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Non linear shallow water modelling of bore-driven swash: Description of the bottom boundary layer

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ABSTRACT

The paper presents a simple approach to estimate the bottom shear stress in the swash zone by coupling the Non Linear Shallow Water Equations with the momentum integral equation for the bottom boundary layer. The approach allows not only the computation of the frictional dissipation term in the equations but also to have an insight into the flow structure in the water column during a swash event. The numerical results have been compared with a new set of experiments involving a single dam-break generated swash event. Three different grain sizes, ranging from coarse sand to gravel, have been tested in the laboratory.
A sensitivity analysis on the only calibration parameter of the model, the bed roughness, is presented and its optimal value is chosen. The numerically predicted free surface, depth averaged velocity and velocity profiles have been compared with the measured ones. Results are very good in the run-up stage, where also the bottom shear stress is well modelled. In the backwash the frictional energy dissipation is better modelled for the gravel beach than for the coarse sand one. Results show that the simple model accurately predicts the flow parameters during the swash event. Also the velocity profiles are reasonably well predicted, especially during the run-up.

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1. Introduction

Swash flows can successfully be modelled with depth-integrated numerical approaches based on the Non-Linear Shallow Water Equations (NLSWE) as numerous studies (see Brocchini and Dodd, 2008 for a review) show. Recently an increasing number of researchers have made use of this class of models for the prediction of the bed evolution in the swash zone (e.g. Kelly and Dodd, 2009; Briganti et al., 2011). A key issue for this class of applications is the modelling of the bottom shear stress, which is crucial for sediment entrainment and drag exerted on the flow. This is usually introduced using the Chezy approach, originally derived for steady flows.

The approach is limited as it is recognized that in the case of non-steady flow the friction factor is not constant (see the seminal works on oscillatory flows by Jensen et al., 1989 and Lodahl et al., 1998). Recently the works by Barnes and Baldock (2010) and O'Donoghue et al. (2010) have shown experimental evidence of the variability of the friction factor during a swash cycle, providing further motivation to improve the present approach in NLSWE modelling.

In alternative to the NLSWE it is possible to use models that are able accurately to describe the bottom boundary layer, such as those based on depth resolving hydrodynamic equations (see Puleo et al., 2007 and Zhang and Liu, 2008). However, these are more complex and computationally expensive than those based on NLSWE. Therefore, it is highly desirable to retain the simplicity of the NLSWE framework, and complement it with the capability of describing the bottom boundary layer. This is achieved by coupling the equations for the hydrodynamics with a sub-model that is able to describe the evolution of the boundary layer and provide the value of the shear stress. The approach followed by Clarke et al. (2004) is particularly suitable for our purposes. It employs the momentum integral method described in Fredsøe and Deigaard (1993). A similar approach is used by Barnes and Baldock (2010), who developed their model from a Lagrangian point of view. Their paper also offers a very good review of experimental and theoretical work on the matter. A further example of the use of momentum integral equations in the context of NLSWE is Packwood (1980). The author uses the complete set of equations for the momentum integral, which includes both time and spatial derivatives, unlike the model described by Fredsøe and Deigaard (1993) that includes only the time derivative of the layer thickness.

In this paper the momentum integral method is used and coupled to the NLSWE. The model is tested against the experiments carried out at the University of Aberdeen within the EPSRC funded project "Experimental and Numerical Modelling Study of Swash Zone Hydrodynamics and Sediment Transport" (EP/EO10407/1 and EP/E011330/1). These experiments have been designed specifically to investigate the flow structure during a single dam-break generated,

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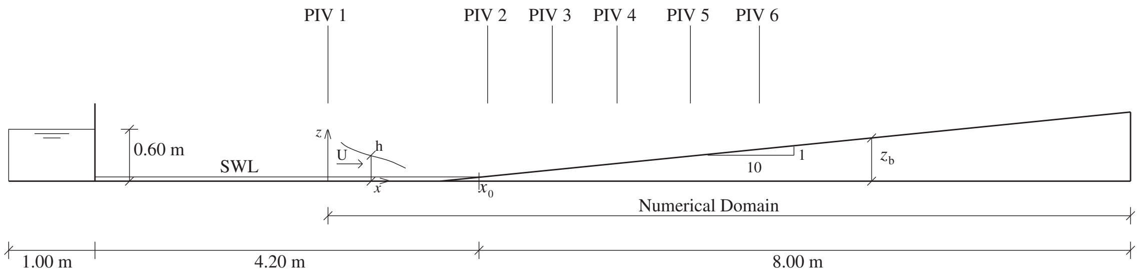

Fig. 1. The Aberdeen Swash facility. The position of the centre of the PIV measurements areas is indicated with vertical lines.

