Sediment transport and bedform development in the lee of bars: Evidence from fixed- and partially-fixed bed experiments

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ABSTRACT: The co-existence, interaction, and repeated (re-)establishment of bars, dunes and ripples in natural channels is responsible for many important flow-form-flow dynamics. Small bedforms are constantly generated, superimposed on larger ones, particularly in zones affected by large-scale secondary circulation patterns produced by the larger bedforms. These superimposed bedforms migrate onto the downstream stoss slope of larger-scale forms where they i) generate additional form-roughness, ii) change sediment transport dynamics, iii) control bedform splitting and merging, iv) alter the geometry of the host lee slope, and v) change the resultant sedimentary structures. Our understanding of superimposed bedform development is derived from investigations of bedform development on flat beds in uniform flow and does not adequately describe bedform development in distinctly non-uniform flows and areas with large-scale secondary circulations.

In order to expand our understanding of bedform initiation, this paper presents fixed-bed and partially-fixed-bed experiments that investigate the effect of a host-bedform's separated flow on the development of smaller, secondary bedforms in its trough. The results show that: 1) scour in the trough of bars increases in depth and decreases in downstream length with increasing flow velocity over the crest; 2) the point of bedform initiation moves downstream and the amplitude of the incipient ripples decreases with increasing flow velocity; 3) crest-trough velocity gradients and coherence of the separated flows in the lee of ripples in bar troughs depend on their position relative to the separated flow of the larger-scale host bedform and tend to increase downstream.

These observations indicate that the development of secondary bedforms is hindered by the host bedform's separated flow and is also dependent on the length of the downstream stoss slope. The reduction of bedform amplification is attributed to the reduced strength and coherence of the separated flows in the lee of the secondary bedforms as a result of the stronger separated flow of the host bedform. Thus, this study presents a step towards a fuller understanding of bedform initiation and development in areas with complex topography and local variability in the flow field.

1 INTRODUCTION

Bedforms of different sizes and shapes co-exist and interact via a broad range of flow-form-flow feedback mechanisms that significantly affect many aspects of their natural environment, such as water depths, flow velocities, and the nature of preserved strata. Detailed knowledge of hydro-dynamic interactions is sparse and our overview of feedback mechanisms remains incomplete because of the extensive range of bed shapes, substrate characteristics, flow characteristics, and time-space scales that are possible. As a consequence of this natural diversity, research on fluvial morphodynamics faces two fundamental and opposing challenges: to expand our knowledge of diverse flow-form-flow feedback mechanisms, and, to quantitatively test the increasing number of known feedbacks in controlled and reproducible experiments over a broad range of conditions. This paper presents an experiment that reproduces bedform trough scour, and the initiation and amplification of secondary, or superimposed, bedforms within a narrow set of boundary conditions. Thus, the methods reproduce a very limited set of naturally occurring conditions but effectively isolate a limited range of processes for analysis, whilst simultaneously providing a template that is easily reproduced and modified for further research.

1.1 *Interaction of different scales of bedforms*

The coexistence of different types and sizes of bedforms is both the cause and effect of a broad range of important non-linear water-sediment dynamics in rivers, estuaries and coastal seas: the product of morphodynamic feedbacks (Bridge 2003). Distributions of sizes of bedform types (e.g. dunes) generally resemble log-normal or gamma-distributions that are skewed to the smaller forms (Paola & Borgman 1991; Leclair & Bridge 2001; Bridge 2003). This skewness implies that superimposition of bedforms is ubiquitous, and that interactions between forms are abundant because individual migration rates will vary according to bedform volume (Bridge, 2003). The lower limit of identifiable superimposed bedform sizes is often prescribed by the resolution of the measurements. High-resolution measurements have shown that millimetre-thin sediment waves on the backs of dunes are a fundamental mechanism by which bedload sediment moves over dunes, and therefore a primary mechanism for dune migration (Venditti et al, 2005a). Superimposed bedform dynamics enable dunes to grow and decay in response to changes in discharge and water depth (Kleinhans, 2002; Venditti et al. 2005b; Martin and Jerolmack, 2013). In particular, superimposed bedform generation is prerequisite to the splitting of bedforms that is needed to reduce bedform length (Raudkivi & Witte 1990; Gabel 1993; Coleman & Melville 1994; Warmink et al. 2013). As such, bedform superimposition is a fundamental mechanism by which dunes interact when they re-establish a (more) stable pattern (Venditti et al. 2005b; Kochurek et al. 2010).

