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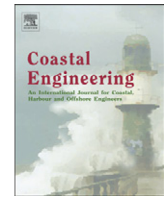

Advances in numerical modelling of swash zone dynamics☆

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ABSTRACT

We present a comprehensive and critical review of work on the numerical modelling of swash zone processes between 2005 and 2015. A wide range of numerical models has been employed for the study of this region and, hence, only phase-resolving approaches (i.e., depth-averaged and depth-resolving models) are analyzed. The current advances in the modelling of swash zone processes are illustrated by comparing different numerical models against laboratory experiments of a dam-break-driven swash event. Depth-averaged and depth-resolving models describe well the swash flow for both coarse sand and gravel impermeable beach cases. Depth-averaged models provides a practical tool for engineering use, whereas depth-resolving models improve the flow description, especially for the backwash phase, with a significantly higher computational cost. The evolution and magnitude of bed shear stresses predicted by all models is reasonable when compared with laboratory estimates based on the log-law. However, differences between modelling approaches cannot be rigorously evaluated owing to the uncertainty in shear stress estimates while employing such approximation. Furthermore, small-scale processes, such as turbulence evolution, are investigated with depth-resolving models, finding differences between the two-dimensional and three-dimensional approaches. Numerical models allow us to investigate other processes such as beach morphology changes, the evolution of the turbulence coherent structures, and the infiltration/exfiltration effects on the swash flow. A discussion on the advantages and limitations of each model is presented. The future of swash zone modelling depends on the increase of the computational power and, more importantly, on the improvement of the current capability to obtain intra-wave measurements for model validation, calibration, and greater resolution of physical processes.

1. Introduction

The beach region alternatively covered and uncovered by the short and long wave-induced water level fluctuations is known as the swash zone. The understanding of this region is fundamental to predict beach erosion and inundation during both extreme and mean wave conditions. Furthermore, it can be expected that the effects of climate change (e.g., sea level rise and storm intensification) will produce a more drastic impact on this region of the foreshore. However, the investigation of the physics of the transient, shallow, turbulent and multi-phase swash flow is a challenge for the fluid mechanics, because conducting measurements in this region is very difficult (Puleo et al., 2012). Therefore, the numerical modelling of the swash zone dynamics has been the focus of active research during the past decade (see Brocchini and Baldock, 2008).

The 1*st* International Workshop On Swash Zone Processes (Puleo and Butt, 2006) that took place in 2004, provided guidance regarding to where swash dynamics research efforts should be directed. During the meeting, some of the key topics on the hydrodynamics and sediment transport that needed to be addressed were identified. These topics included: the spatio-temporal structure of velocity profiles and turbulence, the boundary layer dynamics, the effect of infiltration/exfiltration on sediment transport within the swash zone, and the modelling of morphological changes.

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The aim of the present contribution is twofold. On one hand, the paper aims at presenting a comprehensive review of work on swash zone processes modelling published in the decade 2005–2015 (Section 2). In ten years a wide range of numerical models have been used in the context of swash processes and hence we focus only on the intra-wave (phase-resolving) approaches. On the other hand, we critically analyze the ongoing work by comparing different models through a specific, representative, benchmark case of dam-break-driven swash experiments. A general description of the depth-resolving and depth-averaged models employed in this work is given in Section 3. The different phase-resolving models are compared with the benchmark case and are further employed to investigate other processes in Section 4. This is followed by a discussion on the models capabilities/limitations based on the results from the previous section (Section 5). Finally, concluding remarks are presented in Section 6.

2. The recent past: review of swash zone modelling

Swash zone modelling efforts using phase-resolving models have been devoted to improve the knowledge of intra-swash flow and bed evolution. Here, a review of recent work related to these topics is presented. The approach here followed is that of describing the hydrodynamics moving in the surface-to-bottom direction and the morphodynamics from the small-scales to the large-scales.

2.1. Description of the flow

2.1.1. Flow velocity, turbulence, acceleration

The detailed and accurate description of the flow structure at any stage of bore generated swash events (i.e., bore shoaling, collapse, run-up and down-rush) is of paramount importance for the knowledge of swash processes and, in particular, for the understanding of the interaction between the flow and the sediment. Numerical models based on depth-resolving equations are best suited to provide an insight in the flow structure and they contributed in describing features of such flow at scales so small that cannot be resolved with experimental methods. The resolution of these features and the description of the evolution of flow parameters and turbulence are among the most significant advances in the knowledge of swash flows of the last decade.

