Morphology and dynamics of subaqueous dunes generated under unidirectional flow

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ABSTRACT: The flow velocity over mobile sandy dunes subjected to unidirectional current was investigated using a UB-Lab 2C, an acoustic velocity profiler newly developed by UBERTONE. A space-localized wavelet approach was used in order to detect the temporal evolution of the main dune's wavelength. The acoustic tool has provided promising results concerning the flow and sediment dynamics over migrating dunes.

1 INTRODUCTION

Dunes in natural marine environments are subject to various, complex and unsteady hydrodynamic forcings. Understanding and forecasting their morphology and dynamics is an important task, especially when interacting with marine structures, as the bedform-related roughness strongly influences sediment transport. In shallow waters and intertidal environments in particular, subaqueous dunes are strongly influenced by waves which combine with unidirectional or reversing currents. Their morphology can also be strongly modified by extreme events. Physical experiments in flumes constitute a common approach to the study of natural systems that helps to test independently the influence of each forcing occurring in nature. To date, most of the physical experiments conducted on marine dunes in flumes have been performed under unidirectional steady current (Blom et al., 2003; Boguchwal and Southard, 1990; Bridge and Best, 1988; Kleinhans, 2004; Naqshband et al., 2014), or under long-period oscillating flows in tunnel flumes (Perillo et al., 2014). Thus, there is still a need to explore how dunes grow in the presence of currents interacting with short-period waves, longer storm waves or extreme events, and to understand how waves modify the dune morphology, in comparison with current-only dynamic equilibrium morphology.

In this paper, we present preliminary experiments of a study which aims at understanding, using physical experiments, the response of dunes to wave-current interactions. We report the development, equilibrium morphology and flow structure of dunes under unidirectional current, a simple flow condition which will serve as a comparison for future experiments using combined flows. Dune growth and equilibrium morphology was surveyed thanks to a laser distance meter, and a space-localized wavelet approach was used in order to detect the temporal evolution of the main dune's wavelength. Quantitative information on flow structure and sediment transport was obtained by deploying the UB-Lab 2C, a new acoustic Doppler profiler manufactured by UBERTONE, which provides high spatial and temporal measurement of both two-component flow velocity and sediment concentration profiles over the entire water column.

The information of sediment concentration can be derived from the UB-Lab 2C backscatter intensities following the methodology of Hurther et al. (2011). This offers the ability to explore sediment flux profiles in the suspension layer. The inversion from intensity to concentration is done by iterating downwards from the emitter while accounting for the signal attenuation occurring along the water depth, as described in detail by Batteridge et al. (2008) and Thorne and Hurther (2014). The interpretation of the acoustic backscatter intensity requires calibration of the system. In this study, dimensionless concentration results will be given as to date, the calibration system is still under development.

2 MATERIAL AND METHODS

The present data were acquired within the MOdelling of marine DUnes: Local and Large-scale EvolutionS in an OWF context (MODULLES) project. The tests have been carried out in the wave and current circulating flume of the M2C laboratory located in Caen (France). The flume is 16 m long, 0.5 m wide and 0.5 m deep, and is equipped with a piston type wave maker and a centrifugal pump for water recirculation.

In order to ensure the uniformity of the flow, a 20 cm-high honeycomb was installed at the entrance of the flume, followed by a 1 m-long pebble bed to ensure the fast development of a turbulent boundary layer. A sediment trap was also installed at the end of the flume to collect the bedload sediment. The longshore coordinate *x* was defined as 0 at the beginning of the sandy bed (Figure 1), increasing toward the other end of flume and the still water depth was 0.3 m. For present tests, a coarse sand of median diameter D_{50} = 0.6 mm and relative density $s = \rho/\rho s = 2.65$ is selected based on the bedform phase diagram (Southard and Boguchwal, 1990).

