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Proudění hydrosměsí v potrubích a pohyb splavenin v korytech

Transport of Solids in Enclosed Pipes and Open Channels

Summary

Vast masses of cohesionless solids are transported in natural channels with a mobile bed (in particular during flood events) and in industrial enclosed pipelines. This lecture discusses processes and mechanisms that govern the transport of solids under the condition of high bed shear in enclosed (pressurized) pipes and open channels. It is stressed that in both applications solid-liquid flows exhibit significant similarities in friction- and transport mechanisms.

In Chapter 1, most common applications of hydraulic transport of solids through pipelines are summarized and typical conditions described that lead to the occurrence of sediment transport at high bed shear in open channels. Chapter 2 surveys the state of the arts in the research on transport phenomena associated with particle-laden flows interacting with a mobile bed. The existing experimental facilities and modern measuring techniques are listed and sources are tabled of experimental data used further in Chapter 3 for an analysis of the transport processes. A brief survey of the modeling tools used in research and/or practice is given as well. Chapter 3 reports on author's recent contributions to experimental and analytical work on solids-laden flows interacting with an eroded deposit at high bed shear and outlines a work in progress. Between 2003 and 2008, the author used two experimental setups to produce slurry-flow data for four different fractions of sand. These data and the data collected from the literature were used to either calibrate or validate components of the proposed predictive model (sLM) for slurry pipes with deposits. Two components are discussed in more details. One is the solids transport formula and the other the friction-law formula for the top of the deposit. New forms of the both formulae are proposed for flows transporting particles as combined loads at high bed shear. An example is given of a possible application of the friction-law formula in the river-engineering practice for a determination of the relationship between the flood discharge and the water stage in a steep natural channel. The last chapter (Chapter 4) gives a brief view of future steps in the discussed research and its link to educational activities.

Souhrn

Při různých průmyslových aplikacích se pro přemístění zpracovávaných sypanin (pevných nekohezních částic) používá hydraulické dopravy v potrubí. Také koryta neupravených toků provádějí, zejména za povodňových průtoků, velké objemy splavenin, tj. pevných nekohezních částic splavených ze zemského povrchu. V této publikaci jsou pojednány procesy a mechanismy řídící transport hrubozrnných částic v proudící kapalině za podmínky vysokého smykového napětí působícího na zrnité dno v tlakových potrubích a otevřených korytech. Jedním z cílů je ukázat, že v případě obou těchto aplikací se z pohledu třecích a disperzních mechanismů proudění směsi kapaliny a částic chová podobně.

Kapitola 1 popisuje nejčastější příklady použití hydraulické dopravy sypanin v potrubí a specifické podmínky vedoucí k pohybu splavenin v tocích za intenzivní eroze pohyblivého dna. Kapitola 2 přináší přehled současného stavu vývoje ve výzkumu proudění kapalin nesoucích částice a erodujících pohyblivé dno. Je podán stručný přehled nejvýznamnějších laboratoří a jejich experimentálního vybavení a jsou tabelovány zdroje experimentálních dat z odborné literatury pro pozdější použití (v kapitole 3) při analýze transportních procesů. Dále jsou v kapitole 2 zmíněny různé modelové přístupy používané v současném výzkumu a praxi oborů hydraulické dopravy a pohybu splavenin. Kapitola 3 shrnuje autorovy experimentální a analytické příspěvky do zkoumání interakce proudící směsi se zrnitým dnem za podmínek intenzivní eroze povrchu dna a mapuje pokračující výzkumné aktivity. V letech 2003-2008 autor prováděl měření postupně na dvou různých laboratorních trubních linkách a testoval proudění směsí čtyř různých zrnitostních frakcí písku. Výsledky těchto měření, společně s výsledky získanými z literatury, byly použity ke kalibraci nebo validaci rovnic, jež jsou součástí autorem navrženého předpovědního modelu (sLM) pro proudění hrubozrnné směsi nad sedlinou v potrubí. Dvě rovnice modelu jsou v kapitole přiblíženy detailněji. Jednou je transportní rovnice pro průtok částic v proudící kapalině a druhou třecí rovnice pro povrch erodované sedliny. Byly navrženy nové tvary těchto rovnic pro situace kdy je část zrn transportována v kontaktu s povrchem sedliny (dnové splaveniny) a část bez kontaktu se sedlinou (nesené splaveniny), a to za podmínek intenzivní eroze povrchu sedliny. V kapitole uvedený příklad ilustruje možnost použití třecí rovnice v praxi říčního inženýrství při určení závislosti mezi povodňovým průtokem a stavem vody v přirozeném korytě svažitého toku. Poslední kapitola (kapitola 4) nastiňuje stručný výhled budoucí výzkumné práce a jejího propojení s výukou ve sledovaném oboru.

Klíčová slova: pohyb splavenin, hydraulická doprava, proudění hydrosměsi, odpor proudění, drsnost koryta, stabilita dna, laboratorní experiment

Keywords: sediment transport, hydraulic transport, slurry flow, flow resistance, channel roughness, mobile bed stability, laboratory experiment

Contents

1. INTRODUCTION

Transport of solids in flowing liquid is a very common phenomenon in nature and it is often used as a mean of transportation in industry as well. In nature, solids transport is associated with erosive and suspension abilities of fast flowing water streams in open channels as alluvial rivers or creeks. Masses of transported solids through open channels can be enormous, in particular during flood events. Sediment transport is an important factor in an evaluation of river development and maintenance. In many industries, hydraulic transport through either artificial open channels or much more often enclosed pipes is a major mean of transportation of particulate solids. Worldwide, vast masses of solids are moved hydraulically in the dredging-, mining-, and mineral-processing industries. In the Czech Republic the hydraulic transport is most often used in power engineering and mining. A survey of recent examples of solids transport applications in industry is given in [8]. A condense survey of a history of pipeline hydrotransport is in [26].

During the last twelve years, a number of devastating floods that hit different regions of the Czech Republic over the same period of time was higher than ever before. As a reaction, various appropriate flood mitigation measures have been sought, discussed and applied. Understanding of flow processes in channels during extraordinary high discharges is one of the key issues in predicting and simulating effects of future flood events, and so is an important tool in decision-making process for flooding prevention. Sediment transport is an important factor in the flood flow process as an amount of transported sediments tends to increase tremendously during floods. Sediment particles present in the flow affect significantly the relation between the discharge and the water stage in a channel and hence contribute to damages caused by a flood. Moreover, the transported sediments contribute to changes in the morphology of the channel itself.

In slurry-pipelining practice, design- and operation engineers need tools to optimize a pipeline design and performance. Such an optimization can be successful only if it is based on a sufficient knowledge of a behavior of a slurry flow in a pipeline and if it is carried out using reliable predictive models for pipeline flow of slurries. The operation engineers usually want to keep their pipes deposit free as flows with deposits have a reputation to be instable and potentially dangerous (a line blockage danger). In some cases, however, economical or other reasons lead to operations at velocities that are too low to avoid formation of a granular bed at the bottom of the pipe. For instance, long pipelines used for long-term mining-, or dredging operations often operate with a stationary bed.

Mechanisms governing flows of slurries in pipes and flows of sediments in open channels under conditions describe above are very similar and hence many research findings reached in one research area can inspire to suitable modification and application in the other area. The synergy between the research areas can be beneficial for both.

