



Particle saltation trajectories in supercritical open channel flows over a smooth fixed bed

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Abstract

High sediment transport dominated by bed load particle motion in supercritical flows cause (I) bedrock incision in high-gradient mountain streams, and (II) hydro-abrasion at hydraulic structures such as Sediment Bypass Tunnels (SBTs), and Sediment Flushing Channels (SFCs). Therefore, a better understanding of high-speed flow characteristics and bed load particle dynamics is of prime importance for the sustainable design of hydraulic structures, as well as studies of river and landscape evolution. To this end, we experimentally investigated single particle dynamics in supercritical open channel flow over a fixed planar bed. The experiments were conducted in a laboratory flume at VAW simulating a straight section of a SBT. Flow depth at the flume inlet was varied twice with $h_o = 0.045$ and 0.10 m corresponding to the aspect ratios (flume width to water depth) of 4.44 and 2, respectively. 3D flow conditions occurred at such aspect ratios (narrow open channel flow) corresponding to hydraulic conditions of most SBTs. The approach flow Froude numbers were $F_o = 2, 2.5, 3, 3.5, 4, 4.5$ and 5. Motions of two particle types differing in shape and hardness (limestone and quartz) with a constant diameter, $D \approx 7$ mm were investigated at each hydraulic condition. By means of high-speed camera recordings with up to 250 frames/sec, the particle trajectories and velocities were determined. The results showed that the transport mode of particles was dominantly saltation, and the effect of particle shape on particle dynamics was negligible. The saltation characteristics such as hop lengths and particle velocities were in agreement with the literature data.

Keywords: Narrow open channel flow, supercritical regime, high-speed camera measurements, particle tracking, saltation trajectory, SBT hydraulics

1 Introduction

Under the strong impact of climate change, sediment availability, sediment transport from glaciers and rivers and reservoir sedimentation have strongly increased worldwide (Boes and Müller Hagmann 2015). SBTs and SFCs are measures to mitigate reservoir sedimentation, particularly in small- to medium-sized reservoirs in mountainous, non-arid regions. However, high transport rates of bed load particles combined with high flow velocities may cause severe hydro-abrasion on the inverts of SBT and SFCs as well as bedrock incision (Auel *et al.* 2017a, b). For landscape evolution investigation and sustainable design and operation of hydraulic structures, a predictive hydro-abrasion

model is of fundamental importance. To this end, we investigate the supercritical turbulent open channel flow characteristics, bed load particle motion, hydro-abrasion and their interrelations. This study covers the investigation of particle dynamics.

In general, particle motion is divided into three different transport modes: sliding or rolling, saltation, and suspension. Hydro-abrasion on steep bedrock rivers and hydraulic structures is dominantly controlled by the impacts of saltating particles (Beer and Turowski 2015, Auel *et al.* 2017b). Saltation is defined as the sequential particle hops following regular trajectories with downward accelerations of the particles between their bed impacts (Müller Hagemann 2017). The particle saltation trajectory in a flowing water is described by the particle velocity, particle hop length, and particle hop height (Fig. 1). The continuously improving recording and data treatment techniques such as high-speed camera systems have resulted in a number of recent research studies on particle motion (Ancey *et al.* 2002, Lajeunesse 2010, Frey 2014). However, only a few studies exist on the particle dynamics at highly supercritical open channel flows with low roughness heights as in steep bedrock rivers and hydraulic structures (Chatanantavet *et al.* 2013, Auel *et al.* 2017a, b). Sklar and Dietrich (2004) proposed a mechanistic abrasion-saltation prediction model for bedrock abrasion based on a wide range of literature data, and proposed non-dimensional fits for the hop height, hop length and particle velocity versus the transport stage $T^* = (\theta/\theta_c) - 1$, where $\theta = U_*^2/[(s-1)gD]$ = non-dimensional Shields number and θ_c is the critical Shields number, U_* = friction velocity, $s = \rho_s/\rho$ with ρ_s = particle density, ρ = fluid density, g = gravitational acceleration, D = particle diameter, and θ_c = non-dimensional Shields number at incipient motion. Chatanantavet *et al.* (2013) conducted experiments in a wide range of flow conditions up to $F = 5.3$, and proposed a Froude number scaling. In general, all data fits showed that particle hop heights and lengths increase with increasing flow strength expressed by T^* or F . In a recent study, Auel *et al.* (2017a, b) showed that the transport stage T^* represents a more adequate scaling for both the literature and their experimental data. Such a scaling is also relevant for the application of saltation-abrasion models.

