BED-LOAD PARTICLE MOTION IN SUPERCRITICAL OPEN CHANNEL FLOW

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1. INTRODUCTION

Supercritical sediment-laden open channel flows occur in many hydraulic structures including dam outlets, weirs, and bypass tunnels. Due to high flow velocities and sediment flux severe problems such as erosion and abrasion damages are expected in these structures (Jacobs et al., 2001). Sediment bypass tunnels (SBT), as an effective measure to decrease reservoir sedimentation by bypassing sediments during floods, are exceptionally prone to high abrasion causing significant annual maintenance cost (Sumi et al., 2004; Auel and Boes, 2011). The Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of ETH Zurich conducted a laboratory study to counteract these negative effects (Auel, 2014). The main goals of the project were to analyze the fundamental physical processes in supercritical flows as present in SBTs by investigating the mean and turbulence flow characteristics (Auel et al., 2014a), particle motion (Auel et al., 2014b; 2015b), and abrasion development caused by transported sediment. Besides new insights into the three listed topics, paramount interest is given to their inter-relations and the development of an easily applicable abrasion prediction model (Auel et al., 2015a). This paper presents selected results on the second topic, i.e. the analysis of saltation trajectories of single coarse particles in supercritical flow.

2. EXPERIMENTAL SETUP

The experiments were conducted in a 13.50 m long, 0.30 m wide laboratory flume with a maximum discharge of Q_{max} = 250 l/s. Sediment motion was recorded using a high-speed camera system with a framerate of 240 Hz at a resolution of 2560 × 400 pixels. Each particle was separately added by hand at the flume inlet. In total 264 experiments were conducted by systematically varying the bed slope S_b = 0.01 and 0.04, the approach flow depth h_o = 50 and 100 mm, particle diameter D ≈ 5, 10, and 17 mm, particle type (spheres and natural sediment) and Froude number $\mathsf{F}_o = U/(gh_o)^{0.5}$ = 1.25, 1.5 to 6.0 (in 0.5 steps) with U = flow velocity, and g = gravitational acceleration. Every run included both glass spheres and sediment grains and was repeated 20 times to allow for a sound statistical analysis. Image processing was carried out by an in-house developed Matlab Code based on a similar algorithm as applied by Detert and Weitbrecht (2012) for the object detection software Basegrain. Detailed information regarding the model flume as well as the recording technique and the data analysis are found in Auel (2014) and Auel et al. (2014b, 2015b).

3. SELECTED RESULTS

A particle trajectory in saltation motion in a water stream is defined by its particle hop length L_p and hop height H_p. Figures 1 and 2 show the results of both parameters obtained from the data analysis conducted in Auel (2014) and described by Auel et al. (2015b). L_p and H_p are scaled with D as a function of the Shields parameter, $\theta = U_*^2 / [(\rho_s / \rho - 1) gD)]$ with U_* = friction velocity, ρ_s = particle density, and ρ = fluid density for both materials (a) focusing on the effects of the particle shape and (b) the flume slope S_b. A submergence effect, i.e. an effect of the water level on the particle trajectory was rarely observable in the experiments since only 1.5% of the test runs are above a relative submergence of h/D > 0.5.

L_p/D as well as H_p/D linearly scale with θ for both materials, i.e. the higher the flow or friction velocity, the longer and higher the particle jump. The correlation is excellent for the scaled hop length and still good for the scaled hop height. However, the data scatter around ±20%. A shape effect is hardly observed, but a slight slope dependence is visible in Figures 1b and 2b, respectively. In general, the normalized hop lengths are slightly larger at the mild bed slope (S_b = 0.01) than those at the steep slope (S_b = 0.04). The higher the bed slope the lower the scaled hop length for identical Shields parameter. Similar behavior is found in the data from Ancey et al. (2002).

