Large scale, 4-component, settling slurry tests for validation of pipeline friction loss models

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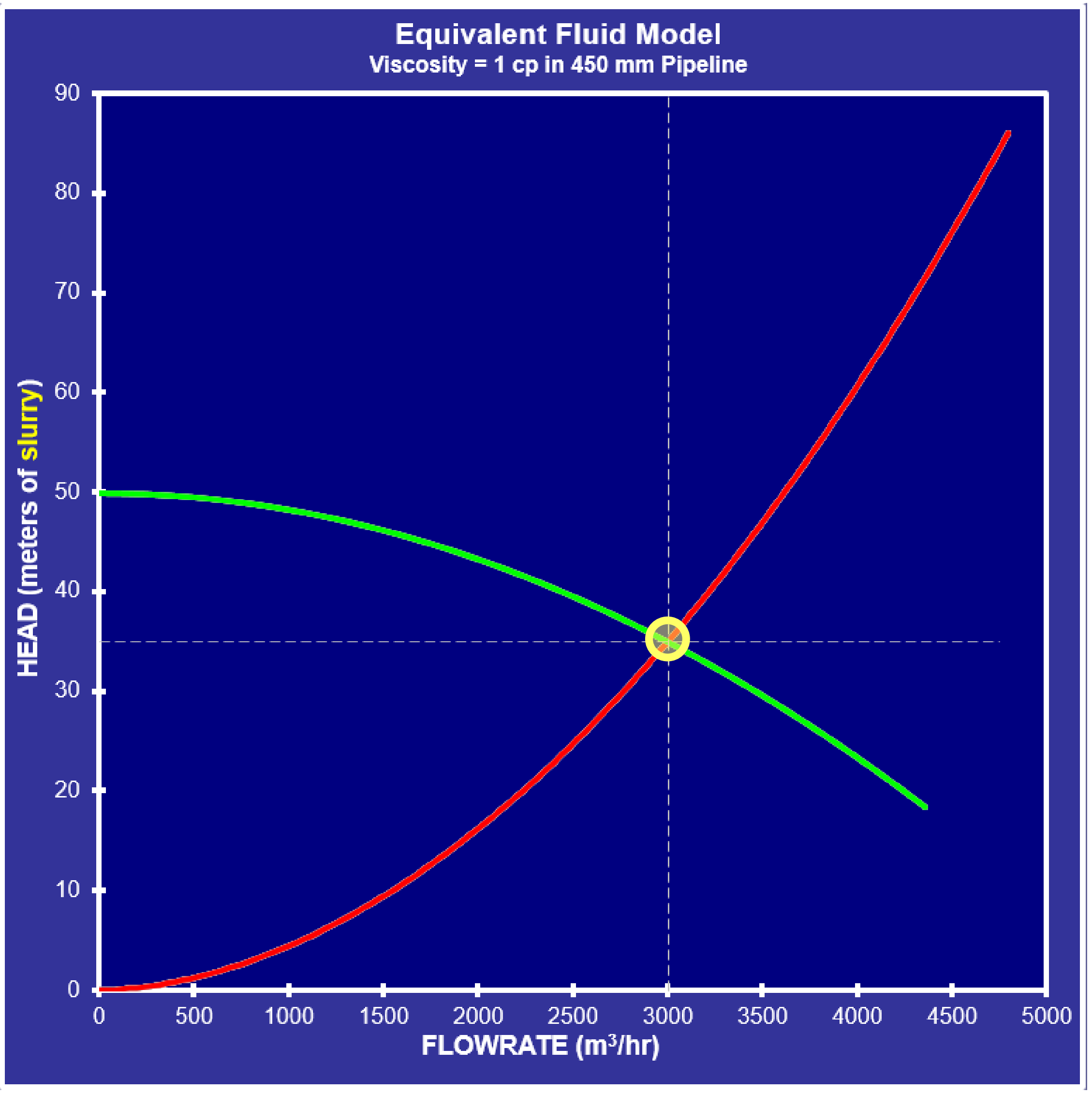
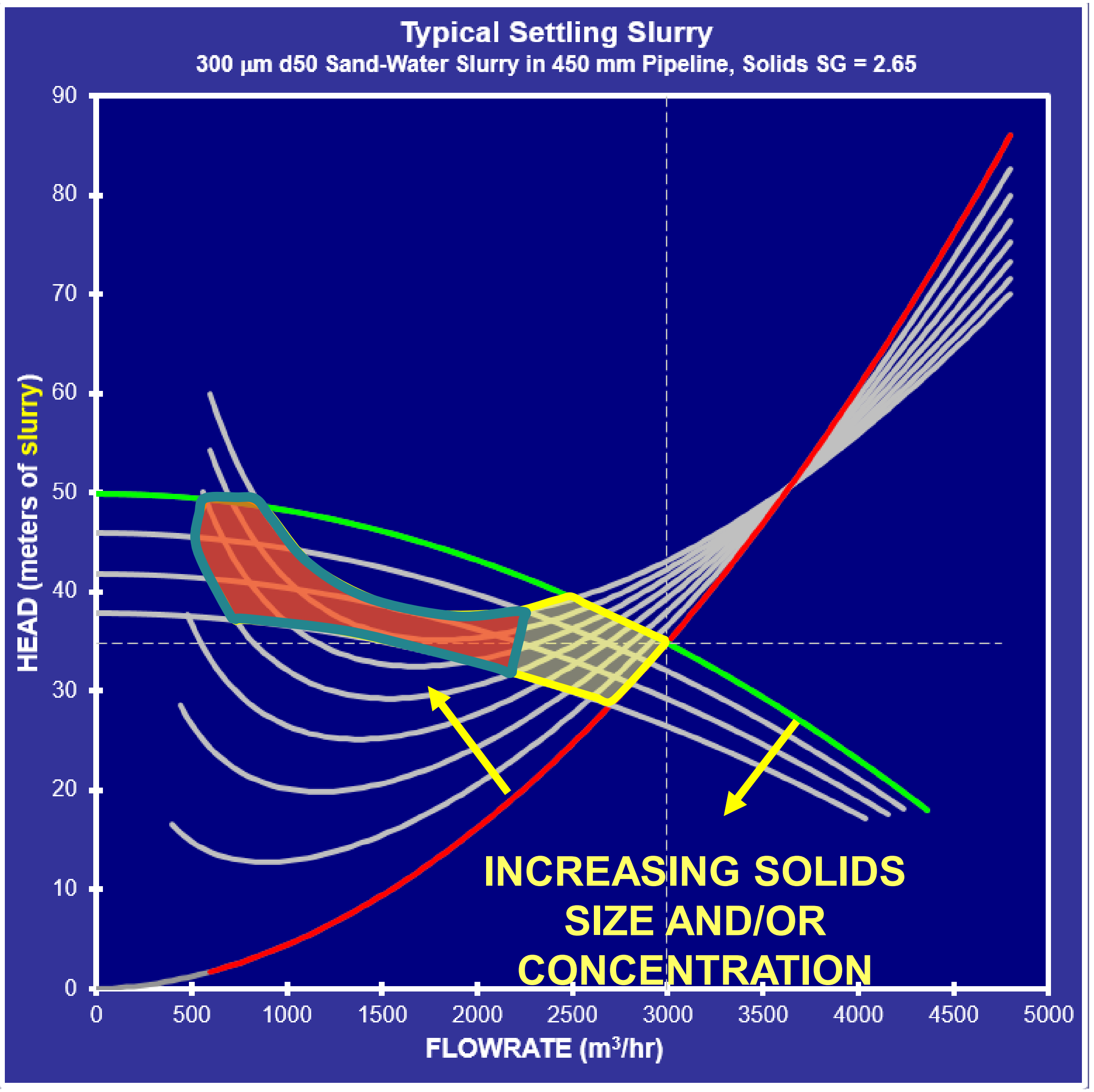
Why do settling slurry flow models matter?



