TOPOGRAPHICAL CHANGES DURING BEDFORM DEVELOPMENT

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ABSTRACT

3D development of underwater bedforms is studied visually in a laboratory. A bed of uniform coarse sand (d_{50}=0.8-mm) covered the flume floor. The sand bed was flattened initially. Each mobile-bed experiment (flat sand bed to equilibrium bed forms) was carried out over several hours. The recorded sand bed was treated as a continuous field of sand-bed elevations, rather than subdivided into discrete bedforms. Multiple Transducer Arrays (MTAs), manufactured by Seatek, were used for measurement of multiple bedform profiles with varying spatial and temporal domains. The data were ultimately transformed into a temporal record of a 3D field of sand-bed elevations. The filtered and cleaned sand-bed elevation data sets were used to obtain contour plots for each individual temporal sweep. Changes in bedform height, or in elevation, are indicated by an increase or decrease in colour density. Changes in crest orientation, or 3D topographical changes, are also discernable. Topographical changes during bedform development were studied visually, the observations showing the multiple interaction processes between bedforms along the flume. Comparisons of processes of aeolian dune field patterns, as well as underwater bedform development captured by photographic media, are presented. We can conclude that 2D analysis of bedform growth provides insufficient information about how bedforms interact with each other.

Keywords: Topography, pattern, bedform, flume.

1. INTRODUCTION

The initiation and development of bedforms from a flat sand bed to equilibrium in one-directional water flows (rivers, canals) is an important aspect in sediment transport studies. Improving our knowledge of how the shape and topography of bedforms varies during development is important in order to accurately describe hydraulic roughness characteristics and sediment transport rates for different flow conditions.

In the past, bedform development was studied mainly through analysing longitudinal profiles of recorded sand-bed elevations in the laboratory. Developing bedform profiles can be obtained either in the spatial domain or in the temporal domain, recording the 2D shape of bedforms as either a function of space or a function of time.

A common challenge in studies dealing with evolution of shapes, such as growing bedforms, is characterization of topographical patterns. Friedrich and Melville (2008) studied visually bedform development for fine sand for a small (0.44-m square) flume segment. Plan-view images of early 3D bedform growth were captured, starting from a flat sand bed. Based on a study of aeolian dune patterns by Kocurek and Ewing (2005), Friedrich and Melville (2008) could identify processes such as merging, termination and defect migration during bedform development. These studies show that 2D analysis of bedform growth provides insufficient information about how bedforms interact with each other. The various lateral merging/termination processes involved are not accounted for in a 2D projection of a 3D event. A complete 3D pattern analysis is necessary in order to better understand the processes that take place during bedform development and early bedform growth.

For this study, area contour plots of plan-view dune evolution are used to discuss how bedforms interact with each other.

2. BACKGROUND

Recently, Venditti et al. (2005) presented results from bedform development experiments undertaken in laboratory flumes, focusing on plan-view footage of 3D bedform growth. Venditti et al. (2005) argued that widespread coalescence does not take place, neither during growth nor equilibrium studies. Coalescence is a phenomenon of geometrical change of dune dimensions during 2D dune development studies, firstly addressed by Raudkivi and Witte (1990). Venditti et al. (2005) argue that instead of widespread coalescence, a crest realignment takes place, which can be mistaken for bedform coalescence by projecting the bedform profile in 2D.

Friedrich and Melville (2008) obtained plan-view underwater bedform footage during early development, starting from a flat sand bed, in a laboratory. They discussed pattern changes during bedform development in relation to previous known knowledge of fluvial and aeolian bedform changes (Figure 1).

Besides the 3D studies by Venditti et al. (2005) and Friedrich and Melville (2008) no other study is known to the authors where evolution of underwater bedform patterns are studied in 3D. Whereas the studies by Venditti et al. (2005) and Friedrich and Melville (2008) are based on visual footage obtained with photographic hardware, this study shows how bedform evolution can be studied with the help of contour plots obtained using acoustic sensor technology.