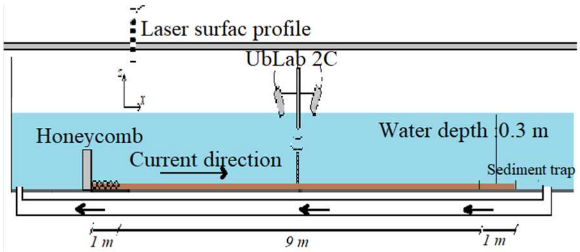

Figure 1. A schematic showing the experimental setup in the test section of the water flume.

The flow velocity was measured with the totally submerged UB-Lab 2C. The UB-Lab 2C allows to acquire co-located two (2C) instantaneous velocity profiles with three transducers (2 emitters and 1 receiver). The two instantaneous velocity components are denoted (*u*,*v*) along the directions (*x*,*z*) respectively. Figure 2 shows a comparison between a velocity profile u(z) given by the UB-Lab 2C and a velocity profile given by the two well established instruments, the PIV and the ADV.

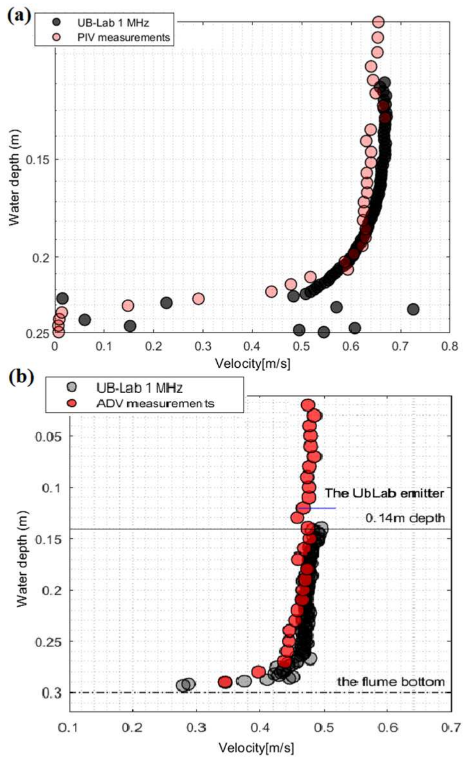

Figure 2. Comparison between velocity profiles u(z) given by the UB-Lab 2C and (a) PIV measurements (b) ADV. The averaging time for the two acoustic tools is 2 minutes and 30 s for the optical tool. The sampling frequency is 20 Hz for UB-Lab 2C, 100 Hz for the ADV and 200 Hz for the PIV.

The experimental procedure was conducted as follows. First, the sandy bed installed over 9 m was flattened to reach a thickness of 10 cm (around $0.5m^3$ of sand). The uniform current $U = 0.65$ m/s was then generated in the flume and UB-Lab 2C flow and concentration measurements were performed. Experiments were stopped every 15 minutes to collect the sand trapped downstream and to reinject it upstream, as the sediment was not recirculated automatically. The overall duration of the experiment was around 300 min.

The 9m-long sandy bed topography was surveyed every 15 minutes along 5 parallel longitudinal transects, using a laser distance-meter mounted on a carriage. The longitudinal profiles were then interpolated to obtain maps of the bottom topography.

3 RESULTS AND DISCUSSION

3.1 Topography evolution of dunes

Starting from plane bed, ripples appeared instantaneously as the flow was introduced in the flume. Dunes subsequently developed and finally a steady state condition was obtained where the dunes migrated through the flume with a relatively constant speed. Figure 3 shows 20 selected maps of the bed evolution in time along the effective measuring section of the flume. Quasi equilibrium state is here defined as the moment when dunes morphologic characteristics (mean wavelength and height) does not change substantially.

Topographic instantaneous profiles are overlaid chronologically at regular time intervals (i.e., 15 min) in order to plot the space-time diagram (Figure 4) which was used to calculate the dune velocity ($U \sim 2$ m/h) at equilibrium.