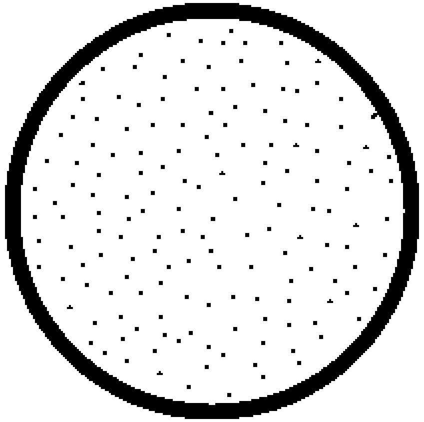
- When pumping simple liquids, centrifugal pumps interact with their piping systems in a pretty straightforward way.
- The piping system resistance curve (red) is generally upward sloping.
- The pump performance curve (green) is generally downward sloping.
- Their combined action leads to a stable operating condition at the point where the two curves intersect.
- In many cases, the stability of this condition can be maintained with little oversight.

Why do settling slurry flow models matter?



- When pumping slurries, additional variables must be considered, especially changes in the concentration and size of the solid particles.
- Both the system resistance and the pump performance may be strong functions of these changing properties.
- Such changes may occur on a regular and somewhat uncontrolled basis, due to natural changes in the source of solids and/or variability in the process itself.
- The range of possible intersections between pump and system curves may now span a large area.
- In some cases, certain combinations may be unstable or not even feasible, leading to unexpected swings in flowrate and the potential for system blockage.
- Accurate models are needed to predict both the pump and pipeline response to slurry properties, so these conditions may be analyzed, and safe operating procedures developed.

Idealized Settling Slurry Flow Regimes



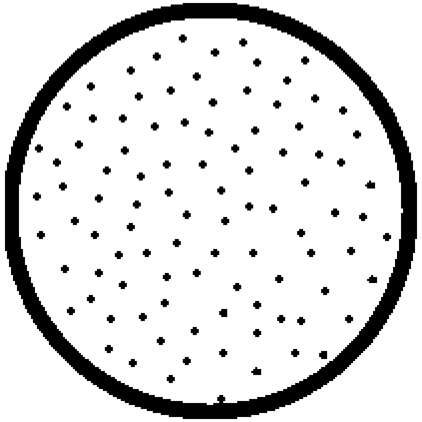
“Carrier Fluid”

particles < 40μm

Solids assumed to “combine” with the liquid.

Solids may affect the mixture viscosity.

A standard “pure-fluid” model may be used.



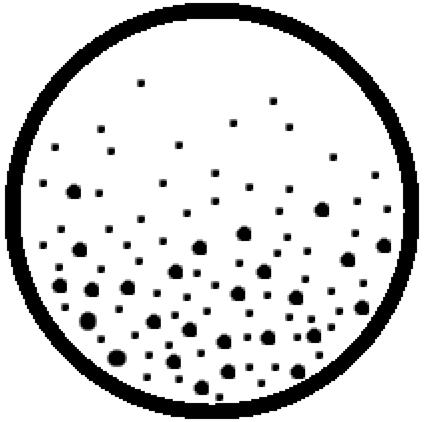
“Pseudo-homogeneous”

40 μm < particles < 200 μm

Solids fully supported by turbulence.

Solids do not affect the mixture viscosity.

Treated as an “equivalent fluid”.



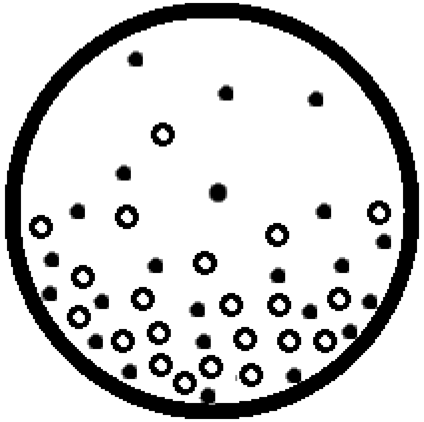
“Heterogeneous”

200 μm < particles < 0.015D

Solids supported by a combination of turbulence and mechanical contact with the pipe wall.

A partly-stratified model of slurry flow is required.

(D = pipe diameter)



“Fully Stratified”

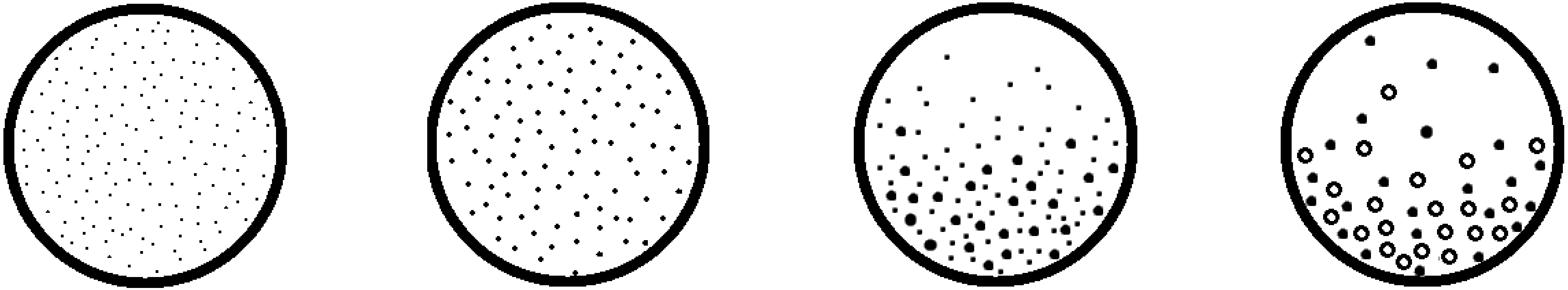
0.015D < particles

Solids supported mainly by mechanical contact with the pipe wall.