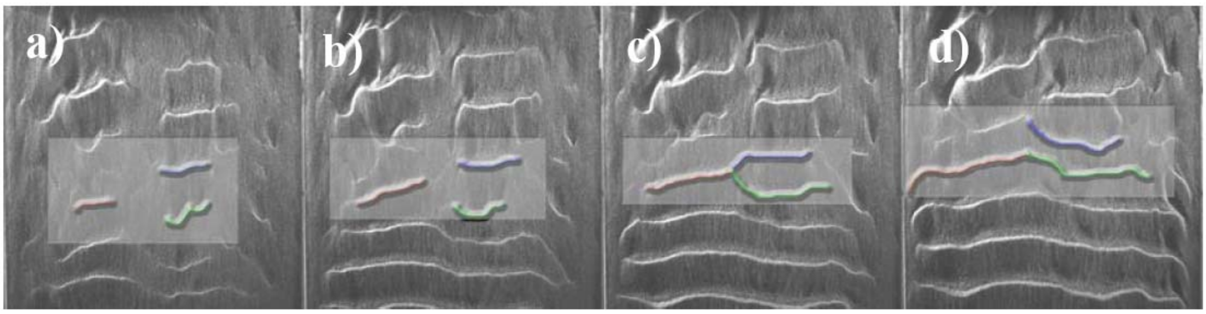

Figure 1 Plan-view images of early 3D bedform growth for fine sand. Lateral merging of terminations results in increased crest length. Flow is from bottom to top. a) t=0sec, b) t=19sec, c) t=33sec, d) t=56sec (Friedrich and Melville, 2008).

Due to more widely available aerial photography of aeolian dunes, many studies focused on pattern changes of aeolian dunes. Schwämmle and Herrmann (2003) studied barchan sand dunes mathematically and showed how these dunes can traverse through one another, without major changes to their shape. They distinguish between coalescence (both dunes merge into one), breeding (the creation of three baby dunes) and solitary wave behaviours during the fusion of two dunes. A follow-up study (Duran et al., 2005) suggested that additionally a budding scenario (the small dune, after “crossing” the big one, is unstable and splits into two new dunes) can take place. Similar to the budding scenario, Hersen (2005) states that rather than a simple coalescence behaviour, an absorption/emission process takes place, when a smaller dune merges into a bigger dune, prompting the emission of several small dunes.

From observations in nature and model simulations, Kocurek and Ewing (2005) derived a dune-pattern ordering for natural systems. The ordering system shows dune–dune interactions. Kocurek and Ewing (2005) distinguish five different patterns: a) merging – the simplest interaction, when bed forms are small, diverse in size and closely spaced; b) lateral coalescing of terminations – which can be seen as lateral merging and results in increased crest length; c) defect migration – a crest termination merges with the downwind crest and results in emission of a new crest termination further downwind; d) repulsion – similar to merging, but once merged results in the emission of another small dune; e) termination creation – whereby at first two crests merge and later a pair of terminations is created.

Friedrich and Melville (2008) discussed how the patterns observed for aeolian dunes can also be studied during underwater bedform development in the laboratory. Processes such as merging, termination and defect migration are qualitatively presented in Friedrich and Melville (2008).

3. EXPERIMENTAL SETUP

A 5-MHz Seatek ultrasonic ranging system, comprising 31 transducers (Figure 2), was employed for the measurements of the sand bed. The moving probe arrangement, which travelled up-and-down the flume on a moving carriage and which measured the 3D elevations of a developing sand bed, is introduced in Friedrich et al. (2005), a methodology paper describing experiments undertaken in a narrow 440-mm-wide flume. This paper utilises data obtained during experiments in a larger 5-ft-wide flume. Brief explanatory notes illustrating the 5-ft-flume methodology are given below.

The 31 transducers were interrogated sequentially (starting from sensor 1 and finishing with sensor 31), with the same sequence repeated every 0.2-s. The sensors were mounted on a skewed grid to allow for the movement of the carriage in the time interval between readings of the components of the sensor array. This ensured that measurements were obtained on an equivalent rectangular recording grid (Figure 3).

