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Effect of surface texture and structure on the development of stable fluvial armors

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ABSTRACT

Stable fluvial armors are found in river systems under conditions of partial sediment transport and limited sediment supply, a common occurrence in nature. Stable armoring is also readily recreated in experimental flumes. Initially, this bed stabilizing phenomenon was examined for different flow discharges and solely related to surface coarsening and bedload transport reduction. The models developed suggest a specific armor composition (i.e., texture) dependent on the parent bed material and formative discharge. Following developments in topographic remote sensing, recent research suggests that armor structure is an important control on bed stability and roughness. In this paper, replicated flume runs during which digital elevation models (DEMs) were collected from both exposed and flooded gravel beds are used to interpret armoring manifestations and to assess their replicability. A range of methodologies was used for the analysis, providing information on (i) surface grain size and orientation, (ii) bed-elevation distributions, (iii) the spatial coherence of the elevations at the grain-scale, (iv) surface slope and aspect, (v) grain imbrication and (vi) the spatial variability in DEM properties. The bed-surface topography was found to be more responsive than bed-material size to changes in flow strength. Our experimental results also provide convincing evidence that gravel-beds' response to water-work during parallel degradation is unique (i.e., replicable) given the formative parameters. Based on this finding, relationships between the armors' properties and formative parameters are proposed, and are supported by adding extensive data from previous research.

Classification

7000: Fluvial processes and landforms

1. Introduction

Stable fluvial armors commonly occur in poorly-sorted gravel-bed rivers during partial sediment transport (i.e., when the imposed bed shear stress is less than the critical shear stress required to initiate motion of all particles on the bed surface), with little to no sediment supply from upstream (Proffitt, 1980; Chin et al., 1994; Gomez, 1994; Vericat et al., 2006). The inherent stability-seeking mechanism for the formation of a stable armor is the preferential entrainment (winnowing) of fine mobile particles, uncovering coarse immobile particles forming a layer typically ~1–2 grain diameters thick, which isolates the underlying bed material from the flow to prevent further bed degradation (Parker and Klingeman, 1982; Gomez, 1983; Parker and Sutherland, 1990; Richards and Clifford, 1991; Gomez, 1993; Pitlick et al., 2008). Stable armors hence form as a result of a progressive reduction in sediment transport to practically zero (Gessler, 1967). Stable armors are found downstream of dams and lakes. They also gradually develop in initial reaches of a channel in response to flow and sediment supply, and propagate downstream and activate the same transport reduction in the following reaches (Willets et al., 1988; Paris, 1992).

In the literature, stable armors are also referred to as static armors or pavement, in comparison to mobile or dynamic armors. For the latter, sediment supply from upstream allows for the progressive equalization between the bedload and the subarmor composition (Paris, 1992; Marion et al., 2003; Mao et al., 2011). Mobile armors typically persist over floods (Parker and Klingeman, 1982; Wilcock and DeTemple, 2005; Clayton and Pitlick, 2008), eroded grains being replaced by similar-sized grains originating from upstream reaches. In contrast, stable armors may only persist during floods of a lesser magnitude than the formative flow, as they can “break up” with subsequent river-bed incision during higher flows (Laronne and Carson, 1976; Proffitt, 1980; Gomez, 1983; Chin et al., 1994; Vericat et al., 2006). Armors are also known to (re-)form on the falling limb of a hydrograph, together with a reduction in sediment mobility (Hassan et al., 2006; Mao, 2012). When all particle sizes present on the bed are in motion, no armor can form (e.g., Chin et al., 1994) and the bed's response involves other mechanisms, such as a slope reduction.

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In nature, full mobilization of surface grains in gravel-bed rivers is not a frequent event. For instance, field observations in Carnation Creek in Canada (Haschenburger and Wilcock, 2003) and the lower Ebro in Spain (Vericat et al., 2006) indicate full mobilization for floods with a 7-yr return period or more. Thus, large portions of gravel beds typically remain in the state of partial transport over long periods of time, allowing stable armors to form. This aligns with the assumption that a correct description of sediment transport in most gravel-bed rivers is that of low rates of bed material influx over an already structured bed (Church et al., 1998; Hassan and Church, 2000).

Besides a possible wide occurrence in nature, recreating stable armoring in the laboratory allows the study of bed-flow interactions and the evolution of a gravel streambed under simple experimental conditions (i.e., partial transport and no sediment feed). A recent review by Yager et al. (2015) shows how various feedback mechanisms such as flow turbulence, bed arrangement and sediment transport, are only possible to be studied through laboratory investigations, which in turn will help for our understanding of field processes. Through laboratory studies measuring textural changes for different flow strengths, predictive relationships have been developed and suggest a specific (hence replicable) armor composition, dependent on the parent-bed material and the formative discharge (e.g., Odgaard, 1984; Chin et al., 1994; Garde et al., 2006). This is an important finding, providing means to predict gravel-bed texture given the formative parameters, with important implications also for bed roughness parameterization based on sediment size and use in flow resistance and sediment transport equations. However, surface coarsening and the accentuated hiding of fines by bigger particles that protrude into the flow are primary manifestations of streambed armoring early in the degradation process (Church et al., 1998; Garde et al., 2006; Heays, 2012). To explain the progressive decline in transport characteristic of stable armors, research is evolving to consider not only texture but the actual surface structure (i.e., topography), since the latter offers new perspectives on bed stability and roughness (Lane, 2005; Hodge et al., 2013). For instance, it was hypothesized early that armor formation involves the slow and complete rearrangement of the bed-surface material (Gomez, 1994). This rearrangement can manifest itself through structural changes, e.g., particle imbrication and interlocking (Laronne and Carson, 1976), the formation of small bedforms such as clusters (Chin et al., 1994; Heays et al., 2014) and reticulate stone cells (Church et al., 1998; Hassan and Church, 2000), which increase bed stability.

