The fluid dynamics of low-angle river dunes: results from integrated field monitoring, laboratory experimentation and numerical modelling

Jim Best[(1)], Ray Kostaschuk[(2)] and Richard Hardy[(3)]

(1) School of Earth Sciences, University of Leeds, Leeds, West Yorkshire, LS2 9JT, United Kingdom. E-mail: j.best@earth.leeds.ac.uk
(2) Department of Geography, University of Guelph, Guelph, Ontario, N1G 2W1, Canada. E-mail: rkostasc@uoguelph.ca
(3) School of Geography, University of Leeds, Leeds, West Yorkshire, LS2 9JT, United Kingdom. E-mail: r.hardy@geography.leeds.ac.uk

Abstract

Combined physical and numerical modelling of flow over low-angle river dunes, whose morphology is based on dunes monitored in the Fraser River, Canada, shows that the flow field is dominated by flow acceleration over the stoss side, flow expansion in the leeside and the absence of a region of permanent flow separation. Both physical and numerical models show the absence of permanent flow separation but suggest that intermittent flow separation may characterise flow in the leeside. The numerical model is used to investigative the role of upstream inherited flow structure on eddy shedding from the leeside and suggests that the instantaneous nature of flow, and thus sediment suspension, is dictated by the turbulent flow field in the leeside that is inherently linked to the flow fields of upstream dunes. Turbulence modulation of flow by the upstream flow field may thus be important for interpreting the flow fields over individual dunes, highlighting the possible significance of bedform superimposition in bedform dynamics.

1. Introduction

Dunes are vital elements of the fluvial landscape and play a key role in the transport of sediment (Ashley, 1990; Nelson *et al.*, 1993, 1995) and the nature of the turbulent flow field. Additionally, the morphology and depositional products of sand dunes are of key importance when reconstructing the palaeoenvironments of past alluvial deposits, and in which sand dunes may be one of the most common depositional elements (Bridge, 2003; Best *et al.*, 2003). Because of the importance of dunes within both contemporary and ancient sedimentary environments, many studies have been devoted to the study of dune morphology and shape (Saunderson and Lockett, 1983; Gabel, 1993; Wilbers and ten Brinke, 2003), dune migration and its use in estimating bedload sediment transport (Engel and Lau, 1980; Wilbers, 2004), the role of dunes in the prediction of friction factors (Julien *et al.*, 2002, Wilbers, 2004) and the flow fields associated with dunes (van Mierlo and de Ruiter, 1988; Nelson *et al.*, 1993; Bennett and Best, 1995; Kadota and Nezu, 1999; Kostaschuk, 2000). Many of these studies have assumed that the cross-sectional geometry of dunes is characterized by an asymmetric profile in which the downstream termination of the dune is at a steep, often angle-of-repose (25-35°), slipface where sediment transported up the stoss side of the dune avalanches down the steep leeface. Although these dunes are common in many environments, and are associated with appreciable energy losses and often large-scale flow separation in the dune leeside, several field studies have shown that many dunes may possess far lower leeside angles, perhaps of only 2-10° (Kostaschuk and Villard, 1996; Roden, 1988; Kostaschuk *et al.*, this volume), that may impart considerably different characteristics to the flow field. The aim of this study was to combine the physical modelling of flow over low-angle dunes, which were scaled to a field prototype, with numerical modelling in order to address three main questions: 1) what is the nature of the mean and turbulent flow field over low-angle dunes?; 2) is permanent flow separation present in the dune leeside?, and 3) what is the influence of the inherited upstream flow field on the characteristics of both mean and temporal flow over these dunes?. Questions 1) and 2) will be addressed herein by results from a simple physical flume experiment that has been used to verify and validate a computational fluid dynamic model.

The numerical model is then employed to address question 3) and highlight some key issues regarding the flow field over both low-angle and angle-of-repose dunes in a range of sedimentary environments.

2. Field Prototype: dunes in the Fraser River Estuary

The Fraser River, British Columbia, Canada has a mean annual discharge of 3400 m^3 s^{-1}, with maximum flows over 11 000 m^3 s^{-1}, and discharges into the Strait of Georgia, a mesotidal marine basin on the west coast of Canada. The Main Channel of the Fraser Estuary has a sand bed with a median grain size of 0.25-0.32 mm (Kostaschuk *et al.*, 1989). Dunes in the estuary range from 0.1 m to 4 m in height and 2 m to more than 100 m in length (Kostaschuk *et al.*, 1989, this volume) and have a curved, concave-downstream planform geometry with circular depressions on crests and associated pits in the dune troughs (Kostaschuk and MacDonald, 1988). Dunes migrate around low tide during high river discharge when sand is in transport (Kostaschuk *et al.*, 1989; Kostaschuk and Church, 1993; Kostaschuk and Villard, 1996; Kostaschuk *et al.*, this volume), although Helley-Smith bedload sampling together with pump sampling of the suspended load (Kostaschuk and Ilersich, 1995) suggests that bedload accounts for less than 1% of the total sand transport with the remainder travelling in suspension.

