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SEGREGATION IN BIMODAL CONTACT/COMBINED LOAD: TILTING-FLUME STUDY

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ABSTRACT: In this contribution, the effects of solids segregation on intense transport of solids and bed friction in a laboratory flume are evaluated by comparing bimodal solids flows with the corresponding flows of unimodal solids. The comparison is carried out for two types of solids transport: contact-load transport and combined-load transport. Experiments with intense transport of bimodal solids mixtures composed of two solids fractions that differ primarily in particle size showed a process of vertical sorting, resulting in partial segregation of the fractions in a flume. The segregation affected a layered structure of flow above the plane surface of an eroded bed. Lightweight solids fractions of different colors were used in the experiments to enable clear visual observation of the segregation. Measurements of integral quantities of steady, uniform solid-liquid flow were used to quantify solids transport parameters and bed friction parameters. The observed segregation patterns differ for the two types of solids transport and so differ their effects on solids discharge and bed friction coefficient in flows of the two bimodal mixtures.

KEY WORDS: sediment transport, laboratory experiment, solid-liquid flow, open channel flow, mobile bed

1. INTRODUCTION

In sediment-laden flow in an open channel with a mobile bed, the stage-discharge relationship is strongly affected by bed resistance. The sensitivity of the variation of the depth of flow with the discharge of water is particularly high if the bed is eroded and intense transport of sediment develops in the channel. Bed friction is related to the flow-induced bed shear stress, and so is sediment transport, i.e., the discharge of solids in the sediment-laden flow. Intense transport of sediment at high bed shear is typical for steep flows and high discharges of water, such as those that occur during flood discharges in mountain streams.

Early research on flow with intense transport of solids above an eroded bed was conducted in pressurized pipes (e.g., Wilson 1966, Nnadi & Wilson 1992, Sumer *et al.* 1996, Pugh & Wilson 1999). These investigations revealed that if the top of the bed is almost unsheared and is subject to nearly no erosion (low discharges of water), then it can be considered as a fixed boundary with roughness related to the size of the particles occupying the plane surface of the bed. However, if the bed gets eroded and the shear layer (also called the transport layer) develops of several particle sizes in thickness, then the roughness increases considerably, and another relation must apply to its determination.

The bed resistance is quantified using the bed friction coefficient (f_b), which is related to the bed roughness (k_b) as expressed in the Nikuradse formula, $\left(\frac{8}{f_b}\right)^{1/2} = \frac{1}{\kappa} ln \frac{B_r R_b}{k_b}$. In the formula, R_b is the bed hydraulic radius, κ is the von Karman constant (κ = 0.4), and B_r is constant. The formula applies to both pressurized flow in a pipe and gravity-driven flow in an open channel, the only difference being a value of B_r and a determination of R_b.

The increase in the bed resistance due to solids transport is demonstrated in Figure 1, where the coefficient f_b is related to the delivered concentration (C_{vd}), which is defined as a ratio of the solids discharge and the total discharge. At very low flow velocities, the C_{vd} is also very low, showing that the erosion of the top of the bed is weak. The coefficient f_b in this case is successfully predicted by the Nikuradse formula, with the roughness equal to double the size of the sand particle.

If, however, the flow velocity increases, causing more erosion of the top of the bed (Figure 2), and hence a higher C_{vd}, then an assumed value for roughness equal to twice the particle size predicts considerably lower values of f_b than those obtained by the measurements. Apparently, the roughness must increase with C_{vd} as well. For details on the determination of the bed friction coefficient and its use in calculations of settling slurry flows in pipes, see Chapter 4 in Visintainer *et al*. (2023).

If translated to open-channel flow, then the result in Figure 1 suggests that the depth of a flow of a certain water discharge can be greater in a channel with an eroded bed than in the same channel with a fixed bed. However, so far, investigations in open channels (laboratory flumes) have been less common than investigations in pressurized pipes. Typically, flume tests use lightweight sediments rather than natural sediments to mimic intense transport of sediment (e.g., Armanini *et al*., 2005, Capart & Fraccarollo 2011).

