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Research paper

Numerical simulation of sediment particles released at the edge of the viscous sublayer in steady and oscillating turbulent boundary layers

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Abstract

The movement of suspended sediments in a turbulent boundary layer over a flat bed was numerically studied. Large Eddy Simulation was used to generate the velocity field, and the motion of individual particles was calculated using a modified version of the Maxey and Riley equation (1992). Three types of flows were considered: steady unidirectional, oscillating, and pulsating, with particle sizes ranging from silt to fine sand. In each experiment, 4096 particles were released at the upper edge of the viscous sublayer. The suspension rate, defined as the percentage of particles still afloat after the initial shakedown, depended strongly on the ratio of vertical root-mean-square (rms) velocity fluctuation to settling velocity in all types of flows. This is because the individual motion of sediment particles was strongly influenced by fluctuating flow structures even in the steady unidirectional flows, although the fluctuating small eddies did not last long. In the unsteady cases, a nontrivial relationship was also found with the phase of the flow as the survival rate of sediments was strongly correlated with the time of their initial releases. The survival rate significantly reduced with height in the oscillating flow compared with the pulsating flow because the turbulent fluctuations were confined within the thin boundary layer and did not extend to higher elevations in the oscillating flow.

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1. Introduction

Sediment suspension events and the movement of suspended sediments remain poorly understood even though suspended sediments may contribute significantly to total sediment transport. In coastal areas, the problem is further complicated by the unsteady nature of flow because of surface gravity waves. Waves are generally believed to be mainly responsible for sediment suspension, while currents carry away the entrained sediments. Thus, to investigate sediment suspension in this regime, an understanding of turbulent oscillating flows is necessary.

Experimenting with turbulent oscillatory flows over rough beds, Sleath (1987) demonstrates that turbulent intensities significantly fluctuate during cycles with two peaks per cycle. Jensen et al. (1989) outline their experimental results on purely oscillating turbulent boundary layers; particularly important is the observation that, without a mean current, oscillating flows cycle between the laminar and the turbulent state, with the transition usually occurring just before near-boundary flow reversal. Turbulent fluctuations due to the oscillatory free stream are usually confined within a thin oscillating boundary layer (Tardu et al., 1994; Scotti and Piomelli, 2001). Because of this, detailed measurements are often difficult to perform, and sometimes the interpretation of data is controversial.

The difficulties of using experimental methods to understand turbulent boundary layer dynamics have led to recent increases in the use of numerical methods. For the numerical

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computation of turbulent flows over a seabed, Reynolds-averaged Navier–Stokes (RANS) equations are often employed (e.g., Saffman, 1970; Launder and Sharma, 1974; Tjerry, 1995; Wilcox, 1998). RANS models use various closure schemes such as K-ε or K-ω to create the turbulent energy field, and they have been widely used for coastal engineering applications because of their low computational cost. However, Chang and Scotti (2004) found that RANS models underestimate the amount of Reynolds stresses in unsteady boundary layer flows. They also found that Large Eddy Simulation (LES) successfully generated the correct amount of turbulent quantities in near-bed regions. LES resolves the large-scale eddies that are considered to be important in energy transfer and models the smallest "sub-grid-scale" eddies (Moin and Kim, 1982; Rogallo and Moin, 1984). Also, RANS models were found to have some limitations on realizing small scale turbulence in many applications (e.g., Rehmann and Hwang, 2005; Hwang et al., 2006). Therefore, LES results are usually less sensitive to modeling errors than those obtained using a RANS method. LES may also have advantages over RANS in application to sediment suspension dynamics, which highly depend on the accuracy of the amount of generated turbulent energy.

Chang and Scotti (2003) found that the effect of coherent structures over small-scale ripples was sufficiently strong to influence the motions of sediments with LES. Moreover, they reported that, even over a flat bed, such coherent structures are important in suspending the sediments at the time of flow reversals, which causes strong sediment convective flux (Chang and Scotti, 2006). In relation to the ejection of sediments in the channel flow for the oscillatory boundary layer, fine sediment transport was simulated by Ozdemir et al. (2010). In lower concentrations of suspended particles, the suspension is believed to relate to the coherent structures of turbulence vortices. Soldati and Marchioli (2009) reviewed the processes and mechanisms of suspension and deposition of sediments under diverse conditions.

