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COMPARISON OF TRANSPORT AND FRICTION OF MONO-SIZED AND TWO-SPECIES SEDIMENT IN UPPER PLANE BED REGIME

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The paper focuses on a comparison of transport and friction characteristics of mono-sized and two-species sediments at comparable flow conditions in the upper plane bed regime. Two fractions of artificial sediment (glass beads of the same density 2500 kg/m^3 and different size 1.5 and 3 mm) were tested in sediment-transport experiments in a tilting flume. First, the sediments were tested separately and then mixed together. Measured flow quantities enable to evaluate bed load transport and bed friction from the tests. Furthermore, velocity profiles are mutually compared and relation among profile shapes, sediment transport, and bed friction is investigated. The velocity-distribution measurements include results from a grain transport layer above the erodible deposit. This enables to evaluate flow conditions in this layer and its role in bed-load transport and bed friction.

KEY WORDS: bed load, mixture, sediment transport, vertical sorting, tilting flume experiment

1. INTRODUCTION

River beds are usually composed of non-uniform sediment mixture. The composition of bed material is usually described by the grain size distribution (GSD). It is generally known that the GSD of transported sediment is different from the GSD of bed deposits. This is a result of material sorting in time and space. Several authors have dealt with sorting of bed materials in bed forms (e.g. Blom et al. 2008) and armoring of the bed (e.g. Wilcock and DeTemple 2005), but to our knowledge no work has dealt with sorting under the condition of intense transport of sediment in the upper plane bed (UPB) regime. The structure of flow under the UPB condition is typically layered (Matoušek et al. 2014, 2015). Clear water and occasionally saltating particles occupy the uppermost layer just below the water surface. Stationary particles form the bottom layer. A majority of material is transported through the interlaying transport layer.

A quantity of transported sediment mixture can be calculated in several ways. The first approach is based on calculation of the effective mean diameter (d_m) from GSD of bed particles $d_m = \sum d_i \Delta p_i / \sum \Delta p_i$, where d_i is diameter of sieve opening and Δp_i denotes the weight percentage of particles passed. The transport rate is calculated in the same way as in the case of uniformly graded material with the same d_m. Another option is to compute the transport rate separately for individual fractions in the mixture. This method is usually used in mathematical models for rivers. The most novel approach is based on a combination of a 3D mathematical model of turbulent flow with a granular model based on kinetic theory (Savage and Lun, 1987) describing collisional interaction between particles. This method is demanding on computing power and time. Thaxton and Calantoni (2006) presented a mathematical model which dealt indirectly with selected transport. He included vertical sorting in oscillatory sheet flow. The model described the sorting of bimodal material and the move up of the coarser particles. He confirmed the theory of vertical separation, which was not previously included in models.

This paper compares the experimentally obtained data on unimodal and bimodal grain size in the context of the above described methods and models.

2. METHODS

All the experiments were carried out in tilting flume in the Water Engineering laboratory of the Czech Technical University in Prague. The rig is described in detail in Zrostlík et al. (2015). Experiments were carried out under the condition of steady uniform flow and upper plane bed regime.

2.1 EXPERIMENTAL WORK

Firstly, the experiments were carried out with the fraction of glass beads of the diameter of 3 mm (TK30) and with the fraction of 1.5 mm glass beads (TK1216). The density of TK30-beads and TK1216 beads was 2500 kg/m^3, 2480 kg/m^3, respectively. 19 experimental runs were measured with TK30, 23 with TK1216.

Work continued with mixture of small and large beads (TK30 + TK1216 = sTK1230). The flume was filled with the same amount of large and small beads, but particle sorting caused that the proportion of fractions in transported mixture differed run by run. At the beginning of each experimental run, the flow rate was increased and all particles were mixed in suspension to prevent effect of flow history due to previous particle sorting. Then the desired flow rate was set, particles started to settle and – after a few minutes – a steady uniform flow developed above stationary bed with particle sorting characteristic for the installed flow conditions. 35 experiments were measured following this procedure.