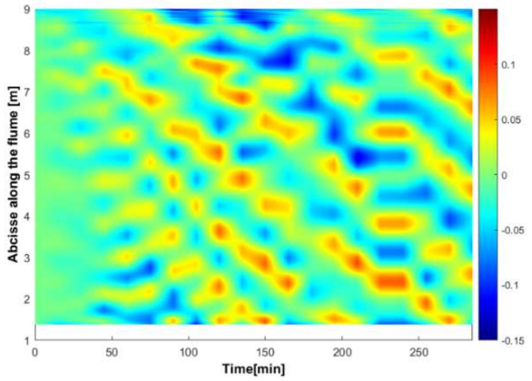

Figure 4. The space-time diagram which reflects the topography along time.

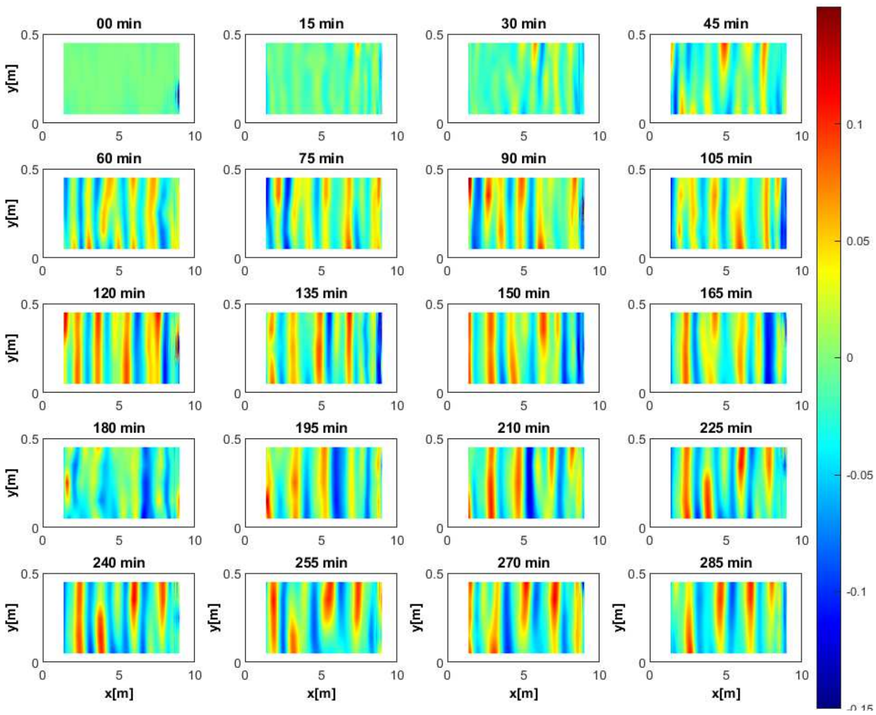

Figure 3. Bed temporal evolution along the flume.

3.2 Wavelet analysis

Wavelet analysis was used to study spatial series bed elevation profiles acquired every 15 min. The objective is to be able to account for the variability of the signal frequency at the different positions along the study section. The continuous wavelet transform *WT(a,τ)* of the topography spatial signal, $x_n(t)$, is defined as a convolution integral of $x_n(t)$ with a mother wavelet, $\psi^*_{a,\tau}$ that is translated and scaled along the signal:

$$WT(a,\tau) = \int_{-\infty}^{+\infty} x_n \, \psi^*_{a,\tau} \, dx \qquad (1)$$

where the asterisk indicates the complex conjugate, *ψ(a,τ)* represents the mother wavelet function dilated by a factor *τ* and scaled by a factor *a*, and *dx* the spacing. The mother wavelet can be dilated by a factor *τ* and scaled by a factor *a*. Scales can be written as fractional powers of two:

