

**BED LEVEL MOTIONS AND SHEET FLOW PROCESSES IN THE SWASH ZONE:  
OBSERVATIONS WITH A NEW CONDUCTIVITY-BASED CONCENTRATION  
MEASURING TECHNIQUE (CCM<sup>+</sup>)**

Joep van der Zanden<sup>1</sup>, José M. Alsina<sup>2</sup>, Iván Cáceres<sup>3</sup>, René H. Buijsrogge<sup>1</sup>, Jan S. Ribberink<sup>1</sup>

1: Marine and Fluvial Systems group, University of Twente, Drienerlolaan 5, 7522 NB Enschede, The Netherlands.

[j.vanderzanden@utwente.nl](mailto:j.vanderzanden@utwente.nl) (corresponding author, tel. +31534894038), [r.h.buijsrogge@utwente.nl](mailto:r.h.buijsrogge@utwente.nl),  
[j.s.ribberink@utwente.nl](mailto:j.s.ribberink@utwente.nl)

2: Fluid Mechanics Section, Department of Civil and Environmental Engineering, Imperial College London, South Kensington Campus, SW7 2AZ, UK. [j.alsina@imperial.ac.uk](mailto:j.alsina@imperial.ac.uk)

3. Laboratori d'Enginyeria Marítima, Universitat Politècnica de Catalunya, C. Jordi Girona, 1-3 08034 Barcelona, Spain. [i.caceres@upc.edu](mailto:i.caceres@upc.edu)

## **Abstract**

Detailed measurements of bed level motions and sheet flow processes in the lower swash are presented. The measurements are obtained during a large-scale wave flume experiment focusing on swash zone sediment transport induced by bichromatic waves. A new instrument (CCM<sup>+</sup>) provides detailed phase-averaged measurements of sheet flow concentrations, particle velocities, and bed level evolution during a complete swash cycle. The bed at the lower swash location shows a clear pattern of rapid erosion during the early uprush and progressive accretion during the middle backwash phase. Sheet flow occurs during the early uprush and mid and late backwash phases. Sheet flow sediment fluxes during these instances are highest in the pick-up layer. Sediment entrainment from the pick-up layer occurs not only during instances of high horizontal shear velocities but also in occurrence of wave-backwash interactions. As opposed to oscillatory sheet flow, the pivot point elevation of the sheet flow layer is time-varying during a swash event. Moreover, the upper sheet flow layer concentrations do not mirror the concentrations in the pick-up layer. Both differences suggest that in the lower swash zone the dynamics of the upper sheet flow layer are not only controlled by vertical sediment exchange (such as in oscillatory sheet flows) but are strongly affected by horizontal advection processes induced by the non-uniformity of the flow.

**Keywords:** Sheet flow, swash zone, bed level changes, sediment transport, bichromatic waves, large-scale wave flume

## 1. Introduction

The swash zone is the area that connects the surf zone to the emerged beach. This zone is characterized by the alternating exposed and submerged state of the bed. The swash is a highly dynamic area where water and sediment flows occur within a highly transient, aerated, and shallow water layer. The hydrodynamic forcing occurs at both short- and long-wave frequencies and as a result, also bed levels experience rapid and large changes at similar frequencies as the waves (Puleo *et al.*, 2014). Magnitudes of sediment fluxes in the swash are large and various modes of transport (sheet flow, suspended load) may coexist (Masselink and Hughes, 1998). Moreover, interactions between incident waves and bores with preceding uprush or backwash result in rapid alteration of the flow field, increased turbulence, and enhanced sediment suspension during a swash event (e.g. Hibberd and Peregrine, 1979; Hughes and Moseley, 2007; Masselink *et al.*, 2009; Blenkinsopp *et al.*, 2011; Caceres and Alsina, 2012).

The small water depths and the continuous alternating state of the bed (exposed, submerged) make it extremely challenging to measure and understand the sediment dynamics and hydrodynamics in detail. Our present knowledge of the swash zone sediment dynamics is primarily based on measurements of near-bed sediment concentrations (Aagaard and Hughes, 2006; Alsina *et al.*, 2012), estimations of sediment transport from inter-wave bed level changes (Turner *et al.*, 2008; Blenkinsopp *et al.*, 2011), or sediment trap measurements (Baldock *et al.*, 2005; Alsina *et al.*, 2009). Common instruments particularly fail at obtaining high-quality measurements of (i) sheet flow dynamics and (ii) bed level evolution throughout complete swash events (for both exposed and submerged state).

Sheet flow is a sediment transport mode that occurs during highly energetic flow conditions. When near-bed velocities are sufficiently high, sand transport is confined to a high-concentration (100 to 1600 g/L) layer with a typical thickness of 10 to 100 times the grain diameter (Ribberink *et al.*, 2008). The high cross-shore sediment fluxes in this layer contribute importantly to net transport rates in the near-shore region (Ribberink and Al-Salem, 1995). Sheet flow dynamics have been studied extensively for uniform oscillatory flow conditions in laboratories, i.e. oscillatory flow tunnels (e.g. Horikawa *et al.*, 1982; O'Donoghue and Wright, 2004; van der A *et al.*, 2010) and wave flumes (e.g.

Dohmen-Janssen and Hanes, 2005; Schretlen, 2012). The sheet flow layer can be divided into a pick-up/deposition layer and an upper sheet flow layer, which are respectively found below and above the still-water bed level (Ribberink *et al.*, 2008). During a wave cycle, the vertical concentration gradient changes continuously as a result of vertical sediment exchange. More specifically, the concentration profiles pivot around a vertical reference point (pivot point) which marks the top of the pick-up layer and which is at an approximately fixed elevation throughout the wave cycle (O'Donoghue and Wright, 2004).

Sheet flow transport has been highlighted as an important contributor to swash zone sediment transport (Yu *et al.*, 1990; Beach *et al.*, 1992; Jackson *et al.*, 2004; Masselink and Puleo, 2006). However, knowledge on swash zone sheet flow dynamics is limited since only few instruments are capable of obtaining high-quality measurements of sheet flow concentrations. Conductivity-based instruments showed the occurrence of sheet flow during early uprush and late backwash instances (Yu *et al.*, 1990; Lanckriet *et al.*, 2013; Lanckriet and Puleo, 2015). Vertical concentration profiles during isolated backwash events, measured with a recently developed Conductivity Concentration Profiler (CCP), showed strong similarities to observations for oscillatory sheet flow (Lanckriet *et al.*, 2014). During the early uprush, the sheet flow thickness may be larger than for oscillatory flows with similar hydrodynamics and sediment characteristics (Lanckriet and Puleo, 2015). This increased thickness is likely attributed to additional bore turbulence (Lanckriet and Puleo, 2015). Despite these recent advances, the number of studies on sheet flow layer dynamics in the swash is still limited and does not cover the full range of swash hydrodynamics. In particular, no studies have been able to quantify sediment fluxes for swash zone sheet flow.

In terms of bed level measurements, only few instruments are able to sample the bed during both submerged and exposed state (see Puleo *et al.*, 2014, for an overview). The aforementioned CCP seems to be the only instrument with sufficient accuracy (1 mm) and temporal resolution (sampling > 1 Hz) to study the intra-wave bed evolution in detail. Field measurements of the CCP in the inner surf and lower swash zone show how mean bed levels decrease or increase almost monotonically during a swash event (Puleo *et al.*, 2014). It has been shown that swash events with relatively high onshore

velocities and long onshore duration (compared to offshore velocities and duration) are more likely to induce erosion of the seaward swash region, while local accretion is predominantly caused by events with stronger offshore velocities and longer backwash duration (Puleo *et al.*, 2014). Previous experimental studies have not addressed the effects of wave-swash interactions on intra-event bed level changes. In addition, previous studies did not connect the intra-event bed level observations to sheet flow dynamics and sediment fluxes.

The limited knowledge on swash zone sediment transport processes and fluxes hampers the development of improved swash zone sediment transport formulae that can be applied in morphologic models. Energetics-based sediment transport models, which are commonly used for the near-shore region, often fail at predicting adequately the sediment transport rates in the swash zone (Masselink *et al.*, 2009). One of the main reasons is that sediment transport rates in the swash are not fully determined by local hydrodynamics as advection of pre-suspended sediment is important too (Pritchard and Hogg, 2005; Alsina *et al.*, 2009).

In this paper we present the results of recent large-scale wave flume experiments with bichromatic waves focusing on intra-event bed level variations and sheet flow dynamics. The laboratory setting allows us to generate repeatable swash events and to study sediment transport processes in great detail. The main objectives of the paper are (i) to study bed level evolution and (ii) to characterize the dynamics of the sheet flow layer in the lower swash zone.

High-quality measurements of the bed level and sheet flow concentrations and particle velocities are obtained through a new conductivity-based measuring instrument (CCM<sup>+</sup>) which is presented in Section 2 and evaluated in Appendix A. The experimental set-up and wave conditions are presented in Section 3, followed by the beach profile evolution (Section 4). Section 5 presents bed level measurements at different time scales. Section 6 presents measurements of the sheet flow dynamics in the lower swash zone. Finally, we reflect on the obtained new insights and their connection to existing knowledge on swash zone and sheet flow dynamics and to sediment transport modeling (Section 7).

## **2. Description of CCM<sup>+</sup>**

The CCM<sup>+</sup> system is based on existing CCM technology (c.f. Ribberink and Al-Salem, 1995; McLean *et al.*, 2001; Dohmen-Janssen and Hanes, 2005). Previous CCM versions required constant repositioning of the measuring sensors in order to cope with the time-varying bed level. Moreover, they relied on another instrument for a measurement of the reference bed level. In the new CCM<sup>+</sup> technology, these problems are overcome with a new tracking system that allows automatic repositioning of the sensors. Sheet flow concentrations are measured by one pair of sensors, while an independently operating third sensor is used to measure the bed level.

## 2.1 Hardware

The exterior of the CCM<sup>+</sup> tank is formed by a closed stainless-steel cylinder with a 0.48 m diameter and height of 0.63 m (Figure 1). The tank is welded to a steel base plate that can be mounted to the flume bottom or a palette, which in combination with the heavy weight (70 kg) of the tank ensures the stability for compensating buoyancy and other destabilizing mechanisms. The probes containing the measuring sensors are mounted to two slim stainless-steel rods that emerge from the tank. Both rods operate independently and can move vertically over a range of 28 cm. Their positions are controlled with sub-mm accuracy by electromagnetic servomotors within the tank. O-rings prevent water and sand intrusion. The tank is equipped with a total of three probes (Figure 2, top left). Probes 1 and 2 are mounted to the same rod, while a third probe is mounted to the second rod. Reference to the former, combined probe is made as ‘probe 1/2’.

The sensors in the top of each probe are formed by four platinum electrodes with a thickness of 0.3 mm and spacing of 0.6 mm, covered by an epoxy topping such that the exposed part of the electrodes is 0.8 mm high (Figure 2, top right). The two sensors on probe 1/2 are aligned in cross-shore flow direction with 1.5 cm spacing, and can be used to determine sediment velocities through cross-correlation of the high-pass measured signal (McLean *et al.*, 2001). Sensors 1/2 and sensor 3 are co-located in terms of cross-shore position and separated 9 cm in longitudinal direction.

The measuring principle of the sensors is conductivity-based. An alternating current is generated over the outer two electrodes while the inner two electrodes measure the electrical resistance of the water

which is translated to a voltage  $U_m$ . This voltage can be translated to a sediment volume concentration  $C$  (m<sup>3</sup> sand/m<sup>3</sup> mixture):

$$C = \left(1 - \frac{U_0}{U_m}\right) \cdot f_{cal} \quad (1)$$

where  $U_0$  is the reference voltage for clear water (V) and  $f_{cal}$  is a dimensionless calibration factor that usually approaches unity. Both  $U_0$  and  $f_{cal}$  depend on probe characteristics and in-situ water conditions. Before the start of an experiment, the voltages in clear water and in a loosely packed sand bed are measured in order to calibrate the measurements.

During an experiment, the tank and rods are fitted into the sand bed and only the probe sensors reach into the sheet flow layer (Figure 2, bottom). In the lowest position, the sensors in the tips of the probes are at 14 cm above the tank. Hence, the tank itself is always far from the bed and is not expected to affect sediment transport.

The sampling volume of the probe was assessed by moving the probe up and down a sand bed (grain diameter  $D_{50} = 0.24$  mm). The calibration graphs showed a concentration change from 0.10 to 0.90 times the volumetric concentration in the bed over a vertical range of 1.5 mm. This indicates that the sampling volume of the sensor extends vertically up to 1-2 mm. During initial pilot tests, the sensors were vertically positioned in the upper half of a water column that was frequently aerated by wave collapsing. The conductivity measurements did not reveal a noticeable change in signal as a result of bubble presence.

## 2.2 Signal processing and bed level tracking system

Within the CCM<sup>+</sup> system, two types of signals are sampled: (i) the conductivity-measurements of the sensors; (ii) their vertical positions ( $z_{1,2}$  and  $z_3$ ). The sampling frequency is a set 1000 Hz, which is required for determining the particle velocities.

Figure 3 shows a simplified flow chart of the various subsystems, their main tasks, and the signals between the subsystems. The system is controlled through LabVIEW. An Ethernet cable connects the PC to a Beckhoff PLC control unit inside the control box. The new feedback loop for automatic

concentration or bed level tracking is programmed in this unit. The computation step simply translates the difference between the measured voltage  $U_m$  and a set target voltage  $U_t$ , that represents a specific target concentration, to a velocity for vertical probe movement:

$$v = (U_m - U_t) \cdot k_p \quad (2)$$

where  $v$  is the velocity of probe movement (m/s; defined positively upward);  $U_t$  (V) is the target voltage that corresponds to a target concentration through Eq. (1); and the ‘gain factor’  $k_p$  (m/s/V) is an input factor that controls the sensitivity of the probe’s response. A measured voltage (concentration) that exceeds the target value results in a positive vertical velocity through Eq. (2), so the probe will move upward. where voltages (hence concentrations) are lower. The speed of movement is proportional to the offset of the measured voltage with respect to the target value. A typical target value used when tracking the bed is the voltage corresponding to half the concentration in the loosely packed bed. This ensures that the probe moves continuously towards the interface between bed and water.

The PLC control unit is equipped with a correction for probe exposure to air when measuring in the swash zone, preventing the probes to move upwards when above water. After the computation step, the PLC control unit transfers the velocity to two Copley Controls Xenus Plus motor controllers inside the tank, which each contain a motion controller that translates the velocity to a desired position.

The CCM<sup>+</sup> electrodes are connected to a sensor interface, which contains a chip that treats the measured voltage signal (e.g. demodulating and analogue filtering). The analogue position and voltage (concentration) signals are translated into digital signals by the motor controller. By digitizing the signal near the source, signal distortions are minimized. The bed level tracking loop is repeated every 0.02 s and the  $U_m$  value used in Eq. (2) represents the moving average with a lag of 20 samples (buffering step to reduce effect of signal variations).

The performance of the bed level tracking system greatly depends on the system’s ability to respond rapidly and adequately to a concentration offset. Therefore, the signal processing scheme is developed such that a stable vertical probe motion is realized with minimum delay between input (measured concentration) and response (probe movement) of the tracking system. The probes are able to move

with velocities over 0.1 m/s, but the users risk unstable probe behavior and overshooting of the target concentration level when the applied gain factor value is too high.

Section 3.3 provides more details about the applied tracking system settings of the 3 CCM<sup>+</sup> probes throughout the experiment.

### **3. Description of the experiments**

#### **3.1 Experimental set-up**

The CCM<sup>+</sup> system was applied during the ‘CoSSedM’ experimental campaign that was done in the Canal de Investigacion y Experimentacion Maritima (CIEM) at the Universitat Politècnica de Catalunya (UPC), Barcelona. This is a large-scale wave flume of 100 m length, 3 m width and 4.5 m depth. The aim of the experimental campaign was to study cross-shore morphology and swash-zone sediment transport processes under various bichromatic wave conditions of equal wave energy but different modulation periods. In this paper we consider the measurements for one erosive condition, labeled ‘BE1\_2’. For this condition, the experiment consisted of 8 runs of approximately 30 min.

