Predicting bedforms and primary current stratification in cohesive mixtures of mud and sand

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ABSTRACT: Most sedimentary environments possess significant quantities of fine sediment, as fine silt and clay, that are transported in suspension and may affect the properties of the flow. This paper summarizes an extensive series of physical experiments that sought to investigate the influence of fine suspended clays on the fluid dynamics of unidirectional flows and the effects this may have on sediment transport and bedform development. These data illustrate that a predictable sequence of transitional flows, which undergo progressive turbulence modulation, are produced as clay concentration increases, and that such flows yield modified bedforms, and hence stratification, to clearwater flows. A new bedform phase diagram for decelerating flows that transport a mixture of sand and mud is proposed.

1. INTRODUCTION

Despite the fact that the overwhelming majority of sedimentary environments contain significant quantities of mud, most past work on bedform generation and the fluid dynamics of bedforms has considered essentially clearwater flows and cohesionless sediment. Little feedback has been envisaged between fine sediment in suspension, or incorporated within the bed, and either fluid flow or bedform development. However, as clays are added to a shear flow, they exert a feedback on the flow structure that produces a predictable sequence of changes that characterize flows that are *transitional* in their behaviour between a turbulent flow and flow with a laminar nature. Our aim here is to present a summary of an extensive series of experiments investigating the flow dynamics of such transitional flows, and show data illustrating the influence of such flows on bedforms and stratification produced in mixtures of mud and sand under rapidly-decelerated flows.

2. METHODS

Laboratory experiments were conducted in a recirculating hydraulic flume (Figure 1) equipped with a slurry flow pump. Flow was monitored using an array of ultrasonic Doppler velocity profilers (UDVP) that work well in opaque sediment-laden flows. Different volumetric concentrations of kaolinite and bentonite (from *c.* 0-25%) were established over a flat bed in experiments investigating the flow dynamics of transitional flows, whereas a bimodal mixture of silt and sand within clay-rich flows (D_{50} = 0.085 mm and modal sizes of 0.048 and 0.300 mm) was used in the mobile bed experiments. In these latter experiments, the flows were recirculated at a high flow rate (50 Ls^{-1}) and then decelerated to *c.* 35 Ls^{-1} to allow the development of bedforms. Clay concentration was sampled using siphons, and sidewall photographs and observations were used to document bedform characteristics and their temporal evolution. We documented the changes in size, shape and internal organization of current ripples below rapidly decelerated mud–sand flows to washed-out ripples and upper-stage plane beds.

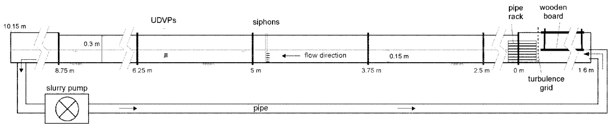

Figure 1. Schematic diagram of the experimental set-up.

3. RESULTS

These experiments allow proposition of a model for flows that are transitional between a turbulent and laminar behaviour (Figure 2), and that is based on the changing nature of the velocity profiles and turbulence characteristics as volumetric clay concentration is increased. Five stages of turbulence modulation can be discerned:

1. Turbulent flow (TF)
2. Turbulence-enhanced transitional flow (TETF)
3. Lower transitional plug flow (LTPF)
4. Upper transitional plug flow (UTPF)
5. Quasi-laminar plug flow (QLPF)

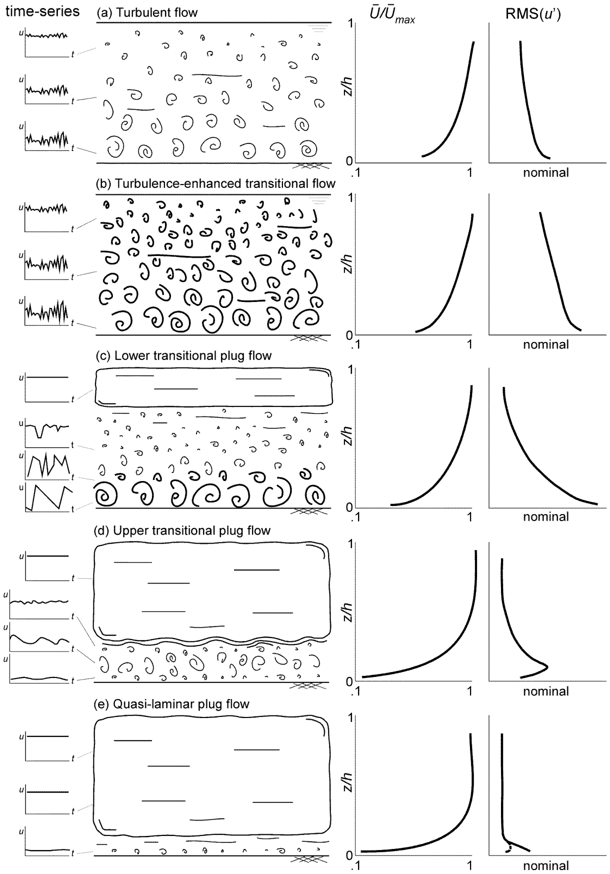

Figure 2: Schematic models of turbulent, transitional and quasi-laminar clay flows over a smooth, flat bed. Characteristic streamwise velocity time series at various heights in the flows are given on the left-hand side. The graphs to the right of the models represent characteristic vertical profiles of dimensionless downstream velocity (U_{max} is maximum flow velocity) and RMS(u′) that are the root-mean-square values of the streamwise velocity fluctuations (after Baas and Best, 2002; Baas *et al.*, 2009)

