Bedform development and morphodynamics in mixed cohesive sediment substrates: the importance of winnowing and flocculation

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ABSTRACT: There remains a lack of process-based knowledge of sediment dynamics within flows over bedforms generated in complex mixtures of cohesionless sand and biologically-active cohesive muds. The work presented here forms a part of the UK NERC "COHesive BEDforms (COHBED)" project which aims to fill this gap in knowledge. Herein results from a set of large-scale laboratory experiments, conducted using mixtures of non-cohesive sands, cohesive muds and Xanthan gum (as a proxy for the biological stickiness of Extracellular Polymeric Substances (EPS)) are presented. The results indicate the significance of biological-active cohesive sediments in controlling winnowing rates and flocculation dynamics, which contributes significantly to rates of bedform evolution.

1. INTRODUCTION

Understanding and quantifying sediment dynamics within flows over bedforms generated in complex mixtures of cohesionless sand and biologically-active cohesive muds, is a key to parameterizing physical processes in natural estuarine systems. Such processes ultimately control morphodynamics at local and regional scales (French, 2010). Moreover, understanding sediment movement is also significant for monitoring water quality, fate of pollutants, and even for the success of coastal dredging operations (Rao et al., 2011). Fine sediments, which commonly exist in natural estuarine flow systems and are composed of fine silts and clays, with biological agents that have cohesive properties that modulate the complex interactions between flow, sediment transport and morphological evolution (Baas and Best, 2008). In morphodynamic investigations, the properties and influence of the substrate has largely been ignored but can significantly impinge on the behaviour and dynamics of sediment transport, which ultimately influences and interacts with the form and the size of bedforms.

2. METHODS

2.1. Flume and substrates

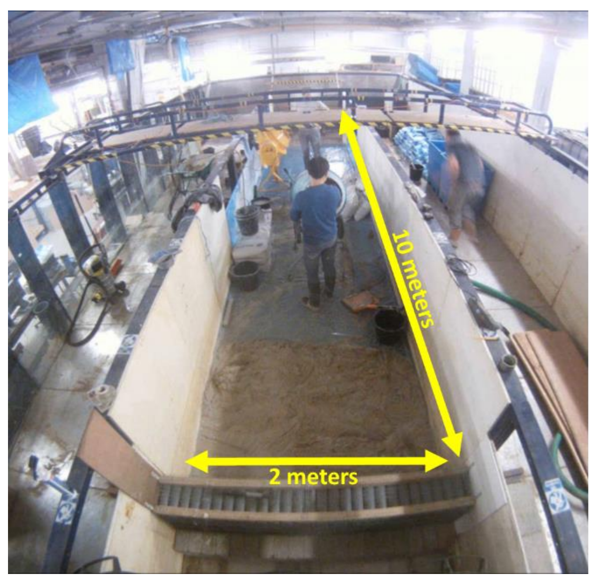

Fig.1. Flume lab set-up

Experiments were undertaken at the University of Hull's Total Environment Simulator flume/wave tank facility (Fig.1). The tank was a recalculating flume channel, 10 m long and 2 m wide, and filled with homogeneously mixed substrata with varying ratios of sand, clay and EPS (Xanthan gum was used as a proxy for EPS found in natural sediment (e.g. Tolhurst et al.,2002)). Flow depth was set at d = 0.38 m. Depth-mean flow velocity (U) over the initial flat bed set to a zero slope was 0.80 m/s, yielding a Froude number Fr = $U/(gd)^{0.5}$ = 0.40 and a Reynolds number Re = Ud/n = 212,000, where g is the acceleration due to gravity and n is the kinematic viscosity. The salinity was 15–17 PSU, approximating estuarine conditions, and temperature was kept as constant as possible, varying between 16 and 19 °C. A total of 14 experimental runs were performed that included a series with mixed substrata of (1) fine sand with a median diameter, D50, of 239 μm and kaolin clay with a D50 of 3.4μm in run A1 to run A6, and (2) varying ratios of fine sand, clay and EPS in run B series (B1-3, three runs with low EPS % and various clay %) and run C series (C1-3, high EPS % and various clay. Three series of experimental runs were conducted. Run A1 to A6 (section 1) and run B1 to 3, and C1 to C3 (section 2), were prepared by incrementally increasing initial substratum mud (kaolin clay) content respectively (1.9 % < m < 14.1 % in section 1 runs and 2.8 % < m < 17.7 % in section 2 runs, both in dry weight). The detailed percentages of clay and EPS in initial bed of each run is shown in fig.2).

