Coastal Engineering 89 (2014) 99–105

Contents lists available at ScienceDirect

Coastal Engineering

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

Short communication

Sediment transport and morphodynamics generated by a dam-break swash uprush: Coupled vs uncoupled modeling

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ARTICLE INFO

Article history:
Received 10 January 2014
Received in revised form 4 April 2014
Accepted 7 April 2014
Available online 4 May 2014

Keywords:
Sediment transport
Swash zone
Dam break
Laboratory experiments
Hydro-morphodynamic solver

ABSTRACT

The present work analyzes the hydro-morphodynamics characterizing the swash region during the uprush stage. A comparison is illustrated between the sediment transport measured in a series of dam-break experiments and that predicted by the numerical hydro-morphodynamic model of Postacchini et al. (2012). The primary aim is to investigate the differences arising between the weakly coupled or uncoupled model and the measurements, in terms of hydrodynamics, tip celerity and sediment transport. The hydrodynamics are well described by the model and results have been used to calibrate both friction factor and subgrid turbulent viscosity. Comparison of numerically-computed tip celerity with experimental data reveals a fairly good agreement, i.e. a mean error of about 10%, while modeled sediment transport differs by about 40% from the available data. No evident differences are found between results obtained from the coupled and uncoupled model runs (2% for the celerity and 11% for the sediment transport rate at the tip), suggesting that for the specific flow under investigation, at the leading edge of the swash front, hydro-morphological coupling is not an issue of fundamental importance. However, for the special case here of a swash forced by a dam-break, scour occurs at the dam location, and in this case the erosion of the bed is significantly larger in the uncoupled model.

1. Introduction

Because of the fundamental influence of the swash zone morphodynamics on the beach-face evolution (e.g. the cross-shore sediment exchange between subaerial and sub-aqueous zones, intense longshore sediment transport), much research is being devoted to this subject (e.g. Brocchini, 2013; Brocchini and Baldock, 2008; Elfrink and Baldock, 2002; Masselink and Puleo, 2006). Studies range from laboratory (e.g. Alsina et al., 2012; Baldock et al., 2011) to field (e.g. Aagaard and Hughes, 2006; Blenkinsopp et al., 2011; Masselink and Russel, 2006) experiments, with an increasing interest in the flexibility and power of numerical experiments (e.g. Bakhtyar et al., 2010). The usefulness of such numerical experiments is a function of a balance between suitable representation of the physics at hand and the computational costs entailed by the calculations. In this respect, depth-averaged solvers provide optimal performance and enable long-enough computations for morphological purposes, at least over short time-scales.

Typically, Nonlinear Shallow Water Equations (NSWE) are solved in conjunction with a sediment mass continuity equation. As for many phenomena influenced by multiple physical processes, coupled/uncoupled modeling of such mechanisms can lead to significant differences in predictions. In principle, it is reasonable to envisage significant differences between computations where the hydrodynamics are fully-coupled, weakly-coupled or uncoupled with the morphodynamics. Recent studies discussing this problem, e.g. Zhu and Dodd (2013), show that differences between fully coupled and uncoupled approaches accumulate during a swash event, dependent on the sediment transport formula in use.

The present study aims to understand the importance of coupled/un-coupled modeling for predictions of the swash zone sediment transport and morphology. In more details, we show that for dam-break events, similar to those forcing swash uprush events, weakly-coupled and uncoupled solutions are similar far from the dam, especially for steeper beach slopes. Closer to the dam-break location, corresponding to the location of the initiation of the swash, differences are larger.

The paper is structured as follows. The second section provides a brief description of the model background, the solver framework and the model limitations. Subsequently (Section 3.1), laboratory experiments and numerical setup are illustrated. Results are detailed in Section 4, including hydrodynamic calibration of the model and comparison between measured and predicted tip celerity and sediment transport. Final conclusions close the paper.

2. Numerical model

The solver used for the numerical simulations, described in Postacchini et al. (2012), is based on the NSWE, which are depth-

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http://dx.doi.org/10.1016/j.coastaleng.2014.04.003
0378-3839/

averaged, wave-resolving equations of conservation of mass and momentum. They describe wave breaking in terms of flow discontinuities and include seabed friction. The sediment flux and bed-level changes are calculated using standard sediment transport models and the Exner equation, which represents the solid mass conservation equation. One of the difficulties in obtaining good solutions derives from the large number of closure laws that are available to describe the sediment transport.

The NSWE/Exner system, written in conservative form, is a quasi-linear, hyperbolic set of equations. Such a fully-coupled system, could be solved through the "method of characteristics", this requiring intricate and, at times, analytically unsolvable computations for finding the resulting eigenvalues (e.g., see Kelly and Dodd, 2010). Hence, our solver is based on a rather different perspective. It does not directly solve the "method of characteristics", which requires the computation of the wave structure for the entire system, rather it is built on a weakly-coupled approach, which combines the separate hydrodynamic and morphodynamic solutions. By means of a switch, the model can solve the NSWE separately from the Exner equation. This makes the solver suitable to be used as either a weakly-coupled model, which we refer to as "coupled" hereafter, or an uncoupled model. In the former case, the hydrodynamic solution represents the initial condition for the morphodynamic solution, which, in turn, is the initial condition for the hydrodynamic solution at the following time step. In the latter case, the hydrodynamics are the initial condition for the Exner equation, whose solution does not affect the following hydrodynamic solution, but is only used to find the morphodynamic solution at the following time step.

