INFLUENCE OF STORM SEQUENCING AND BEACH RECOVERY ON SEDIMENT TRANSPORT AND BEACH RESILIENCE (RESIST)

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Large-scale experiments on beach profile evolution and detailed sediment transport processes under varying wave conditions were performed within the HYDRALAB+ transnational access project 'RESIST'. Five wave conditions were tested, of which two presented high energy wave conditions and three presented low energy wave conditions (including one very low energy condition that was run for a long duration (24 h)). These five wave conditions were combined into three sequences of alternating high-low energy conditions, with similar total power of each sequence. Each sequence departed from an initial 1/15 sloped profile. The experiments resulted in a large data set comprising measurements of high temporal-spatial resolution of the beach profile, water surface elevation, velocity field, sediment concentrations as well as the collection of sediment samples and observations of wave breaking and runup/rundown. The analysis of the beach profiles in the context of storm sequence forcing has highlighted the evolution of the beach towards an equilibrium state for each wave condition. The analysis of sediment transport and bed level changes under high energy, alternating swash events has provided new insights into sand transport processes, including the influence of small differences in wave-swash interactions on transport rates, and the mobilisation of sediment in the swash.

1. INTRODUCTION

Research on beach evolution and sediment transport has largely focussed on erosive processes with only little emphasis on processes under recovery conditions or alternating wave climates. In line with that, most of the existing data sets obtained under controlled, large-scale morphodynamic conditions have focussed on high energy (storm) wave conditions, of which some were followed by one low energy (recovery or accretive) event. Normally, no long sequences of alternating high-low energy conditions have been performed (Eichentopf et al., 2018). Reasons for the large focus on high energy conditions can be related to the strong effects and related threats that a storm poses onto the beach, large efforts (costs and time) for long sequences of wave conditions in physical modelling, potentially long recovery times, and difficulties in measuring flow velocities and sediment concentrations under low energy conditions.

Conditions of alternating, or cyclic, periods of high and low energy conditions ('storm sequences') have increasingly been regarded to become more relevant in a climate change scenario (e. g. Webster et al., 2005; Knutson et al., 2010). In terms of beach evolution, recent research indicated more severe erosion of beaches under storm sequence forcing compared to isolated storm events at specific field sites (e. g. Karunarathna et al., 2014). This implies an important responsibility for coastal researchers to investigate the subject of beach evolution under storm sequence conditions in more detail and to work towards recommendations on how to react to potentially more severe beach changes under storm sequence forcing (Eichentopf et al., 2019b). Therefore, an important step to improve our understanding of beach response to cyclic wave conditions as well as the underlying processes is to perform controlled, large-scale morphodynamic experiments comprising cyclic high-low energy wave conditions and to investigate their effect on beach evolution.

For storm sequences, low energy wave conditions and associated beach recovery are of particular interest as they might present the key to avoid long-term beach erosion. However, especially for low energy wave conditions, beach profile evolution and sediment transport patterns are not well understood. This becomes evident through the limited number of available (large-scale) morphodynamic data sets comprising low energy conditions (Eichentopf et al., 2018) and the poor performance of numerical models under low energy compared to high energy conditions (van Rijn et al., 2011). Recent advances in the development of state-of-the-art instrumentation to acquire high-resolution sediment transport data have opened new possibilities to improve our understanding on sediment transport dynamics (Hurther et al., 2011; van der Zanden et al., 2015). The developed instrumentation has, however, primarily been applied to the study of sediment transport under high energy conditions (e. g., van der Zanden et al., 2015, 2017).

Consequently, research on the short-term processes of beach evolution and sediment transport processes has provided only limited understanding of beach erosion and recovery patterns under alternating wave conditions. The existing simplistic erosion-recovery approach of high-low energy wave conditions does not provide the level of detail required for coastal management and for the development of numerical modelling capabilities. This paper focusses on the design and performance of new, large-scale morphodynamic experiments that were performed within the HYDRALAB$^+$ transnational access project 'RESIST' and hence, the paper provides a comprehensive overview of the methodology in the measuring campaign and the acquired data. A considerably large amount of high-quality data with high temporal-spatial resolution has been acquired in the experiments and is being analysed. Recent results on the beach profile evolution under alternating wave conditions (Eichentopf et al., 2019a) and on sand transport dynamics under a high energy alternating swash event (van der Zanden et al., 2019) are resumed.