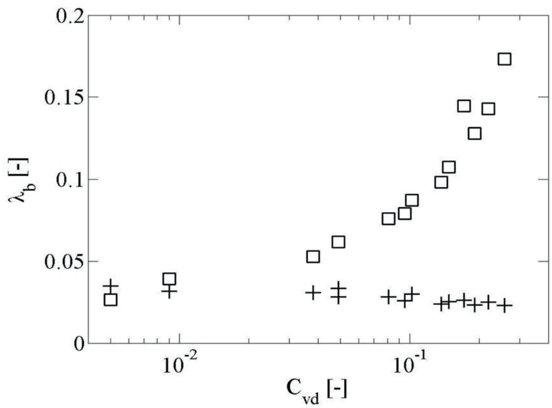

Figure 1 Bed friction coefficient f_b versus delivered concentration C_{vd} for flow of slurry of 0.37mm sand above deposit in 150 mm pipe (Matoušek & Krupička 2012). Legend: square – measurement; cross – prediction using Nikuradse formula for roughness twice particle size.

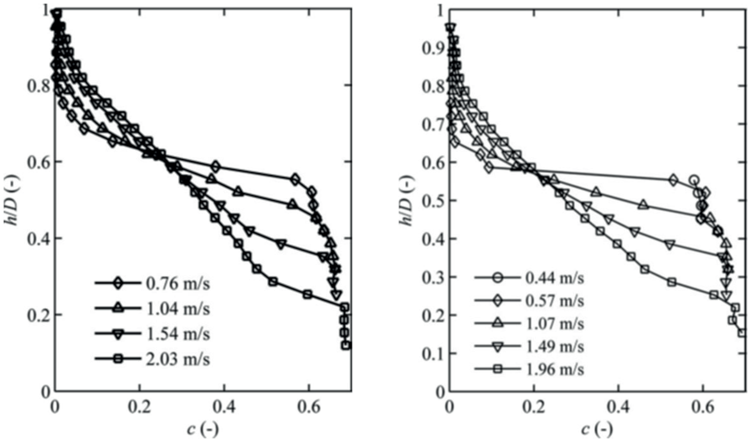

Figure 2 Solids distribution across flow of slurry of 0.37mm sand above deposit in 150 mm pipe (Matoušek 2009). Legend: average velocity of flow through entire pipe cross section V_m in m/s.

Our contributions to this research on the intense transport of solids in an open channel are associated with experiments in our laboratory tilting flume. Results of our recent experiments with various model lightweight solids in a tilting flume produced information suitable for an evaluation of intense transport of solids above an eroded bed in the upper plane bed regime. Evaluations of unimodal contact-load transport and unimodal combined-load transport have been published recently (Matoušek 2022).

This contribution discusses a description and quantification of the solids transport and bed resistance in the case of transported bimodal solids composed of two fractions of very similar density and different particle sizes.

2. TILTING FLUME EXPERIMENTS

Our laboratory flume experiments are focused on the intense transport of model sediments in turbulent open channel flow. So far, tests with several unimodal sediments and two bimodal sediments have been conducted.

2.1. EXPERIMENTAL SET-UP AND MEASURING TECHNIQUES

A recirculating tilting flume is situated in the Water Engineering Laboratory of the Czech Technical University in Prague. It is 200 mm wide, 8 m long, and its measuring section is 6 m long. The flume can be tilted to a broad range of longitudinal slopes. A detailed description of the laboratory setup, measuring techniques, and experimental procedures is provided elsewhere (Matoušek *et al*. 2015; Matoušek *et al*. 2019). The setup includes measuring equipment to collect information on total discharge (discharge of liquid and solids), discharge of solids, and elevation of the water surface along the flume. Positions of the top of the bed at the bottom of the flume are observed visually, obtained from video images, and alternatively also from distributions of velocity and concentration across a flow cross section (e.g., Rebai *et al*. 2022).

2.2. LIGHTWEIGHT SOLIDS FRACTIONS

The properties of lightweight solids fractions used to produce bimodal mixtures are summarized in Table 1. The fractions contain plastic particles that are nearly monodispersed. The solids properties were determined experimentally. In Table 1, the size represents the diameter of an equivalent sphere having the same volume as a solid particle.

