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OBSERVING SHORELINE FLUXES. IMPLICATIONS FOR *SWASH* AND *SURF* ZONE MODELLING

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Abstract

The scarcity of reliable and controlled observations of water and sediment fluxes near the shore is one of the main reasons for the many remaining challenges in the field of morphodynamics. In this paper we shall present three large-scale data sets from the CIEM flume of the Maritime Engineering Laboratory (LIM/UPC) in Barcelona, looking for the distinctive behaviour of such fluxes between erosive and accretive conditions. Two different erosive conditions are presented, which report an expected different behaviour of the bar and measured physical parameters (wave height, velocity and suspended sediment cocentration). These erosive time series also report an unexpected similitude on the profile comparisson between both data sets from the bar until the shoreline. The acquired data under accretive conditions present the important control played by the initial bar, controlling the hydrodynamics of the surf and swash zones.

Key words: surf, swash, experimental, fluxes, morphodynamics.

1. **Introduction**

Near shore processes, encompassing the swash and surf zones are difficult to observe in Nature with enough resolution and accuracy so as to allow advancing our understanding and predictive capabilities for that area. This is due to a multiplicity of factors, including the highly energetic and turbulent environment, the multiple time and space scales where the motion takes place and to the fact that part of the domain is alternatively wet and dry (this can be illustrated by the crest to trough layer or the swash zone) which introduce further difficulties for both the observations and the numerical simulations.

Most of the presently available observations come from small scale tests under controlled conditions but suffering from a significant scale distortion since the experiments have been scaled with the Froude law and, thus, do not reproduce turbulent processes correctly. The rest of available observations have been obtained in field campaigns, with no scale distortions but where the data represent uncontrolled conditions, combining multiple drivers and responses (e.g. not only wave induced currents but also those due to the wind and regional circulation), this makes it difficult to extract averaged trends or to identify correctly the variations or gradients in time and space, due to the poor resolution of the measurements. Very few large scale data sets, encompassing both the surf and swash zone and with enough resolution so as to capture the peaks in water and sediment fluxes are available. And yet it is being progressively accepted (Masselink et al. 2009 or Alsina and Caceres 2011) that those fluxes are responsible for most of the morphodynamic evolution taking place in the coastal zone at least for “engineering” scales.

In this paper we present three such data sets, with the novelty of considering simultaneously erosive and accretive wave sequences. The discussed large scale experiments cover the surf and swash zones and possess enough resolution to capture the water and sediment pulses above mentioned.

In section 2 we describe the three sets of experiments, in terms of the facility and the observational equipment layout, together with the resulting data and the performed analyses. The emphasis is on the limits of the experimental facility, particularly for the extrapolation to real conditions of the obtained results and aiming at quantifying the uncertainty inherent in the observations. In section 3 we discuss the results in terms of hydrodynamics and morphodynamics. The performed analyses are discussed, showing

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the differences in results depending on the sequence of pulses and the initial condition (e.g. initial beach profile). This should contribute to establishing the memory effect in near shore processes and the limits of the corresponding predictions.

Finally in section 4 there is a comparative discussion of results, presenting the mean value and the standard deviation and showing how the scatter varies as a function of the hydrodynamic settings and the experimental arrangement. In the conclusions we shall assess the applicability of the obtained experimental data to improve our knowledge about surf/swash morphodynamics, to calibrate numerical models for the dominant processes in those areas and, eventually, to improve coastal engineering decisions.