Figure 1 Transport of solids in flowing liquid: hydraulic transport of solids in enclosed pipes and sediment transport in open channels

2. STATE OF THE ARTS IN RESEARCH

The contents of the contemporary scientific and technical journals on hydraulic engineering (e.g. Journal of Hydraulic Engineering of the American Society of Civil Engineers and Journal of Hydraulic Research of the International Association of Hydro-Environment Engineering and Research) indicate that the issue of sediment transport in open channels is one of the most discussed hydraulic issues in the hydraulic-research community. Surprisingly enough, issues of the pipeline conveying of solids are in the academic world discussed in a quite different group of specialists. While the sediment transport related issues are investigated predominantly by people with their background in the civil-, or environmental engineering, the industry-associated pipeline transport is more seen as an area of interest to chemical-, mechanical-, or mining engineers and researchers publishing their works in journals like Powder Technology by Elsevier, Particulate Science and Technology by Taylor and Francis, or Canadian Journal of Chemical Engineering. This is why there is so little overlap or exchange of information and inspiration between the two areas and groups. It is sad because many problems are common for slurry flows in enclosed pipelines and sediment flow in alluvial channels. As an example, problems can be mentioned associated with flow resistance or interaction of phases (flowing carrier and conveyed solid particles) during the transport process. Perhaps the greatest overlap can be found if comparing the settling-slurry flow above a stationary deposit in a pressurized pipe to the sediment flow in a steep natural channel under a flood condition. Coincidentally, both these issues belong to ones that are the least understood in the field.

Predictive models for slurry flows and sediment flows should be based on a description of major mechanisms that govern the flow. The development and verification of such models requires sophisticated experiments. Simple tests (covering measurements of the integral flow parameters only) may indicate phenomena occurring in a pipeline flow of a mixture but they cannot identify the mechanisms governing the phenomena. The identification of mixture flow mechanisms requires identification of the internal structure of the mixture flow. Hence the experimental and theoretical approaches must be closely interrelated in this research discipline.

2.1 Experimental research

In the last decades, a development of various measuring techniques and their transfer to applications engineering have progressed fast. It has been a task of the day for slurry researchers to introduce those techniques that are suitable to detection of the internal structure of a slurry flow to their experimental practice. Slurries are difficult to handle and even more difficult to measure. It is virtually impossible to use invasive measuring techniques due to problems with wear of the instrument and/or problems with flow (e.g. pipe blockage). Some non-invasive techniques cannot be used as well because a presence of a large amount of particles in flowing slurry distorts the technique (e.g. Laser Doppler Anemometry). However, the major slurry-flow laboratories are successful with introduction and application of some other techniques.

The slurry pipeline research is conducted systematically at several major laboratories. The Pipe Flow Technology Center of the Saskatchewan Research Council (SRC) in Canada possesses five pipe loops of different sizes and currently perhaps the most complete database of own test data for different types of slurries. The SRC has been developing and applying measuring instruments for detection of a spatial distribution of solids concentration (a radiometric profiler) and velocity (an intrusive conductivity probe) in pipe flows of slurries. The SRC cooperates with the sand-oil industry that is very active in Canada during the last two decades. The CSIRO Materials Science and Engineering in Australia is active in testing both settling and non-settling slurries, in particular for a strong Australian mining industry. Ten years ago, it introduced pioneering results of the MRI (Magnetic Resonance Imaging) based monitoring of the internal structure of complex slurries and their comparison with the ERT (Electrical Resistance Tomography) technique. The Flow Process Research Centre of the Cape Peninsula University of Technology (South Africa) focuses activities in their fine equipped laboratory to flows of non-Newtonian slurries in both pipes and open channels. It is currently developing an ERT instrument for an application in highly concentrated slurries. The Centre conducts experiments with the acoustic UVP (Ultrasonic Velocity Profiler) in those slurries as well. The Hydraulic Laboratory of the slurry-pump manufacturer GIW Industries in the U.S.A. is in possession of test loops (Fig. 2) that are used for both research activities and commercial testing.

Figure 2 Example of laboratory loops for slurry-flow testing: GIW Industries loops for slurry-pump testing (larger loops, blue), and slurry-pipe testing (smaller loops, yellow)

Slurry flow tests can be conducted in both laboratory circuits and field pipelines. This is not the case in testing of sediment transport under flood conditions in open channels. Field testing is virtually impossible at high discharges and hence the flood conditions must be simulated and controlled in laboratory set ups (usually flumes). Many laboratories possess sediment-transport flume facilities, e.g. the Ven Te Chow Hydrosystems Laboratory at the University of Illinois of Geomorphology, the Sediment Transport Laboratory of USGS (U. S. Geological Survey), or laboratories of the U.S. Army Corps of Engineers.

For the analysis discussed in the Chapter 3, experimental data from slurry circuits composed of enclosed pipes of different shapes were collected in the literature (Table 1). In Table 1, tested solids are characterized by the mass-mean diameter, d_{50}, and the relative density, S, of solid particles.

Table 1 Experimental data from laboratory loops collected in literature

Solids	Conduit [shape, size in mm]	No. of data points	Ref.:
sand d_{50} = 0.3 mm, narrow graded, S = 2.65	○ 105	6	[20]
sand d_{50} = 0.56 mm, narrow graded, S = 2.65	○ 105	4	[20]
bakelite d_{50} = 1.05 mm, narrow graded, S = 1.53	○ 105	8	[20]
sand d_{50} = 0.354 mm, narrow graded, S = 2.67	□ 98 x 98	30	[18]
sand d_{50} = 0.55 mm, narrow graded, S = 2.66	□ 98 x 98	26	[18]
sand d_{50} = 0.7 mm, narrow graded, S = 2.67	□ 98 x 98	47	[27]
sand d_{50} = 1.1 mm, narrow graded, S = 2.66	□ 98 x 98	30	[18]
bakelite d_{50} = 0.67 mm, narrow graded, S = 1.57	□ 98 x 98	13	[18]
bakelite d_{50} = 1.05 mm, narrow graded, S = 1.54	□ 98 x 98	33	[18]
nylon d_{50} = 3.94 mm, narrow graded, S = 1.14	□ 98 x 98	12	[27]

2.2 Modeling

In practice, predictive models for the hydraulic performance of slurry pipelines are usually based on an empirical approach rather than on a mathematical description of the slurry-flow mechanisms. Empirical correlations are easy to use, simple to establish and to calibrate using relatively simple experiments that cover only measurements of integral flow parameters and can be carried out even in a field pipeline. An origin of some of the correlations goes back to the 1950s. More physics-conscious approaches started to emerge in 70s and have improved ever since with the growing capability to measure besides integral flow parameters also local parameters in flows as the local concentrations and velocities of solids. Perhaps the most successful concept for settling slurry flows has been a two-layer model (2LM) proposed in 1970s [28] and developed further for various flow conditions (as inclined flows, stratified flows with a non-Newtonian carrier etc.) as in e.g. [3,4,7,22]. The model relates in a simple form_dissipation of mechanical energy with an internal structure of settling-slurry flow for situations in which the flow is stratified and a certain portion of transported particles forms a sliding bed at the bottom of a pipe and the rest travels in a faster moving layer of mixture of the particles and a carrying liquid above the sliding bed. It must be stressed that this concept does not assume a stationary bed (deposit) at the bottom of the pipe and cannot be used for such a condition. The same holds for the empirical correlations calibrated for slurry flows with no deposits.

In the near future, models based on the techniques of CFD (Computational Fluid Dynamics) and DEM (Discrete Element Method) can be expected to start playing role in slurry flow modeling. Currently, the CFD software is widely accepted as a modeling tool for fluid (not slurry) flow applications. The DEM technique has been increasingly used to study the behavior of particulate solids in motion. To make the techniques applicable to modeling of solid-liquid flows the coupling of the CFD and DEM will be necessary.