The beach consisted of commercial well-sorted medium sand with a characteristic diameter ( $D_{50}$ ) of 0.25 mm, a narrow grain size distribution ( $D_{10} = 0.15$  mm and  $D_{90} = 0.37$  mm), a measured settling velocity of 0.034 m/s, and a porosity of 0.36 when loosely packed. The beach was shaped to a 1:15 constant slope prior to the experiment (Figure 4).

The vertical coordinate  $z$  is defined positively upwards from the still water level (SWL). The shoreline (intersect between SWL and initial profile) at the start of the experiment is used as horizontal datum. Cross-shore coordinates  $x$  are defined positive towards the beach (onshore) and negative (offshore) towards the wave paddle (Figure 4). The toe of the bed profile is located at  $x = -42.5$  m. waves are generated by the wave paddle at a water depth of 2.48 m and an  $x$ -position of -75.2 m. Between the wave paddle and the toe of the profile, the waves travel over the concrete bottom of the wave flume.

Figure 4 includes the instrumentation applied during the campaign. Outside and at the surf zone, water surface elevations were measured through a sequence of Resistive Wave Gauges (RWGs). Most instrumentation was located at the targeted research area (around shoreline), corresponding to the

inner-surf and swash zones. Here, instruments at various cross-shore positions measured velocities (Acoustic Doppler Velocimeters, ADVs), suspended sediment concentrations (Optical Backscatter Sensors, OBSs) and water surface elevation (Acoustic Wave Gauges, AWGs; Pore Pressure Transducers, PPTs). Two CCM<sup>+</sup> tanks were installed close to the shoreline (Figure 4). This paper focuses on the lower swash zone, so results of CCM<sup>+</sup> tank 2 are not considered.

CCM<sup>+</sup> tank 1 was located at an x-position of 0.60 m shoreward of the SWL intersect. As is shown and discussed later (Section 4), this position is within the lower swash zone (following the submergence criterion of Aagaard and Hughes, 2006). An AWG and ADV were installed at the same cross-shore position. Above the tank, the downward-looking AWG measured water surface and exposed bed levels with a practical accuracy of about 1 mm and sampling frequency  $f_s$  of 40 Hz. The ADV, a Nortek side-looking laboratory Vectrino, measured all three velocity components ( $f_s = 100$  Hz). Prior to each experimental run, the ADV was vertically re-positioned in order to maintain a constant elevation of 0.03 m with respect to the bed.

A mechanical bed profiler, consisting of a pivoting arm and a wheel that are deployed from a mobile trolley, was used to measure the beach profile along the centerline of the wave flume. The profiler is able to measure both the sub-aerial and the sub-aqueous beach and is described in detail by Baldock *et al.* (2011). Given the wheel-diameter of 0.2 m, the profiler is unable to follow individual ripples and it has an estimated accuracy of +/- 10 mm (Baldock *et al.*, 2011). Profile measurements were obtained prior to the experiment and after each 30-minute run.

### 3.2 Wave conditions

Throughout the CoSSedM experimental campaign, various types of bichromatic wave conditions were run. Wave condition BE1\_2, considered in this paper, is an erosive condition which was expected to lead to highly energetic flow conditions in the swash. The bichromatic wave consists of a frequency component  $f_1$  of 0.303 Hz with wave height  $H_1$  of 0.30 m and a frequency component  $f_2$  of 0.237 Hz with wave height  $H_2 = 0.25$  m (Table 1). Together they form a bichromatic wave group with a frequency  $f_{gr} = f_1 - f_2 = 0.067$  Hz ( $T_{gr} = 15.0$  s).

For this particular condition it is important to note that not all wave groups repeat exactly at the group frequency. Instead, there is a gradual transition of the short-wave phase within the group. This type of modulation at the so-called ‘repeat frequency’ ( $f_R$ ) has been reported earlier by Baldock *et al.* (2000). It is emphasized that the modulations at the repeat frequency change the short-wave phase and overall shape of the wave groups, but they have minor effect on the wave energy of the individual groups.

For this experiment,  $f_R$  equals 0.0051 Hz (repeat period  $T_R = 195$  s). As a result of the modulations at  $f_R$ , the short-wave phase within the group repeats exactly after 13 wave groups but it repeats approximately every second wave group. As will be shown later, the groups that are similar in terms of short-wave phasing are also comparable in terms of hydrodynamics and sediment dynamics at the CCM<sup>+</sup> measuring location (bed level changes; Sections 5.2 and 5.3). This allows us to phase-average sheet flow measurements for two different ‘characteristic swash events’ that are induced by comparable wave groups.

Some characteristics of the measured water levels are presented in Figure 5 at three cross-shore positions. Close to the wave paddle, the spectrum (Figure 5b) clearly shows the two wave components ( $f_1$  and  $f_2$ ) forming the bichromatic wave group, plus a sub-harmonic at the group frequency related to the wave group envelope. While the waves propagate towards the shoreline, the energy of the higher frequencies dissipates and is transferred to other harmonics and to the wave group frequency (Figure 5d). This process is well-described in literature (Longuet-Higgins and Stewart, 1964; Baldock *et al.*, 2000; Janssen *et al.*, 2003). As a result, the shape of the wave group changes. At the CCM<sup>+</sup> location in the lower swash, the energy content is predominant at the wave group frequency  $f_{gr}$  (Figure 5f).

Each swash event at the CCM<sup>+</sup> location is characterized by three major surf bores followed by the backwash (Figure 5e). Note that during the final backwash phases, just before the arrival of the first bore of an event, a thin swash lens of  $O(\text{mm})$  may still exist.

The results in Figure 5 also illustrate how modulations at the repeat frequency  $f_R$  affect the short-wave phase but not the wave energy of the 15-second groups. The time series reveal different shapes of the four swash events, as a result of the short-wave phase modulations at  $f_R$  (Figure 5e). Evidently, the relative timing of the arrival of the bores differs for each event. The relative phase of the bores within

the swash event is found to repeat approximately every second event. At the same time, the spectral energy at  $f_R$  is negligible (Figure 5b,d,f). In addition, low-pass filtering of the AWG measurements showed that water level fluctuations at the repeat frequency  $f_R$  were of  $O(\text{mm})$  in the inner-surf and swash zone (results not shown). These observations on the effects of the  $f_R$  modulations are in line with the work of Baldock *et al.* (2000).

### 3.3 CCM<sup>+</sup> settings

Each of the two probes of the CCM<sup>+</sup> tank serves a different purpose. Hence, different control settings of the bed level tracking system are applied for each probe. As detailed below, probe 1/2 is used to measure instantaneous concentration at fixed vertical levels ( $C(z,t)$ ), while probe 3 measures the continuous instantaneous bed level ( $z_{bed}(t)$ ).

Probe 1/2 (sensors 1 and 2) is set to a slow tracking mode ( $k_p = 0.5 \text{ m/s/V}$ ), which means that in terms of vertical repositioning, the probe responds only to gradual bed motions. On an intra-group time scale, the probe can be considered to be on a fixed vertical position. Note that at this fixed level, sediment concentrations are time-varying due to vertical and horizontal advection processes that occur on time scales shorter than the wave group period. The concentration changes at this level are captured by the sensors. In order to capture the complete profile of time-varying concentrations in the sheet flow layer, concentration measurements are required at different (fixed) vertical levels. This is achieved by varying the target concentration (target  $C$  values between  $0.15$  and  $0.45 \text{ m}^3/\text{m}^3$ ). Consequently, probe 1/2 slowly traverses through the sheet flow layer providing (intra-wave-group) concentration information at varying vertical levels under the repeating swash events.

Probe 3 is set to a quick tracking mode ( $k_p = 5 \text{ m/s/V}$ ). The target voltage of the probe corresponds to a concentration of  $0.30 \text{ m}^3/\text{m}^3$ , which roughly equals half the sediment concentration in the bed and which is close to the middle (or ‘pivot point’) of the sheet flow layer (see O'Donoghue and Wright, 2004). In this way probe 3 is able to follow the evolution of the interface between sediment bed and water on a wave-group-averaged time scale (time scales  $\geq 15 \text{ s}$ ). This result is used as reference bed level  $z_{ref}$  for the concentrations measured with probe 1/2. It should be noted that the control system is

not fast enough to allow perfect tracking of the bed at time scales of seconds and shorter. Instead, probe 3 shows a reduced amplitude and phase-delays of about 2 s with the actual intra-wave bed level (see Appendix A). In the CCM<sup>+</sup> tank set-up this high-frequency bed level information can still be obtained from the concentration behavior as measured with probe 1/2 (see Section 5.3.3).

The results of the CCM<sup>+</sup> bed level and concentration measurements are discussed further in the framework of the swash measurements (see Sections 5 and 6). Reference is made to Appendix A for more details about the CCM<sup>+</sup> performance in terms of bed level measurements.

#### **4. Morphological evolution of the swash zone**

Figure 6a shows the bottom profile evolution during the complete experiment (240 minutes), measured by the wheeled bottom profiler. The mean net transport rates for each run (Figure 6b) were obtained through solving the mass balance by means of integrating the volume change, starting from the toe of the profile where net transport was known to be 0 (see e.g. Baldock *et al.*, 2011). Figure 6 shows a rapid erosion at the shoreline during the first two runs (0 to 60 min.), leading to a semi-equilibrium state that is reached after the second run. During the next six runs, net transport at the shoreline is still offshore although the magnitude is minor compared to the first two runs.

A bar forms initially at around  $x = -9.7$  m, migrates slightly offshore, and stabilizes around  $x = -10.0$  m. Over the eight runs, the shoreline retreats with 1.95 m. The erosion of the shoreline includes erosion of the inner-surf and mid-low swash area (where the CCM<sup>+</sup> tank is located), from  $x = -3.6$  m to  $x = 4.6$  m approximately. Furthermore, berm formation and accretion of the upper/mid-swash can be observed from  $x = 4$  m to  $x = 9$  m.

The shoreline retreat induces a shift in minimum run-down location. The swash zone length was visually measured and inspected by linear interpolation of the AWG and PPT signals, and was found to cover a wave flume extension of 10.4 m (from  $x = -1.4$  to  $+9.0$  m) during the initial run and of around 9.0 m ( $x = 0.25$  to  $9.3$  m) during the final run. Positions in the swash zone can be characterized depending on the relative exposure duration of the bed. Following the definitions of Aagaard and Hughes (2006), the lower swash zone runs from  $x = 0.25$  to  $1.6$  m (up to 25% of time exposed), the

mid swash from  $x = 1.6$  to  $4.7$  m (25 to 60% exposed) and the upper swash for  $x > 4.7$  m (over 60% exposure time). Hence, the CCM<sup>+</sup> tank was situated in the lower swash zone, 0.35 m shoreward from the inner surf zone. This location also corresponds to the outer swash zone following the definition of Hughes and Moseley (2007), being the sub-region where wave swash interactions occur – as opposed to the inner swash zone where the swash events are free of interactions.

## **5. Bed level motions in the lower swash**

### **5.1 Spectral analysis**

In this section the CCM<sup>+</sup> bed level measurements (probe 3) are analyzed in both time and frequency domain, in order to identify and characterize dominant time scales of bed level changes.

Figure 7 presents time series of the CCM<sup>+</sup> probe 3 position, for three selected time frames with increasing level of detail. AWG data is included as a reference. Figure 7a shows the gradual erosion during the complete experiment (8 runs of 30 min = 14,400 s). During instances of bed exposure, the CCM<sup>+</sup> levels match well (order: millimeters) with the lower boundary of the AWG levels (Figure 7a,b). The measured local erosion of the bed over the experiment (magnitude of 0.1 m), agrees with erosion observed in the beach profile measurements (Figure 6a). While the AWG data can be used to study gradual bed level changes, the CCM<sup>+</sup> provides additional information about the existence of regular bed oscillations at smaller time scales. The bed clearly responds to the passing of the 15-second wave groups (Figure 7c).

Figure 7c also shows the vertical motion of the ‘slow’ concentration-measuring probe CCM<sup>+</sup> probe 1/2 (colored circles), lagging behind the actual bed level as measured by the ‘quick’ bed level probe 3. Probe 1/2 traverses the near-bed layer while measuring concentrations at varying elevations (see colors). When probe 1/2 is positioned below the bed interface, clearly higher concentrations are found than when it is positioned above the bed interface. Offsets between concentration measurements of probe 1/2 and the depicted bed level by probe 3 are the result of small local wave flume asymmetries.

The spectrum of the CCM<sup>+</sup> bed level measurements is shown in Figure 8. To derive this figure, power spectral densities (PSDs) were calculated for the measured bed levels by CCM<sup>+</sup> probe 3 (after subtracting the gradual erosion trend) with a Fast Fourier Transform. This was done for each of the last six runs, when the bed reached a semi-equilibrium state (experimental time  $t > 60$  min), and the obtained PSDs were subsequently averaged. As discussed earlier (see also Appendix A) it is expected that bed level spectral energy at frequencies equal to or larger than the wave group frequency  $f_{gr}$  is underestimated.

The spectrum contains dominant peaks at three frequencies, all of which can be related to the hydrodynamics. The highest peak is at a frequency of 0.067 Hz, which corresponds to the frequency of the bichromatic wave groups  $f_{gr}$  ( $T_{gr} = 15$  s). At this cross-shore location, also the water-surface level spectra were shown to be dominated by this group frequency (Figure 5f). The other two bed level spectral peaks are not visible in the water-surface level spectrum, but can both be related to the modulation of the short-wave phase at the repeat frequency as discussed in Section 3.2. The peak at 0.005 Hz corresponds to the repeat frequency  $f_R$  of the wave groups ( $T_R = 195$  s), i.e. the frequency at which the sequence of 13 wave groups repeats exactly. The peaks at 0.031 Hz and a smaller peak at a slightly higher frequency are close to half the frequency of the wave group ( $0.5 \cdot f_{gr} = 0.033$  Hz) and can be related to the short-wave phase repeating approximately every second wave group. Apparently, there is a clear response of the bed level to the systematically varying short-wave phase within the groups – even though the water level spectra show negligible energy at these frequencies. These bed level oscillations with a period of  $T_R = 195$  s can also be identified from the time series of the experiment (Figure 7a) and are studied in the next section (5.2).

## 5.2 Bed level motions at time scale of the wave group sequence ( $T_R = 195$ s)

In order to study the bed level motions in more detail, the measurements are phase-averaged at different time scales. Due to the observed variability between successive swash events, phase-averaging of the CCM<sup>+</sup> probe 3 bed level measurements is firstly done for the occurring sequences of

13 swash events (i.e. over the repeat period  $T_R = 195$  s). For this analysis, the first sequence of 13 wave groups and the last incomplete sequence of groups within each run were not considered. This leaves seven sequences per run, adding up to 42 repetitions of the sequence during semi-equilibrium conditions. The ensembles are normalized using the start of the uprush of the first wave group in the time series.

Phase-averaged results of the hydrodynamic measurements (water levels  $\eta$  and cross-shore near-bed velocities  $u$ ) at the CCM<sup>+</sup> cross-shore position are found in Figure 9. Due to emergence of the ADV probe, the velocity measurements are discontinuous. The relatively small standard deviations (Figure 9a,b) indicate that the sequences of 13 wave groups repeat themselves rather well. The individual wave-group-induced swash events within the ensemble (marked by the alternating gray/white backgrounds in Figure 9) are also to a large extent comparable. Each event consists of two or three major broken waves that can be identified from the water surface levels. Cross-shore velocities reveal a strong onshore maximum at the start of each uprush with magnitudes up to about 1 m/s. Maximum velocity magnitudes are measured in the backwash, where offshore velocities reach 1.5 m/s.

Despite hydrodynamic patterns being largely similar for all groups, subtle differences exist in timing and magnitude of the individual waves composing the swash events. As shown before (Figure 5e), the wave groups show better repeatability with every second preceding group than with each directly preceding group. This leads to slightly different velocities and wave-swash interactions for each swash event. These interactions are for some events described in more detail in the next section.

