The response of bedforms and bed elevation to sudden hydrodynamics changes

H. Hu *University of Hull, Hull, UK – H.Hu@2014.hull.ac.uk*
D.R. Parsons *University of Hull, Hull, UK*
A. Ockelford *University of Hull, Hull, UK*
R.J. Hardy *Durham University, Durham, UK*
P.J. Ashworth *University of Brighton, Brighton, UK*
J. Best *University of Illinois Urbana- Champaign, USA*

ABSTRACT: Investigations of bedform generation and development has mostly been conducted under steady flow conditions. However, all fluvial and estuarine environments exhibit temporal variations in flow discharge, creating unsteadiness in flow-sediment transport interactions. The research presented here investigates how bedforms develop under changes in hydrodynamics, and discusses the impact which induces the unexpected development. The results confirm the effect of water depth and velocity on equilibrium bedform height under steady flow, and also highlights the importance of bed elevation adaptions in reaching equilibrium after hydraulic condition variation. The rate of bed elevation variation plays a significant role on bedform generation and development: the higher the flow velocity is, the greater inhibiting effect the bedforms suffers. These Findings provide a specific findings and enrich our comprehension of bedform generation and development under sudden hydraulic condition jumps.

1. INTRODUCTION

The majority of our systematic research on bedforms is based on steady uniform flows in controlled flume experiments. However, all fluvial and estuarine environments exhibit temporal variations in flow discharge, which creates unsteady changes in the flow field. Previous research on dunes under unsteady flow conditions [*Raudkivi*, 1966; *Raudkivi and Witte*, 1990; *Dalrymple and Rhodes*, 1995; *Julien and Klaassen*, 1995; *Yen and Lee*, 1995; *Carling et al.*, 2000a; *Carling et al.*, 2000b; *Hendershot*, 2014] focused primarily on field observations, and fundamental questions about the interactions between morphology, hydrodynamics and sediment transport remain unresolved and there is no universal explanation for the development and response of bedforms to unsteady flows [*Best*, 2005; *Venditti*, 2013].

Rapid changes in hydraulic conditions is an extreme condition in the field, and has rarely been investigated [*Wijbenga and Klaassent*, 2009]. This research aims to investigate how bedforms develop and sediment transport processes respond to sudden changes in water depth or flow velocity in a set of laboratory experiments.

2. METHODS

Two series of mobile sand bed experiments were undertaken in the TES Flume Facility at the University of Hull. The TES is a large recirculating flume which was configured as a 1.6 m wide and 10 m long channel. The bed material sediment used herein was medium sand with $D_{50} = 400\ \mu m$.

Table1. List of experimental conditions of the six basic states (Series 1)

Depth (m) Velocity (m/s)	0.2 m	0.4 m
0.6 m/s	State 1	State 4
0.75 m/s	State 2	State 5
0.9 m/s	State 3	State 6

In series 1 (Table 1), six basic states were set to run over 6 hours to meet equilibrium conditions, which would provide preliminary views of these six different hydraulic conditions. Additionally, based on the bedform phase diagram of *Southard and Boguchwal* [1990], the six states all locate at the area where dunes should be generated (Figure 1).

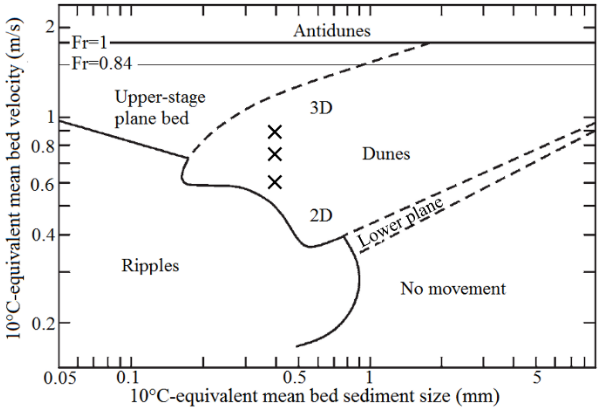

Figure 1. Hydraulic conditions in the bedform phase diagram (after Southard and Boguchwal, 1990).

In series 2, five different hydraulic condition changes were run. For Run 7, 8 and 9, water depth (h) changes from 0.2 to 0.4 m, with velocity keeping constant, while for Run 10 and 11, velocity (U) increase from 0.6 to 0.9 m/s, but water depth remained unchanged. All of the first stage (the first 6 hours) of the five experiments in Series 2 can be treated as basic state runs (Figure 3), as they start from a flat bed, followed by a continuous six hours running to reach equilibrium before the hydraulic conditions were altered again.

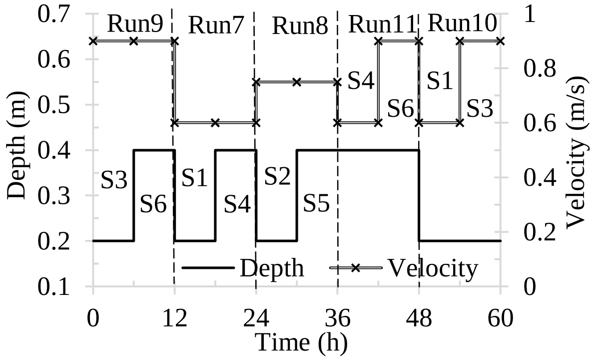

Figure 2. Summary of Series 2. The time here indicates the order of these experiments carried out.