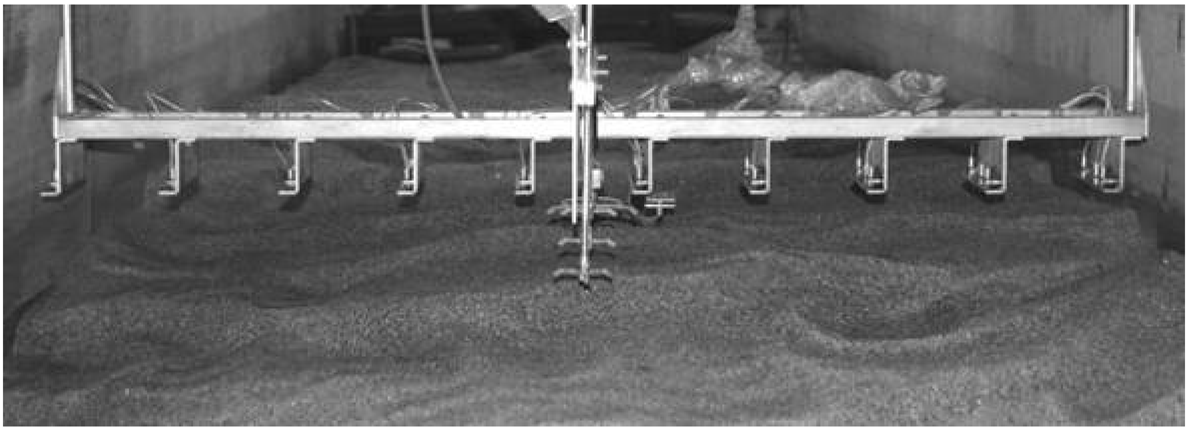

Figure 2 Arrangement of the moving probes across the 5-ft flume. Four Acoustic Doppler Velocimeters (ADVs) are placed in front of the acoustic sensors on the centerline of the flume to measure the flow field at different water depths.

Figure 3 Schematic display of sand-bed elevation recording grid in the 5-ft flume. The carriage travels downstream (for recording) and upstream (with the sensors out of the water) along the flume over a length of 18.48-m.

Each mobile-bed experiment (flat sand bed to equilibrium bed forms) utilising moving probes was carried out over several hours. Experimental parameters for these experiments are given in Table 1.

The sequence of operation was as follows. Initially, the moving carriage with submerged sensors travelled downstream for 56-s. Then the carriage was stationary for a waiting period of 4-s, which was used to raise the sensors above the water, in order to reduce the water surface disturbance when travelling upstream for a period of 56-s. After a further waiting period of 4-s, and submerging the sensors again, the carriage moved downstream into the second cycle. Each cycle duration was two minutes. The experiment was continued with repeated cycles until appropriate bedform development had occurred. Recording of the bed profiles occurred only during the down-stream-moving portion of each cycle, based on the configuration of the recording grid. The frequency of recording of bed profiles was one profile every two minutes. Sensor no. 31 was inverted and used to record the water surface elevation, meaning that only 30 sensors were used to record bed elevations. Overall, ten longitudinal profiles with a transverse resolution of 150-mm were recorded over each sweep of a length of 18.48-m.

Table 1 Experimental parameters.

Run Name	d_{50}	D	T	S_e	Run Duration	Equilib-rium	U_{avg}	Fr	Re
	[mm]	[m]	[°C]	[-]	[hh:mm:ss]		[m/s]	[-]	($x10^3$)
wsc07b	0.85	0.15	22	0.292	05:50:00	no	0.38	0.313	190
wsc85a	0.85	0.15	18	0.350	04:44:00	yes	0.43	0.354	215
wsc85b					05:34:00	yes			
wsc10a	0.85	0.15	18	0.394	05:02:00	yes	0.48	0.396	241
wsc10b					05:16:00	yes			
wsc115	0.85	0.15	18	0.430	03:58:00	yes	0.57	0.470	286
wsc115					03:56:00	yes			
wdc25a	0.85	0.52	17	0.058	07:02:00	no	0.56	0.248	692
wdc25b					05:34:00	no			
wdc30a	0.85	0.52	17	0.146	05:18:00	yes	0.70	0.310	865
wdc33a	0.85	0.52	17	0.190	06:54:00	yes	0.75	0.332	926
wdc33b					02:26:00	no			
wdc35a	0.85	0.52	17	0.219	06:14:00	yes	0.81	0.359	1000
wdc35b					04:04:00	yes			