This paper is organised as follows: In section 2 the experimental setup and the data acquisition is described. Section 3 describes the evolution of the beach profile under the performed storm sequence conditions. Section 4 focusses on the analysis of sediment transport data and detailed bed level measurements obtained in the swash zone. A discussion and conclusions follow in section 5.

2. EXPERIMENTS

The experiments were performed within the EU funded HYDRALAB$^+$ Transnational Access project RESIST ('Influence of storm sequencing and beach REcovery on SedIment tranSporT and beach resilience'). This project had two major objectives:

- obtain large-scale morphodynamic data on beach profile evolution under sequences of alternating high-low energy wave conditions; and
- obtain sediment transport data of high temporal-spatial resolution under both erosive and accretive wave conditions in the surf and swash zone.

In this section, the experimental set-up is presented, including a description of the wave flume and the measurements as well as the wave conditions that made up the storm sequences.

2.1. WAVE FLUME

The experiments within the RESIST project were performed in the Canal d'Investigació I Experimentació Marítima (CIEM) at Universitat Politècnica de Catalunya (UPC) in Barcelona, Spain. This is a large-scale wave fume which measures 100 m, 3 m and 4.5 m in length, width and height, respectively. The water depth of the still water level in the deep water part of the flume was 2.5 m throughout the measuring campaign.

The beach consisted of commercial fine to medium size sand with a narrow grain size distribution (d_{50} = 0.25 mm, d_{10} = 0.15 mm, d_{90} = 0.37 mm). Before the start of each sequence of wave conditions (see section 2.2.), the beach was manually shaped to an initial, plane profile with a slope of 1/15. Following Baldock et al. (2017), two thin metal plates of 6 m length and 0.7 m height ('dividers') were placed in the swash zone (see right photo in figure 1) in order to reduce cross-tank asymmetries generated by the interactions of the runup and rundown. These dividers were placed parallel to the flume walls and divided the flume in three equal widths of 1 m (0.75 m, 1.5 m and 0.75 m in the beginning of the measuring programme).

Figure 1: Preparation of the beach profile (view towards the wave paddle). Left photo: manually shaped beach. Right photo: filling the wave flume (dividers in the front).

2.2. WAVE CONDITIONS AND SEQUENCES

In the RESIST experiments, different wave conditions were performed to generate three sequences of varying wave conditions. The wave conditions with their target values of wave height, wave period and dimensionless sediment settling velocity Ω (-) (Gourlay, 1968; Dean, 1973) are summarised in table 1.

Table 1: Details of the performed benchmark and bichromatic wave conditions (target values).

Wave condition		Observations	H_s (m)	T_p (s)	Ω (-)
B	Benchmark	Random waves	0.42	4	
E1	Erosive 1	Highly energetic storm	0.64	3.7	5.09
E2	Erosive2	Lower energy storm	0.49	3.7	3.90
A1	Accretive1	Low energy condition	0.32	4.7	2.00
A2	Accretive 2	Intermediate low energy condition	0.27	5.3	1.50
A3	Accretive 3	Very low energy condition	0.20	5.7	1.03

Condition B refers to the benchmark condition which was run for one test at the beginning of each sequence to homogenise the profile. Condition B presented a random wave condition with a Jonswap spectrum ($\gamma = 3.3$). The other wave conditions presented repeatable wave groups (bichromatic waves) allowing for ensemble averaging which is essential for the analysis of sediment concentration and velocity data obtained by means of ACVP and CCM+ (see section 2.3.) as well as for the detailed analysis of the effect of individual waves within the groups on beach profile evolution. Bichromatic waves were previously reported to have a similar effect on beach profile change as random wave conditions (Baldock et al., 2011).

Details of the bichromatic wave conditions are shown in table 2. T_p refers to the mean primary frequency ($T_p = (f_1+f_2)/2$), T_g is the group frequency ($T_g = f_1-f_2$) and T_R presents the period after which the defined number of groups repeats exactly ('repetition period'). For erosive conditions, T_R comprised two wave groups and the waves were fully modulated (N = 1), i. e. the amplitude at the two primary frequencies was the same. The accretive wave conditions repeated every three wave groups and were partly modulated where the amplitudes at the two frequencies differed by a factor of two (N = 0.5).

Table 2: Details of the performed bichromatic wave conditions (target values).