Recently, the collection and processing of alluvial bed-elevation data at high spatial and temporal resolutions have considerably grown the options to monitor riverbed structures and their adjustments to various flows (Coleman et al., 2011). Analysis of gravel-bed armors using digital elevation models (DEMs) can provide useful information on grain packing, orientation and imbrication, as well as on horizontal and vertical measures of bed roughness at the scales considered (e.g., Nikora et al., 1998; Aberle and Nikora, 2006; Millane et al., 2006; Cooper and Tait, 2009; Qin et al., 2012; Qin et al., 2013; Bertin and Friedrich, 2014). This proved pivotal in understanding the changes in sediment mobility and flow hydraulics due to the armor layer, when traditional surface sampling methods failed (Marion et al., 2003; Cooper et al., 2008; Hodge et al., 2009; Mao et al., 2011; Hodge et al., 2013). Likewise, some workers found the standard deviation of bed elevations (σ_Z) to be a robust measure of effective bed roughness in flow resistance equations (e.g., Smart et al., 2002). Other flume studies showed that gravel-bed topography is indicative of the flows that shaped the surface (e.g., Aberle and Nikora, 2006; Powell et al., 2016), with typical manifestations such as increasing roughness, decreasing bed-surface complexity and flourishing bedforms with increasing flow discharge. Ockelford and Haynes (2013) proved that sub-threshold flows also are able to change bed structure, mainly by re-orientating unstable grains. It has also become clear that fluvial surfaces are regulated by the parent-bed material, sediment shape (Gomez, 1994), and by the amount of sand in the mixture (Curran and Tan, 2014). Summarizing these findings, comparisons between some armor structural properties and formative parameters have been presented (e.g., Mao et al., 2011; Powell et al., 2016). However, whilst previous research recognized the strong correlation between armor structure (e.g., σ_Z) and bed composition (see Pearson et al., 2017 for a summary of the different relationships), it did not make conclusions on the replicability in surface structure. Particularly, Aberle and Nikora (2006) reported differences in armor properties after replicating one of their flume tests, thus casting doubts on the uniqueness of the bed response to a given parent bed material and formative discharge.

In this paper, we use a series of replicated flume experiments to determine stable armor manifestations, extending the range of surface metrics representing texture and structure compared to previous work, and to assess their replicability. Previous studies investigated armor properties for different flow and sediment conditions (Gomez, 1993; Chin et al., 1994; Gomez, 1994; Church et al., 1998; Aberle and Nikora, 2006; Garde et al., 2006; Cooper and Tait, 2009; Mao et al., 2011; Ockelford and Haynes, 2013). Other works studied the changes during the armoring process itself (Hassan and Church, 2000; Marion et al., 2003; Heays et al., 2014; Powell et al., 2016). Here we examine the extent to which fluvial armors are replicable under identical flow and parent sediment bed conditions, in other words, is there a specific relationship between the armor properties and the flow and sediment forming them? To answer this question, we present new insights on the spatial variability within water-worked gravel beds. We also examine the connections between armor properties and formative parameters, and compare our results with extensive data from previous research.

2. Experimental methodology

The armored beds examined in this study were formed in a laboratory flume using sediments mixed from natural river-worn sands and gravels. Six replicated runs were performed, during which an initially screeded flat and poorly-sorted gravel bed was water-worked successively with two discharges until stable armors were formed, in condition of parallel degradation (i.e., no sediment feed and selective entrainment). Bedload reduction during armoring was thus a result of textural and structural changes at the bed surface, rather than a shear stress reduction due to decreasing bed slope. For each test, bedload rate and composition were measured during the degradation process; bed texture and structure were determined prior and after armor formation. To assess the replicability of our experiments, each experimental run was set up identically and flow conditions were kept as constant as possible within and between runs. Water temperature, discharge, shear velocity, and bed levels were monitored throughout each run, with adjustments made when necessary. In particular, the condition of a constant bed shear stress despite bed degradation was justified by raising the sediment bed according to the depth of erosion, to maintain bed and water surface slopes steady, a technique successfully used previously (e.g., Chin et al., 1994; Heays et al., 2014).

2.1. Experimental environment

The experiments were conducted in a non-recirculating tilting flume with glass side-walls, 19 m long, 0.45 m wide and 0.5 m deep, shown in Fig. 1. A 0.95 m long, 0.45 m wide and 0.13 m deep sediment recess (called the test section), with a vertically adjustable table that supported the movable sediment bed, was installed 10.4 m from the flume inlet. To facilitate the development of a fully turbulent boundary layer and homogeneous hydraulic conditions, the approach bed was roughened by an attached single-particle-thick layer of gravel, simulating the roughness of an armored bed; the flume bed downstream of the test section was coated with an exact replicate (plastic mold) of a stable armor obtained at the Leichtweiss-Institute for Hydraulic Engineering in Braunschweig, Germany (Spiller et al., 2012), with a texture and structure resembling (parent bed $D_{50} = 5$ mm, $D_{100} = 31.5$ mm, and