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EVALUATION OF LOCAL TURBULENT SUPPORT OF PARTICLES IN INTENSE TRANSPORT OF CONTACT LOAD

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Intense transport of colliding solid grains in sheet flow (open-channel steady uniform turbulent flow at high bed shear) is evaluated using experimentally and theoretically determined distributions of governing flow quantities. The experimental distributions include results of measurements of granular concentration and velocity across sheet flow above an eroded bed in a laboratory tilting flume. Two fractions of lightweight model sediment (plastic grains) were tested within a broad range of flow conditions in the upper plane bed regime. Momentum equations and constitutive relations of the kinetic theory of granular flows were employed to derive distributions of granular and liquid stresses across the flow from the measured distributions of concentration and velocity. Hence the conditions were set for an evaluation of the ability of the flow of the carrying liquid to locally support transported sediment particles by the diffusive action of carrier turbulent eddies. Local values of the carrier shear velocity and particle settling velocity are mutually compared in order to evaluate the ability of the local turbulent support. The results indicate that the chance for the turbulent support (as additional mechanism to collisional support) does not vary significantly in the core of the collisional layer developed in the sheet flow while it tends to disappear in the lowest part of the flow depth if the long-term intergranular contacts associated with high local concentration of grains dominate the particle support.

KEY WORDS: sediment transport, flume experiment, kinetic theory.

NOTATION

c	Local solids concentration by volume (-)
s	Local solids shear stress (Pa)
sS	Local total shear stress (Pa)
S	Local fluid shear stress (Pa)
T	Local granular temperature (m^2/s^2)
u	Local solids velocity (m/s)
u_{*f}	Local friction velocity (m/s)
v_t	Terminal settling velocity of grain (m/s)
y	Vertical position above bed (m)
θ	Bed Shields parameter (-)
ρ_f	Fluid density (kg/m^3)

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1. INTRODUCTION

In steady uniform turbulent sheet flow, bed load grains are transported through a layer adjacent to the eroded mobile bed. The grains are non-uniformly distributed throughout the transport layer with the local concentration being zero at the top of the layer and tending to the bed concentration at the bottom of the layer. Interparticle collision is the dominating support mechanism for the conveyed sediment grains, particularly in the lower part of the layer where the local concentration is high. A threshold value of the ratio of the local fluid shear velocity and the grain settling velocity, u_{*f}/v_t, is often used as a criterion for turbulent support for individual grains in flow. Different flow conditions at different heights within the transport layer lead to different local values of the fluid shear velocity and give rise to a question whether or not the turbulent suspension of the grains is effective locally in the layer (Berzi and Fraccarollo 2015, 2016).

We use our experimental results obtained for sheet flows carrying lightweight sediments in a laboratory tilting flume to analyse distributions of the criterion velocity ratio across the transport layer for different flow conditions. In order to identify local values of u_{*f} within the transport layer, local shear stresses (total, granular, and fluid) are calculated based on experimental inputs. The results show that the tendency to turbulent support of grains is the highest in the core of the transport layer although none of the tested fractions was effectively supported by carrier turbulence.

2. EXPERIMENT WITH INTENSE TRANSPORT IN SHEET FLOW

The experiments were carried out in the recirculating titling flume at the Water Engineering Laboratory of Czech Technical University in Prague (CTU). The set-up, its measuring equipment and a typical experimental procedure is described elsewhere (e.g. Matoušek et al. 2015, 2018).

2.1 FLOW CONDITIONS

The conditions of the observed flow transporting lightweight grains above the bed of the same lightweight grains in the flume are:

- gravity-driven open-channel flow, steady-state uniform flow;
- flow over mobile bed at upper-stage plane bed regime (high bed shear);
- transported sediment grains supported predominantly by mutual contacts;
- broad range of bed slopes, flows depths, sediment flow rates, and total flow rates.

Typically, our measuring campaigns include tests for different discharges and a broad range of delivered volumetric concentrations of tested sediment.

