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DEPOSITION LIMIT VELOCITY: EFFECT OF PARTICLE SIZE DISTRIBUTION

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Industrial settling slurries often consist of particles of very different sizes; the particle size distribution may cover sizes which differ with two orders of magnitude. A broad particle size distribution affects parameters of slurry flow including deposition limit velocity. We present experimental results of the deposition limit velocity collected during a comprehensive experimental campaign testing slurry flows composed of solids of different fractions in the GIW Hydraulic Laboratory in 2016. Four narrow graded fractions (carrier fluid, pseudo-homogeneous, heterogeneous, and stratified) were tested in permutations from the individual components to the complete mixture at various concentrations. The primary experiments were carried out in a 203-mm pipe, and selected corresponding experiments were repeated in a 103-mm pipe. The experimental results show that interactions among components affect the resulting deposition limit velocity in flows of broadly graded settling slurries. The effect of particle size distribution on the deposition limit velocity is not benign. The deposit velocity is not necessarily lower in a flow of slurry composed of four components than in slurry flow of one component with the highest deposit velocity from the four components. We discuss possible modifications of a deposit velocity predictive model in order to take effects of a broad particle size distribution into account.

KEY WORDS: settling slurry flow, deposit in pipe, four component model, mixture flow experiment.

1. INTRODUCTION

We consider the deposition limit velocity, V_{dl}, as an average flow velocity at which grains first stop moving and start to develop a deposit at the bottom of a pipe. If coarse grains are transported at high delivered concentrations C_{vd} (say $C_{vd} > 0.2$, see e.g. Matoušek and Krupička, 2013a), they tend to form a sliding bed at velocities higher than V_{dl} and hence V_{dl} is a threshold at which the bed stops sliding. In flow of low concentration of coarse grains, no compact sliding bed is formed if the flow decelerates towards V_{dl}. Instead the grains tend to form temporal clusters at the bottom of the pipe if the flow velocity gets close to V_{dl}, and the clusters interrupt movement before they come to a final stop at V_{dl}. If fine grains are transported instead of coarse grains in settling slurry flow, they do not form a sliding bed or any clusters before the deposit develops. In such a flow, a development of the deposit is a much more stable process than in coarse settling slurry flow, where it is often associated with a development of density waves, particularly in closed loops (Matoušek and Krupička, 2013b).

A measurement of V_{dl}, or its determination by visual observation in a clear pipe, is associated with considerable uncertainty caused both by the unstable process of bed forming and by the individual character of each observer's decision making. Hence, a considerable scatter must be expected to occur in experimental results and an expected deviation of predictions from experimental data must be considered generally larger than the deviation for a frictional pressure drop at standard operating velocity in slurry flow. While the deviation up to say 10% is considered good for frictional pressure drop predictions, for V_{dl} the deviation may be considered satisfactory if it does not exceed 20%.

The deposition limit velocity is sensitive to pipe diameter, to properties of both solids (size, density) and carrying liquid (density, viscosity) and to the concentration of transported solids. Experimental data from large pipes of industrial size are extremely scarce, and a majority of available data are from pipes of diameters up to 100 or 150 mm. Much more experimental experience than for an effect of the pipe size is available for an effect of the particle size on V_{dl}, although data for particles smaller than say 100 micron are not as common. The experience learns that there is a certain critical size at which V_{dl} is maximal in a given pipe. This size is of about 0.5 mm (medium sand in water), with coarser and finer grains of the same density forming granular deposits at lower flow velocities.