Most of the previous studies focused on the single particle motion in sub- and low supercritical flow conditions over a rough bed as present in rivers, but the effects of secondary currents and highly supercritical flows on particle motions in both smooth and rough bed channels were not systematically studied. To fill these research gaps, we systematically investigate the saltation trajectories of natural limestone and quartz particles in supercritical open channel flow with F_o up to 4 and the aspect ratios of $b/h_o = 2$ and 4.44 over a smooth fixed concrete bed. The latter aspect ratio was chosen to compare the present data with the literature.

2 Experimental setup

The experiments were conducted in a $b = 0.20$ m wide, $h = 0.5$ m deep, and $l = 13.5$ m long laboratory model (Fig. 1a). The flume sidewalls were glass and wood, respectively, and the flume bed was made of concrete of 42.2 MPa compressive strength. The supercritical flow conditions were provided with a jetbox system developed at VAW that converts the pressurized flow into the free-surface flow. The jetbox system was gate controlled to adjust the initial flow depth h_0 . The flow depth h was measured every 0.5 m along the flume by Ultrasonic Distance Sensors (UDS) and a point gauge to determine the hydraulic parameters such as friction velocity U^* and flow uniformity. The roughness Reynolds number $k_s^+ = k_s u^* / \nu$ with k_s is the equivalent sand roughness height and ν is the kinematic viscosity. It describes the hydraulic roughness of the bed and was determined by log-fits of the velocity profiles. The flow was in the hydraulically smooth regime with $k_s^+ < 5$. Particle motions in the flow were recorded with the pco.edge® scientificCMOS high-speed camera with a resolution of 2560×400 pixels. The camera system was put at $x = 10$ m, and the recorded frame length was 1100 mm (Fig. 1a). The data acquisition rate was 250 fps with 0.25 ms exposure time. No distortion on the recorded images was determined and one pixel corresponded to 0.476 mm.

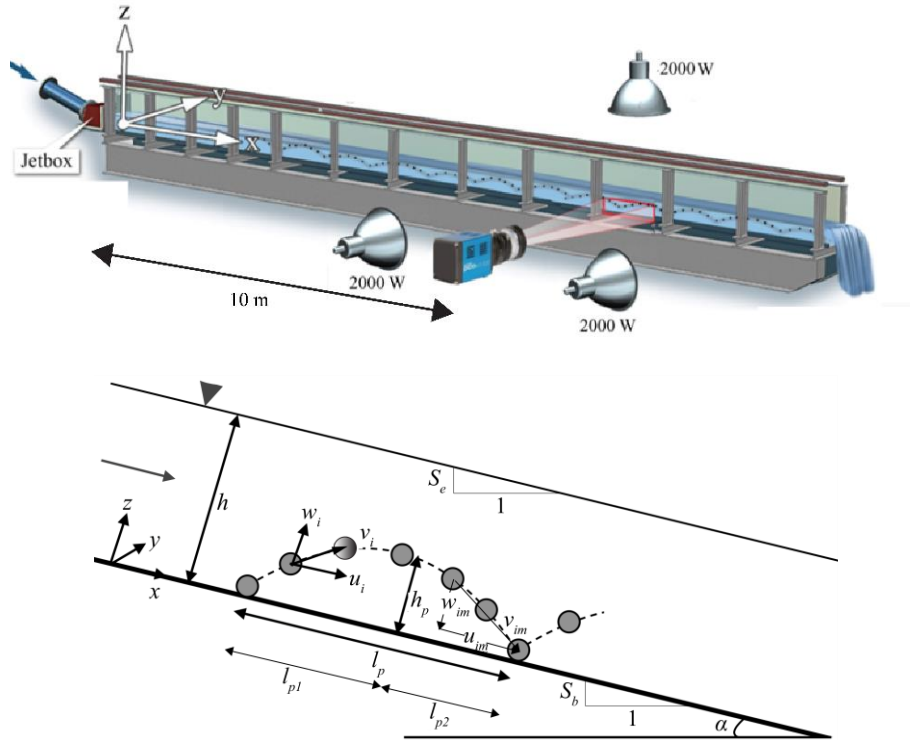


Fig. 1: (a) Experimental setup (b) Parameter definitions for the saltation trajectory of a particle