2.2 EXPERIMENTAL CONDITIONS

The experiments were carried out for two fractions of plastic grains (fraction codes FA60 and FA30). Both fractions are basically mono-size. The FA60 grains are of a cylindrical shape (Figure 1) and their mass-median diameter of equivalent sphere is 6.42 mm, the density 1419 kg/m^3, and the terminal settling velocity 0.179 m/s (all determined experimentally). Measurements of the FA30 grains revealed that their mass-median diameter was 3.65 mm, the density 1368 kg/m^3, and the terminal settling velocity 0.114 m/s.

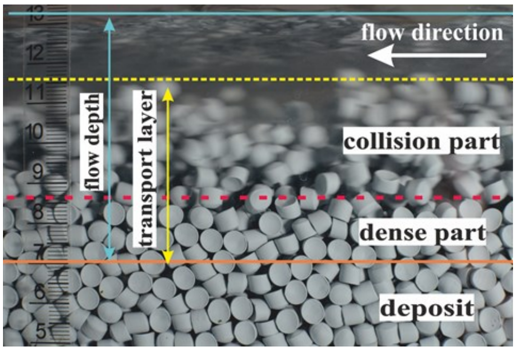

Figure 1. Layered flow condition in flow transporting the FA60 plastic grains (Matoušek et al. 2018)

The observed flows exhibited a layered structure as shown in Figure 1. Typically for our experimental conditions, the flow depth above the bed deposit is composed of the water layer (through which no grains are transported) below the water surface and the transport layer (see Figure 1). At very high bed shear, the transport layer can be divided into the upper collisional part and the lower dense sliding part (in which grains slide over each other). The thickness of the individual layers varies with the bed shear stress (bed Shields parameter), typically the collisional region tends to dominate at high bed shear.

Central to our experiments and analyses is a determination of distributions of flow quantities along the flow depth. Figure 2 shows schematically the measuring techniques used for acquiring of velocity and concentration profiles of grains transported in the flow.

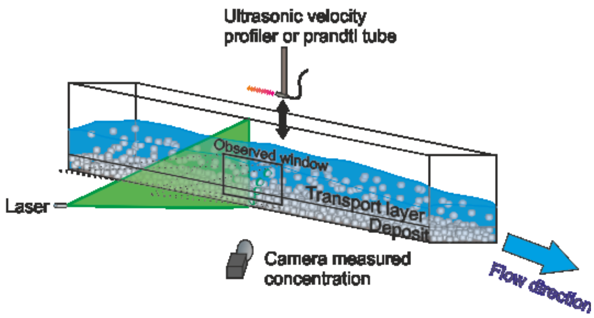

Figure 2. Schematic measurement techniques for local quantities in CTU flume (Matoušek et al. 2019)

The distribution of solids concentration is measured by the laser stripe technique (Spinewine et al. 2011, Krupička et al. 2018) using a camera capturing a deformation of a laser strip penetrating through the flow in the near-wall region of the channel flow. Details of the method application in our flume are described in Matoušek et al. (2018, 2019). The distribution of the velocity is measured by the UDVP acoustic technique as described elsewhere (e.g. Matoušek et al. 2015).

3. OBSERVED DISTRIBUTIONS OF LOCAL QUANTITIES AND EVALUATION OF LOCAL TURBULENT SUPPORT

Figures 3-8 demonstrate distributions of different flow quantities relevant to an evaluation of the local turbulent support of the solid grains. The flume measurements provide the distributions of solids velocity, u, and concentration, c. Those distributions are plotted together with the identified interfaces between individual layers identified a layered character of flow in Figures 3-8. Also plotted together with the interfaces are the distributions of the total shear stress, sS, and of the solids shear stress, s. Those distributions are results of calculations. The total shear stress is calculated from the momentum balance of mixture flow (the measured local concentration is one of the inputs to the calculation) and the solids shear stress obtained from the constitutive relation in the kinetic theory of granular flow (the measured velocity and concentration are inputs). The used equations are described in Matoušek and Zrostlík (2018), principles of kinetic theory in, e.g. Berzi and Fraccarollo (2013), Spinewine and Capart (2013).