The river engineering practice uses modeling tools (usually one- or two-dimensional) that couple a hydrodynamic model with a sediment model. A typical hydrodynamic model solves both the steady and unsteady flows and a typical sediment transport model includes settling, deposition and re-suspension of multiple-size fractions of cohesive and non-cohesive sediments. Transport models recognize different concepts for bed-load transport (transport of solid particles associated with the mobile bed) and suspended-load transport (transport of particles with no contact with the bed, the particles are suspended in flowing carrying liquid). A comprehensive survey of the sediment models is given in [23].

3. RECENT DEVELOPMENTS AND WORK IN PROGRESS

During the last few years the author's research objectives have focused to transport of relatively coarse particles (particles that do not interact with the carrying liquid in a way that they alter the rheological properties of the carrier) in enclosed pipes with a deposit at the bottom of the pipe and in open channels under flood conditions.

3.1 Scope of investigation: interaction between flowing liquid and mobile bed

A lot of effort has been devoted to the investigation of mobile-bed roughness at values of the bed shear stress that are typical for usual flow conditions in open channels (for recent literature survey see [23,25]). In such conditions, the bed shear stress produces values of the bed Shields parameter, $\theta = \frac{\tau_b}{(\rho_s - \rho_f) \cdot g \cdot d}$ (τ_b = bed shear stress, ρ_s = density of solids, ρ_f = density of liquid, g = gravitational acceleration, d = diameter of solid particle) that are usually smaller than 0.6. Weak sediment transport and bed undulation are associated with the flow conditions at low shear stress.

A surface of a mobile bed is composed of cohesionless particles. An interaction between the bed and the flow of liquid carrying solids above the bed is an important feature in a study of the behavior of flows above the bed. The "law of the wall" of the top of the bed takes into account a development of the boundary layer at the interface between the flow and the bed. On one hand the interface can be seen as a hydraulically rough boundary but on the other hand it does not behave as a fixed boundary if subjected to erosion. The boundary condition is the simplest for $\theta < \theta_c$ (θ_c is θ at the incipient motion of bed particles), where particles at the top of the bed are not in motion. The boundary is clearly defined and its equivalent roughness can be considered as related to the size, d, of the particles covering the top of the bed. For $\theta < \theta_c$, the value of the roughness is usually related to a certain characteristic size of particles forming the top of the bed. For $\theta_c < \theta < 0.8$ (approximately), the relation between the roughness and the particle size is further complicated by the presence of both the bed forms and the (weak) sediment transport at the interface between the flow and the bed. This increases bed resistance and various authors take this effect into account through a multiplication of the characteristic particle size in the roughness relationship. The direct method for an implementation of bed forms to the bed roughness superposes the grain roughness and the form roughness to the total roughness of the bed [23,25].

At $\theta > 0.8$ the bed forms are washed out by the high shear stress and the bed becomes plane again (the upper-plane-bed regime). The top of the bed is eroded and intense sediment transport takes place. The eroded part of the bed is called the shear layer. The resistance of the eroded plane bed, and hence its roughness, are affected not only by the size of particles at the top of the grain deposit but also by particles transported through the shear layer adjacent to the top of the deposit. The mechanism that governs bed friction is much less understood for this high-bed-shear flow at than for flows at lower θ. The upper-plane-bed regime is characteristic for flows at high bed shear in both enclosed pipes and open channels. The flow in the upper-plane-bed regime is typical for e.g. open-channel flows of steep slopes and/or high discharges (flood conditions) or enclosed-pipe flows above stationary deposits. Flows over stationary beds in enclosed pipes are typical high-bed-shear flows. In a pressurized conduit, a large value of the hydraulic gradient (the slope of the energy line) is responsible for high shear stress at the top of the bed. Under certain circumstances the upper-plane-bed regime can be replaced by the antidune regime in an open channel, pipe flows are always antidune-free. Fairly less information is available on mechanisms governing flows under these conditions than for flows at low shear stress [18,19,20,21,24].

3.2 Experimental work

Laboratory pipe loops manufactured to convey slurries are appropriate for testing phenomena related to both hydraulic transport through pipelines and sediment transport at high shear stress in open channels. This is because a broad range of flow conditions can be installed in the loop. Currently, there is still only a limited number of experimental data suitable to investigation of transport and resistance of a flow above a mobile bed for high-shear stress flows, particularly for flows of Shields-parameter values larger than 2. In 2003-2009, the author used two test loops composed of pipes of two different inner diameters (150 mm, 100 mm) to carry out tests with settling-slurry flows above deposits (mobile beds) in enclosed pipes. A development of new experimental setups for tests in new conduit geometries is a work in progress. A development of new measuring techniques with a higher spatial resolution of detecting the local quantities of a slurry flow is a work in progress as well.

3.2.1 Laboratory of Dredging Engineering of Delft University of Technology (2003-2004)

The 150-mm circuit (Fig. 3) in the Laboratory of Dredging Engineering of Delft University of Technology consisted of a 24-m long test loop that could be inclined from horizontal to vertical positions, an 18-m long vertical U-tube, the connecting pipes and the sump tank by means of which solids were introduced into the pipeline and in which solids were stored at the end of each experimental run. During measurements the tank could be bypassed. The entire pipeline circuit had a diameter of 150 mm and was versatile in the total length. For the 2003-2004 tests the measuring loop was prolonged so that each leg of the U-tube was 20 meter long. A centrifugal pump driven by a 164 kW diesel engine with variable speed served the system. Both measuring sections of the test loop were equipped with a differential pressure transmitter and a radiometric density meter adapted as a radiometric concentration profiler. The inverted, vertically mounted, U-tube was used as the counter-flow meter to determine the mixture density in the pipeline. A magnetic flow meter was installed in the descending limb of the U-tube to measure the average velocity of slurry in the pipe. A more detailed description of the test loop and its measuring equipment is in [6]. The circuit was dismantled and moved to a new location in 2005.

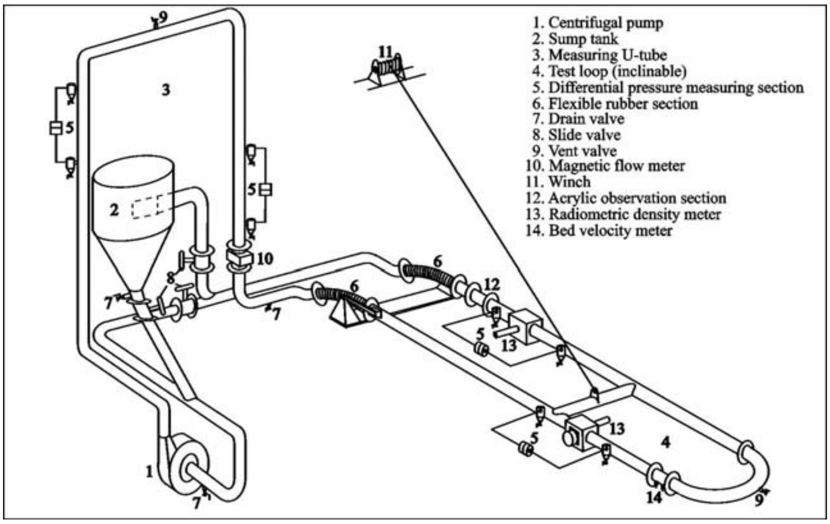

Figure 3 Laboratory circuit in Laboratory of Dredging Engineering (LDE) of Delft University of Technology (in operation to 2005).