Superimposition of bedforms changes the flow field by increasing bed roughness (Van Rijn, 1994) and by changing the spatial patterns of momentum exchange and energy dissipation within the flow (Bennett & Best 1995; Best, 2005). Superimposed bedforms that migrate across the host crest change the strength and geometry of the host's separated flow (Fernandez et al. 2005; Best, 2013). Passage of successive bedforms therefore causes systematic fluctuations in the separated flow of the host bedform. The superimposition of relatively large superimposed bedforms (approx. 25-30% of the host bedform height) causes reduction of the host bedform lee slope and the creation of reactivation surfaces. Both upstream trapping of bedload and active erosion of the host slope by the superimposed bedform's separated flow are responsible for the nature of such reactivation surfaces (McCabe & Jones 1977, Allen 1982; Collinson et al. 1980; Reesink & Bridge 2007, 2009, 2011). Bar-scale deposits commonly contain series of reactivation surfaces that are identified as stacks of inclined sets (Rubin & Hunter 1982; Haszeldine 1982) with thicknesses that exceed those of near-horizontal sets (Reesink & Bridge 2009, 2011). Such increased thicknesses are expected in areas of flow deceleration, where high aggradation rates and low migration rates enhance bedform preservation (Allen 1982; Rubin & Hunter, 1983; Paola and Borgman, 1991; Bridge 1997; Leclair and Bridge 2001; Reesink and Bridge 2009, 2011).

1.2 *What controls the existence of superimposed bedforms?*

As outlined above, bedform co-existence and superimposed bedform dynamics underpins many fundamental process dynamics. However, our understanding of the initiation of new bedforms in non-uniform flow conditions generated by larger bedforms is inferred from bedform development on flat beds (Raudkivi & Witte 1990; Coleman & Melville 1994; Baas, 1994). The existence of superimposed bedforms has been interpreted as an expression of disequilibrium between the dunes and an unsteady flow (Allen 1982), as an expression of the naturally occurring variability in dune size (Bridge 2003), and as an inherent characteristic of the re-establishment of a boundary layer on bedform stoss slopes (Rubin & McCulloch 1980). Together, these views provide a fairly coherent picture of the key controls on bedform superimposition. However, a critical assessment of their relative significance is prevented by a lack of understanding of the mechanics of superimposed bedform initiation, amplification, and dissipation. Rubin & McCulloch's (1980) hypothesis on the internal boundary layer has been used to support the comparison of superimposed-bedform development to development of bedforms on flat beds (Fernandez et al. 2005; Warmink et al. in press). However, the observed alteration of a host's separated flow by a superimposed bedform (Fernandez et al. 2005) ought be larger in the inverse: where a host's separated flow affects small bedforms in its trough. A logical hypothesis that follows this line of thought is that flow separation, which is considered essential to bedform growth, does not occur in the lee of small forms in the host reattachment zone. Thus, the locality of superimposed bedform initiation lies somewhere in the co-flow region (Jopling, 1961; Boersma et al. 1968), and is affected by the characteristics of the host's separated flow. At a larger scale, flume-like uniform flows, on which our current understanding of bedform stability is based, are highly unusual in natural channels. Non-uniform flows and secondary circulations are abundant in nature. Multiple scales of secondary circulation generated by large bedforms, bends, and tributaries are known to affect bedform stability. It is clear that gaps in our understanding of the mechanics of bedform interaction and superimposition undermine a broad range of qualitative and quantitative research on bedforms.

2 METHODS

In order to improve our understanding of bedform development in areas affected by secondary flows, this paper investigates the influence of the separated flow in the lee of a bar on the hydro-dynamics of ripples in its trough. A bar form and was made of plywood with 300 µm sand glued onto it to create a realistic roughness, with a height of 0.15 m and a lee slope of 30 degrees was installed in a 8 m long 0.3 m wide Armfield recirculating flume with an adjustable slope. The slope was set at such that the flow over the 2.2 m long, flat bar-top was uniform. Flow velocity was measured using a Nortek Vectrino II acoustic velocity profiler. The raw velocity measurements were filtered as outlined in Thomas et al. (2013). Bed elevations were measured after the water had been drained from the flume using a laser scanner mounted on a robotic traverse.