A series of 12 ultrasonic sensors (URS) perpendicular to the main flow were set and used to continuously measure a 4.5m long and 0.6m wide swathe in the middle of the channel. Meanwhile, a set of four Acoustic Doppler Velocimeters (ADV) and one Vectrino ADV profiler were used to quantify the three-dimensional flow velocities. An Acoustic Backscatter Sensor (ABS) system, which was used to quantify suspended sediment dynamics, was set up downstream of the end of URS measurement area.

3. RESULTS

3.1. Six steady states

3.1.1. Variation between experiments with same water depth

From the first stages of Figure 3a-c ($h = 0.2\ m$), it is clear that with the increase of flow velocity from 0.6 to 0.9 m/s, the equilibrium bedform height (H_e) increased from nearly 4 cm to 5.8 cm. Similarly, the red dashed lines of Figure 3a-c, which present Run 4 to 6 ($h = 0.4m$), respectively, show how H_e rises from 4 to nearly 8 cm.

Both of the hydraulic conditions of the first stage of Run 7 (Figure 3a) and Run 10 (Figure 3d) are the same (0.6 m/s flow velocity and 0.2 m water depth), but the processes of the bedform generation and development are different. For the former experiment, the bedform height (H) rises from 2.5 to 4.5 cm within 30 minutes, and reaches equilibrium immediately, while for the latter, H grows from 2.5 to 7 cm within 30 minutes, followed by a decrease to reach equilibrium ($H = 4\ cm$) in 150 minutes. Additionally, both the first stage of Run 8 and Run 9 displays an increase-decrease-equilibrium trend, but the time for reaching equilibrium, which is 100 and 70 minutes respectively, shows a negative relationship with flow velocity. Nevertheless, for the three experiments with a 0.4m water depth (red lines in Figure 3a-c), the increase-decrease-equilibrium trend for H is not evident, and all of the bedform heights in these three experiments attain equilibrium at the very beginning of each experiment.

For experiments with different flow velocities (Figure 3a-c), the processes of bed elevation display somewhat different results. For $h = 0.2\ m$, the processes of the bed elevation of Run 7 and 10 (i.e. state 1) decrease from nearly 3 to -2 cm during the whole six hours, while those of Run 8 and 9 drop to -2 cm at 180 and 100 minutes respectively, and then keep approximately constant. However, the variations of bed elevation for $h = 0.4\ m$ present different trends that both that of Run 7 and Run 8 displays a slight fluctuation along 3 cm during the whole 6 hours, while that of Run 9 increases dramatically from 1 to 6 cm within 30 minutes, followed by a large fluctuation along 6 cm.

Additionally, from Figure 3, it is evident that, the higher velocity the experiments has, larger and more vigorous fluctuations in TKE.

3.1.2. Variation between experiments with the same flow velocity

For experiments with the same velocity but different water depth, H_e is higher in larger water depths, except those with lowest velocity ($U = 0.6\ m/s$) whose H_e remains unchanged (Figure 3).

3.2. Sudden hydraulic condition changes

Figure 3d and e show the results of sudden velocity chang from 0.6 to 0.9 m/s with water depth 0.2 and 0.4m respectively. In terms of Run 10 (Figure 3d), the initial bed condition of its latter half part (i.e. stage 2) is generated by state 1 which has already developed bedforms, while for Run 3, it starts from flat bed. The sudden change of velocity (Run10) does not affect H_e and it reaches equilibrium rapidly like Run 3, as well. Moreover, both of their bed elevations are about -1.5 cm at equilibrium. The initial bed elevation for the second stage of Run 10 is nearly -2 cm, while that of Run 3 is nearly 4 cm, and it takes 110 minutes to reach equilibrium. However, the variation of TKE does not display a clear trend corresponding to that of bedform height and bed elevation, except that the TKE of Run 3 is generally smaller in magnitude.

Interestingly, for Run 11, the sudden enhancement of velocity does not rise bedform height, instead vanishing to a very low level. Besides, unlike run 6, the bed elevation of stage 2 of Run 11 remains constant, and the fluctuations of TKE are also more intense.

4. DISCUSSIONS

Bedform height prediction is one of the main scientific questions which has been thoroughly investigated during the past 50 years, but remains unsolved [*Fredsoe*, 1982; *Van Rijn*, 1984; *Yalin*, 2013]. As it is well known, equilibrium bedform height under steady flow is related to water depth, particle size and flow velocity [*Van Rijn*, 1993] and more recently, clay content [*Schindler et al.*, 2015]. However, our experiments confirm the effect of water depth and velocity, and reflect the importance of bed elevation adaption to equilibrium bedform height for sudden hydraulic condition changes, as well. For our experiments, the sediment is water worked and circularly recirculated. Therefore, the whole system can be regarded as sediment supply limited.