2. Experimental set up and data analysis

Three different data set are here reported: SANDS experiments, performed in 2008, Benchmark Mobile Bed Test, carried out in 2012 and WISE experiments, developed during the first months of 2013. All data sets were collected in the CIEM (Canal d'Investigació i Experimentació Marítima) flume, a large research facility, located within the Maritime Engineering Laboratory of the Universitat Politècnica de Catalunya in Barcelona. This facility is 100 m long, 3 m wide and 5 m deep. The simulated time series reproduce random waves that follow a Jonswap spectral density function with a width or gamma parameter equal to 3.3; the rest of wave characteristics are reported in Table 1. The experimental protocol was the same in all tests. The experiments start from a 1/15 mobile bed initial profile and the same "target" time series is run over and over again as summarized in Table 2, with the sequential numbering of the experiments. Once the desired erosion or accretion interval has been reached there is some time gap to run the bed profiler to recover the bed evolution after the incoming wave series and to re calculate the distances from the bed of all instruments. This is particularly critical for the ADV vertical levels (affecting the interpretation of the measurements) and also to reposition all swash zone gear within this zone that, as expected, evolves in the vertical and horizontal with the beach profile. With this periodic control we can ensure the distance of the ADVs to the bottom (5 to 9 cm in general for the lowest position). After this we can restart the experimental time series and repeat the sequence. Table 2 present the different runs performed for each of the data sets; in red there are the tests after which the bottom profile has been recovered. In all cases an initial bottom profile has been measured to determine with as little error as possible the initial condition. In the case of the SANDS and WISE experiments, after the *erosive* tests (numbered 47 for SANDS and 8 for WISE), the *accretive* wave conditions were started without reshaping the profile or emptying the flume. This means that the accretive conditions start with the previously generated "erosive" bar which has different characteristics from series to series and, in particular between SANDS and WISE tests, due to the different wave conditions and length of erosive tests run for each data set.

Table 1. Summary of wave conditions for the SANDS, Benchmark and WISE experiments, showing the wave height, period and dimensionless fall velocity (Dean, 1973) characteristics.

		H_s (m)	T_p (s)	H_s/w_sT	nº of waves
SANDS	Erosive	0.53	4.14	3.74	500
	Accretive	0.32	5.44	1.71	500
Benchmark	Erosive	0.47	3.7	3.74	500
WISE	Erosive	0.47	3.7	3.74	500
	Accretive	0.32	4.7	2	400

The Benchmark experiments were run to further characterize the bar evolution under erosive and accretive conditions, looking for a more stable "final" beach profile, where the morphodynamics tend asymptotically to a geometry in equilibrium with incoming waves. This allows a better assessment of the erosive and accretive trends obtained in the WISE series.

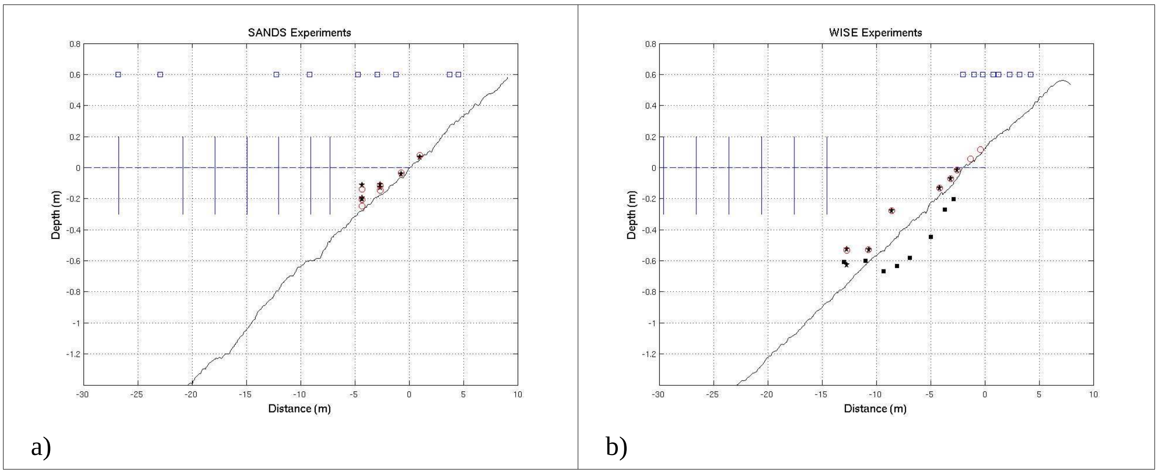
In our experiments the beach consisted of specially selected (commercial) well-sorted clean sand, with a median sediment size (d_{50}) of 0.25 mm and with a narrow grain size distribution (d_{10} = 0.154 and d_{90} =

0.372 mm). This gives an average (measured) settling velocity of 0.034 m/s.