3.2.2 Laboratory of Institute of Hydrodynamics of Academy of Sciences of Czech Republic (2005 - 2008)

The 100-mm circuit (Fig. 4) for slurry-flow testing was 55 meter long. Two measuring sections for differential pressure measurements were positioned one after another in one leg of the horizontal test loop. The first pressure tap was located 10 meter behind the U-bend leaving the straight section of pipe of the sufficient length of 100 pipe diameters for flow development between the fitting and the pressure tap. The average velocity of slurry flow in the circuit was sensed using the magnetic flow meter mounted to the vertical section of the circuit. The flow divider allowed collecting slurry samples in the sampling tank of the calibrated volume. Weighting of slurry samples collected in the sampling tank gave information about the delivered concentration of solids in flowing slurry. The thickness of a stationary bed was determined from observed positions of the top of the bed in the glass pipe section that was positioned 4 meters after the U-bend.

The circuit was removed in November 2009 and will be substituted by a new circuit in early 2010. The new circuit will be more versatile in a choice of the loop geometry than the old one and better equipped with modern measuring techniques.

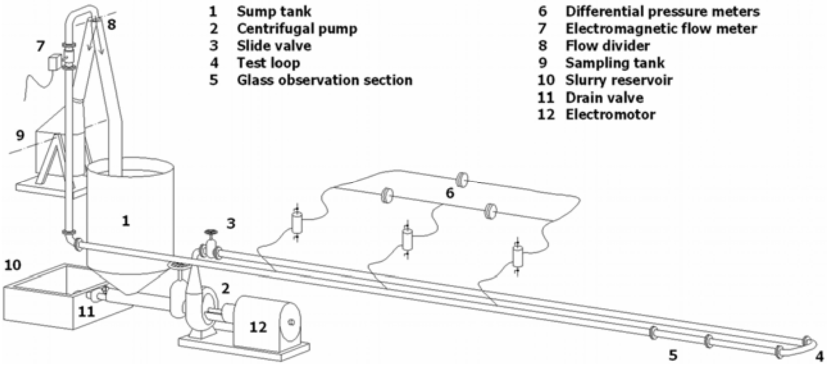

Figure 4 Laboratory circuit in laboratory of Institute of Hydrodynamics (IH) of Academy of Sciences of CR (in operation to 2009).

3.2.3 Tested solids

Table 1. Own experimental data collected in 2003-2008

Solids	Conduit [shape, size in mm]	No. of data points	Laboratory
sand d_{50} = 0.37 mm, narrow graded, S = 2.65	○ 150	14	LDE
sand d_{50} = 1.36 mm, narrow graded, S = 2.65	○ 100	28	IH
sand d_{50} = 0.22 mm, narrow graded, S = 2.65	○ 100	6	IH
sand d_{50} = 0.38 mm, narrow graded, S = 2.65	○ 100	8	IH

3.2.4 Typical measured concentration profiles

Typically, the shapes of measured concentration profiles indicated the position of the top of the deposit and a gradual drop in local concentration at vertical positions more distant from the top of the deposit (Fig. 5). The analyses of the shapes are described in details in [5,9,11].

As shown in [9], shapes of the measured concentration profiles in the discharge area above the deposit are virtually linear for u_{*b}/w_t values (u_{*b} = bed shear velocity, w_t = terminal settling velocity of solid particle) lower than say 6. The non-linear shape of the concentration profiles at higher values of u_{*b}/w_t seems to be associated with the presence of a considerable proportion of suspended particles in the total load of particles transported above the deposit.

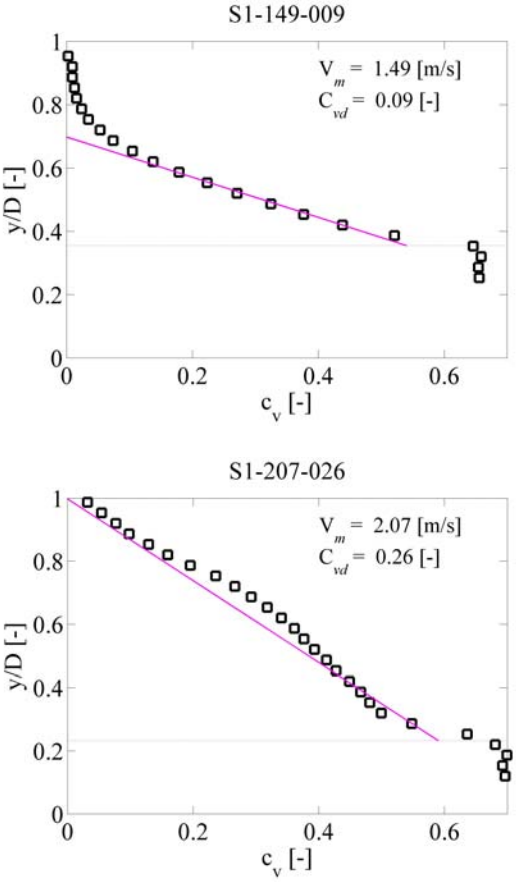

Figure 5 Measured concentration profiles in 0.37-mm-sand slurry flow above stationary deposit in 150-mm pipe in Laboratory of Dredging Engineering (Legend: V_m = average velocity in pipe, C_{vd} = average delivered concentration of solids by volume)

3.3 Analysis

3.3.1 Frictional pressure drop in pipe flow above stationary bed

Little is known about friction conditions of settling-slurry flows with deposits in enclosed pipes as very little studies have been conducted in laboratory- and field pipes to understand their behavior better. The recent analyses [10,12,16] led to the proposal of a predictive model (sLM) for the frictional pressure drop and the thickness of the deposit in a flow of a settling slurry in a pipe. The model principles are summarized below.

Basically, a flow of settling slurry through a discharge area above a stationary deposit is confined by two boundaries (the pipe wall, the top of the bed) of two different values of the hydraulic roughness. As a result, the velocity profile in the vertical cross section is deformed and the hydrodynamic axis shifted towards the top of the pipe (see the schematic sketch in Fig. 6). Moreover, a concentration profile develops across the discharge area with the maximum local concentration at the bottom of the discharge area, i.e. at the top of the deposit with the concentration C_{vb}, and the minimum local concentration near the top of the discharge area (Fig. 6). The non-symmetrical distribution of liquid velocity and solids concentration across the discharge area has a profound effect on boundary friction and thus on the frictional pressure drop in the slurry flow.

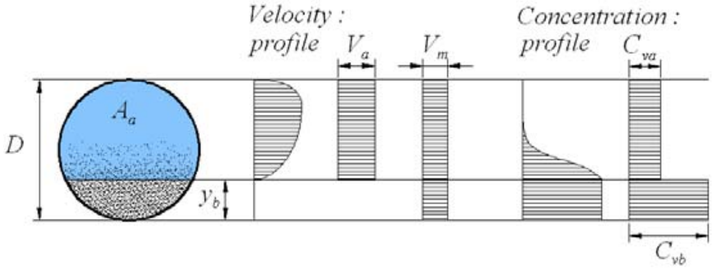

Figure 6 Schematic sketch of internal structure of settling-slurry flow above deposit in enclosed pipe

Figure 6 shows also a schematic geometry of the discharge area in a cross section of a slurry pipe with a deposit as it is used in the pressure-drop model. The discharge area, A_a, in the cross section of a pipe of the internal diameter D is confined by the pipe wall and by the top of the stationary bed (the thickness of the bed, y_b). The area A_a is divided into two sub-areas, each associated with one of the boundaries. Usually the pipe wall is in accordance with experimental experience with slurry pipes considered a hydraulically smooth boundary. The top of the stationary bed is considered a hydraulically rough boundary with its own friction law. The model operates with the area-averaged values of the slurry velocity and solids concentration (V_a, V_m, C_{va} in Fig. 6) instead of the local values for each vertical position.