A sliding bed friction model of slurry flow is required.

(D = pipe diameter)

Idealized Settling Slurry Flow Regimes

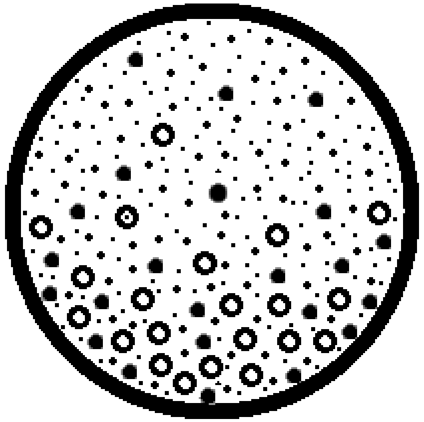


“Carrier Fluid”	“Pseudo-homogeneous”	“Heterogeneous”	“Fully Stratified”
particles < 40μm	40 μm < particles < 200 μm	200 μm < particles < 0.015D	0.015D < particles

Modelling challenges:

- Effective models exist for each regime, however, in combining them, each coarser fraction must consider the supporting effects of the finer fractions below it.
- Quality data across all regimes in industrial sized pipelines with accurate PSD sampling is scarce.

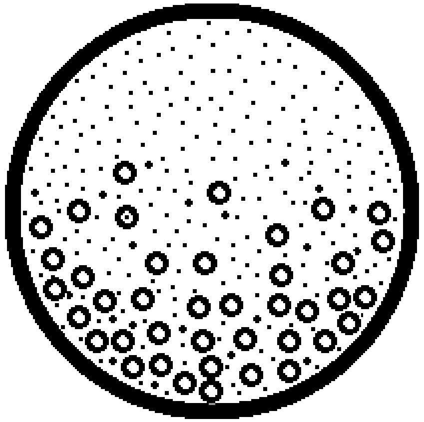
Practical Settling Slurry Flow Examples



"Broad size distribution"

Particles range from less than 40μm to greater than 0.015D

Often generated by mineral processing operations (crushing, grinding, etc.)



"Bi-modal size distribution"

Particles grouped into two different size ranges

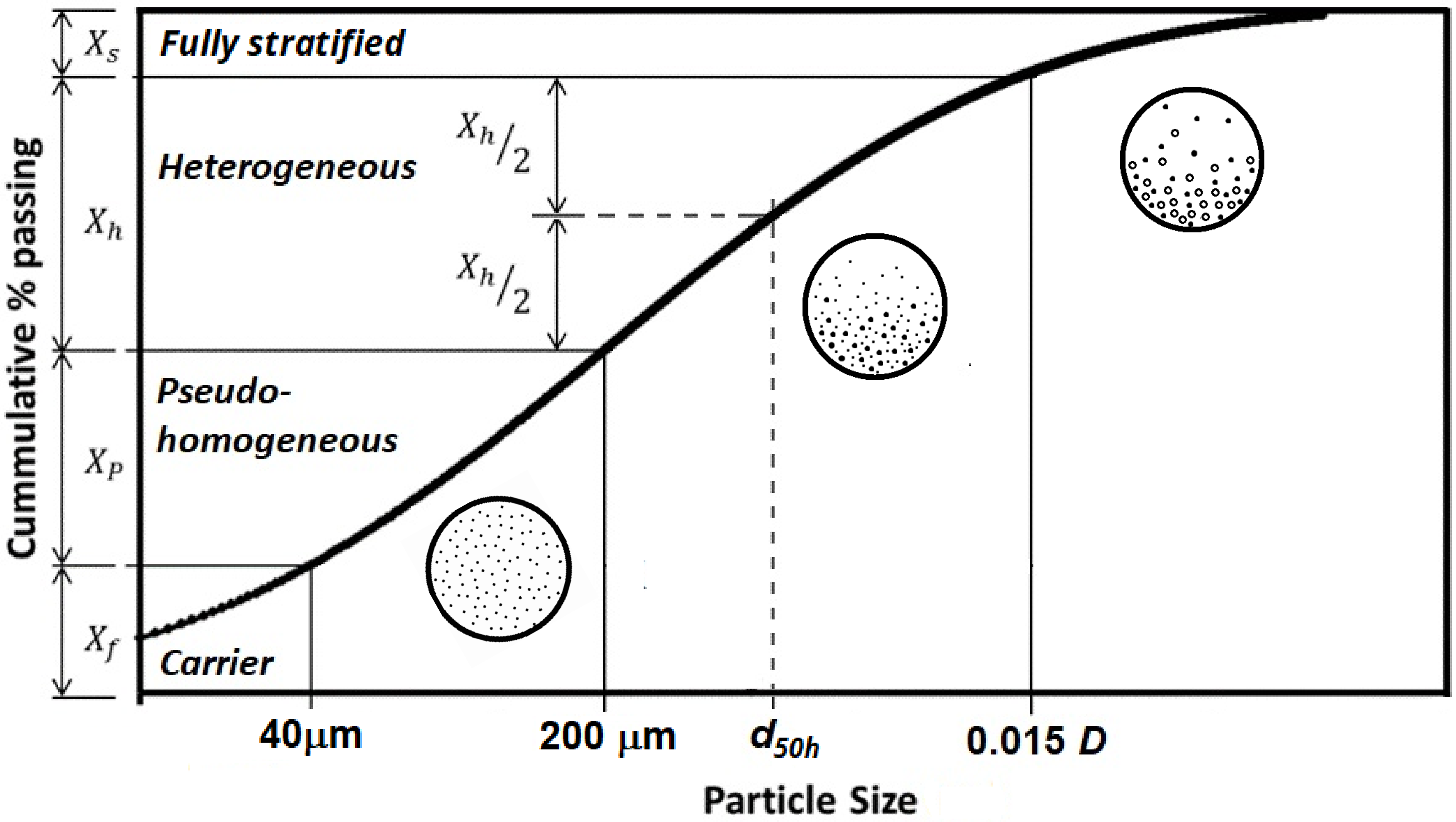
Often generated by hydrotransport operations (Oil Sands, Phosphate, Industrial minerals, Dredging)

- Of special interest are broad and bi-modal particle size distributions.
- These are not accurately described by any model developed for only one basic flow regime, or by models which describe the overall distribution of solids with only one or two average particle sizes.