Condition	Component 1		Component 2					
	H_1 (m)	f_1 (Hz)	H_2 (m)	f_2 (Hz)	T_p (s)	T_g (s)	T_R (s)	$N = H_1/H_2$
Erosive 1	0.320	0.3041	0.320	0.2365	3.7	14.80	29.60	1
Erosive 2	0.245	0.3041	0.245	0.2365	3.7	14.80	29.60	1
Accretive 1	0.101	0.2276	0.202	0.1979	4.7	33.68	101.05	0.5
Accretive 2	0.085	0.2018	0.171	0.1755	5.3	37.98	113.95	0.5
Accretive 3	0.063	0.1877	0.126	0.1632	5.7	40.85	122.55	0.5

The presented wave conditions were combined into three sequences of alternating high-low energy conditions (see table 3). In sequences 1 and 2, the same set of wave conditions was performed but with varying order of the high energy (erosive) conditions. Sequence 3 comprised the same order of high energy conditions as sequence 1 but with different low energy (accretive) conditions.

Table 3: Combination of wave conditions into storm sequences.

Sequence 1		Sequence 2		Sequence 3	
Case	Duration (min)	Case	Duration (min)	Case	Duration (min)
B	30	B	30	B	30
E1	240	E2	120	E1	240
A1	600	A1	600	A2	780
E2	120	E1	240	E2	120
A1	600	A1	600	A3	1440

2.3. INSTRUMENTATION AND DATA ACQUISITION

A large number of measurements was performed throughout the measuring programme, including measurements of the beach profile, water surface elevation, velocity field, sediment concentrations, the collection of sediment samples and observations of the location of outmost and innermost breaking as well as maximum runup and rundown.

The beach profile was measured along a central line of the wave flume by means of a mechanical profiler that is capable of measuring the profile depth in both the emerged and the submerged part of the beach. The spatial resolution of the profile measurements was 2 cm. The beach profile was measured before the start of each sequence and after each performed wave run resulting in a total of 119 beach profile measurements.

At the end of the measuring programme (after completion of sequence 3 (after condition A3)), the flume was drained, and sediment samples were collected from the top of the bed at 20 cross-shore locations with a spatial resolution of 0.5 m or 1 m (see figure 2 for locations of bed samples collected from the evolved profile after A3). The cross-shore region from which the samples were collected extended from offshore of the bar to the top of the berm. The sediment samples were later analysed regarding their grain size distributions in the soils lab at Imperial College London by means of a laser-based particle detection instrument (QicPic).

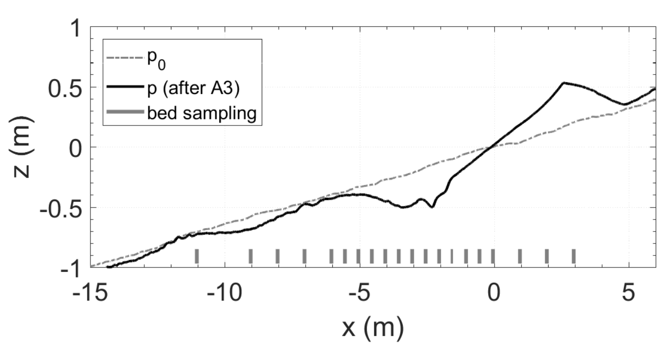

Figure 2: Locations of bed sediment samples collected after completion of the measuring programme (after condition A3).

A variety of instrumentation to measure water surface elevation, flow velocities and sediment concentration was deployed at fixed locations before the start of the measuring programme. The locations of the fixed instrumentation are shown in table 4.

Table 4: Locations of fixed instrumentation at the start of the measuring programme.

Instrument	N°	Cross-shore location (in m) with respect to shoreline of initial profile; in parenthesis, vertical elevation with respect to bed (where applicable)
RWG	13	-63.40, -63.40, -48.22, -46.71, -42.32, -35.23, -31.16, -27.12, -23.18, -19.21, -17.42, -15.66, -11.30
AWG	20	-61.77, -56.04, -44.94, -21.85, -20.55, -14.66, -13.26, -9.57, -7.38, -5.57, -3.44, -1.57, -0.52, 0.47, 1.25, 2.31, 3.5, 4.55, 5.56, 6.51
PPT	12	-54.49, -51.94, -50.22, -43.52, -40.75, -39.11, -37.21, -33, -28.9, -24.5, -8.71, -4.68
ADV	6	-4.72 (0.10), -1.54 (0.03), -0.52 (0.03), 0.27 (0.03), 1.28 (0.03), 2.26 (0.03)
OBS	5	-1.68 (0.03), -0.45 (0.03), 0.38 (0.03), 1.28 (0.03), 2.36 (0.03)
CCM$^+$ tanks	2	-0.52 m (tank 2), 1.28 m (tank 1)