2.1 Test conditions

In total, 20 tests were conducted on a constant bed slope $S_b = 0.01$ with $h_0 = 0.045$ and 0.01 m, and $F_o = 2-5$ depending on the flow depth (Table 1). In the experiments, natural

limestone and quartz particles were used that were different in hardness. Limestone features a Mohs hardness of 3.5, while quartz is a hard material with 7.0 on the Mohs scale. Every test run was conducted with $n = 120$ different particles of the same size. Based on the camera recordings, the mean diameter of the limestone and quartz particles was determined as $D = 6.93$ and 7.32 mm, respectively. The shape factor κ_R that describes the particle roundness is defined as (Auel *et al.* 2017a):

$$\kappa_R = \frac{P_p^2}{4\pi A_p} \quad [1]$$

Where P_p is the particle perimeter and A_p is the particle area in a 2D profile. The particle is spherical for $\kappa_R = 1$, whereas it becomes elliptical for $\kappa_R > 1$. Based on the high-speed camera measurements, the shape factors were obtained as $\kappa_R = 1.27 \pm 0.10$ and $\kappa_R = 1.20 \pm 0.05$ for limestone and quartz particles, respectively.

Table 1: Parameters of conducted test runs

Test run	S_o	F_o	h_o	b/h_o	U_{*c}	θ_c	ρ_s	D	Particle	MH*
	[-]	[-]	[cm]	[-]	[m/s]	[-]	[t/m ³]	[mm]		
T1-T5	0.01	2: 0.5: 4	10	2	0.017	0.0030	2.40	6.93	limestone	3.5
T6-T10	0.01	3: 0.5: 5	4.5	4.44	0.017	0.0030	2.40	6.93	limestone	3.5
T11-T15	0.01	2: 0.5: 4	10	2	0.017	0.0024	2.65	7.32	quartz	7.0
T16-T20	0.01	3: 0.5: 5	4.5	4.44	0.017	0.0024	2.65	7.32	quartz	7.0

MH* represents Mohs hardness

2.3 Data analysis

In the experiments, the particles were dominantly transported in saltation. The particle center coordinates and their displacements on x - z plane were determined from each recorded image i and two consecutive images, respectively, using a VAW-developed and MATLAB-based image processing software. The instantaneous streamwise and normal velocities u_i and w_i (Fig. 1b) were computed by dividing the particle displacements by the time interval between these images as:

$$u_i = \frac{\Delta x}{\Delta t}, \quad w_i = \frac{\Delta z}{\Delta t} \quad [2]$$

The resultant instantaneous velocity v_i and the mean particle velocity V_p follows from

$$v_i = \sqrt{u_i^2 + w_i^2}, \quad V_p = \frac{1}{n} \sum_{i=1}^n \left(\frac{1}{i} \sum_{i=1}^i v_i \right) \quad [3]$$

The particle impact velocity v_{im} was determined from the instantaneous particle velocities just before every single particle impact. The mean particle impact velocity V_{im} was obtained averaging v_{im} over the recording section for $n = 120$ particles. The saltation trajectory of a single particle is defined by the hop length l_p and hop height h_p between

two particle impacts. l_{p1} and l_{p2} donate the rising and falling limb lengths, respectively, $l_p = l_{p1} + l_{p2}$, and h_p is the highest distance of the particle center from the bed (Fig. 1b). The mean hop length L_p and hop height H_p were thus determined by averaging l_p and h_p values over the recording section and the number of recorded particles.

3 Results

The particle velocity is expressed in a dimensional form using the friction velocity as (Auel *et al.* 2017a):

$$V_p = a(U_* - U_{*c}) \quad [4]$$

where a is the flow parameter and U_{*c} is the critical friction velocity at motion onset. The friction velocity U_* was obtained for each experiment using the energy line slope (S_e) as $U_* = (gR_h S_e)^{0.5}$, where $R_h = A/P = bh/(b+2h)$ is the hydraulic radius, with A = cross-sectional flow area and P = wetted perimeter and for rectangular cross-section. Figure 2 shows that the mean particle velocity V_p linearly increases with the friction velocity U_* and particle properties do not affect this relationship. The curve fitting gives:

$$V_p = 24(U_* - 0.017) \quad [5]$$

Using the mean critical friction velocity $U_{*c} = 0.017$ m/s, the mean critical Shields number $\theta_c = U_{*c}^2 / [(s-1)gD] = 0.0027$ is determined (Fig. 2). As expected the critical Shields number is smaller than that of Auel *et al.* (2017a) because the flume bed in the present study is hydraulically smooth compared to Auel's transitionally rough bed condition.