The bed level measurements required additional processing data processing prior to phase-averaging. The gradual erosion trend was removed by applying a high-pass Fourier filter, with a chosen cutoff frequency (0.004 Hz) that was slightly lower than the frequency of interest (being  $f_R = 1/T_R = 0.0051$  Hz). In addition, in order to characterize the pattern and magnitude of the bed level fluctuations that are exclusively the result of the short-wave modulations at  $f_R$ , a band-pass filter was applied (with lower and upper cutoff frequencies of 0.004 Hz and 0.020 Hz, respectively). The applied upper cutoff frequency is slightly lower than the lowest spectral peak associated with the individual wave groups

(0.031 Hz, see Figure 8). The band-pass filter removes both gradual erosion and the bed level oscillations induced by the individual wave-group-induced swash events. The accordingly obtained phase-averaged bed levels are shown in Figure 9c,d.

The bed measurements show that for each 15 s event the uprush induces local erosion, that for some waves continues during the first part of the backwash and which alters to sedimentation during the later backwash stage (Figure 9c). It also becomes evident that, although the group-to-group differences seem small in terms of hydrodynamics, the magnitudes of intra-group bed level oscillations vary substantially (see Section 5.3.2 for further discussion). An additional larger-scale sedimentation/erosion pattern can also be seen: during the first 6 groups the bed slowly accretes, while during the following 7 groups a slow erosion process occurs (Figure 9cd). Apparently, the sequence of net erosion/accretion events of each swash event drives an overall bed level fluctuation at the repeat frequency. The oscillation approaches a sine form with a period equal to the repeat period ( $T_R = 195$  s) and with an amplitude of about 1.5 mm, and it explains the bed level spectrum peak at  $f_R$  (Figure 8).

### **5.3 Bed level motions during individual swash events**

#### **5.3.1 Selection of characteristic swash events**

A more detailed analysis of sediment transport process measurements by the CCM<sup>+</sup> at the wave group time scale requires a substantial amount of repeating wave cycles. This holds in particular for sheet flow concentration profiles and particle velocities. Phase-averaged results for the 42 repetitions of the 195 s sequence (Section 5.2) proved to contain too much scatter to draw solid conclusions. Therefore, for this section and Section 6, measurements are phase-averaged at the group period  $T_{gr}$  ( $= 15$  s). Since hydrodynamics and sediment transport processes are not exactly the same for each swash event, two selections are made of characteristic swash events within the sequence of 13 groups.

For each selection, wave-group-induced swash events that induce similar behavior in terms of horizontal velocities and bed level changes are chosen. In order to arrive at two ensembles that are to a

large extent complementary, succeeding events were selected. In the following we refer to events of type “A” (marked by blue diamond symbol in Figure 9a) and type “B” (red star symbol in Figure 9a). The obtained ensembles (Figure 10) consist of 210 repetitions for event A and 168 repetitions for event B. For each ensemble,  $t/T_{gr} = 0$  refers to the arrival of the first bore of the swash event.

The selection of the events forming the two ensembles may appear somewhat arbitrary, since the selected wave groups do not repeat exactly within the sequence. Consequently, differences between the individual swash events within each ensemble can be observed, for instance in terms of timing of the incoming bore during the backwash of event A ( $t/T_{gr} = 0.5$  to  $0.7$ , Figure 10a – gray lines). However, the bed level ensemble does not show any enhanced variation at this instance (Figure 10e). Overall there is good qualitative and quantitative agreement between the various swash events that form the ensemble. In terms of water levels, it is pointed out that the differences within the two ensembles A and B are small compared to the differences between the two ensembles. The latter statement cannot be repeated for the velocity measurements, which show substantial variation caused partly by turbulent velocity fluctuations that were not removed (Figure 10c,d).

### 5.3.2 Hydrodynamics

Both events are formed by three major incident waves, and are similar in terms of maximum onshore and offshore velocities (Figure 10a-d). Also the relative duration of uprush and backwash is similar for both types of swash events. Differences between the events are found mainly in terms of timing of incident-bore arrival. These bores induce differences in terms of timing and magnitude of wave-swash interactions, which are described in the following. The characterization of interactions is supported by visual (video) observations and additional AWG measurements. Reference is made to existing literature that describes these interactions in more detail (e.g. Hughes and Moseley, 2007; Caceres and Alsina, 2012).

For swash event A, the early uprush is generated by a single bore. A second bore arrives during the uprush, lagging the first bore with about 2 s (wave capture; Peregrine, 1974; Hughes and Moseley, 2007). The backwash formed by these waves reaches offshore-directed velocities of high magnitude

(up to 1.5 m/s), but gets interrupted by the arrival of a third bore (around  $t/T_{gr} = 0.62$ ). The incident bore is halted by the preceding backwash, and the momentum exchange results in a stationary bore at/close to the CCM<sup>+</sup> location. This stationary bore is the result of strong wave-backwash interactions and has been compared to a hydraulic jump (Hughes and Moseley, 2007). The injection of air bubbles into the water column and the entrainment of sediment by this bore (Caceres and Alsina, 2012) may explain the loss of ADV signal despite water depths being sufficiently large. During the final stage of the swash event ( $t/T_{gr} = 0.7$  to 1), the remainder of the bore is washed seawards by the backwash.

Swash events of type B (Figure 10b,d) are characterized by a strong single uprush that results from the combination of two incident bores ( $t/T_{gr} = 0.1$  to 0.2). The second bore captures the front of the uprush, that was generated by the first bore, close to the CCM<sup>+</sup> location (wave-uprush interactions; Hughes and Moseley, 2007). A third bore arrives at the start of the backwash (around  $t/T_{gr} = 0.32$ ), i.e. at an earlier stage within the swash event cycle than for event A. In contrast to event A, the incident bore in event B is not completely halted at the CCM<sup>+</sup> location but continues to propagate shoreward (weak wave-backwash interactions at the CCM<sup>+</sup> location). Subsequently, it results in a stationary bore (strong wave-backwash interactions) about a meter shoreward from the CCM<sup>+</sup> location. This bore dissipates and is washed seaward during the final backwash stage.

Evidently, near-bed velocities are not in phase with water levels. Of particular notice are the backwash velocities for event B, which remain negative while the incident bore passes the measuring location ( $t/T_{gr} = 0.32$  to 0.50). The observed (video/AWG measurements) onshore propagation of the bore suggests that velocities in the top of the water column are directed onshore, while measured near-bed velocities are offshore-directed. This suggests a strong velocity shear in the water column, which has been shown to occur for incident bores before (Butt *et al.*, 2004; Cowen *et al.*, 2003).

### 5.3.3 Bed level motions

Bed level motions throughout the swash event are quantified in two ways. Firstly, the direct intra-wave measurements of CCM<sup>+</sup> probe 3 are analyzed. Secondly, the bed can be estimated from the time-variant vertical concentration profile as measured by probe 1/2. For both approaches, intra-wave bed

level fluctuations are presented with respect to a reference wave-averaged bed level ( $z_{ref}$ ). This wave-averaged bed level should include the mean bed evolution trend plus the fluctuations occurring at the repeat frequency as displayed in Figure 9d. Therefore,  $z_{ref}$  is given by the low-pass filtered (0.020 Hz cutoff) bed level measurement by the ‘quick’ CCM<sup>+</sup> sensor 3 ( $z_3$ ).

The direct intra-wave bed level measurements by probe 3 ( $z'_3$ ) are obtained by subtracting  $z_{ref}$  from  $z_3$ .

Before extracting the bed from the concentration profiles (probe 1/2), we need to define which concentration value adequately represents the bed level. We try to differentiate between local intra-group erosion/accretion of the bed as a result of incoming/outgoing sediment advection (this section), and time-varying bed level fluctuations as a result of sheet flow dynamics (Section 6). Note that for uniform sheet flow conditions, the maximum level of the immobile bed varies in time due to vertical sediment exchange (pick-up and deposition). As a result, this level seems inappropriate to study net horizontal advection. Instead, we suggest that for a situation with simultaneous sheet flow occurrence and net bed level changes, the intra-group bed level is best represented by the sheet flow pivot point elevation. At the pivot point elevation, which marks the middle of the sheet flow layer, concentrations in uniform conditions are nearly constant throughout a wave cycle (O'Donoghue and Wright, 2004). Consequently, changes in the elevation of the pivot point for non-uniform conditions are likely driven by horizontal advection processes and not by vertical exchange of sediment in the sheet flow layer. Section 6.1 explains how the pivot elevation was extracted from the measurements.

For both swash event types, all bed level measurements within the  $z'_3$  ensemble show a consistent pattern of local bed erosion during the uprush and accretion during the backwash (Figure 10e-f). This confirms previous observations (Figure 9). However, as stated repeatedly, the CCM<sup>+</sup> sensors are unable to perfectly track the bed on time scales smaller than the swash event (see Appendix A). The pivot point elevation (white lines in Figure 10e,f) provides therefore a more accurate estimate of the bed. Evidently, the bed measurements by probe 3 show a reduced amplitude and a phase lag compared to the pivot elevation (Figure 10e-f).

The time-varying pivot point elevation shows a similar pattern as  $z'_3$ . Rapid local erosion occurs during the early uprush ( $t/T_{gr} = 0$  to  $0.1$ ) and starts upon arrival of the first incident bore. During the mid backwash phase ( $t/T_{gr} = 0.6$  to  $0.8$ ), the bed accretes to a level close to the state at the start of the event. This accretion is more gradual than the erosion during the uprush. Although patterns are similar, the magnitudes of the bed level fluctuations differ substantially between the two groups: about 6 mm for swash event A and about 13 mm for swash event B.

The net bed level change induced by a single swash event results from the sum of erosion during the uprush and accretion during the backwash. The net effect is small compared to the bed level fluctuations during the event. Also in terms of net bed level change, both events are different. Swash event A leads to net accretion (about 2 mm), while event B induces net erosion (about 3 mm) at the lower swash zone. Recall that bed level changes that occur at the repeat frequency  $f_R$  were removed before this analysis.

## 6. Sheet flow dynamics

The measured sediment concentrations and grain velocities, as obtained from the CCM<sup>+</sup> sensors 1 and 2, are studied at the time scale of the individual wave groups. Existing knowledge about oscillatory sheet flow dynamics (Ribberink and Al-Salem, 1995; O'Donoghue and Wright, 2004) is used as a comparison to obtain insights in sheet flow characteristics in the swash. The concentrations shown in this section were measured with sensor 2, which proved to be slightly more stable in terms of calibration values than sensor 1. Overall, phase-averaged results by sensors 1 and 2 were highly comparable. Hence, perturbations caused by one sensor being in the lee of the other seem to be negligible.

### 6.1 Vertical concentration profiles

Each of the instantaneous concentration measurements  $C$  by sensors 1 and 2 was taken at a certain known absolute elevation of the probe ( $z_{1/2}$ ). To proceed, these concentration measurements are related

to the wave-group-averaged bed through  $z'_{1/2} = z_{1/2} - z_{ref}$ . As the bed is dynamic, the height  $z'_{1/2}$  of a concentration point measurement at a relative instance  $t/T_{gr}$  is different for each swash cycle (see also Figure 7c). Through phase-averaging, the  $C(z',t)$  values that were obtained at different elevations  $z'$  but at the same relative phase  $t/T_{gr}$  of repeating swash events can be combined into time-varying vertical concentration profile ensembles for each phase. These concentration profiles consist of 210  $C(z',t)$  points for event A and 168 for event B (amounts equal total number of repetitive swash events). Next, these profiles are for each phase smoothened by taking the median  $C$  measurement for vertical bin classes with 0.5 mm step size.

Figure 11 shows these vertical concentration profiles for 10 phases of event A. The errors bars are occasionally high when the number of concentration measurements within an elevation class is small. Even after averaging, some scatter can still be seen. Nevertheless, the profiles consistently follow concave shapes with concentrations decreasing with height, much alike observations for oscillatory sheet flow (e.g. O'Donoghue and Wright, 2004).

As a result of the chosen control settings of the CCM<sup>+</sup>, the sheet flow layer was not captured completely at all wave phases (Figure 11). Therefore, in order to make a quantitative comparison between sheet flow observations in this experiment and previous observations for oscillatory flow conditions, the empirical model of O'Donoghue and Wright (2004, from here on: ODW04) for sheet flow layer concentrations profiles was fitted through the  $C(z',t)$  measurements. Although this model was originally derived for uniform conditions, Lanckriet *et al.* (2014) and Lanckriet and Puleo (2015) illustrated the applicability of the equation to sheet flow concentration profiles during uprush and backwash in the swash zone. The approach is also supported by the apparent similarity between the measured concentration profiles in Figure 11 and the profiles of O'Donoghue and Wright (2004). The adopted ODW04 function reads:

$$C(z',t) = C_b \cdot \frac{\beta(t)^\alpha}{\beta(t)^\alpha + [z' + z_e]^\alpha} \quad (3)$$

Where  $C(z',t)$  is the volumetric concentration at height  $z'$  (mm) relative to the original bed at instance  $t$ ;  $C_b$  is the concentration in the bed ( $=0.64 \text{ m}^3/\text{m}^3$  in this experiment);  $\beta(t)$  and  $\alpha$  are shape factors; and

$z_e(t)$  is the so-called erosion depth of the sheet flow layer at time  $t$  which marks the bottom of the sheet flow layer.

We used a least-square method to fit Eq. (3) through the data. A fixed value of 1.5 was used for  $\alpha$  (O'Donoghue & Wright, 2004), while leaving the variables  $\beta$  and  $z_e$  as two free fitting parameters. Values for the shape factor  $\beta$  are directly connected to the sheet flow thickness (Section 6.4). The agreement between fit and measurements is reasonably good, with an average coefficient of determination  $r^2 = 0.85$ .

The curve fitting results include quantitative estimates of the time-dependent bed/water interface or pivot point level (where  $C = 0.3$ ) and the time-dependent lower boundary of the sheet flow layer ( $C = C_b = 0.64$ ). These elevations were used in Section 5.3.3 to study the intra-wave bed level behavior (Figure 10e,f).

The time-varying nature of sheet flow concentration profiles becomes evident from Figure 11. For  $t/T_{gr} = 0.2$  and  $0.3$ , the profiles show a sharp interface between the immobile bed and the water. This suggests that the bed is at rest (no sheet flow). Note that these instances correspond to low near-bed velocity magnitudes (c.f. Figure 10c). Towards  $t/T_{gr} = 0.6$  and  $0.7$ , the concentration gradient becomes less steep as the sheet flow layer develops. From  $t/T_{gr} = 0.1$  to  $0.7$ , the pivot elevation is at a more or less fixed level and the temporal variation in vertical concentration gradients is attributed to vertical exchange of sediment. At  $t/T_{gr} = 0.8$ , the bed starts to rise which agrees with bed level measurements of probe 3 (Figure 10e).

## 6.2 Time series of sheet flow concentrations

Concentration time series are noisy, and more insights are obtained when focusing at phase-averaged concentrations obtained at different vertical elevations. Phase-averaging is done for six concentration bin classes, ranging from  $C = 0$  to  $0.6 \text{ m}^3/\text{m}^3$  with steps of  $0.1 \text{ m}^3/\text{m}^3$ . These bin classes are based on wave-group-averaged concentrations per swash cycle and consequently, intra-wave-group concentration fluctuations are still captured (Figure 12e,f). For each concentration class, the mean vertical elevation  $z'$  with respect to the wave-averaged bed was calculated. In the present experiments

the six classes contain about 30 swash repetitions and it is estimated that the mean elevations have an accuracy of about  $\pm 1$  mm. This small variation explains why occasionally concentrations are found to increase with height (Figure 12e,f). This way of presenting the CCM concentration data was developed for oscillatory sheet flow measurements (Ribberink and Al-Salem, 1995; McLean *et al.*, 2001) and is especially useful when studying the sheet flow response at various elevations of the sheet flow layer (e.g. pick-up layer and upper sheet flow layer).

