface under varying cylinder submergences and Froude numbers. Besides, quite a few new progresses have been reported in the improvement of ISPH numerical schemes, such as the high accuracy first-order derivative calculation (Zheng et al., 2017), the optimized particle regularization (Khayyer et al., 2017a), the energy conservation of project-based particle methods (Khayyer et al., 2017b) and the enhanced two-step semi-implicit pressure solution (Xu and Lin, 2017).

On the other hand, some good progresses have also been made in the SPH modeling of sediment flows. Zanganeh et al. (2012) incorporated a soft contact approach to simulate the inter-particle collisions by a two-phase Lagrangian coupling model and studied the scouring beneath a marine pipeline, where the fluid and sediment phases were respectively modeled as Newtonian and non-Newtonian fluids, respectively. Ran et al. (2015) developed an ISPH sediment erosion model based on the concept of pick-up flow velocity, in which the sediment was initiated when the local flow velocity exceeded the critical value. This model was used to the movable bed scour and sediment grain movement under a dam break. Fu and Jin (2016) treated the sediment motion as multiphase flow and they developed a particle-based rheological model with higher-order viscosity smoothening scheme for the open channel flow scouring and water–sediment dam break flow. Fourtakas and Rogers (2016) proposed an SPH scheme by treating the liquid–sediment phases using the Newtonian and non-Newtonian Bingham-type constitutive model. This was further strengthened with the Drucker–Prager yield criterion to predict onset motion of the sediment grains. Khanpour et al. (2016) developed a two-phase SPH model in which both the water and sediment materials were treated as continuum to follow the governing equations of motion. They successfully reproduced the sediment scouring and deposition areas for a wall-jet and the sediment failure slopes for a flushing case. The model principle was that both the Mohr–Coulomb and the Shields yielding criteria were combined to determine the critical shear stress, above which the sediment materials start to behave like a viscous fluid. In a more recent study, Pahar and Dhar (2017) developed a robust multi-phase ISPH model further including the particle contact mechanism to account for the interactions between the water and sediment and the relevant drag forces. In addition, an early pioneering review on the multi-phase particle modeling techniques has been made by Gotoh and Sakai (2006).

In terms of existing SPH practice to model the sediment scouring, there are two different approaches: (1) Most of documented works treated the water and sediment as different fluid components and therefore, relevant interaction models are used to link the two phases (Shakibaeinia and Jin, 2011; Manenti et al., 2016); (2) The other approach, which will also be adopted in the present paper, considered the counterbalance between the fluid force and the sediment bed resistance. In the present work, it is explored that the latter approach could more realistically reflect the sediment erosion and scouring mechanism. As a result, either the critical velocity (Hayashi et al., 2003; Ran et al., 2015) or the critical shear stress (Manenti et al., 2012) criterion can be used to determine the initiation of sediment particles when the threshold condition is satisfied. The purpose of present research is to develop a 3D ISPH sediment erosion model to study movable bed scours around a vertical circular cylinder. The model is a significant expansion of the previous 2D Turbidity Water Particle approach (Wang et al., 2016) by further including the sediment initiation model in both longitudinal and transverse directions. For the validation, laboratory flume experiment was carried out in Tianjing University, where detailed real-time dynamic scouring processes were recorded on multi-locations of the observation area. The cylinder diameter used in the experiment was 60 cm, and this reaches a reasonable scale to approximate the practical situation. In this work an incompressible SPH (ISPH) numerical scheme is adopted. One important advantage of the ISPH over the standard weakly compressible SPH is the accurate flow field computation. The ISPH can obtain the noise-free particle distribution, velocity and pressure patterns without any additional numerical smoothing techniques, such as the XSPH or density filtering widely used in the standard WCSPH. For the proposed study of flow passing around a vertical cylinder and associated sediment bed scouring, the relevant physical process should be very sensitive to the computed flow velocity and pressure field near the cylinder. Therefore the ISPH model could be expected to provide a better representation of the physical reality.