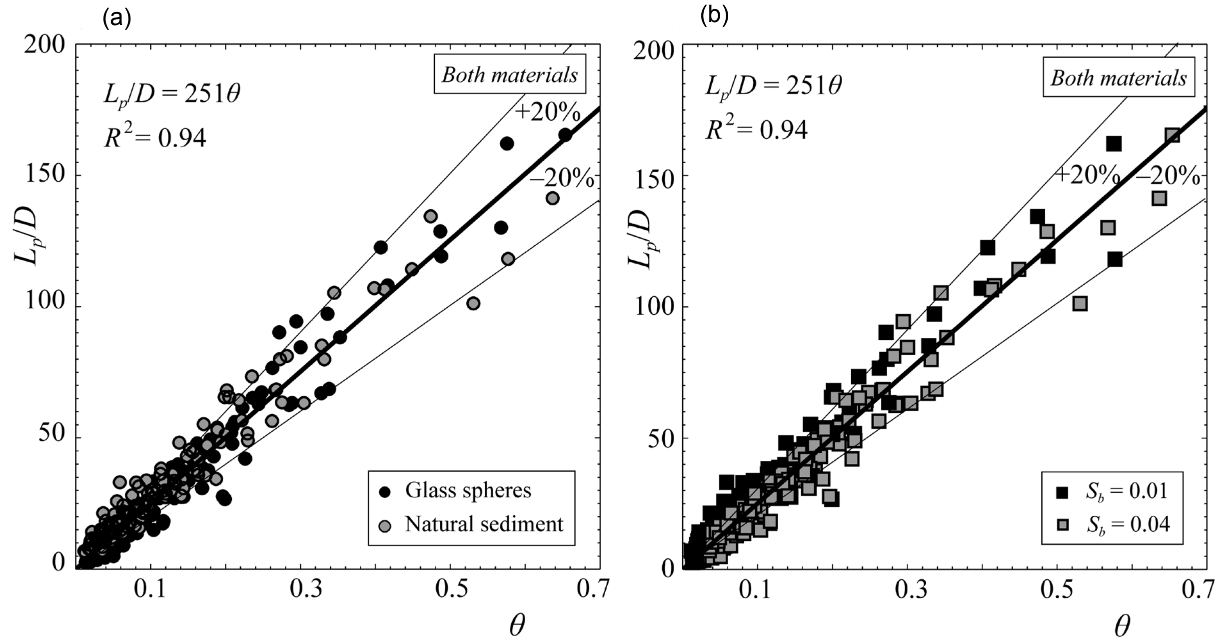

Figure 1: Scaled hop length L_p/D as a function of θ, a) particle type comparison, b) flume slope comparison. Error range ±20%.

The linear fit for the hop length including all data points follows:

$$\frac{L_p}{D} = 251\theta \quad R^2 = 0.94 \qquad [1]$$

This fit is limited to the transport mode shift from saltation to suspension and does not apply for high Shields parameter θ >> 1. To account for the mode shift, Eq. [1] can be rewritten applying a denominator introduced by Sklar and Dietrich (2004) as:

$$\frac{L_p}{D} = \frac{251\theta}{\left(1-\left(U_*/V_s\right)^2\right)^{0.5}} \qquad [2]$$

where V_s = particle settling velocity in still water after Dietrich (1982) or Ferguson and Church (2004).