Table 2. Summary of test series – denoted by their numbering – in the SANDS, Benchmark and WISE experiments. The red color is used to highlight the tests after which the bottom profile was surveyed and recovered.

SANDS	Erosive	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47.
	Accretive	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35.
Benchmark	Erosive	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37.
WISE	Erosive	1, 2, 3, 4, 5, 6, 7, 8
	Accretive	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31

The distribution of equipment is reported in Figure 1 stems from an initial analysis of the expected hydro-morpho-dynamics on the beach profile (Alsina and Cáceres 2011) and with the aim of characterizing the inner surf and swash zone fluxes. The x-coordinate origin is at the initial shoreline with a still water level of 2.47 m and 2.5 m for SANDS and WISE experiments, respectively; negative x values are towards the wave paddle (offshore) and positive towards the beach face (onshore). The wave height at different points of the profile were measured by means of resistive wave gauges in the deeper part of the flume, and Pore Pressure Transducers (PPTs) and Acoustic Displacement Sensors (ADSs) in the surf and swash zones. The velocity field was mapped by means of Acoustic Doppler Velocimeters (ADVs), while several Optical Backscatter Sensors (OBSs) were used to recover the suspended sediment concentration. Most of the equipment was deployed close to the shoreline in order to resolve the gradients in suspended sediment concentration, transport velocities, bore heights and swash thickness. The aim was to cover, as comprehensively as possible, the inner surf and swash zones, so that an overall assessment could be also performed.



a)

b)

Figure 1. Schematization of the CIEM wave flume configuration for the SANDS (a) and WISE (b) experiments, showing the initial profile shape (solid black line). The marks show the position for ADVs (solid black pentagram), OBSs (empty red circles), PPT (solid black squares) and ADSs (empty blue squares).

Throughout the experiments considerable efforts were made to co-locate the ADVs, OBSs and ADSs so that spatial gradients (responsible for the resulting morphodynamics) could be adequately resolved. This should be the basis for characterizing the local and advective pulses that control most of the suspended sediment concentration (SSC) transport in the border between the surf and swash zones. Whenever physically possible (i.e. in most cases with some exceptions due to the facility constraints) the ADV locations coincided with those of OBSs in the vertical and in the cross-shore coordinates. This was to improve the correlation between local velocity and concentration measurements across the inner surf and swash zones (Figure 1). However, the observation points did not coincide in the long shore direction (perpendicular to the wave flume walls), the ADVs were usually located close to one of the flume walls, whilst the OBSs were located in the same cross-shore location and vertical elevation with respect to the bed level but close to the opposite wall (with a distance between both measuring equipment of about 2.3 m). The OBS and ADV vertical elevations with respect to the sandy bed were checked at the beginning and end of each test series, to maintain it between 5 and 9 cm from the bottom in its lowest position.

