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Period and amplitude of bedload pulses in a macro-rough channel

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ABSTRACT

It is known that bedload fluctuates over time in steep rivers with wide grain size distributions, even under conditions of constant sediment feed and water discharge. Bedload fluctuations, which are a consequence of grain sorting, are periodic and are related to fluctuations in the flow velocity and channel-bed morphology. The presence of large relatively immobile boulders, such as erratic blocks that are often present in mountain streams, has a strong impact on flow conditions and sediment transport. However, their influence on bedload fluctuations has not been studied. Sediment transport fluctuations were investigated in this study in a set of 38 laboratory experiments carried out on a steep tilting flume under several conditions of constant sediment and water discharge for three different slopes ($S = 6.7\%$, 9.9%, and 13%). Sediment transport, bulk mean flow velocities, and variables describing the channel-bed morphology were measured regularly during the experiments. Periodic bedload pulses were clearly visible in all of the experiments, along with flow velocity and channel-bed morphology fluctuations. Correlation analysis showed that the durations of these cycles were similar, although they were not necessarily in phase. The pulses were characterized by their amplitude and period as a function of various boulder spatial densities and diameters. We could show that for higher stream power the fluctuations decrease in cycle duration and in amplitude. The presence of boulders increases the stream power needed to transport a given amount of sediment, thus decreasing the bedload fluctuations.

1. Introduction

Despite the importance of mountain rivers in the control of the sediment supply to lowland mild-slope rivers (Wohl, 2000; Yager et al., 2007), only a few studies were conducted on steep channels; and these were primarily performed in the last two decades. Steep channels are a subset of mountain rivers and are typically characterized by longitudinal slopes larger than 4–5% (Comiti and Mao, 2012) and by channel beds composed of coarse mobile sediments and large and relatively immobile blocks or boulders (Rickenmann, 2001; Papanicolaou et al., 2004; Yager et al., 2007). Boulders can be found in steps spanning the whole channel width (step–pool morphology) or in a more irregular manner (cascade morphology) (Montgomery and Buffington, 1997). In these streams, the water depth is typically shallow in comparison to the roughness of elements such as the large boulders, the latter being considered macro-roughness elements when the relative roughness – defined as the ratio between the roughness scale and the water depth – exceeds the unit value (Bathurst, 1978).

The wide grain size distribution present on steep slopes has a noticeable impact on bedload, causing its fluctuation even under constant water and sediment feed (Iseya and Ikeda, 1987; Frey et al., 2003). According to Iseya and Ikeda (1987), two main factors cause sediment transport to fluctuate, namely, migration of bedforms and segregation of the surface grain size distribution, which results in the formation of an armor layer. According to these authors, the longitudinal sediment sorting occurs when graded sediments are constantly fed into a flume, producing rhythmic fluctuations in the bedload transport rate. The occurrence of longitudinal sediment sorting influences, in turn, the availability of sediment particles and determines the magnitude of the sediment transport rate and its pulses. Recking et al. (2009) indicated that the fluctuation of sediment transport rate is accentuated in low-flow conditions (small discharge) and is associated with fluctuations of bed slopes, bedload, and bed state. Recking et al. (2008a, 2009) carried out tests with uniform and wide grain size distribution on similar installations and noticed that bedload fluctuations were not observed in setups with uniform grain size distributions, confirming that fluctuations are a consequence of grain sorting in mixed sediment compositions.

Isolated boulders, such as those found in streams characterized by a cascade morphology (Montgomery and Buffington, 1997), are another fact that affects the bedload transport rate (Yager et al., 2007). Boulders that act as macro-roughness elements endure a significant part of the total stress and disrupt the flow by altering the channel roughness (Wohl, 2000; Yager et al., 2007; David et al., 2011). The form drag caused by boulders increases with the number of boulders, resulting in lower shear stresses available at the bed for sediment entrainment (Bathurst, 1978; Lenzi et al., 2006; Yager et al., 2007, 2012). Hence, the presence of boulders decreases the sediment transport capacity (Yager et al., 2007, 2012; Ghilardi and Schleiss, 2012). The effect of

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boulders on flow conditions (i.e., bed shear stress and bed resistance equations) and thus on sediment transport capacity can be accounted for via several morphological parameters, such as their protrusion, their cross section, the bed surface area occupied by them, the distance between boulders and a drag coefficient (Bathurst, 1978; Canovaro et al., 2007; Yager et al., 2007; Pagliara et al., 2008; Yager et al., 2012). The presence of hydraulic jumps downstream of steps or boulders is another parameter clearly linked to the channel-bed morphology, as described by several authors (Comiti and Lenzi, 2006; Wilcox and Wohl, 2007; Endreny et al., 2011; Nitsche et al., 2011). Along with the form drag resistance caused by boulders, energy can be dissipated by spill resistance from flow acceleration and deceleration, which usually occur over or downstream of steps in rivers (Curran and Wohl, 2003; David et al., 2011). These energy losses caused by spill resistance are linked to the presence of hydraulic jumps downstream of steps or boulders and are proportional to the drop height (Curran and Wohl, 2003; Comiti and Lenzi, 2006). The presence of hydraulic jumps and the associated energy dissipation will therefore have an impact on the sediment transport capacity.