The ratio of two velocities (one representing the settling tendency and the other the diffusive tendency) are considered for an evaluation of the local turbulent support of transported grains. In the collisional part of the transport layer, sheet flow exhibits gradients of granular concentrations and velocity resulting from the dominant mechanism of grain support in the flow. Coarse grains are supposed to be predominantly supported by mutual collisions generated by shearing. However, local turbulent support option should be scrutinized as well. In our analysis, it is based on the following assumptions:

- the terminal settling velocity of a grain, vt, represents the settling tendency,
- the hindered effect on grain settling is neglected.
- the local fluid shear velocity, u_{*f}, is a measure of vertical velocity fluctuation and hence represents the support by the diffusive action of carrying fluid turbulence.

Based on the assumptions, v_t is independent of the vertical position of a grain in the flow, but u_{*f} varies with the vertical position y. Its local value $u_{*f} = (S/\rho_f)^{0.5}$, where S = sS - s and can be calculated from the earlier obtained distributions of shear stresses.

The resulting distributions of the velocity ratio u_{*f}/v_t are plotted in the right-hand-side plots of Figures 3-8. Also plotted in the same plot are the concentration distribution (in order to relate the local velocity ratio to the local concentration) and the relative granular temperature T/T_{max} (T_{max} is the maximum value of T in a distribution across the flow depth). The granular temperature T is a measure of granular velocity fluctuations due to collisions and as one the key parameters of the kinetic theory of granular flows it is used in the determination of the solids shear stress, s. Values of T are calculated from one of the constitutive relations using measured c values (see Matoušek and Zrostlík 2018).

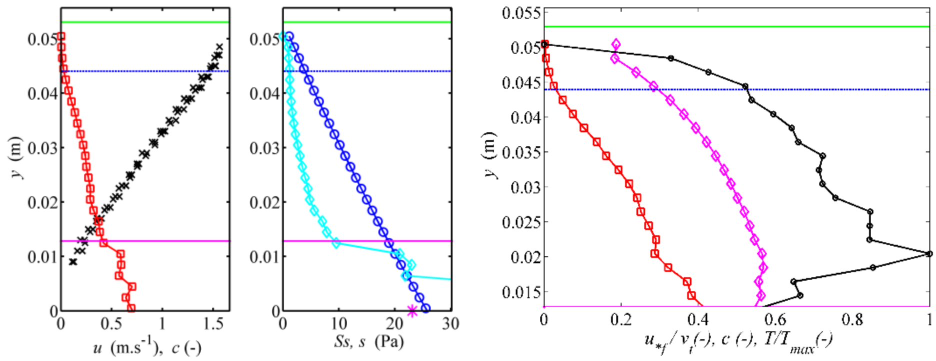

Figure 3. Distributions in layered flow of FA60-mixture at θ = 0.89. Left plot - measured concentration and velocity. Central plot – calculated total shear stress and solids shear stress. Right plot – calculated velocity ratio and relative granular temperature. Legend: black x – velocity, red square – concentration, blue circle - total shear stress, cyan diamond – solids shear stress, magenta star – bed shear stress calculated from measured integral data, magenta diamond – velocity ratio, black circle – relative granular temperature; interfaces from top to bottom: green line - water surface, blue line – top of transport layer, magenta line - top of dense layer.

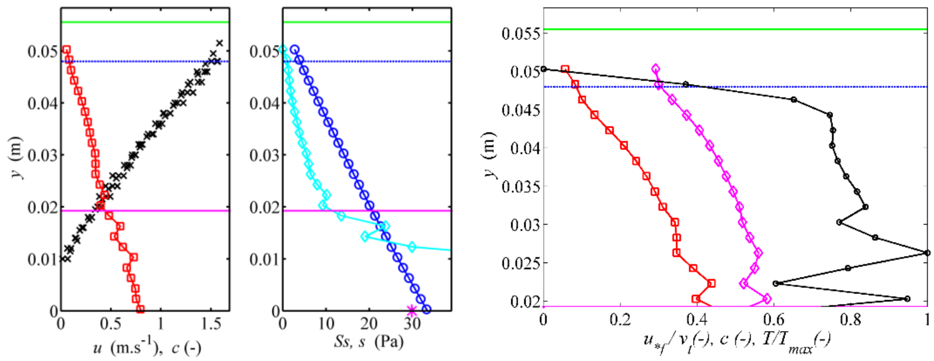

Figure 4. Distributions in layered flow of FA60-mixture at θ = 1.15. Legend as for Figure 3.