$$a_i = a_0 2^{i\delta}, i = 1, 2, 3 \ldots M \qquad (2)$$

$$M = \frac{1}{\delta} log_2(\frac{N\Delta t}{a_0}) \qquad (3)$$

Where $a_0 = 0.005$ is the smallest resolvable wavelength, M the largest wavelength, and δ the scale factor. The selected scale factor was $\delta = 0.0005$, giving a total of 382 wavelengths. The space sampling and the number of points were, respectively, $\Delta x = 0.005$ m and $N = 2000$. The selection of the mother wavelet was made based on several tests performed in the data. Finally, a complex Morlet mother wavelet was used, in accordance with the suggestion by Cataño-Lopera et al. (2009) and with the results obtained by Gutierrez et al. (2013) in the analysis of the capability of different mother wavelets to retrieve ripple periodicities from synthetic signals. The complex Morlet wavelet can be interpreted as a sine wave multiplied by a gaussian envelope.

The wavelet transform WT (a,τ) is here displayed as a 2D colour plot (Figure 5) showing wavelength versus space (distance along the flume), with the colours representing the magnitudes of $|WT(a,\tau)|^2$. Initially, between 30 and 75 min, the evaluated wavelengths corresponded to wavelengths ranging between 1 m and 1.4 m, which is a currently accepted length criteria to define dunes in the literature (Ashley, 1990). Figure 5 shows that the most energetic wavelengths vary temporally. From 30 to 200 min, the extremes correspond to wavelengths of around 1.2 m and 1.6 m. With increasing time (t > 200

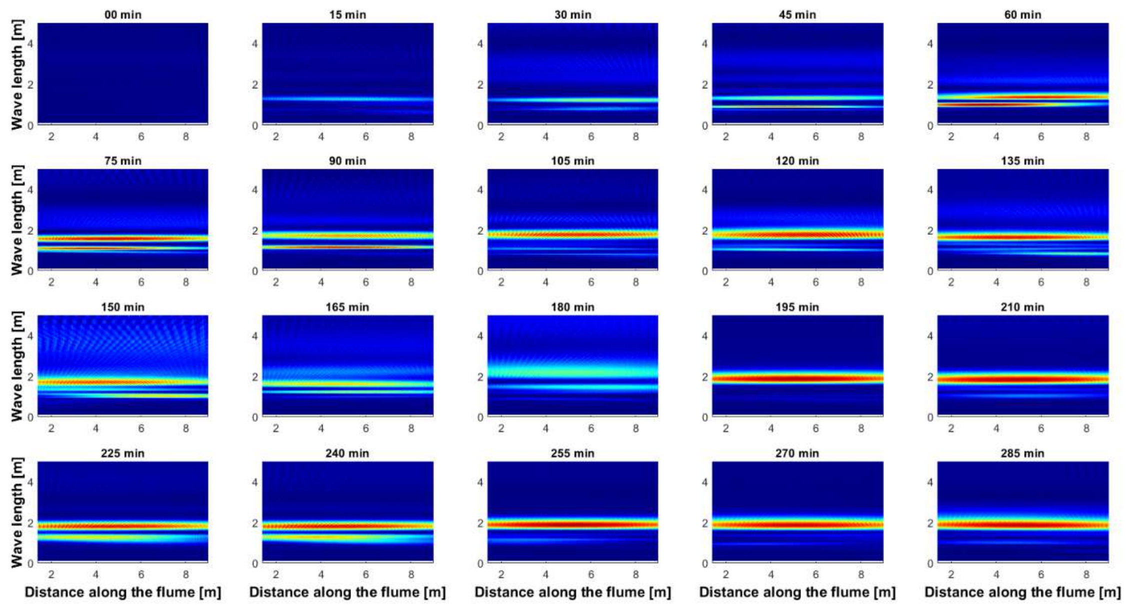

Figure 5. Wavelet magnitude for dunes resulting from steady current during the 285 min of experiments and their corresponding mean wave power for each wavelength.

min), a noticeable energetic band centred at λ = 1.8 m appears. Figure 6 summarizes the temporal evolution of the λ – distance along the flume relation. It is found that at t > 200 min, no noticeable changes are observed in the dune's main wavelength and height (~ 9.5 cm).