Measured integral data included Q_m - discharge of mixture, H - depth of flow, H_{sh} - thickness of transport layer, I_e - hydraulic gradient (slope of energy grade line), C_{vd} - delivered concentration, vertical velocity profile and GSD of transported material determined from a collected sample. Measuring methods, data evaluation and accuracy of the procedure is described in detail in Matoušek et al. (2014, 2015).

2.2 VELOCITY DISTRIBUTION

Vertical profiles of longitudinal time-averaged component of velocity were measured 4.2 m downstream from the flume inlet using Prandtl tube. The vertical step was 4 mm in clear water and 2 mm in transport layer. Outer diameter of the tube was 6 mm and inner was 1 mm. It is a traditional and robust method.

A velocity profile in the UPB regime is expected to be composed of the logarithmic part in clear water layer and the linear part in the transport layer (Figure 1). Formula for the distribution of local velocity in the logarithmic part can be written as:

$$\frac{u}{u_b*} = 2.5 \cdot \ln\left(\mathrm{B}\frac{y - y_{ini}}{k_{s,\log}} \right) \tag{1}$$

and in the linear part as:

$$\frac{u}{u_{tr}} = \left(\frac{y - \Delta y}{y_{tr} - \Delta y} \right)^n \tag{2}$$

where u – local velocity at vertical position y, u_b* – bed shear velocity, u_{tr} – local velocity at vertical position y_{tr}, y_{tr} – position of smooth transition from linear to logarithm profile, Δy – position of zero velocity for linear profile, y_{ini} – position of origin of logarithmic profile, $k_{s,\log}$ - bed equivalent roughness for logarithmic law of velocity distribution, B and n - constants. The parameters describing the logarithmic and linear parts of the composite profile can be found by an optimization procedure described by Zrostlík et al. (2015). Five parameters are subject to optimization: y_{tr}, Δy, y_{ini}, u_b* and $k_{s,\log}$. The exponent n is 1 (linear profile).

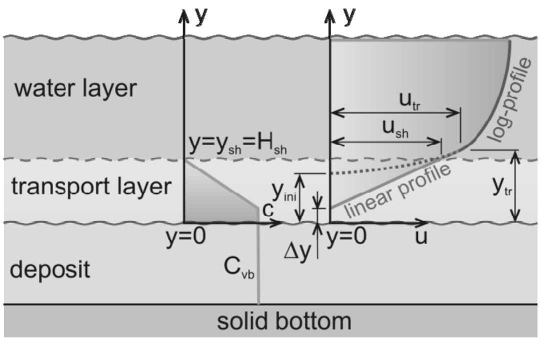

Fig.1 Scheme of velocity and concentration profiles in UPB regime

3. RESULTS

The volume of transported particles is known from mixture sampling at the outlet of the flume and the proportion of the individual fractions in the sample is evaluated from the sieve analysis. Figure 2a shows the GSD after each experiment with mixture and the original GSD of TK30 and TK1216. Figure 2b shows the computed mean diameter of transported particles in relation with flow Reynolds number $Re = V_m.4.R_b/\nu$, where V_m is mean velocity of mixture, R_b is the hydraulic radius associated with bed and ν is the kinematic viscosity.

It appears that the lower limit of the mean grain diameter decreases with the increasing Reynolds number. In other words, the proportion of small particles in the transported mixture increases with the increasing flow Reynolds number. The proportion of the smaller particles was from 8 to 38% of the total transported volume depending on *Re* (Figure 2a).