Another way of presenting the same data is through color contours of the time-varying concentration profiles (Figure 12i,j). Note that for wave A, the concentration profiles in Figure 12i corresponds to the profiles in Figure 11. Also included in Figure 12i,j are the pivot elevation (corresponding to Figure 10e,f) and the time-varying bottom of the sheet flow layer derived from the ODW04 curve fit.

Typical sheet flow layer pick-up behavior, as known from oscillatory sheet flows, can be observed in the concentration time series (Figure 12e,f) at the lowest elevations where the concentrations are close to 0.6 (packed-bed). The concentrations show temporary dips at instances of sediment pick-up from the bed. Deeper dips suggest stronger sediment pick-up. This pick-up happens once during the uprush (shortly after bore arrival; around  $t/T_{gr} = 0.10$  for both swash events) and one or two times during the backwash phase (around  $t/T_{gr} = 0.5$  and  $0.65$ ). For swash event A the strongest pick-up occurs during the backwash (around  $t/T_{gr} = 0.65$ ), while for event type B this happens during the uprush. Similar to oscillatory sheet flows, this pick-up behavior is observed at low elevations in the bed where the concentrations exceed the bed-water interface value ( $C > 0.3$ ) and it occurs generally when velocity magnitudes are high.

At higher elevations, in the so-called upper sheet flow layer ( $C < 0.3$ ), the concentration behavior differs strongly from oscillatory sheet flows. For oscillatory sheet flows in wave tunnels (O'Donoghue and Wright, 2004) as well as under non-breaking surface waves (Schretlen, 2012), sediment exchange occurs between pick-up and upper sheet flow layer. The consequence of this predominantly vertical exchange is that a concentration dip in the pick-up layer is accompanied by a similar concentration peak in the upper sheet flow layer (mirroring behavior). Moreover, this sediment exchange occurs

around a steady interface elevation where  $C = 0.3$  (pivot point). In the present swash experiments this type of behavior is not clearly visible. Firstly, the pivot level is not steady but fluctuates over a vertical distance of several millimeters during the wave cycle (Figure 12i,j). Secondly, the present swash experiment does not show the mirroring behavior in concentrations during each instance of sheet flow. During the early uprush, the sediment pick-up around  $t/T_{gr} = 0.1$  is not accompanied by an increase in upper sheet flow layer concentrations. Instead, concentrations drop at all elevations as a result of the strong bed level decrease (Figure 12i,j). During the pick-up event in the backwash (around  $t/T_{gr} = 0.65$  for both events), concentrations in the upper sheet flow layer are indeed increasing. Although this may point towards vertical sediment exchange (pick-up), during the remainder of the backwash the upper sheet flow layer concentrations continue to increase even though no pick-up is observed ( $t/T_{gr} = 0.65$  to  $0.90$ ). These observations are discussed in more detail in Section 7.2.

### 6.3 Particle velocities and fluxes in the sheet flow layer

Particle velocities in the sheet flow layer were calculated following the approach of McLean *et al.* (2001). This method assumes that (clouds of) particles travel past the co-located sensors 1 and 2, and the travel time can be found by estimating the phase lag through cross-correlating the high-pass filtered (1 Hz cutoff) signals of the two sensors. This cross-correlation is done for each individual wave and for a selected number of phases of the wave cycle (in this case 100). For each phase, the cross-correlation output for all wave cycles is averaged. This averaging is done per wave-averaged concentration bin class, using the same six classes as in Section 6.2. For each bin class and phase, the time lag corresponding to the maximum averaged cross-correlation output is used to estimate the mean travel time of particles between both sensors. Data for which the maximum cross-correlation value did not exceed the background noise are emitted. Particle velocities are defined as the distance between both sensors (1.5 cm) divided by the derived travel time. Figure 12c,d shows that particle velocity estimations are only obtained when instantaneous ADV velocity magnitudes approach or exceed a threshold of roughly 1.0 m/s.

Although the measurements show considerable scatter, it is clear that for both swash events the measured particle velocities in the sheet flow layer (Figure 12c,d) follow a similar intra-wave pattern as the flow velocities measured by the ADV at an elevation of about 3 cm above the bed. During both uprush and backwash the particle velocities in the sheet flow layer can reach large magnitudes (1 m/s and higher). Particle velocities in the upper sheet flow layer approach the near-bed water velocity magnitudes, which is not uncommon for sheet flow observations (e.g. McLean *et al.*, 2001). Vertical structure of the particle velocities is only evident for the long backwash of swash event B, with particle velocities decreasing towards the bed (in line with observations of McLean *et al.*, 2001; Dohmen-Janssen and Hanes, 2005; Schretlen, 2012).

The combination of concentration and particle velocity measurements by the CCM<sup>+</sup> sensors allows us to directly estimate the intra-wave horizontal sediment fluxes, as the product of the measured particle velocities (Figure 12c,d) and concentrations (Figure 12e,f) per bin class. The horizontal sediment fluxes (Figure 12g,h) show a similar oscillating pattern as the particle velocities. Both swash events A and B show large fluxes during the relatively short uprush, followed by a longer period with smaller fluxes during the backwash. The magnitudes of the fluxes during swash event B are clearly larger than during event A. Despite the scatter of the data a general tendency can be seen: the fluxes increase with decreasing elevations in the sheet flow layer (see e.g. the backwash of wave B). The reduction of velocities towards the bed is more than compensated by the larger volumetric sediment concentrations at these levels. Note that also for oscillatory sheet flows, highest fluxes were found in the pick-up layer (McLean *et al.*, 2001; Dohmen-Janssen and Hanes, 2005; Schretlen, 2012).

#### **6.4 Sheet flow layer thickness**

The thickness was estimated from the interpolated profiles derived from the ODW04 fit (Section 6.1). The sheet flow layer thickness ( $\delta_s$ ) is defined as the distance between the bottom of the sheet flow layer and the level where the volume concentration reaches  $0.08 \text{ m}^3/\text{m}^3$  (Dohmen-Janssen and Hanes,

2002; O'Donoghue and Wright, 2004). Hence, the thickness relates to the vertical concentration gradients (Figure 12i,j and Figure 11).

Temporal behavior of  $\delta_s$  (Figure 12k,l) agrees with results in previous sections. The thickness increases at the previously identified instances of sediment pick-up (during early uprush and mid backwash phase; Figure 12e,f). There is also a clear correspondence between thick, well-developed sheet flow layers, and the derived fluxes (Figure 12g,h).

The measured maximum  $\delta_s$  values are substantially higher than observations of oscillatory sheet flow with similar grain-size and velocity magnitudes. Tunnel measurements of O'Donoghue and Wright (2004) with narrow-distributed medium-grained sand ( $D_{50} = 0.28$  mm) and peak velocities of 1.5 m/s, yielded maximum sheet flow thicknesses of 8 mm (case MA5010). Measurements under progressive surface waves in a wave flume (Schretlen, 2012; case RE1575m) yielded sheet flow thicknesses of 10.3 mm for medium-grained sand ( $D_{50} = 0.245$  mm) and crest velocities of 1.63 m/s. Compared to aforementioned experiments, peak flow velocities are lower but sheet flow thicknesses during both uprush and backwash are over twice as high. This holds in particular for swash event B.

## 7. Discussion

The new experiments with the CCM<sup>+</sup> instrumentation have resulted in new detailed results in the bed level and sediment (sheet flow) dynamics during swash events in the lower swash zone. In this section, the bed level (7.1) and sheet flow (results) are connected to existing knowledge on sediment dynamics in the swash and to previous observations of oscillatory sheet flows.

### 7.1 Bed level motions at various time scales

The measured intra-group bed levels in the lower swash show a consistent pattern of rapid erosion during the uprush and gradual accretion during the backwash phase. Steep horizontal sediment transport gradients, induced by the strong non-uniformity of the waves and flow in the swash as pointed out for instance by Hughes *et al.* (2007), may directly lead to these types of erosion/accretion

events. The measurements suggest that the sediment mobilized at the start of the event is transported onshore during the uprush and brought back during the backwash (i.e. cross-shore advection). The importance of cross-shore sediment advection on swash morphology has been addressed before and has been associated to suspended sediment settling lags due to enhanced turbulence and hindered settling (Pritchard and Hogg, 2005; Hughes *et al.*, 2007; Alsina *et al.*, 2009). The results further show that the net bed level change after a single swash cycle results from a difference between uprush erosion and backwash accretion, and support the idea that the swash zone bed level change results from a small difference of two opposing sediment movements with similar high magnitudes (Masselink and Hughes, 1998). Our observations for one wave condition do not object reported cases for random wave conditions, where a few “large” swash events were responsible for the measured beach face elevation changes (e.g. Puleo *et al.*, 2014).

Swash events A and B are similar in terms of wave energy, peak onshore and offshore velocities, and relative durations of uprush and backwash. The modulation of the short-wave phase at the repeat frequency triggers different types of specific wave-swash interactions, that are characteristic for the lower swash zone (Hughes and Moseley, 2007). This leads to local differences in terms of hydrodynamics (e.g. velocities, turbulence, pressure gradients) which in return affect sediment transport patterns. Little is known about the effects of wave-swash interactions on bed level changes. Here, effort is made to relate the observations in bed level changes to the wave-swash interactions observed for both events in a qualitative sense.

The bed level drop during the early uprush for event B is larger than for event A, suggesting steeper horizontal sediment transport gradients for event B at this instance. The higher sheet flow thickness and fluxes for the event B uprush suggest that this uprush is more energetic, in terms of bed shear, horizontal pressure gradients, and/or turbulence (Lanckriet and Puleo, 2015). These same factors affect local sediment entrainment by bores (Puleo *et al.*, 2000; Butt *et al.*, 2004; Jackson *et al.*, 2004). The interaction between the two incident bores which form the uprush of event B and which are close in phase at the CCM<sup>+</sup> measuring location may partly explain why uprush B is more energetic than uprush A. Note that the bed level change is a result of instantaneous sediment transport gradients,

which means that pre-suspended sediment that is advected from the inner surf towards the lower swash zone may also be an important factor (Jackson *et al.*, 2004; Pritchard and Hogg, 2005).

For event A, strong wave-backwash interactions result in a stationary bore at the CCM<sup>+</sup> location which seems to promote sediment pick-up (Figure 12i,  $t/T_{gr} = 0.5$  to  $0.7$ ). Sediment suspension events under stationary bores have been observed before (Caceres and Alsina, 2012) and relate to strong vertical (turbulent) velocity fluctuations (Aagaard and Hughes, 2006). Accretion of the bed starts a couple of seconds after the incident bore arrives at the measuring location, and is possibly explained by a decrease in velocities and sediment settling as a result of the backwash interruption (Puleo *et al.*, 2014). For event B, the combination of strong accretion and high near-bed sediment concentrations during the mid-final backwash stage suggests a large amount of advected sediment arriving from the shoreward direction (i.e. a larger amount than for event A). This large amount of sediment is possibly mobilized by the stationary bore that was observed about 1 m shoreward from the CCM<sup>+</sup> location for event B.

The sequence of the various erosion and accretion events induced by the individual wave groups forms an overall bed level fluctuation at the repeat period  $T_R$  ( $= 195$  s). This slow bed level fluctuation is of similar magnitude (1-2 mm amplitude) as the net bed level change induced by each swash event (2-3 mm), which suggests that both are potentially relevant for swash zone morphology. To the authors' knowledge, only one study discusses the effects of this repeat frequency on near-shore processes. Baldock *et al.* (2000) report the potential relevance of wave phase modulations at the repeat frequency on the generation of wave breakpoints and on water surface levels and run-up in the swash. Similar to Baldock *et al.* (2000), the low-frequency regions in our experiment show negligible energy in the water level spectrum (Figure 5f) and the wave groups are approximately equal in terms of wave energy. This suggests that the bed level changes occurring at  $f_R$  are the result of sediment transport processes repeating at this repeat frequency, e.g. processes driven by wave-swash interactions during uprush and backwash, rather than the result of water surface oscillations associated to this frequency. A spectral coherence analysis between bed levels (CCM<sup>+</sup>) and water surface levels (AWG) for these data supports this explanation, showing minor energy at  $f_R$  compared to the values at  $f_{gr}$  (Alsina *et al.*,

2014). This marks a clear difference from previous studies that highlighted the importance of low-frequency (infra-gravity) waves on swash zone sediment transport processes (Beach and Sternberg, 1991) and bed level changes (Puleo et al., 2014), as these studies found substantial energy in the low-frequency bands of the water level spectrum.

The present results highlight the importance of wave-swash interactions on bed level changes and swash morphology. However, a more thorough explanation of the observed local bed level changes requires a characterization of bed level changes and sediment transport rates along the complete swash zone. Moreover, bed level measurements for a wider range of swash conditions (e.g. including uprushes and backwashes that are free of interactions) are required for a more generic assessment of the importance of these interactions.

## **7.2 Sheet flow dynamics and implications for modeling sheet flow transport in the swash**

Sheet flow transport is observed at instances with sufficiently high instantaneous velocities ( $> 1$  m/s), which agrees with observations of oscillatory sheet flows (O'Donoghue *et al.*, 2006). These instances occur mainly during the uprush and during the middle/final stage of the backwash phase, which agrees with earlier observations for natural swash zones (Yu *et al.*, 1990; Lanckriet *et al.*, 2013; Lanckriet *et al.*, 2014). The dynamics of the sheet flow layer for the lower swash in this experiment exhibit both similarities and differences with oscillatory sheet flow. Differences are attributed to (i) effects of bore-induced turbulence and (ii) the importance of flow non-uniformity and horizontal advective transport.

At the lowest vertical elevations, the pick-up of sediment during the wave group shows a strong similarity with the pick-up occurring in oscillatory flows (also surface waves). Pick-up events occur predominantly at instances of large horizontal velocities and accelerations (during uprush and backwash) and can probably largely be explained by horizontal shear-induced turbulence (see e.g. Kranenburg *et al.* 2013). However, in line with Lanckriet and Puleo (2015), our results indicate that not only horizontal shear but also bore turbulence can promote sediment pick-up and sheet flow layer growth. This is observed firstly for the early uprush ( $t/T_{gr} = 0$  to 0.1) of both events, where pick up is

major and sheet flow thicknesses are higher than for oscillatory sheet flow studies with similar sediment and peak velocities, and secondly for the backwash, where the stationary bore at the CCM<sup>+</sup> location for swash event A (from  $t/T_{gr} = 0.6$  to  $0.8$ ) promotes vertical sediment exchange even though water and particle velocities are low.

During the backwash, the local bed slope may promote the mobilization of sediment. However, the absence of sediment pick-up during the final backwash stage suggests that the high near-bed sediment mass is not locally entrained (vertical exchange) and must therefore be arriving from the middle/higher swash (horizontal advection). The accretion of the bed during the backwash supports this idea of a large amount of advected sediment arriving from the onshore direction. This large transport is confined to a small water layer, so sediment concentrations are likely of similar magnitude as concentrations restricted to upper sheet flow layers for oscillatory flow conditions. As a result, the sheet flow layer thickness during the backwash of both events is larger than expected based on local hydrodynamics and previous observations for oscillatory sheet flows. This is in particular true for event B, where backwash sediment advection is likely higher (see Section 7.1), resulting in a large sheet flow thickness.

The new measurements show that cross-shore sediment advection in the swash is not only relevant for suspended sediment transport, but it also affects the characteristics of the sheet flow layer. Consequently and unlike previous observations for oscillatory sheet flow, the sheet flow dynamics and fluxes during uprush and backwash are not purely controlled by local hydrodynamics. This implies firstly that vertical profiles of particle velocities and fluxes do not necessarily scale to sheet flow thicknesses: sediment fluxes may be low even when sheet flow thicknesses are high (e.g. below stationary bore during event A backwash). A second implication is that ‘local’ formulations for sheet flow sediment transport of the type of Meyer-Peter & Mueller (e.g. Nielsen, 2006) may not be valid for the swash zone. Instead, sheet flow transport models for the swash may require a coupling with an intra-wave advection-diffusion model that calculates time-dependent near-bed suspended sediment transport (such as Alsina *et al.*, 2009; Zhu and Dodd, 2015). On the other hand the measurements showed that (i) especially the upper sheet flow layer is influenced by advection effects – the pick-up

layer still shows a strong resemblance with oscillatory sheet flows; (ii) the largest sheet flow fluxes seem to occur in the lower parts of the sheet flow layer. Therefore, characteristics of the sheet flow pick-up layer may still be locally controlled, and sand transport in this layer could be modeled as such.

