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A wave-resolving model for nearshore suspended sediment transport

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ABSTRACT

This paper presents a wave-resolving sediment transport model, which is capable of simulating sediment suspension in the field-scale surf zone. The surf zone hydrodynamics is modeled by the non-hydrostatic model NHWAVE (Ma et al., 2012). The turbulent flow and suspended sediment are simulated in a coupled manner. Three effects of suspended sediment on turbulent flow field are considered: (1) baroclinic forcing effect; (2) turbulence damping effect and (3) bottom boundary layer effect. Through the validation with the laboratory measurements of suspended sediment under nonbreaking skewed waves and surfzone breaking waves, we demonstrate that the model can reasonably predict wave-averaged sediment profiles. The model is then utilized to simulate a rip current field experiment (RCEX) and nearshore suspended sediment transport. The offshore sediment transport by rip currents is captured by the model. The effects of suspended sediment on self-suspension are also investigated. The turbulence damping and bottom boundary layer effects are significant on sediment suspension. The suspended sediment creates a stably stratified water column, damping fluid turbulence and reducing turbulent diffusivity. The suspension of sediment also produces a stably stratified bottom boundary layer. Thus, the drag coefficient and bottom shear stress are reduced, causing less sediment pickup from the bottom. The cross-shore suspended sediment flux is analyzed as well. The mean Eulerian suspended sediment flux is shoreward outside the surf zone, while it is seaward in the surf zone.

1. Introduction

Nearshore sediment suspension is controlled by both the bottom boundary layer processes and wave breaking. In the surf zone, wave nonlinearity and irregularity influence the magnitude and distribution of suspended sediment concentrations (Nielsen, 1992). Wave breaking plays an instrumental role in sediment suspension and coastal sedimentary process. Previous studies (Nadaoka et al., 1989; Kubo and Sunamura, 2001; Ting, 2006, 2008) have revealed that wave breaking generates large-scale turbulent flow structures known as the obliquely descending eddies and downbursts of turbulent fluid, which may bring intense turbulence to the bottom and lift up a large amount of sediment into suspension (Ndaoka et al., 1988). Due to the complexity of surf zone hydrodynamics and sediment-flow interactions, nearshore suspended sediment transport is still not fully understood.

Due to its importance on coastal morphologic processes, there has been a number of studies focusing on sediment suspension in the surf zone. Some of these studies are based on laboratory and field measurements. For example, Ndaoka et al. (1988) performed laboratory experiments to study the detailed velocity field in the surf zone and its relationship to the sediment suspension. Their studies revealed the existence of obliquely descending eddies and that the sediment suspension is mostly governed by such large scale eddies in a wide extent of the surf zone. Sato et al. (1990) investigated the sand suspension due to breaking waves and proposed that the amount of suspended sand can be related to the breaking wave height, near-bottom velocity amplitude at breaking point as well as the fall velocity of the sand. The laboratory experiments of Kubo and Sunamura (2001) found the existence of "downburst", which was argued to be more vigorous than the oblique eddies on bottom sediment suspension. In the field, Voulgaris and Collins (2000) revealed that, inside the surf zone, vortices induced by breaking waves and bores are the main mechanism for sediment resuspension. Within the inner surf zone, hydraulic jumps (associated with strong offshore flows) are responsible for sediment resuspension. Numerical models have also been established to study this issue. Deigaard et al. (1986) conducted a numerical study on sediment suspension under broken waves by applying the transport equation for turbulent kinetic energy. Their model is far from maturity as the breaking wave and associated

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turbulence production are not simulated. Hsu and Liu (2004) presented a depth- and phase resolving model for two-phase suspended sediment transport under water waves based on the 2D Volume-of-Fluid (VOF) wave hydrodynamic model COBRAS. Their model can reasonably predict wave-averaged suspended sediment profiles under breaking waves. Suzuki et al. (2007) carried out a large eddy simulation of intermittent sediment suspension under surfzone breaking waves using a 3D VOF wave resolving model. Their model is capable of capturing the spatial and temporal intermittency of the sediment suspension, which induced by intermittent coherent motions under breaking waves (Cox and Kobayashi, 2000).

Prediction of nearshore sediment suspension highly resorts to robust and efficient numerical models. The VOF models (e.g. Hsu and Liu, 2004; Suzuki et al., 2007) are computationally expensive and impractical to be applied in the field scale. The Boussinesq-type equation models (e.g. Wei and Kirby, 1995; Lynett et al., 2002; Shi et al., 2012) have demonstrated a certain success in modeling surf zone hydrodynamics. However, these models are essentially one-layer models and do not resolve the vertical flow structures, thus are not capable of predicting the suspended sediment profiles. The non-hydrostatic approach has recently become a powerful tool on modeling surf zone hydrodynamics (e.g. Ma et al., 2012; Stelling and Zijlema, 2003; Smit et al., 2013). The basic difference from conventional Navier–Stokes models is that the free-surface is described as a single-value function of the horizontal plane, which allows the non-hydrostatic models to more efficiently compute free surface flows than VOF models. In this paper, we will develop a suspended sediment transport model based on the non-hydrostatic free-surface model NHWAVE, which was originally developed by Ma et al. (2012) for simulating nearshore wave processes. In modeling suspended sediment in the surf zone, a critical issue we need consider is the dynamic coupling between the turbulent flow and suspended sediment. Due to the high suspended sediment concentration, it is necessary to simulate the turbulent flow and suspended sediment in a coupled manner (Winterwerp, 2001; Wang, 2002; Hsu and Liu, 2004; Conley et al., 2008). In this paper, we will consider sediment-flow interactions from the macroscopic point of view.