Table 1

Properties of tested fractions of lightweight solids

Fraction code	colour	size [mm]	density [kg/m^3]	shape
HSF	white	3.18	1358	rice
TLT50	black	5.41	1307	cylinder
SUN25	red	2.80	1280	prism
FA30	green	3.65	1368	lens

2.3. TESTED FLOW/TRANSPORT CONDITIONS

The tilting-flume experiments were carried out for sediment-laden (solid-liquid) flows over eroded mobile beds under conditions of steady, intense transport of solids. Such flows tend to be stratified, with the plane top of the eroded bed as the most important interface (the upper plane bed regime). Typically, a transport layer develops above the bed, occupying a certain portion of the flow depth between the top of the bed and the water surface. Solids are transported through this layer at local concentrations, diminishing with increasing distance from the top of the bed (as in Figure 2 for a pressurized pipe flow). The fractions HSF, TLT50, and FA30 were predominantly transported as contact load, while particles of the finest fraction SUN25 tended to be supported, at least partially, by turbulent eddies of carrier flow (combined load) (Matoušek 2022).

Two types of bimodal solids mixtures were tested, one transported as a contact load, and the other as combined load. The bimodal mixture (code HT) transported as a contact load was composed of the TLT50 solids (the coarser fraction, black color in Figure 3) and the HSF fraction (the finer fraction, white color in Figure 3). The other bimodal mixture (FAS), transported as combined load, was composed of the coarser FA30 fraction (green color in Figure 3) and the finer SUN25 fraction (red color).

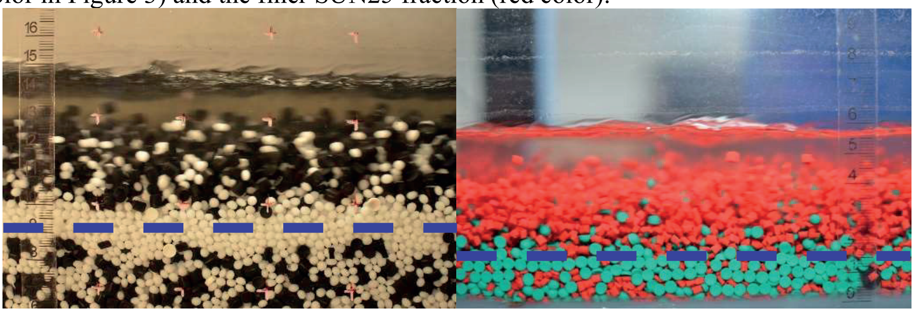

Figure 3 Bimodal contact-load transport of coarser black particles and finer white particles (left) and bimodal combined-load transport of coarser green particles and finer red particles (right) in a tilting flume. Legend: dash line – visually observed elevation of top of stationary bed.

The bimodal mixtures, introduced to the flume, were composed of equal volumes of the two solids fractions, i.e., the proportion of the two fractions in the bimodal mixtures was 50% : 50%.

Flows of both bimodal mixtures exhibited segregation of the fractions above a stationary deposit in the flume. Apparently, the segregation was different in the two bimodal mixtures. The contact-load bimodal mixture created a layer of the finer particles at the top of the deposit (the white interfacial layer in Figure 3), above which particles of both fractions were transported, and transport of the coarser fraction dominated (more than two thirds of the total volume of transported particles was occupied by the coarse fraction). In the combined-load bimodal mixture, however, the top of the deposit was composed predominantly of the coarser particles (the green top of the deposit in Figure 3), above which both fractions were transported, and transport of the finer fraction dominated. The objective of our study is to show how the different segregation patterns affect solids transport and bed friction in the flows of the two bimodal mixtures.

3. SOLIDS TRANSPORT

Figure 1 shows that the experimentally determined bed friction coefficient f_b for the eroded bed of narrow-graded medium sand in a pressurized pipe is highly correlated with the delivered concentration C_{vd}, (i.e., with the ratio of the solids discharge and the total discharge, $C_{vd} = q_s/q_m$). A tight correlation between the two quantities also occurs if a bed composed of lightweight solids is eroded by open-channel flow (e.g., Matoušek 2022). Moreover, the ratio q_s/q_m strongly correlates with the bed slope ω (Figure 4) and thus demonstrates a sensitivity of the solids transport to the bed slope.