## **8. Conclusions**

Measurements of bed level fluctuations and detailed sheet flow characteristics throughout a complete swash cycle are presented. These measurements were obtained in the lower swash during a wave flume experiment involving bichromatic wave groups. A new instrument (CCM<sup>+</sup>), capable of measuring continuous gradual bed level evolution as well as concentrations and particle velocities in the sheet flow layer, was applied for the first time.

At the lower-swash location studied here, observations of the CCM<sup>+</sup> system show a consistent pattern of rapid net bed erosion during the early uprush and gradual accretion during the middle backwash phase. Subtle differences in hydrodynamics between the various wave groups lead to substantial differences in both the magnitude of the intra-group bed level fluctuations (6-13 mm) and in the net bed level change (2-3 mm erosion or accretion) induced by each group. This causes the bed to respond not only at the group frequency of the bichromatic waves, but also at the repeat frequency of the wave group sequence.

Sheet flow transport was observed at the early uprush and during the middle and late backwash phase. At the early uprush, the growth of the sheet flow layer and the drop in bed level occur almost simultaneously. The sheet flow layer exhibits some features similar to oscillatory sheet flow, such as sediment entrainment from the pick-up layer. This pick-up is observed not only when horizontal shear velocities are high, but also in occurrence of wave-swash interactions during the backwash. Direct cross-shore sediment flux measurements in the sheet flow layer from the CCM<sup>+</sup> show similarities with oscillatory sheet flow conditions, with highest flux rates found in the pick-up layer.

Notable differences from observations of oscillatory sheet flow are (i) a time-varying elevation of the concentration pivot-point within a wave group cycle; (ii) an absence of mirroring concentration behavior in pick-up layer and upper sheet flow layer. These differences can be explained from the highly non-uniform flow conditions. Sediment advection dominates the upper sheet flow layer concentration behavior and the properties of the sheet flow layer are not fully locally determined. This implies that existing ‘local’ formulations for sediment transport may not be valid for the swash zone.

## **Acknowledgments**

We would like to thank the staff of the TCO department at the University of Twente for their expertise on building the CCM<sup>+</sup> tanks and software, and the staff of CIEMLAB, Universitat Politècnica de Catalunya for their great efforts during the experiments. The research presented in this paper is part of the SINBAD project, funded by STW (12058) and EPSRC (EP/J00507X/1, EP/J005541/1). The CoSSedM experiments were funded by the European Community’s Seventh Framework Programme through the Integrating Activity HYDRALAB IV, Contract no. 261520. We would also like to thank professor Suzanne Hulscher and dr. Bas Borsje, as well as professor Tom Baldock and three additional anonymous reviewers for their feedback which helped us to improve the manuscript.

## **Appendix A. Evaluation of CCM<sup>+</sup> bed level measurements**

The new concentration tracking system is in essence a feedback loop between concentrations and sensor movement, ensuring that the sensor will always move in the direction of a certain target concentration. If the tracking system would perform ideally, the system would be able to keep the measured concentrations at all times at a target value through continuous adjustment of the sensor elevation. In practice, the probe fluctuates around the elevation of the target concentration. This is due to (i) the limitations of control system (e.g. system lags and probe risks overshooting); (ii) the spiky nature of the measured concentration signal; (iii) the time-varying vertical concentration gradients. As a result of the latter, there is not a single perfect setting for the tracking system's gain factor for an experiment, as the response sensitivity (in terms of vertical distance to be covered for a certain measured concentration offset) should be constantly varying.

This section evaluates the performance of the new concentration tracking system. This is done in two ways: (i) by studying the probe's tracking ability in the spectral domain (Section A.1); (ii) by comparing the phase-averaged intra-group bed level measurements of the 'quick' CCM<sup>+</sup> probe 3 with bed level estimations obtained from the CCM<sup>+</sup> probe 2 concentration measurements (Section A.2). The results are evaluated in Section A.3.

### **A.1 Evaluation of CCM<sup>+</sup> in the spectral domain**

As a start, the probe's response at various time scales is analyzed. Rather than examining the time series of the probe, the power spectra of concentrations and positions of the various CCM<sup>+</sup> probes are studied. In order to explain this, consider a first case of a fixed probe at a constant level near the bed interface (so no bed level tracking). This probe measures concentration fluctuations as a result of sheet flow behavior or bed level motions. The various types of fluctuations will appear as energy peaks in a power spectrum of the measured concentrations. Now consider a second case of an ideally tracking probe, i.e. the probe is able to keep up with all elevation changes necessary to keep the measured concentration constantly at its target value. In this situation the power spectrum of the (constant) concentration signal will not show any energy, while on the other hand the power spectrum of the

probe elevation will show energy peaks at the dominant physical frequencies. In practice, the probe control system is not ideal, and it can be expected that especially the high-frequency fluctuations of the bed cannot be followed by the probe. Consequently, these frequencies will not appear in the power spectrum of the probe elevation but will appear in the power spectrum of the concentration signal instead.

Power spectra of concentrations and positions for both probes are found in Figure A.1. Concentration measurements of probe 2 show distinct peaks at  $f_{gr}$  (0.067 Hz) and  $0.5f_{gr}$ , and a smaller peak at  $f_R$  (0.005 Hz). Physical explanations of these peaks are given in Section 5.1. Spectral energy of this probe's position is restricted to the lower-frequency bands, with a clear peak at  $f_R$ . This suggests that probe 2 moves with the lower-frequency bed level motions, but it is at an approximately fixed level at frequencies higher than 0.01 Hz. At these higher frequencies, the probe measures concentrations while being at a close-to-fixed position – so its movements do not distort the measurement.

Probe 3 shows a reverse pattern. As expected, the total energy in the concentration spectrum is less than for probe 2, while there is more energy in the position spectrum. The concentration spectrum shows negligible energy at frequencies lower than  $f_{gr}$ . Apparently, in this lower frequency range, the probe is able to keep concentrations constantly at its target value, i.e. the probe is well able to follow bed level evolution. The peak in the concentration spectrum of probe 3 at  $f_{gr}$  indicates that the probe is not able to respond perfectly to bed level changes driven by the wave groups. The spectral energy of this peak in  $C$  is much smaller for probe 3 than for probe 2, which suggests that the probe approaches but not perfectly tracks the intra-group bed level.

Based on these results in the present swash experiments, CCM<sup>+</sup> probe 3 is only used to provide bed level (reference) information at time scales larger than the wave group time scale (frequencies < 0.067 Hz). CCM<sup>+</sup> probe 2 is used to provide concentration information at time-scales equal to or smaller than the scale of individual wave groups ( $f > 0.067$  Hz).

## **A.2 Evaluation of the CCM<sup>+</sup> bed level tracking system in the time domain at short (intra-wave group) time scales**

Figure 10e,f can be used to compare the phase-averaged intra-group bed level measurements (CCM<sup>+</sup> sensor 3) and the pivot elevation extracted from the concentration measurements (sensor 2). The latter approaches closely the real bed, as it should not be experiencing any phase delay.

Qualitatively, the intra-wave bed measurement (probe 3) resembles the actual pattern of pivot level fluctuations. It is obvious that the magnitudes of the intra-group bed level measurements by probe 3 (4 and 6 mm for events A and B, respectively) are smaller than the observed pivot point fluctuations (event A: 6 mm; event B: 13 mm). In addition, the bed level measurements of probe 3 lag the pattern of the “real” bed with a delay up to about 2 s. This is most evident during the uprush phase where erosion is severe. Apparently, the probe is not able to follow the bed when it evolves rapidly on a time scale of 1 to 2 s.

### A.3 Discussion of CCM<sup>+</sup> capabilities

The CCM<sup>+</sup> in quick tracking mode is well able to track the bed at frequencies lower than  $f_{gr}$  (0.067 Hz) in the present swash experiment. At frequencies similar to or higher than  $f_{gr}$ , the quality of the CCM<sup>+</sup> measurement decreases. On an intra-group time scale the CCM<sup>+</sup> bed level measurement shows a smoothened and lagged representation of the actual bed. This smoothening and lagging depends on the magnitudes and time scales of the erosion and accretion events that induce the bed level fluctuations. E.g. for swash event A, characterized by a less severe erosion/accretion pattern than event B, the direct bed level measurement of CCM<sup>+</sup> is of better quality.

The CCM<sup>+</sup> probes are physically able to move substantially faster than during the current experiment. The gain factor that controls the probe’s movement sensitivity can be increased. However, this soon results in probe overshooting and unstable behavior, in particular when sheet flow layers are small or absent (i.e. when there is a direct vertical transition from the immobile bed to ‘clear’ water). The CCM<sup>+</sup> tracking capabilities can possibly be improved by including more sophisticated proportional-integral-derivative (PID) control loops. However, for experiments with repeating wave conditions as

reported herein, the main purpose of the CCM<sup>+</sup> bed level tracking system would be to measure the gradual erosion patterns only; something the measuring system is well capable of.

As discussed in the introduction, most of the ‘classic’ instrumentation (e.g. echo sounders) fails to measure the bed during both exposed stages and submerged stages of the bed. In terms of concentration measurements, most instruments (e.g. OBSs) fail at measuring the high concentrations during the early uprush and late backwash phase when water depths are shallow. The recently developed Conductivity Concentration Profiler (CCP; Lanckriet *et al.*, 2013) is the only instrument capable of measuring sheet flow concentration profiles and bed level changes with high temporal ( $f > 1$  Hz) resolution. The CCP measures a complete sheet flow concentration profile at once, which is a major advantage in many conditions. However, it also has limitations, e.g. (i) sheet flow thicknesses smaller than 3.5 mm cannot be resolved (Lanckriet *et al.*, 2013); (ii) the measuring window (30 mm) is limited, which may lead to a substantial loss of data when the bed is evolving (Puleo *et al.*, 2014); (iii) the system is unable to measure particle velocities. Regarding the latter, it is stressed that to the authors’ knowledge none of the existing instrumentation but the CCM<sup>+</sup> is capable of direct particle velocity measurements. Yet, these measurements are of crucial importance for estimation of sediment fluxes and understanding of swash morphology.

Obvious limitations of the CCM<sup>+</sup> system are (i) it cannot directly measure rapid instantaneous bed level changes; (ii) it provides a point measurement of concentrations (and not a complete profile). As a result, phase-averaging is required to sample the complete sheet flow layer including time-varying bed levels during a wave (group). More of practical nature is the fact that the dimensions and weight of the tank make it an instrument more suitable for laboratory than field conditions.

## References

Aagaard, T. and M. G. Hughes (2006). *Sediment suspension and turbulence in the swash zone of dissipative beaches*. Marine Geology **228**(1-4): 117-135. doi: 10.1016/j.margeo.2006.01.003.

- Alsina, J. M., S. Falchetti and T. E. Baldock (2009). *Measurements and modelling of the advection of suspended sediment in the swash zone by solitary waves*. Coastal Engineering **56**(5-6): 621-631. doi: 10.1016/j.coastaleng.2009.01.007.
- Alsina, J. M., I. Caceres, M. Brocchini and T. E. Baldock (2012). *An experimental study on sediment transport and bed evolution under different swash zone morphological conditions*. Coastal Engineering **68**: 31-43. doi: 10.1016/j.coastaleng.2012.04.008.
- Alsina, J. M., I. Caceres, J. van der Zanden, J. S. Ribberink and T. E. Baldock (2014). *Large scale experiments on beach evolution induced by bichromatic wave groups with varying group period*. Proceedings of the 34th International Conference on Coastal Engineering, Seoul, Korea, 10 pp.
- Baldock, T. E., D. A. Huntley, P. A. D. Bird, T. O'Hare and G. N. Bullock (2000). *Breakpoint generated surf beat induced by bichromatic wave groups*. Coastal Engineering **39**(2-4): 213-242. doi: 10.1016/S0378-3839(99)00061-7.
- Baldock, T. E., M. G. Hughes, K. Day and J. Louys (2005). *Swash overtopping and sediment overwash on a truncated beach*. Coastal Engineering **52**(7): 633-645. doi: 10.1016/j.coastaleng.2005.04.002.
- Baldock, T. E., J. A. Alsina, I. Caceres, D. Vicinanza, P. Contestabile, H. Power and A. Sanchez-Arcilla (2011). *Large-scale experiments on beach profile evolution and surf and swash zone sediment transport induced by long waves, wave groups and random waves*. Coastal Engineering **58**(2): 214-227. doi: 10.1016/j.coastaleng.2010.10.006.
- Beach, R. A. and R. W. Sternberg (1991). *Infragravity-driven suspended sediment transport in the swash, inner and outer-surf zone*. Proc. Coastal Sediments, ASCE: 114-128
- Beach, R. A., R. W. Sternberg and R. Johnson (1992). *A fiber optic sensor for monitoring suspended sediment*. Marine Geology **103**(1-3): 513-520. doi: 10.1016/0025-3227(92)90036-h.
- Blenkinsopp, C. E., I. L. Turner, G. Masselink and P. E. Russell (2011). *Swash zone sediment fluxes: Field observations*. Coastal Engineering **58**(1): 28-44. doi: 10.1016/j.coastaleng.2010.08.002.

- Butt, T., P. Russell, J. Puleo, J. Miles and G. Masselink (2004). *The influence of bore turbulence on sediment transport in the swash and inner surf zones*. Continental Shelf Research **24**(7-8): 757-771. doi: 10.1016/j.csr.2004.02.002.
- Caceres, I. and J. M. Alsina (2012). *A detailed, event-by-event analysis of suspended sediment concentration in the swash zone*. Continental Shelf Research **41**: 61-76. doi: 10.1016/j.csr.2012.04.004.
- Cowen, E. A., I. M. Sou, P. L. F. Liu and B. Raubenheimer (2003). *Particle image velocimetry measurements within a laboratory-generated swash zone*. Journal of Engineering Mechanics-Asce **129**(10): 1119-1129. doi: 10.1061/(Asce)0733-9399(2003)129:10(1119)
- Dohmen-Janssen, C. M. and D. M. Hanes (2002). *Sheet flow dynamics under monochromatic nonbreaking waves*. Journal of Geophysical Research **107**(C10). doi: 10.1029/2001jc001045.
- Dohmen-Janssen, C. M. and D. M. Hanes (2005). *Sheet flow and suspended sediment due to wave groups in a large wave flume*. Continental Shelf Research **25**(3): 333-347. doi: 10.1016/j.csr.2004.10.009.
- Horikawa, K., A. Watanabe and S. Katori (1982). *Sediment Transport Under Sheet Flow Condition*. Proceedings of the 18th International Conference on Coastal Engineering, Cape Town, South Africa: 1335-1352
- Hibberd, S. and D. H. Peregrine (1979). *Surf and Run-up on a Beach - Uniform Bore*. Journal of Fluid Mechanics **95**(Nov): 323-345. doi: Doi 10.1017/S002211207900149x.
- Hughes, M. G., T. Aagaard and T. E. Baldock (2007). *Suspended Sediment in the Swash Zone: Heuristic Analysis of Spatial and Temporal Variations in Concentration*. Journal of Coastal Research **236**: 1345-1354. doi: 10.2112/05-0531.1.
- Hughes, M. G. and A. S. Moseley (2007). *Hydrokinematic regions within the swash zone*. Continental Shelf Research **27**(15): 2000-2013. doi: 10.1016/j.csr.2007.04.005.
- Jackson, N. L., G. Masselink and K. F. Nordstrom (2004). *The role of bore collapse and local shear stresses on the spatial distribution of sediment load in the uprush of an intermediate-state beach*. Marine Geology **203**(1-2): 109-118. doi: 10.1016/S0025-3227(03)00328-1.