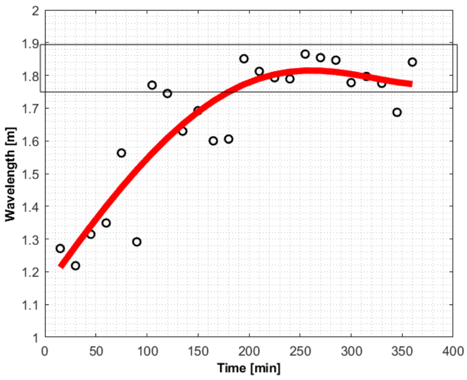

Figure 6. Temporal evolution of dune's wavelengths.

3.3 Flow and concentration analysis

The UB-Lab 2C probe was placed downward-looking at *x* = 7 m and the dunes migrated underneath it with a relatively constant velocity. The acoustic tool provides flow velocity and sediment concentration profiles of 23 cm length and pulse repetition frequency (PRF) of 900Hz at high spatial (3 mm) and temporal resolution (20 Hz).

The sediment concentration estimation is based on a statistical model of the recorded squared voltage (Equation 4). It is derived from semi-theoretical and experimental determinations of the acoustical backscattering and attenuation properties and it is valid under incoherent scattering conditions (Thorne and Hurther, 2014).

$$C = \left(\frac{r\Psi}{K_s R}\right)^2 V_{rms}^2 e^{4r(\alpha_\omega + \alpha_s)} \quad (4)$$

r is the range from the emitter which varies between 0.05 m and 0.3 m, *Ψ* represents the departure from the signal spreading within the transducer nearfield and R is the system constant. K_s represents the sediment backscattering properties, α_s is the attenuation due to suspended sediment scattering and α_ω is the sound attenuation due to water absorption. A typical example of the relative root-mean-square backscatter signal V_{rms} is shown in Figure 7. The first 0.09 m data are not shown because this part of measurements is contaminated by the crosstalk between the transmitter and the receiver during the acquisition. Figure 7 shows a decreasing trend of the backscattered signal with depth due to the r^{-1} term in Equation 4.

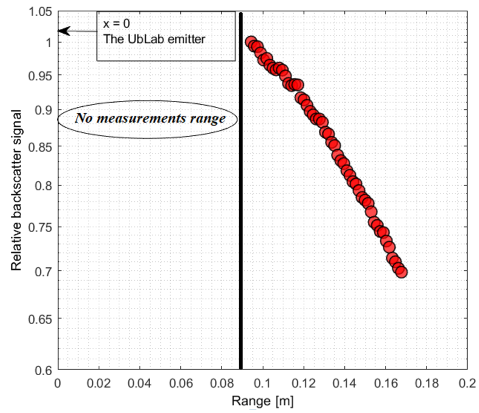

Figure 7. Typical measurements of the relative backscatter signal with range in the flume.

Bed elevation were extracted from the UB-Lab 2C backscattered signal intensity. One example of the bed detection is shown in Figure 8. The sudden and large increase of the backscattered signal intensity corresponds to the bottom echo, and agrees well with the location of zero-velocity on the horizontal velocity profile.

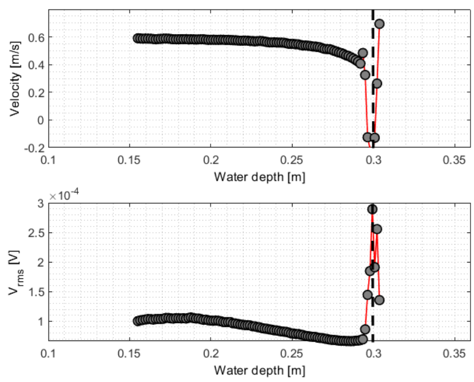

Figure 8. Example of bed detection based on mean backscattered signal intensity profile (bottom) and mean streamwise velocity profile (top).