The 4-Component Model

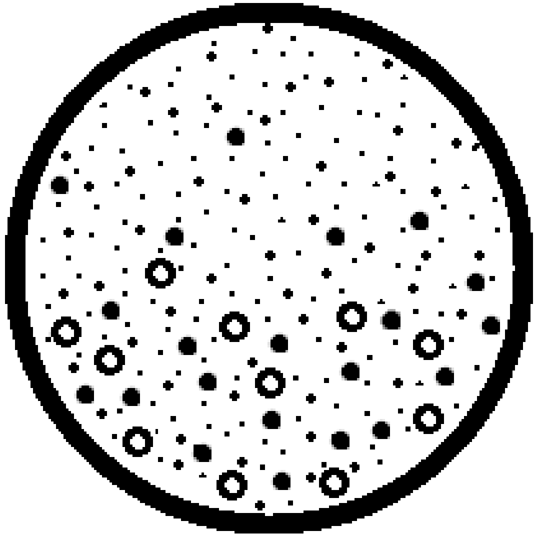
The four volume fractions or "components"

$$X_f + X_p + X_h + X_s = 1$$

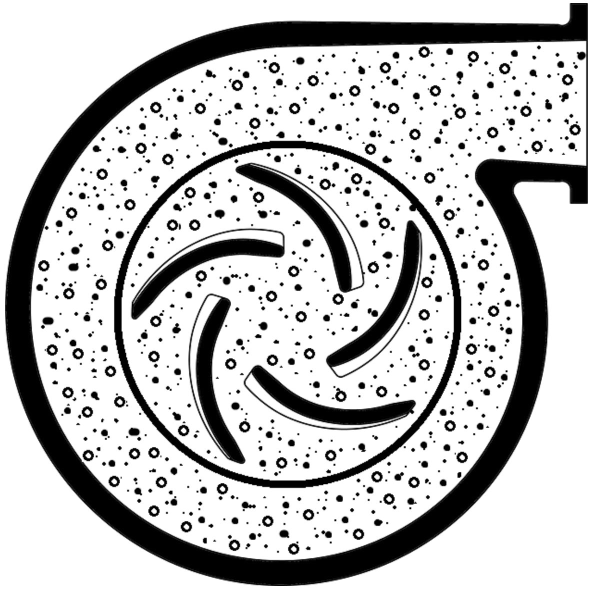


1. The slurry solids are divided into 4 groups or volume "fractions" based on the 4 basic flow regimes.
2. An established model for pipe friction or pump solids effect is applied to each fraction.
3. The fractional results are combined to provide the total effect.

Advantages of the 4-Component Models



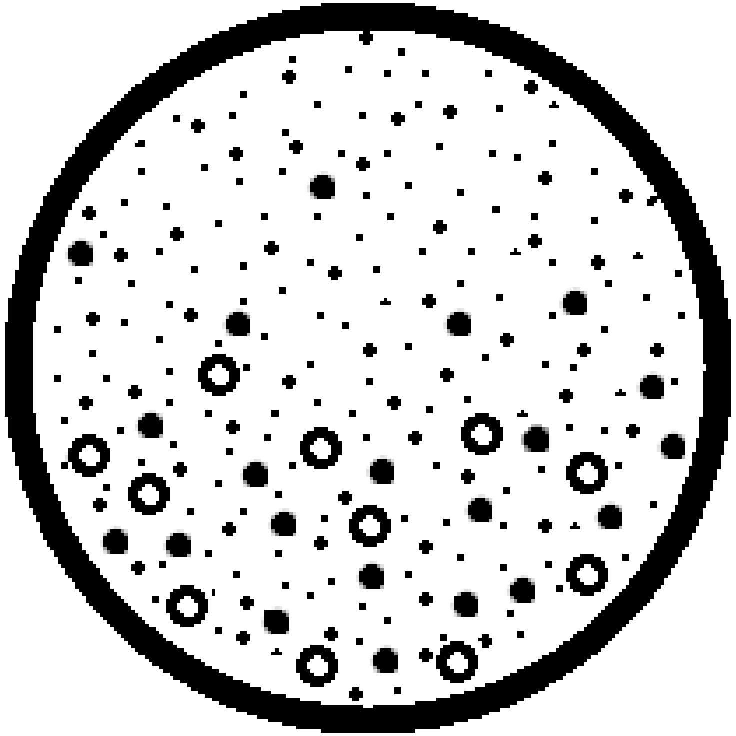
Pipeline Friction Loss



Pump Solids Effect

- Based on well established sub-models for each fraction.
- Can handle broad or bi-modal slurries … but collapse to established models as the particle size distribution narrows.
- Default calibrations are available for common settling slurries … or custom calibrations can be derived from test data.
- “Open source” formulae.

The 4-Component Model for Pipeline Friction Loss



The 4-component slurry

The pressure gradient (friction loss) for the complete mixture is determined as the sum the "Carrier Fluid" pressure gradient, plus the additional contributions (excess gradients) from each successively coarser fraction.

$$i_m = i_f + \Delta i_p + \Delta i_h + \Delta i_s$$

$$j_m = i_m / S_m$$

Where:

i = pressure gradient in meters of ***water*** head per meter of pipe.

i_m = total mixture pressure gradient.

i_f = pressure gradient of the "Carrier Fluid".

Δi_p = excess pressure gradient of the "Pseudo-homogeneous" fraction.

Δi_h = excess pressure gradient of the "Heterogeneous" fraction.

Δi_s = excess pressure gradient of the "Fully Stratified" fraction.

j_m = hydraulic gradient in meters of ***slurry*** head per meter of pipe.

S_m = specific gravity of the total slurry mixture (density relative to water).

