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Modeling net sheet-flow sediment transport rate under skewed and asymmetric oscillatory flows over a sloping bed

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ABSTRACT

A one-dimensional-vertical model is developed for net sheet-flow sediment transport rate under oscillatory boundary layer flows. This model couples the boundary-layer model proposed by Yuan and Madsen (2015) with new predictors for bedload and suspended-load transport rates. Sediment concentration is modeled by solving the advection-diffusion equation with a parameterized turbulence diffusivity and a bottom pick-up rate. The slope effect is included in the predictions of instantaneous bedload transport rate and sediment pick-up rate, so the model can rigorously account for wave nonlinearity (velocity skewness and asymmetry) together with a mild bottom slope. The model performance on net sediment transport rate is excellent for large grain sizes, except that the velocity-asymmetry effect seems to be moderately underestimated. For small grain sizes, the model performance deteriorates, but is still acceptable for many cases. This is possibly because the model does not consider turbulence damping due to stratification and underestimates the phase-lag effect. Using the validated model, it is found that a boundary layer streaming due to velocity skewness and/or asymmetry can be a major contributor to net transport rate, when significant sediment suspension occurs. A simple case study also suggests that a mild bottom slope can be equally important as the wave nonlinearity for producing net sediment transport rate. Model predictions show that wave-nonlinear and bottom-slope effects can be linearly superimposed, which provides a simple way for incorporating bottom slope into existing transport-rate formulas.

1. Introduction

Sediment transport is directly related to beach erosion and scour of coastal structures, and therefore is of primary interest to coastal scientists and engineers. Under very strong flow conditions, e.g. storm waves in shallow waters, intense sediment motion occurs in the immediate vicinity of a dynamically plane bed, which is often referred to as sheet-flow sediment transport. A number of previous studies, e.g. Wilson (1987) and Sumer et al. (1996), suggest that the thickness of sheet-flow layer is scaled with the product of sediment diameter and certain characteristics Shield parameter, and therefore can be only a few mm to a few cm. For wave-induced sheet flows, the net (time-averaged) transport rate is of the top importance, and therefore attracts a substantial amount of research efforts over the past decades (reviewed by Ribberink et al., 2008). A near-bed wave orbital motion with two symmetric half-periods cannot produce a net transport rate over a horizontal bed, so a non-zero net transport rate is due to some factors that introduce a small imbalance between the two wave half-periods.

Wave nonlinearity is believed to be a key factor. Shoaling waves become increasingly nonlinear as they travel into shallow waters, and the nonlinearity makes the bottom oscillatory flow skewed (the onshore half-period has a larger peak velocity but shorter duration than the offshore one) and asymmetric (the velocity time series has a “sawtooth” shape). If sediment transport rate is assumed to vary with flow condition in a quasi-steady manner, velocity skewness makes the total transport under the onshore half-period larger than that under the offshore half-period, leading to a net onshore transport rate. This is often referred to as the wave-shape effect. A number of sheet-flow experiments with skewed flows in oscillatory water tunnel (OWT) (e.g. Dibajnia and Watanabe, 1992; Ribberink and Al-Salem, 1994) have been conducted, and an onshore transport rate is indeed observed for tests with medium or coarse sediment grains. However, for fine sediments, a net offshore sediment transport rate is observed in many tests (e.g. Dibajnia and Watanabe, 1992; O'Donoghue and Wright, 2004). The phase-lag effect (e.g. Dohmen-Janssen et al., 2002) is believed to be the main reason, i.e. sediments suspended during the onshore half-period cannot settle back to the movable bed before the flow reversal, which significantly enhances the suspended-load transport during the offshore half-period. Velocity

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asymmetry, according to Nielsen (1992), makes the boundary layer under the onshore half-period thinner than that under the offshore half-period. Consequently, the vertical velocity gradient and bottom shear stress under the onshore half-period is larger. This argument is supported by some recently boundary-layer-flow experiments (e.g. van der A et al., 2011). Such a wave-shape effect will possibly lead to a net onshore transport rate, which is indeed observed in a few OWT sheet-flow experiments (e.g. van der A et al., 2010). Some observations of near-bed sediment concentration (e.g. Watanabe and Sato, 2004) suggests that the phase-lag effects may further enhance the onshore net transport rate for purely asymmetric oscillatory flows. This is because the sediment settling time before flow reversal is shorter for the offshore half-period, so the phase-lag effect can better benefit the suspended-load transport under the onshore half-period.

Many process-based model have been proposed for predicting net sheet-flow sediment transport rate due to skewness and asymmetry. Most of them are based on the 1-dimensional-vertical (1DV) approximation, i.e. flow is uniform in the bottom-parallel direction (as in OWTs), and adopt the one-phase approach (e.g. Davies and Li, 1997; Hassan and Ribberink, 2010), which treats suspended sediments as passive tracers. The main difference among existing models is the closure of turbulent fluid stress, e.g. from simple mixing-length-based theories (e.g. Styles and Glenn, 2000) to more complicated one-equation (e.g. Villaret and Davies, 1995) and two-equation (e.g. Hassan and Ribberink, 2010) closure models. High sediment concentration damps local turbulent and leads to hindered setting of sediments, so modifications of turbulent closure schemes and parameters for sediment diffusivity have been incorporated into various one-phase modeling techniques (e.g. Davies and Li, 1997; Guizien et al., 2003). Ruessink et al. (2009) investigated the effects of skewness and asymmetry on net transport rate under realistic field conditions. Recently, Caliskan and Fuhrman (2017) extended an 1DV and one-phase model to graded sands. To better describe the sediment motion in the sheet-flow layer, two-phase models are becoming popular (e.g. Hsu and Hanes, 2004; Liu and Sato, 2006; Li et al., 2008). These models differ in turbulence closure schemes, closures of sediment-phase turbulent stresses and fluid-sediment interactions. The reader is referred to the reviews by Amoudry et al. (2008) and Kranenburg et al. (2014) for more in-depth discussions. High-fidelity numerical models are still too computationally expensive to be integrated into large-scale nearshore models for coastal hydrodynamics and sediment transport, so it is desirable to develop simple yet realistic model that can balance computational efficiency and model accuracy.