ADV velocity data were acquired with Nortek's Vectrino Velocimeters; the data were processed and spikes filtered using the method developed by Goring and Nikora (2002). Low quality data, where the signal to noise ratio was below 15 dB and/or the signal amplitude was below 75, were discarded and cubic interpolation was performed (for gaps below a maximum length) to provide a reliable and continuous time evolution. The quality of the velocity data was very high, with only a small percentage (below 1% on average) having to be discarded based on the battery of quality tests performed. The OBS employed are OBS-3 from the D & A Instrument Company; each OBS was calibrated before deployment by using various CIEM sand samples and the glycerol technique developed by Butt et al. (2002). The worst regression coefficient (R^2) obtained from the linear regression resulting from this calibration was 0.98 (based on 13 different points). Despite the air bubbles effects on the optical backscatter sensors, reported in the ongoing discussion in scientific literature, see e.g. (Puleo et al., 2006), air bubbles have not been considered important in the present data set, based on local observations and correlations. Because of this only the spikes clearly produced by non-physical effects have been eliminated (e.g. sudden peaks in the intensity with short duration that does not match the expected behavior from previous values or previous data series under similar conditions). It must be remarked that during the presented experiments fresh water was used in all cases, that the flume sediment has a narrow grain size distribution with a low amount of fine particles and no mud (as mentioned before and to facilitate the optical measurements within the facility) and that during the experiments no foam could be appreciated in the swash zone. These three factors reduce the amount of false positives in the OBS signals and support the quality of the observations. On the other hand some slight scouring, not able to distort the important and repeated SSC measured events, was observed around some of the OBS deployed, showing that the high density of instruments was locally near the limit of physically obstructing the “natural” fluxes during the performed experiments.

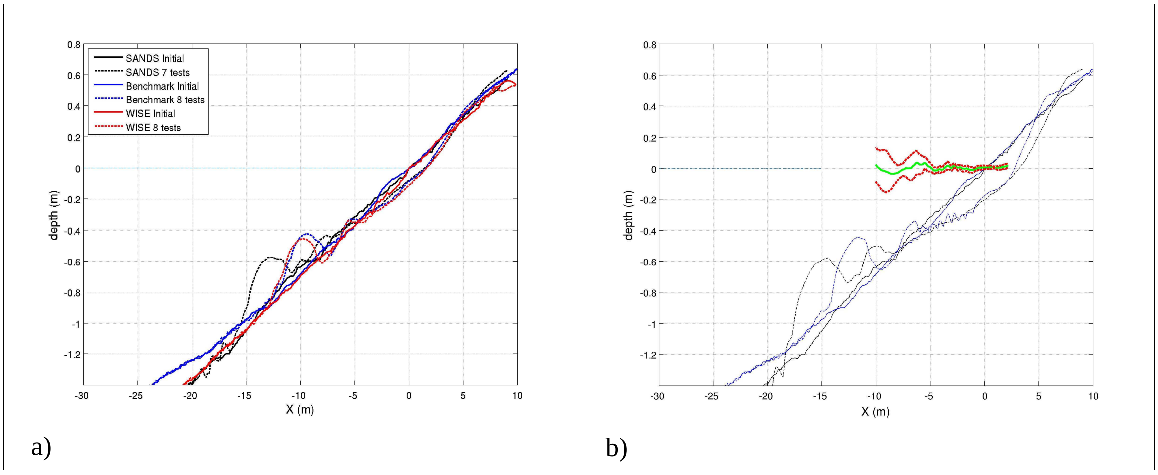
3. Preliminary Results and Analysis

In figure 2 a) we present the initial and subsequently measured profiles for the three compared tests after a significant but not final (i.e. 7 and 8) erosive time series. The blue line (Benchmark test) presents an initial slope with a slight difference compared to the “target” 1/15 slope; however, this happens above the more active profile area and the slope from the -13 m horizontal position is, indeed, 1/15 as it was the case for the experiments in WISE and SANDS. This ensures that in all three cases we can assume that the initial hydro-morphodynamic conditions are as physically equivalent as possible.

This figure displays a comparison of the bar evolution up to comparable time steps for the three studied cases. The small differences between the Benchmark and WISE erosive profiles fits within the accuracy of the mechanical profiler, that originates from the manual reshaping error when adjusting to a 1/15 slope in a large scale flume and from the different compaction degrees that we obtain every time we reshape the beach. Despite that, the mean between the difference of both measured initial profiles is 0.025 m and it's standard deviation 0.02, while these values are close to 0.018 for the mean of the two profiles difference and 0.02 m for the standard deviation when comparing both profiles after the 8th erosive sequence (last profile before starting the accretive conditions in the WISE data set). The differences between the WISE / Benchmark / SANDS erosive profiles are mainly due to the energetic content of the incoming wave series. This is also reflected in the deeper position of the SANDS breaker bar, which features also an significantly larger depositional volume (typical volumes of 3.6 m^3 and 2.16 m^3 for the WISE and SANDS bars respectively).