Model calculation strategy

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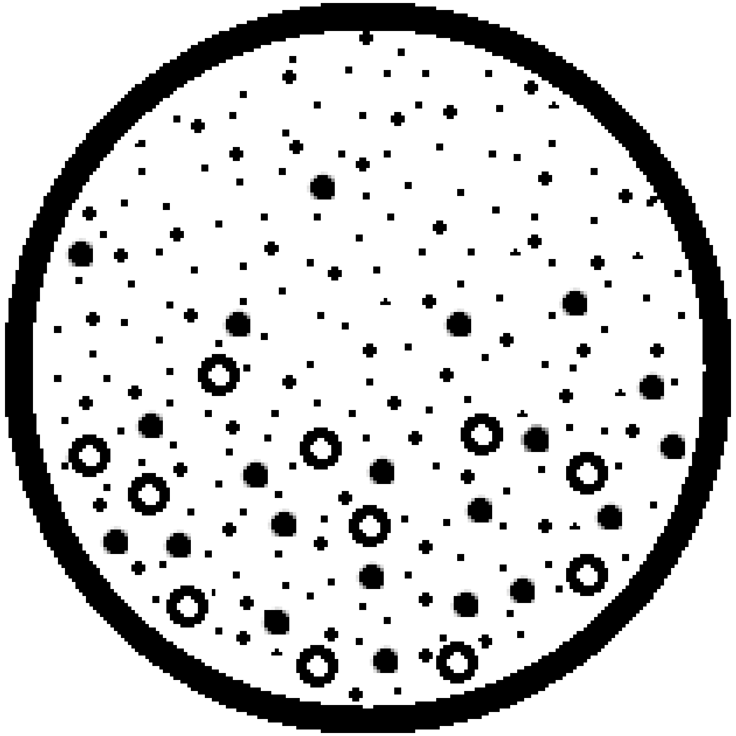
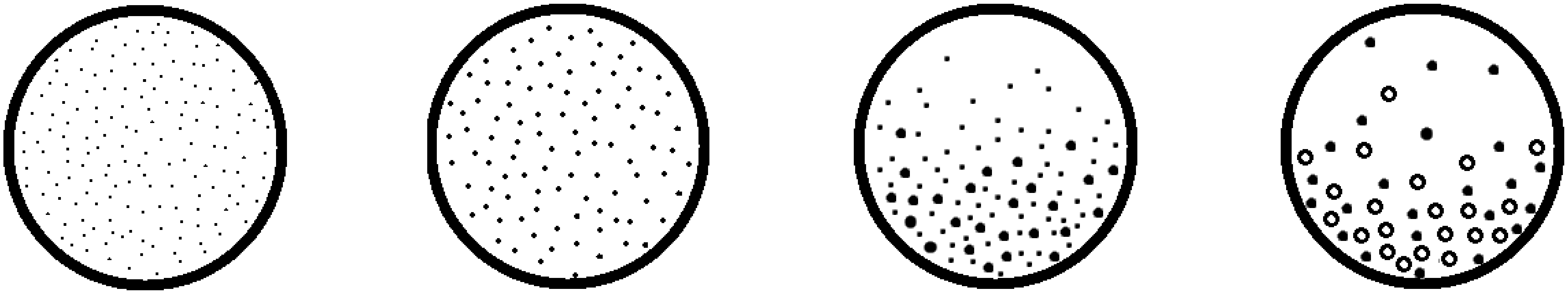


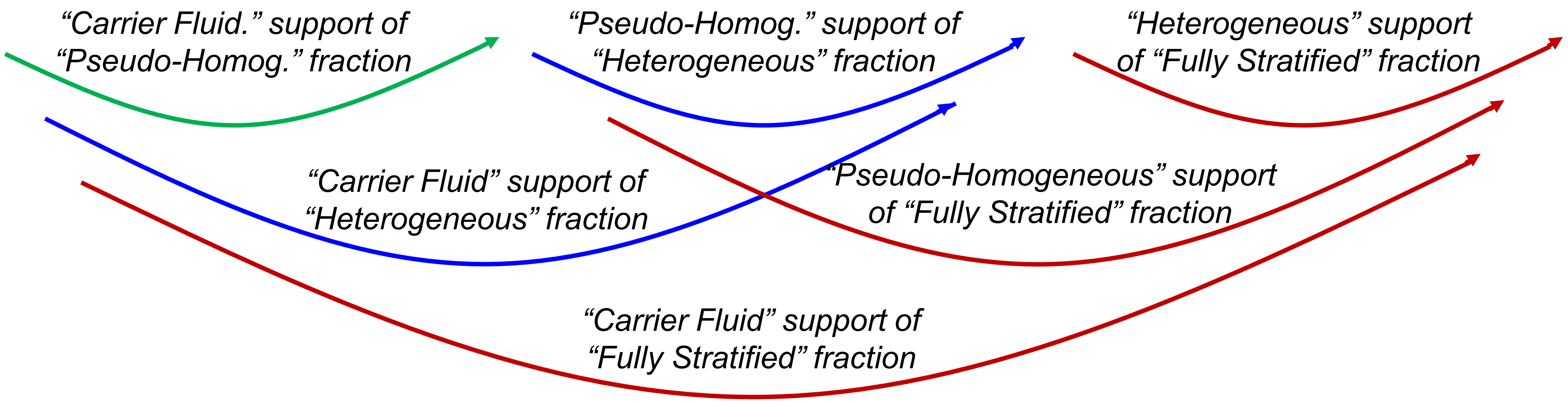
The 4-component slurry

1. The contribution of each component is calculated using a settling flow model applicable to that particle size range.
2. The contributions are weighted according to the concentration of that component present in the mixture.
3. In applying each model, the solids for that component are treated as running in a “fluid mixture” whose density includes all of the previous, finer components.
   - *This captures that portion of the interaction between components due to mixture density effects.*
4. For particle-particle interaction effects between components, additional “cross correlating” empirical parameters are needed. These are weighted according to the relative velocity of the flow.
   - *More weight at lower velocity (i.e. with stratified flow).*
   - *Less weight at higher velocity (i.e. with well mixed flow).*

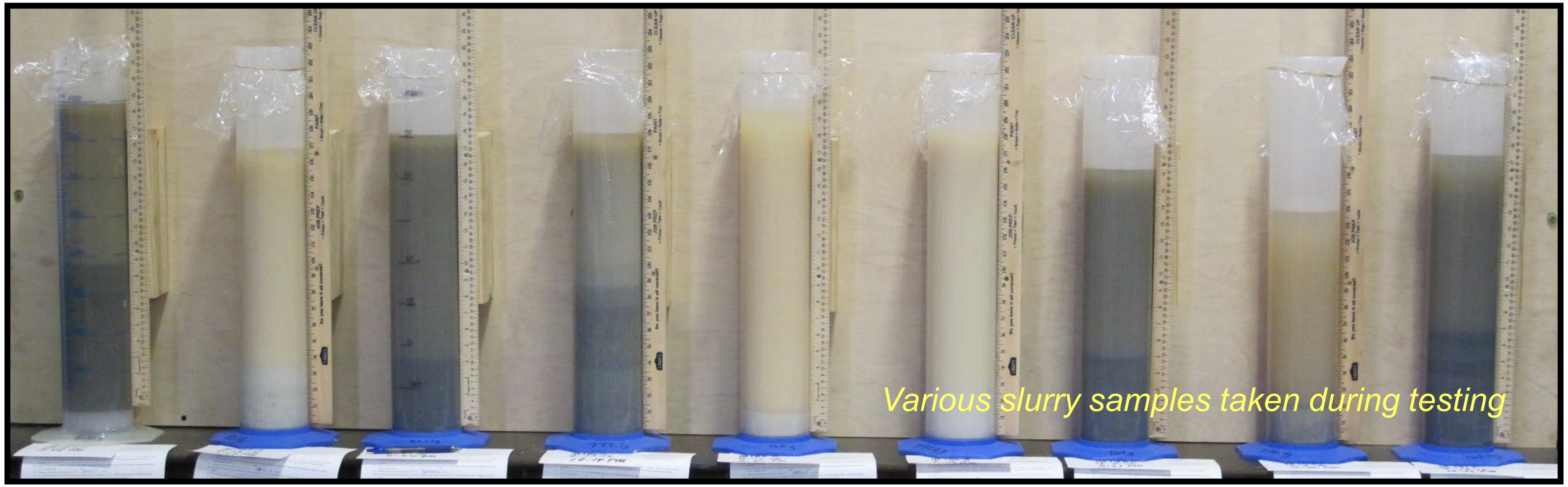
Empirical “Cross-Correlation” Parameters