Note: Kinematic viscosity ν=0.000001-m^2/s; Specific gravity s=2.65; Critical shear velocity u_{*c}(d_{50}=0.85-mm)=0.0215m/s

d_{50} Median grain size, D Flow Depth, T Water Temperature, S_e Flume Slope, U_{avg} Average Flow Velocity, Fr Froude Number, Re Reynolds Number

4. TOPOGRAPHICAL MAPS

Ten longitudinal profiles with a transverse resolution of 150-mm were recorded over each sweep of a length of 18.48-m. An example of the 2D projection for bedform development of experiment wdc33a is given in Figure 4. The filtered and cleaned sand-bed elevation data sets were used to plot contour plots for each individual sweep (Figure 5). The mean bed level of the flattened sand bed at the beginning of each experiment was calculated and development of the bedforms is displayed with the level of the flattened bed as a reference level. Green indicates the flattened sand bed level, red indicates bedform crests and blue indicates bedform troughs. From the plots, one can easily follow the qualitative 3D bedform development for each experiment. The x and y scales are 1:1 in order to accurately follow the development of each bed form. Changes in sand-bed slopes are discernable with reference to the colour bar. Changes in bedform height, or in elevation, are indicated by an increase or decrease in colour density. Changes in crest orientation, or 3D coalescence events of bed forms, are discernable.

