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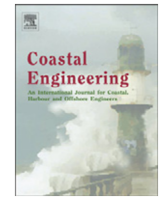

Well-balanced and flexible morphological modeling of swash hydrodynamics and sediment transport

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A B S T R A C T

Existing numerical models of the swash zone are relatively inflexible in dealing with sediment transport due to a high dependence of the deployed numerical schemes on empirical sediment transport relations. Moreover, these models are usually not well-balanced, meaning they are unable to correctly simulate quiescent flow. Here a well-balanced and flexible morphological model for the swash zone is presented. The nonlinear shallow water equations and the Exner equation are discretized by the shock-capturing finite volume method, in which the numerical flux and the bed slope source term are estimated by a well-balanced version of the SLIC (slope limited centered) scheme that does not depend on empirical sediment transport relations. The satisfaction of the well-balanced property is demonstrated through simulating quiescent coastal flow. The quantitative accuracy of the model in reproducing key parameters (i.e., the notional shoreline position, the swash depth, the flow velocity, the overtopping flow volume, the beach change depth and the sediment transport rate) is shown to be satisfactory through comparisons against analytical solutions, experimental data as well as previous numerical solutions. This work facilitates an improved modeling framework for the swash hydrodynamics and sediment transport.

1. Introduction

The term "swash zone" refers to narrow coastal regions that are successively covered and uncovered by water due to run-up and backwash of waves (Masselink and Hughes, 1998; Masselink and Puleo, 2006). Although the swash hydrodynamics and sediment transport have been studied for three decades (Brocchini, 2006), they still are insufficiently understood. For example, in a very recent paper by van Rijn (2014), the challenge of estimating the sediment transport rate in the swash zone was mentioned at least seven times. Here we present a morphological modeling technique for the swash zone which is both "well-balanced" and "flexible", the meaning of which is explained in the following paragraphs.

Among the different modeling approaches (e.g., the Reynolds-averaged Navier–Stokes equations, the Boussinesq equations, and the nonlinear shallow water equations), the present model adopts the nonlinear shallow water equations due to its relative simplicity but widely recognized applicability in the swash zone (Brocchini and Dodd, 2008; Hibberd and Peregrine, 1979). As suggested in Toro (2001) and Brocchini and Dodd (2008), the total variation diminishing (TVD) finite volume method, which is shock-capturing, is one of the most promising methods for solving the nonlinear shallow water equations. According to this method, the finite volume discretization is implemented to solve the governing equations, and the numerical flux is treated as a Riemann problem. Examples for modeling coastal flows are abundant, such as those using the exact Riemann solver (Wei et al., 2006), the weighted average flux (WAF) solver (Brocchini et al, 2001; O'Donoghue et al., 2010; Postacchini et al., 2012, 2014), the approximate Roe's solver (Dodd, 1998; Hubbard and Dodd, 2002), the HLL solver (Borthwick et al., 2006; Briganti and Dodd, 2009a, b; Hu et al., 2000; Kuiry et al., 2012; Mahdavi and Talebbeydokhti, 2011), and the centered approximate Riemann solver (Mahdavi and Talebbeydokhti, 2009). Other models for the swash zone include those based on the method of characteristics (Kelly and Dodd, 2010; Zhu and Dodd, 2013; Zhu et al., 2012) and the McCormack method (Briganti et al., 2012a, b), etc. Great progress has been made, but further improvement is critical for refined modeling quality, as detailed below.

First, as discussed in the comprehensive review by Brocchini and Dodd (2008), most numerical models have focused on the swash flow free of sediment transport (Borthwick et al., 2006; Briganti and Dodd, 2009a, b; Brocchini et al., 2001; Dodd, 1998; Hu et al., 2000; Hubbard and Dodd, 2002; Kuiry et al., 2012; Mahdavi and Talebbeydokhti, 2009, 2011; O'Donoghue et al., 2010; Wei et al., 2006), whereas only a few morphological models have been developed for the swash zone

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(Briganti et al., 2012a, b; Dodd et al., 2008; Kelly and Dodd, 2010; Masselink and Li, 2001; Postacchini et al., 2012, 2014; Zhu and Dodd, 2013; Zhu et al., 2012). However, due to the dominant use of the upwind-type numerical schemes and thus the involvement of the eigenstructures of the governing equations that depend on the use of a particular empirical sediment transport relation, it can be quite tedious to modify these models to implement other sediment transport relations, which makes them relatively inflexible. Unfortunately, flexibility in dealing with sediment transport is quite important due to the fact that there is no generally applicable empirical sediment transport relation, nor is it likely that any will be available in the near future. It is therefore no surprise to see the development of a TVD-McCormack scheme-based morphological model by Briganti et al. (2012a, b) that was designed to be flexible. However, an empirical sediment relation is still involved in the TVD-McCormack scheme. Moreover, the necessity of switching off the TVD function for sub-threshold sediment motion makes the model difficult to be extended to non-uniform sediment transport because sediment particles of different sizes have different threshold conditions (Hu et al., 2014). Note that the centered-type finite volume method intrinsically avoids the use of the aforementioned eigenstructures (Canestrelli et al., 2010; Toro et al., 2009), and thus allows for a more flexible modeling regarding the use of empirical sediment transport equations. However, this modeling technique has rarely been seen in morphological modeling of coastal flows (Mahdavi and Talebbeydokhti, 2009).