- Janssen, T. T., J. A. Battjes, and A. R. van Dongeren (2003). *Long waves induced by short-wave groups over a sloping bottom*. Journal of Geophysical Research, **108**(C8): 3252, 1-14.  
doi:10.1029/2002JC001515,
- Kranenburg, W.M., Ribberink, J.S., Schretlen, J.L.M. & Uittenbogaard, R.E. (2013). *Sand transport beneath waves: the role of progressive wave streaming and other free surface effects*. Journal of geophysical research. Earth surface, 118(1), 1-18.
- Lanckriet, T., J. A. Puleo and N. Waite (2013). *A Conductivity Concentration Profiler for Sheet Flow Sediment Transport*. Ieee Journal of Oceanic Engineering **38**(1): 55-70. doi: 10.1109/joe.2012.2222791.
- Lanckriet, T., J. A. Puleo, G. Masselink, I. L. Turner, D. Conley, C. Blenkinsopp and P. Russell (2014). *Comprehensive Field Study of Swash-Zone Processes. II: Sheet Flow Sediment Concentrations during Quasi-Steady Backwash*. Journal of Waterway, Port, Coastal, and Ocean Engineering **140**(1): 29-42. doi: 10.1061/(asce)ww.1943-5460.0000209.
- Lanckriet, T. and J. A. Puleo (2015). *A semianalytical model for sheet flow layer thickness with application to the swash zone*. Journal of Geophysical Research: Oceans **120**(2): 1333-1352. doi: 10.1002/2014jc010378
- Longuet-Higgins, M. S. and R. W. Stewart (1964). *Radiation Stresses in Water Waves - a Physical Discussion, with Applications*. Deep-Sea Research **11**(4): 529-562. doi: 10.1016/0011-7471(64)90001-4.
- Masselink, G. and M. Hughes (1998). *Field investigation of sediment transport in the swash zone*. Continental Shelf Research **18**(10): 1179-1199. doi: 10.1016/S0278-4343(98)00027-2.
- Masselink, G. and J. A. Puleo (2006). *Swash-zone morphodynamics*. Continental Shelf Research **26**(5): 661-680. doi: 10.1016/j.csr.2006.01.015.
- Masselink, G., P. Russell, I. Turner and C. Blenkinsopp (2009). *Net sediment transport and morphological change in the swash zone of a high-energy sandy beach from swash event to tidal cycle time scales*. Marine Geology **267**(1-2): 18-35. doi: 10.1016/j.margeo.2009.09.003.

- McLean, S. R., J. S. Ribberink, C. M. Dohmen-Janssen and W. N. Hassan (2001). *Sand Transport in Oscillatory Sheet Flow with Mean Current*. Journal of Waterway, Port, Coastal, and Ocean Engineering **127**(3): 141-151. doi: 10.1061/(asce)0733-950x(2001)127:3(141).
- Nielsen, P. (2006). *Sheet flow sediment transport under waves with acceleration skewness and boundary layer streaming*. Coastal Engineering **53**(9): 749-758. doi: 10.1016/j.coastaleng.2006.03.006.
- O'Donoghue, T. and S. Wright (2004). *Concentrations in oscillatory sheet flow for well sorted and graded sands*. Coastal Engineering **50**(3): 117-138. doi: 10.1016/j.coastaleng.2003.09.004.
- O'Donoghue, T., Doucette, J.S., Werf, J.J. Van der, Ribberink, J.S. (2006). *The dimensions of sand ripples in full-scale oscillatory flows*. Coastal Engineering, 53 (2006), 997-1012
- Peregrine, D. H. (1974). *Water-wave interactions in the surf zone*. Proceedings of 14th Conference on Coastal Engineering, Copenhagen Denmark, (28):500-517
- Pritchard, D. and A. J. Hogg (2005). *On the transport of suspended sediment by a swash event on a plane beach*. Coastal Engineering **52**(1): 1-23. doi: 10.1016/j.coastaleng.2004.08.002.
- Puleo, J. A., R. A. Beach, R. A. Holman and J. S. Allen (2000). *Swash zone sediment suspension and transport and the importance of bore-generated turbulence*. Journal of Geophysical Research **105**(C7): 17021. doi: 10.1029/2000jc900024.
- Puleo, J. A., T. Lanckriet and C. Blenkinsopp (2014). *Bed level fluctuations in the inner surf and swash zone of a dissipative beach*. Marine Geology **349**: 99-112. doi: 10.1016/j.margeo.2014.01.006.
- Ribberink, J. S. and A. A. Al-Salem (1995). *Sheet Flow and Suspension of Sand in Oscillatory Boundary-Layers*. Coastal Engineering **25**(3-4): 205-225. doi 10.1016/0378-3839(95)00003-T.
- Ribberink, J. S., J. J. van der Werf, T. O'Donoghue and W. N. M. Hassan (2008). *Sand motion induced by oscillatory flows: Sheet flow and vortex ripples*. Journal of Turbulence **9**(20): 1-32. doi: 10.1080/14685240802220009.
- Schretlen, J. L. M. (2012). Sand transport under full-scale progressive surface waves. PhD Thesis, University of Twente, The Netherlands.

- Turner, I. L., P. E. Russell and T. Butt (2008). *Measurement of wave-by-wave bed levels in the swash zone*. Coastal Engineering **55**(12): 1237-1242. doi: 10.1016/j.coastaleng.2008.09.009.
- van der A, D. A., T. O'Donoghue and J. S. Ribberink (2010). *Measurements of sheet flow transport in acceleration-skewed oscillatory flow and comparison with practical formulations*. Coastal Engineering **57**(3): 331-342. doi: 10.1016/j.coastaleng.2009.11.006.
- Yu, Z., H. D. Niemeijer and W. T. Bakker (1990). *Site investigation on sand transport in the sheet flow layer*. Proceedings of the 22nd International Conference on Coastal Engineering, ASCE.
- Zhu, F. & Dodd, N. (2015). *The morphodynamics of a swash event on an erodible beach*. J. Fluid Mech. **762**, 110-140. doi: 10.1017/jfm.2014.610

Table 1. Overview of wave components bichromatic wave condition BE1\_2.

| <b>Wave component</b> | <b>Subscript</b> | <b><math>f</math> (Hz)</b> | <b><math>T</math> (s)</b> | <b><math>H</math> (m)</b> |
|-----------------------|------------------|----------------------------|---------------------------|---------------------------|
| Short wave 1          | <i>1</i>         | 0.303                      | 3.3                       | 0.30                      |
| Short wave 2          | <i>2</i>         | 0.237                      | 4.2                       | 0.25                      |
| Wave group            | <i>gr</i>        | 0.067                      | 15.0                      | -                         |
| Repeat frequency      | <i>R</i>         | 0.005                      | 195                       | -                         |

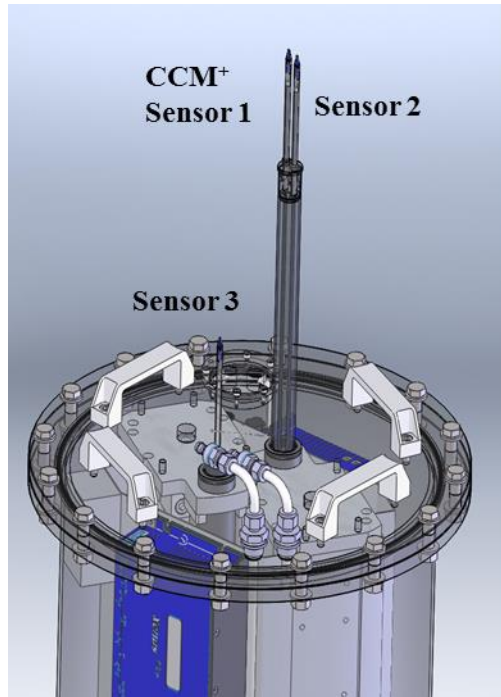


Figure 1. SolidWorks image of CCM<sup>+</sup> tank with three sensors.



Figure 2. Photos of CCM<sup>+</sup> system. Top: probes in lowest position (left) and probe sensors (right). Bottom: installation of tanks during an experiment (left) and zoom of probes after installation (right; note that during an experiment, the probes are lowered such that only the probe sensors emerge from the bed).

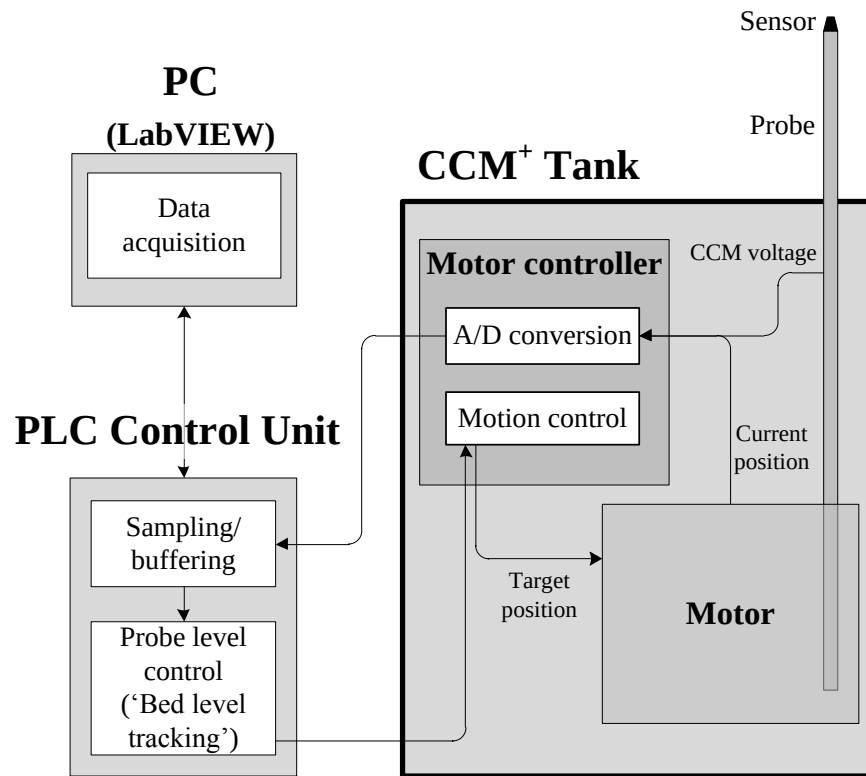


Figure 3. Flow chart of signals in CCM<sup>+</sup> system.

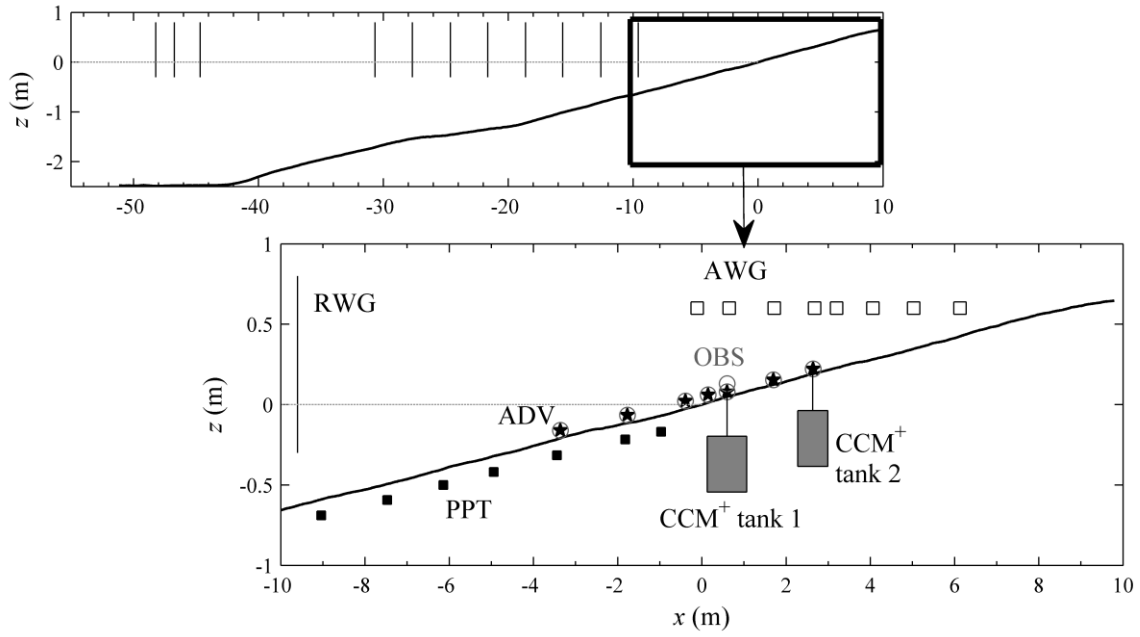


Figure 4. Wave flume configuration with measured bathymetry averaged over all initial profiles obtained during the experimental campaign. Upper panel: general view with Resistive Wave Gauge (RWG) positions (vertical black lines); Lower panel: amplification of the beach-face area with instrument locations. Solid squares are Pore Pressure Transducers (PPTs), open squares are Acoustic Wave Gauges (AWGs), open circles correspond to Optical Backscatter Sensors (OBSs) and stars symbols refer to Acoustic Doppler Velocimeters (ADVs).

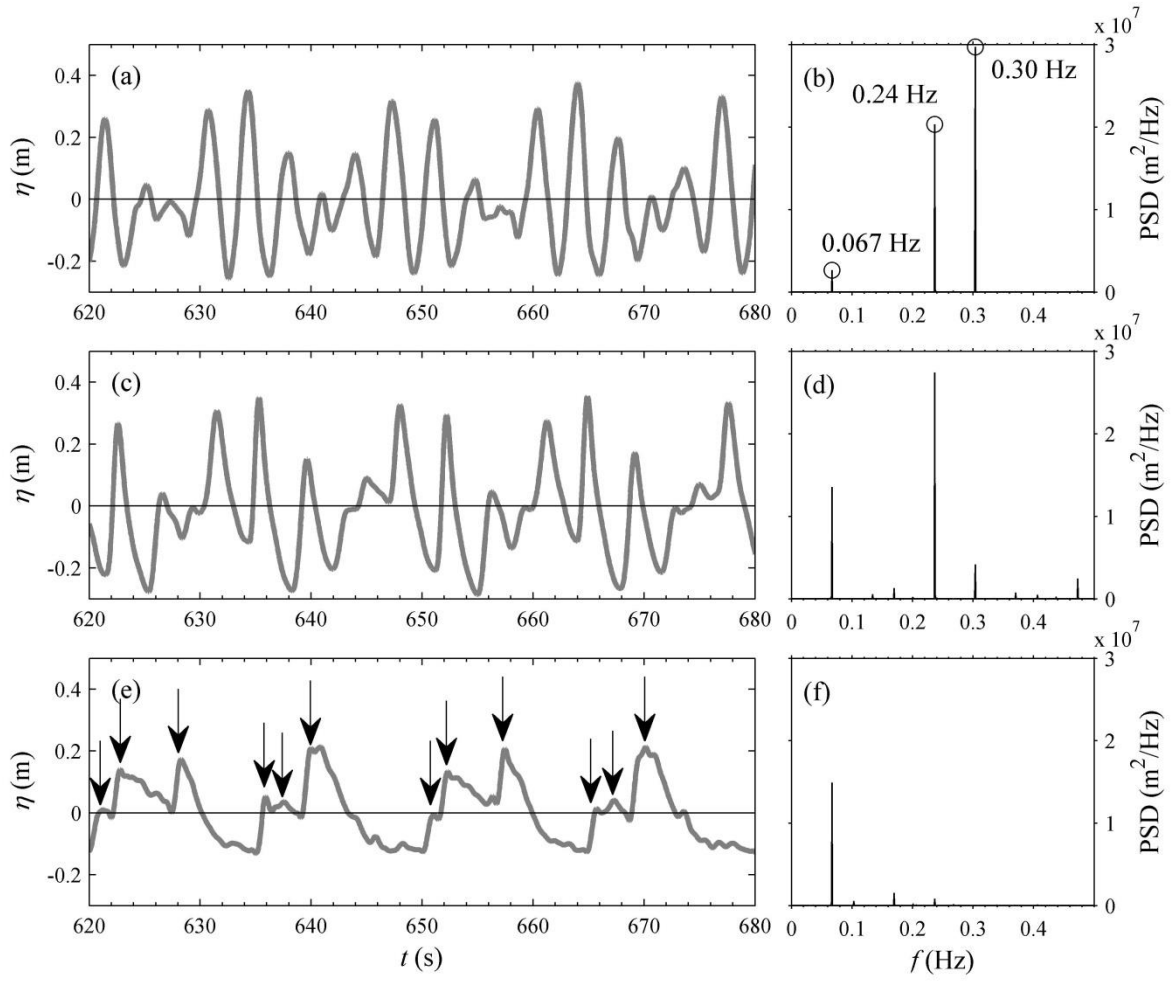


Figure 5: Time series for a 60 s time slot (four swash cycles) and power spectral densities of water levels for one of the semi-equilibrium runs, at three  $x$  locations: (a,b) resistive wave gauge at  $x = -67.6$  m (close to wave paddle); (c,d) resistive wave gauge at  $x = -9.7$  m (around breaker bar); (e,f) acoustic wave gauge at  $x = 0.60$  m (lower swash zone). Arrows in panel (e) mark the incident surf bores.