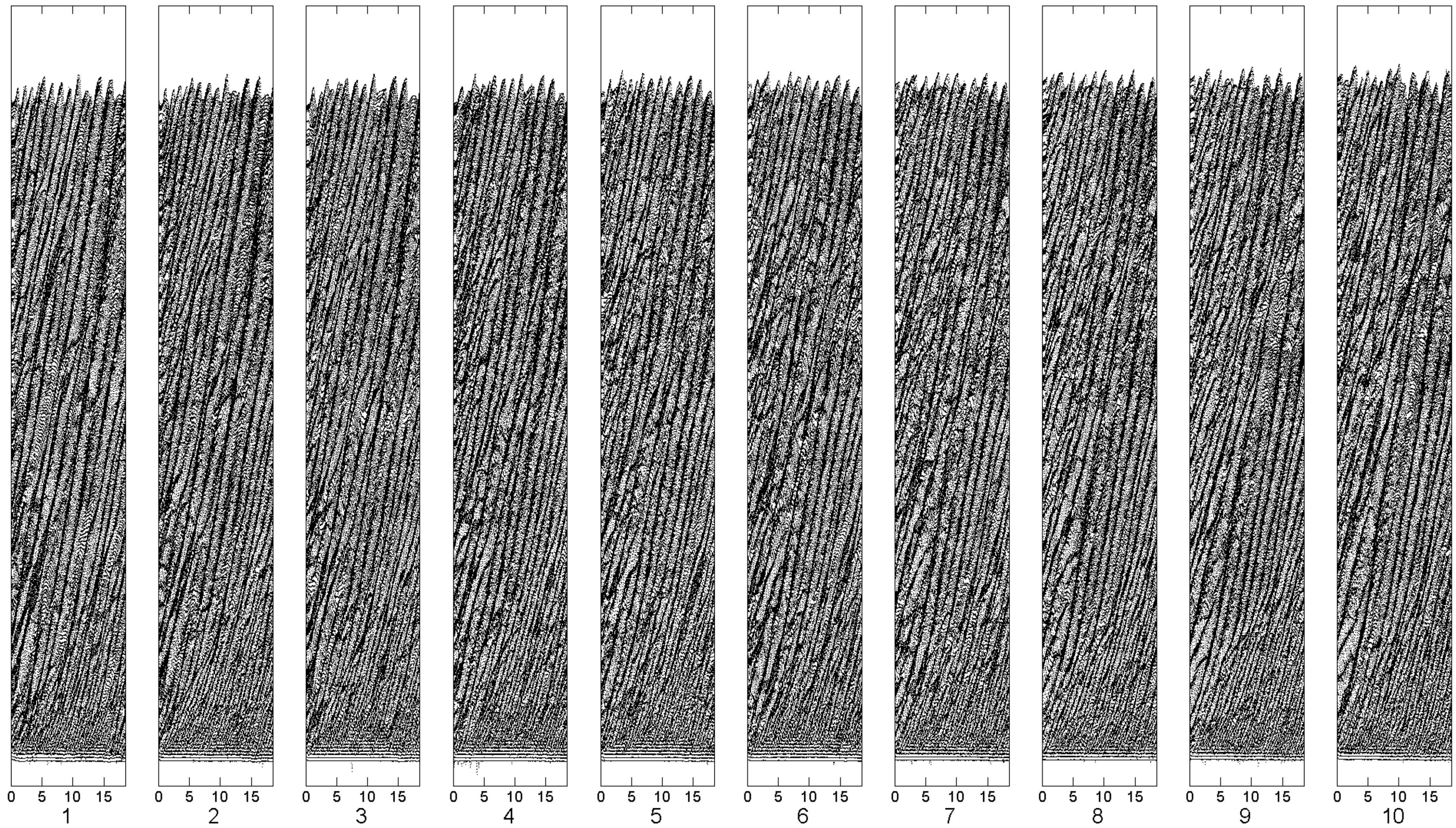

Figure 4 Longitudinal plots of wdc33a – bedform development duration is 412 minutes. x-axis shows profile number (1 to 10) and measurement distance along the flume in m (0 to 18.48-m). y-axis shows development over 412 minutes.