Figure 4 compares the results of tilting-flume experiments with two unimodal sediment fractions (coarser TLT50 and finer HSF) with results for their bimodal mixture (HT) transported as contact load. In the left-hand side panel of Figure 4, the data collected over the entire range of the installed flow conditions is plotted. In the right-hand side panel, the selected data representing flows with virtually the same values of the water discharge q_f and the slope ω are plotted. The plots indicate negligible differences in the relation between the ratio and the bed slope for the different transported solids except for the steepest slopes, where a value of the ratio for the transported bimodal solids is between values of the ratios for transport of the two unimodal solids fractions. Figure 5 confirms that the bimodal solids discharge q_s is virtually the same as the discharges of the unimodal solids fractions at the same water discharge and bed slope.

Figure 6 compares experimental results for another two sediment fractions (coarser FA30 transported as a contact load and finer SUN25 transported as a combined load) with results for their mixture (FAS) transported as a combined load. The comparison exhibits the same trend as the bimodal contact-load (HT) transport. The values of q_s/q_m are virtually the same for unimodal solids and bimodal mixtures at mild bed slopes. The value for the bimodal mixture is between the values of the unimodal fractions at the steep slopes.

As the next step, it is of interest to compare how the bed friction coefficient correlates with the bed slope for the transport of unimodal solids and bimodal mixture.

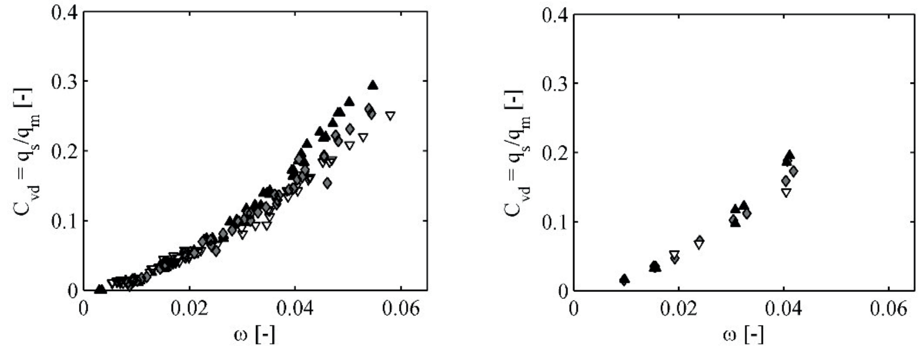

Figure 4 Ratio of solids discharge and total discharge versus longitudinal bed slope for transport of contact load: (left) all tests; (right) tests of virtually the same water discharge and bed slope. Legend: black – coarser TLT50, white – finer HSF, grey – mixture HT = TLT50+HSF.

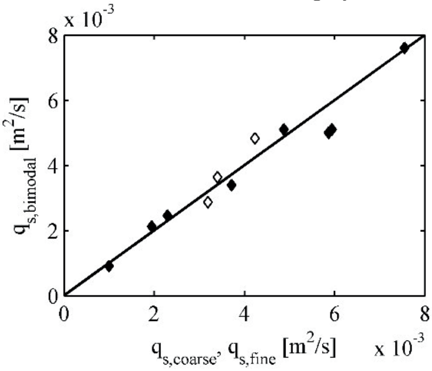

Figure 5 Solids discharge for bimodal mixture transport versus solids discharge for unimodal transport: selected tests of virtually the same water discharge and bed slope. Legend: black – coarser fraction TLT50, white – finer fraction HSF, line – perfect match.