The variation in erosive evolution for the “last” comparable erosive profiles in the SANDS and Benchmark experiments appears in figure 2 b). After 35 erosive time series the main differences are found on the bar location, height and volume; the horizontal (x coordinate) location of the bar crest was between -14.4m and

-11.6 m for SANDS and Benchmark respectively. The bar crest heights with respect to the initial profile are 0.41 and 0.34 m and the associated bar volumes equal 7.05 m^3 and 4.56 m^3 for the mentioned SANDS and Benchmark tests, respectively. The surf zone profile shape, despite the previous differences, and the final slope (1/6.8 for both data set) turned out to be quite similar with just some small differences in the shoreline position (3.15 and 2.74 m) and berm heights (0.13 and 0.08 m) for SANDS and Benchmark respectively. The breaker bar for our analysis is defined to be the point of maximum difference between each profile and the initial shape; this parameter is considered to reflect better the bar depositional feature rather than the point of maximum bar height, or the conventional bar crest, used in previous analyses. This method of quantifying the breaker induced morphodynamics is found to be more robust when using profiles of the bar migration under accretive conditions, since in this case the incoming waves produce gentler shapes on the morphology as can be seen on Figure 3.



a) b)

Figure 2. a) Initial profiles for the SANDS (black), Benchmark (blue) and WISE (red) experiments, together with the final profiles after 7 erosive wave series for SANDS (black dashed), and 8 erosive wave series for Benchmark and WISE (blue and red dashed respectively). b) Initial (continuous) and well developed (dashed) profiles after 35 erosive wave series for SANDS (black) and Benchmark (blue) experiments. The green line represents the mean differences between “equal” (in the corresponding time evolution) profiles, while the red dashed lines indicates its standard deviation between these same profiles.

Figure 2b also allows quantifying the overall differences that appear between the SANDS and Benchmark “comparable” erosive profiles in the surf and inner swash zones. Such profile variations, at comparable time instants, have been computed after checking that the results were above the resolution of the profiler. From the obtained differences the mean (continuous green) and standard deviation (dashed red) have been obtained and are presented in the figure along the x axis. The surf and inner swash zone present close profile evolutions, despite the important decrease in the energy content of both erosive time series (being in SANDS 27 % higher than in Benchmark conditions). The measured velocities for comparable surf zone measurement points show mean values for the SANDS data set of order 0.2 m/s at the beginning of the experiments and decreasing up to 0.15 m/s around test 22 of the erosive sequence. We have also computed the mean of the 30 highest (positive and negative) velocity peaks measured at each position. The obtained data is of order 1.18 m/s at the beginning of the experiments (the bar is still forming), while the velocity peaks decrease to 1.07 m/s around test 22 of the erosive sequence. The values obtained under Benchmark or WISE conditions tend to be 20 % lower when considering mean values and 17 % lower when considering the mean of the 30 more energetic peaks (considering both offshore and shoreward velocity peaks).

At the beginning of the accretive conditions for the SANDS experiments, which start at the end of each erosive test series, the bar is found to be at x = -16.56 m and with a height of 0.56 m. For the WISE tests the bar is found at x= -10.51 m and with a height of 0.25 m, from the initial 1/15 profile shape. The bar volume has been computed when considering the differences from the developed profile relative to the initial 1/15 slope and considering a closure depth of -1.5 m (based on state of the art formulations and the experienced profile evolution) and up to the crossing point between the bar and the constant initial slope (just a short distance shoreward from the trough). The bar volume in SANDS is 8.35 m^3· while the measured volume is 2.16 m^3 for WISE.