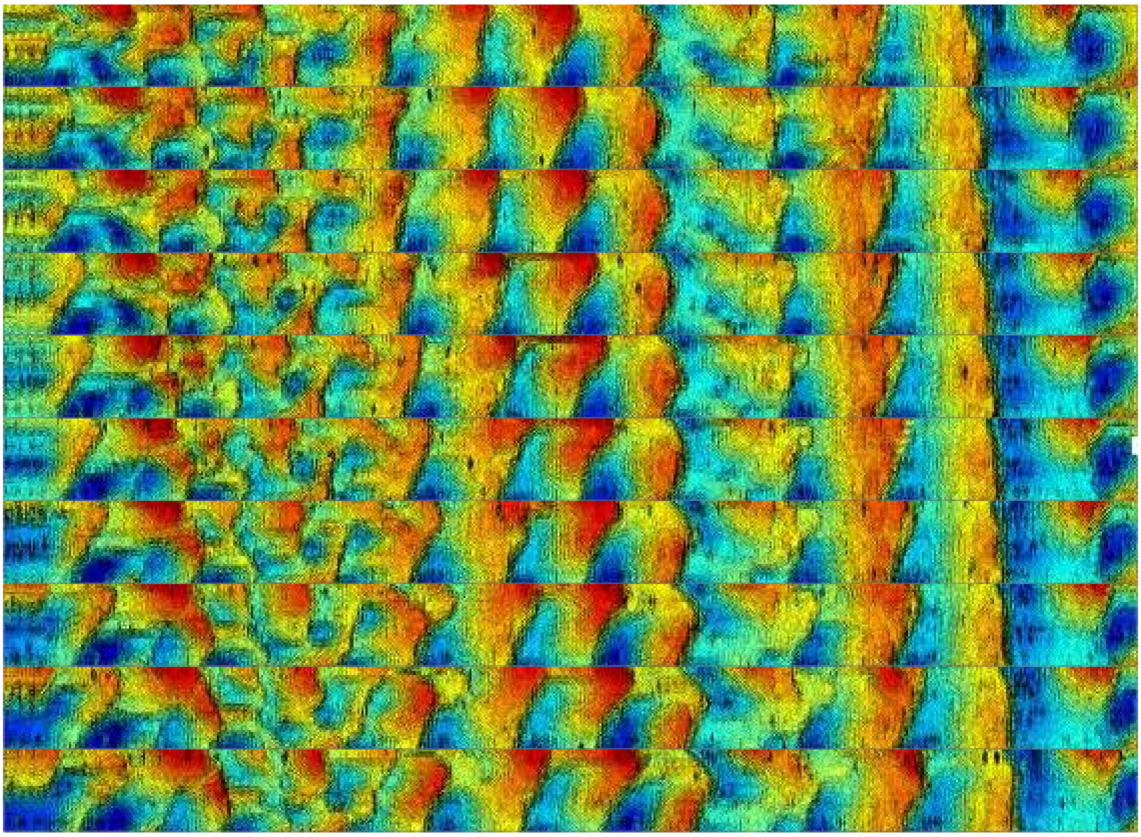

Figure 5 Developing bed-profile contour plots for wdc33a – minutes 394-412; profile every two minutes; flow from left to right; x=18.48-m; y=1.35-m; green=sand-bed level of flattened bed; red=crest; blue=trough.

The sweep contour plots can be used as the basis of pattern analysis. General trends displayed in the sweep contour plots are the increase in migration speed for faster flow velocities for each set of experiments with similar flume width to flow depth ratios. Similar to the longitudinal bedform development plots (Figure 4), the bedform height development can be compared for experiments with different flow depth values. An increase of bedform height is clearly identifiable with increase in flow depth. The most fascinating feature is the readily observable spatial evolution of bedforms along and across the flume.

5. RESULTS AND DISCUSSION

In Friedrich and Melville (2008) we identified processes such as merging, termination and defect migration during underwater bedform development. As the available data for this paper are more complex (in the spatial and temporal domains) only two figures are presented (Figure 6 and 7). These figures illustrate, and are used to discuss, the complexity involved in defining topographies of underwater bedforms. The figures show how underwater bedform topographies develop over time and how bedforms interact with each other. Observations are qualitatively described.

Depending on the conditions under which bedforms develop, such as sediment size and uniformity, ratio of flume width to flow depth and flow velocity, resulting topographical bedform complexity can vary even in a controlled flume environment. Although the presented contour plots for this paper are obtained for unidirectional flow experiments in a laboratory flume, the width of the flume (1.5-m), in particular, allowed the bedforms to adopt a complex pattern, generated through multiple interactions between bedforms along the measurement section.

Studying Figures 6 and 7 shows that feedback mechanisms between bedforms play a key role in the formation of the recorded bedform topographies.

Highlighted areas in Figure 6 show the formation of a channel, diagonally across the flume width, at the upstream section, and further downstream the termination of a crestline in order to allow the passing through of more sediment further downstream. Most interestingly, in the upstream section, the deposition area highlighted by the smaller circle, migrates rapidly towards the smaller deposition area at the perimeter of the bigger circle and both deposition areas unify during the channel development, therefore essentially reducing the local migration speed of the originally smaller deposition area. The formation of the channel suppresses immediate sediment transport downstream, shown by the minimal change of the neighbouring downstream bedform.

The highlighted area in the downstream section of Figure 6 shows a termination. Friedrich and Melville (2008) showed that terminations seem to be important in order for the bedform field to develop. Often a new termination later re-attaches with either a downstream or upstream crest, depending on its own sand volume, compared to the neighbouring crests. This scenario can be identified upstream of the highlighted new termination, where a termination attaches to the highlighted crestline.

Attention should be also drawn to the events 16-m along the measurement section in Figure 6 (non-highlighted). A saddle pattern exists originally, only to be terminated during the downstream development of a barchan-like shaped bedform.

The highlighted area in Figure 7 shows the termination of a downstream part (small ellipse) of a y-junction dune (big ellipse) and the following attachment to the neighbouring downstream dune. Due to the complexity of the bed-profile topographies and the limited space for this paper, other pattern changes, which can be identified in the figures, are not discussed.