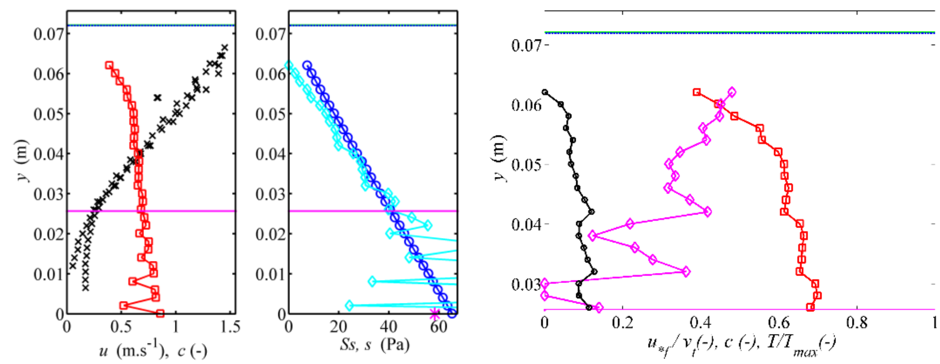

Figure 5. Distributions in layered flow of FA60-mixture at θ = 1.92. Legend as for Figure 3.

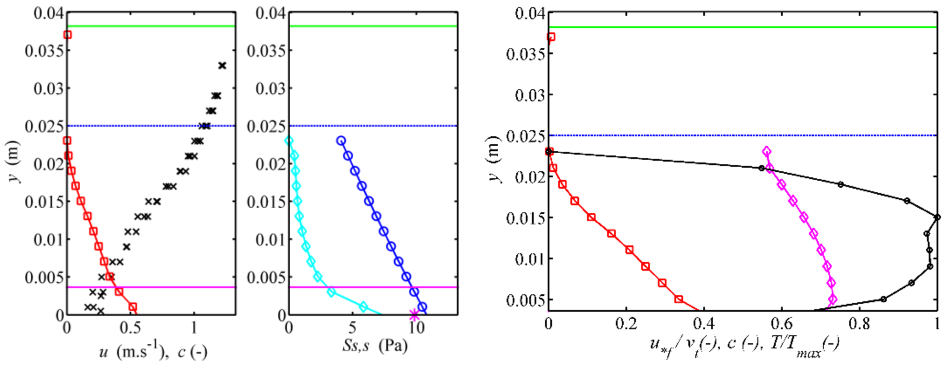

Figure 6. Distributions in layered flow of FA30-mixture at θ = 0.74. Legend as for Figure 3.

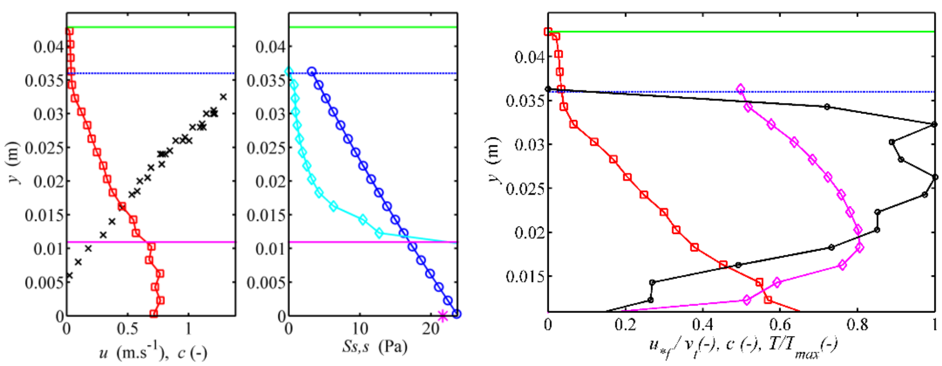

Figure 7. Distributions in layered flow of FA30-mixture at θ = 1.64. Legend as for Figure 3.

