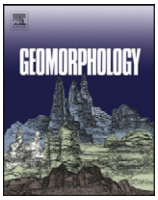
Geomorphology 182 (2013) 19–32

Contents lists available at SciVerse ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph



Bedform development in mixed sand–mud: The contrasting role of cohesive forces in flow and bed

Jaco H. Baas *, Alan G. Davies, Jonathan Malarkey

School of Ocean Sciences, Bangor University, Menai Bridge, Isle of Anglesey, LL59 5AB, Wales, United Kingdom

ARTICLE INFO

Article history:
Received 2 June 2012
Received in revised form 19 October 2012
Accepted 22 October 2012
Available online 1 November 2012

Keywords:
Flume experiments
Sedimentary bedforms
Mixed sand–mud
Clay
Cohesion
Winnowing

ABSTRACT

The majority of subaqueous sediment on Earth consists of mixtures of cohesive clay and cohesionless sand and silt, but the role of cohesion on the development and stability of sedimentary bedforms is poorly understood. The results of new laboratory flume experiments on bedform development in cohesive, mixed sand–mud beds are compared with the results of previous experiments in which cohesive forces in high concentration clay flows dominated bedform development. Even though both series of mixed sand–mud experiments were conducted at similar flow velocities, the textural and structural properties of the bedforms were sufficiently different to permit the designation of key criteria for identifying bedform generation under cohesive flows against bedform generation on cohesive substrates. These criteria are essential for improving bedform size predictions in sediment transport modelling in modern sedimentary environments and for the reconstruction of depositional processes in the geological record. The current ripples developing on the cohesive, mixed sand–mud beds, with bed mud fractions of up to 18%, were significantly smaller than equivalent bedforms in noncohesive sand. Moreover, the bedform height showed a stronger inversely proportional relationship with initial bed mud fraction than the bedform wavelength. This is in contrast with the bedforms developing under the cohesive clay flows, which tend to increase in size with increasing suspended clay concentration until the flow turbulence is fully suppressed. Selective removal of clay from the mixed beds, i.e., clay winnowing, was found to be an important process, with 82–100% clay entrained into suspension after 2 h of bedform development. This winnowing process led to the development of a sand-rich armouring layer. This armouring layer is inferred to have protected the underlying mixed sand–mud from prolonged erosion, and in conjunction with strong cohesive forces in the bed may have caused the smaller size of the bedforms. Winnowing was less efficient for the bedforms developing under the cohesive clay flows, where bedforms consisting of muddy sand were more characteristic. The winnowed sand was also found to heal irregularly scoured topography, thus reestablishing classic quasitriangular bedform shapes. In cohesive flows, the bedforms had more variable shapes, and the healing process was confined to lower transitional plug flows in which strong turbulence is only present close to the sediment bed. Furthermore, the bedforms on the cohesive beds tended to form angle-of-repose cross lamination, whereas low angle cross lamination was more common in bedforms under cohesive flows. In general terms, *erosional* bedforms prevail when cohesive forces in the *bed* dominate bedform dynamics, whereas *depositional* bedforms prevail when cohesive forces in the *flow* dominate bedform dynamics. Empirical relationships between the proportion of cohesive mud in the mixed sand–mud bed and the development rate and size of the bedforms are defined for future use in field and laboratory studies.

1. Introduction

Sedimentary bedforms are fundamental in controlling fluxes of particulate and dissolved matter in many modern terrestrial and marine environments (Best, 1996, 2005) and thus form an indispensable tool for interpreting palaeoflow directions, palaeoflow strengths, and past depositional environments from cores and outcrops (Allen, 1984; Rubin and Carter, 2006). Despite the wide recognition of the importance of sedimentary bedforms, the role of fine-grained cohesive sediment in bedform dynamics is poorly understood. Since bedforms scale with sediment size and flow properties (Baas, 1994, 1999; Soulsby and Whitehouse, 2005a; Van Rijn, 2006, 2007; Soulsby et al., 2012), being able to accurately predict their size and migration rate is crucial for the management and regional modelling of contemporary sedimentary systems, notably for flood event simulations, the prediction of sediment transport, and the assessment of engineering infrastructure stability. Important for predicting ways to build the three-dimensional architecture of clastic successions in sedimentary basins that may contain petroleum reservoirs, groundwater reservoirs, and carbon sequestration assets is

---

* Corresponding author: Tel.: +44 1248712975; fax: +44 1248716367.
E-mail addresses: j.baas@bangor.ac.uk (J.H. Baas), a.g.davies@bangor.ac.uk (A.G. Davies), j.malarkey@bangor.ac.uk (J. Malarkey).