The sLM model is supposed to predict the frictional pressure drop and the thickness of a stationary deposit for different flow conditions (e.g. different average slurry velocities and concentrations of solids in slurry pipes) by modeling the conservation laws and prevailing mechanisms that govern solids dispersion and solids friction in the flow. To serve this objective the model is composed of the equations for continuity, momentum, boundary friction, particle support, and solids transport. The model is one-dimensional and accommodates acceptable simplifications that make it easy to handle for engineers in practice. It considers solids friction at the top of the stationary deposit as a major contributor to the frictional pressure drop in a settling-slurry flow through a pipe. An example of the sLM model outputs is in Fig. 7.

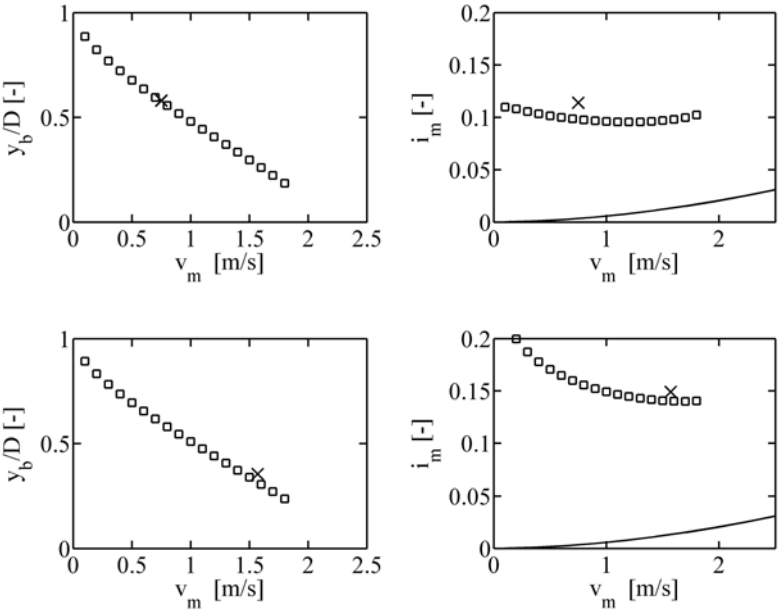

Figure 7 Frictional pressure drop (expressed as hydraulic gradient, i_m) and relative thickness of deposit, y_b/D, as function of average velocity, V_m, for 0.37-mm-sand slurry in 150-mm pipe for two average delivered concentrations of solids (upper: C_{vd} = 0.22, lower: C_{vd} = 0.22) predicted using sLM model (squares) and measured in LDE (x).

3.3.2 Solids flow rate at high shear stress

Essentially, the solids throughput depends on the shear stress that the flow exerts on the top of the mobile bed. Transported particles are non-uniformly distributed in the flow and form a concentration profile across the cross section of the discharge area. The particles are transported either as a contact load or as a suspended load, depending on the dispersive mechanism that keeps the particles within the fluid flow. Combined load transport occurs if a certain proportion of transported particles contributes to the suspended load and the rest to the contact load.

A solids transport formula relates the volumetric solids flow rate q_s (for a unit width of the flow, m^2/s) with pertinent flow parameters. For sediments transported as contact load the dimensionless formula of the MPM (Meyer-Peter and Müller) type is often used, $\Phi = \alpha \cdot (\theta - \theta_C)^\beta$ (Φ = Einstein transport parameter, θ_C = critical Shields parameter, α and β

= empirical coefficients). In the equation, the Einstein transport parameter $\Phi = q_s / \sqrt{(S-1)\cdot g\cdot d^3}$ (S = relative density of solids, i.e. solids density / fluid density). The critical value of the Shields parameter, θ_C, gives the threshold for the incipient motion for particles of certain size and density. In the original MPM equation [17], $\alpha = 8$, $\beta = 1.5$, and $\theta_C = 0.047$. Wong and Parker [31] reanalyzed the original MPM data and suggested new values: $\alpha = 3.97$, $\beta = 1.5$, and $\theta_C = 0.0495$. In the upper-plane bed regime, θ values are much higher than θ_C and thus for our considerations the effect of θ_C can be neglected,

$$\Phi = \alpha\cdot\theta^{\beta} \qquad (1).$$

Bagnold [1] formulated a bed-friction principle for flows transporting bed loads. At the top of a bed, the shear stress exerted by the flow, τ_b, is fully balanced by the solids shear stress, τ_{sb}, derived from the submerged weight of bed load particles. Bagnold [2] employed this principle to formulate a bed-load transport equation for high bed-shear-stress conditions. The equation can be written as $q_s = \eta/\tan\varphi'\cdot V_a\cdot\tau_b/\left[\rho\cdot(S-1)\cdot g\right]$ (η = velocity ratio - see below, φ' = dynamic friction angle for the top of the bed). Re-written to the form of Eq. (1), the formula reads $\Phi = \eta/\tan\varphi'\cdot V_a/u_{*b}\cdot\theta^{1.5}$, in which the bed shear velocity u_{*b} is defined as $u_{*b} = \sqrt{\tau_b/\rho_f}$. Provided that $\tau_b = \tau_{sb}$, the efficiency of bed-load transport can be interpreted as the ratio of the average velocity, V_{sH}, of solids within the shear layer and V_a. If all particles travel within the shear layer (it is the case in a no-suspension sheet flow in which no particles are present above the top of a shear layer), then $V_{sH} = V_{sa}$, which is the average velocity of solids in the discharge area. Therefore, for shear-layer flows (no-suspension sheet flows), $\eta = V_{sa}/V_a$, and hence

$$\Phi = \frac{1}{\tan\varphi'}\cdot\frac{V_{sa}}{u_{*b}}\cdot\theta^{1.5} \qquad (2).$$

A comparison of Eq. (2) with Eq. (1) shows that $\alpha = (1/\tan\varphi')\cdot(V_{sa}/u_{*b})$ and $\beta = 1.5$.

Wilson [29] used the Bagnold's bed-friction principle and combined it with an assumption of a linear distribution of solids concentration across a shear layer in order to relate the shear-layer thickness, H, to the Shields parameter. The shear stress balance, $\tau_b = \tau_{sb}$, gives $\tau_b = \rho_f\cdot(S-1)\cdot g\cdot H\cdot C_H\cdot\tan\varphi'$ (C_H = average volumetric concentration of solids within the shear layer, because of the linear concentration profile across the shear layer, $C_H = C_{vb}/2$), and hence $H = \tau_b/\left[\rho\cdot(S-1)\cdot g\cdot C_H\cdot\tan\varphi'\right] = \theta\cdot d/\left[C_H\cdot\tan\varphi'\right]$.

Pugh and Wilson [21] reported about their laboratory tests of mixture flows at high shear stress above a mobile bed in an enclosed circular pipe. The measurements contained concentration- and velocity profiles across the flow for two fractions of sand and one fraction of bakelite. The tests justified the earlier assumption of a linear distribution of concentration across a shear layer, and revealed a relationship between the local velocity at the top of a shear layer, u_{sH}, and the bed shear velocity ($u_{sH} = \gamma\cdot u_{*b} \approx 9.4\cdot u_{*b}$) ($\gamma$ = empirical coefficient).