“Carrier Fluid”	“Pseudo-homogeneous”	“Heterogeneous”	“Fully Stratified”
particles < 40μm	**40 μm < particles < 200 μm**	**200 μm < particles < 0.015D**	**0.015D < particles**



The Test Program



In order to provide a comprehensive data set for validation and calibration of the models, pipe loop test have been carried out over a range of particle size distributions, solids concentrations, pipeline diameters and pump sizes:

- 28 tests in a 200 mm pipe loop with 2.65 SG solids and GIW 8x10 LSA-32 pump with 806.5 mm impeller.
- 12 tests in a 100 mm pipe loop with 2.65 SG solids and GIW 3x4 LCC-12 pump with 310 mm impeller.
- 19 tests in a 100 mm pipe loop with 4.75 SG solids and GIW 4x6 LCC-16 pump with 395 mm impeller.
- 24 tests in a 500 mm pipe loop with 2.65 SG solids and GIW 24x24 TBC 57 pump with 1435 mm impeller.

Pipe Loop Set-up

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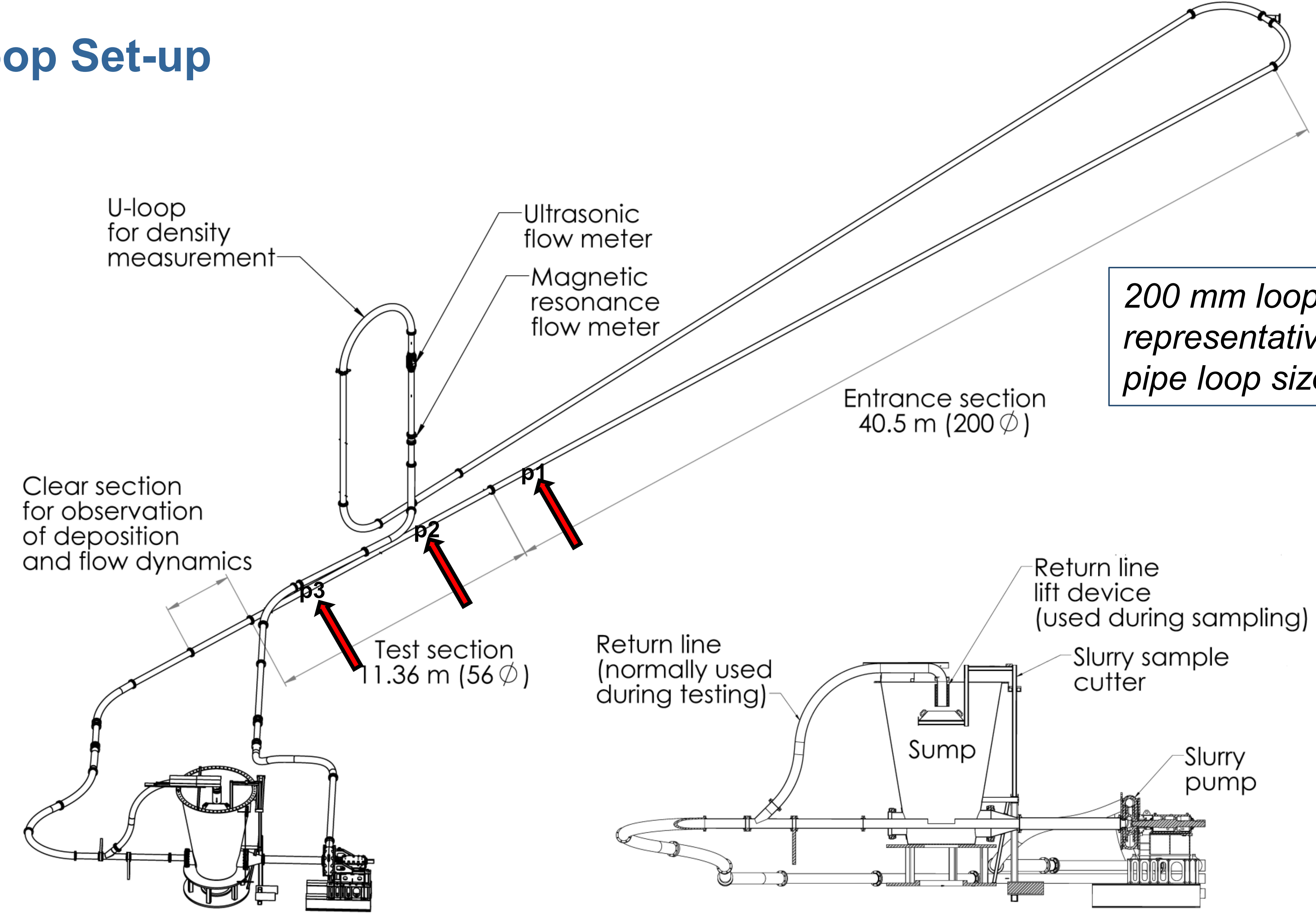

200 mm loop shown - representative of other pipe loop sizes

Pump and Sump for 200mm (8") Pipe Loop

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Pump and Sump for 500mm (20”) Pipe Loop

500mm (20”) Pipe Loop

Sample taking

- Retractable discharge pipe lifted above surface of slurry.
- Sample cutter passes through entire flow stream.
- Sample taken at slurry velocity about midway between deposition and pseudo-homogeneous flow.