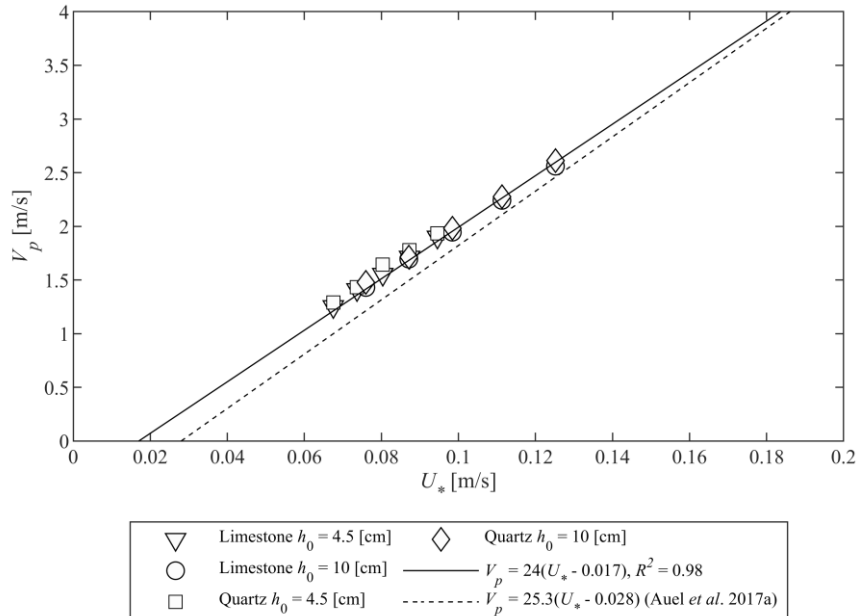


Fig. 2: Particle velocity (V_p) versus friction velocity (U_*)

To compare our data with the literature data, the transport stage T^* was calculated using the following formula:

$$T^* = \frac{\theta}{\theta_c} - 1 = \left(\frac{U^*}{U_{*c}} \right)^2 - 1 \quad [6]$$

Figure 3a shows the hop length L_p , normalized by the particle diameter D versus T^* for our data with the best fit, and the fits proposed by Sklar and Dietrich (2004) and Auel *et al.* (2017a). The present data fit results in:

$$\frac{L_p}{D} = 4.73(T^*)^{0.62} \quad R^2 = 0.98 \quad [7]$$

Although Sklar and Dietrich's (2004) data fit highly deviates from our data, the equation developed by Auel *et al.* (2017a) matches with our data with $R^2 = 0.75$. This correlation is considered as satisfactory because there is only 20 experiments presented. Figure 3a also reveals that the effects of different material properties such as hardness, shape and specific weight of limestone and quartz as well as the present hydraulic conditions, i.e. low aspect ratio, on the hop lengths is negligible.

