Bedforms in Froude-supercritical flow

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ABSTRACT: Sedimentary bedforms formed under unidirectional Froude-supercritical flow have been called antidunes, bedwaves, sandwaves, sediment waves, gravel ridges, gravel cells, transverse ribs, chute-and-pool structures and cyclic steps. Trains of supercritical bedform fall into two classes; forms that scale with flow thickness and grain transport properties and those that are totally independent of the grain properties. These two classes of bedforms may coexist or, more often, occur independently. Trains of bedforms may occur in isolation or succeed each other through time. Although they have some superficial similarity in form to each other the resulting sedimentary structures are distinctly different. Here field data, published literature and flume experiments are used to consider bedform development and classification. This paper is as an "aunt Sally" to stimulate discussion.

1 INTRODUCTION

1.1 *Supercritical flow*

Unidirectional flows occur in two regimes; supercritical (rapid or chuting; Fr>1) and subcritical (tranquil; Fr<1) that are defined in terms of the Froude number,

$$Fr = U / \sqrt{gd} \qquad (1)$$

where U = mean velocity, g = acceleration due to gravity and d = flow thickness. In subaqueous settings such as turbidity currents the densiometric Froude number is defined to be

$$Fr = U / \sqrt{\frac{gd\Delta\rho}{\rho}} \qquad (2)$$

where ρ = density, and $\Delta\rho$ = bulk density contrast.

Water flow may become supercritical (Fr>1) in glacial outbursts, dam bursts, submarine turbidity currents, volcanic lateral blasts, on the beds of fast flowing rivers and in backwash on beaches. Supercritical turbulent flow over a deformable boundary is inherently unstable and interaction between the flow and the surface rapidly generates sedimentary features that may have a strong feedback to the flow behaviour.

Although a variety of bedforms have been observed in these settings, sedimentary structures formed in association with supercritical flow are poorly documented and generally very poorly understood in comparison with those formed in subcritical flows. They are far more difficult to observe directly or to produce in the laboratory.

The two key fluid dynamical factors that influence the bedforms are stationary (standing) waves and hydraulic jumps.

1.2 *Stationary waves*

Stationary waves (colloquially termed standing waves) will form in supercritical flow when the Froude number is near one. They form over deforming or non-deforming boundaries, but form more easily over rough boundaries. The more commonly used term "standing waves" is technically incorrect in that they do not behave in the manner of e.g. standing waves generated on a violin string where the string goes up and down at one location. Instead these waves posses crests and troughs which remain in stationary positions (or slowly move).

Stationary waves that form over a deforming boundary generate in-phase bed waves (or nearly in phase as in Fig. 1), here all called antidunes. Growth of the bed topography may encourage wave breaking (as in Fig. 1). Hand (1969) predicted that the ratio of the antidunes height to the water surface wave height at the point of breaking is 0.42-0.61 and the experimental values fall in this range. In this situation, where the waves break, the bed topography is modified (as discussed by Alexander *et al*. 2001) and the wave reforms. The resulting sedimentary structures have been fairly well documented although they remain infrequently identified in deposits.

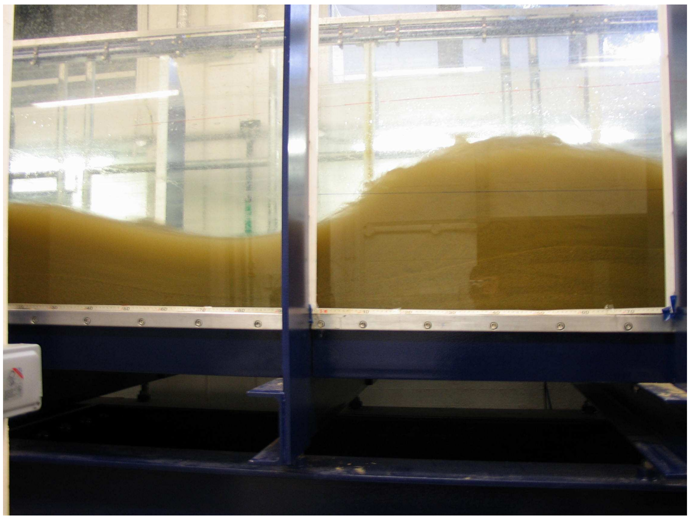

Figure 1. Stationary waves forming over a sandy bed. The water surface is a little out of phase with the sediment surface as the wave begins to break. Flow is from left to right.