Analytical solution of transport equation for sheet flow: It is important to realize that an analytical solution of the general transport equation $q_s = \int_{y_0}^{H} c(y)\cdot u_s(y)\cdot dy$ (y = vertical position above datum, y_0 = initial vertical position of profiles of solids velocity and concentration, u_s = local velocity of solids, and H = height of shear layer) leads to the dimensionless equation of the MPM type (originally MPM [17] proposed their equation as a semi-empirical equation) for a sheet flow. This is the case if the assumptions suggested in [21] are taken into account together with some simple suggestion for a solids-velocity distribution across the shear layer. For the vertical distribution of local volumetric concentration, $c(y) = C_{vb}\cdot(H-y)/(H-y_0)$. If the vertical distribution of the local solids velocity is considered linear as well, then $u_s(y) \approx \gamma\cdot u_{*b}\cdot(y-y_0)/(H-y_0)$. Assuming $y_0 = 0$ and integrating the q_s equation over the height of the shear layer, the solids-flow rate equation reads $q_s \approx \gamma/6\cdot C_{vb}\cdot u_{*b}\cdot H$. An implementation of $u_{*b} = \sqrt{\theta\cdot(S-1)\cdot g\cdot d}$, and $H = \frac{d\cdot\theta}{C_H\cdot\tan\varphi'}$, to the q_s equation leads to $q_s \approx \gamma/6\cdot C_{vb}\cdot\sqrt{(S-1)\cdot g\cdot d^3}\cdot\frac{\theta^{1.5}}{C_H\cdot\tan\varphi'}$. In shear-layer flows, $C_H = C_{vb}/2$ and hence $q_s \approx \gamma/(3\cdot\tan\varphi')\cdot\sqrt{(S-1)\cdot g\cdot d^3}\cdot\theta^{1.5}$. Re-written to the form of Eq. (1), the transport formula reads

$$\Phi = \frac{\gamma}{3\cdot\tan\varphi'}\cdot\theta^{1.5} \approx \frac{3.13}{\tan\varphi'}\cdot\theta^{1.5} \qquad (3).$$

A comparison of Eq. (3) with Eq. (1) shows that $\alpha \approx 3.13/\tan\varphi'$ and $\beta = 1.5$. The equation of the MPM type (Eq. 1) is a result of an analytical solution of the general transport equation also if a more general power-law velocity profile is assumed for the shear layer (which is in a better agreement with the experimental results in [21] than the linear-profile assumption). If $u_s(y) \approx \gamma\cdot u_{*b}\cdot(y/H)^n$ then $\alpha = \frac{2\cdot\gamma}{(n+1)\cdot(n+2)\cdot\tan\varphi'} \approx \frac{18.8}{(n+1)\cdot(n+2)\cdot\tan\varphi'}$ and $\beta = 1.5$. According to this analysis, the coefficient α is affected by the shape of the velocity profile across a shear layer and by friction at the bottom of the shear layer. The coefficient β remains constant for different conditions of flow through a shear layer.

A comparison with a database composed of data with fractions in Tables 1 and 2 confirmed that the MPM-type of the solids transport equation is appropriate not only for pure sheet flows but for flows above a plane bed different from pure sheet flows as well [11,13]. In that case, the values of both coefficients α and β vary with flow conditions.

Semi-empirical generalized transport formula: Data for eleven different solids fractions (sand, bakelite, nylon) collected from the literature and own tests exhibited a good correlation between Φ and θ [11]. The data covered a broad range of u_{*b}/w_t values, including values above the upper threshold for the regime of the pure sheet flow as it is suggested in suggested in [9,30]. Considerable differences in both α and β have been found for different solids fractions. Eq. (2) was generalized [11] in order to cover the observed big differences in values of the transport formula coefficients α and β. The particle Reynolds number, $\mathrm{Re}_p = w_t \cdot d \cdot \rho_f / \mu_f$ (w_t = terminal settling velocity of solid particle, μ_f = dynamic viscosity of carrying liquid) was found to be a suitable parameter to describe the variation in α and β values for different analyzed solids fractions. The tentative generalized formula for contact-load- and combined-load transport in enclosed conduits at high shear stress reads

$$\Phi = \left(\frac{3.13}{\tan \varphi'} + \frac{58}{\mathrm{Re}_p^{0.62}} \right) \cdot \theta^{1.2+\frac{1.3}{\mathrm{Re}_p^{0.39}}} \qquad (4),$$

when $\tan\varphi' = 0.6$. Eq. (4) was further validated for $5 \le \mathrm{Re}_p \le 280$ using experimental data for three fractions of very different sands (fine, medium, and coarse, Fig. 8) [13]. The coefficients α and β in the MPM-formula for high bed shear tend to decrease with increasing values of the particle Reynolds number Re_p. Apparently, both coefficients are very sensitive to Re_p values for Re_p smaller than say 30. For Re_p bigger than say 80, the coefficients seem to be much less sensitive to Re_p. In summary, the transport formula of the MPM type seems to be appropriate for predicting the solids flow rate of both contact-load- and combined-load flows at high shear stress provided that the formula coefficients are considered dependent on the particle Reynolds number.

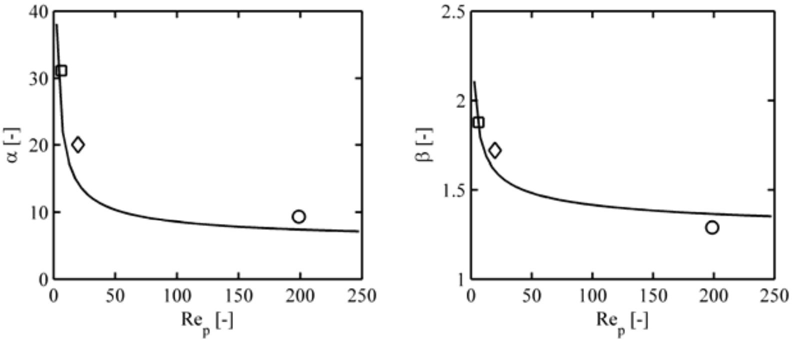

Figure 8 Values of empirical coefficients for generalized solids transport formula [square: 0.22-mm sand; diamond: 0.38-mm sand; circle: 0.36-mm sand; line: coefficients in Eq. (4)]

3.3.3 Equivalent roughness of bed at high shear stress

In the literature, the roughness of a mobile bed has been investigated extensively for flow conditions typical in open channels, i.e. for the conditions associated with low bed shear and weak sediment transport. Much less information is available about flows at high bed shear, i.e. flows that erode the top of the mobile bed, prevent a development of bed forms (the upper-plane-bed regime), and cause intense transport of sediments. Solid particles are picked up from the top of the bed experiencing high shear stress acting from the flowing liquid and carried in a large amount with the flow. The intense transport of solids affects considerably bed resistance and hence the equivalent roughness of the top of the bed.

Analytical solution of the law of the bed for sheet flow: Basically, an analytical approach to the evaluation of bed friction requires knowledge of velocity and concentration distributions throughout the flow above the top of the bed. This information is available for sheet flows, i.e. for flows in which all particles are transported as a bed load (contact load) within a shear layer linked to the top of the eroded stationary bed. The theory [21] that assumes a logarithmic profile of liquid velocity linked to the profile of a certain characteristic slope at the top of the shear layer suggests that the equivalent roughness of the bed, k_s, is independent of the particle size and there is a linear relationship between k_s/d and θ. This can be derived from a combination of the Nikuradse's equation for a liquid-velocity profile above a rough boundary $\frac{u}{u_{*b}} = 2.5 \cdot \ln\left(\frac{30 \cdot y}{k_s}\right)$ (u = local velocity of liquid at vertical position y, k_s = equivalent roughness of bed) with the experimentally determined conditions at the top of a shear layer. The vertical position of the top of the shear layer above the origin of the logarithmic profile is equal to roughly one half of the thickness of the shear layer [21], i.e. $y = y_{sH} = 0.44.H$ and the local velocity at the top of the shear layer $u = u_{sH} = \gamma u_{*b} \approx 9.4 u_{*b}$. The combination of the three equations above gives $\frac{u_{sH}}{u_{*b}} = 2.5 \cdot \ln\left(\frac{30 \cdot y_{sH}}{k_s}\right)$ and thus $\frac{9.4 \cdot u_{*b}}{u_{*b}} = 2.5 \cdot \ln\left(\frac{30 \cdot 0.44 \cdot H}{k_s}\right)$. The rearrangements give