Second, existing numerical models for the swash zone rarely consider the well-balanced property (i.e., the balance between the bed slope source term and the flux gradient), making them in most cases unable to simulate quiescent flow (Hubbard and Dodd, 2002; Mahdavi and Talebbeydokhti, 2009; Wei et al., 2006). The reason for why so little of attention has been paid to the well-balanced property is that most coastal flows are highly dynamic (Brocchini and Dodd, 2008). However, the inability to model quiescent flows necessarily introduces uncertainties even to the modeling of such highly dynamic flows. It is the unknown magnitude of these uncertainties, which makes well-balanced modeling highly desirable (Aureli et al., 2008; Bollermann et al., 2013; Canestrelli et al., 2010; Capilla and Balaguer-Beser, 2013; Donat et al., 2014; Hou et al., 2013; Hu et al., 2012; Hubbard and Dodd, 2002; Li et al., 2014; Mahdavi and Talebbeydokhti, 2009; Siviglia et al., 2013; Wei et al., 2006; Zhou et al., 2001).

Motivated by the above background, this paper presents a well-balanced and flexible morphological model for coastal engineering purposes and tests its quantitative accuracy for swash flow. The governing equations of the model include the nonlinear shallow water equations for swash hydrodynamics and the Exner equation for beach morphological change. The governing equations are discretized by the shock-capturing finite volume method, in which the numerical flux and the bed slope source term are estimated by a well-balanced version of the SLIC (slope limited centered) scheme. The model is thoroughly validated through comparisons against analytical solutions, existing numerical solutions, and experimental data. Particular attention is paid to quantitative accuracy of the shoreline position, the swash depth, the swash velocity, the overtopping flow volume, the beach morphological change, and the sediment transport rate. The contribution of this paper is two-fold. First, it may be one of the first well-balanced morphological models for the swash zone. Second, it facilitates a flexible morphological modeling framework for the swash zone.

2. Mathematical formulations

2.1. Governing equations

The nonlinear shallow water equations coupled with the Exner equation for the swash zone are written in a vector form as (Briganti et al., 2012a, b; Kelly and Dodd, 2010; Postacchini et al., 2012, 2014; Zhu and Dodd, 2013; Zhu et al., 2012)

$$\frac{\partial \mathbf{U}}{\partial t}+\frac{\partial \mathbf{F}}{\partial x}=\mathbf{S}_b+\mathbf{S}_f \tag{1}$$

$$\mathbf{U}=\begin{bmatrix} h \\ hu \\ (1-p)z \end{bmatrix},\quad \mathbf{F}=\begin{bmatrix} hu \\ hu^2+gh^2/2 \\ q_b \end{bmatrix},\quad \mathbf{S}_b=\begin{bmatrix} 0 \\ (-\partial z/\partial x)gh \\ 0 \end{bmatrix},\ \mathbf{S}_f=\begin{bmatrix} 0 \\ -\tau_b/\rho_w \\ 0 \end{bmatrix} \tag{2a, b, c, d}$$

where $t=$ time; $x=$ horizontal coordinate; $h=$ flow depth, $u=$ depth-averaged flow velocity, $p=$ bed sediment porosity, $z=$ beach elevation, $g=$ gravitational acceleration; $q_b=$ sediment transport rate, $-\partial z/\partial x=$ beach slope, $\tau_b=$ bed shear stress, and $\rho_w=$ density of water. Here the bed shear stress is estimated as a bulk frictional force using the Manning roughness: $\tau_b=\rho_w u_*^2=\rho_w g n^2 u|u|/h^{1/3}$, where $n=$ Manning roughness, $u_*=$ bed shear velocity. The empirical relation for the sediment transport rate will be introduced in relation to the specific numerical cases in Section 3.

2.2. Numerical scheme

2.2.1. Finite volume discretization

Implementing the finite volume discretization along with the operator-splitting method, one obtains (Aureli et al., 2008; Hu et al., 2012)

$$\mathbf{U}_i^*=\mathbf{U}_i^n-\frac{\Delta t}{\Delta x}\left[\mathbf{F}_{i+1/2}^n-\mathbf{F}_{i-1/2}^n\right]+\Delta t\mathbf{S}_{bi} \tag{3a}$$

$$\mathbf{U}_i^{n+1}=\mathbf{U}_i^*+\Delta t\mathbf{S}_f\left(\mathbf{U}_i^*\right) \tag{3b}$$

where $\Delta x=$ spatial step, $\Delta t=$ time step, the superscripts n and * are time step indexes, the subscript $i=$ spatial index, and $\mathbf{F}_{i+1/2}=$ inter-cell numerical flux. The time step is constrained by the Courant–Friedrichs–Lewy condition using the Courant number Cr as a controller: $Cr=\left(u+\sqrt{gh}\right)\Delta t/\Delta x\le 1$.

2.2.2. Estimation of the numerical flux and bed slope source term

This sub-section introduces the WSDGM (weighted surface depth gradient method) version of the SLIC scheme, which is well-balanced and used to estimate the numerical flux and bed slope source term. The SLIC scheme results from the replacement of the Godunov flux (an upwind Riemann solver) by the first order centered (FORCE) flux in the MUSCL-Hancock scheme (Toro, 2001). In the SLIC scheme, the estimation of the numerical flux is seen as a Riemann problem with the two edge states defined at the two sides (referred to as left side and right side below) of the inter-cell edge. To achieve the second-order accuracy, the edge states are obtained by first using the interpolation from the cell center to the cell edge, and second evolving the interpolated states over a half time step. The original SLIC scheme is termed as the DGM (depth gradient method) version because it makes use of the spatial gradient of the water depth for the interpolation, which is stable for cases with small spatial gradients of the water depth. In practice, bed topographies are usually irregular and favor large spatial gradients, for which the DGM version may not be able to preserve the quiescent flow because of the unbalance between the bed slope source term and the flux gradient over an irregular topography. This motivated the development of the SGM (surface gradient method) by Zhou et al. (2001), which is well-balanced but may produce physically unrealistic results over a regular topography (Aureli et al., 2008). Retaining the good capabilities of both the DGM and the SGM, Aureli et al. (2008)