Figure 9a shows the contour map of the mean streamwise flow velocity $\bar{u}$ evolution with time. The position of the dune topography is detected thanks to the UB-Lab 2C backscattered signal and is represented by a solid black line. The flow is from right to left. From Figure 9a, we can distinguish three main flow features over the migrating dune. The first feature concerns the presence of a zone of deceleration in the lee side zone. Negative streamwise velocities (counter-currents) are localized in the through region, and associated to the recirculating cell. The second feature is the presence of an acceleration zone in the stoss side region of the dune with high streamwise velocities. The third feature is the development of a millimetric internal boundary layer on the dune crest. These results are qualitatively similar to those found in Naqshband et al. (2014).

Figure 9b shows the contour maps of the mean vertical $\bar{v}$ flow velocities along the migrating dune. The main feature in this figure is the presence of positive vertical velocities almost along the entire migrating dune.

Figure 9c represents the contour map of the dimensionless sediment concentration along the migrating dune. Two zones of high sediment concentration are observed. These are associated to (1) the lee side of the dune, where significant sediment deposition occurs by avalanching from the crest, and by settling in the decelerating recirculation zone; (2) the boundary layer reattachment point, where significant erosion occurs during turbulent bursts.

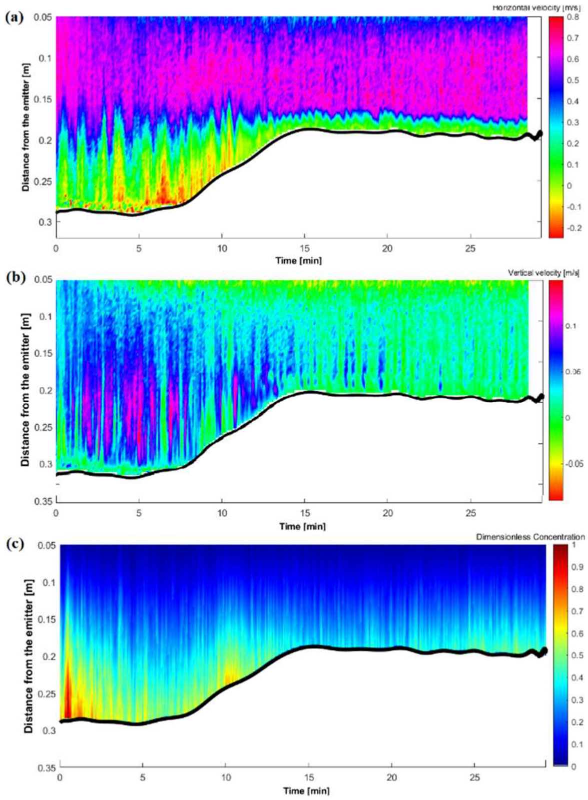

Figure 9. (a) Contour map of the mean streamwise flow velocity $\bar{u}$. (b) Contour map of the mean vertical flow velocity $\bar{v}$. (c) Contour map of the mean dimensionless sediment concentration. The solid black line shows the dune profile.

4 CONCLUSIONS AND PERSPECTIVES

This paper presents a study of the morphology, dynamics, flow structure and sediment concentration over a migrating dune under unidirectional current, using physical experiments. The wavelet approach was used to quantify the mean dune wavelength and its evolution with time. It takes into account the variability of the wavelengths along the flume extension, and so, it permits the identification of the dune wavelengths in different sections. This study strengthens the utility of the UB-Lab 2C acoustic tool in detecting flow and concentration features over migrating dunes.

For the near future, we plan to perform the calibration of the backscattered signal in order to obtain quantitative results concerning the concentration and the flux above the migrating dune. Morever, in order to expand results found in this study, new tests involving the presence of regular and irregular waves propagating on the background of a steady current will be performed. To our knowledge, there has not yet been flume experiments investigating dune dynamics under extreme waves. Therefore, there is a strong need to conduct experiments on dune dynamics in the presence of group focused waves in order to derive general formulation and deepen our knowledge of dune morphodynamics under nonlinear forcings.

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