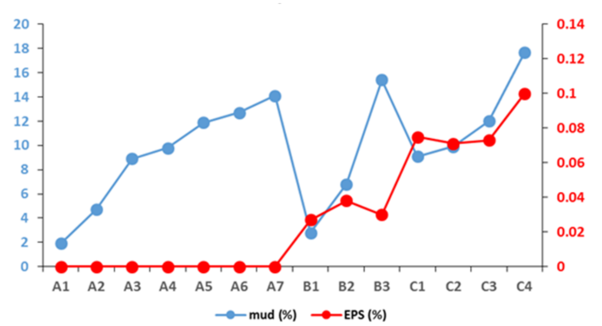

Fig.2. The percentages of clay and EPS in initial substrates of each experimental runs.

2.1. Instrument settings

Various instruments were set to collect bedform, suspension and flow properties. Bed topography of each run was measured with ultrasonic probes driven by and automatic traverse across a swathe of the channel bed during and at the end of each experiment. Suspended sediment dynamics were measured through: (1) ABS (Acoustic backscatter profiling sensors) that obtains profiles at 1, 2 and 4 MHz (throughout all runs); (2) vertically spaced OBS (Optical backscatter point sensor); (3) LISST-100X (bulk samples taken every 30 mins of each run); (4) physical water samples used for both gravimetrically derived suspended sediment concentrations and grain size distributions (every 30 mins of each run). Water samples also were analyzed using LabSFLOC (e.g. Manning et al., 2002) every half an hour for selected runs, facilitating the measurement of the size, settling velocities and thus densities of suspended particulates and flocs. Consequently, the effects of varying suspended sands, clays and EPS on flocculation were monitored throughout each run. Flow velocity was monitored by four vertically-stacked 10 MHz Acoustic Doppler Velocimeters (ADVs), located close to the flume centreline, at an acquisition rate of 25 Hz throughout each experiment run.

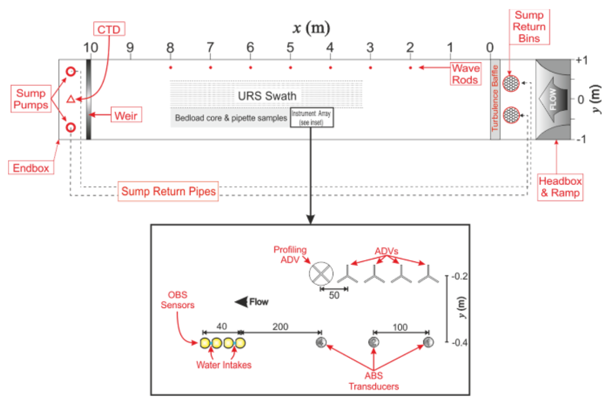

Fig.3. Instruments settings in the experimental flume channel

3. RESULTS

3.1. Bedform morphology

The experimental results reveals that higher mud fraction in initial bed leads to slower bedform growth and larger bedform size. The existence of EPS in the initial bed results in a significantly more stable bed and a dramatic reduction in bedform size. At very high concentrations the bed remains flat with no bedforms generated.

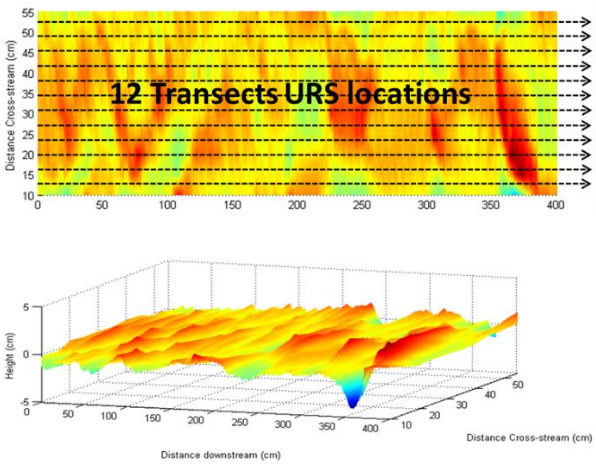

Fig.4. 3D bedform rendering example

3.2. Flow turbulence

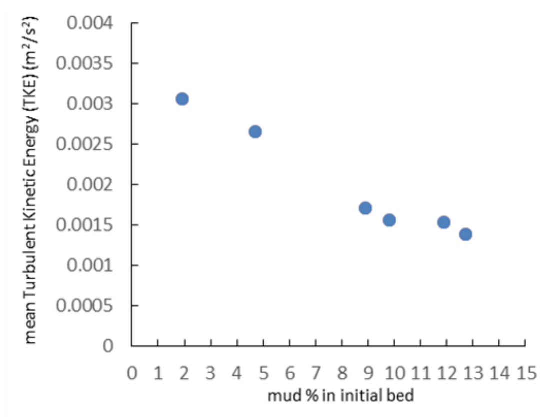

Fig.5. The relationship between Turbulence Kinetic Energy (TKE).