This trend has been confirmed by a number of experiments, recently e.g. by Kesely et al. (2017) for different fractions of glass beads (0.18 mm, 0.44 mm, 0.53 mm, and 0.9 mm) in a 100-mm pipe. The same work looked also at an effect of the delivered concentration and confirmed that high delivered concentrations of particles tend to decrease V_{dl} in a pipe. The work compared the experimental results with predictions of two V_{dl} models: the VSCALC model by GIW (Wilson et al. 1997) and two versions of the Durand model (Durand and Condolios 1952, Durand 1953). The VSCALC model combines the Wilson formulae for medium and coarse fractions with the Thomas formula for fractions finer than say 100 microns. The model gives a maximum value of deposit velocity for given sizes of particle and pipe (V_{sm}) and a value modified for different delivered concentrations (V_s). A comparison with the glass beads experiment exhibited a very good agreement except for C_{vd} higher than 0.3, where the model tended to under predict the deposition limit velocity. The Durand model uses an empirical nomograph which relates the dimensionless V_{dl} (F_L) with the particle size and solids concentration (C_v up to 0.15). There are two versions of the nomograph in the literature (Miedema 2016). Predictions using the 1952-version of the nomograph agreed well with the experimental results for C_{vd} up to 0.15, while the 1953-version considerably over predicted the deposit velocity at any concentration (Kesely et al. 2017).

2. EXPERIMENTAL WORK

In July-August 2016, a comprehensive experimental data set was collected for slurry flows composed of solids of different fractions in the GIW Hydraulic Laboratory in Grovetown, Georgia, USA. Four narrow graded fractions (components of the four-component friction loss model: carrier fluid, pseudo-homogeneous, heterogeneous, stratified) were tested in permutations from the individual components to the complete mixture at various concentrations. The components were:

1. carrier fluid: a silica based "rock flour" with approximately 88% passing 40 μm,
2. pseudo-homogeneous fraction: a silica sand product with approximately 90% falling between 40 μm and 0.2 mm,
3. heterogeneous fraction: waste rock from a granite quarry, screened in the lab to remove the fines, resulting in a product with approximately 80% falling between 0.2 and 3 mm,
4. stratified fraction: a commercially screened granite product with approximately 90% larger than 3 mm and a top size of approximately 12.5 mm.

The primary experiments were carried out in a 203-mm (8-inch) pipe, and selected corresponding experiments were repeated in a 103-mm (4-inch) pipe. Pipe friction loss, deposition limit velocity, and pump solids effect were measured. The experiments and their conditions are described in details elsewhere (Visintainer et al. 2017).

Curves of particle size distribution (PSD) were determined for each particular fraction and also for each combination of fractions tested (composed of 2 to 4 components, i.e. individual fractions). The V_{dl} was determined by visual observation (including video recording) of a clear pipe section mounted to a pipe loop just downstream of pressure drop measuring sections at the end of a long stretch of straight piping (200D).

3. DEPOSITION LIMIT VELOCITY BY EXPERIMENT AND PREDICTION

In this chapter, we discuss the experimental results and compare them with predictions using selected appropriate models (VSCALC, 1952-Durand, and SRC model as in Shook et al. 2013). We evaluate the quality of agreement between the experimental results ($V_{dl,MEAS}$) and predictions ($V_{dl,CALC}$) using the relative error, E_r, defined as

$$E_r = \sum\left[ABS\left(\frac{V_{dl,CALC} - V_{dl,\mathrm{MEAS}}}{V_{dl,\mathrm{MEAS}}}\right)\right]/N \tag{1}$$

in which N = number of experimental data points.

3.1. INDIVIDUAL FRACTIONS

Experimental results of V_{dl} for individual fractions are in a general agreement with expected trends and predictions by the established predictive models. The models scale well with pipe diameter, and values of their relative errors are similar for the error analysis done at all (N = 56) data points in a 203-mm pipe and at all (N = 22) data points in a 103-

mm pipe. In both pipes, a weak effect of delivered concentration on V_{dl} was observed, although V_{dl} decreased considerably less at high C_{vd} than predicted by VSCALC. The observed effect of a particle size also satisfied our expectations, with the heterogeneous fraction exhibiting the highest V_{dl}.