Kostaschuk and Villard (1996) examined horizontal velocity profiles over six low-angle 'symmetric' dunes, which were found to be the equilibrium duneform during high river discharge in the Fraser River. These dunes had a height of 1.09-2.42 m and a wavelength of 29.9-38.1 m in flow depths of 11.1-12.8 m. Velocities were measured with an electromagnetic current meter equipped with an internal compass in order to determine flow direction. Since the current meter had a measurement sphere with a radius of 0.2 m, the closest that measurements could be taken to the bed was 0.5 m. The current meter was deployed from a research launch anchored at 3-6 positions over individual dunes and a velocity profile was measured at each position. Each point in a velocity profile was sampled at 1 Hz for 90 s, the short sampling period being necessary so that all velocity profiles could be completed during the 2-3 hour period of steady flow around low tide. Mean flow velocity over the dunes was 1.10-1.68 m s^{-1}, the Froude number was 0.10-0.15 and the Reynolds number was 9.95-14.2 * 10^6. The flume study detailed in the present paper used the 'June 20' dune of Kostaschuk and Villard (1996) as the prototype for the scale model (Fig. 1). The morphology of the experimental dune (see Best and Kostaschuk, 2002, for details) is consistent with other low-angle dunes in the Fraser River and the velocity profiles are representative of spatial variations over the dunes examined by Kostaschuk and Villard (1996).

upper

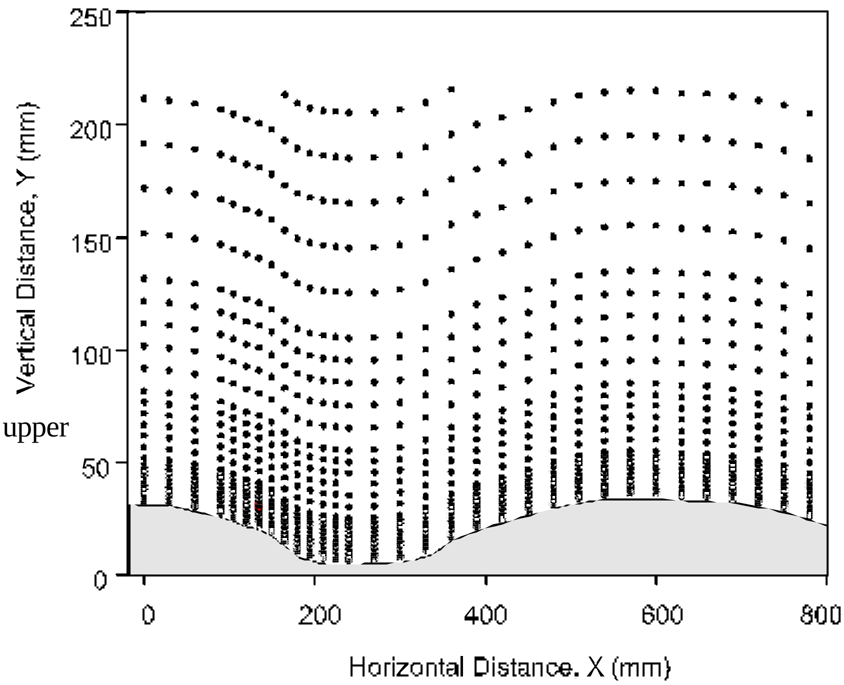

Figure 1: Profile of the low-angle dune used for physical and numerical modelling in this study, together with measurement points for the laser Doppler anemometry. The water surface is approximately 3 mm above the measurement point in each profile. Flow left to right. Vertical exaggeration x2.7.