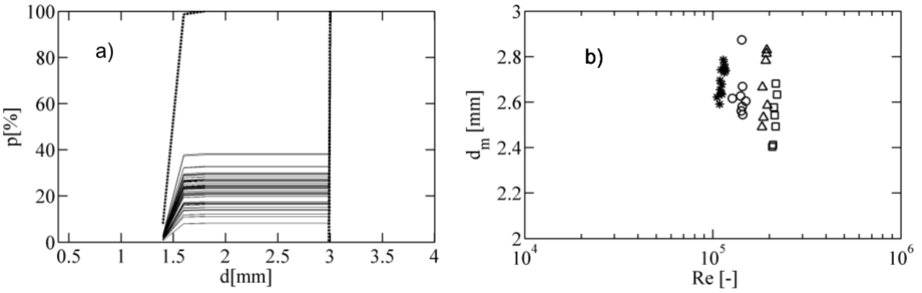

Fig 2. a) Grain size distribution of transported material. Legend: full lines TK1230 for different Re, dotted lines TK30 and TK1216, b) mean diameter of transported sediment in experiments with mixture versus flow Reynolds number. Legend: flow discharge: stars 7-8 l/s, circles 8-10 l/s, triangles 10-13.5 l/s, squares 13.5-15.2 l/s.

3.1 TRANSPORT AND FRICTION CHARACTERISTICS

As seen in Figure 3, the relationship between delivered concentration and the slope of energy grade line is only slightly affected by the effective size of transported material.

Figure 4 shows the dimensionless sediment transport parameter (Einstein parameter) Φ plotted against the dimensionless shear stress (Shields parameter) θ. The panel a) shows results computed using the effective mean diameter of mixture (d_m) as the characteristic particle dimension, whereas the panel b) shows results computed using d_{50} (the median particle size). A comparison shows that the mixture seems to be less mobile than the two fractions tested separately, if d_m is used for the sediment mixture. As no effect of grain size is observed at the relationship between I_e and C_{vd} (Figure 3), the median grain diameter d_{50} may be more appropriate parameter to express the characteristic grain size of the sediment mixture and it is used in the further considerations below. Regardless the used characteristic particle size, the finer fraction appears to be more mobile than the coarser one when tested separately. It was interesting to see that coarser fraction dominated in all samples collected during the sediment mixture tests.

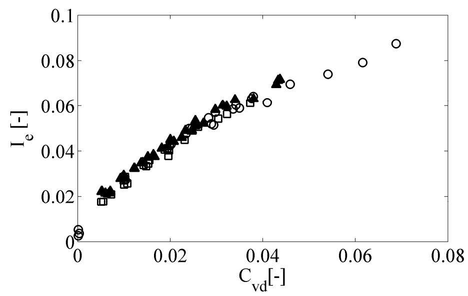

Fig 3. Relation between hydraulic gradient and delivered concentration. Legend: empty circles – TK30, empty squares - TK1216, full triangles - TK1230.

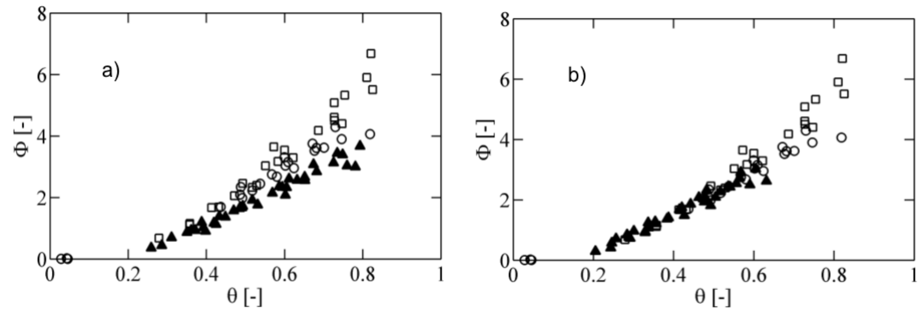

Fig 4. Dimensionless sediment transport, a) using d_m b) using d_{50}. Legend: empty circle – TK30, empty squares - TK1216, full triangles - TK1230.