The VSCALC-model gives predictions close to the observations if V_{sm} is taken as V_{dl} and the effect of C_{vd} is ignored (the model exaggerates the concentration effect, predicted values of V_s are too low). The 1952-version of the Durand model gives similar values of the relative error as VSCALC for the 203-mm pipe (d_{50} used as grain size in the models: $E_{r,VSCALC\text{-}Vsm} = 0.161$, $E_{r,1952\text{-}Durand} = 0.161$ in 203-mm pipe, $E_{r,VSCALC\text{-}Vsm} = 0.033$, $E_{r,1952\text{-}Durand} = 0.248$ in 103-mm pipe). The SRC-model provides similar results for the two coarser fractions and does not give predictions for the two finer fractions, where Archimedes number is below 125.

Figure 1 shows results for individual fractions expressed by dimensionless numbers, Durand factor $F_L = \frac{V_{dl}}{\sqrt{2gD\left(\rho_s - \rho_f\right)/\rho_f}}$ (g = gravitational acceleration, D = pipe diameter, ρ_s = particle density, ρ_f = carrier fluid density) and Archimedes number $Ar = \frac{4\rho_f g d^3\left(\rho_s - \rho_f\right)}{3\mu_f^2}$ (d = particle diameter, μ_s = carrier fluid dynamic viscosity). A characteristic particle size of each fraction is represented by the mass-median diameter d_{50}. A scatter of experimental data for F_L of a certain fraction (approximately constant Ar) is due partially to the effect of variable delivered concentration; note that C_{vd} does not participate in either F_L or Ar. Plots of Fig. 1 show that the heterogeneous fraction (Ar of about 2 x 10^4) indeed exhibits the biggest V_{dl}. The plots also show a reasonable agreement between the experiments and predictions by three different models.

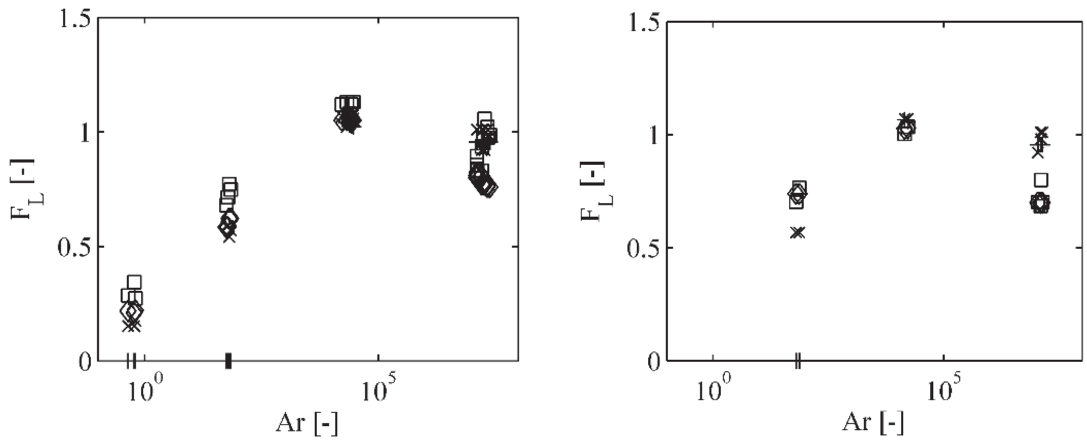

Fig.1. Relationship between dimensionless deposit velocity F_L and Archimedes number Ar for four individual fractions. Left panel – 203-mm pipe, right panel – 103-mm pipe. Legend: square = experiment, diamond = VSCALC-V_{sm}, x = 1952-Durand, + = SRC.

3.2. COMBINED FRACTIONS (MIXED COMPONENTS)

The impact of particle size distribution can be introduced to a calculation of V_{dl} in different ways. We have tested the following 3 approaches:

I. The mass-median size d_{50} is determined from a PSD curve and used in a V_{dl} model.
II. The weighted mean size of transported solids is determined and used instead of d_{50} in a V_{dl} model.
III. V_{dl} is calculated separately for each fraction and then the weighted mean V_{dl} is determined.