1.3 *Hydraulic jumps*

A hydraulic jump marks the downstream transition from super- to subcritical flow and is characterized by a marked increase in flow surface elevation between supercritical incident flow and deeper, slower, subcritical flow. They occur spontaneously. Figures 2 and 3 give views of a hydraulic jump that formed spontaneously in the ENV flume with water flowing steadily over a smooth planar, gently-sloping bed. Many hydraulic jumps occur in isolation, for example at levee breaches, where steep channels enter lakes and at submarine canyon mouths. Isolated hydraulic jumps are well studied, and they may form distinct bed topography (hydraulic jump unit bars cf. Macdonald *et al. in prep*).

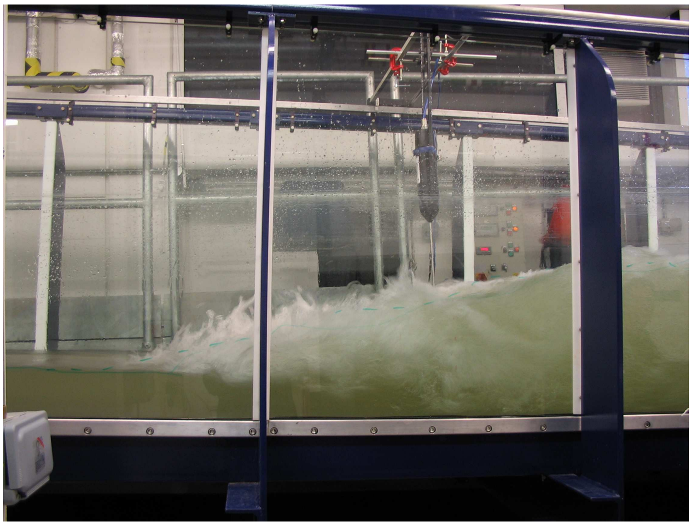

Figure 3. View through glass sidewall of hydraulic jump spontaneously formed over a flat flume bed. Flow from left to right. Flume wall height 1m.

Figure 2.View downstream over a hydraulic jump in the ENV flume. Flume width is 1m.

In contrast to antidunes, the sedimentary features associated with hydraulic jumps are relatively poorly documented and only isolated examples have been described (e.g. Carling, 1995; Macdonald *et al*., *in prep*).

In some situations trains of hydraulic jumps develop. This can only occur if the flow is repeatedly accelerated by flow down an increased gradient and decelerated, or if there are cyclic changes in flow width. To generate trains of hydraulic jumps, therefore requires changing boundary conditions. Unlike stationary waves or isolated hydraulic jumps, trains of hydraulic jumps can not occur over a planar non-deformable bed.

Probably the most important setting, where trains of hydraulic jumps develop, is where supercritical flow moves over a deformable bed where the critical bed shear stress for particle motion is exceeded. In this situation growth of a bed irregularity and feedback between the bed and flow causes instability downstream that spontaneously generates spatially periodic patterns of supercritical and subcritical flow and trains of bed features develop.

2 THE BEDFORMS

In flows where the net regime is supercritical therefore, two styles of bedform train may form: (1) antidunes associated with stationary waves and (2) cyclic steps or chutes and pools.