6. CONCLUSION

Underwater bedform development and migration is influenced heavily by sediment availability and flow structures. Understanding underwater bedform evolution is difficult because the process is hidden from our eyes and the study of bedform topography is not necessarily seen as the most important one in sediment transport research. Often knowledge gained from 2D bedform analysis seems to be accepted as adequate.

Recently, Venditti et al. (2005) presented results from bedform development experiments undertaken in laboratory flumes, the results being focussed on plan-view footage of 3D bedform growth. Friedrich and Melville (2008) also obtained plan-view early underwater bedform development footage in a laboratory. Literature research showed that no other plan-view footage of underwater bedform growth exists. In regards to defining the topography of bedforms and, therefore, pattern changes during bedform development, conceptual models exist, but most are based on 2D analysis of temporal or spatial sand-bed elevation data sets. As Venditti et al. (2005) argued, coalescence theory originating from 2D bedform growth studies, can also resemble lateral crest realignment when viewed in 2D.

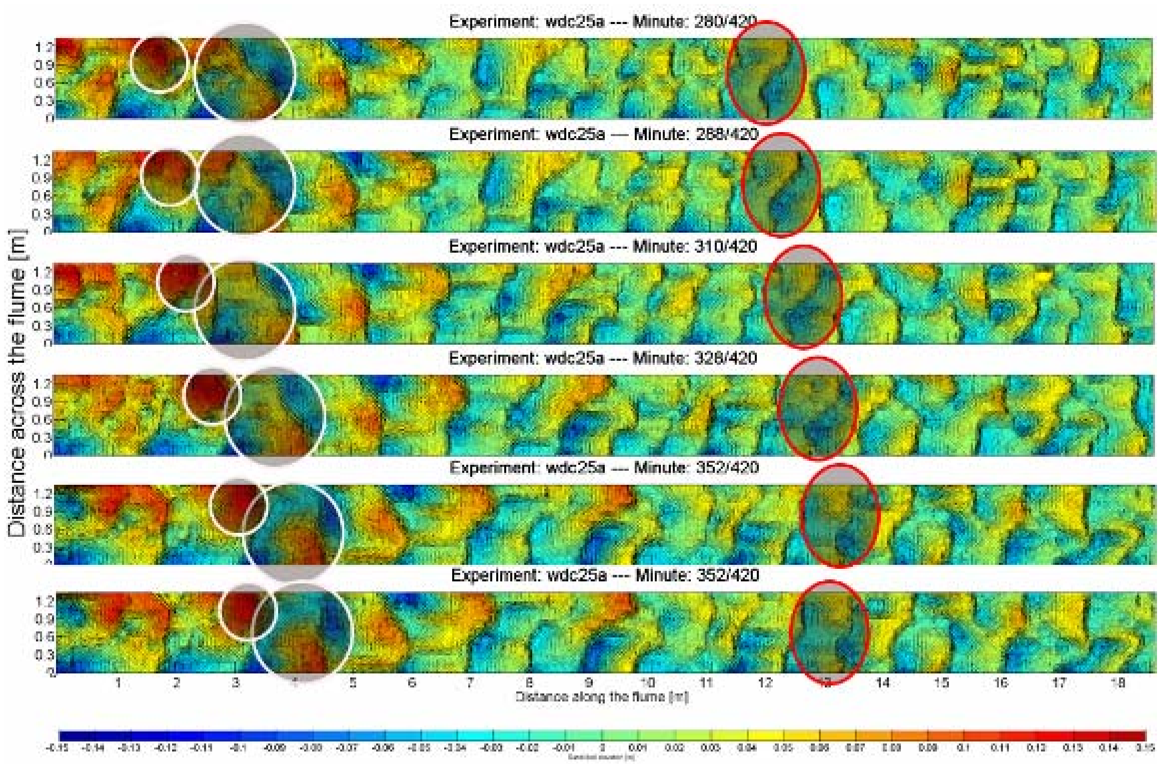

Figure 6 Dune development plot. Amongst other topographical changes, attention is drawn to a channel creation (circles) at the upstream end and a termination creation (ellipse) with increased downstream sediment deposition at the downstream side. Flow from left to right.