Water surface elevation data were usually acquired at 45 fixed cross-shore locations by means of Resistive Wave Gauges (RWG), Pore Pressure Transducers (PPT) and Acoustic Wave Gauges (AWG) which were (primarily) deployed in the offshore, the breaking and the surf/swash region, respectively. Water surface elevation data were measured at a sampling frequency of f_s = 40 Hz. Acoustic Doppler Velocimeters (ADV) were deployed in the inner surf and swash zone to acquire data on the three-dimensional velocity field. Optical Backscatter Sensors (OBS) were co-located with the ADVs to measure sediment concentrations at the same elevation as velocities. ADVs and OBSs were deployed at 3 cm from the bed. This vertical position was controlled and, if necessary, adjusted before each test. ADVs and OBSs acquired data at f_s = 100 Hz and f_s = 40 Hz, respectively. Figure 3 shows examples of deployed ADVs, OBSs and AWGs.

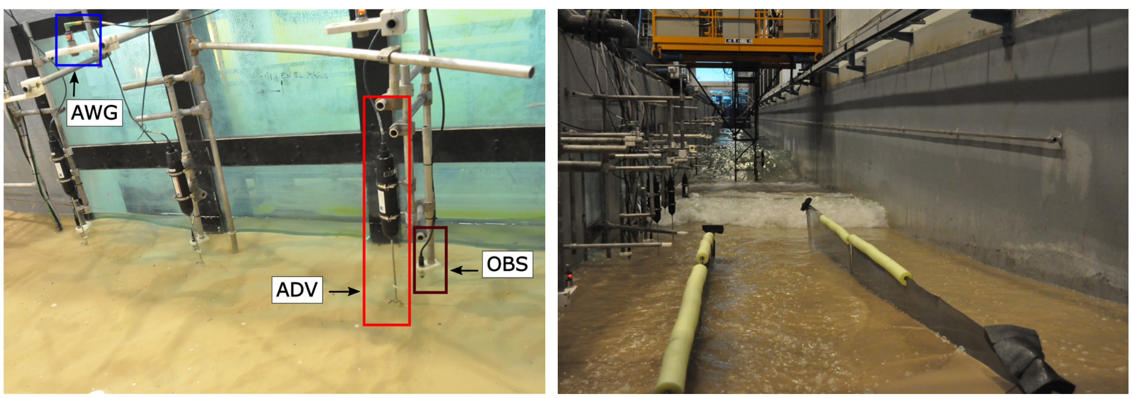

Figure 3: Measurements in the CIEM. Left photo: deployed ADV, OBS and AWG. Right photo: waves arriving on the beach (dividers in the front).

Two conductivity-based concentration measuring tanks (CCM$^+$ tanks) were installed in the inner swash zone for measurements of bed level motions and sediment concentrations in the sheet flow layer (see van der Zanden et al. (2015) for detailed information on the CCM$^+$ technology). The two tanks were buried into the beach before the start of the experiments and hence, took measurements from below in order to minimise flow disturbances (see figure 4). Both CCM$^+$ tanks were deployed close to the shoreline of the initial beach profile: tank 1 at circa 1 m onshore, tank 2 at circa -0.5 m (see table 4). Tank 1 (70 kg tank) has three probes (a single and a twin probe), where the single probe tracked the continuous bed level and the twin probe was used to measure particle velocities in the sheet flow layer (by alternating between concentration measurement and bed level tracking mode). Tank 2 (50 kg) has one single probe that alternated between concentration measurement and bed level tracking mode (as the twin probe of tank 1). The CCM$^+$ data were sampled at f_s = 1000 Hz.

Figure 4: CCM⁺ instrumentation. Left photo: Moving CCM⁺ tank 2. Right photo: Probes of CCM⁺ tank 1 (in red square) measuring within the bed.