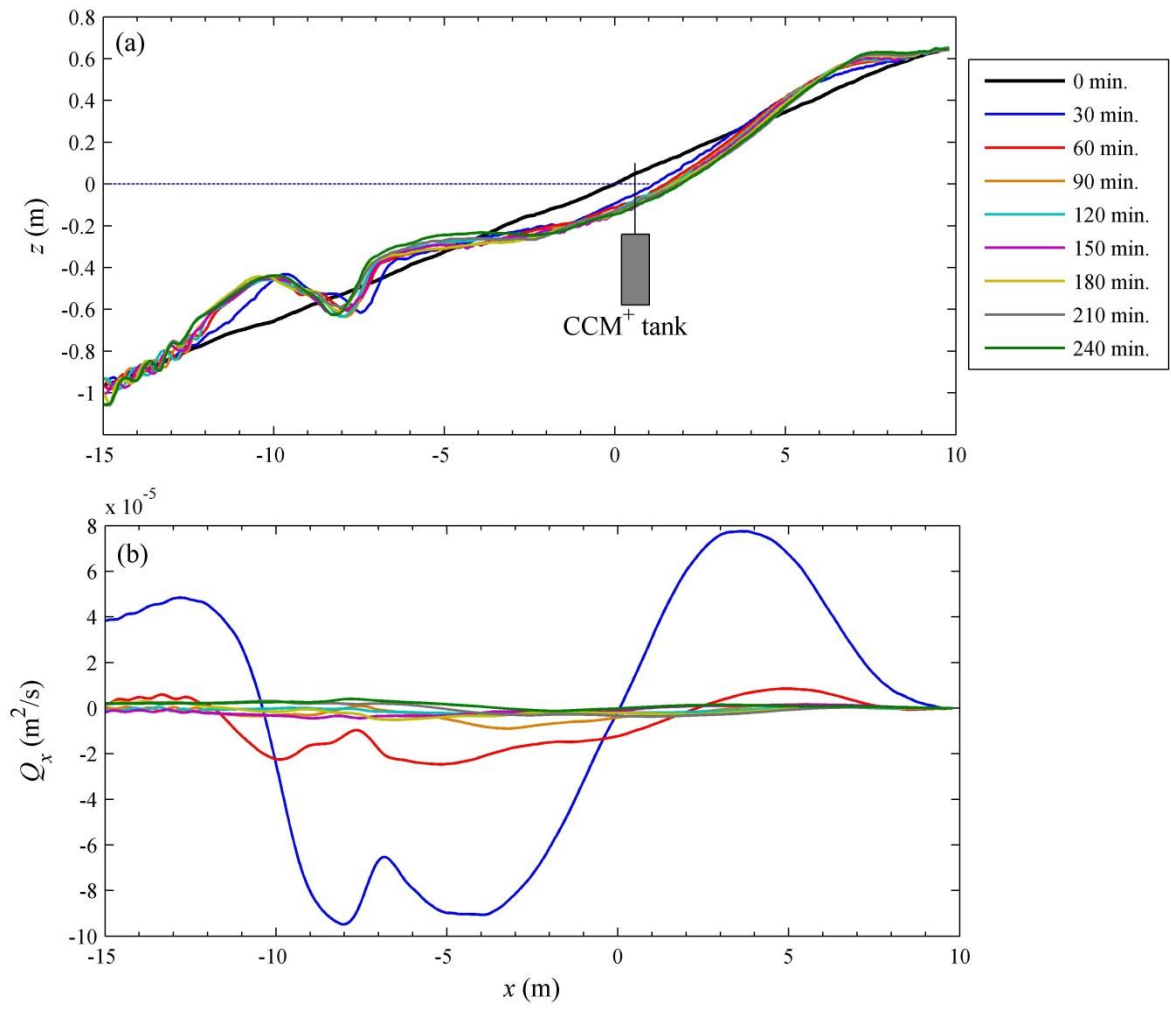


Figure 6. Beach profile evolution (top); net sediment transport rates ( $Q_x$ ) for each profile measurement (bottom).

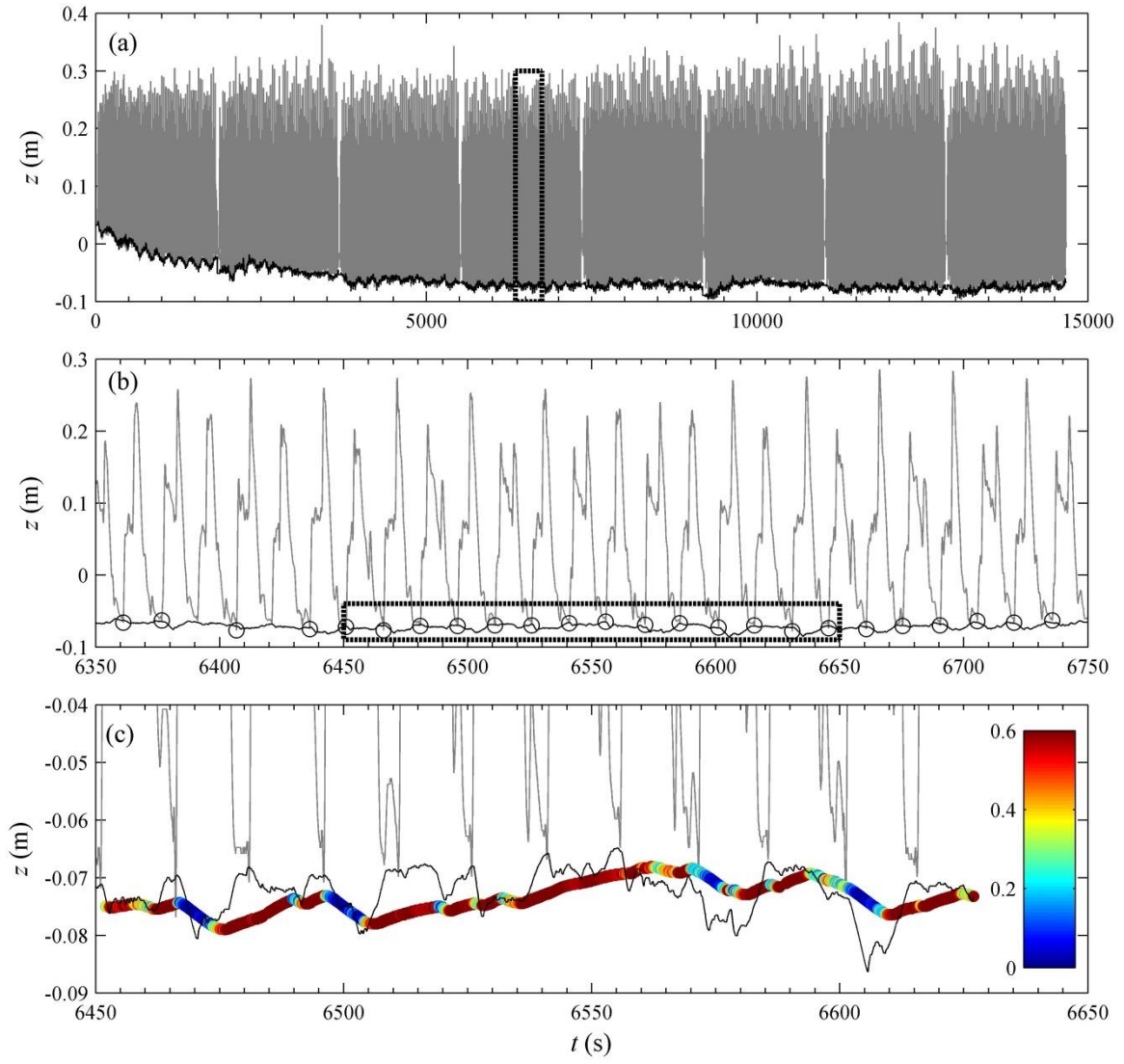


Figure 7. Time series of acoustic wave gauge (gray lines) and bed level measurements by CCM<sup>+</sup> probe 3 (black lines), for three time frames: (a) continuous time series for complete experiment (8 runs of 30 minutes); (b) close-up of one of the semi-equilibrium runs; (c) close-up of bed level and concentration measurements. Open circles in panel (b) mark identified instances of bed exposure; filled circles in panel (c) mark position of sensor 1/2, with colors referring to the instantaneous concentration measurement. The target concentration of sensor 1/2 for the period in panel (c) equaled 0.45.

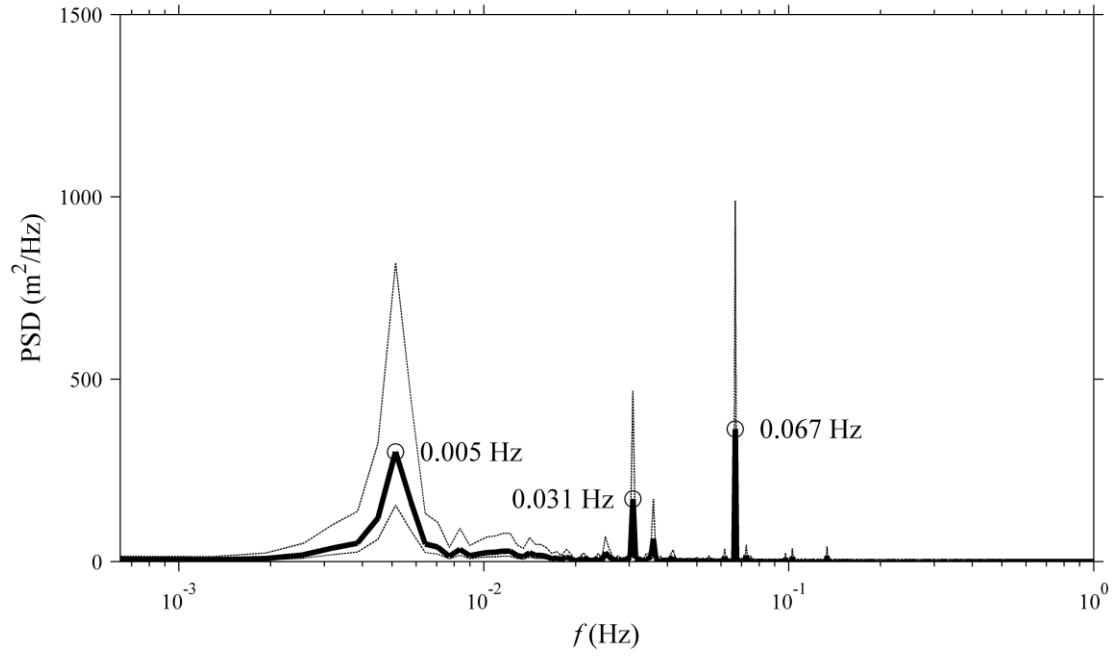


Figure 8. Mean spectral density function of the bed level measurements (CCM<sup>+</sup> probe 3). Average spectrum of 6 semi-equilibrium runs (thick solid line) and 95% confidence interval based on a chi-square distribution with 12 (twice number of runs used) degrees of freedom (dashed lines).

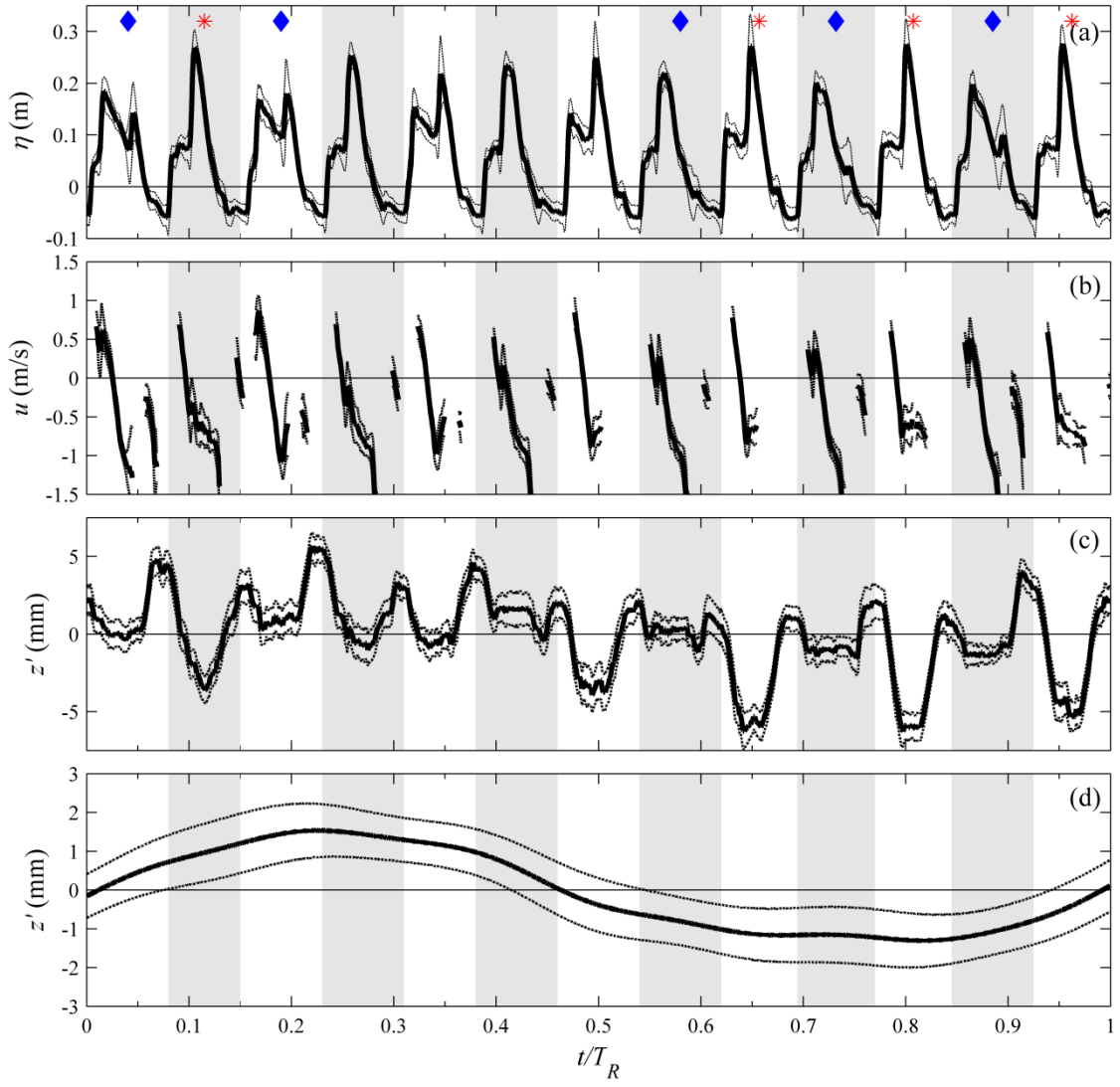


Figure 9. Phase-averaged hydrodynamics and bed level measurements at the CCM<sup>+</sup> location for the repeat period  $T_R = 195$  s: (a) water level (w.r.t. SWL) measured by AWG, ensemble mean  $\pm$  standard deviation; (b) cross-shore velocities measured by ADV, ensemble mean  $\pm$  standard deviation; (c) high-pass filtered bed level measurements (cutoff frequency 0.004 Hz) by CCM<sup>+</sup> probe 3, ensemble mean and 95% confidence interval; (d) bed level measurements, band-pass filtered (high pass cutoff frequency 0.004 Hz and low-pass cutoff 0.020 Hz). Gray-white background pattern highlights the various 15.0 s wave groups within the ensemble. Symbols in panel (a) mark the selected events for in-depth analysis: swash event of type “A” (blue diamond) and type “B” (red star).

