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Sediment transport partitioning in the swash zone of a large-scale laboratory beach

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ABSTRACT

Swash zone sheet flow and suspended sediment transport rates are estimated on a coarse sand beach constructed in a large-scale laboratory wave flume. Three test cases under monochromatic waves with wave heights of 0.74 m and wave periods of 8 and 12.2 s were analyzed. Sediment flux in the sheet flow layer exceeds several hundred kg m^{-2} s^{-1} during both uprush and backwash. Suspended sediment flux is large during uprush and can exceed 200 kg m^{-2} s^{-1}. Instantaneous sediment flux magnitudes in the sheet layer are nearly always larger than those for suspended sediment flux. However, sediment transport rates, those integrated over depth, indicate that suspended load transport is dominant during uprush for all cases and during the early stages of backwash except in the case for the 12.2 s wave case when the foreshore was steeper. Results could not be obtained for an entire swash event and were particularly truncated during backwash when water depths fell below the elevation of the lowest current meter.

1. Introduction

Quantifying and predicting sediment transport in the swash zone continues to be a challenge for coastal engineers and scientists. The swash zone, where wave-driven flows alternately wash up and down the beach face, is challenging due to rapid, turbulent, shallow, ephemeral flows. Sediment concentrations near the bed are extremely high and occur in a thin layer whereas suspended sediment concentrations may also be large and nearly uniform throughout the water column depending on forcing conditions.

The majority of present knowledge of swash-zone sediment transport arises from field studies that focus on suspended sediment fluxes. Suspended sediment fluxes are estimated as the product of local velocity and sediment concentration (e.g. Alsina and Caceres, 2011; Butt and Russell, 1999; Masselink et al., 2005; Puleo et al., 2000). Given the challenges associated with sensor deployment, flux estimates are obtained at a limited number (1–3) of elevations leading to a coarse under-resolution of the vertical variability and bulk mass flux estimate. Improved vertical resolution is attainable using fiber or miniature optic backscatter sensors (FOBS or MOBS) that can yield a concentration profile at up to 0.01 m resolution (Butt et al., 2009; Conley and Beach, 2003; Puleo, 2009; Puleo et al., 2000). However, neither OBS nor FOBS/MOBS provide any information on sediment flux processes that occur in the high concentration lower flow region near the bed. These nearbed sediment fluxes include contributions from bed load and/or sheet flow. There may be considerable overlap between the two transport modes. The commonly assumed formulation is followed in that bed load is characterized as saltating grains whereas sheet flow is composed of an entire layer of sediment under active transport. A study on time-integrated sediment transport indicated the importance of nearbed sediment transport relative to suspended sediment transport (Horn and Mason, 1994). Other limited in situ data from the swash zone (Yu et al., 1990) quantified the magnitude of the nearbed sediment concentration but flux estimates were not presented. New sensors have been designed that more fully resolve the vertical profile of sediment concentration in the sheet layer (Lanckriet et al., 2013, 2014; Puleo et al., 2010). Preliminary results using these sensors indicate the nearbed sediment transport is a significant fraction of the total load sediment transport (Puleo et al., 2014b). Horizontal gradients in the total load sediment transport (depth-integrated bed load plus suspended load), regardless of the dominant transport mode, drive small-scale local morphological change on an inter-swash basis (Blenkinsopp et al., 2010; Masselink et al., 2009; Puleo et al., 2014a). In an alongshore uniform environment (or assumption thereof), fluxes can also be estimated with the sediment continuity equation by measuring the morphologic change at numerous cross-shore locations (Blenkinsopp et al., 2011; Masselink et al., 2009).

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However, this inference does not quantify individually the contribution of each of the two sediment transport modes.

As mentioned previously, sediment concentration and velocity are both needed to quantify sediment flux. Sediment transport studies normally focus on the cross-shore component and utilize impeller (e.g. Puleo et al., 2000), electromagnetic (e.g. Masselink et al., 2005) or Acoustic Doppler Velocimeters (ADVs; e.g. Raubenheimer, 2002). Typical impellers have a diameter that does not allow for measurements in close proximity to the bed. The other two sensor types have a smaller measuring volume and can be located within just a few centimeters of the bed. Only several of these sensors can be deployed above a particular horizontal location to measure the vertical distribution of swash-zone velocity due to their size and/or measuring characteristics. Recently, a new profiling velocimeter (Craig et al., 2011) has been used to quantify the vertical distribution of the nearbed velocity at high spatial resolution (0.001 m) under benign (Puleo et al., 2012; Wengrove and Foster, 2014) and more energetic (Puleo et al., 2012, 2014b) forcing conditions.