0169-555X/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.geomorph.2012.10.025

understanding how bedforms in the geological record were formed, and under which environmental conditions (Posamentier and Walker, 2006).

In mixed cohesive sediments, the segregation of sediments of different sizes gives rise to different petrological properties (e.g., porosity and permeability) of laminated sedimentary facies (e.g., Nordahl et al., 2006). A detailed understanding of these changes is a prerequisite for improved accuracy in reservoir modelling and for improving palaeoenvironmental reconstructions. Quantifying and modelling bedform dynamics, including the complexities of sediment mixtures, is thus key to parameterising physical processes at the flow-bed interface and ultimately to predicting natural sediment transport at local and regional scales (e.g., French, 2010). Such predictions rely strongly on accurate knowledge of relationships between the form and size of bedforms, hydrodynamic forcings, the feedback between bedform roughness and flow dynamics, and bed material properties.

Recent laboratory experiments have shown that flows that transport cohesive clay particles by advection greatly influence the development and stability of bedforms on a sand bed (Baas et al., 2011). The size, shape, three-dimensionality, and internal organisation of these bedforms are controlled in a predictable manner by the balance between turbulent and cohesive forces in the flow, which is in turn governed by the hydrodynamic forcing and the concentration and mineralogy of the suspended clay particles (Sumner et al., 2008; Baas et al., 2009; Sumner et al., 2009). Baas et al. (2011) found that the mean height and wavelength of current ripples (sensu Ashley, 1990; Baas, 2003) increase with increasing suspended clay concentration until a concentration is reached above which ripples cannot form on the sediment bed as a result of suppression of flow turbulence.

The flume experiments of Baas et al. (2011) focussed on the effects on bedform dynamics of the spatiotemporal modulation of shear-generated turbulence by cohesive forces *within the flow* (cf. Baas and Best, 2008; Baas et al., 2009). However, bedform development should also be influenced by the presence of cohesive clay particles *within the bed*, as grain size is a primary control on equilibrium bedform height and wavelength (e.g., Baas, 1994; Raudkivi, 1997; Baas, 1999), and the addition of cohesive clay to a noncohesive sand or silt bed has been shown to increase the critical shear stress for bed erosion dramatically (e.g., Mitchener and Torfs, 1996; Jacobs et al., 2011). Experimental research on bedform development in mixed cohesive sediment is surprisingly rare and cursory (e.g., Simons et al., 1963; Guy et al., 1966). Yet, such research is essential to attain a better understanding of the sedimentological properties of sand–clay mixtures given their common occurrence in modern depositional environments and in the geological record.

The present paper describes the first systematically acquired set of laboratory flume data on the development of current ripples in mixed, cohesive muddy sand. The aims of these experiments were (i) to find possible empirical relationships between the initial proportion of cohesive mud in the mixed sand–mud bed and the development rate, size, and shape of bedforms forming under steady, uniform flow conditions; (ii) to determine the role of grain size segregation (i.e., winnowing of fine sediment) on flow-bed feedback relationships in general and bedform development in particular; and (iii) to compare the influence on bedform development of cohesive forces in the bed and cohesive forces in the flow.