2.1 *Antidunes*

Antidunes have been studied in flumes (e.g. Alexander *et al*. 2001) and observed in rivers and marine settings. For example, characteristics of small antidunes and the resulting sedimentary structures in aggrading sand beds were documented experimentally by Alexander *et al*. (2001). They have been observed in modern environments, for example, in Queensland long-wavelength, undulating, sand and gravel bedforms (Fig. 4) are observed on the river beds in the dry season, at sites where stationary waves were present in preceding high-magnitude short duration floods (Alexander & Fielding, 1997) and deep marine seabed undulations have been attributed to stationary waves by a number of researchers (e.g. Morris *et al*. 1998). However, there is some debate on the origin of deep marine bed undulations and according to Fildani *et al*. (2006) some may be cyclic steps (see below)

One key feature of antidunes is that their wavelength is the same as the associated surface waves and this is related to flow depth and independent of sediment characteristics. Kennedy (1963) demonstrated that the minimum wavelength, λ, of 2D antidunes and the associated flow-surface waves is

$$\lambda = \frac{2\pi U^2}{g} \qquad (3)$$

and he determined an equations for the dominant wavelengths:

$$Fr^2 = \frac{2 + kd \tanh(kd)}{(kd)^2 + 3kd \tanh(kd)} \qquad (4)$$

where tanh is the hyperbolic tangent and $k = 2\pi/\lambda$. As discussed below this is distinctly different to cyclic steps and may be a help to discriminate the origin of deep marine bed undulations.

Figure. 4 Gravel and sand bedforms on Brigalow point bar in the Burdekin River, Queensland, Australia. The preceding very high discharge event flowed directly across this site towards the camera. Note person on right of picture.

2.2 *Cyclic steps and chutes and pools*

Trains of hydraulic jumps, resulting from strong feedback between a flow and its bed, produce a range of bedforms depending on the sediment characteristics and the flow. In situations where the bed is in net degradation, such as in many mountain streams, the trains of hydraulic jumps and related bed topography have been descriptively called cyclic steps (e.g. Winterwerp *et al*., 1992; Parker & Izumi, 2000). Where developed on sand with bed equilibrium or net aggradation they have been termed chute-and-pool structures (e.g. Alexander *et al*., 2001) although these may be a subclass of cyclic steps (Taki & Parker, 2006; Sun & Parker, 2006).

Cyclic steps are invoked by Fildani *et al*. (2006) to explain *sandwaves* on the Monterey submarine fan. Backset beds attributed to chutes-and-pools have been interpreted in ancient deposits of rivers (Power, 1961; Fralick, 1999), fan deltas (Nemec, 1990; Massari, 1996) and volcanic base surges (Schmincke, *et al*. 1973).

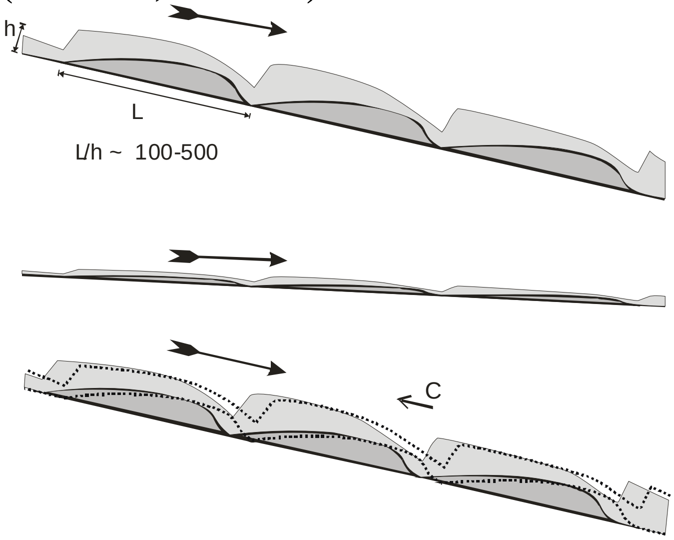

Figure 5. Diagrammatic representations of cyclic steps. The larger arrow indicates flow direction, the dark grey the bed and the light grey the water flow. Bedform length and height are indicated by L and h. C indicates the bedform migration. The doted lines represent surfaces preceding the solid lines. The upper and lower diagrams have a lot of vertical exaggeration, while the middle one is nearer the true bedform aspect ratio.