Two sets of experiments are presented here (Table 1) with: (1) a fixed 2D bar form with a mobile trough and; (2) a fixed 2D bar form with a fixed rippled trough. The first set of experiments reproduces the development of the scour and ripples in the trough of a fixed 2D bar from flat bed under different flow conditions. In each experiment, the flume was run until the deepest part of the trough scour was about 20 mm below the initial, flat bed level. The second set of experiments, with a fixed rippled trough, allows the comparison of ripple hydrodynamics between locations where they naturally exist and locations where they are ordinarily attenuated.

Table 1. Overview of the experiments presented in this paper

Experiment	Morphology		Boundary conditions	
	bar	trough	H_{crest} (m)	$\bar{U}$ (m/s)
Semi-mobile 1	fixed	300µm	0.1	0.6
Semi-mobile 1	fixed	300µm	0.1	0.7
Semi-mobile 1	fixed	300µm	0.1	0.8
Fixed with ripples	fixed	fixed	0.1	0.6

3 RESULTS

3.1 *Fixed bar with a mobile trough*

As flow velocities and sediment transport rates increased, the location where ripples develop in the trough (Figure 1, label S) was located further downstream. This downstream shift in the location of bedform development contrasts with the stable position of the trough (Figure 1, label T) and the maximum return-flow accumulation (Figure 1, label R). In addition to the shift in bedform development, amplification of the incipient ripples relative to the sediment transport and trough scour also decreased with increasing flow velocities.

The depth-length characteristics of the trough scour varied with flow velocity (Figure 1, label T). The scour in the trough of bars increased in depth and decreased in downstream length with increasing flow velocity. Near the re-attachment zone, the direction of sediment transport associated with distinct turbulent events is visually isotropic: with sediment displacement in all directions appearing equal in amount and distance. Conversely, in the co-flow zone, downstream-directed currents and shear visually cause sediment transport to become strongly anisotropic in its transport direction.

The maximum accumulation of the return flow (Figure 1, label R) is located at a distance away from the toe of the host lee slope. The decrease in sediment transport towards the toe of the host lee slope may be attributed to the decrease in transport by turbulent eddies hitting the bed in the reattachment zone, by the relatively weak current of the host's separated flow (a clockwise current in Figure 1), and by the potential development of an additional current in the corner where the lee slope joins the horizontal trough bed (a counter clockwise current in Figure 1). Notably, return-flow ripples that were migrating towards the host lee slope did not migrate onto the lee slope. Observations suggest that the separated flows in the lee of ripples migrating towards the host lee slope increase in strength as they approach the host lee slope. Instead of migrating onto the lee slope, return-flow ripple crests stay in place while aggradation continues. Note that no sediment was introduced into the system from the crest or slope of the bar. The reduced migration of ripples in the return flow in an area of ongoing deposition leads to the formation of climbing ripples strata that are, in most natural situations, eventually buried by the prograding bar lee slope. It is likely that cross-lamination formed by ripples climbing onto a bar lee slope (Basumalick et al. 1966; Reesink & Bridge 2011) are only possible in oblique currents.

3.2 *Fixed bar with a fixed rippled trough*

Informed by our first experiments, we installed fixed ripples between the reattachment zone where no ripples are found and the zone in the co-flow where ripples were found. Somewhat contrary to what might be expected, the geometries of the separated flows in the lee of the ripples were comparable for all but one ripple (Figure 2B-G, left column). Thus, the geometry of the time-averaged separated flow cells does not appear to correlate with observations of ripple development. The only significant exception in the ripples' separated flow volumes is that of the second ripple (label C), located directly downstream from the reattachment point, which had a separated flow with a reduced volume. The ripple nearest the bar and the reattachment point (Label B) had a stronger return-flow compared to the other ripples. Here, the ripple crest likely provides more sheltering from downstream-directed currents in comparison to upstream-directed currents, which increases the magnitude of the time-averaged return-flow in the lee of the ripple. Return-flow currents had very low velocities (exceeding -0.03 m/s) and are expected to be near or below the threshold for motion. However, the contrast between the separated flows and the current over the crest did significantly increase between successive ripples. Since sediment deposition depends on the spatial gradient of velocity, such an increased velocity contrast is a likely driver of bedform amplification. Observations of sediment transport motion indicated that turbulence and sediment transport (an-) isotropy change dramatically between the reattachment zone and the co-flow where ripples form. The directionality of the sediment transport is visualised here by the coherence in the directionality of the flow (Figure 2B-G, right column). The measurements show that the directionality in the reattachment zone is split evenly (≈ 0.5), and that the flow recovers gradually over successive ripples. Thus, bedform development depends strongly on gradients of flow velocity and sediment transport, which require the current to be coherent in its direction.