In order to analyze the influence of incoming wave conditions and the initial “state” of the “receiving” beach profile, we have considered in the analysis both accretive and erosive wave trains, allowing them to act on evolving flume profiles to study the evolution of fluxes and pulses with accretive and erosive transitions. The breaker bar (figure 2b) continues evolving with time, as a function of the energy of incoming waves and depending on the distance to “equilibrium” or to the asymptotic shape of the sedimentary deposit. The development of truly stable profile geometry has not been reached and this conditions the evolution under accretive wave sequences, as shown in figure 3. The bar formation keeps on being active, as illustrated by the comparison between figures 2b) and 3a).

Figure 3 presents the bottom evolution under accretive conditions for SANDS (left) and WISE (right) after 31 and 29 accretive wave series respectively. As previously stated, the initial conditions of both accretive time series is significantly different, but considering the fact that both wave trains have the same energy contest and result in the same range of Dean numbers (lower for SANDS conditions, see Table 1) the final state of both profiles can be compared at “equivalent” time intervals.

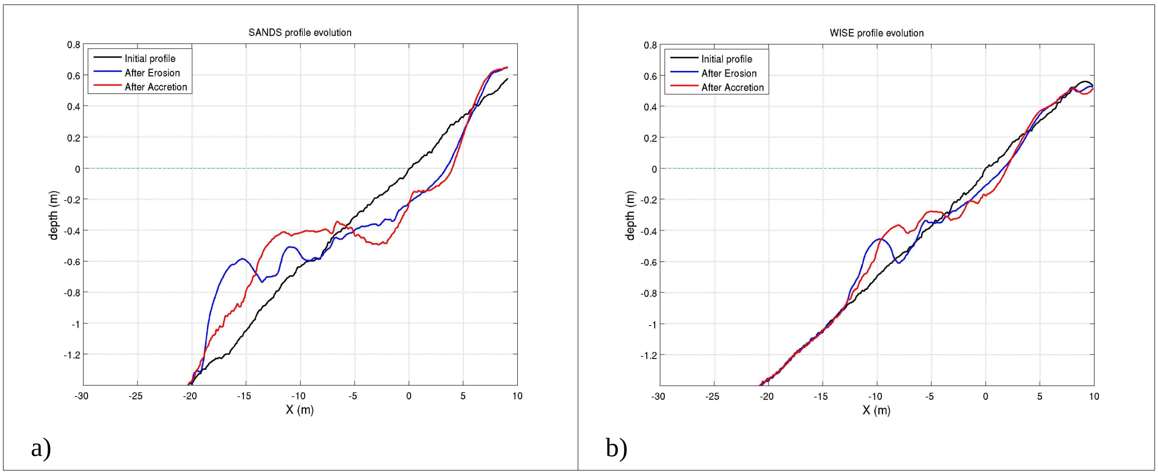


Figure 3. a) Profile evolution after SANDS 31 accretive wave series and starting from the SANDS erosive geometry; b) Profile evolution after WISE 29 accretive wave series and starting from the WISE erosive geometry (different from the previous case).

The bar volume accreted under the SANDS wave sequence is up to 3.7 m^3 while this volume for the WISE experiments is 1.8 m^3; these values correspond to the bar migration towards shoreline for each set of experiments (figure 4). A non-dimensional number can be obtained from these volumes when considering the initial bar shape at the beginning of accretive conditions. If the accreted volume is divided by the initial bar volume, the sedimentary accumulation for SANDS is 0.44 and for WISE is 0.83, showing a clearer trend in this latter case.

For the analysis of wave height fields for the two data sets we have found some limitations due to the lack of good measurements on the SANDS tests. Despite that there is a clear differences between both experiments presenting SANDS a wider and smoother breaking area while the WISE experiments feature a better defined and more energetic breaking zone at the bar location (at -11.5 m from the accretive shoreline at the beginning and moving progressively towards the -10 m position) and a second breaking zone at the terrace that is formed behind the trough.