Pipe system	Solids SG	Sample cutter opening (mm x mm)	Sample cutter velocity (m/s)	Slurry velocity (m/s)	Ave. sample volume (litres)
500 mm (20 inch)	2.65	76 x 760	2	7.5	22
200 mm (8 inch)	2.65	27 x 600	1	5	8
100 mm (4 inch)	2.65	30 x 310	0.45	4	3.5
100 mm (4 inch)	4.75	20 x 310	0.5	4.5	2

500 mm (20”) Pipe Loop Sample Cutter

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500 mm (20”) Sample Taking

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PSD processing

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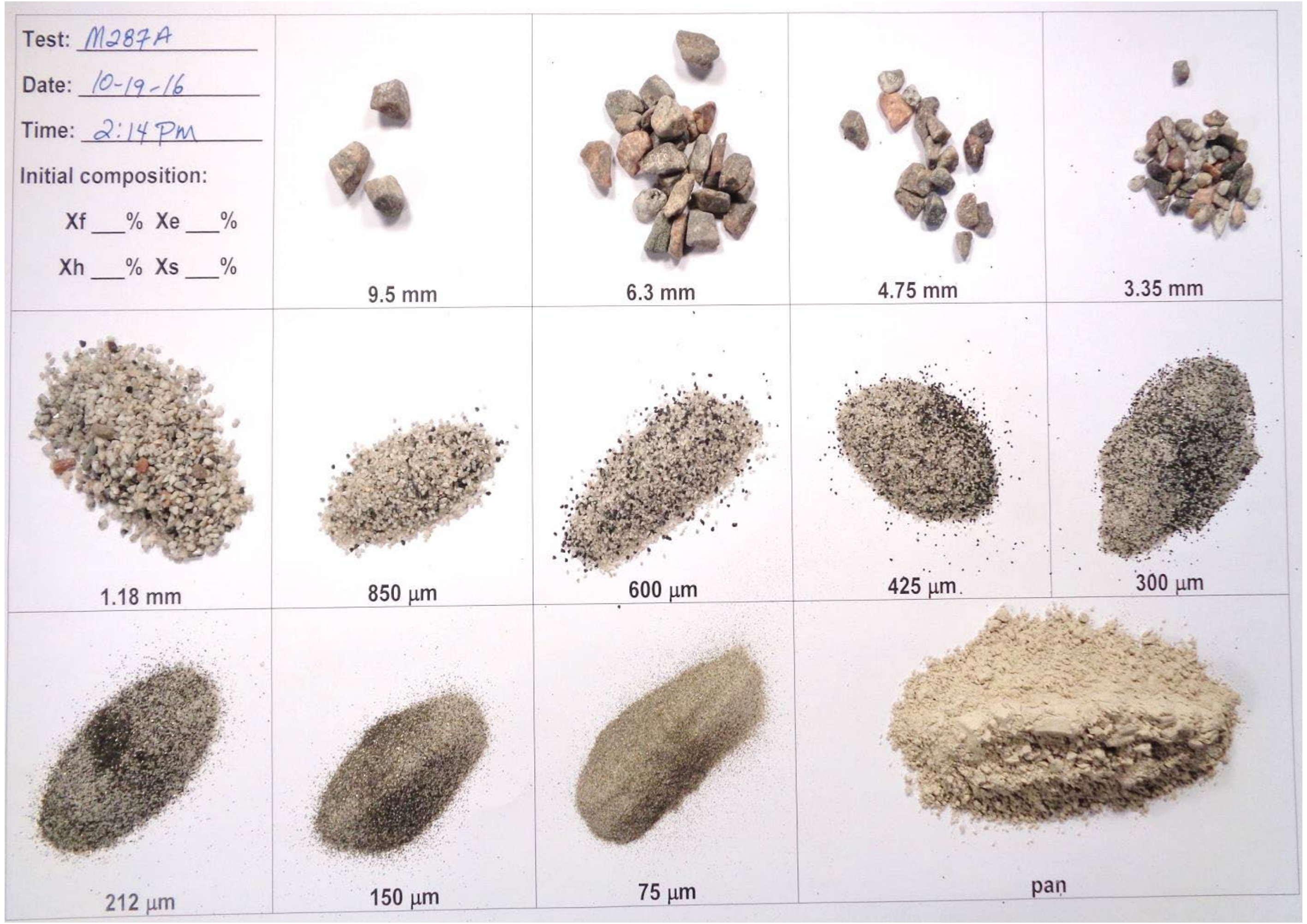
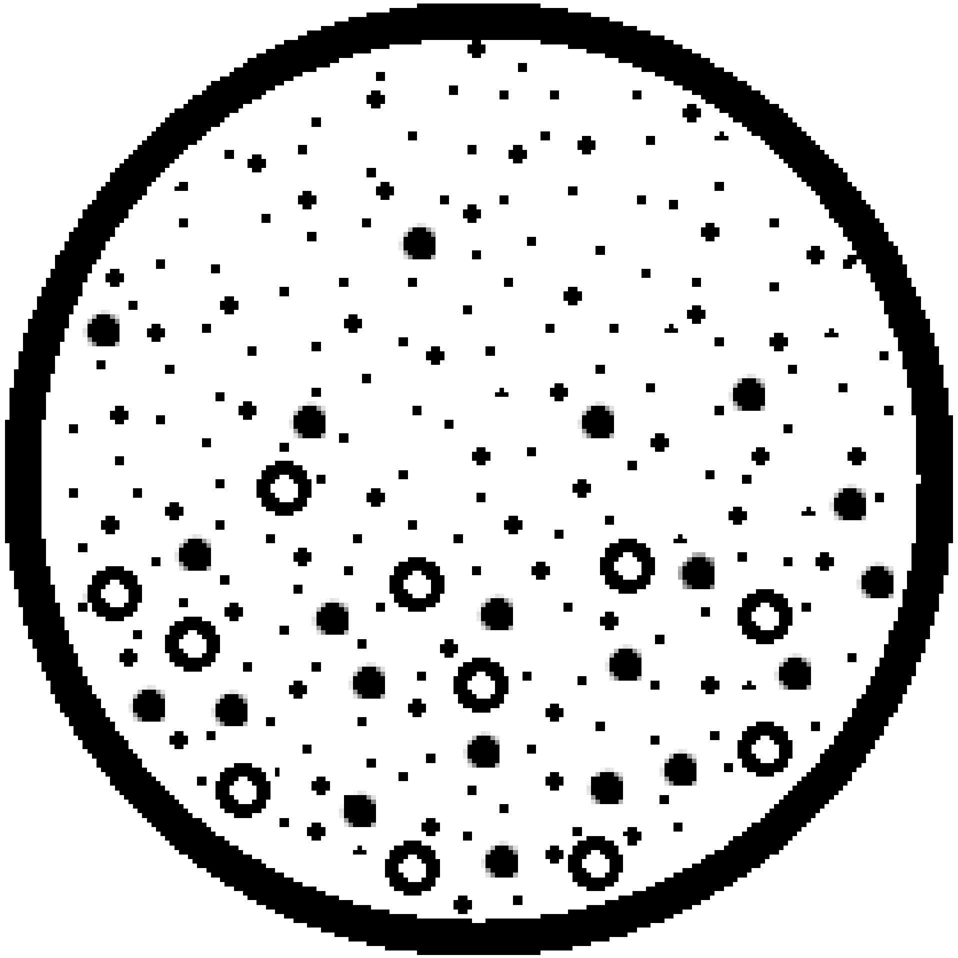


- All >6.3 mm particles cut from sample by a manual wet screening, dried, sieved and weighed.
- Remaining <6.3 mm solids dried and weighed in aggregate.
  - Mixed and split to produce a representative sub-sample of 0.3 - 0.6 kg.
  - Sub-sample wet-sieved down to 40 μm.
  - Individual size fractions dried and weighed.
  - Total weight for each size fraction calculated from ratio of the sub-sample to the total <6.3 mm sample weight.
  - Finally, the <40 μm solids, were captured in a filter press, dried and weighed, and their total sample weight calculated in a similar manner.