Ad I. This is the same procedure as for mono-disperse slurry, d_{50} is affected by PSD.
Ad II. The weighted mean diameter $d_m = \sum(X_i d_i)/\sum X_i = \sum(X_i d_i)$, in which index i denotes the individual components (i.e. i = f,p,h,s) and X_i is the proportional volume fraction, i.e. $\sum X_i = X_f + X_p + X_h + X_s = 1$.
Ad III. The weighted mean deposit velocity $V_{dl} = \sum(X_i V_{dl,i})$, in which $V_{dl,i}$ is the deposition limit velocity for a particular i-fraction.

To calculate V_{dl}, the density and viscosity of carrier fluid are modified for X_f using methods described in Visintainer et al. (2017). All three V_{dl}-calculation approaches give similar results ($E_{r,I} = 0.154$, $E_{r,II} = 0.157$, $E_{r,III} = 0.214$ in the 203-mm pipe, $E_{r,I} = 0.140$, $E_{r,II} = 0.086$, $E_{r,III} = 0.164$ in the 103-mm pipe using the VSCALC-V_{sm} model) although there are differences among the methods in the distribution of the relative error. Methods I and II, expressing an effect of PSD by altering the particle size, produce predictions which are less sensitive to changes in flow conditions than the experimentally determined V_{dl} (points gather to clusters with a predominantly horizontal orientation in the two upper rows of plots in Fig. 2). Method III seems to produce results which are more sensitive to the flow conditions than the methods based on the grain size modification (the clusters are oriented in the direction of the perfect-fit line rather than the horizontal direction in the lowest row of plots in Fig. 2). However, the results of Method III also demonstrate that the relative error tends to increase with the increasing V_{dl} meaning that the model tends to under predict V_{dl} more at higher values of the observed V_{dl}. This trend is particularly apparent in the 203-mm pipe.

The highest deposition limit velocities were observed in flows of the heterogeneous (X_h) component alone and in flows of mixtures composed of more components including the X_h-component. Apparently, there is a disproportional impact of $V_{dl,i}$ of individual fractions on V_{dl} of flow of the total mixture. The experimental results indicate that the heterogeneous component (X_h) has a prominent role in forming of deposit in multi-component mixtures.

Note that the effect of broad PSD on the deposition velocity is not benign, which is in contrast with the effect on frictional pressure drop at standard operating velocities (Visintainer et al. 2017).