The specific objectives of the current paper are to: (1) develop a robust and efficient suspended sediment transport model, which can simulate nearshore sediment suspension as well as sediment-flow interactions in both laboratory and field scales; (2) examine the relative importance of suspended sediment effects on turbulent flow field and self-suspension; and (3) investigate suspended sediment flux inside and outside surf zone. The paper will focus on wave-resolving sediment transport phenomenon, the time scale of which is relatively short compared to those associated with tides and pronounced morphological variability. Therefore, tide-induced wetting and drying as well as coupling with bathymetric changes are disregarded. The paper is organized as follows. The governing equations, boundary conditions as well as numerical schemes are presented in Section 2. The model applications on simulating sediment suspension under nonbreaking waves, surfzone breaking waves and a rip current field experiment (RCEX) are given in Section 3. The numerical results are discussed in Section 4, particularly focusing on understanding the relatively importance of suspended sediment effects on self-suspension and the cross-shore sediment flux. The conclusions are presented in Section 5.

2. Formulation

In this study, we will develop a non-cohesive sediment transport model into NHWAVE, which is a non-hydrostatic wave-resolving model recently developed by Ma et al. (2012). NHWAVE solves the incompressible Navier–Stokes equations in well-balanced conservative form, formulated in time-dependent, surface and terrain-following σ coordinates. The governing equations are discretized by a combined finite volume/finite difference approach with a Godunov-type shock-capturing scheme. The model is wave-resolving and can provide instantaneous descriptions of surface displacement and wave orbital velocities. The model has been applied to study wave damping in the vegetated environment (Ma et al., 2013a) and tsunami wave generation by submarine landslides (Ma et al., 2013b). In this section, we will briefly introduce the governing equations, boundary conditions as well as numerical schemes.

2.1. Governing equations

It is commonly recognized that, in the sediment-laden flow, the interactions between suspended sediment and turbulent flow may cause an appreciable modification of the turbulent flow structures (Crowe et al., 1996; Winterwerp, 2001; Ozdemir et al., 2010). In the surf zone, wave breaking may generate intense turbulence in the water column, which lifts up a large amount of sediments into suspension. The sediment concentration is so high that it is necessary to simulate sediment transport and turbulent flow in a coupled way. From the macroscopic point of view, the presence of sediment in the water column not only changes the density of the mixture, but also affects the turbulent velocity fluctuations as well as bottom boundary layer. In this study, the inter-granular interactions are neglected for simplicity. The sediment-laden flow is considered as a mixture of water and sediment, with the mixture density ρ_m defined as

$$\rho_m = (1 - C)\rho_0 + C\rho_s \tag{1}$$

where C is the sediment volume concentration, ρ_0 is the density of water, and ρ_s is the density of sediment.

The governing equations are transformed into a surface and terrain-following σ coordinate (Phillips, 1957), which is given by

$$t = t^* \quad x = x^* \quad y = y^* \quad \sigma = \frac{z^* + h}{D} \tag{2}$$

where (x^*, y^*, z^*) is the Cartesian coordinate system. $D = h + \eta$ is the total water depth, h is the still water depth, and η is the surface displacement.

With the sediment effects, the continuity and momentum equations in well-balanced conservative form (Liang and Marche, 2009; Ma et al., 2012) can be written as

$$\frac{\partial D}{\partial t} + \frac{\partial Du}{\partial x} + \frac{\partial Dv}{\partial y} + \frac{\partial \omega}{\partial \sigma} = 0 \tag{3}$$

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}}{\partial x} + \frac{\partial \mathbf{G}}{\partial y} + \frac{\partial \mathbf{H}}{\partial \sigma} = \mathbf{S}_h + \mathbf{S}_p + \mathbf{S}_\rho + \mathbf{S}_\tau \tag{4}$$

in which $\mathbf{U} = (Du, Dv, Dw)^T$, (u, v, w) are velocities in Cartesian coordinates. ω is the vertical velocity in σ coordinates, defined by

$$\omega = D\left(\frac{\partial \sigma}{\partial t^*} + u\frac{\partial \sigma}{\partial x^*} + v\frac{\partial \sigma}{\partial y^*} + w\frac{\partial \sigma}{\partial z^*}\right) \tag{5}$$

with

$$\begin{aligned}
\frac{\partial \sigma}{\partial t^*} &= -\frac{\sigma}{D}\frac{\partial D}{\partial t} \\
\frac{\partial \sigma}{\partial x^*} &= \frac{1}{D}\frac{\partial h}{\partial x} - \frac{\sigma}{D}\frac{\partial D}{\partial x} \\
\frac{\partial \sigma}{\partial y^*} &= \frac{1}{D}\frac{\partial h}{\partial y} - \frac{\sigma}{D}\frac{\partial D}{\partial y} \\
\frac{\partial \sigma}{\partial z^*} &= \frac{1}{D}
\end{aligned} \tag{6}$$