The coefficient of bed friction (λ) was evaluated from the measured quantities using the equation $\sqrt{\frac{8}{\lambda}} = \frac{V_m}{\sqrt{g \cdot R_b \cdot I_e}}$, where g was the gravity acceleration. Figure 5a shows λ plotted against Shields parameter. The friction coefficient is smaller for the fine fraction than for the coarse one and λ for sediment mixture is somewhere in between.

In all experiments with sediment mixtures, a layer of small beads was observed at the interface between the transport layer and stationary deposit. This layer started to develop immediately after the installation of a required flow rate at the beginning of each experimental run. As coarse particles slid and rolled over the bed, free space opened among the grains which was filled with the finer fraction. Hence, the coarser beads were slowly replaced by the finer ones. This effect is sometimes called the squeeze of bigger particles, see e.g. Rosato et al. (1987) and Savage and Lun (1987). Our observations confirm an existence of vertical sorting also in uni-directional flow at the UPB condition. We call the developed layer of fine particles the sliding layer.

We estimated the thickness of the sliding layer from video recordings. The thickness of the sliding layer increased with the increasing delivered concentration as can be seen in Figure 5b.

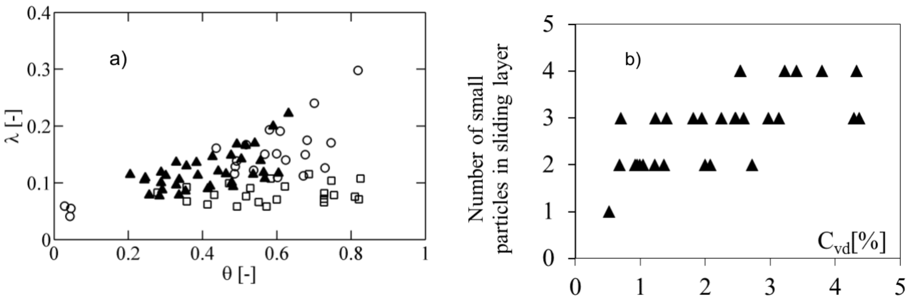

Fig 5 a). Bed friction coefficient versus Shields parameter computed with d_{50}. Legend: empty circles – TK30, empty squares - TK1216, full triangles - TK1230; 5 b) Thickness of sliding layer in number of TK1216 particle sizes versus delivered concentration of sediment

3.2 VERTICAL VELOCITY DISTRIBUTION

Three parameters (y_{tr}, u_{tr} and Δy) were optimized in the equation for the linear part of the composite profile (Equation 2). All these parameters are associated with the vertical gradient of velocity over the linear part of the velocity profile. Figure 6a shows a relation between the velocity gradient and the Shields parameter. The gradient is bigger for the finer beads, and it is nearly the same for the mixture as for the coarser beads.

The vertical position of the top of stationary deposit is estimated by visual observation. If this position is defined as the position of zero velocity, then the position Δy can be interpreted as an error in the visual observation. Figure 6b shows that the position of deposit is overestimated by the visual observation in case of the finer fraction whereas it is underestimated in case of the coarser fraction. Linear and logarithmic portions of the velocity profile are smoothly connected at the top of transport layer. The origin of the logarithmic curve (i.e. the position of the curve asymptote) y_{ini} lies within the transport layer. Figure 7a shows how y_{ini}, normalized by the visually observed thickness of the transport layer H_{sh}, varies with the Shields parameter θ. The mean value of y_{ini}/H_{sh} is 0.6 and no trend is recognized in the relation with θ or particle size d. The equivalent roughness $k_{s,log}$ is another parameter affecting the logarithmic velocity profile (Equation 1) above the transport layer. The optimization procedure leads to enormous scatter in values of this parameter as shown in Figure 7b. However, a general trend can be distinguished: $k_{s,log}$ is the biggest for the TK30 fraction and TK1216 exhibits slightly smaller $k_{s,log}$ than the mixture of fractions. This is in agreement with a trend observed for the equivalent roughness determined from the integral parameters of the flow (bed slope etc.) using Nikuradse's friction law.