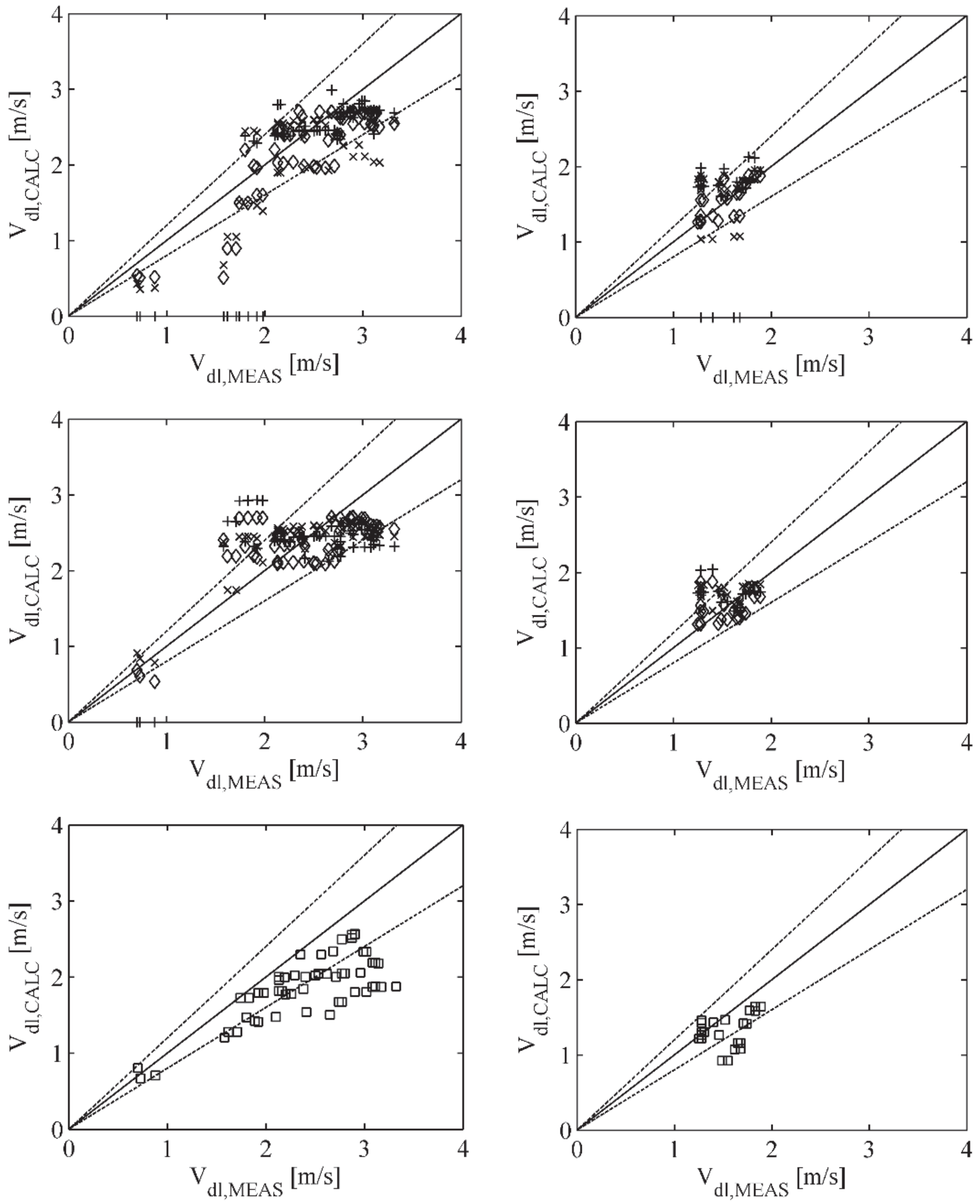

Fig.2. Comparison of experimentally determined and predicted deposition limit velocity for slurries composed of one to four components. Upper row: Method I using different models, middle row: Method II using different models, lower row: Method III using VSCALC-V_{sm} model by Eq. 2 with W_i' = 1).
Left panel – 203-mm pipe, right panel – 103-mm pipe.
Legend: diamond = VSCALC-V_{sm}, x = 1952-Durand, + = SRC, lines = perfect fit and ±20% deviation.

To take the disproportionate impact of individual components into account, we apply an additional constant W_i' to the V_{dl}-formula of Method III. The constant W_i' accounts for effects of an interaction among components from which the mixture is composed and modifies the V_{dl}-formula to the following form,

$$V_{dl} = \frac{\sum\left(W_i^{'} X_i V_{dl,i}\right)}{\sum\left(W_i^{'} X_i\right)} = \frac{W_f^{'} X_f V_{dl,f} + W_p^{'} X_p V_{dl,p} + W_h^{'} X_h V_{dl,h} + W_s^{'} X_s V_{dl,s}}{W_f^{'} X_f + W_p^{'} X_p + W_h^{'} X_h + W_s^{'} X_s} \tag{2}$$

There are various options how to determine W_i' in order to minimize E_r by using Eq. 2. We assume $\sum\left(W_i^{'} X_i\right) = 1$ so that if $X_i = 1$ then $W_i' = 1$ and we also assume that W_i' is related to X_i. It follows that an appropriate relation can be $W_i^{'} = X_i^{n_i}$ and hence

$$V_{dl} = \sum\left(X_i^{n_i+1} V_{dl,i}\right) / \sum\left(X_i^{n_i+1}\right) \tag{3}$$

