Marine Geology 349 (2014) 99–112

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margeo

Bed level fluctuations in the inner surf and swash zone of a dissipative beach

J.A. Puleo [a,*], T. Lanckriet [a], C. Blenkinsopp [b]

[a] Center for Applied Coastal Research, University of Delaware, Newark, DE 19716, USA
[b] Department of Architecture and Civil Engineering, Bath University, Bath, UK

ARTICLE INFO

Article history:
Received 22 August 2013
Received in revised form 7 January 2014
Accepted 11 January 2014
Available online 23 January 2014

Communicated by J.T. Wells

Keywords:
Beaches
Erosion
Morphology

ABSTRACT

A field study was conducted on a dissipative beach to quantify inner surf and swash-zone bed level change during periods of inundation and throughout a tidal cycle. Elevation changes were acquired at millimeter resolution with a new conductivity concentration profiler that allowed quantification of the bed level throughout the duration of the wave/swash cycle and also during periods of bed exposure. Bed level change spectra showed the highest energy at low frequencies even though event-scale net bed level changes were observed to exceed the tidal-scale net bed level change. Net bed level change for individual events was nearly normally distributed with most individual events displaying little or no net bed level change. "Large" erosion and accretion events with bed level elevation magnitudes that exceeded net tidal elevation change occurred with similar frequency. The similarity between the frequency of large erosion and large accretion events suggests that a few events may be ultimately responsible for the observed net elevation change over the tidal cycle. The large events displayed different hydrodynamic characteristics. Erosion events had longer duration onshore-directed flow and higher maximum onshore-directed velocity magnitude than offshore-directed velocity magnitude. The opposite was found for accretion events that had longer duration offshore-directed flow and a higher maximum offshore-directed velocity magnitude than onshore-directed velocity magnitude.

1. Introduction

The swash zone is the region of the surf zone that links dynamically the land and sea. Swash-zone processes are highly variable with rapid and large variations in water depth, cross-shore and alongshore velocity, sediment load, bed level variations, turbulence and aeration. These various processes, often occurring in water depths less than 0.1 m, make measurement campaigns difficult to undertake and cause swash-zone processes to be more poorly understood than those occurring further offshore. Yet, progress has been made with more technologically advanced and miniaturized sensors and expanded numerical modeling techniques (see Bakhtyar et al., 2009; Brocchini and Baldock, 2008; Butt and Russell, 2000; Elfrink and Baldock, 2002; Masselink and Puleo, 2006 for reviews).

Swash zone laboratory and field research often focus on the velocity fields and sediment transport rates. Findings have indicated differences between uprush and backwash flow. It is now generally accepted that uprush flows tend to have larger velocities (Hughes et al., 1997; Masselink and Hughes, 1998), larger bed shear stresses (Conley and Griffin, 2004; Barnes et al., 2009), higher water column turbulence resulting from surface injection (Cowen et al., 2003; Aagaard and Hughes, 2006) and higher suspended sediment loads (Puleo et al., 2000; Masselink et al., 2005). Backwash flows tend be bed-dominated with turbulence resulting from bed shear (Cowen et al., 2003) and thus sediment transport may be dominated by bed load processes but the latter conjecture has yet to be fully substantiated.

Differences between uprush and backwash sediment transport lead to net morphological change that when integrated over time determines overall beach morphology. Less attention has been paid to the temporal variability in the bed level elevation (BLE) relative to investigations regarding hydrodynamics and sediment transport. However, it is clear that the top centimeters of sediment on the foreshore must be active due to the high observed sediment loads (Puleo et al., 2000). A key need for swash zone research, specifically sediment transport, is the ability to quantify time-dependent BLE (Puleo and Butt, 2006). One reason for this need is the ability to infer the net flux of sediment from the rate of profile evolution via sediment conservation. Recent efforts have improved knowledge of the quantity of material that may be transported over a single swash event up through entire tidal cycles (Turner et al., 2008; Masselink et al., 2009; Blenkinsopp et al., 2011). Elevation changes observed pre- and post-swash event of up to 0.043 m were observed. Inferred maximum net sediment transport rate for a single swash event exceeded 500 kg m^{-1} and is similar to the total net beach face evolution over a tidal cycle of ~1700 kg m^{-1}

* Corresponding author. Tel.: +1 302 831 2440.
E-mail addresses: jpuleo@udel.edu (J.A. Puleo), thijs@udel.edu (T. Lanckriet), c.blenkinsopp@bath.ac.uk (C. Blenkinsopp).

0025-3227/$ – see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.margeo.2014.01.006

(Blenkinsopp et al., 2011). The aforementioned studies have furthered understanding of swash zone morphological evolution and corresponding sediment transport rates. However, the methodology used could only yield a BLE when the bed became exposed and did not permit the BLE to be determined during a swash event or in the inner surf zone.

The purpose of this paper is to investigate BLE variability throughout a tidal cycle including during intra-event motion using a newly-designed conductivity profiler. Section 2 describes past efforts used to quantify BLE variability in the inner surf and swash zones. Section 3 details the field site and experimental deployment including the use of new conductivity concentration profilers. An overview of the tidal variability in BLE is also provided. Section 4 describes data quality control procedures with specific emphasis on how BLE is determined from the conductivity profile and how individual hydrodynamic events are defined. Section 5 compares BLE derived from the conductivity profile and an acoustic sensor to indicate similarity between the measurement principles. BLE variability over event and tidal time scales and comparisons to observed hydrodynamic forcing are given in Section 6. Section 7 discusses the results with emphasis on the importance of quantifying instantaneous BLE, potential errors in hydrodynamic quantities due to inadequate knowledge of time-dependent BLE and some drawbacks in defining typical events for understanding event processes. Conclusions are provided in Section 8.