Regarding the dynamics of the particulate phase, an advection–diffusion equation is commonly used to consider the evolution of the Suspended Sediment Concentration (SSC). In advection–diffusion equations, the time variation of the volumetric concentration of a control volume is balanced by flow advection, turbulent diffusion, and settling due to gravity (Nielsen, 1992; Fredsoe and Deigaard, 1992). By combining the flow fields calculated by RANS models or LES with an appropriate SSC equation, the suspended concentration field can be calculated at each time step. Andersen (1999) used a K-ω-type RANS model to calculate the SSC and investigate ripple dynamics. Chang and Hanes (2004) used the same model for comparison with field data measured in a near-shore region. They showed that turbulent eddies are formed even by low-amplitude ripples with steepness 1/15, and the sediment suspension events are affected by these eddies. Zedler and Street (2001) used LES for three-dimensional calculations of the SSC in channel flow over ripples of 0.25 cm in height and 5 cm in length.

Even though the volume concentration calculation from the sediment advection–diffusion equation is efficient for practical purposes, it has a significant shortcoming. Because of the lack of knowledge about the transport mechanism, the eddy diffusivities for the mixing and transport modeling of the momentum and sediments may result in under- (or over-) estimation of the SSC predictions. To address these issues, individual motions of sediment particles are calculated according to the ambient flow motion, instead of estimating SSC based on a diffusivity model. Maxey and Riley (1983) include in their equation the effects of ambient pressure gradient, added mass, Stokes' drag, Basset force, and buoyancy on a single particle. This equation has been widely used for investigating the motion of small particles in turbulent flows (Pedinotti et al., 1992; Ahmed and Elghobashi, 2001; Armenio and Fiorotto, 2001; Wang and Squires, 1996a, 1996b; Armenio et al., 1999). Recently, Chang and Scotti (2003, 2006) coupled a modified Maxey and Riley equation (Wiberg and Smith, 1985) to a LES for application to problems in coastal environments because the seabeds are rippled instead of smooth and because the flow is unsteady owing to gravity waves. Soldati and Marchioli (2012) point out the weakness of the one-way coupling between liquid and particle, but they agree that LES may provide valid results of sediment flux in relation to resuspension.

The present work investigated sediment particle dynamics by coupling LES with the sediment particle equation as in Chang and Scotti (2006). That work focused on the numerical discovery of sediment convective flux due to flow reversal, which was closely related to coherent structures. However, unlike Chang and Scotti (2006), the present study focused on settling and suspending processes in relation to various flow and sediment conditions. Thus, both steady flow and unsteady flow were modeled with parameters as close as possible to those found in the environment, and with various particle sizes ranging from silt to small sand.

2. Numerical model

Details of the numerical models, such as the modeling schemes for fluid and particulate parts, are well described by Chang and Scotti (2003, 2006) and are introduced here only briefly.

At low concentration, the presence of sediments does not significantly alter the properties of the flow, and the fluid phase can be modeled separately from the particulate phase. The governing equations employed in the present study for the fluid phase are the filtered Navier–Stokes equations:

$$\frac{\partial \overline{u}_i}{\partial t}+\frac{\partial}{\partial x_j}\left(\overline{u}_i\overline{u}_j\right)=-\frac{\partial \overline{P}}{\partial x_i}+\nu\frac{\partial^2 \overline{u}_i}{\partial x_i \partial x_j}-\frac{\partial \tau_{ij}}{\partial x_j}, \tag{1}$$

$$\frac{\partial \overline{u}_i}{\partial x_i}=0. \tag{2}$$

The standard geophysical convention is used, where (x, y, z) or $(1, 2, 3)$ denote the streamwise, spanwise, and vertical directions, respectively, and (u, v, w) or (u_1, u_2, u_3) denote the flow velocities in the respective directions. The computational domain is a rectangular channel with height $2H = 0.2$ m, where H is the mid-depth of the channel, width $L_x = 0.6$ m, and length $L_y = 0.2$ m.

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