Further instrumentation was deployed at the mobile frame (see left photo in figure 5) which, together with the movable trolley, allows positioning of instrumentation in the vertical and horizontal direction, respectively. The position of the mobile frame and hence, of the deployed instrumentation, was varied between tests in order to cover a wide range of locations around the outer breaker bar (i. e. in the shoaling to inner surf zone). On the mobile frame a variety of instruments was deployed, namely ADVs, OBSs, PPTs as well as an Acoustic Concentration and Velocity Profiler (ACVP). The ACVP allows the acquisition of sediment concentration and velocity profiles with high temporal-spatial resolution in proximity to the bed (see Hurther et al. (2011) for detailed information on the ACVP technology).

Figure 5: Instrumentation on the mobile frame. Left photo: mobile frame. Right photo: ACVP and the three nozzles of the TSS.

A transverse suction system (TSS) was installed at the mobile frame with three nozzles at three different vertical elevations within 20 cm from the bed (see right photo in figure 5). The nozzles were connected to pumps which were started circa 10 min after the beginning of each test and which were run for 10-12 min for collection of the sediment-water mixture. Following design criteria by Bosman et al. (1987), the nozzles were positioned normal to the direction of wave propagation with a ratio of the intake to the ambient velocity beyond three so that the measurements were insensitive to inversion of the flow direction. Through the TSS, sediment samples were obtained which allow the investigation of the time-averaged concentration profile of each test as well as the investigation of the sediment grain size distribution of the samples. All samples, including the 20 bed samples collected after A3, were dried, stored in plastic bags and shipped to Imperial College London for further analysis.

In addition to the data acquired by the presented high-quality, specialised instrumentation, information on the outmost and innermost breaking location as well as the maximum runup and the maximum rundown location were acquired by means of visual observations within the first 5-10 min of each test.

3. BEACH PROFILE EVOLUTION UNDER STORM SEQUENCE FORCING

In the RESIST experiments, a very large number of beach profiles was measured which allowed the investigation of beach evolution under the performed storm sequence wave climate. Results on this part of the analysis comprising data of beach profile measurements, wave breaking observations as well as data from the 20 sediment bed sampled (collected after completion of condition A3) are presented in Eichentopf et al. (2019a) and most important aspects are resumed here.

The influence of storm sequencing and beach recovery was studied in terms of shoreline and breaker bar evolution. Both indicators evolve towards an equilibrium with the breaker bar reaching its equilibrium location much faster than the shoreline suggesting differences in the transport processes involved in the bar and shoreline evolution. The final equilibrium configuration is specific for each wave condition and, for the present experiments, does not depend of the previous morphological beach configuration. Overall, storm sequencing did not produce increased beach erosion and the final beach configuration after a sequence of storms seems controlled by the last wave condition in the sequence.

However, the sequence of storms is important when determining the sediment transport processes as the initial beach configuration controls the sediment dynamics producing the equilibrium state. Therefore, when the beach profile is not yet fully recovered before being disrupted by the following storm, further erosion is not necessarily caused by the storm, but it can move sediment onshore and be part of the recovery of the shoreline (compare condition E2 in figure 6a-c).

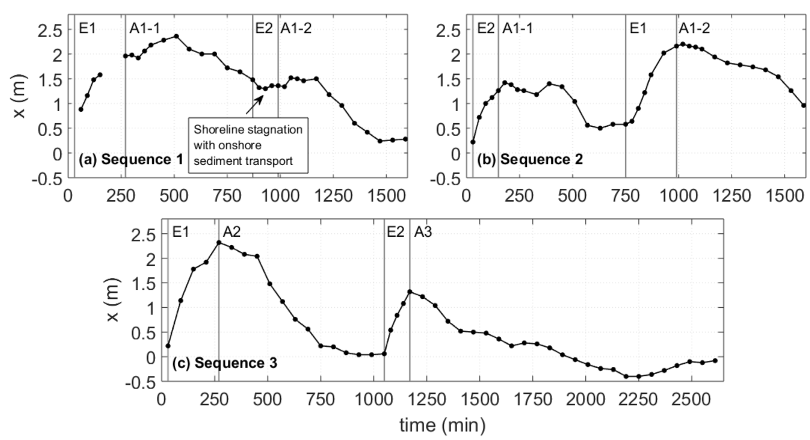

Figure 6: Shoreline evolution during RESIST experiments in the three performed sequences of wave conditions.

Examination of the beach profile evolution during the long-duration recovery wave condition (condition A3) shows cases of full beach recovery and the development of a reflective beach state with no plunging wave breaking and the formation of a steeply sloped berm (see figure 2).