Table 1
Sediment sizes for the three beaches tested in Aberdeen.

Diameters [mm]	*IMP015*	*IMP060*	*IMP100*
D_{10}	10	36	65
D_{35}	12	50	77
D_{50}	13	54	84
D_{65}	1.5	5.8	91
D_{84}	18	64	105
D_{90}	19	69	109

Table 2
Locations of the centre of the PIV/LIF measurement stations and investigation areas.

Station	x[m]	PIV area [mm] × [mm]
PIV1	−1.802	223.7 × 167.8
PIV2	0.072	211.7 × 158.8
PIV3	0.769	199.7 × 149.7
PIV4	1.559	201.4 × 151.1
PIV5	2.365	164.7 × 123.5
PIV6	3.161	106.6 × 79.9

swash event. For this reason they are perfectly suited for an in-depth analysis of the description of the flow characteristics with the approach proposed here. The paper is organized as follows: Section 1 is the Introduction, and Section 2 describes the governing equations for the flow and boundary layer. Section 3 briefly describes the experiments. Section 4 describes and discusses the numerical results. Conclusions are given in Section 5 and an Appendix A gives details on the computation of the free stream velocity in the model.

2. The governing equations and the numerical solver

The proposed numerical model is based on the NLSWE. Fig. 1 describes the variables of the problem. Here x is the horizontal abscissa, t is time, U denotes the depth-averaged horizontal velocity, h is the local water depth, and z_B is the bed level:

$$\frac{\partial h}{\partial t} + \frac{\partial hU}{\partial x} = 0 \tag{1}$$

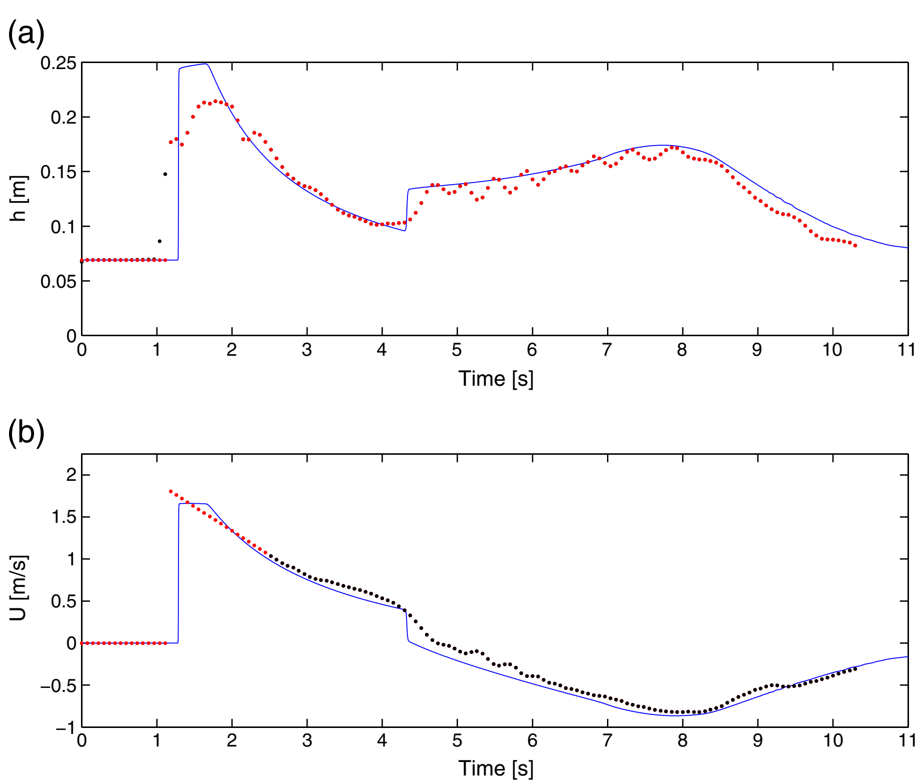

Fig. 2. Initial conditions for the numerical simulations. Panel (a): h. Red dots: actual data used for the simulations. Black dots: data removed. Blue solid line: predicted h using the whole swash domain. Panel (b): U. Black dots: actual signal from PIV1; red dots, extrapolated data. Blue solid line: predicted U using the whole swash domain.

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