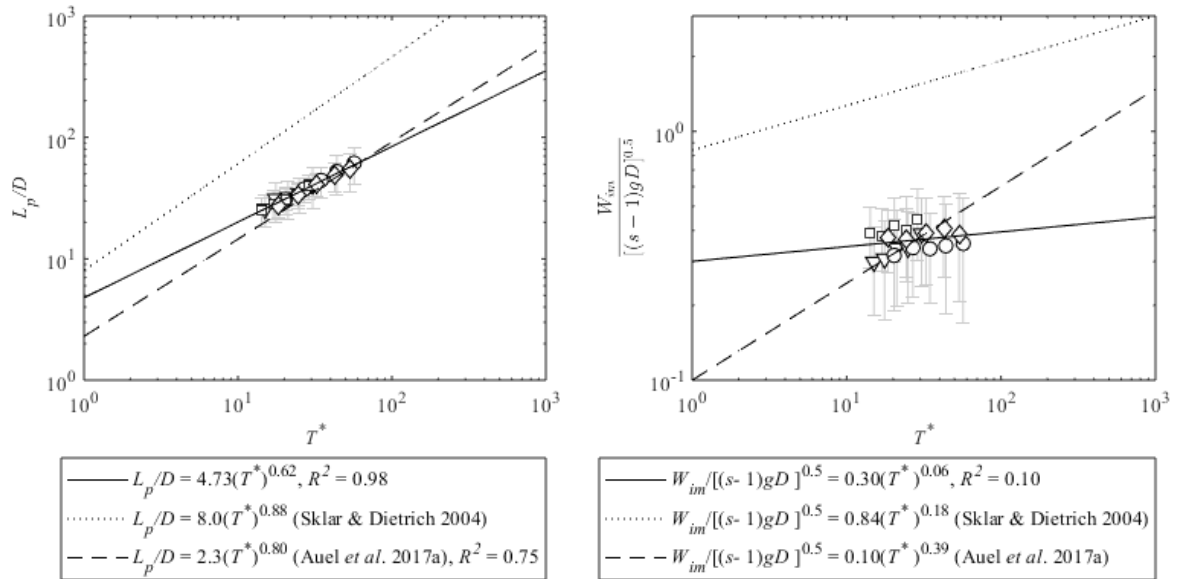


Fig. 3: (a) Normalized hop length (L_p/D) versus excess transport stage (T^*) (b) Normalized vertical impact velocity ($W_{im}/[gD(s-1)]^{0.5}$) versus excess transport stage (T^*); symbols as in Fig. 2. Error bars denote standard deviation.

Figure 3b shows the normalized vertical impact velocity W_{im} versus the transport stage T^* for our data together with the best fit, and the fits developed by Sklar and Dietrich (2004) as well as Auel *et al.* (2017b). The present data fit yields:

$$\frac{W_{im}}{[(s-1)gD]^{0.5}} = 0.30(T^*)^{0.06} \quad R^2 = 0.10 \quad [8]$$

Equation 8 presents a low correlation to our data, with a standard deviation of W_{im} of $\sigma = 0.14 \pm 0.02$ m/s. Similar to the hop length data fitting (Fig.3 a), Sklar and Dietrich's fit strongly deviates from our data, whereas the fit developed by Auel *et al.* (2017a) overlaps with our data in a small range of T^* . Figure 3b indicates that the vertical impact velocities slightly depends on the particle shape and/or specific weight. Rice (1991) stated that decreasing sphericity causes longer and flatter trajectories on aeolian sediment transport. As a result, W_{im} decreases with decreasing sphericity for a given transport stage due to longer and flatter trajectories. This is in agreement with our finding, i.e. lower W_{im} of limestone particles compared to quartz.

4 Conclusions & Outlook

This paper reports the results of a systematic study on single particle motions in supercritical flow in a narrow and hydraulically smooth bed open channel simulating a SBT section. The trajectories of limestone and quartz particles that are different in shape, hardness and specific weight were determined for a wide range of hydraulic conditions up to $F_0 = 4$ and aspect ratios of 2 and 4.4 using a high-speed camera set-up and a VAW-developed particle tracking software. The results are compared with literature data from Sklar and Dietrich (2004) and Auel *et al.* (2017a, b). The present equations developed for the particle dynamics largely deviate from those from Sklar and Dietrich (2004), whereas they are mostly in agreement with those from Auel *et al.* (2017a, b). All the data fits show that particle hop lengths and velocities increase with increasing flow strength expressed by transport stage T^* . The effect of particle properties such as the shape, and hardness of the particles on saltation trajectories were negligible. The findings of this paper will help to advance our understanding of the particle motion characteristics in 3D supercritical open channel flows and accordingly contribute to adapt the mechanistic abrasion models. Further experiments with different particles, i.e. sandstone, quartzite and dolomite will be conducted over both smooth and abraded, i.e. rough, beds under the same hydraulic test conditions, and accordingly the present equations will be revised.

Acknowledgement

This project is financially support by the Swiss National Science and Foundation (SNSF), Project No: 166253. VAW's activities in hydropower research are embedded in the Swiss Competence Center for Energy Research, Supply of Electricity (SCCER-SoE), i.e. an initiative funded by the Swiss Confederation through Innosuisse (Swiss Innovation Agency).

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