4 DISCUSSION

4.1 *Scour and deposition in bar troughs*

The geometry of the separated flow has proven relatively stable for a range of velocities given a fixed bedform geometry (Paarlberg et al. 2007; Unsworth 2013). The results of this investigation show that the maximum depth of trough scours and return-flow accumulations did not vary with flow velocity. The stable position of these maxima can therefore be attributed to the relatively stable geometry of the return-flow, as opposed to its velocity characteristics. The return-flow accumulation did not attach to, or merge with, the host lee slope. This observation complicates traditional views (e.g. Jopling 1961, Allen 1982) in which tangential strata can be generated by significant sediment transport to the host lee slope by the return-flow current. Such tangential strata are more likely a product of oblique flows (Reesink & Bridge 2011).

4.2 *Return-flow accumulation*

In contrast to the stable positions of the trough and return-flow accumulation, the width-depth characteristics of the trough and the location of bedform initiation did vary with flow velocity. In the case of trough shape, morphological change depends directly on sediment transport, and hence on the magnitude of (excess) shear stresses relative to the threshold for motion (Van Rijn, 1994). Thus, the results suggests that an increase in velocity over the bar crest increases the erosivity of the reattaching flow, which locally increases scour and creates a narrow, deep trough. Decreased velocity over the crest is then associated with a decrease in the erosivity of the reattaching flow and a relatively larger role of sediment transport by coherent flow structures that sweep sediment across over a larger area.

4.3 *Isotropy and diffusion in sediment transport*

The observations in these experiments highlight how the nature of sediment transport changes from isotropic sediment motion in the reattachment zone, to distinctly anisotropic bursts and sweeps in the co-flow zone. This simple observation on changes in the directionality of erosion, transport, and deposition implies that sediment diffusion varies across bedforms and notably so in areas affected by secondary currents. The nature of the transition from isotropic to anisotropic sediment dispersion between the trough and stoss slope has a potential role in controlling the three-dimensionality of dune forms.

4.4 *Amplification of bedforms in secondary flows*

The fixed bed experiment indicates that turbulent fluctuations in flow direction may play a role in reducing the coherence of the separated flows in the lee of the ripples. No clear trends were found that correlate the geometry of the separated flows in the lee of ripples directly to bedform amplification. However, distinct changes were observed in the velocity gradients between the crests and troughs and in the coherence in flow direction (Figure 2). These results suggest that turbulent fluctuations reduce bedform stability by reducing the coherence of the separated flows in the lee of the bedforms, whereas downstream-directed shear increases bedform stability. Thus, at the scale of secondary bedforms, sediment transport gradients and directional coherence are important for bedform amplification.

The partially-mobile bed experiments (Figure 1) show that the distance to the point of secondary bedform initiation increases with increasing velocity. Although the host bar geometry was fixed, the change in bedform development implies that, at the host bedform scale, the amplification of superimposed bedforms depends on the relative magnitudes of bedform length (given a fixed height) and the velocity over the crest.

The reduction of the separated flows in the lee of the ripples due to the larger-scale secondary flow patterns also provides some insights into larger-scale interactions of bedforms. For example, the reductions in dune size that are common in meander bends could be a partial consequence of the effect of the down-welling helical flow on the separated flows in the lee of the dunes. However, the actual magnitude of separated flow modification by larger-scale secondary currents remains to be fully quantified.

5 CONCLUSIONS

A series of simple, adaptable, and easily reproducible experiments were conducted with i) a fixed bar and a mobile trough, and ii) a fixed bar with fixed ripples in its trough. The fixed bar with mobile trough experiments show that the distance between the crest and the point of bedform initiation increases with flow velocity. This suggests that bedform superimposition occurs when host bedforms are long in comparison to the velocity over the crest. Observations indicate a change from isotropic sediment transport in the reattachment zone, where sediment transport is equal in all directions, to anisotropic transport in the co-flow areas, is a key mechanism in controlling bedform dimensionality. The experiments with a fixed bar and fixed ripples in its trough, placed in the reattachment zone into the co-flow area, where ripples are formed in the mobile-bed experiments, show that most geometries of the separated flows in the lee of the ripples are reasonably similar. Flow velocity measurements over successive ripples indicate that bedform amplification is more likely controlled by the downstream-increasing velocity gradients between crests and troughs of the smaller bedforms, and downstream increasing coherence in the direction of flow and sediment transport. Turbulent fluctuations in flow velocity and flow direction are also a likely cause of bedform dissipation. Thus, this study presents a step towards a fuller understanding of bedform initiation and development in areas where complex topography generates secondary circulations, coherent flow patterns, and enhanced turbulence.