For the sake of simplicity, we consider equal values for $n_f = n_p = n_s$ and calculate W_h' (and n_h) from

$$\sum\left(W_i^{'} X_i\right) = \sum X_i^{n_i+1} = 1 \tag{4}$$

For V_{sm} from VSCALC as the deposit velocity of individual components in Eq. (3) ($V_{dl,i} = V_{sm,i}$), we optimize

$$n_f = n_p = n_s = 0.55 \tag{5}$$

to produce results in Fig. 3 ($E_{r,III,modif} = 0.133$ in the 203-mm pipe, $E_{r,III,modif} = 0.115$ in the 103-mm pipe). The resulting W_h' reaches high values at low X_h and converges to 1 at X_h approaching 1, with values of the product W_h'X_h increasing with the increasing X_h, For our test conditions, $n_h \approx -0.65$ at $X_h > 0.1$. Thus, the above procedure handles the disproportional effect of the X_h-fraction on V_{dl} in multi-component slurry flow by magnifying its weight in flows where X_h tends to be low.

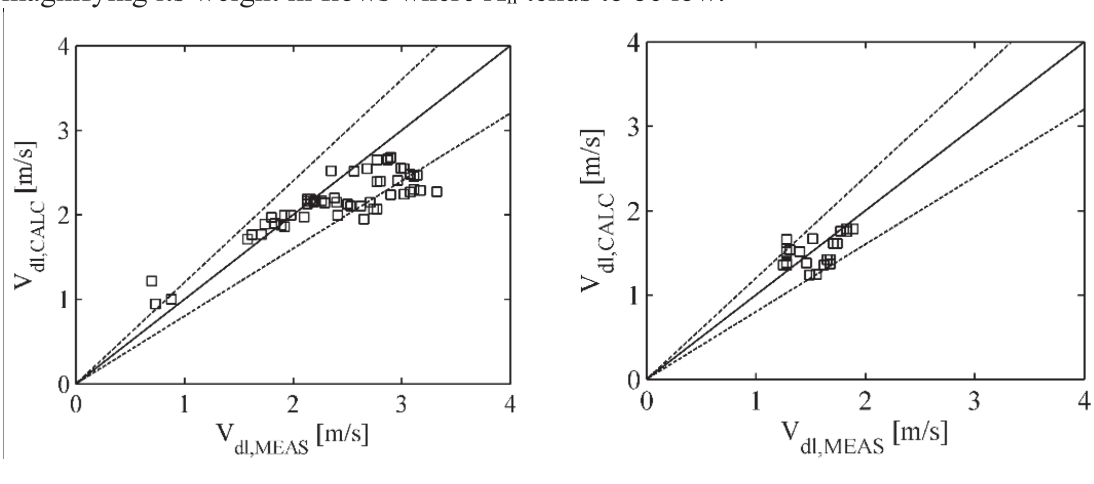

Fig.3. Comparison of experimentally determined and predicted deposition limit velocity for slurries composed of one to four components. Modified Method III (VSCALC-V_{sm} based prediction for weighted mean deposit velocity, Eqs. 3-5). Left panel – 203-mm pipe, right panel – 103-mm pipe.

4. CONCLUSIONS

Contrary to an effect of particle size distribution on frictional pressure drop, the effect of broad particle size distribution on the deposition limit velocity is not benign. In flow of multi-species mixture, a presence of granular fractions (components) with lower deposit velocity does not significantly diminish the deposit velocity of the fastest depositing fraction, which is the heterogeneous fraction (screened waste rock with d_{50} = 0.8 mm in our tests).

A disproportionate contribution of individual components to the deposition limit velocity in mixture flow is taken into account in the proposed multi-component model (Eqs. 3-5). The model takes the VSCALC-V_{sm} model as a basis for a computation of deposit velocities of individual components. Predictions by the calibrated multi-component model agree reasonably well with the experimental results. The model must be further refined to incorporate an effect of mean solids concentration on the deposition limit velocity.

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