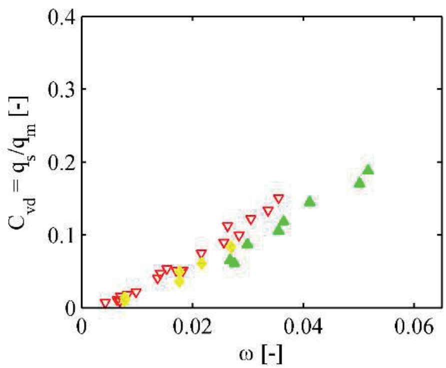

Figure 6 Ratio of solids discharge and total discharge versus longitudinal bed slope for transport of combined load: all tests. Legend: green – coarser FA30, red – finer SUN25, yellow – mixture FAS = FA30+SUN25.

4. BED FRICTION

Values of the friction coefficient f_b are obtained from the measured longitudinal slope ω, flow depth h, and total discharge q_m using the momentum equation $f_b = 8gh^2 R_b \sin\omega / q_m^2$, in which g is the acceleration of gravity. For unimodal fractions tested previously, f_b values correlated well with ω, and the discharge ratio q_s/q_m, although the correlation was not general, and differed slightly for different fractions.

4.1. CONTACT LOAD

In Figure 7, experimental values of the bed friction coefficient are compared for the bimodal contact-load mixture (HT) and its two unimodal components: the coarser TLT50 and the finer HSF.

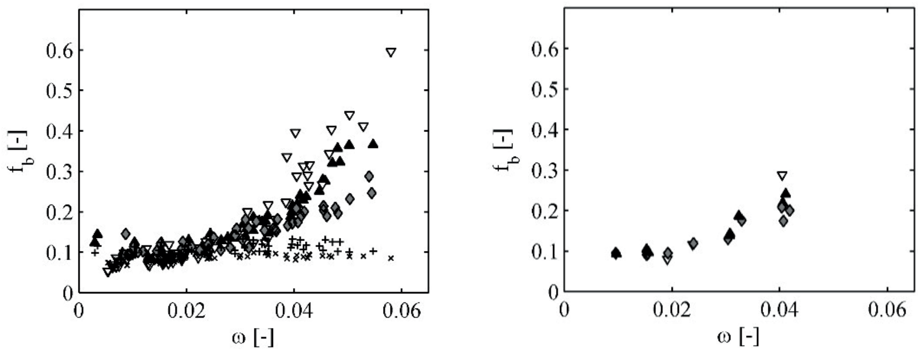

Figure 7 Bed friction coefficient versus longitudinal bed slope: (left) all tests; (right) tests of virtually the same water discharge and bed slope. Legend: black triangle – coarser TLT50, white triangle– finer HSF, grey diamond – bimodal mixture HT, +,x – predictions by Nikuradse formula.

In accord with the observation in Figure 1, bed friction obeys the Nikuradse law, assuming a fixed bed with roughness a multiple of the particle size if the bed slope is mild (low bed shear). If the slope is steep (high bed shear), f_b deviates from the Nikuradse prediction and increases with the bed slope due to the increasing effect of transported contact-load particles on the bed friction. Interestingly, values of f_b for the bimodal mixture are lower than those for the unimodal fractions at the highest slopes, suggesting that the presence of the interfacial layer tends to reduce the bed friction at very high bed shear.

The measure of the friction reduction is shown in the parity plot of Figure 8, which compares flows with virtually the same water discharge and bed slope. It shows that f_b values are lower for the bimodal mixture than for their unimodal counterparts at very high bed shear (the four measured points with f_b greater than 0.15 in Figure 8). In Figure 9, the same four measured points demonstrate that the observed reduction of the bed friction results in depths of flow h of the bimodal mixture being less than h of flows of the corresponding unimodal solids at the same bed slope and water discharge (the points with h less than 0.055 m in Figure 9).

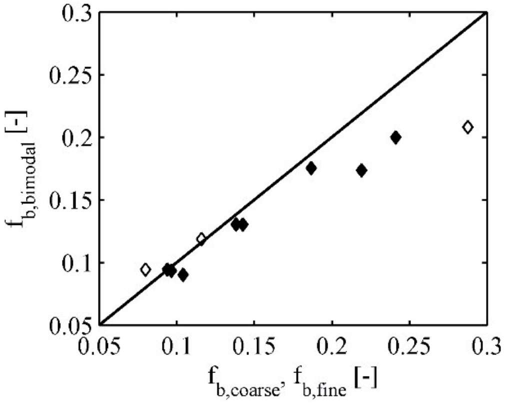

Figure 8 Bed friction coefficient for bimodal mixture transport versus bed friction coefficient for unimodal transport: selected tests of virtually the same water discharge and bed slope. Legend: black – coarser fraction TLT50, white – finer fraction HSF, line – perfect match.