Skewness and asymmetry differentiate the flow turbulence between the two half-periods, which leads to a boundary layer streaming (TI-streaming hereafter) embedded in the oscillatory flow (e.g. Trowbridge and Madsen, 1984). Within the wave boundary layer, TI-streaming usually opposites the wave traveling direction, and therefore can produce an offshore net transport rate. In OWTs, it is balanced by a facility-generated current, resulting in an offshore-oriented residual mean velocity in the very near-bottom region (e.g Ribberink and Al-Salem, 1995). Yuan and Madsen (2015) showed that TI-streaming is quite strong for purely skewed oscillatory flows, but is very weak for purely asymmetric oscillatory flows. This streaming is different from another well-known wave boundary layer streaming first proposed by Longuet-Higgins (1953) (LH-streaming hereafter), which is associated with wave propagation. The LH-streaming is usually in the wave traveling (onshore) direction, so it works against the TI-streaming. A substantial amount of work has been done to account for the LH-streaming in numerical modeling sheet-flow sediment transport (e.g. Fuhrman et al., 2013; Yu et al., 2010; Kranenburg et al., 2013) or some empirical transport-rate formulas (e.g. van der A et al., 2013). However, very little work has been done to investigate the TI-streaming's contribution, although it has been shown that they can be equally important for determining the mean Eulerian velocity (e.g Kranenburg et al., 2012).

In coastal regions, the seabed usually has a mild bottom slope with the downslope direction being offshore. The bottom-parallel component of gravity force can increase the total sediment transport during the offshore half-period but reduce that for the onshore half-periods, so a net offshore (downslope) transport rate can be expected. Although this effect is well recognized, very little work has been done for a good quantitative understanding. King (1991) in his OWT study measured how average sediment transport rate under a half-period of sinusoidal flow varies with bottom slope. Recently, Yuan et al. (2017) reported another experimental study in which net sheet-flow sediment transport rate is measured under sinusoidal oscillatory flows in a sloped OWT. They showed that the net downslope transport rate increases linearly with bottom slope and developed a simple model to illustrate the experimental results. Based on their measurements, they argued that the bottom-slope-induced net transport rate can be as important as those due to skewness or asymmetry. More research effort is required to further justify this argument. Most theoretical models assume a horizontal seabed, so the bottom-slope effect is rarely modeled in a process-based manner. Thus, it is also of interest to model the effect of nonlinear wave shape together with a sloping bed.

The main objective of this study is to investigate the relative importance of TI-streaming and bottom slope for modeling net sediment transport rate, which is not well understood to date. To this end, a process-based model is developed by extending the model proposed by Yuan et al. (2017), so it can rigorously account for a mild bottom slope together with velocity skewness and/or asymmetry. The outline of this paper is as follows. Section 2 presents the model, which is validated in Section 3. The importance of TI-streaming and bottom slope for net transport rate is discussed in Section 4 through some computational experiments. Conclusions are provided in Section 5.

2. A process-based model for net sheet-flow sediment transport rate

In this study, we assume that the flow is uniform in the bottom-parallel direction, which is strictly satisfied for OWT flows, so the governing equations for momentum and sediment suspension are 1DV. It should be noted that the LH-streaming, which comes from the convective acceleration terms in the governing equation, is consequently excluded in our model. This, however, does not defeat the main objectives of this study. The semi-analytical model developed by Yuan and Madsen (2015) (YM15 hereafter) is adopted for modeling turbulent oscillatory boundary layers. Net sediment transport rate is modeled as the sum of bedload and suspended-load components. Model descriptions are provided in the following sub-sections.

2.1. Boundary layer flow

Yuan and Madsen (2015) developed a semi-analytical model for turbulent oscillatory boundary layer flows with (or without) a collinear current. Following the 1DV approximation, the governing equation for Reynolds-averaged bottom-parallel velocity component, u, is

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\partial}{\partial z}\left(\nu_T \frac{\partial u}{\partial z}\right) \tag{1}$$

where ρ is water density, t is time, p is water pressure, x and z are the bottom-parallel and bottom-normal coordinates, respectively, and ν_T is the turbulent eddy viscosity. The pressure gradient is related to the free-stream flow based on the boundary-layer approximation

$$\frac{\partial u_\infty}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial x} \tag{2}$$

where u_∞ is the free-stream oscillatory velocity. In their model, ν_T is expressed as a time-averaged value $\nu_{T0}(z)$ times a temporal variation function $f(t)$, i.e.