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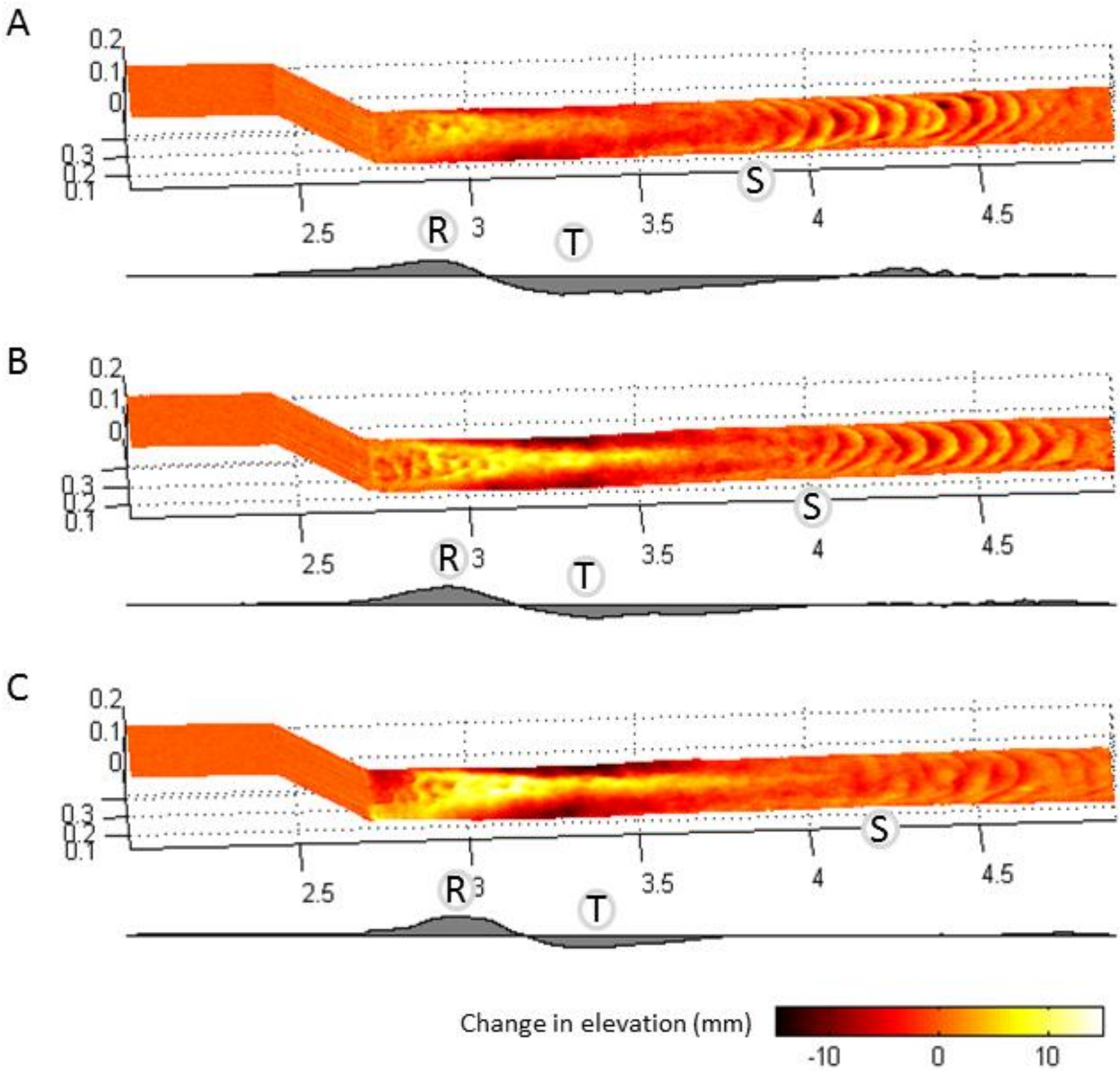

Figure 1: Digital Elevation Models (axis in metres, elevation contours in millimeters) of three experimental runs with a fixed bar, mobile trough, and flow velocities over the crest of approximately (A) 0.6, (B) 0.7, and (C) 0.8 m/s. The DEM's are coloured by the amount of deposition (in mm). The grey profiles visualise the 0.3 x 0.3 m average scour and deposition relative to the initial horizontal bed. Note the difference in trough shapes. S denotes the visible start of the co-flow ripple formation, which varies between the runs, T is the trough, R is the maximum return-flow accumulation.