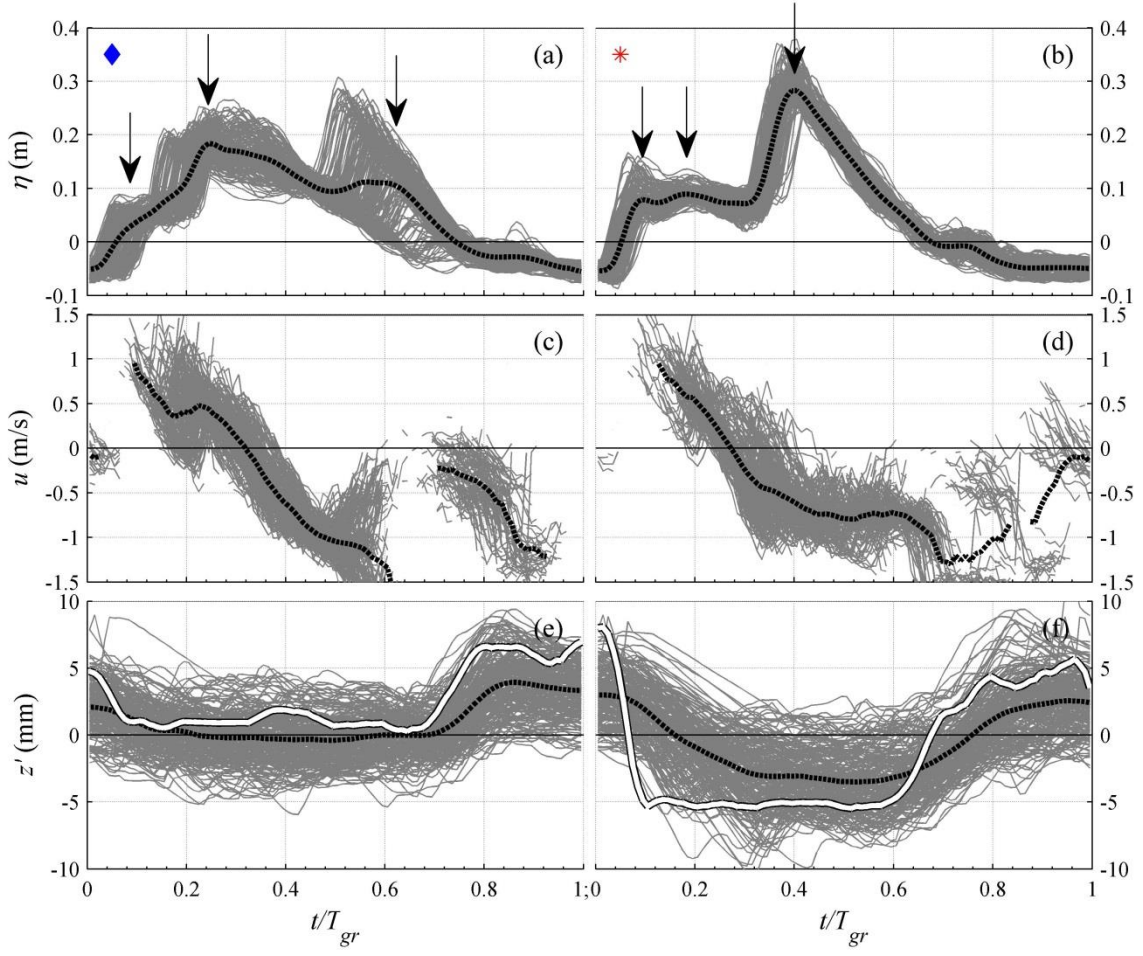


Figure 10. Phase-averaged intra-wave bed level measurements of CCM<sup>+</sup> system for characteristic swash events “A” (left) and “B” (right). (a,b) water level measurements by AWG; (c,d) horizontal velocity measurements by ADV; (e,f) high-pass filtered (cutoff frequency 0.02 Hz) bed level measurements CCM<sup>+</sup> probe 3. All panels contain ensembles (solid gray lines) and ensemble-means (dashed black lines). Also depicted in panels e,f is the elevation of the pivot point (solid white line), derived from the concentration measurements of probe 1/2. Arrows in panels a,b mark the arrival of surf bores that form the swash event.

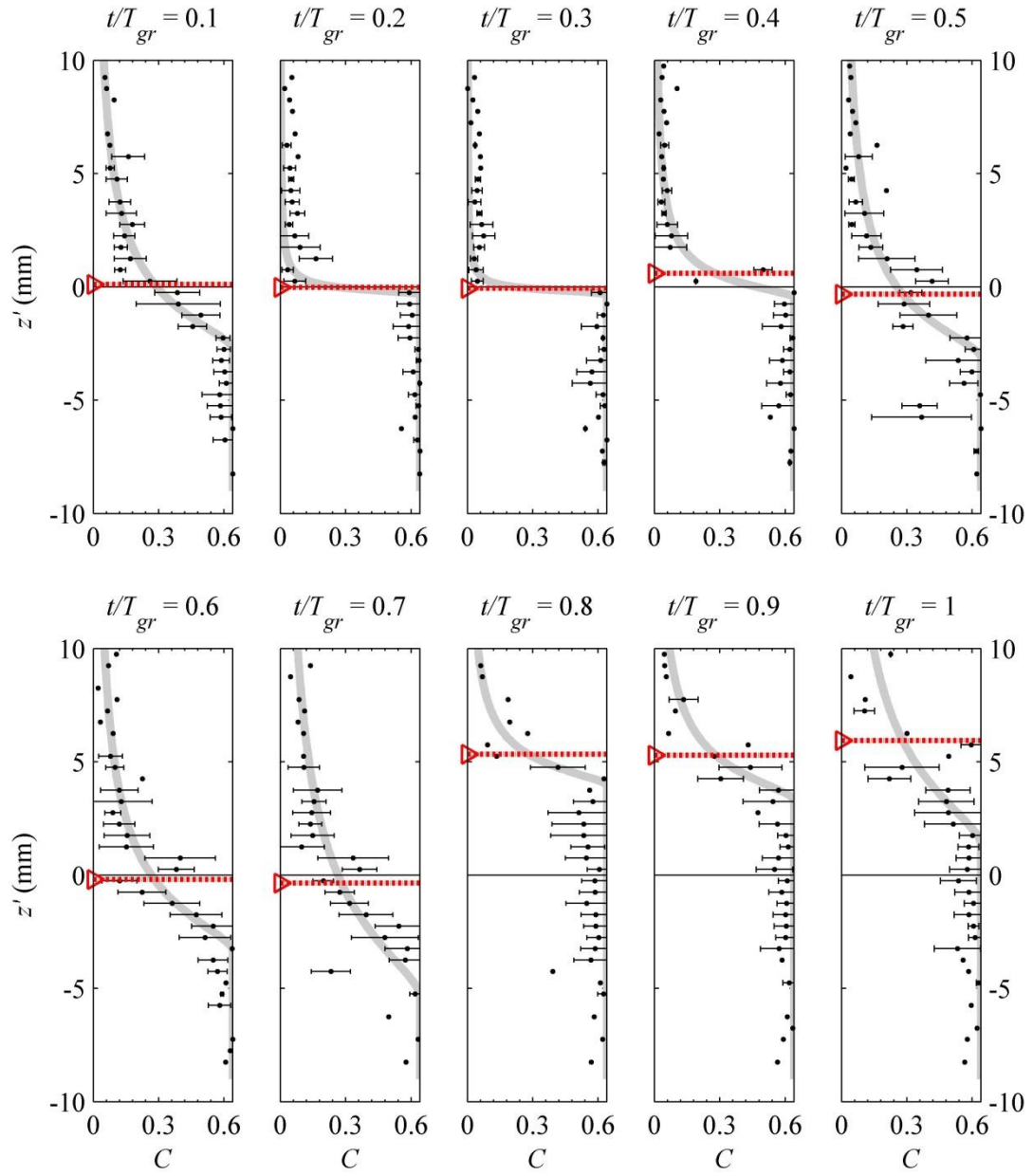


Figure 11. Vertical concentration profiles for various  $t/T_{gr}$  instances of wave group A. Panels include mean  $C(z', t)$  values (black dots), standard deviations of mean (vertical error bands), fitted ODW04 curve (thick gray line), and position of the pivot point (triangle + dotted red line).

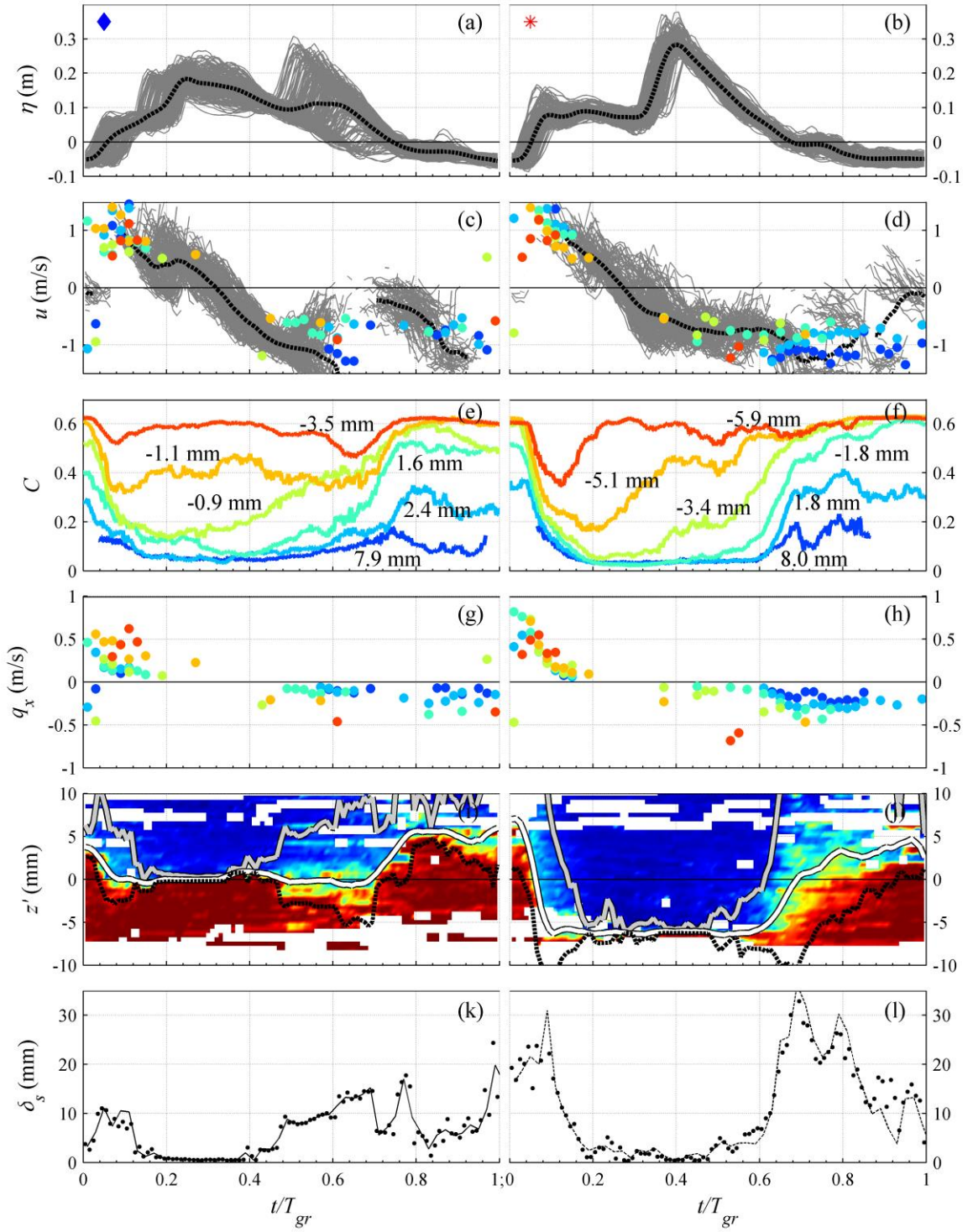


Figure 12. Phase-averaged hydrodynamics and intra-wave sheet flow behavior at group period  $T_{gr} = 15$  s for characteristic swash events "A" (left) and "B" (right). (a,b) water level measurements by AWG, ensemble (gray lines) and mean (dashed black line); (c,d) horizontal velocity measurements by ADV, ensemble (gray) and mean (dashed black line), plus CCM<sup>+</sup> particle velocities for six concentration bin classes (colors corresponding to panels e,f); (e,f) concentration measurements  $C$  for six wave-group-averaged concentration bin classes, including corresponding mean relative elevations  $z'$  per bin class; (g,h) sediment fluxes derived from CCM<sup>+</sup> measurements for six concentration bin classes; (i,j) contour of concentrations  $C(z', t)$  measured by probe 1/2, including elevations of sheet flow layer top (solid gray line), pivot point (solid white line), and bottom (dashed black line); (k,l) sheet flow layer thickness, estimations from ODW04 fit (dots) and spline-smoothed estimations (dashed line).

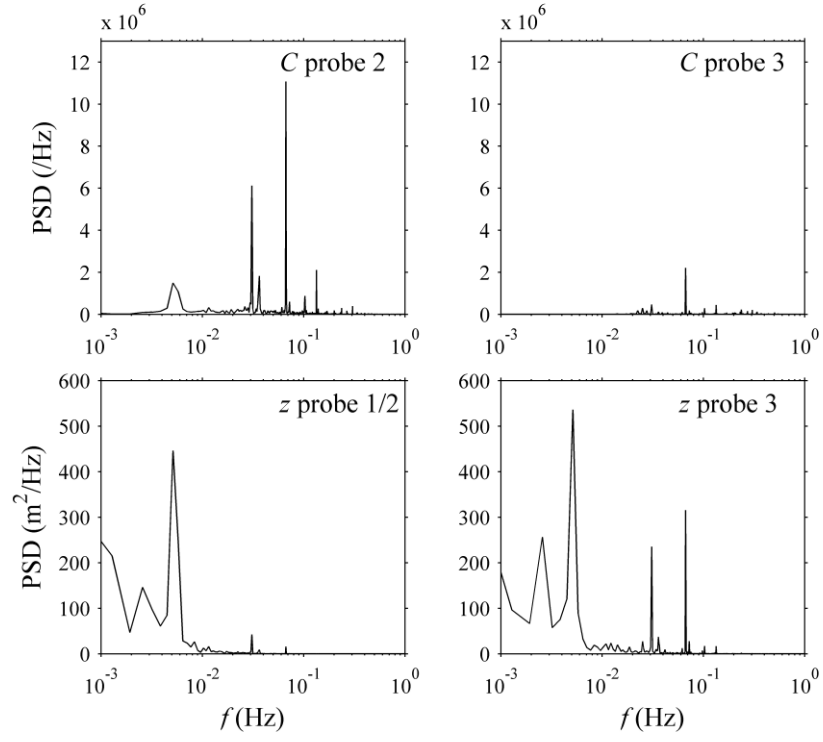


Figure A.1. Power spectral densities of concentrations (upper) and positions (lower) for ‘slow’ probe 2 (left) and ‘quick’ probe 3 (right). Data of one run in semi-equilibrium conditions.