$k_s = \dfrac{30 \cdot 0.44 \cdot H}{\exp\left(\dfrac{9.4}{2.5}\right)} = 0.307 \cdot H \approx \dfrac{H}{3}$ [21]. An implementation of $k_s = 0.307 \cdot H$ to $H = \dfrac{\theta \cdot d}{C_H \cdot \tan\varphi'}$ produces $\dfrac{k_s}{d} = \dfrac{0.307}{C_H \cdot \tan\varphi'} \cdot \theta$. Values of the average volumetric concentration within a shear layer, C_H, and of the coefficient of solids friction, $\tan\varphi'$, can vary for different solids. For the values of $C_H = 0.30$ ($C_H = C_{vb}/2$ and $C_{vb} = 0.6$ is the value typical for a loose-poured bed of e.g. narrow graded sands) and $\tan\varphi' = 0.31$, the above equation simplifies to

$$\frac{k_s}{d} = 3.3 \cdot \theta \qquad (5),$$

which is the relationship that Wilson [30] proposed for sheet flows. This relationship agrees well with the experimental data (Fig. 9) collected for the 1.36-mm sand slurry flow ($0.5 < \theta < 2$) in the circuit of the Institute of Hydrodynamics ASCR. Due to the large particle size of the tested sand, it is reasonable to assume that the observed flow was a sheet flow, i.e. all particles were transported as contact load at all installed flow conditions. However, values of the relative equivalent roughness higher than predicted using the sheet-flow equation (Eq. 5) have been observed for different solids fractions (from fine to coarse, and from light to heavy), at θ values higher than say 2÷4. A steeper slope of the relation between k_s/d and θ indicated that the relationship was not linear at high θ values.

Experimental determination of equivalent roughness of bed: For a majority of bed-friction data in the literature, vertical profiles of liquid velocity and solids concentration across flows different from a sheet flow are not available. Therefore an analytical solution of the bed roughness formula is not feasible for these flows. Instead, the Nikuradse's friction law for a hydraulically rough boundary is adopted for the top of a bed, $\dfrac{V_a}{u_{*b}} = \dfrac{1}{\kappa} \cdot \ln\left(\dfrac{\delta_{rough} \cdot R_{hb}}{k_s}\right)$, i.e. $\sqrt{\dfrac{8}{\lambda_b}} = 2.5 \cdot \ln \dfrac{14.8 \cdot R_{hb}}{k_s}$ (κ = Kármán constant, usually $\kappa = 0.4$, δ_{rough} = empirical coefficient, usually $\delta_{rough} = 14.8$, R_{hb} = hydraulic radius of discharge area associated with bed, λ_b = bed friction coefficient). Experimental tests provide measured values of V_a. The values of u_{*b} and R_{hb} are determined from the additional measured parameters (thickness of the bed, hydraulic gradient) using standard methods, e.g. [10]. Then k_s values can be determined from the Nikuradse's friction-law equation filled with the test results. Further, the correlation is sought among the equivalent roughness of the bed, k_s, and relevant parameters. As appeared from the experimental data processed by the Nikuradse's friction-law equation, flows at very high bed shear tend to exhibit high k_s/d values and their increase with the bed Shields parameter is steeper than for the linear relationship suggested by Eq. (5). The bed roughness values from the results of the 0.37-mm sand tests in [10] satisfied the empirical relationship $\dfrac{k_s}{d} = 1.3 \cdot \theta^{1.65}$. The curve by this equation intersects the sheet-flow line (Eq. 5) at $\theta = 4.2$ and provides a better match to the medium-sand data than Eq. (5) at $\theta > 4.2$ (Fig. 9). The observed medium-sand flow was different from a sheet flow at very high θ values. An analysis of the concentration profiles measured in the medium-sand flow [9] showed that carrier turbulence was a prevailing dispersion mechanism within the upper part of the discharge area above the bed for flow conditions characterized by values of the ratio u_{*b}/w_t higher than say 4.5 (i.e. θ larger than say 9). The shearing action as an exclusive particle dispersion mechanism was confined to the region not far above the top of the bed. Apparently, the high shear stress at the top of the stationary bed was capable of producing turbulent suspension that transported a considerable amount of medium-sand particles (average delivered volumetric concentrations of transported particles up to 0.26) through the 150-mm pipe. A broader comparison of the results for sand fractions of very different particle sizes tested in one pipe indicated that there were effects additional to the effect of θ on the k_s/d values.

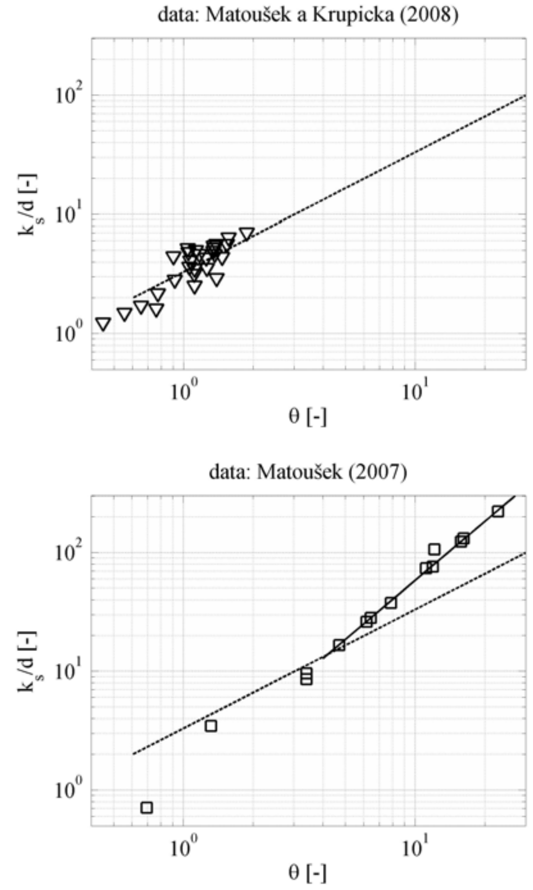

Figure 9 Relative roughness of eroded bed measured for slurries of 1.36-mm sand, 0.37-mm sand (squares) and predicted using Eq. 5 (dropped line) and $\frac{k_s}{d} = 1.3 \cdot \theta^{1.65}$ (solid line)

Semi-empirical generalized formula: The analysis of the database collected from the literature showed that the relationship is more complex for flows different from sheet flows (i.e. for combined-load flows). At high values of Shields parameter (higher than say 2÷4) the roughness tends to increase more with the Shields parameter than the linear relationship predicts. The new semi-empirical formula for the equivalent roughness of a plane bed for combined-load flows in the upper-plane-bed regime recognizes the bed Shields parameter, the hydraulic radius of the discharge area, and the ratio of the flow velocity and the particle-settling velocity as major parameters influencing the k_s value [5]. The formula reads

$$\frac{k_s}{d} = 260 \cdot \frac{R_{ha}}{d} \cdot \left(\frac{w_t}{V_a}\right)^{2.5} \cdot \theta^{1.7} \qquad (6),$$

(R_{ha} = hydraulic radius of the discharge area above deposit). The values of the coefficients in Eq. (6) are subject to modification in the light of increasing number of experimental data available for the formula calibration in future. The temporary values suggest that perhaps the equivalent roughness k_s should be normalized using R_{ha} instead of d. However, a more extensive database is required to generalize this statement.

Application to enclosed pipes: A formula for the mobile-bed roughness is an important part of the predictive models for the frictional pressure drop in stratified flows through slurry pipes with both the sliding bed (the two-layer model 2LM) and with the stationary bed (the model sLM).