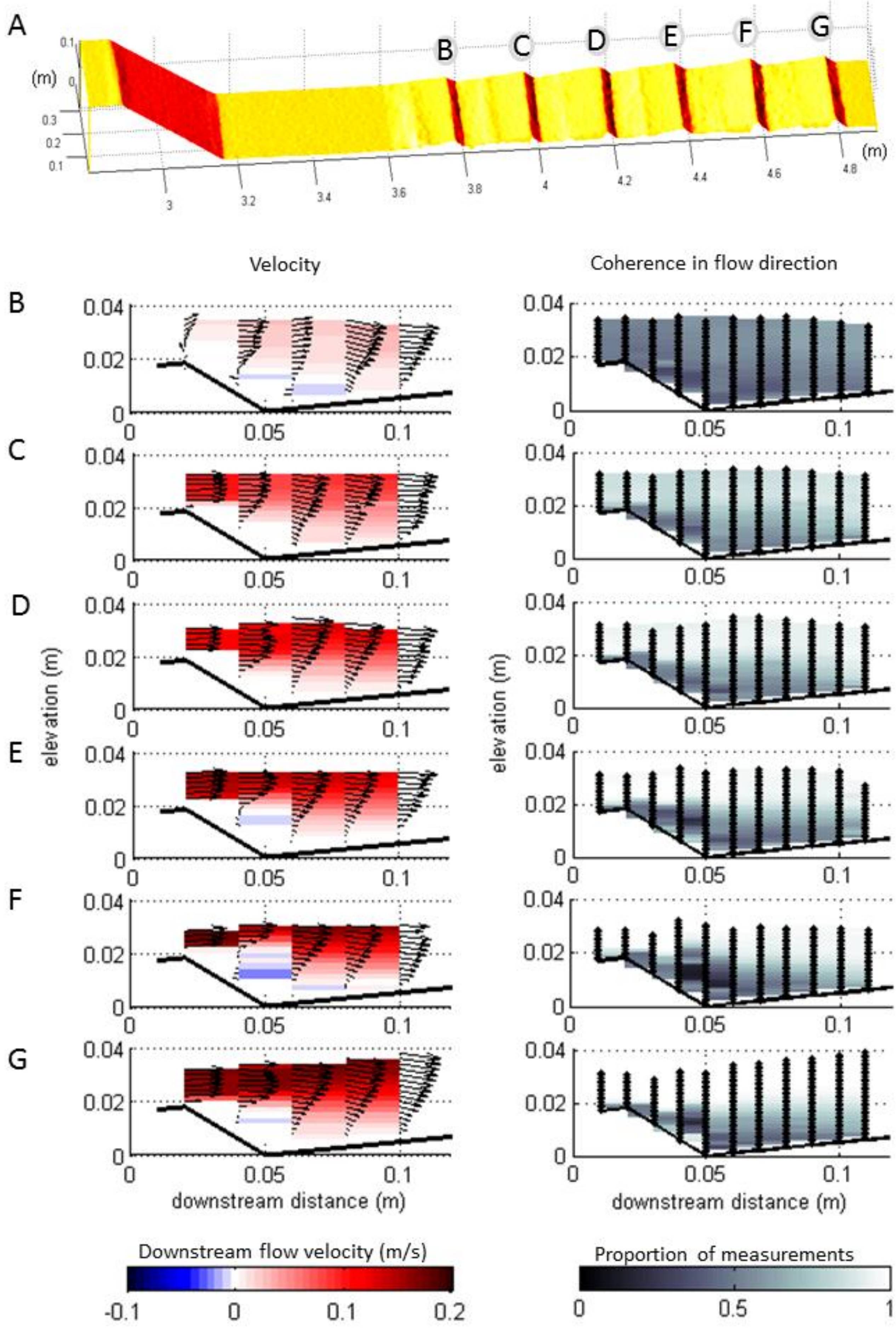

Figure 2: Fixed bar with fixed ripples placed in the reattachment zone, where ripple development is normally suppressed, of the co-flow zone where ripples formed in the mobile bed experiments. Figures B-G are flow profiles over the crests and troughs of the successive ripples and represent the velocity profiles (left column, coloured by downstream velocity) and the coherence in current direction (proportion of velocities directed downstream).