For the lowest velocity run (Run 7), the rate of bed elevation increase is slight, and H_e is not affected. In contrast, for higher velocities (Run 8 and 9), the quicker adaptation of bed elevation apparently influences the generation and development of bedforms. This may be because, the sudden change of water depth (and discharge) alters the mechanisms of sediment transport, such as the ratio of suspended to bedload transport rate and the influence of sediment supplement. This assumption will be verified by data of ABS in further research.

5. CONCLUSIONS

Our experiments confirm the effect of water depth and velocity to equilibrium bedform height under steady flow, and indicates the importance of bed elevation adaption to reach equilibrium, as well.

The results show that:

1. For hydraulic condition with lower velocities, the sudden water depth change induces bed elevation’s automatic adaption, but the slight rate of increase has little or no effect on bedform development.
2. For hydraulic condition with higher velocities (i.e. discharge), the sudden increase of water depth leads to faster growth of bed elevation, which forbids the development of larger bedforms. After the bed elevation reaches equilibrium, the velocity plays a significant role on the development of bedforms. It may attribute to different mechanisms of sediment transport, which will be further investigated by the data of ABS.

These results give a specific point of view on bedform generation and development under unsteady flow, and can be used to improve numerical models.

6. ACKNOWLEDGMENT

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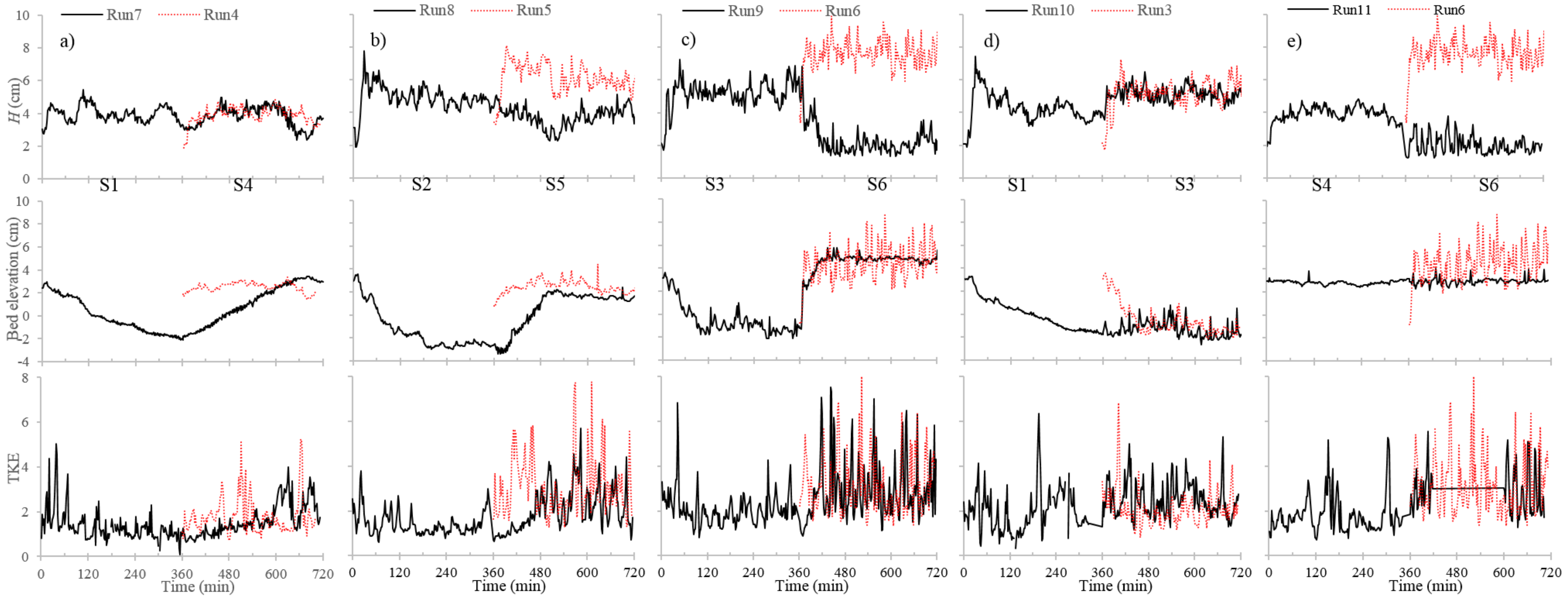

Figure 3. Changes in dune height, derived from the bed profiles using Van der Mark et al. (2008), bed elevation (set at the same datum) and Turbulence Kinetic Energy (TKE, calculated from the lowest ADV, 5 cm above the initial bed): a) Run 7 compared with Run 4; b) Run 8 compared with Run 5; c) Run 9 (i.e. Exp9) compared with Run 6; d) Run 10 compared with Run 3; e) Run 11 compared with Run 6. Notably, the data of ADV was lost between 420 and 600 min, and has been replaced with a straight line; S1-6 denote State 1 to 6.