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# Fluctuations and time scales for bed-load sediment motion over a smooth bed

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ABSTRACT

Results are presented for experiments of bed-load sediment transport over a plane, smooth bed. The smooth-bed configuration, though not adequate for mimicking natural streams, enables the effects of bed roughness to be filtered out, thus, highlighting the role of flow turbulence for particle dynamics. Sediments were individually tracked along their paths, measuring position and velocity of the individual grains. A number of analyses were then applied to the data: probability density function, auto-correlation, and spectra of the grain velocity. Several Lagrangian time scales of particle motion were obtained and compared to available data for the turbulent flow field to determine a phenomenological interpretation of the process.


## 1. Introduction

Recent years have seen research on sediment transport switching from the most classical approaches with development of prediction equations for the solid discharge (e.g., Einstein, 1950; Meyer-Peter & Müller, 1948; Van Rijn, 1984) to more sophisticated analyses of grain kinematics and dynamics (e.g., Ancey et al., 2008; Drake et al., 1988; Lajeunesse et al., 2010; Niño & Garcia, 1998; Roseberry et al., 2012), thanks to continuous advancement in measurement techniques. The scientific community strives in this way towards (i) interpretation of the physical processes governing sediment transport and (ii) development of physically-based transport formulae.

Most of the studies on sediment transport have been conducted for rough-bed conditions. A comparatively lower, still not negligible, number of works exists for sediment transport over a smooth bed. Such a condition is obviously not realistic for natural streams. However, the smooth bed configuration filters out the effect of bed roughness on the moving particles and can, thus, give insight into how the turbulent flow affects the sediment motion, in an attempt to separate the roles of different agents on the transported grains (Campagnol et al., 2014).

A first category of studies on smooth-bed sediment transport has dealt with establishment of thresholds for several phenomenological conditions. For example, Novak and Nalluri (1975, 1984) analysed the incipient motion conditions for bed load; James et al. (2011) studied the mode of motion of particles (in terms of individual or collective motion); even though particle suspension is not within the scope of the present manuscript, it is here recalled that some works attempted delineating a threshold for onset of suspended sediment transport (e.g., Cheng & Chiew, 1999; Hamm et al., 2009; Niño et al., 2003).

Other analyses focused attention on the kinematics of bed-load particles. For example, Hu and Hui (1996) and Julien and Bounvilay (2013) conducted experiments with particle motion by saltation and rolling, respectively, and provided jump-averaged or channel-averaged values of bed-load grain velocity. Results for the smooth-bed condition could be compared with analogous ones for rough beds.

Attempts have finally been made in order to interpret the dynamics of sediment entrainment in light of the structure of turbulent boundary layers and the burst cycle. Rashidi et al. (1990) presented experiments with relatively concentrated particles released over a smooth bed; they argued that particle motion would be triggered by ejection events in the flow field and also analysed the feedback effect of the transported sediments on turbulence intensities and Reynolds stresses. Niño and Garcia (1996) presented experimental visualizations of particle motion over an erodible bed for hydraulically smooth flows; they proposed as well an entrainment mechanism based on flow ejections. Sechet and Le Guennec (1999) coupled Laser-Doppler Anemometer (LDA) measurements of flow velocity at a single point and

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tracking of sparsebed sediments; they compared the statistics of particle resting times to those of the intervals between successive events of the burst cycle, finally proposing an entrainment mechanics based mostly on ejections. These three works, that in summary shared a very fine size of sediments (up to 0.5 mm) but presented different phenomenological combinations of bed type and sediment concentration, are, therefore, in general agreement on the interpretation of particle entrainment.

The present paper describes the results of new sediment transport experiments carried out over a smooth bed. The phenomenological condition studied was that of a continuous particle motion, mostly by rolling, with negligible particle-to-particle interaction. The kinematics of individually tracked bed-load particles is described by several statistical analyses of the grain velocities. The distinctive feature of the present work in comparison with the literature works previously mentioned is a systematic analysis of characteristic time scales of sediment motion that have been, in general, overlooked by works dealing with averaged velocities or focusing on particle entrainment. Available measurements of fluctuating flow velocities are used to support the interpretation of the results. The paper is organized as follows. Section 2 describes the experimental facilities, the tests, and the measuring methods. The core results are outlined in Section 3. A phenomenological discussion is proposed in Section 4 and Section 5 summarizes the major conclusions.

