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Convergent evolution of abrading flow obstacles: Insights from analogue modelling of fluvial bedrock abrasion by coarse bedload

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ABSTRACT

Upstream-facing convex surfaces (UFCS) are formed by bedload abrasion in bedrock rivers and indicate the recent, significant action of bedload abrasion in causing channel incision. Beyond this, little is known of the dynamics of UFCS and the effect of substrate and bedload properties on rates and distribution of bedload abrasion for these bed roughness elements. Grain size populations from 1 to 8 cm (*b*-axis, in 1- or 2-cm bin widths) were used to bombard preshaped marble and limestone targets bolted to the base of an annular flume. The control of initial shape and lithology of the target and the erodent grain size and lithology were investigated by monitoring the evolution of the target form using laser scanning at predefined time intervals. Eleven experiment suites were carried out containing three initial target shapes constructed from two lithologies, four bedload (erodent) grain sizes of either granodiorites or limestone, or clear water flow. All 10 targets abraded by bedload evolved from their initial form into a steady state (time invariant) form, producing UFCSs. Steady state forms were closely similar for all targets despite different initial conditions. Bedload grain size has a strong control on this equilibrium form, related to the transit path of the grains when moving over the target, whilst initial target form has only a weak control. Steady state morphology is achieved more rapidly with harder erodent bedload particles and/or softer targets. Upstream-facing convex surface stoss sides were characterised by a brighter, sugary, granular appearance on the rock-forming grain scale. Increasing erodent grain size, for a fixed bedload mass, increased the bulk abrasion rate at fixed flow speed and discharge. No detectable erosion occurred for a limestone block in clear water flows under the same flow conditions, indicating solution and cavitation were insignificant mechanisms of erosion in this study. During the experiment suites, suspended load abrasion was also found to be an insignificant mechanism in eroding lee or lateral sides. In natural settings, the initial formation of UFCSs can occur for homogenous and/or jointed substrates in close association with plucking or, alternatively, for heterogeneous substrates by variation in substrate erodibility.

1. Introduction

Incision, the vertical erosion into bedrock by a river, is achieved by the synergistic operation of at least five erosion mechanisms: abrasion, dissolution, cavitation, quarrying, and fluid stressing. However, in any given reach of the river where the channel bedrock is exposed identifying which mechanisms are at work and which are important by inspection alone is difficult, with a few exceptions. Quarrying produces characteristic joint-bounded blocks (Hancock et al., 1998), dissolution produces fields of concave depressions called scallops (Allen, 1971), and bedload abrasion produces percussion (impact) marks (Wilson and Lavé, 2013) and upstream-facing convex surfaces (UFCS) (Wilson et al., 2013).

Bedrock bedforms are an expression of the erosion mechanisms producing them (Richardson and Carling, 2005). They not only indicate which erosion mechanisms have occurred in a bedrock river over recent times, but stranded bedforms (e.g., preserved in gorge walls) have the potential to indicate which erosion mechanisms occurred in the past. Morphology, surface textures, and measurements of erosion from UFCSs in Taiwan have been used by Wilson et al. (2013) to argue that the abrasion produced by bedload and suspended load can be determined from monitoring these characteristics at a site. As well as being the direct expression of erosion mechanisms, bedrock bedforms contribute to channel bed roughness and so are important in order to understand and accurately model bedrock river formation and to understand erosion measurements made in natural channels. Rates of erosion on UFCSs for bedrock streams dominated by bedload were found by Wilson et al. (2013) to be significantly higher than on adjacent horizontal surfaces indicating that, where present, UFCS represent locally significant sites of erosion.

Laboratory investigations of erosion have focused either on measuring bulk rates of erosion of bedrock substrate using tumbling barrels or mills (e.g., Sklar and Dietrich, 2001) or the formation of scaled bedrock reaches, valleys, slot gorges, or knickpoints (e.g., Shepherd and Schumm, 1974;

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Holland and Pickup, 1976; Gardner, 1983; Wohl and Ikeda, 1997; Dubinski and Wohl, 2005; Carter and Anderson, 2006; Finnegan et al., 2007; Johnson and Whipple, 2007). Experimental studies simulating bedrock bedforms are rare, except for percussion marks (Wilson and Lavé, 2013) and scallops (Rudnicki, 1960; Allen, 1969, 1971; Goodchild and Ford, 1971), so much scope exists to understand the controls on their formation and how details of their sculpting mechanisms are preserved in their morphology.

In this paper we explore the controls on UFCS formation by bedload abrasion in unscaled laboratory experiments forming UFCSs on rock blocks where morphology was measured using high resolution laser scanning, and surface textures were inspected using macrophotography and scanning electron microscopy. Our main research questions are: (i) Does bedload abrasion produce the UFCS morphology and surface textures observed in field examples? and (ii) What is the effect of bedload and substrate properties on rates of abrasion and morphology of UFCSs?