2. Experimental set-up and methodology

Ten laboratory experiments were conducted using a 10-m-long and 0.3-m-wide recirculating flume in the Hydrodynamics Laboratory, School of Ocean Sciences, Bangor University (Table 1; Fig. 1). Wetted kaolin clay was mixed uniformly with red-coloured natural sand at a prearranged dry weight fraction, f_0, for each experiment (Table 1). Subsequently, a 50-mm-thick layer of this mixed sediment was placed evenly onto the floor of the flume, taking care not to separate the sand and clay while flattening the wet sediment bed. The exception was run 01, which was a control experiment with noncohesive sand only ($f_0 = 0$). The kaolin used in the experiments had a median diameter, D_{50}, of 0.0073 mm, with the particle size distribution spanning the clay and silt classes (Wentworth, 1922), hence the reference to *mud* in the present paper. The sand was fine-grained and moderately sorted, with $D_{50} = 0.143$ mm and inclusive standard deviation $\sigma = 0.93$ (Folk and Ward, 1957). After flattening, the bed was covered slowly with water to avoid bed disturbances; then the flume slope was set to 0.001 in order to achieve approximately uniform flow along the flume; and finally the pump speed was increased gradually to the desired water discharge to further prevent bed disturbance.

Each run was conducted using a steady, uniform flow with a nominal mean water depth above the sediment bed of 0.25 m and a narrow range of depth-averaged velocities between 0.33 and 0.40 m s^{-1} (equivalent to flow discharges of between 25 and 30 L s^{-1}) in order to mimic the steady flow conditions used by Baas et al. (2011). Changes in bed morphology were monitored for a duration of 2 h (extended to 4 h in control run 01) through the sidewall of the flume using digital photographs, line drawings, and detailed descriptions of the sedimentological properties of the bed. The height and wavelength of the bedforms were tracked in the 2.5-m-long measurement section (Fig. 1), replicating the method of Baas (1994). Ultrasonic Doppler velocimetry profiling (UDVP; Best et al., 2001; Baas and Best, 2002, 2008) was used to measure the downstream component of flow velocity. The UDVP quantifies flow velocity by determining the Doppler shift in ultrasound frequency as small particles pass through a measurement volume (Takeda, 1991; Best et al., 2001). The present experiments used UDVP probes with an acoustic frequency of 2 MHz and a diameter of 10 mm. The probes acquired simultaneous velocity data along a profile of up to 128 points (*bins*) along the axis of the ultrasound beam, which in the present experiments extended up to 0.104 m from the probe head (Fig. 2). No velocities were recorded in the proximal 0.01 m of each profile, where the stagnation of the flow caused by the probes was found to be unacceptably large. The UDVP probes collected horizontal velocity data at 10 different heights between 0.007 and 0.210 m above the initial sediment bed level along the centre line of the flume, for a duration of ca. 80 s. The sampling frequency was ca. 2.5 Hz in multiplex mode. In order to quantify the effect of changing bed roughness caused by the ripples and changing suspended sediment concentration, the velocity profiles were acquired three times: directly after the start of a run, after 1 h, and just before the end of a run after 2 h.

The temporal mean flow velocity, $\overline{\overline{U}}$, and the root-mean square deviation of the mean velocity, $RMS(u')$, which approximates the horizontal component of turbulence intensity, were calculated from the time-series of instantaneous velocity data for each probe:

$$\bar{U} = \frac{1}{n}\sum_{i=1}^{n} u_i \qquad RMS(u') = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(u_i - \bar{U}\right)^2} \tag{1}$$

where n is the number of velocity measurements made in each run. Each value of $\bar{U}$ is based on 4200 velocity values, comprising 200 consecutive points in time and 21 bins at around 54 mm in front of the UDVP probe head (Fig. 2). An equivalent, logarithmic, depth-averaged, centre-line flow velocity, $\overline{\overline{U}}$, was computed using u^* and z_0, which were obtained from a curve-fitting procedure based on the logarithmic law for wall-bounded shear flows (e.g., Van Rijn, 1990):

$$\overline{\overline{U}} = \frac{1}{h-z_0}\int_{z_0}^{h}\frac{u_*}{\kappa}\ln\left(\frac{z}{z_0}\right)dz = \frac{u_*}{\kappa}\left(\frac{h}{h-z_0}\ln\left(\frac{z}{z_0}\right) - 1\right) \tag{2}$$

where u_* is the shear velocity, κ is the von Kármán constant ($\kappa = 0.4$), h is the flow depth, z is height above the bed, and z_0 is the bed roughness length at which notionally $\bar{U} = 0$. The coefficients of determination, R^2, for most velocity profile fits were between 0.85 and 0.95, with a few