3. Methods

3.1. Physical Modelling

The flume experiments are fully reported in Best and Kostaschuk (2002) and only a brief resume of the methodology is given herein. The physical modelling experiments were conducted using a recirculating flume 10 m long, 0.3 m wide and 0.3 m deep and followed the principles of Froude scale modelling whereby the Froude number is kept constant between prototype and model but the flow Reynolds number is relaxed, provided the flow is fully turbulent. For the present experiments and flume facilities, a scale ratio between flume and prototype of 1:58 was chosen in order to match the dune dimensions, flow depth and flow velocities. Two-dimensional model dunes were cut from high-density styrofoam that were modelled on the June 20 Fraser dune (Fig. 1), with the maximum lower leeside slope angle of the scale-model dunes being 14^o. The entire length of the flume was covered with identical foam dunes and the bed slope adjusted so that, at the discharge and flow depth imposed by the scale ratio, the water depth was constant along the flume. Based on the 1:58 scale ratio, the mean flow depth in the flume was 0.20 m, the Froude number was maintained at 0.15, the flow was fully turbulent (Reynolds number = 36 000) and the dune height:flow depth ratio was 0.16.

A total of 32 velocity profiles were measured over a 0.775 m test section in the flume (Fig. 1), with between 26 and 28 points in each vertical profile, this yielding a grid of 872 points over the test section. Velocity at each point in a profile was measured for 1 minute at an average data rate of 200 Hz with a DANTEC, two-component fibre-optic laser Doppler anemometer (LDA). The LDA was used in backscatter mode with a 400 mm focal length lens and 100 mW argon-ion laser. A 40-MHz frequency shift was applied to one beam of each beam pair to enable bi-directional measurements of velocity along each axis. Signals were processed with a DANTEC Particle Dynamics Analyser, with signals being validated when Doppler bursts above a sufficient threshold were recorded on both channels. This resulted in a range of sampling rates between 120 and 600 Hz, in excess of those desirable to ensure full characterization of the turbulence spectra (Nezu and Nakagawa, 1993). The four-beam arrangement of the LDA prevented measurement of vertical velocity at heights less than 4 mm above the bed, although horizontal velocities were measured to within 1 mm. Velocity resolution of the LDA was 0.0027 m s^{-1} and the size of the sampling volume was 0.22 mm^2. Flow visualisation was achieved using long-exposure images on both a digital video camera and standard 35 mm camera, with neutrally-buoyant Pliolite particles that were illuminated with a laser light sheet.

3.2 Numerical Modelling

The numerical scheme employed solves the full three-dimensional Navier-Stokes equations discretised using a finite-volume method. The interpolation scheme that has been adopted is hybrid-upwind, where upwind differences are used in high convection areas (Peclet number > 2) and central differences are used where diffusion dominates (Peclet number < 2). Although this scheme can suffer from numerical diffusion, it is very stable. The pressure and momentum equations are coupled by applying SIMPLEST, a variation on the SIMPLE algorithm of Pantankar and Spalding (1972).

Boundary conditions need to be specified at the upstream inlet and downstream outlet, at the sidewalls and at the free surface. At the upstream inlet, a fully developed flow profile calculated from the experimental data is specified and the downstream outlet is specified as a fully developed flow profile with the hydrostatic pressure set at the surface at the downstream outlet. At the bed and banks, the standard law-of-the-wall was used. As the simulations were based upon the flume experiment over smooth fixed-bed models, smooth boundaries were assumed, where $y_o = u/9u_*$, in which y_o is height of zero velocity, u is the kinematic velocity and u_* is the shear velocity. At the free surface, a porosity-based free-surface model was employed, as described in Bradbrook *et al.* (2000), to eliminate mass balance errors in the presence of the rigid lid.

Initially, a steady-state solution was obtained using a RNG k-ε turbulence model. This technique applies Reynolds decomposition, where the flow is separated into a solved mean component (defined as time averaged) and fluctuating modelled components (that sum to zero). Thus, there is no time derivative in this equation. Furthermore, in these simulations, as a steady state solution is being calculated, an implicit time step is used. This was extended to using Large Eddy Simulation (LES) that adopts a different approach to the solution of the Navier-Stokes equations. Instead of manipulating the equations on the basis of mean and fluctuating properties, the re-organisation is based upon a length scale (D), taken to be equal to the grid size employed in the finite-volume solution of the equations. The separation of scales is achieved by applying a filter to the computational domain where the spatial discretisation directly defines the length scale of the turbulence which is solved. Therefore the larger scales are solved with a sub-grid scale model used at smaller scales. In this application, the Smagorinsky SGS Model was applied (Smagorinsky, 1963). The RNG k-ε turbulence model simulation models were used as the initial conditions for the LES simulations.