## 2. Experiments and measurement methods

### 2.1. Laboratory facilities

The experiments reported here were performed at the Hydraulics Laboratory of the Politecnico di Milano using a transparent pressurized duct with rectangular section. Dimensions of the duct were: length of 5.8 m, width of 0.40 m and height of 0.11 m. Steel plates were laid onto the bottom wall while all the other walls were made of plexiglass. In the working section (between 4 and 5 m from the inlet) the bottom was painted black to ensure good contrast with the sediment particles described below. The discharge flowing in the channel was measured by a magnetic flow-metre with an accuracy within $\pm 1\%$. A sketch of the experimental facility is provided in Fig. 1. A covered-flow condition was chosen because the transparent lid ensured good visibility of the experiments (that was necessary as the sediment transport measurements were image-based, see Section 2.2). Such a condition differs from those typically used for sediment transport experiments. However, the suitability of the experimental installation for the study of bed-load sediment transport and local scour processes has been demonstrated in earlier works (e.g., Campagnol et al., 2013; Radice & Tran, 2012; Radice et al., 2009a, 2009b, 2009c, 2010, 2013).

The sediment particles were white PBT (polybutylene terephthalate) grains with a specific gravity $\rho_s/\rho = 1.27$, and the submerged specific gravity was $\Delta = (\rho_s - \rho)/\rho = 0.27$, where $\rho_s$ and $\rho$ are the particle and water densities, respectively. The uniform particles had an aspect ratio of 2 and an equivalent diameter $d = 3.0$ mm.

### 2.2. Experimental runs

Sediment transport tests were run for three discharges of 8.1, 11.1 and 13.0 l/s. Prior to the execution of the transport runs, preliminary experiments in clear-water were conducted to characterize the flow in the duct. Velocity profiles over the vertical were measured with two Ultrasonic Velocity Profilers (UVP) placed on the duct lid at an angle of 80°. The shear velocity $u^*$ was then evaluated by fitting data with the equation $u(z)/u^* = 1/\kappa \times \log(zu^*/\nu) + B$, where: $u(z)$ is the time-averaged stream-wise velocity at elevation $z$; $\kappa = 0.40$ is the von Karman constant; $\nu$ is the kinematic viscosity of water, and $B$ is a constant to be determined by fitting. Fig. 2 depicts the velocity profiles measured in the working section at the duct axis. The vertical resolution of the measurement was 2 mm and the range of elevation used for the estimation of the shear velocity by the logarithmic function was 8–40 mm from the bed.

The sediment transport runs were performed in the following way. The duct was initially filled with water and the desired steady conditions were achieved, then sediment particles were manually fed at the upstream inlet through an opening in the lid (see Fig. 1). The grains touched the bed less than 1 m after the injection point and were not recirculated. The feeding rate was on the order of a few grains over 10 s to minimize the particle-to-particle interaction, and was lower than the transport capacity of the flow; as a result,

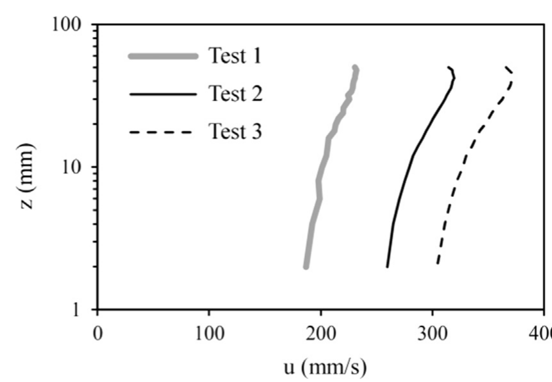


**Fig. 2.** Velocity profiles measured at the duct axis.

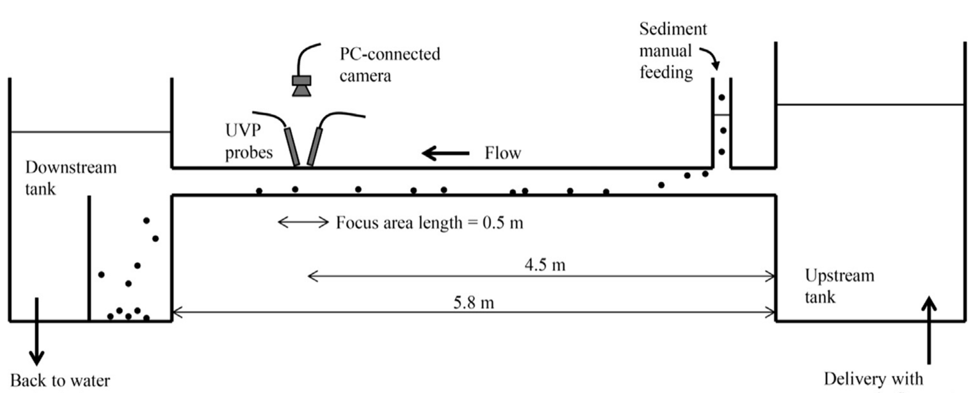


**Fig. 1.** Sketch of the experimental setup.