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# THRESHOLDS OF UPPER-STAGE PLANE BED REGIME FOR INTENSE BED LOAD IN OPEN CHANNEL

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## ABSTRACT

Results are discussed of laboratory experiments on criteria determining the transition between the regime of dunes and the upper stage plane bed (UPB) regime and the transition between the UPB regime and the regime of wavy flow. The experiments were carried for 3 fractions of plastic material and two fractions of glass beads in a broad range of flow conditions (different discharges of water and solids and longitudinal bed slopes) in a tilting flume.

The experiments reveal that, contrary to expectations, a constant value of the Shields parameter is not an appropriate criterion for the transition between the dune regime and the UPB regime. Instead, the criterion seems to be well represented by a constant value of the longitudinal bed slope. The transition between the UPB regime and the wavy regime is found at a constant value of the densimetric Froude number. Relatively high values of Froude number at the threshold are due primarily to the presence of the collisional transport layer which protects the bed from an influence of undulating water surface.

## KEYWORDS

Sediment transport, two-phase flow, bed forms

## INTRODUCTION

A vast amount of sediment can be transported during flash flood events in mountain streams and rivers. The transported sediment is broadly graded and includes coarse fractions forming intense bed load. At high bed shear typical for flood conditions, the transport is associated with the regime of the upper-stage plane bed (UPB). In the UPB regime, the top of eroded bed is plane (no bed forms occur) and the flow above the bed is stratified [1-2]. Basically, the flow structure is composed of three dominant layers: the bed (deposit) at the bottom, the transport layer adjacent to the bed and the water layer below the water surface (Figure 1). A majority of bed load is transported in the transport layer, where individual particles are subject to intense collisions with surrounding particles. Occasionally, some particles are kicked out of the transport layer to the water layer and spend some time there before they join the collisional transport layer again. In the UPB regime, resistance of flow carrying bed load is due primarily to the interaction of transported particles with the top of the plane bed [1].

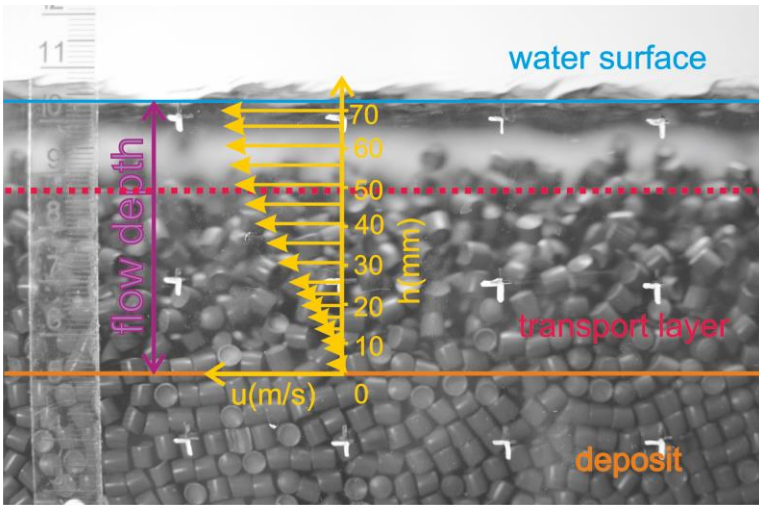


*Fig 1: Typical flow structure in UPB regime*

Mechanisms of friction of sediment-laden flow and transport of intense bed load are subjects of investigation in both the macroscale and the microscale. The macroscopic approach [1] relates the friction- and transport parameters with the integral quantities of flow (the average velocity of flow, the average concentration of transported sediment, the total flow depth, the average shear stress at a boundary etc.). The microscopic approach [2] describes local stresses, velocities and concentrations of sediment in the layered structure of intense bed load. Both approaches address a problem of limits of the UPB regime, i.e. thresholds at which the UPB regime transforms to other regime. In this article, we follow the macroscopic approach to investigate criteria and conditions for the thresholds.

In general, a development of different regimes and thus different bed forms (ripples, dunes, antidunes) is sensitive to density and size of sediment particles (the median diameter, $d_{50}$, particle density $\rho_s$) and to parameters associated with carrying liquid (density of fluid, $\rho_f$, fluid kinematic viscosity, $v_f$) and with flow (average flow velocity $U$, depth $H$, gravity acceleration $g$). In literature, different dimensionless parameters composed of the listed quantities are suggested to express the thresholds for the bed regimes. Some methods do not consider the influence of sediment particle density and focus on a natural sediment of a constant density [3]. Other methods include the sediment density effect, for instance in an expression for a dimensionless particle diameter as in [4].