4. Results

The mean downstream and vertical velocities over the experimental dunes (Fig. 2) show that the main features of flow over these low-angle dunes are: 1) Flow acceleration over the stoss side of the dune (Fig. 2A) associated with topographic forcing of flow over the dune form (Fig. 2B); 2) Flow deceleration in the dune leeside associated with flow expansion (Fig. 2A) as flow is directed towards the bed (Fig. 2B), and 3) The absence of a zone of time-averaged permanent reverse flow in the leeside, indicating that a region of permanent flow separation does not form in the lee of these low-angle dunes. Results from the numerical model (Fig. 3) also show similar

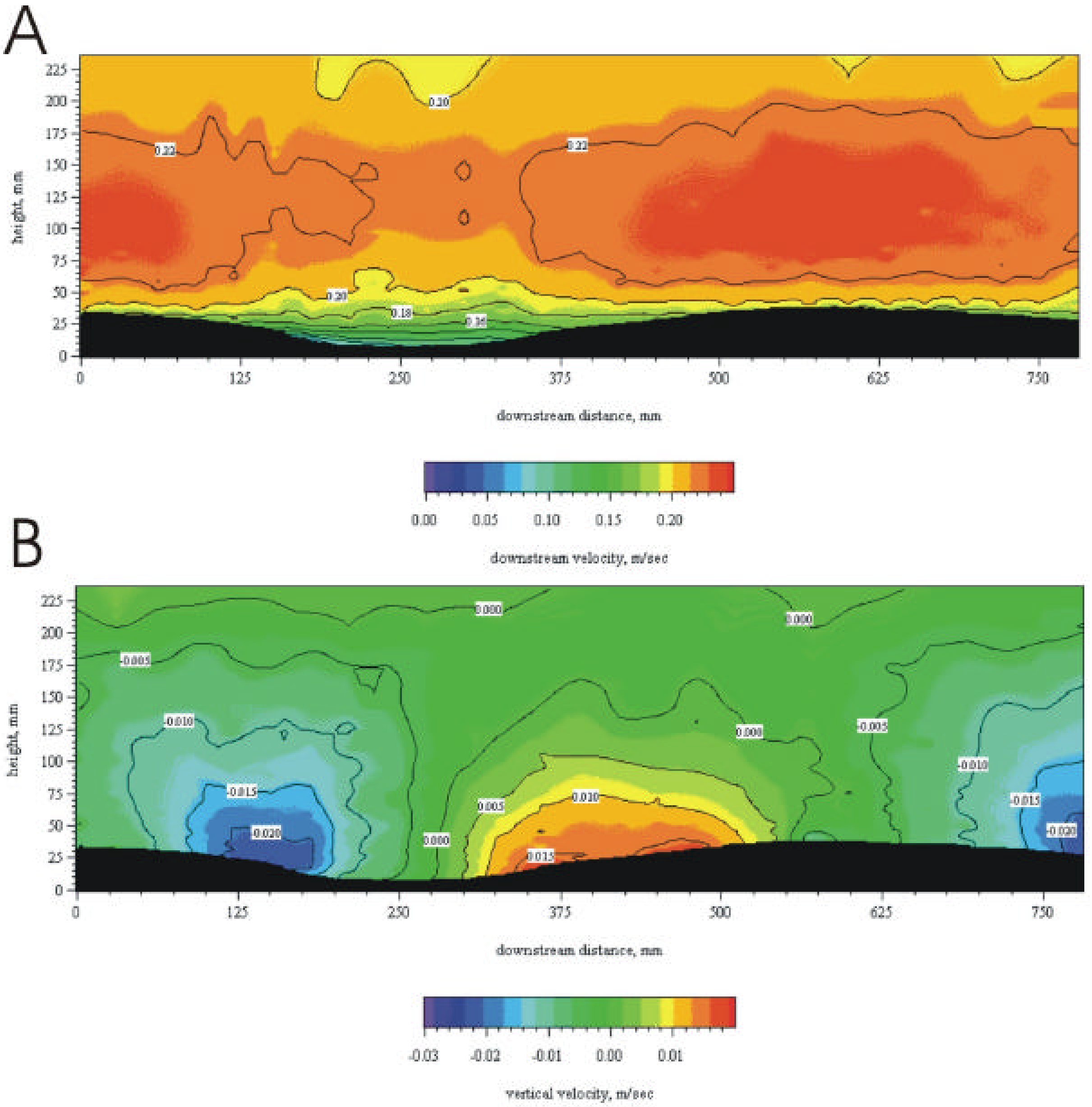

Figure 2: Plots of time-averaged A) downstream velocity and B) vertical velocity associated with the low-angle dunes in the physical model. In B), positive vertical velocity depicts flow away from the bed. Flow is left to right.

features and confirm that no zone of permanent flow separation exits in the dune leeside. Velocity magnitudes between the physical and numerical models agree well with maximum downstream velocities of 0.24 $ms^{-1}$and vertical velocities of + 0.02 and -0.02 ms^{-1}.