Upstream of each hydraulic jump (Fig. 5) bed shear stress is high and erosion may be rapid, while a little downstream of the jump, deposition may be very rapid. These two areas move in tandem upstream and force the hydraulic jumps upstream. Successive sites of erosion define the stream-wise extent of the bedform. The length of an individual deposit unit (one cyclic step or one chute-and-pool structure) is controlled in part by the mean flow depth. It is also controlled by the particle transport properties because these control the rate and distribution of scour and the length over which the entrained bed material returns to the bed downstream of a hydraulic jump. This transport length is controlled by the complex flow structure in the jump (see Macdonald *et al. in prep*) and the settling velocities of the component grains. It is the topography of the growing bed feature that reaccelerates the flow back to supercritical conditions and restarts the next cycle downstream, consequently the wavelength may increase with flow mean depth or grain size (in the non-cohesive range).

Cyclic steps have a characteristic wave length 100-500 times the flow thickness (Taki & Parker, 2006), an aspect ratio that make them particularly difficult to reproduce in the laboratory at scales that will generate significant deposits. Cyclic steps have been well modelled mathematically in conditions where all the sediment transport is in suspension and uniformly mixed through the water column (Taki & Parker, 2006; Sun & Parker, 2006) but these may not be satisfactory approximations for situations where a significant proportion of the load is in traction or temporary suspension and significant deposition occurs. Also the flow structure may be more complex than in these models with wall jet detachment imparting a more complex pattern of sediment distribution and behaviour.

The characteristics of the sedimentary unit in a cyclic step depend on the relative importance of bed and suspension load and the transitions between the two (which are particularly great in this context). In settings with a significant proportion of bed load (or particles in temporary bed load) chute-and-pool configurations give rise to upstream-dipping laminae (backset laminae; e.g. Jopling & Richardson, 1966). However, the origin of the laminae, the lamina-set geometry and the relationship between the geometry and bedform development are known only rudimentarily (e.g. Alexander *et al*., 2001). Very rapid formation of backsets from bulk suspension fall out (and possibly in combination with bedload stalling) leads to inherent tendency to high porosity of the deposit and consequent prevalence of soft sediment deformation.

Fildani *et al*. (2006) stated that cyclic steps are closely related to antidunes, and there are some superficial similarities in how they can be modelled. Superficially trains of cyclic steps may appear very similar to breaking stationary waves. However, the controlling factors are different and in detail the flow structures, evolution and sedimentary structures are different. Flume observations of flow over sand beds demonstrate that antidunes can occur together with chutes and pools (the shorter wavelength stationary waves forming in the supercritical reaches of the chutes). Cyclic steps appear to scale with depth and grain transport properties (thus grain size) while antidune wavelengths do not scale with grain properties. Thus they are related in a similar way as dunes and ripples are related – they are bedforms that may occur together or succeed each other and they have some superficial similarity in form. The resulting sedimentary structures may be distinctly different.

3 CONCLUSIONS

In Froude-supercritical flow two flow behaviours result in formation of trains of bedforms. Stationary (or “standing”) waves cause stream-wise variations in bed shear stress and complex pattern of sediment movement that together result in bed topography in phase with the flow surface waves (or nearly so). In contrast growth of an isolated topographic feature can cause deceleration of supercritical flow and spontaneous development of a hydraulic jump, acceleration down the lee side returns the flow to a supercritical condition and initiates growth of a topographic feature downstream. Thus cyclic steps are forced by growth of bed topography. Cyclic steps (including chutes-and-pools) appear to scale with flow depth and grain transport properties while antidune wavelengths are independent of grain properties. Thus the two groups of supercritical bedforms are related to each other in a similar way as dunes and ripples are related – they are bedforms that may occur together or succeed each other and they have some superficial similarity in form. The resulting sedimentary structures may be distinctly different and considerably variable in character.

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