Three-dimensional Coupled Fluid-sediment Interaction Numerical Model for Suspended Sediment Analysis

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ABSTRACT
A three-dimensional two-way coupled fluid-sediment interaction model applicable to suspended sediment analysis is developed in this study. For validation, the developed model is applied to hydraulic experiments on suspended sediment in a steady uniform flow and a swash zone. For both flow conditions, the predictive capability of the developed model is demonstrated against experimental data in terms of time-averaged suspended sediment concentration. Numerical results for the swash zone show that complex suspended sediment transport relates with three-dimensional vortex motion due to plunging breaking waves, and demonstrate the usefulness of the developed model in investigating suspended sediment transport under breaking waves.

KEY WORDS: Three-dimensional numerical model; suspended sediment; steady uniform flow; breaking wave; vortex.

INTRODUCTION
In the marine environment, fluid flow can induce sediment transport and resulting seabed profile change. At the same time, the evolution of the seabed profile can affect the fluid motion. To investigate such seabed behavior numerically, it is essential to accurately model and simulate dynamic interaction between flow field change and seabed profile evolution in developing a numerical model.

In the literature, a two-way coupling scheme has been used as one of the computational techniques dealing with fluid-sediment interaction (e.g., Roulund et al., 2005; Lee et al., 2008). In the two-way coupling scheme, seabed profile change is computed from fluid motion, and the updated seabed profile is taken into account in computing the fluid flow at the next time step. Nakamura and Yim (2011) developed a three-dimensional (3-D) two-way coupled fluid-sediment interaction model (hereinafter referred to as FSM), in which the two-way coupling scheme was employed to ensure fluid-sediment interaction. The predictive capability of the FSM was verified against experimental data on cross-shore beach profile change due to solitary waves (Nakamura and Yim, 2011) and jet-induced local scouring in front of quay walls (Mizutani et al., 2009). In the FSM, seabed profile evolution due to bed-load sediment transport is computed using a module based on the model of Roulund et al. (2005). However, consistent with the rationale provided by Roulund et al. (2005), suspended sediment transport is assumed to be neglected. Accordingly, the FSM cannot be applied to fluid-sediment interaction phenomena dominated by suspended sediment.

In the past few decades, numerical models for suspended sediment analysis with no assumption of a vertical distribution function of suspended sediment concentration have been developed for channel flow (e.g., Wu et al., 2000; Zhao and Cheng, 2008), oscillatory flow (e.g., Kim et al., 2000; Zedler and Street, 2006), and waves (e.g., Sakakiyama et al., 2004; Gilbert et al., 2007). In applying such numerical models to the marine environment, complex air-water interface motion such as wave breaking needs to be tracked accurately. Furthermore, it is necessary to simulate 3-D phenomena directly because wave-induced vortices and resulting suspended sediment motion are 3-D especially in a surf zone. However, no 3-D suspended sediment numerical model dealing with complex air-water interface motion was available until recently.

To overcome the drawbacks, Suzuki et al. (2007) developed a 3-D numerical model that can compute complex air-water interface motion and suspended sediment transport. The model was applied to hydraulic experiments on suspended sediment in a surf zone with the three-dimensionality of breaking waves, and its predictive capability was demonstrated against experimental data. Although suspended sediment transport processes of pickup, advection, and settling are taken into account in the model, diffusion of the remaining transport process is neglected because sediment transport due to diffusion is assumed to be smaller than that due to advection in the surf zone. The applicability of the model is not satisfactory to predict a wide variety of suspended sediment phenomena accurately.

Another 3-D numerical model for local scouring was developed by Liu and Garcia (2008). The model can track complex air-water interface motion and seabed profile evolution due to bed-load and suspended sediment transport. The predictive capability of the model was verified against experimental data on local scouring due to a wall jet and wave-induced local scouring around a circular cylinder. Unlike Suzuki et al.