Controls on Transitional Flows

This sequence of transitional flows has been found to be robust in flows of both kaolinite and bentonite, with the phase boundaries between the flows being produced at lower clay concentrations for bentonite. Higher mean velocities also require a greater clay concentration to produce a given transitional flow. Additionally, the phase boundaries are influenced by the presence of form/grain roughness that act to provide additional turbulence. *In summary, the balance between cohesive and turbulent forces favours the production of transitional flows: i) at higher clay concentrations, ii) with clays with a more viscous behaviour, iii) in the presence of lesser roughness, and iv) at lower shear stresses for a given clay concentration. Turbulence, whether generated by bed shear or grain/form roughness, creates local shear that acts to break up clay bonds and gels, and thus produces flows with a less laminar behaviour.* However, we have found that irrespective of roughness (Baas and Best, 2009) or shear stress, at some clay concentration this predictable sequence of transitional flows is generated.

A New Bedform Phase Diagram

Our mobile bed experiments allow proposition of a new bedform phase diagram for transitional flows (Figure 3). This diagram uses a grain-related mobility parameter, θ', and the yield strength of the kaolin suspension, τ_Y, for the ordinate and abscissa axes respectively. Bedforms with a modified morphology, as compared to their clearwater counterparts, are produced (see Figure 4).

4. CONCLUSIONS

Transitional flows possess a predictable sequence of flow characteristics as clay concentration is increased, with the boundaries between flow types being dependent on the fluid shear, clay type and boundary roughness. These flows produce bedforms that may display a significantly different morphology to those produced in clear water flows. Ongoing research is investigating the boundary conditions of such flows with respect to flow salinity and extrapolymeric substances, and the nature/preservation of transitional flow deposits in the stratigraphic record.

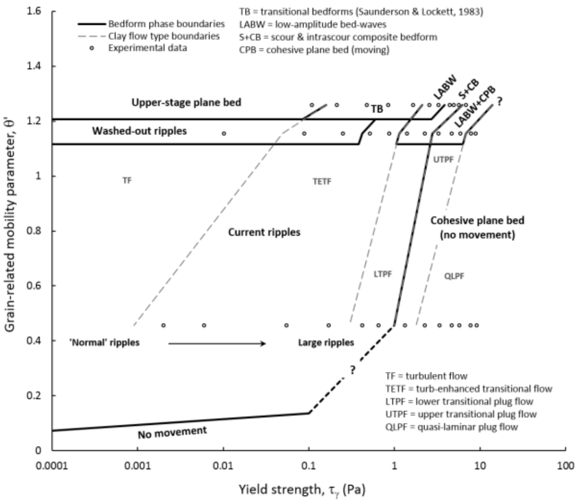

Figure 3: Bedform phase diagram for rapidly decelerated cohesive sand–mud flows, showing the stability fields for different bedform types. This diagram is valid only for poorly sorted sediment with D_{50} = 0.085 mm. At $\tau_Y = 0$ (i.e. for clay-free sand), the boundaries between 'normal' ripples, washed-out ripples and upper-stage plane bed correspond approximately to those in the bedform phase diagram of van den Berg & van Gelder (1993) for a dimensionless grain size, D*, = 2.15. Radical changes in bedform type with increasing yield strength are evident, which are largely associated with changes in flow type. The question marks denote inferred boundaries (from Baas *et al.*, 2015).

5. ACKNOWLEDGMENTS

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6. REFERENCES

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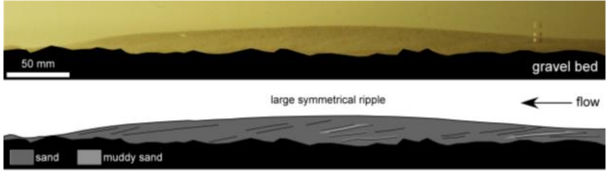
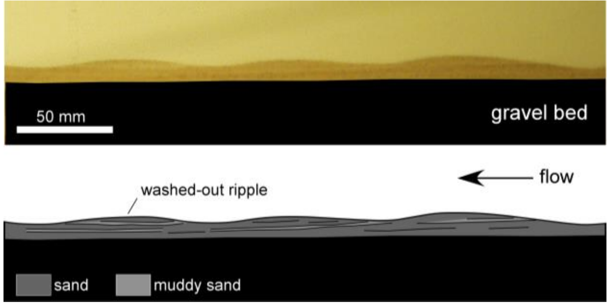
Upper-stage plane bed equivalent bedforms in TETF



Washed-out ripple equivalent bedforms in TETF



Upper-stage plane bed in LTPF, with fluidization pipes

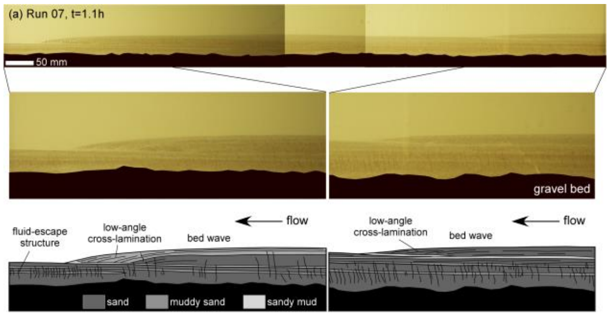


Figure 4: Examples of three distinct types of stratification formed under rapidly-decelerated transitional flow (from Baas *et al.*, 2015).