The results of near-bed turbulence kinetic energy (TKE) (Figure 5), which were obtained from the ADV data shows strong correlation with mud.

3.3. Flocculation and winnowing efficiency

The LabSFLOC camera results indicate both mud and EPS fractions in initial bed can form flocculation in the flow and the existence of EPS component in initial bed significantly increases floc size and slows down the mean settling velocity of the grains as a result(Fig.6. a & b).

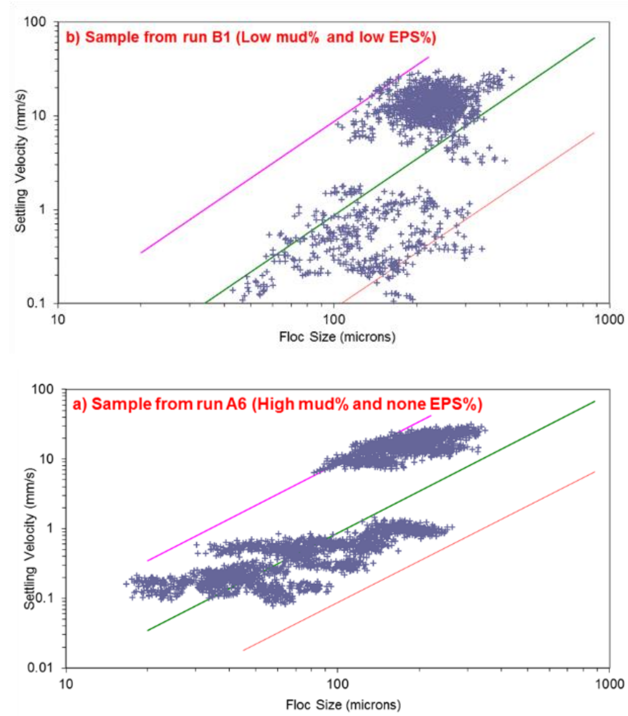

Fig.6. Typical floc samples analysis of typical sand-mud run A6 and sand-mud-EPS run B1, using LabSFLOC floc camera (A.J. Manning, 2006)

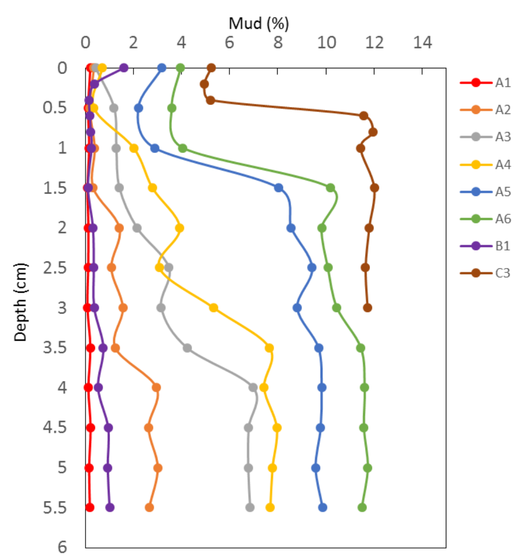

Fig.7. Mud percentages in depth of selected bedform crest of some experimental runs.

Winnowing occurs when fine sediments are systematically removed from the bed over time. Particle size analysis taken through substrates using small push cores taken at the end of the experiments indicate that existence of mud and EPS in bed surface both decreases the rate at which fine sediments winnow from bed, this is especially so for high EPS fractions that stabilize the bed significantly (Fig.7).

4. CONCLUSIONS

Both clay and EPS fractions in the initial bed conditions have a significant influence on the sediment transport over mobile beds. Higher clay and EPS fractions in substrates decrease bedform size, increase bedform evolution time and generally impedes the development of bedforms.

Winnowing and flocculation occur commonly in any flow condition with cohesive substrates (mud or EPS). Mud and EPS fractions in the initial bed decreases the winnowing efficiency, enhances the floc size and thus effect the grain settling velocity of the suspended material.

EPS has a higher efficiency in stabilizing the bed and enhancing the flocculation than clay alone, which highlights the necessity of including biological factors in sedimentological research in estuaries and coastal seas, particularly when considering morphodynamic rates of adjustment.

5. ACKNOWLEDGMENT

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