## METHODS

### Experimental set-up

Our experimental investigation of the UPB limits was carried out in a tilting flume of the Water Engineering Laboratory at Faculty of Civil Engineering of the Czech Technical University in Prague. The flume is a part of a recirculating system through which a mixture of water and sediment is driven by centrifugal pumps (Figure 2). The flume and its measuring instruments are described in details elsewhere [5,6].

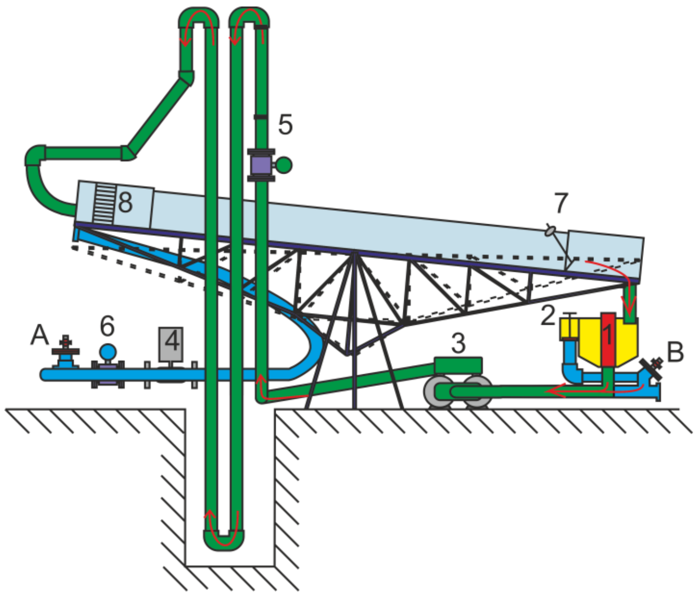


*Fig 2: Tilting flume – 1 - supply and separation tank, 2 – overflow, 3 - centrifugal pump for mixture, 4 - centrifugal pump for water, 5 - flow meter for mixture, 6 - flow meter for water, 7 - outlet with overshot weir, 8 - inlet with flow distributors, A, B - control valves*

## Materials

Five fractions of model sediment were used: two fractions of glass beads of different sizes (TK30, TK1216) and three fractions of plastic granulate (HSF3, TLT25 and TLT50), which differed from each other in size and shape. Properties of the fractions are given in Table 1 ($v_t$ is the terminal settling velocity of particle).

*Tab 1: Properties of used materials*

| *Quantities* | *units* | **HSF3** | **TLT25** | **TLT50** | **TK1216** | **TK30** |
|---|---|---|---|---|---|---|
| $d_{50}$ | *mm* | 3.18 | 4.23 | 5.41 | 1.49 | 3.00 |
| $v_t$ | *m/s* | 0.131 | 0.106 | 0.149 | 0.207 | 0.310 |
| $\rho_s$ | *kg/m³* | 1358 | 1381 | 1307 | 2481 | 2501 |

## Procedures

In total, 216 test runs were carried out in the UPB regime from which 49 runs represented conditions at the limits of the UPB regime. The following criteria were applied to recognize the limits of the UPB regime. In literature, the lower limit of the UPB regime is the threshold at transition to the regime of dunes. In our experiments, however, the transition to dunes was not abrupt and incipient bed undulation got a form of intermittent movement of clusters of particles at the top of the plane bed rather than a form of regular dunes. Hence, we decided to define a development of a continuous transport layer at the top of the plane bed as the criterion for the threshold. Usually, the transport layer was two to three particle diameters thick when it became continuous.

For the upper limit of the UPB regime, literature suggests a transition to the regime of antidunes. Again, our observations indicated a slightly different flow pattern at the transition. We did not observe neither typical standing waves nor downstream/upstream migrating antidunes. Instead, we identified the bottom of the transport layer to become instable and to start following wavy (approximately sinusoidal) paths rather than straight paths typical for the UPB regime. The particle paths seemed to follow the shape of the water surface (the flow was super-critical and the water surface undulated). The top of the bed went through periods of local erosion and deposition synchronized with the wavy shapes of particle paths. We called this condition a wavy flow and considered an incipient development of the wavy flow as the criterion for the threshold of the UPB regime. The upper limit of the UPB regime could not be reached for each mixture discharge in the flume due to limitations given by flow conditions in the connecting pipes of the recirculating system (a danger of deposition of sediment and clogging of the pipes) and the limited capacity of the flume inlet.

## RESULTS

Based on the criteria described above, an experimental data set with points at both thresholds of the UPB regime was collected. Flow conditions at the threshold were evaluated using a modified Shields-Parker diagram with an aim to confirm a bed-load character of the sediment transport. The diagram sorts out flow conditions and bed forms on a basis of two dimensionless groups, the Shields parameter ($\theta$) and shear Reynolds number ($Re_*$). The groups $\theta$ and $Re_*$ are defined respectively as:

$$\theta = \frac{\tau_b}{\left(\rho_s - \rho_f\right) \cdot d_{50} \cdot g} , \tag{1}$$

$$\mathrm{Re}_* = \frac{u^* \cdot d_{50}}{\nu_f} \tag{2}$$

where $\tau_b$ is bed shear stress and $u^*$ is bed shear velocity, $u^* = \sqrt{\tau_b / \rho_f}$ .

