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Boundary layer dynamics in the swash zone under large-scale laboratory conditions

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ABSTRACT

This paper presents the results of a laboratory experiment of swash hydrodynamics on a coarse sand barrier beach backed by a lagoon. Boundary layer dynamics have been analyzed using the high-resolution near-bed velocities measured by Acoustic Doppler Velocity Profilers deployed in the swash zone. Swash events have been ensemble-averaged in order to study mean hydrodynamic patterns. A proposed velocity gradient criterion allowed identification of the boundary layer growth during the backwash phase, but it was unable to characterize boundary layer variability during uprush. Cross-shore velocity profiles were well represented by the logarithmic model for a large portion of the ensemble-averaged swash duration. Uprush and backwash logarithmic-estimated friction factors were of the same order of magnitude with a strong variability related to the boundary layer growth during the backwash. The momentum integral method provided smaller bed shear stresses than the logarithmic model, a result possibly related to either the assumptions involved in the momentum integral method or to an underestimation of the boundary layer thickness during uprush. A decrease of friction coefficients for increasing Reynolds numbers at the early backwash was observed. This behavior is consistent with traditional results for steady and uniform flows in a transitional regime.

1. Introduction

Nearshore waves propagate across the surf zone into shallower depths eventually washing up and down on the beach face. These direction-reversing flows, called uprush and backwash, characterize the swash zone motion and define the moving shoreline. Surf zone waves represent the first-order forcing of swash motions, which are subsequently affected by hydro- and morphodynamic factors such as nearshore currents, wind forcing, groundwater table fluctuations, beach morphology, and sediment characteristics. Interactions between the hydrodynamics and the sandy bottom yield large vertical velocity gradients close to the seabed. As a result, wave energy dissipation occurs in a thin bottom boundary layer characterized by large shear stresses, high turbulence levels, and considerable sediment loads. The bed shear stress induced by boundary layer dynamics is of great importance for bringing sediment into suspension. Nowadays, widely used morphological models implement sediment transport formulations, which include the bed shear stress as the primary mechanism for sediment mobilization in the swash zone.

Observations of the structure of the bottom boundary layer in the swash zone have been reported by means of field, laboratory, and numerical experiments. Recently, useful insights were yielded by the field work of Puleo et al. (2012) and Puleo et al. (2014a), who used a newly developed high-resolution Acoustic Doppler Velocity Profiler (ADVP) to measure the cross-shore velocity profiles under low energetic swell forcing. The increased measurement resolution improved the characterization of the lower boundary layer kinematics and enhanced confidence in the estimated bed shear stress values. In addition to field observations, laboratory studies have taken advantage of controlled experiments in order to address swash dynamics under highly monitored systems (Archetti and Brocchini, 2002; Cowen et al., 2003). Recently, Barnes et al. (2009), O'Donoghue et al. (2010), and Kikkert et al. (2012) achieved high spatial resolution of the swash hydrodynamics over fixed, impermeable beds through laser-induced fluorescence (LIF) and particle image velocimetry (PIV). In particular, Kikkert et al. (2012) were able to resolve the backwash shoreline position and the late backwash phase in which the shallow depths and large velocities challenge reliable data collection. In recent years, numerical models based on the nonlinear shallow water (NLSW) and Reynolds-averaged Navier–Stokes (RANS) equations have become a powerful tool to explore swash hydrodynamics. Barnes and Baldock (2010), Briganti et al. (2011) and Torres-Freyermuth et al. (2013) provided detailed descriptions of the boundary layer evolution in the swash zone by modeling the laboratory experiments of O'Donoghue et al. (2010).

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Recent work dealing with swash zone motions has provided insightful description of boundary layer dynamics under a wide range of environmental conditions. However, the challenging swash zone environments in conjunction with the measurement technique limitations have led to the necessity of making considerable assumptions about the boundary layer structure. Several studies (Masselink et al., 2005; O'Donoghue et al., 2010; Puleo et al., 2012, 2014a) estimated the bed shear stress by fitting the horizontal velocity profiles close to the bed to a logarithmic model. The logarithmic model generally provided good agreement with measurements for a large portion of the swash, but it performed less well during the uprush phase of swash in which aeration and surface-injected turbulence play an important role. Moreover, there is no consensus about the relative magnitudes of the estimated friction factors during uprush and backwash. Kikkert et al. (2012) took advantage of the detailed measurements of velocity in an effort to compare bed shear stress estimations using different approaches such as the logarithmic and the momentum balance methods. Overall, past studies have outlined the necessity of high-resolution velocity measurements for achieving a better estimation of bed shear stresses in the swash zone (Alsina and Caceres, 2011; Butt et al., 2009; Puleo et al., 2000). It has been recognized that a detailed description of the near-bed velocity field is crucial for a proper quantification of sediment fluxes that are ultimately estimated as the product of the velocity and sediment concentration measurements. In fact, despite the increasing attention that the swash zone dynamics have received in the last decade, a complete understanding and characterization of swash boundary layer motions and sediment transport processes is still lacking.