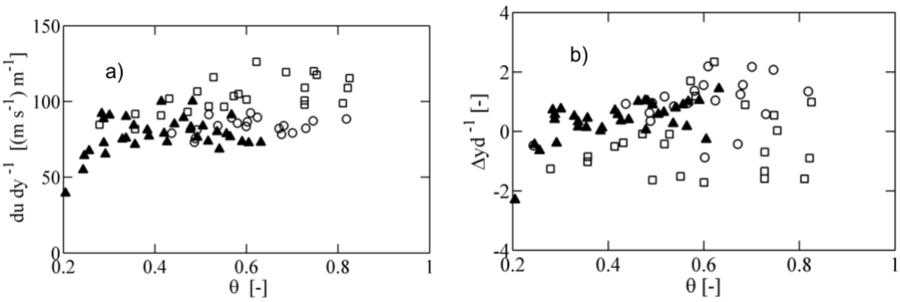

Fig.6 a) Relation between gradient of linear profile and Shields parameter, b) position of zero velocity related to Shields parameter. Legend: empty circles – TK30, empty squares - TK1216, full triangles - TK1230

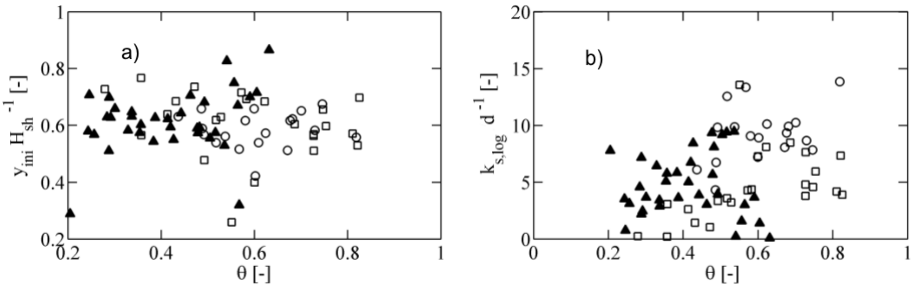

Fig.7 a) Position of origin of logarithmic part (section) of velocity profile b) the optimized roughness. Legend: empty circles – TK30, empty squares - TK1216, full triangles - TK1230

4. CONCLUSIONS

Experimental investigation of sediment transport in the UPB regime was carried out in a rectangular open channel. Two uniformly graded fractions of glass beads were tested separately and then mixed together. Although the volume of both fractions in mixture was the same at the beginning of each experiment, observed vertical sorting of material resulted in more intense transport of the coarser fraction. Another observed effect of mixture sorting was a development of a sliding layer of finer particles at the top of the stationary deposit. The thickness of the sliding layer increased with the increasing delivered concentration of sediment. A difference in transport rates of finer and coarser fractions seemed to be reduced by the increasing flow Reynolds number. This can be explained by the mechanism of sorting. As coarse grains slide over the bed, free space opens among them and it is filled with finer grains of the other fraction. The fine grains are protected against dynamic fluid forces by the coarse grains and a major part of the applied bed shear stress acts on the coarse grains. The effect of sorting is probably damped by more intense turbulence at higher values of Reynolds number.

Vertical profiles of longitudinal velocity were sensed using a Prandtl tube. The profiles were found to be composed of a linear part within the layer of intense transport of sediment and of a logarithmic part within the above laying particle-free layer. The velocity gradient of the linear profile was lower and the equivalent roughness of the bed higher in the case of the coarser fraction than in the case of the finer one. Values for parameters of velocity profiles sensed in flow of mixture of sediments were close to those of the coarser fraction indicating a predominant effect of the coarser fraction on the shape of velocity profiles. The origin of the logarithmic profile was found to lay at the position from 0.5 to 0.7 of the transport layer thickness for most of the experiments regardless of tested material.

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