2. Bed level elevation measurement approaches

A variety of methods with different temporal and spatial resolution exist to determine inner-surf and swash-zone BLE (Table 1 provides some examples but is not meant to be exhaustive). Strahler (1966) used a level and graduated rod to determine beach elevation changes at 30-minute intervals. Waddell (1976) used a capacitance probe to determine the level of the wetted beach surface between swash events. BLE oscillations on the order of 40 s and longer were found and presumed related to groundwater fluctuations. Sallenger and Richmond (1984) used an array of bed-penetrating stakes to quantify BLE. Stake elevations to the nearest millimeter were measured after each backwash. Sediment levels were related to low steepness bed forms with oscillation periods between 6 and 15 min. The use of partially buried stakes is now commonplace (e.g. Degryse-Kulkarni et al., 2004; Horn and Walton, 2004; Weir et al., 2006; Austin and Buscombe, 2008). The BLE measurement sampling rate using this technique varies from 10 s up to 15 min or more. Expected accuracies are on the order of 0.005 m. Other studies determined mixing depth in the swash and surf zones at 10–60-minute intervals used fluorescent tracers (Kraus, 1985; Sherman et al., 1994).

More technologically rigorous methods for measuring BLE include video, photo-electric, ultrasonic and resistivity sensors. Video-based methods generally rely on stereo-metric techniques (Holland and Holman, 1997; Holland and Puleo, 2001) to determine elevation since the coordinate transformation for a single imager from image to real-world coordinates is under-determined (Holland et al., 1997). Field-based techniques can be used to infer BLE from any coincident point within two simultaneously sampled images but swash-zone bathymetry is often obtained on time scales of minutes by averaging over multiple events. Vertical resolution is dependent upon pixel size and accuracy of the geometrical transformations of each camera view (typically several centimeters; Holland and Holman, 1997). Laboratory-based video techniques generally also rely on stereoscopic techniques but utilize a projected structured light pattern to define coincident points within the imagery rather than natural texture (Astier et al., 2011; Stancanelli et al., 2011; Astruc et al., 2012). Controlled conditions allow for highly-accurate bathymetry return of less than a millimeter. However, the use of structured light would render this approach difficult under field scenarios and bed elevations cannot be recorded when the sand surface is submerged.

Photo-electronic erosion pins (PEEP; Lawler, 1991) use an array of photovoltaic cells enclosed in a narrow tube. Ambient light generates a signal that is proportional to the length of tube above the sediment bed. Variations in this length indicate BLE variability. For constant ambient light conditions, accuracy is expected to be within several millimeters (McDermott and Sherman, 2009). Water depth variability in the swash zone attenuates light at different levels throughout the swash duration requiring additional processing to return the BLE (Horn and Lane, 2006; McDermott and Sherman, 2009). Reported sampling rates in the swash zone are 1 Hz. Erlingsson (1991) describes a similar sensor (Sedimeter) that overcomes the ambient light issue using an infrared light emitting diode (LED) and has a vertical resolution up to 1 mm.

Turner et al. (2008) used low-cost ultrasonic distance meters (UDM) to quantify BLE when the sand surface is exposed. The sensor is deployed a distance of roughly 1 m above the sand bed and the measured acoustic 2-way travel time determines the distance to the bed. Sensors are logged at 4 Hz and have a conservative accuracy of 1 mm. Deployment of cross-shore arrays of these sensors has enabled estimation of beach profile evolution and inversion for net cross-shore sediment flux (Masselink et al., 2009; Blenkinsopp et al., 2011). Ultrasonic signals cannot propagate across the air/water interface. Thus, UDM can only return the free surface elevation and not the BLE during the active swash duration or when sensors are located in the inner surf zone.

Resistivity across the sand–water interface can also be used to quantify fluctuations in the BLE. Original sensors consisted of an array of copper ring electrodes on a glass fiber rod embedded in the sediment layer (Ridd, 1992). Vertical accuracy was 0.01 m and BLE was recorded every 2 min. Newer versions of similar sensors have improved sampling speed (10 Hz) and accuracy (Arnaud et al., 2009) but the array spacing of 0.03 m may not be able to capture small-scale, sub-centimeter fluctuations in the inner surf and swash zones. Puleo et al. (2010) developed a similar

Table 1
Methods used to quantify bed level elevation.

Sensor type	Example studies	BLE determined every (s)	Expected accuracy (mm)	Can measure BLE when bed is	
				Submerged	Exposed
Embedded stake	Austin and Buscombe (2008), Degryse-Kulkarni et al. (2004), Sallenger and Richmond (1984), Weir et al. (2006)	10–900	5–10	Yes; but difficult	Yes
Capacitance	Waddell (1976)	0.8	Not specified	No	Yes
Video	Field: Holland and Holman (1997), Holland and Puleo (2001) Lab: Astruc et al. (2012), Stancanelli et al. (2011)	Field: 900 Lab: <1 depending on video frame rate	Field: 10 Lab: <1	No	Yes
Fiber optic	Puleo et al. (2000)	120	10	Yes	Yes
Pressure transducer	Baldock et al. (2006), Jensemn et al. (2011)	60	10	No	Yes
Photo-electric erosion pins	Horn and Lane, (2006), McDermott and Sherman (2009)	0.1	2–5	No	Yes
Sedimeter (infrared)	(Erlingsson, 1991)	Not provided	1	Yes	Yes
Ultrasonic	Blenkinsopp et al. (2011); Turner et al. (2008)	0.25	<1	No	Yes
Resistivity	Arnaud et al. (2009), Ridd (1992)	0.1	20	Yes	Yes
Conductivity	Lanckriet et al. (2014), this paper	0.25	1	Yes	Yes