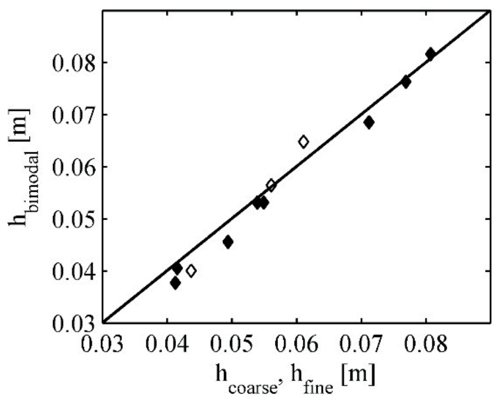

Figure 9 Depth of flow for bimodal mixture transport versus depth of flow for unimodal transport: selected tests of virtually the same water discharge and bed slope. Legend: black – coarser fraction TLT50, white – finer fraction HSF, line – perfect match.

4.2. COMBINED LOAD

In bimodal combined-load transport, particles of the finer fraction (SUN25) do not constitute an interfacial layer at the top of the bed. Therefore, no notable reduction of bed friction due to the bimodal mixture is detected at high bed shear (Figure 10). However, more experimental data are required to confirm the trend at very high bed shear, and a collection of such data is currently in progress.

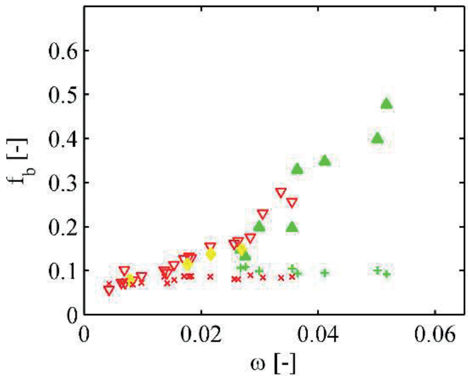

Figure 10 Bed friction coefficient versus longitudinal bed slope: (left) all tests; (right) tests of virtually the same water discharge and bed slope. Legend: green full triangle – coarser FAS30, red empty triangle– finer SUN25, yellow diamond – bimodal mixture FAS, +,x – predictions by Nikuradse formula.

5. CONCLUSIONS

Tilting-flume experiments with intense transport of two different types of bimodal solids mixtures, in which the two fractions differed primarily in particle size, exhibited two different patterns of separation of the fractions due to vertical sorting.

The bimodal mixture of particles transported as contact load exhibited considerable segregation of the fractions in the collisional transport layer, resulting in the development of an interfacial layer composed of the finer particles. This interfacial layer separated the transport layer from the top of the bed. In the transport layer, the transport of the coarser fraction dominated over the transport of the finer fraction. However, the discharge of solids was approximately the same in the bimodal contact-load transport as in the unimodal transport of either of the fractions at the same bed slope and water discharge.

At very high bed shear (where values of the bed friction coefficient are much higher than those predicted by the Nikuradse formula with bed roughness a multiple of the particle size), the presence of the interfacial layer was responsible for a lower value of the bed friction coefficient for the bimodal contact-load transport than were the values of the bed friction coefficient for the unimodal transport of either of the two solids fractions.

The pattern of the other type of bimodal mixture, in which the finer fraction was transported as a combined load, did not contain an interfacial layer at the top of the bed, and transport of the finer fraction dominated above the top of the bed. As a result, no reduction in the bed friction was detected in the bimodal combined-load transport compared to the transport of unimodal fractions at high bed shear, and values of the bed friction coefficient tended to be higher than for the contact-load transport at the same bed slope. However, this observation must be confirmed by more experimental data at very high bed shear.

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