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Sediment transport dynamics in the swash zone under large-scale laboratory conditions

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ABSTRACT

A laboratory experiment was carried out to study sediment transport dynamics occurring in the swash zone of a coarse-sandy beach built in a large-scale wave flume. Hydro- and morpho-dynamic as well as sediment transport data were collected using sensors mounted on a scaffold rig deployed in the lower swash zone close to the moving bed. The high resolution of near-bed data permitted quantitative evaluation of suspended and sheet flow contributions to the total sediment transport. Although sheet flow sediment fluxes were higher than suspended fluxes, the vertically integrated suspended sediment load overcame the sheet flow load during uprush and it was on the same order of magnitude during backwash. The observed cumulative sediment transport was generally larger than the morphological changes occurring shoreward of the rig location implying either an underestimation of the offshore sediment transport or an overestimation of the onshore fluxes obtained from concentration and velocity profile data. Low correlations were found between net swash profile changes and runup parameters suggesting that local hydrodynamic parameters provide little or no predictability of accretion and erosion of an upper beach which is near equilibrium. The balance between erosion and deposition induced by individual swash events brought a dynamic equilibrium with small differences between the profiles measured at the start and at the end of the run.

1. Introduction

Incoming swell waves induce sediment transport fluxes which are particularly intense in shallow waters eventually leading to morphological beach changes. Under wave forcing, the shoreline position evolves as a consequence of swash hydrodynamic processes which enable a sediment exchange between the submerged and the emerged regions of the beach (Masselink and Hughes, 1998). The shallow, rapid, turbulent and aerated flows in the swash zone bring large sediment concentrations within the water column leading to large suspended sediment transport rates (Elfrink and Baldock, 2002; Masselink and Puleo, 2006). In addition, near-bed sediment transport contributes to the total swash zone sediment transport.

The intense near-bed sediment transport observed in the swash zone is induced by advection from the surf zone and by large bed shear stresses resulting in a flattening of the bed which does not present the typical surf zone bedforms (Bagnold, 1956; Nielsen, 1992). Whereas the mobilizing mechanism of the suspended transport is flow turbulence, under sheet flow conditions intergranular collisions become the primary agent for sediment suspension (Hsu et al., 2004). Sheet flow is usually observed in the nearshore on the crest of sandbars (Nielsen, 1992) and in the swash zone (Masselink and Puleo, 2006). Horn and Mason (1994) showed that the large sediment rates which characterize sheet flows play a significant role in the overall swash zone sediment transport budgets.

A large number of studies dealing with sediment transport in the swash zone focused the attention on suspended load (Puleo et al., 2000; Masselink et al., 2005; Caceres and Alsina, 2012). On the other hand, the improvement in the understanding of sheet flow processes (inside and outside the swash zone) has progressed slowly due to the scarcity of detailed measurements which have been mainly provided by oscillatory flow tunnel experiments (O'Donoghue and Wright, 2004; van der et al., 2010). Recently, Lanckriet et al. (2013, 2014) developed a new CCP sensor to measure the vertical profile of sediment concentration within the sheet flow layer. Puleo et al. (2014, 2016) performed an analysis of CCP data yielding important insights into sheet flow processes with unprecedent detail. These studies highlighted the relative importance of sheet flow sediment transport especially during backwash phase of swash and investigated the bed level changes

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induced by individual swash events. At the same time they warned about the limitation associated with the temporal gaps in data collection which can potentially lead to an artificial truncation of the backwash.

The objective of this work is to use the near-bed flow velocity and concentration measurements obtained through the large scale laboratory experiments BARDEX II to investigate sediment transport processes and morphological changes in the swash zone. In particular, the individual contribution of suspended and sheet flow sediment transport is highlighted and the relationship between hydrodynamics and profile changes is studied. The paper is structured as follows. Section 2 describes the laboratory experiments and the analysis technique used in this work. The results with relative discussion are presented in Sections 3 and 4. Section 5 provides the main conclusions.

2. Methods

2.1. Laboratory experiments

The BARDEX II experiment was carried out in the Delta flume, The Netherlands, to study nearshore processes in the presence of a sandy beach backed by a lagoon (Masselink et al., 2016). The Delta flume is 200 m long, 5 m wide and 7 m high; waves are generated by hydraulically-driven piston-type wave maker located at one end of the flume. A relatively coarse sandy beach (a median grain diameter of 0.43 mm) 4.5 m high backed by a lagoon was built in the flume. The beach slope before the wave action was 1:15 and the still water depth at the wave maker position was set to 3 m. A permeable wall separated the sandy barrier from the lagoon. The coordinate system was established with the horizontal axis x increasing onshore and the vertical z-axis increasing upward. Swash hydrodynamics and sediment concentrations were collected by sensors mounted on a scaffold rig deployed in the swash zone. Different runs were performed with significant wave height ranging between 0.4 and 1 m and peak period ranging between 4 and 12 s. This paper presents data from the 1-h-long irregular-wave run *A*2_05 characterized by a significant wave height H_s of 0.8 m and a peak period T_p of 8 s. A minimal change of the beach profile and the total amount of sediment in the swash zone (0.005 m^3/m) was observed during the run. Taking advantage of the fact that sheet flow probes are not rapidly buried or exposed during the run *A*2_05, it has been specifically chosen as representative of a dynamic equilibrium configuration in which the beach does not experience significant erosion or deposition over a long time scale. The wave action steepened the beach face in the previous runs yielding a beach slope of 0.09 which showed little variability during run *A*2_05. The measurements analyzed in this paper derive from the central swash rig where sensors were submerged for a relatively high portion of time and the sensor configuration allowed a high vertical resolution across the water column.

The horizontal components (u, v) of flow velocity within the water column were measured by 2 Valeport ElectroMagnetic Current Meters (EMCM) separated by 0.03 m in the vertical direction and deployed approximately 0.05 and 0.08 m from the bottom. The 3 components (u, v, w) of the near-bed velocity profile with a vertical resolution of 0.001 m up to 0.03 m above the sandy bottom were collected using a Nortek Acoustic Doppler Velocity Profiler (ADVP). A Bed Level Sensor (BLS) array recorded the fluctuations of the water free surface and the exposed bed in the swash zone with a horizontal spatial resolution of approximately 0.7 m. EMCM, ADVP and BLS data were recorded at 6, 100 and 4 Hz, respectively.

Two different types of sensors collected suspended and sheet flow sediment concentrations. Suspended sediment concentrations (SSC) were measured by 4 Campbell Scientific Optical Backscatter Sensors (OBS) separated by 0.02 m in the vertical direction. OBS were deployed approximately from 0.04 to 0.1 m above the sandy bottom covering the same vertical range as the EMCM. Concentrations were sampled by OBS at 16 Hz. Near-bed sediment concentration profiles were measured by 3 partially-overlapping Conductivity Concentration Profilers (CCPs) designed at the University of Delaware (Lanckriet et al., 2013, 2014). Each CCP provided a spatial resolution of 0.001 m over a range of 0.029 m. The upper sensor was buried with only a small sampling portion exposed to the flow with the aim to cover the active sheet layer and detect the bed location. CCPs were sampled at 8 Hz. Fig. 1 shows the beach profile with the location of the swash rig and the instrumentation. A picture of the sensors mounted on the swash rig is displayed in Fig. 2.

2.2. Data analysis

The nature of swash dynamics represents a challenge for an accurate collection of hydro and morphological experimental observations (Hughes et al., 1997). Swash flows are intermittent by definition; moreover, gaps in time series measurements exist due to instrument limitations (Puleo et al., 2014). Noise in EMCM data is likely to occur when the transducers are hit by the incoming bore. ADVP data present the same issue and they have an additional drawback represented by turbulent bubbly flows. Here, EMCM, ADVP, CCP and OBS time series data were retained only during the portions of time in which the control volume of the relevant sensor was submerged. EMCM, CCP and OBS time series required no additional treatment but ADVP measurements needed additional filtering to remove flow data when at least one of the two following circumstances occurred (Aagard and Hughes, 2006; Puleo et al., 2012): (1) the instantaneous (averaged over the four beams) Correlation (Corr) values were less than 65%; (2) the instantaneous (averaged over the four beams) Signal-to-Noise-Ratio (SNR) values dropped below 20. These criteria have been chosen to remove unreliable data associated with air-entrainment, bubbles and large sediment concentrations. Finally, additional noise and spurious data points were eliminated from the ADVP velocity time series by using the despiking method proposed by Mori et al. (2007).

In addition to temporal gaps due to instrument recording limitations, spatial measurement gaps are likely to occur due to the difficulty in obtaining a complete instrument coverage of the vertical profile. The following interpolation procedures were applied in order to extend velocity measurements across the flow field. Velocities from the EMCM and the ADVP were linearly interpolated through the water column. For the time instants in which a gap exists between the lowest flow data measured either by EMCM or ADVP and the top of the sheet flow layer, the velocity profiles in this region were reconstructed by assuming a logarithmic shape extending between the lowest velocity measurement and the zero-velocity bottom of the sheet flow layer. A linear velocity profile was assumed to extend from the top of the sheet flow layer, where the velocity can be either measured by ADVP or reconstructed using the logarithmic profile, to the bed level, where a zero velocity is considered. A similar procedure was adopted for the concentration data that were linearly interpolated over the region covered by the OBS measurements. No extrapolation was carried out in the region above the highest OBS location which inevitably leads to the exclusion of the upper water column region from the present analysis. An exponential profile according to the Rouse curve was used to fill the gap between the lowest OBS and the location of the top of the sheet flow layer detected by the CCP. As a result, CCP data above the sheet flow layer were replaced by the theoretical curve and therefore not considered, mainly due to