4. SAND TRANSPORT PROCESSES AND BED EVOLUTION IN THE SWASH ZONE

Detailed intra-wave sediment transport was measured for wave condition E1 in the inner surf and swash zones using conductivity probes (CCM^+ tanks) and results were analysed and discussed in van der Zanden et al. (2019) (see figure 7). The intra-wave mobilisation of sand increases both as sheet flow and suspended load from the inner surf zone to the mid swash zone. Large quantities of sediment are mobilized during the uprush and backwash within the swash zone, but the amount of sediment exchanged with the inner surf zone is comparably small within the period of one swash event and becomes increasingly important for longer time scales.

Strong instantaneous bed level changes occur in the low swash region especially during the early uprush and during instants of strong wave-swash interactions. The net bed level change in the swash zone induced by single events is primarily explained by sediment redistribution within the swash zone. The sediment transport along the swash zone is strongly influenced by horizontal sediment advection during the uprush and backwash whereas in the inner surf zone, the vertical sediment exchanges in the water column seem more important.

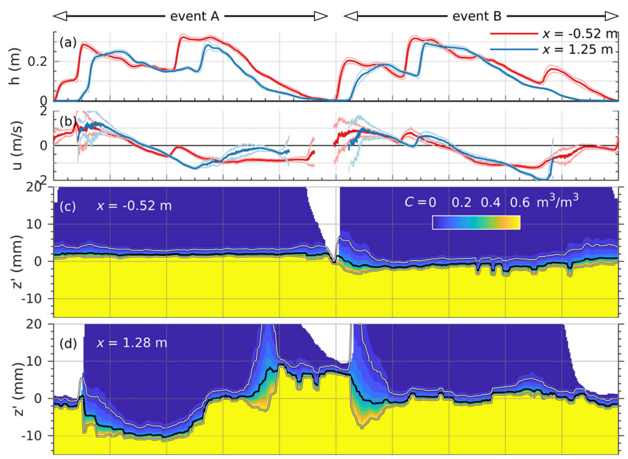

Figure 7: Ensemble-averaged water depths (a), velocities (b) and sediment concentration profiles (c,d) measured at the two CCM+ locations. The concentration profiles cover the sheet flow layer, white lines mark the bottom and top of the sheet flow layer.

The use of controlled bichromatic wave conditions with controlled wave phasing modulation produced two alternating swash events with similar offshore statistics but with different wave-swash interactions. Small differences in the wave-wave phasing and wave-swash interactions produced large differences in the observed sediment transport and bed evolution.

5. DISCUSSION AND CONCLUSIONS

Large-scale experiments, that were performed within the HYDRALAB+ transnational access project 'RESIST', have been presented. These experiments have resulted in a unique, high-quality data set which comprises measurements of high resolution in space and time of the beach profile, water surface elevation, velocities and sediment concentrations. In addition, visual observations of locations of wave breaking and runup/rundown as well as sediment samples were obtained.

The presented experiments involved the generation of controlled wave sequences with similar cumulative wave power but varying storm chronology as well as variations in the duration and wave conditions of the recovery phases. Consequently, based on these experiments the beach profile evolution under both storm and recovery conditions and the influence of isolated influencing factors, such as storm chronology and varying recovery conditions, and potentially enhanced erosive effects due to storm sequencing can be studied.

Observations of the wave breaking and runup/rundown locations have been very valuable for the data analysis as they provide information on the extent of the breaking region and swash zone, respectively. The collection of sediment samples from the bed after draining the wave flume was important for the investigation of sediment sorting by means of sediment grain size analysis. An increased collection of bed samples in large-scale wave flume experiments would be desirable in future experiments to advance the study of graded sediment transport. The acquisition of data on water surface elevation and velocity with high cross-shore resolution provides a detailed picture of the wave height and velocity transformation which can be linked to the profile evolution. In addition, the use of conductivity probes (CCM+ tanks), ACVP and the performance of controlled, repeated wave conditions allow the analysis of detailed sediment transport processes in the breaker bar region and the swash zone.

Two journal papers are currently under review focusing on the influence of storm sequence forcing on the evolution of the breaker bar and the shoreline (Eichentopf et al, 2019a) and sediment transport processes in the swash zone during high energy wave conditions (van der Zanden et al., 2019). Further aspects from the performed experiments are currently being analysed. This analysis includes the investigation of hydrodynamic and sediment transport patterns that result in the described beach profile evolution under varying wave conditions as well as the analysis of sediment transport data obtained by means of the ACVP under both high and low energy wave conditions.

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