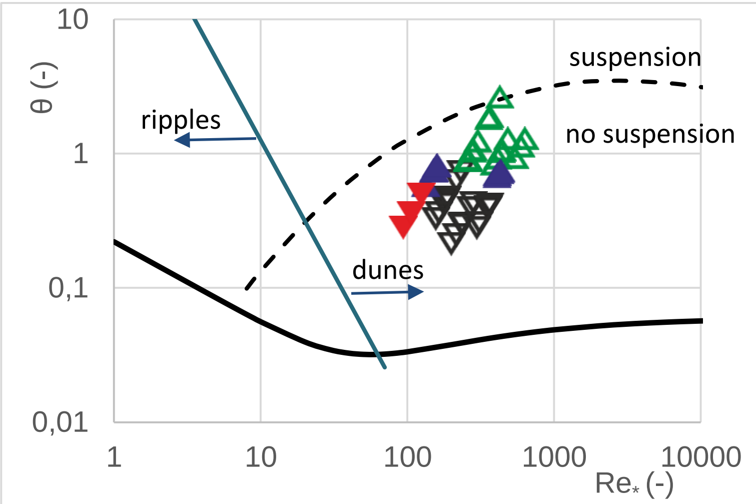


*Fig 3: Experimental results in modified Shields – Parker diagram. Legend: empty symbols = plastic particles, full symbols = glass particles, down-oriented triangles = lower threshold, up-oriented triangles = upper threshold.*

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The evaluation confirmed an absence of suspended load in flows at threshold conditions (Figure 3). Also, the plot shows that the upper threshold of the UPB regime (the transition between the UPB and wavy flow) cannot be associated with a constant value of $\theta$ as suggested in [4].

Figure 4 plots the thresholds at different total discharges of mixture, $Q$, against the corresponding slope of the energy grade line (i.e. the longitudinal slope of the bed in observed uniform flows), $I_e$. The plot reveals an interesting fact that for both the plastic and glass fractions the lower threshold occurs at approximately constant slope no matter how big is the total discharge. It also shows that the threshold slope is sensitive to sediment density, giving the higher slope for the material with the higher density. Our tests revealed a very tight correlation between the slope of the energy grade line and the average delivered (transport) concentration of sediment in the flow for all tested sediment fractions [6]. The delivered concentration is defined as a ratio of the volumetric discharge of sediment and the total volumetric discharge. Hence, the lower threshold seems to occur at a constant value of the ratio of the sediment and mixture discharges.

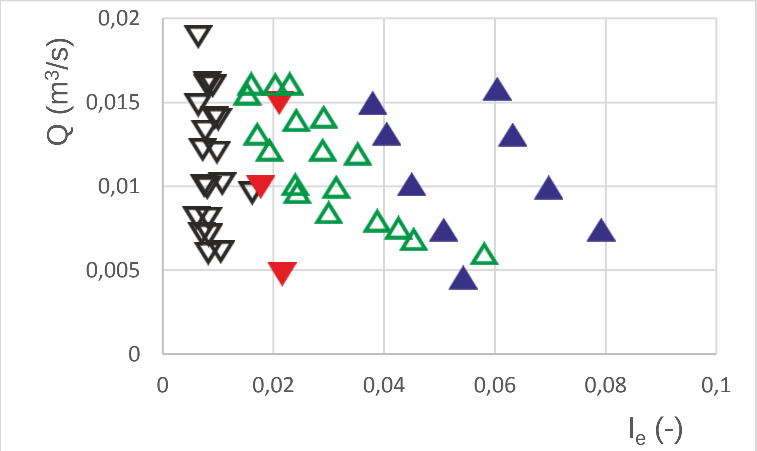


*Fig 4: Relation between total discharge and slope of energy grade line. Legend: as in Figure 3.*

For the upper threshold of the UPB regime, the plot in Figure 4 indicates that a higher slope is required for a lower total discharge to reach the threshold. Thus for low total discharges, the threshold occurs at relatively high delivered concentration and hence at high proportional transport of bed load. It seems that intense transport of bed load stabilizes the UPB regime because the developed collisional transport layer protects the top of the bed from an undulating influence of the water surface.

