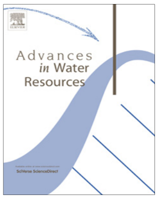
Advances in Water Resources 72 (2014) 57–70

Contents lists available at ScienceDirect

Advances in Water Resources

journal homepage: www.elsevier.com/locate/advwatres



Two-phase modeling of sheet-flow beneath waves and its dependence on grain size and streaming

Wouter M. Kranenburg [a,*], Tian-Jian Hsu [b], Jan S. Ribberink [a]

[a] Marine and Fluvial Systems Group, Twente Water Center, University of Twente, Box 217, 7500 AE Enschede, The Netherlands
[b] Center for Applied Coastal Research, Civil and Environmental Engineering, University of Delaware, Newark, DE 19716, USA

ARTICLE INFO

Article history:
Available online 27 May 2014

Keywords:
Sheet-flow
Sand transport
Turbulent wave boundary layers
Two-phase modeling

ABSTRACT

We study erosion depth and sediment fluxes for wave-induced sheet-flow, and their dependency on grain size and streaming. Hereto, we adopt a continuous two-phase model, applied before to simulate sheet-flow of medium and coarse sized sand. To make the model applicable to a wider range of sizes including fine sand, it appears necessary to adapt the turbulence closure of the model. With an adapted formulation for grain–carrier flow turbulence interaction, good reproductions of measured erosion depth of fine, medium and coarse sized sand beds are obtained. Also concentration and velocity profiles at various phases of the wave are reproduced well by the model. Comparison of sediment flux profiles from simulations for horizontally uniform oscillatory flow as in flow tunnels and for horizontally non-uniform flow as under free surface waves, shows that especially for fine sand onshore fluxes inside the sheet-flow layer increase under influence of progressive wave effects. This includes both the current-related and the wave-related contribution to the period-averaged sheet-flow sediment flux. The simulation results are consistent with trends for fine and medium sized sediment flux profiles observed from tunnel and flume experiments. This study shows that the present two-phase model is a valuable instrument for further study and parameterization of sheet-flow layer processes.

1. Introduction

Under high waves sand in the near-shore zone is transported as sheet-flow. The main characteristics of this phenomenon are that bed forms are washed away and that the motion of sediment extends down to several grain diameters below the initial bed level (erosion depth). This moving layer with high concentrations of sediment (sheet-flow layer) is held responsible for the larger part of the sediment transport. Good predictions of wave-induced sediment transport rates are of utmost importance for coastal engineering work. Therefore, it is relevant to gain detailed insights in sheet-flow characteristics and transport mechanisms and to develop tools to quantify transport rates in the sheet-flow regime.

Usually, morphodynamic models make use of (semi-)empirical sediment transport formulas (e.g. [45]). These formulas are generally based on sets of experiments with a limited number of wave and bed conditions. Besides, most of these experiments have been carried out in oscillating flow tunnels, while it has become clear from recent flume experiments that free surface effects not included in these tunnel experiments can largely affect the transport rates and underlying processes. Detailed numerical models can be helpful to investigate parameter values that have not been investigated experimentally and to improve the insight in underlying processes. Subsequent parameterization of the numerical model results can help to improve the physical basis of these transport formulas.

For these process-studies and parameterizations various types of numerical models are available. Here we mention (quasi) single phase and continuous two-phase wave boundary layer models. In single phase or suspension models, particles are, apart from the settling velocity, assumed to move with the fluid velocity, and sediment concentrations are determined from an advection–diffusion equation with a fixed-level lower boundary condition that relates the near-bed concentration or vertical sediment flux to the local shear stress through an empirical reference concentration or pick-up function. Models of this type have been very helpful to investigate the influence of e.g. the wave shape [26,47], grain size [21], stratification [10] and free surface effects [6,18,27,35,36] on boundary layer flow and/or sediment transport. Besides, they have been applied to predict bar migration [22,28]. An important lesson from these studies – in line with empirical findings of [12,43] – concerns the phase-lag behavior of fine sand: due to a small

---

* Corresponding author. Tel.: +31 53 4892959; fax: +31 534895377.
E-mail addresses: w.m.kranenburg@gmail.com (W.M. Kranenburg), thsu@udel.edu (T.-J. Hsu), j.s.ribberink@utwente.nl (J.S. Ribberink).

http://dx.doi.org/10.1016/j.advwatres.2014.05.008
0309-1708/© 2014 Elsevier Ltd. All rights reserved.

settling velocity fine sand can be stirred up during the flow motion in one direction but (partly) transported during the reverse motion. For velocity skewed oscillatory flow (modeling e.g. 2nd order Stokes waves), this can result in net offshore transport for fine sand compared to onshore transport for medium and coarse sized sand. Another lesson concerned the contribution to onshore sediment transport by 'progressive wave streaming', an onshore directed bottom boundary layer current under influence of vertical orbital motions in the horizontally non-uniform flow beneath progressive waves [38]. For medium sized sand, this process leads to increased onshore transport rate compared to what is found in tunnels. However, for fine sand it can even reverse the net transport direction from offshore (in oscillatory flow) to onshore (under progressive waves) [6,18,35].