Sediment transport phenomena are generally analyzed in terms of excess bed shear stresses (Fernandez Luque and van Beek, 1976; Smart, 1984; Rickenmann, 1997; Recking et al., 2008b). Several authors noted the possible dependence of critical bed shear stress on the channel gradient (Papanicolaou et al., 2004; Lamb et al., 2008; Recking et al., 2008b) and channel-bed morphology (Church et al., 1998), along with the channel roughness and hiding effects associated with a wide grain size distribution (Buffington and Montgomery, 1997; Lenzi et al., 2006). However, bed shear stress calculations require a precise knowledge of the channel hydraulics, which has a high local variability in mountain rivers and is difficult to assess. Various studies expressed therefore bedload transport rates as a function of stream power (Bagnold, 1966, 1980; Parker et al., 2011), which quantifies the rate of loss of energy as water flows downstream and thus the power available for performing geomorphic work (Bagnold, 1966; Ferguson, 2005; Petit et al., 2005; Parker et al., 2011). According to Bagnold (1966), the stream power per unit width ω depends on such bulk channel properties as the river width and slope, combined with the discharge of the river, as expressed in the following equation:

$$\omega = \rho g q S = \tau U \tag{1}$$

where ρ (kg m^{-3}) is the fluid density, g (m s^{-2}) is the acceleration caused by gravity, q (m^3 s^{-1} m^{-1}) is the specific discharge, S (−) is the slope, τ (N m^{-2}) is the total bed shear stress, and U (m s^{-1}) is the average flow velocity. Bagnold proposed that the bedload transport rate increases nonlinearly with stream power above a threshold or critical value. Petit et al. (2005) suggested that the critical specific stream power increases with the bedform scale because of the significant loss of energy available for sediment transport.

The goal of the research discussed herein was to identify the feedback between the time-varying flow velocity, channel-bed morphology (boulder protrusion, boulder surface, and number of hydraulic jumps), and sediment transport pulses in steep channels with cascade morphology. To reach this goal, systematic experimental tests were performed using a laboratory flume and varying channel slope, size, and spacing of boulders, as well as time-constant water and sediment supply.

2. Research methods

The effect of randomly distributed, relatively immobile boulders, reproducing a cascade morphology as described by Montgomery and Buffington (1997), on bedload fluctuations was investigated by means of laboratory experiments carried out on a steep (S = 6.7%, 9.9%, and 13%), 8-m-long (7-m-usable), 0.25-m-wide tilting flume at the Laboratory of Hydraulic Constructions (LCH) of the Ecole Polytechnique Fédérale de Lausanne (EPFL) (Fig. 1A).

A plane bed of 0.2 m thickness was prepared before the experiments and the boulders, with mean diameters ranging between one-third and one-half of the flume width, were placed in the flume half covered by mobile sediments, which corresponded to a protrusion of ~30% of the diameter ($P^* \approx 0.3$). Boulders are herein defined as elements that are not transported by the flow, although they may move up to several times their diameter during experiments, mainly caused by the scour holes formed around them. The boulder diameter D (m) and the dimensionless distance between boulders λ/D (−) (where λ (m) is the average distance between boulders; Yager et al., 2007) used for a given test (cf. Table 1) determined the number of boulders to be used during the experiment. Their position was randomly determined on the transversal and longitudinal axis in such a way that they would not be superimposed (Ghilardi, 2014). Water and sediments were supplied at the flume inlet. Measurements of bedload, flow velocity, and several morphological parameters were performed as explained next.

Water discharge, supplied constantly by the closed general pumping system of the laboratory, was controlled by an electromagnetic flow meter (±0.01 l/s). Sediments were constantly fed into the system by a calibrated sediment feeder situated upstream (1 in Fig. 1A). A filtering basket (2 in Fig. 1A) suspended from a balance (3 in Fig. 1A) recovered the sediments at the outlet, where the weight (±1 kg) was measured every minute. The 1-min interval sediment discharge measurement was then averaged over a sliding window ($q_{s,out,X}$, where X represents the size of the window), to provide a smoothed overview of the bedload time evolution. The size of the sliding window (X) is visually defined in order to reproduce all peaks in sediment transport; for the several experiments, it ranged between 3 and 10 min. Sediments were

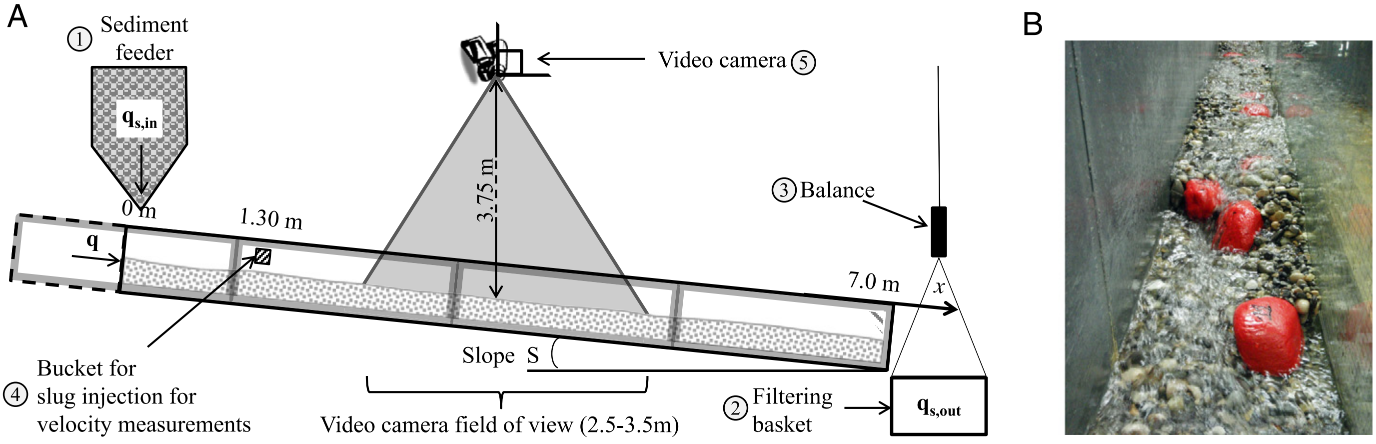

Fig. 1. (A) Sketch of the experimental setup; (B) example of the channel-bed morphology during an experiment.