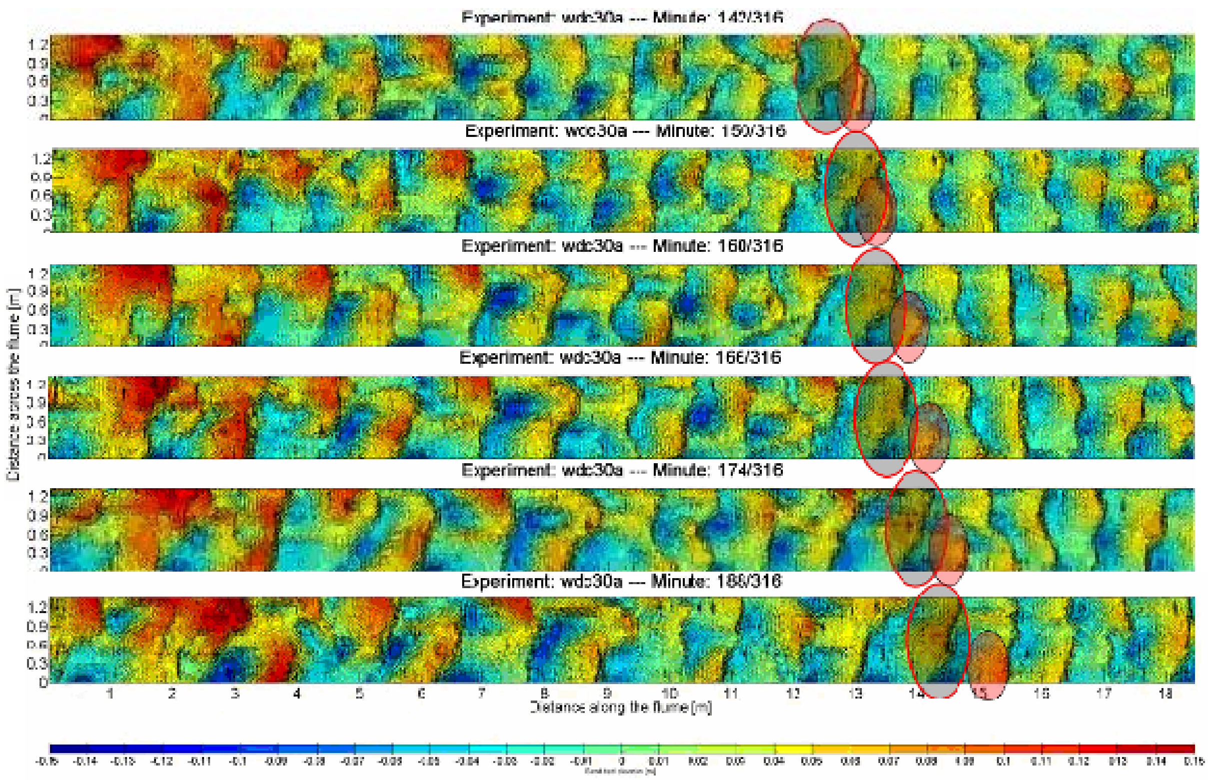

Figure 7 Dune development plot. Amongst other topographical changes, attention is drawn to the termination of a downstream part (small ellipse) of a y-junction dune (big ellipse) and the following attachment to the neighbouring downstream dune. Flow from left to right.

In this study, contour plots obtained with acoustic sensors are introduced and the use of these plots in regards to topography analysis discussed. We can conclude that contour plots of developing bedforms provide new insights into how individual bedforms interact with each other. The research is seen as an important step in improving 3D numerical simulations because it is necessary to know how bedforms interact with each other in certain environments. In future, improved sampling resolution would be advantageous in order to gain more insight into complex bedform patterns (multiple patterns spatially superposed).

It is hoped that this paper will help stimulate the study of underwater bedform topography by introducing examples of how to obtain 3D topography data as well as discussing examples of the topographical evolution. A comparison with aeolian dune research shows there is substantial potential for drawing useful parallels between underwater and aeolian dunes, exhibiting similar aspects of their patterns.

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