2. Flume experiments

2.1. Experimental apparatus

Flume experiments were conducted in an annular flume (Attal et al., 2006). This is a recirculating flume in which grain motion is induced by water current (Fig. 1). The facility can simulate and measure hydrodynamic conditions prevailing during floods in mountain rivers with flow velocities up to 4 ms^{-1} (Attal et al., 2006). This flume and apparatus has a 1:1 scaling with natural flows, in other words the experiments are unscaled. A reservoir tank contains 5 m^3 of tap water that is pumped at discharges up to 140 Ls^{-1} through a flow distributor where it is split into four similar flows. These are fed by flexible piping into the flume tank body at four equally spaced tangential injection points located 0.55 m above the flume base (Fig. 1) inducing grain motion. The outer flume wall on the wetted side is protected from wear by polycarbonate armour plating situated 1 cm away from the outer wall. The base of the flume is covered by durable tyre rubber (Attal et al., 2006) that ensures nonsliding conditions for bedload transport, i.e., rolling and mostly saltation. Injection velocity is monitored by an integrated flow meter. During operation, a vortex is created from the centrifugal force on the water column (Attal et al., 2006). The inner part of the vortex overflows the inner flume wall and is funneled through the central sink back into the reservoir tank thus completing the circuit. Chang (1988) showed that for a radially uniform flow, the size of a vortex is related to the mean water velocity across the flume according to

$$dZ \approx \frac{U^2 w}{g r_m} \quad (1)$$

where dZ is the height of the vortex (the height difference between the outer and inner flume walls), U is the mean flow velocity across the flume section, w is the flume width, g is acceleration due to gravity, and r_m is the mean curvature radius (radius of the midline) of the flume (Attal et al., 2006). From this equation and measurements of dZ, U can be determined. Direct measurements of flow velocity were made by Attal et al. (2006) using a Pitot Tube. These agreed well with mean water velocity estimates deduced from vortex heights for low bed roughness. For situations with high bed roughness, mean velocity estimates derived from vortex heights can only be used as crude estimates of actual fluid velocity caused by radial variation in measured velocities.

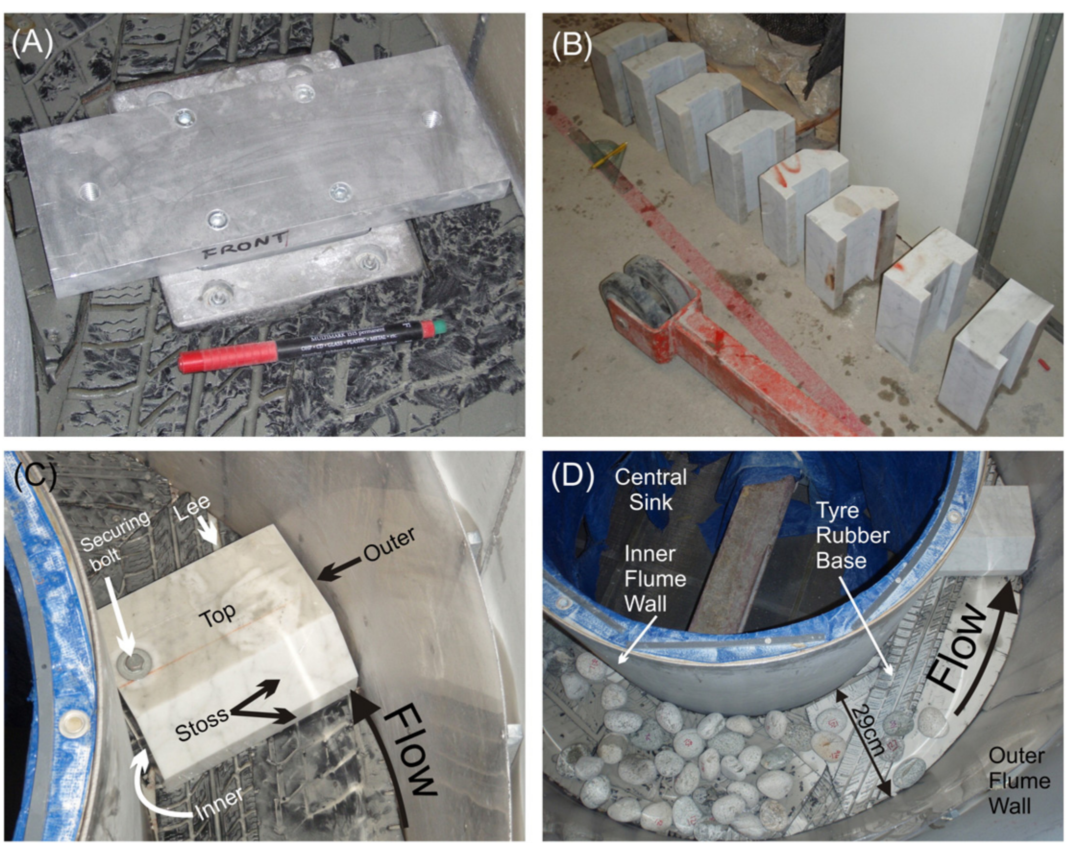

Fig. 1. Experiment apparatus. (A) Anchor manifold in situ in the flume. Note the large threaded hole on the left of the picture for attachment of securing bolt (B) 8 marble specimens (on end) pencil for scale. (C) View of a bedrock specimen inside of the flume (Attal et al., 2006). The specimen can be seen fixed in place on top of the rubber base, with the inner and outer flume walls also visible covered with plastic armour. Note that the outer surface is shielded by the outer flume wall, and the securing bolt is close to the inner flume wall. (D) View of the interior of the flume with 41 of the 72 pebbles used in this experiment suite (M6, 6–8 cm b-axis crystalline pebbles) visible.