This work reports measurements of swash hydrodynamics collected during recent laboratory experiments carried out in a large-scale wave flume (Masselink et al., 2016). We report high-resolution cross-shore velocity profiles recorded in the swash boundary layer of a sandy beach under irregular wave conditions. The main aim of this paper is to take advantage of the high-resolution measurement dataset obtained under controlled laboratory experiments to improve the characterization of boundary layer dynamics. In particular, bed shear stress is inferred by means of logarithmic and momentum integral methods, and the two approaches are compared and discussed. In addition, friction factor patterns for different swash phases, separate locations in the swash zone, varying degrees of bed saturation, and different Reynolds numbers are analyzed.

This paper is organized as follows. Section 2 provides a review of the most common theories and approaches used for boundary layer dynamics and bed shear stress characterization. The methods including the description of the laboratory experiments and the data analysis techniques are provided in Section 3. Sections 4 and 5 present and discuss the laboratory results. Section 6 outlines some conclusions.

2. Boundary layer velocity profiles and bed shear stresses

2.1. The momentum integral method

In the case of horizontal uniform flow, the momentum conservation equations for the boundary layer read:

$$\rho\frac{\partial u}{\partial t} = -\frac{\partial p}{\partial x} + \frac{\partial \tau}{\partial z} \tag{1}$$

$$\frac{\partial p}{\partial z} = -\rho g \tag{2}$$

where u is the horizontal velocity, t is the time, p is the pressure, τ is the shear stress, g is the gravitational acceleration, and ρ is the water density. Eqs. (1) and (2) imply that inside the boundary layer, the pressure is hydrostatic, and the longitudinal pressure gradient $\partial p/\partial x$ is constant across the boundary layer thickness. By assuming that the shear stress vanishes outside the boundary layer, it is possible to write the horizontal momentum equation on the top of the boundary layer as

$$\frac{\partial p}{\partial x} = -\rho\frac{\partial U_0}{\partial t} \tag{3}$$

where U_0 represent the free stream velocity (see Fig. 1 providing a sketch with the relevant variables). By inserting Eq. (3) into Eq. (1), the defect velocity law (Fredsøe and Deigaard, 1992; Nielsen, 1992) describing the evolution of the boundary layer is obtained:

$$\rho\frac{\partial}{\partial t}(U_0 - u) = -\frac{\partial \tau}{\partial z} \tag{4}$$

The bed shear stress τ_b can be obtained by integrating this equation across the boundary layer thickness δ:

$$\tau_b = \rho\left(\delta\frac{\partial U_0}{\partial t} - \int_{z_0}^{z_0+\delta}\frac{\partial u}{\partial t}\,dz\right) \tag{5}$$

Two main assumptions are involved in the derivation of Eqs. (4) and (5) from the general momentum conservation equations. The first assumption concerns the flow uniformity leading to negligible advective terms and dynamic pressure in the boundary layer. A zero shear stress at the top of the boundary layer represents the second assumption. It is worth mentioning that in the swash zone, the boundary layer thickness is not much smaller than the water depth h (Puleo and Holland, 2001). In case the boundary layer covers the entire swash depth, the assumption of $u(h) = U_0$ is considered (Briganti et al., 2011).

As already stated, the momentum integral method assumes a hydrostatic pressure field inside the boundary layer; in case pressure can be considered hydrostatic across the whole swash zone water column, Eq. (3) can be replaced by

$$\frac{\partial p}{\partial x} = \rho g\frac{\partial \eta}{\partial x} \tag{6}$$

where η is the free surface elevation. Eq. (6) leads to an alternative version of the momentum integral equation:

$$\tau_b = \rho\left(-\delta g\frac{\partial \eta}{\partial x} - \int_{z_0}^{z_0+\delta}\frac{\partial u}{\partial t}dz\right) \tag{7}$$

Herein, Eqs. (5) and (7) are referred to as MIM_U_0 and MIM_ η. The performance of the two versions of the momentum integral method relies upon the capacity of estimating the pressure gradient $\partial p/\partial x$ inside the boundary layer. It is important to point out that different assumptions are considered into equations MIM_U_0 and MIM_ η. In fact, MIM_ η assumes a hydrostatic pressure field across the entire swash water column, whereas equation MIM_U_0 requires negligible shear stresses at the top of the boundary layer. Nielsen (2002) used the local acceleration $\partial U_0/\partial t$ as a proxy to $\partial p/\partial x$. On the other hand, Baldock and Hughes (2006) and Barnes and Baldock (2010) suggested that since flow decelerates for most of the swash event, $\partial p/\partial x$ can be calculated using the hydrostatic assumption through the free surface gradient $\partial \eta/\partial x$ (see also Othman et al., 2014, who provided additional discussion). However, it is still not clear a priori which of these two approaches is more reliable for the estimation of $\partial p/\partial x$ inside the swash boundary layer.