In literature, the transition from the UPB regime to antidunes is often related to the transition from the sub-critical to super-critical flow, i.e. flow at Froude number $Fr$ = 1 (e.g., 1.0-1.2 in [4]). In our experiments, we take the side-wall effect into account in a calculation of the Froude number so that:

$$Fr = \frac{U}{\sqrt{gR_b}} \tag{3}$$

where $R_b$ is the hydraulic radius of the part of the discharge area associated with the bed.

In Figure 5, $Fr$ is plotted against $\theta$ and the plot shows that the upper threshold is at an approximately constant value of Fr slightly higher than one only for plastic sediments. The threshold

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for the glass sediments corresponds with considerably higher values of *Fr*, say between 1.5 and 2. Following our hypothesis of a collisional layer protecting the top of the bed from the undulation of the water surface in the super-critical flow, it seems that the collisional layer composed of particles of a higher density is more effective in protecting the bed from the undulation than the layer composed of lightweight particles.

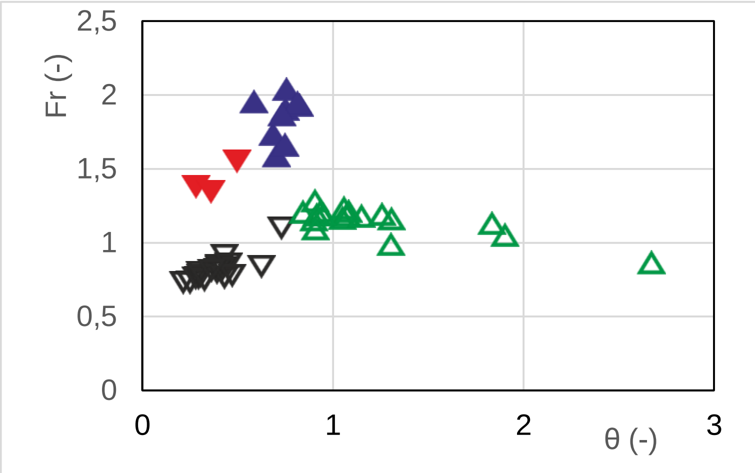


*Fig 5: Relation between Froude number and Shields parameter. Legend: as in Figure 3.*

The question arises - how the effect of different density of particles should be included. We examined a number of regime maps including the effect of $\rho_s$ in the literature and found that our data weas either outside the range of a map or map thresholds did not match our observed thresholds.

We decided to employ the densimetric Froude number in the form which is commonly used to determine a deposition-limit velocity for solid-liquid flows in pressurized pipes [7]. Modified simply for conditions in the open-channel flow, the densimetric Froude number reads:

$$Fr_d = \frac{U}{\sqrt{8 \cdot (s-1) \cdot g \cdot R_b}} \tag{4}$$

in which the relative density $s = \rho_s / \rho_f$ .

An introduction of $Fr_d$ improves significantly a correlation between the Froude number and the Shields parameter (Figure 6) for fractions of different densities.

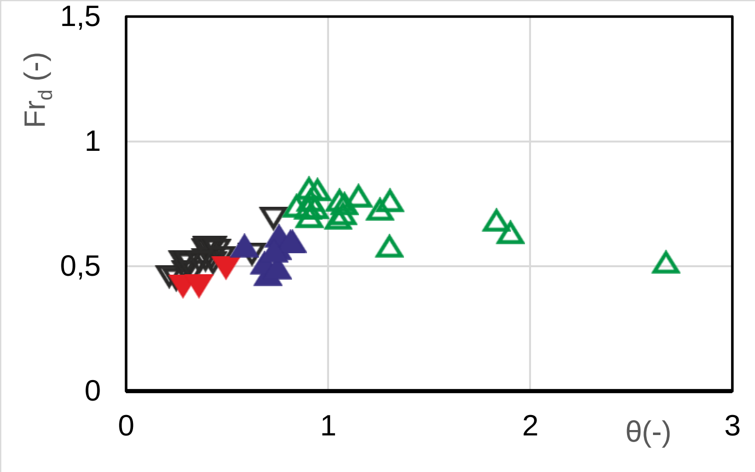


*Fig 6: Relation between densimetric Froude number and Shields parameter.*
*Legend: as in Figure 3.*

## CONCLUSIONS

Laboratory experiments in a tilting flume enabled to investigate thresholds of the upper-stage plane bed regime and their sensitivity on sediment size, density and transport rate. The lower threshold (at transition to the regime with intermittent bed-load transport) is well represented by a constant bed slope and thus by a constant value of the ratio of the volumetric discharge of sediment and the volumetric discharge of mixture. Threshold values are sensitive to sediment density.

The upper threshold (at transition to the wavy regime) is associated with an approximately constant value of the densimetric Froude number. Relatively high values of the Froude number observed at the upper threshold seem to be related to the development of a collisional layer occupying a major part of the flow depth and protecting the bed from impacts of water surface undulations in super-critical flow.

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