Application to open channels: The roughness of a mobile bed affects considerably a relationship between the flow rate and the water stage in open channels. This relationship is of major practical importance for an estimation of water stages under flood conditions giving e.g. a prediction of the maximum water stage for a certain (flood) discharge in a channel. In practice, the relationship is also used for an estimation of the flood discharge from flood marks (the marks or lines to which a flood rose) in a channel after a flood event.

3.3.4 Methodology for determination of equivalent roughness of mobile bed in alluvial channels (with particular attention to flood conditions)

Recently, a methodology has been proposed for a determination of the roughness of a mobile bed of a steep open channel at flood conditions. It takes into account the effect of the high bed shear stress on resistance of steep-slope channels at extremely high discharges with intensive sediment transport. The methodology suggests three successive steps that lead to an appropriate choice of an equivalent-roughness value:

A. the determination of a characteristic value of the Shields parameter for the mobile bed,
B. the evaluation of the bed conditions based on the Shields parameter (bed forms, sediment transport), see Fig. 10,
C. the calculation of the equivalent roughness using an appropriate equation (e.g. Eq. 5) for the identified bed conditions.

The methodology is described in [14] together with an example of an application of the methodology for the mountain river Dubská Bystřice during an extreme flood in August 2002.

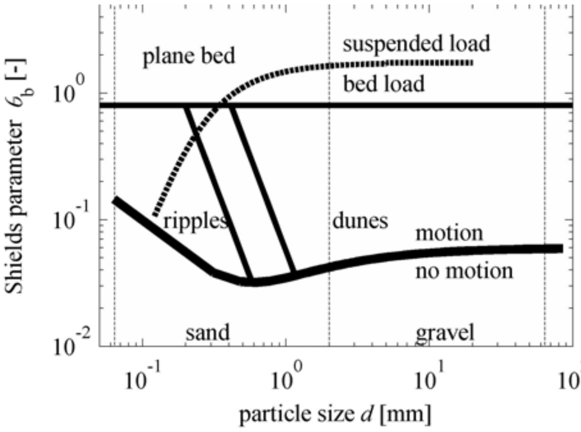

Figure 10 Extended Shields diagram

4. CONCLUDING REMARKS AND FUTURE OUTLOOK

The research on eroded-bed friction and on transport of solids interacting with a flowing liquid and with the bed in industrial pipes and natural channels led to suggestions for an improvement in modeling of the solids flow processes. New formulae were proposed for the equivalent roughness of the eroded bed and for the solids flow rate under the condition of combined-load transport at high bed shear. The formulae have been used in a new model (sLM) for a prediction of the hydraulic gradient (frictional pressure drop) and the thickness of a stationary deposit in an enclosed slurry pipe. Furthermore, a similarity was studied between solids transport processes in enclosed pipes and open channels and an application of the bed-roughness analysis was proposed for a determination of the relationship between the flood discharge and the water stage in steep open channels.

A further extension of the experimental database for validation and improvement of the proposed modeling tools is required. Moreover, a more detailed look, both experimental and theoretical, at the processes in a micro-scale is required in order to involve the CFD modeling tools to the solids-transport research activities.

Two new experimental loops that will help to extend our database and to enhance our experience with a complex behavior of two-phase flows are currently under construction. In the Institute of Hydrodynamics of Academy of Sciences the old experimental set up DN100 (Fig. 4) will be replaced with the new loop DN100 which will be both much more flexible in use and much better equipped with modern measuring techniques than the old one. The new set up will contain a horizontal loop and an optional inclined U-loop. The horizontal loop could be prolonged or shortened to serve different needs of different tested slurries. The measuring equipment will contain two radiometric density meters adapted as radiometric profilers that will be mounted to the system in a special way that will enable to rotate the meters round a pipe cross section and use them for the purposes of the spatial measurement of local concentrations of solids in the pipe cross section (a radiometric tomography method). In the Laboratory of Water Engineering of Faculty of Civil Engineering of the Czech Technical University in Prague, a pipe circuit built in 2007 is currently extended with exchangeable transparent pipe sections of different shapes in order to explore the loop for slurry and sediment tests. This loop will be also instrumental in educational activities. Students following courses of River Engineering, Advanced Hydraulics, Hydraulics of Technological Processes etc. can experience demonstrations of bed forms and different regimes of sediment transport in the loop and carry out slurry-flow resistance tests.

It is believed that the new equipments and ideas will attract more researchers and students for future research activities in the areas of hydraulic transport of solids in pipes and sediment transport in open channels. An international exchange of information is considered an important part of the research and education process.

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reviewer to more than 10 impacted journals;
peer-reviewer for National Science Foundations (Czech Republic, Georgia, South Africa);
20 peer-reviewed publications in international journals; 4 invited keynote lectures; more than 50 peer-reviewed contributions to international conferences, more than 15 technical reports;
30 citations in WoS, 11 more in Scopus, and 2 more in ScienceDirect;

Teaching:

1994 - 2005	lecturing courses Dredging; Dredging Processes; Dredge Pumps and Slurry Transport (in English and Dutch), supervising Bc and MSc students (in total 27 MSc students), mentoring project groups (Holland)
2005 -	lecturing courses (in Czech) Hydraulics I and III; Two-Phase Flow; Hydraulics of Technological Processes; Hydraulic Modeling, supervising Bc, MSc, PhD students (Czech Republic)
2007 -	faculty member for annual technical courses organized by GIW Industries and Augusta State University (USA).

Selected publications in 2000-2009:

Journals with impact factor:

Matoušek, V. (2002). Pressure drops and flow patterns in sand-mixture pipes. Journal of Experimental Thermal and Fluid Science (Elsevier), 26, 693-702.

Matoušek, V. (2005). Research developments in pipeline transport of settling slurries. Powder Technology (Elsevier), 156(1), 43-51.

Matoušek, V. (2007). Interaction of slurry pipe flow with a stationary bed. The Journal of The Southern African Institute of Mining and Metallurgy (SAIMM), 107(6), 365-72.

Matoušek, V. (2009). Concentration profiles and solids transport above stationary deposit in enclosed conduit. Journal of Hydraulic Engineering (ASCE), 135(12), 1101-1106.

Matoušek, V. (2009). Pipe-wall friction in vertical sand-slurry flows. Particulate Science and Technology. An International Journal (Taylor & Francis), 27(5), 456-468.

Matoušek, V. (2009). Predictive model for frictional pressure drop in settling-slurry pipe with stationary deposit. Powder Technology (Elsevier), 192(3), 367-374.

International peer-reviewed journals:

Matoušek, V. (2000). Experimental investigation of slurry flow mechanism in a pipeline. Journal of Dredging Engineering (WEDA), 2(3), 18-39.

Matoušek, V. (2000). Concentration distribution in pipeline flow of sand-water mixtures. Journal of Hydrology and Hydromechanics, 48(3), 180-196.

Ni, F., Zhao, L., Matoušek, V., Vlasblom, W.J., and Zwartbol, A. (2004). The two phase flow of highly concentrated slurry in a pipeline. Journal of Hydrodynamics, Series B, 16(3), 325-331.

Lee, M.S., Matoušek, V., Chung, C.K., and Lee, Y.N. (2005). Pipe size effect on hydraulic transport of Jumoonjin sand – experiments in a dredging test loop. Terra et Aqua (IADC), 99, 3-10.

Matoušek, V. (2007). Distribution of medium-sand particles in flow above erodible bed. Journal of Hydrology and Hydromechanics, 55(4), 274-281.

Matoušek, V., and Krupička, J. (2009). On equivalent roughness of mobile bed at high shear stress. Journal of Hydrology and Hydromechanics, 57(3), 191-199.