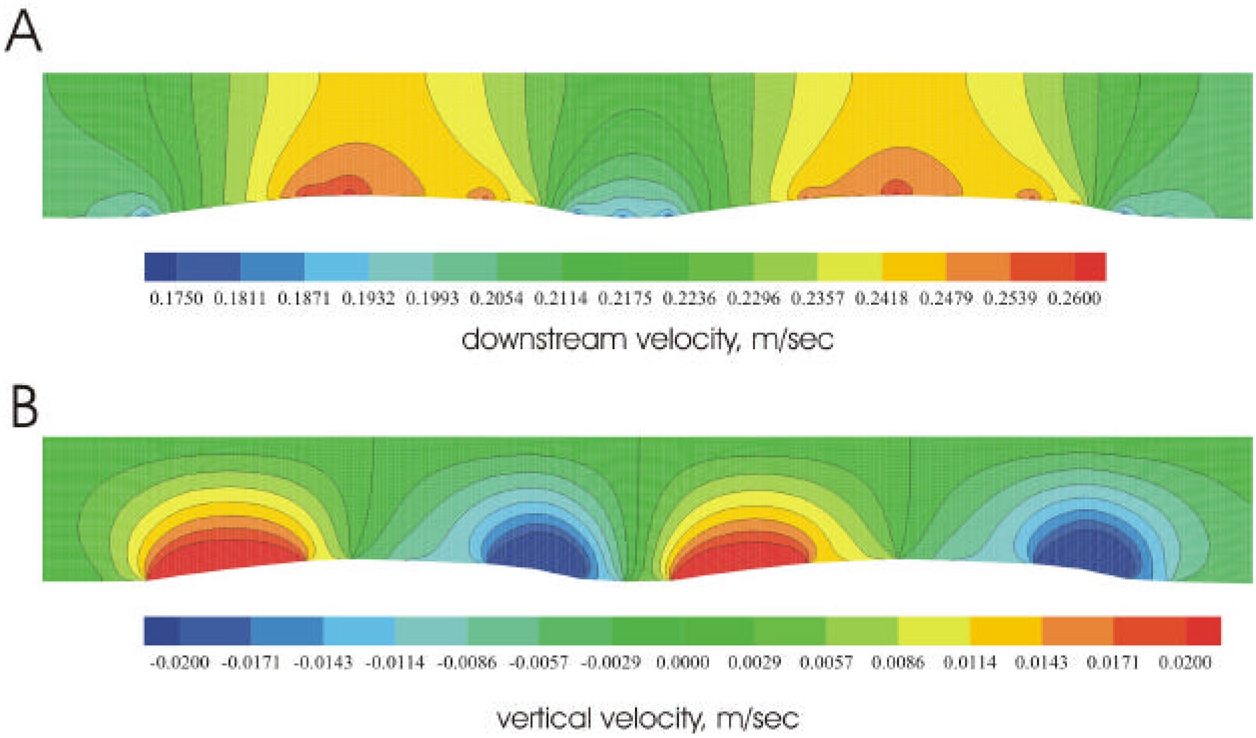

Figure 3: Plots of time-averaged A) downstream velocity and B) vertical velocity associated with the low-angle dunes obtained in the numerical model. In B), positive vertical velocity depicts flow away from the bed. Flow is left to right.

4. Summary

Flow over low-angle dunes possesses similar mean flow patterns to that over angle-of-repose dunes in the presence of topographically induced flow acceleration over the stoss side and flow expansion in the leeside. However, physical and numerical models both show that a region of permanent flow separation in absent in the leeside of low-angle dunes and that this region is characterised by flow expansion and intermittent flow separation, this possibly related to generation of temporary shear layers in the leeside. Flow and sediment suspension over these low-angle dunes may thus be different to that over steeper dunes, although large-scale turbulence is still present over these lower-angle bedforms. Additionally, numerical modelling illustrates the interaction between the flow fields of adjacent bedforms and highlights the importance of bedform superimposition in bedform dynamics.

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