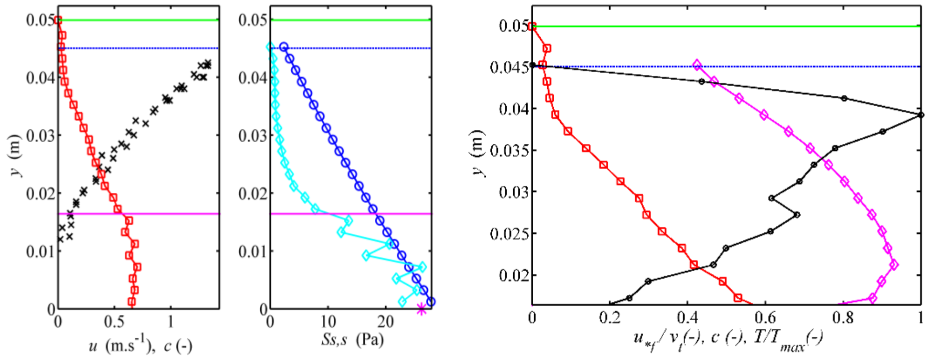

Figure 8. Distributions in layered flow of FA30-mixture at θ = 1.98. Legend as for Figure 3.

Figures 3-5 show FA60-flows at 3 different values of the bed Shields parameter θ (Figure 3 showing flow for the lowest θ and Figure 5 the highest θ). Flow of higher θ transports more solids and exhibits higher values of c, particularly in the lower part of the collisional layer. This affects the distribution of u_{*f}/v_t values. In flows of θ equal to 0.89 and 1.15, the local c does not exceed 0.4 even at the positions very near the bottom of the collisional layer showing that the granular contacts are very sporadic leading to large velocity fluctuations as can be seen on local values of T. At this flow condition, the variation of u_{*f}/v_t across the collisional layer is weak and reaches the highest values not far above the bottom of the collisional layer approximately in the region of the maximum T. It is generally accepted that turbulent eddies are able to fully support grains if a value of the local ratio u_{*f}/v_t exceeds approximately unity. Considering this criterion, the observed local values of u_{*f}/v_t are low indicating that local turbulent support of FA60-grains is weak across the entire flow depth. High-concentrated flow at θ = 1.92 exhibits c values significantly higher than 0.4 in the major part of the flow depth. As a result of that, granular contacts are much more frequent and local turbulent support more marginal, which is manifested by the trend of local u_{*f}/v_t decreasing towards the bottom of the collisional layer and tending to zero the bottom of the layer.

The FA30-grains are smaller and lighter than the FA60-grains and hence their support by fluid turbulence seems more probable. In their flows at θ between 0.84 and 1.98, they indeed exhibit higher local values of u_{*f}/v_t than the comparable FA60-flows. Furthermore, the distributions show higher local values in flows of higher Shields parameter reaching maximum values not far below unity at θ = 1.98. It is interesting to observe that local values of u_{*f}/v_t diminish if local c exceeds say 0.4 in the region near the bottom of the collisional layer (see Figures 7 and 8).

4. CONCLUSIONS

Local values of the carrier shear velocity (calculated by kinetic-theory relations using experimental inputs) and terminal settling velocity of a grain are mutually compared in order to evaluate local turbulent support of grains in open-channel sheet flow.

The results for two different grain fractions indicate that the chance for the turbulent support (as additional mechanism to collisional support) does not vary significantly in the core of the collisional layer developed in the sheet flow while it tends to disappear in the lowest part of the flow depth if the long-term intergranular contacts associated with high local concentration of grains dominate the particle support. Not surprisingly, the fraction of smaller and lighter grains exhibits a stronger tendency to turbulent support in the sheet flow than the heavier fraction.

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