Despite the overall accretive sediment volumes measured at both data sets, there is a clear shoreline erosion and an important depth increase previous to a terrace formation close to the shoreline in the SANDS data set. That through appearing in the SANDS experiments behind (shoreward) the bar, shows a steady formation trend and keeps growing while the bar movement slows down in time due to the arrival of a “stable” accretive profile. The mean velocities in the surf zone between SANDS and WISE accretive conditions do not present significant differences at comparable locations but the mean peak velocities present higher intensities (20 % in average) for the SANDS conditions, with values around 1.05 m/s.

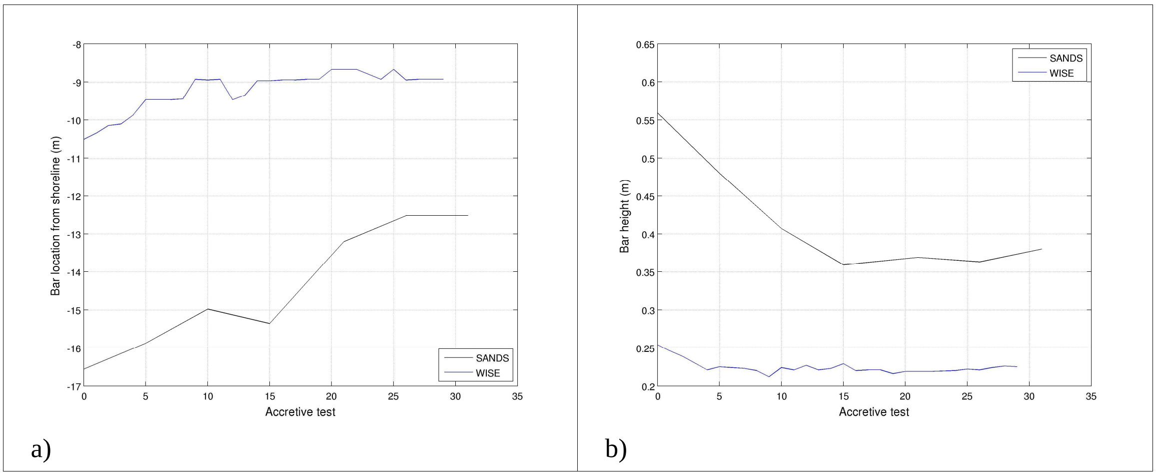


Figure 4. Bar horizontal location a) and height b) evolution under accretive waves, starting from the “last” erosive profile in the SANDS (black) and WISE (blue) experiments.

When comparing the suspended sediment concentration measurements form the two experiments at “equivalent” surf locations (x = -4 m from accretive shoreline), the sediment suspension concentrations turn out to be significantly different. Figure 5, a) for SANDS and b) for WISE data sets, reports the suspended concentration measurements at 5 different tests (starting from test 3 on the top panel and each lower panel presenting a step of 5 additional accretive test series, so that the second panel corresponds to the 8th accretive time series). We start from the 3rd test due to a generation problem on the two initial accretive SANDS time series. The suspended sediment measurements present a clear discrepancy between both data sets; the amount of suspended sediment events is reasonably “constant” for the SANDS experiments, while there is an important decrease for the WISE SSC measurements with time. This decrease in the WISE SSC events occurs at all location between -6 and -1 m from shoreline (i.e. within the surf zone). Previous locations, mainly measurement points at x = -10 m, where the bigger waves are breaking over the bar, do not present any SSC event decay along the experiment development, such as it occurs at the inner swash measurement points due to the control role played in this area by the wave-backwash interactions occurring at the shoreline.