2.1. The HM solver

The hydro-morphodynamic (HM) solver is built on the NSWE/Exner system. In its non-conservative form this reads:

$$d_{,t} + (ud)_{,x} + (vd)_{,y} = 0, \tag{1}$$

$$u_{,t} + uu_{,x} + vu_{,y} + gd_{,x} = -gz_{b,x} - B_x + F_x, \tag{2}$$

$$v_{,t} + uv_{,x} + vv_{,y} + gd_{,y} = -gz_{b,y} - B_y + F_y, \tag{3}$$

$$z_{b,t} + \mu^{-1}\nabla\cdot\mathbf{q} = 0, \tag{4}$$

where (x, y, z) are Cartesian orthogonal coordinates, d the total water depth, z_b the seabed position with respect to the still-water level, $\mathbf{v} = (u, v)$ the depth-averaged velocity vector, g gravitational acceleration, $\mathbf{q} = (q_x, q_y)$ the sediment transport flux and μ the grain packing. B_x and B_y represent the seabed friction, defined using a Chezy-type formulation by means of the dimensionless coefficient C_f.

In comparison to Postacchini et al. (2012), two further terms are introduced, i.e. F_x and F_y, which are the dissipative forces induced by subgrid turbulence, i.e. that turbulence which evolves at scales smaller than the water depth. Turbulent stresses are evaluated as:

$$F_x = \frac{(dT_{xx})_{,x} + \left(dT_{xy}\right)_{,y}}{d}, \quad F_y = \frac{\left(dT_{xy}\right)_{,x} + \left(dT_{yy}\right)_{,y}}{d}, \tag{5}$$

$$T_{xx} = 2\nu_T u_{,x}, \quad T_{xy} = \nu_T\left(u_{,y} + v_{,y}\right), \quad T_{yy} = 2\nu_T v_{,y}, \tag{6}$$

and the eddy viscosity is modeled as:

$$\nu_T = \lambda g^{1/2} d^{3/2}, \tag{7}$$

where λ is a calibration factor, similar to that adopted by van Prooijen et al. (2005).

An operational-split solution of the NSWE/Exner system is achieved by separately solving the NSWE and the Exner equation. The former is solved using the Weighted Average Flux (WAF) method, described in Brocchini et al. (2001), which has also been applied for the solution of the Exner equation. Further details on the solution of both the NSWE and Exner equation and the procedure used for their coupling can be found in Postacchini et al. (2012).

The morphodynamic module has been developed to properly match the hydrodynamic solver, which provides the forcing to update (4) in time. Uncoupled models are often characterized by the use of different approaches to solve the system at hand; Postacchini et al., (2012) decided to be consistent with the numerical scheme used for the hydrodynamic solver, thus choosing a finite-volume method for the Exner equation.

The solver enables the user to choose among different types of sediment transport closure laws, the total sediment transport ($\mathbf{q}$) being computed as the sum of both bedload ($\mathbf{q}_b$) and suspended ($\mathbf{q}_s$) contributions. Due to the weakly-coupled approach, both simple and complex closures that are available in the literature can be used in the solver (e.g. Grass, 1981; van Rijn, 1984). Implementation of these formulae requires the evaluation of the transport coefficients which are contained in the various formulations.

Since the present study is only aimed at comparing the solid transport predicted by the model with available total load measurements, the suspended sediment contribution is deactivated, while the modified Meyer–Peter–Müller formula (see Besio et al., 2003) is used for the total load description:

$$\mathbf{q} = C\sqrt{(s-1)gd_{50}^3}\left(|\boldsymbol{\theta}-\gamma\nabla z_b|-\theta_c\right)^{\frac{3}{2}}\frac{\boldsymbol{\theta}-\gamma\nabla z_b}{|\boldsymbol{\theta}-\gamma\nabla z_b|}, \tag{8}$$

where the Shields parameter for the incipient sediment motion is defined as

$$\boldsymbol{\theta} = \frac{C_f\mathbf{v}^2}{(s-1)gd_{50}}. \tag{9}$$

Closure (8) accounts for the water (ρ) and sediment (ρ_s) density through $s = \rho_s/\rho$, the median sediment diameter (d_{50}), the critical Shields parameter ($\theta_c = 0.05$), the stabilizing effect of gravity ($\gamma = 0.1$, as suggested by Fredsøe (1974)) and the spatial bed level variation estimated (∇z_b), which is computed at the grid scale. The transport coefficient used by Besio et al. (2003) is $C = 8$, but it is here set to 12, in agreement with the observations discussed in the coastal literature (e.g. Baldock et al., 2005; Nielsen, 1992).

2.2. Model limitations

Similarly to the majority of hydro-morphodynamics models (e.g. Zhu and Dodd, 2013), a constant friction coefficient is used, this providing an important constraint for the hydrodynamic calibration. There is considerable discussion on the value of the friction factor to be used during uprush and backwash and how the friction should be incorporated into models (e.g. Puleo et al., 2012). The simplest approach is to use a single value for the uprush and backwash, this depending on both the hydrodynamics and the grain size. Additionally, for swash zone flows the friction factor should be in the range $f_w = 2C_f = 0.01 - 0.05$ for a grain size $d_{50} = 0.2$ mm (Baldock et al., 2005), but not much is known on the range of the friction value for coarser materials (see Othman et al., 2014, for recent measurements and modeling). Nevertheless, the value of friction factor does not necessarily relate to the physical value of the actual friction factor, which is also hard to determine accurately for unsteady flows (e.g., see Barnes et al., 2009).