Puleo et al. (2014b) describe more fully the difficulty in measuring in the shallow water swash-zone flows. Of particular importance is obtaining a velocity time series throughout an entire swash event. Electromagnetic and acoustic sensors are disrupted when they are first wetted by an incoming turbulent bore. Noisy data are more problematic for the acoustic sensor due to the bubbly bore/swash front. Both sensors suffer from positional difficulties in that they are, by necessity, located some finite distance above the bed. Thus, when the backwash recedes and the swash lens thins, there will be a portion of the swash event where velocities cannot be obtained using the same current meter. This “missing” portion may represent more than half the true swash cycle duration (see Section 5) depending on hydrodynamic conditions and current meter elevation. Moreover, in particularly energetic environments, there can be more than a centimeter of morphologic change resulting in considerable variability in the relative position from the bed (Puleo et al., 2014a). Every study that uses an elevated current meter will have this problem of artificially truncating the swash event unless current meter data are supplemented with other information. Ultrasonic distance meters (Turner et al., 2008), LIDAR (Blenkinsopp et al., 2010), or particle image velocimetry (e.g. Holland et al., 2001; Puleo et al., 2003a) can provide some measure of the velocity throughout the full swash cycle. The former two methods are used to quantify the depth-averaged velocity through volume continuity procedures. The latter method is able to quantify only the free surface horizontal velocity.

The flow field in direct vicinity of the bed under field conditions is unknown regardless of the location of the lowest current meter or the use of image-based velocimetry techniques. Flows in this nearbed region (order of several centimeters) are generally assumed to be either depth-uniform using the value from an elevated current meter (e.g. Puleo et al., 2000) or assuming a logarithmic profile (Raubenheimer et al., 2004). Recent velocity profile measurements on a moderately steep, microtidal, low energy beach (Puleo et al., 2012) and a macrotidal, high energy beach (Puleo et al., 2014b) indicated the existence of a logarithmic profile near the bed under much of the measured swash duration. Ruju et al. (2016-in this issue) show that the shape of the nearbed velocity profile on energetic, steep, beaches is also logarithmic for much of the measured swash duration.

This paper focuses on observations of nearbed swash-zone sediment flux obtained during the BARDEX II study (Masselink et al., 2016-in this issue). The main emphasis of this effort is to determine the relative importance of suspended to sheet flow sediment transport. Section 2 describes the experimental details relevant to this paper. Section 3 explains the quality control procedures used on the data set and bed level identification as it varied throughout a swash cycle. Formulations for sediment concentrations and transport are given in Section 4. Section 5 provides results related to sheet flow and suspended sediment flux profiles and integrated transport rates. Ensemble-average events for the three test cases are also presented. Discussion and conclusions are given in Section 6 and Section 7 respectively.

2. Large-scale laboratory experiment and instrumentation

2.1. Set up and conditions

The BARDEX II experiment was conducted in the Delta Flume, the Netherlands to investigate barrier dynamics. Full experimental details are provided by Masselink et al. (2016-in this issue). A right-handed coordinate system was established with x increasing onshore and z' vertically up. The horizontal origin is the neutral position of the wave paddle and the vertical datum for the experiment is the bottom of the wave flume. We note that the vertical coordinate is designated with a prime here because analyses throughout the paper will alter the datum for the vertical coordinate to be that of the instantaneous bed level (see Section 3). The initial beach profile consisted of: an offshore sloping section from 24–29 m up to a sediment thickness of 0.5 m, a uniform thickness section from 29–49 m, a 1:15 sloping section from 49–109 m, a 5 m wide berm crest from 109–114 m and a 1:15 landward sloping section from 114–124 m. The sediment used in the experiment was moderately sorted coarse sand with a median grain diameter of 0.43 mm. Five experiment series were conducted to investigate the different barrier morphological responses (Masselink et al., 2016-in this issue; Table 1). At the end of some of the tests, monochromatic wave runs were conducted providing the potential for ensemble averaging. Data from monochromatic runs following tests A2 (July 12, 2012), A4 (July 14, 2012) and A6 (July 18, 2012) are presented here because they provided the best coverage of bed load and suspended sediment transport. Reference to a particular test refers only to the monochromatic run within that test. Experimental conditions for these monochromatic cases are given in Table 1. The monochromatic wave height was 0.74 m for all three tests but the period changed from 8 s for test A2 and A4 to 12.2 s for test A6. In addition, the water level in the lagoon was higher than sea level for test A2, lower than sea level for test A4 and the same as sea level for test A6.

2.2. Beach profiles

A mechanical beach profiler attached to an overhead carriage recorded the beach elevation along the flume centerline following each run within a test series. Any alongshore non-uniformity cannot be captured with the profiler. Some alongshore non-uniformity in the morphology and accompanying swash flows was observed visually for several of the runs within the A series of tests but was not routinely quantified. Fig. 1 shows the original beach profile and the beach profile following each monochromatic test series described here. The beach steepened through the A series of tests with erosion in the seaward swash and berm development landward. Swash zone data discussed here were collected at a cross-shore location of $x = 89.6$ m (vertical dashed line in Fig. 1). Elevation changes at this cross-shore location are much smaller than those landward and seaward. The foreshore slope measured from 85 m < x < 95 m is 1:10, 1:9.5 and 1:7 for test

Table 1
Monochromatic wave cases used in this study[a].

Case number	H (m)	T (s)	h_s (m)	h_l (m)	Local foreshore slope
A2 (June 12, 2012)	0.74	8	3	4.3	1:8.9
A4 (June 14, 2012)	0.74	8	3	1.75	1:8.7
A6 (June 18, 2012)	0.74	12.2	3	3	1:6.5

[a] H is the wave height; T is the wave period; h_s is the sea level; h_l is the lagoon level.