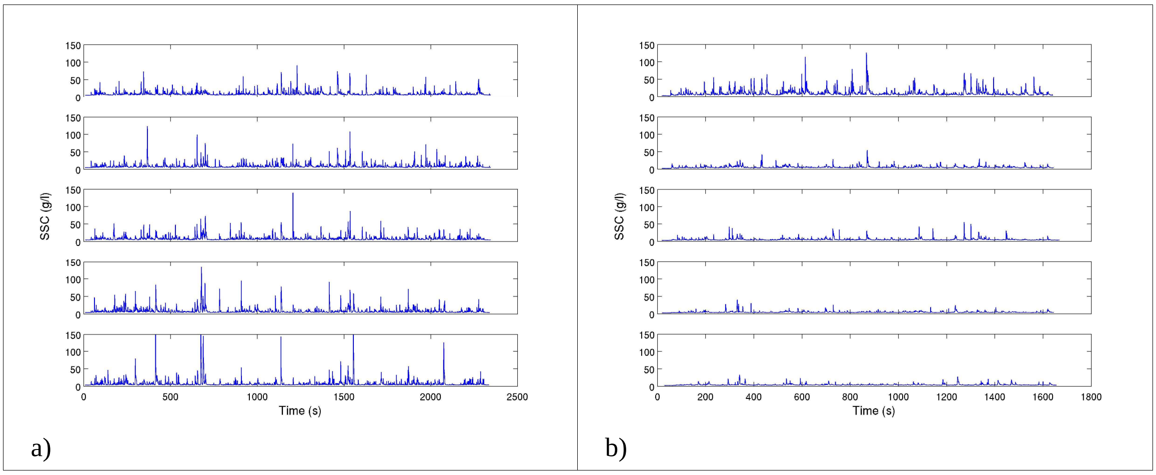


Figure 5. Suspended Sediment Concentration measurements for the SANDS (left) and WISE (right) experiments representing different accretive tests: 3rd , 8th, 13th, 18th and 23rd from top to bottom panels.

4. Conclusions

The profile evolution for different erosive wave sequences, corresponding to the termed SANDS and Benchmark experiments, have been comparatively analyzed as a function of their different energy content and the equal Dean number. This results, as could be expected from basic morphodynamic arguments, in different bar locations with the deeper ones presenting a higher bar volume, an enhanced height from the original slope and a larger free board (over the crest) for the more energetic wave conditions. Despite that differential behavior the surf zones of both experiments are essentially the same, mainly after the secondary bar and up to the shoreline.

The accretive experiments, which start from different initial profiles in both test series, present a clear difference in the accretive evolution and morphodynamic patterns. Although SANDS and WISE feature the same energy content, they have a different Dean number. Both cases present accretion in the form of bar migration towards the shoreline but the pattern of bar “fission” and the displacement rate remain different. However the two tests surprisingly keep on showing shoreline regression, attributed to the lack of dynamic equilibrium between incoming waves and the sedimentary deposit. When considering the total volume of sand moved towards the shoreline, the case with a lower Dean number (SANDS experiments) that should be more clearly accretive presents a larger shoreward (positive) transport. In spite of this, the dimensionless sand transport rates turn out to be larger for the WISE experiments. This can be attributed to the shallower initial bar location at the last experimental setup. After 31 accretive tests both experiments present a clearly asymptotic breaker bar behavior (i. e. bar crest location moving towards the shore and increasing height). The SANDS data set are characterized by a steadier growth of the bar, together with some deepening of the trough behind it. On the other hand the WISE data set presents a clear merging trend for both bars that keep on slowly being unified during the last accretive test sequences.

The initial accretive profile seems to play a key role in the entire hydro-morphodynamic evolution for the performed experiments. The WISE bar, with a smaller freeboard, induces a larger breaker index (ratio) dissipating more energy that will not reach the inner surf zone positions and swash zone. This energetic breaking produces more intense suspended concentration events, while at the same time the energy dissipation importantly decreases the number of SSC pulses at shoreward positions. Under these conditions only the swash has recorded continuous SSC events controlled by the wave-backwash interactions.

The wave breaking pattern for the SANDS accretive wave series appears to be more continuous than for WISE. This can be attributed to a more progressive breaking over the milder and deeper SANDS bar that allows a free path for a larger number of waves that will then break at shallower positions. This induces a more energetic situation (higher velocities and larger, in number and concentration, SSC events) at inner surf zone locations, that result in higher transport rates and morphodynamic response.

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