Notwithstanding these valuable insights in sand transport behavior, the principle set-up of these models implicates that they cannot solve the details of the sheet-flow layer, like the fluctuating position of the bed, the shape of the flux profile up to this level and the adapted flow and sediment dynamics in the region of high sediment concentrations [18]. Alternatively, sheet-flow models have been developed based on theory for continuous two-phase flow. These models describe the motion of water and sediment from the immobile bed into the suspension layer with individual mass and momentum equations and mutual interactions between the phases. In principle, this makes it possible to simulate sediment suspension processes without empirical functions for reference concentrations or sediment pick-up and without any need to distinguish between bed load and suspended load. Examples of this type of models are [4,14,30,37,35]. Differences between the various two-phase models appear in the closures of respectively the turbulent stresses, either with mixing length, one-equation or two-equation turbulence closures, and interparticle stresses, either modeled with rheological equations like Bagnold's expressions for the viscous and inertia regime ([5], see also [1]), or using the concept of 'granular temperature' from collisional granular flow theory for the energy of the particle fluctuations [32]. Next, differences are found in the modeling of the particle–fluid interaction, both on the level of momentum equations (e.g. different descriptions of the drag force, omission of the added mass force) and concerning the particle influence on the carrier flow turbulence. Two-phase models, in principle all able to deal with oscillatory flows of different shape, have been applied in e.g. process-research on the influence of the wave shape [31], and for parameterization of the vertical sediment flux [54]. So far only [55] considered progressive wave streaming and other free surface effects by including horizontal and vertical advection in fluid, sediment and closure equations. However, this two-phase model – like many others – has been validated and is applicable for medium and coarse grains only.

As discussed above, fine sand can show a transport behavior under influence of wave shape and progressive wave effects significantly different from medium and coarse sized sand. To further improve sediment transport formulas, responsible processes need to be understood and parameterized. Therefore, it is the objective of this paper to predict sheet-flow layer behavior under progressive waves for sand sizes ranging from fine to coarse (0.1–0.5 mm). Characteristics we are especially interested in are erosion depth, sheet-flow layer thickness and the vertical distribution of the (wave- and current related components of the) sediment flux. Hereby, the dependency on grain size and the influence of progressive wave effects are central questions. To study this, we adopt the two-phase model of [55] and extend its applicability to fine grains by implementing an improved formulation for the particle influence on the fluid turbulence. We thus combine the advantage of continuum two-phase models over single-phase models in predicting the entire flux profile, with both the inclusion of progressive wave effects and the simulation of fine sand dynamics.

The set-up of the paper is as follows: Section 2 describes the background and set-up of the model. Section 3 describes the data selected for model validation. Section 4 shows validation tests on erosion depths for various grain sizes and explains why the model adaptation proposed in this study improves the model performance for fine sand. Next, Section 5 discusses a model-data comparison on time-dependent concentration profiles and time-dependent and wave-averaged velocity profiles, the latter both with and without progressive wave streaming. Subsequently, in Section 6 the model is applied to investigate trends in sediment flux profiles for fine and medium sized sand both without and with progressive wave streaming. Finally, Sections 7 and 8 respectively provide a discussion and summary of the conclusions.

2. Model formulation

2.1. Model background

The two-phase model we adopt here has been developed originally by Hsu et al. [29] for dilute sediment transport in steady and oscillatory flow. It has subsequently been extended with interparticle stress formulations to model sheet-flow of massive particles [30]. Amoudry et al. [3] have applied the model to sheet-flow of coarse and medium sized sand, meanwhile pointing at the limits for application to fine sand. The model applicability has been extended by Yu et al. [55] from horizontally uniform flow as present in oscillatory flow tunnels to horizontally non-uniform flow as present under propagating waves.

The model can be classified as a 1DV two-phase model with a two-equation (k–ε) fluid turbulence and an interparticle stress closure using the 'granular temperature' concept. The turbulence averaged momentum equations have been derived using Favre-averaging. In Favre-averaging, ensemble-averaging is applied to the momentum per unit mass of each phase instead of the velocity. As a result, the correlation between concentration and velocity fluctuations, commonly called turbulent suspension flux, appears in the momentum equations instead of the continuity equations [40]. The horizontal non-uniformity has been accounted for within the 1DV approach by the transformation:

$$\frac{\partial}{\partial x} = -\frac{1}{c}\frac{\partial}{\partial t} \tag{1}$$

which assumes that the waves propagate (with c the propagation velocity) without changing their form. Below, the model equations are given in the averaged and transformed form, as solved by the numerical model.

2.2. Governing equations

The continuity equations for the fluid (f) and sediment (s) phase are:

$$-\frac{1}{c}\frac{\partial(1-\phi)u^f}{\partial t} + \frac{\partial(1-\phi)w^f}{\partial z} - \frac{\partial\phi}{\partial t} = 0 \tag{2}$$

and

$$-\frac{1}{c}\frac{\partial\phi u^s}{\partial t} + \frac{\partial\phi w^s}{\partial z} + \frac{\partial\phi}{\partial t} = 0 \tag{3}$$

with ϕ the volumetric concentration of sediment and u and w the (Favre-averaged) velocity components in horizontal (x) respectively vertical (z) direction. The momentum equations of the fluid phase in the x- and z-directions can respectively be written as: