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Video-derived near bed and sheet flow sediment particle velocities in dam-break-driven swash

Jack A. Puleo[a,*], Douglas Krafft[a], José Carlos Pintado-Patiño[b], Brittany Bruder[a]

[a] University of Delaware, Center for Applied Coastal Research, Newark, DE, 19716, USA
[b] Laboratorio de Ingeniería y Procesos Costeros, Instituto de Ingeniería, Universidad Nacional Autónoma de México, Sisal, Yucatán, Mexico

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ABSTRACT

This short communication considers a video-based approach to quantify near bed and sheet flow swash zone sediment particle velocities over a mobile bed in a laboratory setting and relate the profile shape to sheet thickness and a velocity that can be measured outside the sheet layer (by for instance a current meter) Near bed high speed imagery was recorded during a dam-break driven swash event in a flume with optically clear walls. Repeated swash events for two different median sediment sizes were tested. Optical Current Meter (OCM) analysis was applied to bed parallel image time stacks extracted at elevations from below the at rest bed to within the lower water column. OCM results were compared to in situ velocity measurements, where possible, obtained with an acoustic Doppler profiling velocimeter (ADPV). OCM results compared well with ADPV measurements for moderate suspended sediment concentrations (based on visual observation; sediment concentrations were not measured). Too high of a sediment concentration over saturated the image and did not provide distinct sediment particle trajectories in a consistent direction for OCM analysis. This saturation occurred during uprush for both sediment sizes. Too little of a sediment concentration provided an inadequate number of sediment particle trajectories to track, such as during flow reversal for the coarser sediment. For coarser sediment, backwash velocities were well resolved in OCM analysis with velocities comparing well (correlation coefficient > 0.8) to ADPV estimates. The dimensionless backwash sheet flow sediment particle velocity profile (normalized by the velocity at the top of the sheet) scaled with the dimensionless elevation (normalized by the sheet layer thickness) to the 0.62 power with 95% confidence intervals for the exponent ranging from 0.47 to 0.76.

1. Introduction

The swash zone is the portion of the beach face intermittently inundated by wave runup. Swash zone flows, often shallow ($O(10^{-1}$ m)), can mobilize and transport sediment differentially along/across the beach face inducing substantial morphologic change. Yet, despite the significance on morphology, swash zone sediment transport predictive capability is poor. Sediment transport estimates arise from coupled flow velocity and sediment concentration measurements; both are difficult to obtain in the shallow and turbulent flows. Measurements throughout the entire profile of active sediment motion and for the complete duration of swash flow are still needed. Swash zone sediment concentrations are often acknowledged as more difficult to collect than velocity. However, measuring flow velocities can also represent a challenge, especially in the direct vicinity of the dynamic bed (Brocchini and Baldock, 2008; Chardon-Maldonado et al., 2016; Masselink and Puleo, 2006 provide extensive discussion on swash zone measurements and associated difficulties).

Swash flow depths undergo rapid variations throughout the different phases of motion (e.g., uprush, flow reversal and backwash). Hence, velocity measurements from any in situ instrumentation that are fixed in the water column refer only to the portion of the swash event when the water depth exceeds the sensor elevation. This limitation is further exacerbated by instantaneous bed level variations on the order of millimeters to centimeters that can encroach upon the sensor or, for acoustic sensors, the blanking distance (e.g., Alsina et al., 2012; Blenkinsopp et al., 2011; Masselink et al., 2010; Puleo et al., 2014b). Even when the water is sufficiently deep, standard instrumentation such as electromagnetic current meters and acoustic Doppler velocimeters are noisy due to intermittent submergence and acoustic attenuation via bubbles. Remote sensing approaches have the potential to overcome some of these limitations and resolve swash velocity time series for a larger portion of

* Corresponding author.
E-mail address: jpuleo@udel.edu (J.A. Puleo).

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the swash duration.

Oblique imagery has been used to quantify surface flow fields (Holland et al., 2001; Puleo et al., 2003) on natural beaches. Other techniques have been used in small-scale laboratory studies by imaging flow through optically clear walls (Cowen et al., 2003; Kikkert et al., 2012; O'Donoghue et al., 2010). Other options have been undertaken for mobile beds including: the use of boroscopic imagers and particle image velocimetry (PIV; Cowen et al., 2009); the use of several imaging towers that pierce the mobile bed (O'Donoghue et al., 2016); and cross-correlating sediment concentration signals obtained from adjacent sheet flow concentration sensors (McLean et al., 2001; van der Zanden et al., 2013). The latter approach returned robust sediment particle velocities at a single elevation as compared to in situ velocity measurements for much of the swash duration. However, repeated runs are necessary to obtain velocities at multiple elevations which cannot be measured simultaneously.

This short communication considers a video-based approach to quantify near bed and sheet flow swash zone sediment particle velocity profiles over a mobile bed in a laboratory setting. High speed imagery of near bed sediment motion was taken during a dam-break driven swash event in a flume with optically clear walls. Optical Current Meter (OCM) analysis was applied to subsections of imagery to estimate sediment particle velocities in the vicinity of the dynamic bed at sub millimeter resolution. The emphasis is on quantifying the vertical profile of sheet flow sediment particle velocity and relating the profile shape to sheet thickness and a velocity that can be measured outside the sheet layer (by for instance a current meter).

2. Methodology

2.1. Experiment set up

Experiments were performed in the University of Delaware precision wave flume (33 m long, 0.6 m wide, 0.77 m deep; Fig. 1). Swash zone flows were driven by a dam-break set up following previous studies (Kikkert et al., 2012; O'Donoghue et al., 2010). A mobile bed with a slope of 1:7 was constructed at one end of the flume and a reservoir was constructed at the offshore end. The reservoir dimensions were 1 m long x 0.6 m wide x 0.77 m deep containing 0.46 m^3 of water. Water was retained in the reservoir using a thin, high density polyethylene gate strengthened with tubular aluminum members. The gate was held in place against narrow stops placed along the walls and floor of the flume under hydrostatic pressure. Foam gaskets along the stops minimized leakage. The gate was raised rapidly (0.33 s over 1.2 m distance) by a weighted rotation mechanism (64.1 kg on a 4.3 m arm) after releasing a catch pin (Fig. 1). The gate lifting operation provided a repeatable swash event (see Section 3). Released fluid traveled as a bore across a 4.3 m horizontal section of the flume (initial water depth of 0.05 m) before impinging on the slope and generating a swash event over the mobile bed. Maximum fluid velocities exceeded 1.5 m s^{-1}, analogous to field observations such that scaling issues with sediment in the flume were avoided.

The coordinate system origin was defined at the intersection of the beach slope with the horizontal section of the flume (Fig. 1). The cross-shore coordinate, x, increases in the onshore direction and the vertical coordinate, z, is positive upwards. The coordinate system was aligned with the bottom of the flume such that the z datum remained fixed.

A high speed camera (Teledyne Dalsa Genie HM; 301 Hz; 640 × 480 pixels) was placed outside the flume with a field of view (FOV) of 87.6 × 65.7 mm (~0.14 mm per pixel) at the glass wall. Data for this study were collected near the seaward limit of rundown at $x = 1$ m in an effort to capture the majority of the swash duration. The angle of the FOV was consistent with the frame of reference (no tilting or rotation). Imagery was recorded using digital video camera recording software *StreamPix 6* by Norpix. Imagery was focused on sediment and fluid motion in the immediate vicinity of the glass wall. A Cooper Lighting 1000 W Halogen light was placed above and seaward of the camera to illuminate the FOV. It is noted that a laser sheet is commonly used to illuminate and study flow away from the flume side wall to reduce side wall effects. However, this technique is not applicable to the study of sheet flow with natural dark sediment because the near bed region becomes completely opaque only 1 to 2 grain diameters from the flume side wall with or without illumination. As a result, side wall boundary layer impacts could not be fully avoided but are assumed to be small relative to bottom boundary layer processes and given the rapid change in flow directions minimizing time for side wall turbulence and boundary layer development (see Section 4).

A Nortek Vectrino II acoustic Doppler profiling velocimeter (Craig et al., 2011) for estimating in situ cross-shore velocity was placed in the FOV and along the flume centerline (Fig. 1B). The ADPV sampled a vertical profile of all three velocity components (cross-shore u, spanwise v and vertical w) at 100 Hz over a 0.03 m range at 1×10^{-3} m bin intervals. The velocity profile begins 0.04 m from the transducer head. The nominal sensor elevation was 0.06 m above the bed such that the profile intersected the initial bed level. ADPVs estimate velocities using the acoustic reflections off particles in the flow field. Micro particles are the reflectors under most scenarios but not necessarily in the case of high sediment concentration. The acoustic signal return is composed of some unknown combination of the return from micro particles that are assumed to travel at the fluid velocity and the sediment particles that are traveling at their respective velocity that is different from the fluid velocity (e.g., Mattioli et al., 2012; Xu and Bodenschatz, 2008). Thus, velocities estimated by the ADPV are assumed to be more representative of the sediment particle velocity rather than the surrounding fluid velocity based on the high near bed sediment concentrations.

Free surface elevations were recorded in the reservoir and at the ADPV location using Massa ultrasonic distance meters (UDM) sampling at 4 Hz. The camera and sensor data were time stamped using

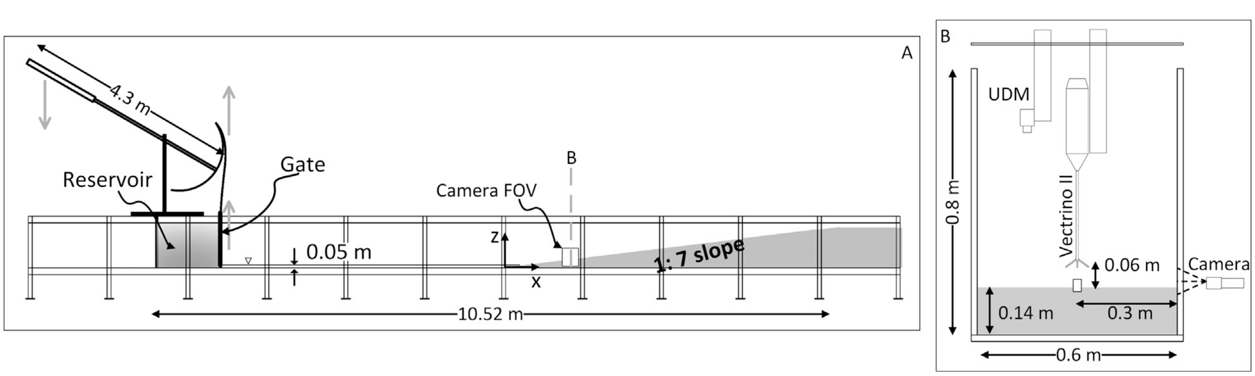

Fig. 1. A) Schematic of the wave flume showing the dam break mechanism and sloping beach. B) Cross-section of the flume at location B identified in panel A and the position of the in situ sensors and high speed camera.