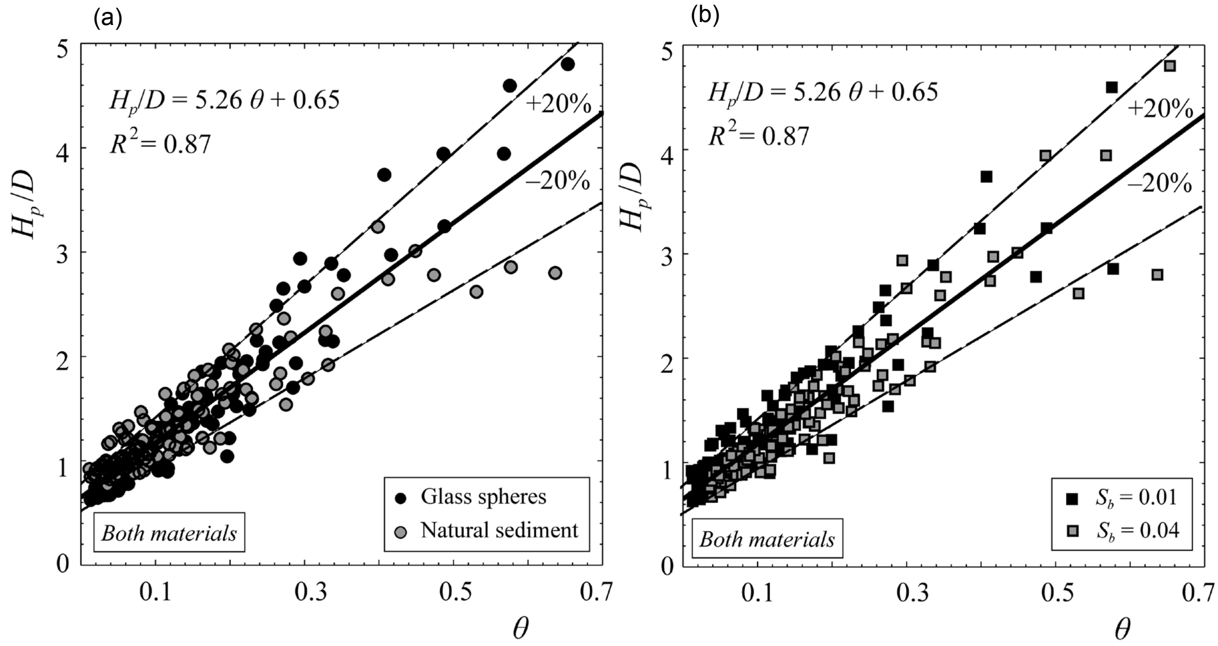

Figure 2: Scaled hop height H_p/D as a function of θ, a) particle type comparison, b) flume slope comparison. Error range ±20%.

The linear fit for the hop height including all data points follows

$$\frac{H_p}{D} = 5.26\theta + 0.65 \quad R^2 = 0.87 \qquad [3]$$

The hop height is defined from the bed to the particle center, consequently the last term on the right hand side should equal to exactly 0.5. The slight deviation of 0.15 is due to the natural gravel grains. The angular shape causes some variation due to the spinning motion. Defining the hop height H_p^* from particle center to particle center means to shift all data by 0.5*D*. This leads to the following fit:

$$\frac{H_p^*}{D} = 5.9\theta \quad R^2 = 0.85 \qquad [4]$$

In most literature studies the hop height H_p is used (Abbott and Francis, 1977; Niño et al., 1994; Hu and Hui, 1996; Niño and García, 1998; Chatanantavet et al., 2013), but also H_p^* seems to be reasonable. Therefore, an exact definition of the hop height is important to avoid misunderstandings.

4. CONCLUSIONS

The hop height and hop length scaled with the particle diameter are primarily sensitive to the bed shear stress and slightly sensitive to the bed slope. However, the particle shape effect on the hop height and length is negligible. The Shields parameter is an adequate parameter to express L_p/D and H_p/D due to the fact, that it does not only involve the bed shear stress, but also the particle density and diameter. Both parameters increase linearly with θ showing a high correlation. The particle trajectories in the present project are rather flat and long compared to literature data analyzed by Sklar and Dietrich (2004). This deviation is due to high Froude numbers and low bed roughness heights, i.e. the transitionally rough bed in the present study. In contrast, the former studies were conducted at sub- and low supercritical conditions. In most studies the bed was either rough or movable. More details on this study including a sound comparison to the literature data can be found in Auel et al. (2015b).

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