Zhang and Liu (2008) provided a comprehensive analysis of a bore-generated swash event using Reynolds-Averaged Navier Stokes (RANS) equations, which has been verified and further extended by subsequent studies. The evolution of the flow in the shoaling region depends on the bore strength, i.e. by its Froude number. Stronger bores are those that break during the shoaling phase, before arriving at the undisturbed position of the shoreline, whereas weaker bores collapse only when they reach the still-water shoreline. The offshore flow parameter hence determines important differences in the other phases of the flow (as also found by Guard and Baldock, 2007) and, in particular in the evolution of the Turbulent Kinetic Energy (TKE). In the strong-bore case the TKE is produced only at bore breaking when the production/dissipation of TKE are roughly in balance. Further up the beach, the TKE undergoes a power-law decay with a 1.3 slope, similar to homogenous grid turbulence. For the weak-bore case the maximum TKE occurs at the beginning of the run-up phase and the TKE decay rate is only half of that occurring at a strong bore. This description of the evolution of the TKE has been confirmed in the subsequent works of Bakhtyar et al. (2009) and Desombre et al. (2013).

After the collapse the run-up phase begins and, as the swash lens stretches on the beach, the velocity profile becomes uniform on the water column and the speed of the tip decreases owing to the effect of the bottom stress. One of the most important small-scale features resolved by Zhang and Liu (2008) is a secondary mini-bore collapse that occurs in the late stage of the run-up in the strong bore case. This was later observed in the laboratory experiments by Kikkert et al. (2012).

The later stages of run-up and the occurrence of flow reversal are critical for the development of the bottom boundary layer (see Subsection 2.1.2) and hence for sediment transport. Depth-resolving models predict that at this stage the vertical structure of the velocity is complex. Reversal starts away from the tip of the swash lens and from the bottom of the water column. This creates velocity profiles similar to those of a strong wall-jet (Zhang and Liu, 2008). However, the implication of these features on sediment transport are not yet determined and numerical models that predict bed evolution (e.g., Briganti et al., 2012) do not currently take this into account.

As the backwash progresses the flow velocity increases and at a later stage the surface forms a bore-like feature, approximately at the position of the still-water shoreline, confirming the onset of a backwash bore discussed in the early work of Hibberd and Peregrine (1979). This feature is also well captured by virtually all models used for swash flows and discussed here. TKE levels in the backwash are much lower than in the uprush and are bed-generated. Together with the dynamics of the TKE, flow accelerations during a swash event have been extensively studied in the last decade as a likely primary agent of enhanced onshore sediment transport. However, shoreward-directed accelerations exist only for up to 22% of the swash cycle, hence, as found in Puleo et al. (2007), using again a RANS model. The aforementioned enhancement occurs only for a short duration. The description of the acceleration provided by Puleo et al. (2007) was also confirmed by O'Donoghue et al. (2010) who used a Non Linear Shallow Water Equations (NLSWE) solver. Furthermore, near bed pressure gradients are poorly correlated to the local fluid acceleration. Further studies (Torres-Freyermuth et al., 2013) suggested that an acceleration-enhanced sediment transport formulation does not improve sediment transport prediction within the swash zone.

2.1.2. Bottom boundary layer dynamics

Beyond the fundamental dynamics that evolve within the water body, the evolution of the Bottom Boundary Layer (BBL) and, in turn, that of the bed shear stress, during a swash event plays an important role in sediment transport. One of the most important issues highlighted by Puleo and Butt (2006) was the need to overcome the formulation of the shear stress based on steady flow results. To this end, numerical models based on NLSWE have been used in conjunction with simplified BBL models to provide a simple yet accurate estimate of the bottom shear stress.

The development of the BBL is impulsive at bore arrival and it quickly becomes depth-limited until the flow slows down and approaches reversal. During the backwash phase the BBL grows again to become depth limited. This description was achieved by using the momentum integral method by Barnes and Baldock (2010) and Briganti et al. (2011) who employed a Lagrangian and Eulerian framework, respectively. These two studies indicated that the momentum integral method provides a reasonable description of the BBL during the uprush, while the accuracy of the models decreases for the backwash. However, details, e.g. that flow reversal occurs close to the bottom first (see Zhang and Liu, 2008), are not captured by these models. Furthermore, the impulsive development of the BBL in the uprush may not be the result of turbulent diffusion; its growth might be explained also with the horizontal straining of fluid parcels associated with the bore arrival (Torres-Freyermuth et al., 2013, Pintado-Patiño et al., 2015). Therefore, the validity of the momentum integral method needs to be assessed. As a consequence of the evolution of the BBL, the landward-directed bed shear stress is maximum during the early stage of run-up, in the region of bore collapse (see Barnes and Baldock, 2010 and Briganti et al., 2011). At different locations, the magnitude of the stress is maximum at the arrival of