Pipeline Friction Loss Results – 500 mm (20”) loop



Test Program – Matrix of tests

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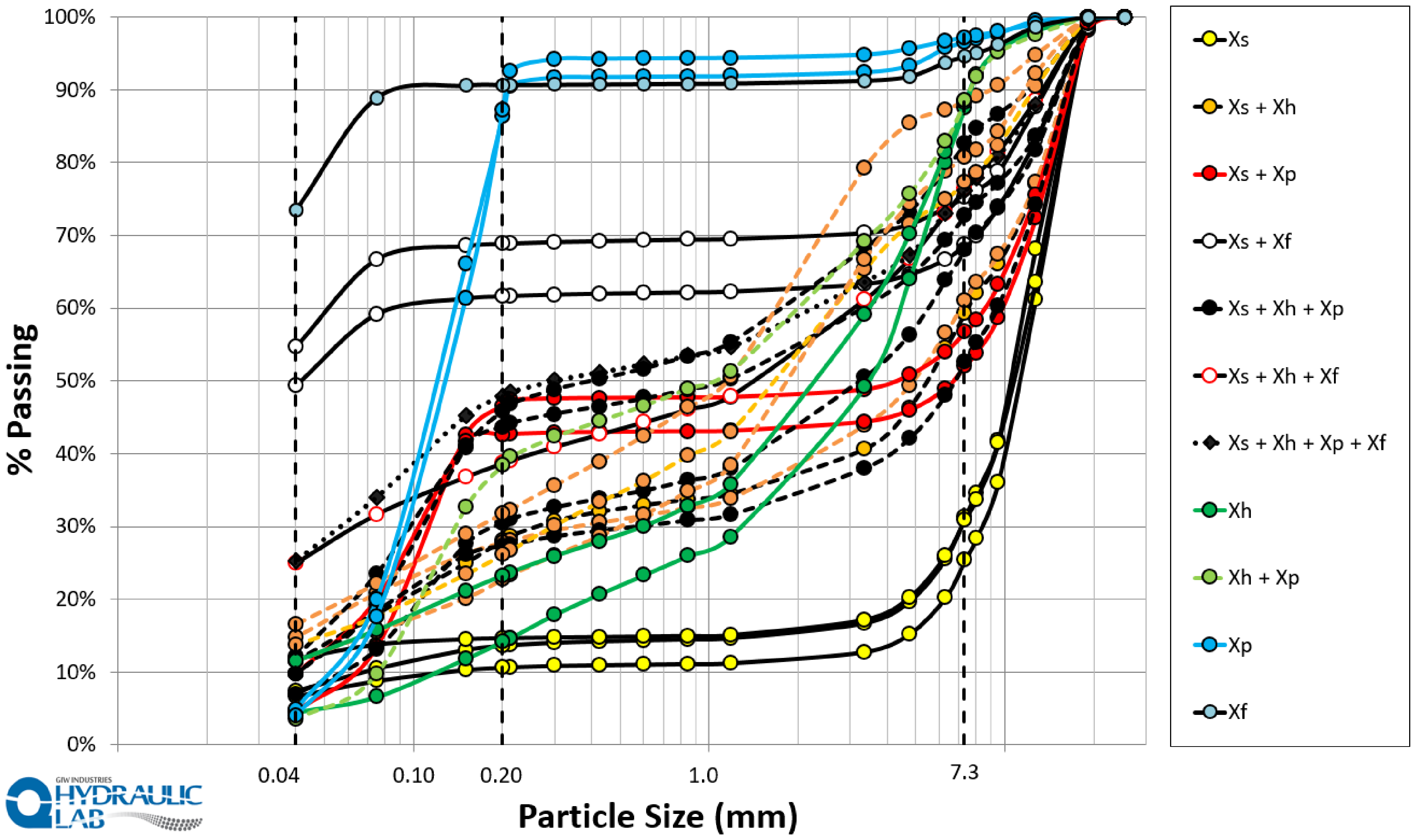
Table 1. Test matrix showing target percentages for volumetric concentration.

Test	1a	1b	2	3a	3b	4a	4b	5a	5b	5c	5d	6a	6b	6c	6d	6e	7a	7b	7c	7d	7e	8a	8b	8c
Xf																	10	10	10	10	10			
Xp								5	5	10	10	5	10	10	10	10					5	5	7.5	10
Xh				10	10	20	20	10	10	20	20					10				15	15	10	15	20
Xs	5	10	20		5		10		5	5	10			5	10	10		5	10	10	10	5	7.5	10
Total	5	10	20	10	15	20	30	15	20	35	40	5	10	15	20	30	10	15	20	35	40	20	30	40

Table 2. Test matrix showing actual measured fraction content and volumetric concentration from the 500 mm loop tests.

Test	1a	1b	2	3a	3b	4a	4b	5a	5b	5c	5d	6a	6b	6c	6d	6e	7a	7b	7c	7d	7e	8a	8b	8c
Xf	.07	.07	.12	.04	.11	.12	.15	.04	.07	.10	.12	.05	.04	.05	.10	.10	.74	.55	.49	.25	.25	.14	.11	.17
Xp	.06	.04	.03	.10	.17	.12	.13	.35	.24	.36	.32	.82	.83	.42	.33	.18	.17	.14	.12	.14	.23	.12	.11	.15
Xh	.18	.15	.16	.73	.31	.65	.33	.50	.38	.37	.29	.10	.10	.10	.10	.25	.04	.06	.07	.38	.28	.51	.58	.57
Xs	.69	.75	.69	.12	.41	.12	.39	.11	.32	.17	.27	.03	.03	.43	.48	.47	.05	.25	.31	.24	.24	.23	.19	.12
%Cv	5.7	10.5	21.7	9.4	13.9	18.4	26.6	16.8	21.2	34.4	39.1	3.9	7.4	11.0	15.6	22.3	11.5	13.3	18.2	32.3	34.9	21.9	32.8	40.4

Solids Size Distributions (PSDs) for 500 mm tests



Dimensionless pressure gradient data for 500 mm tests

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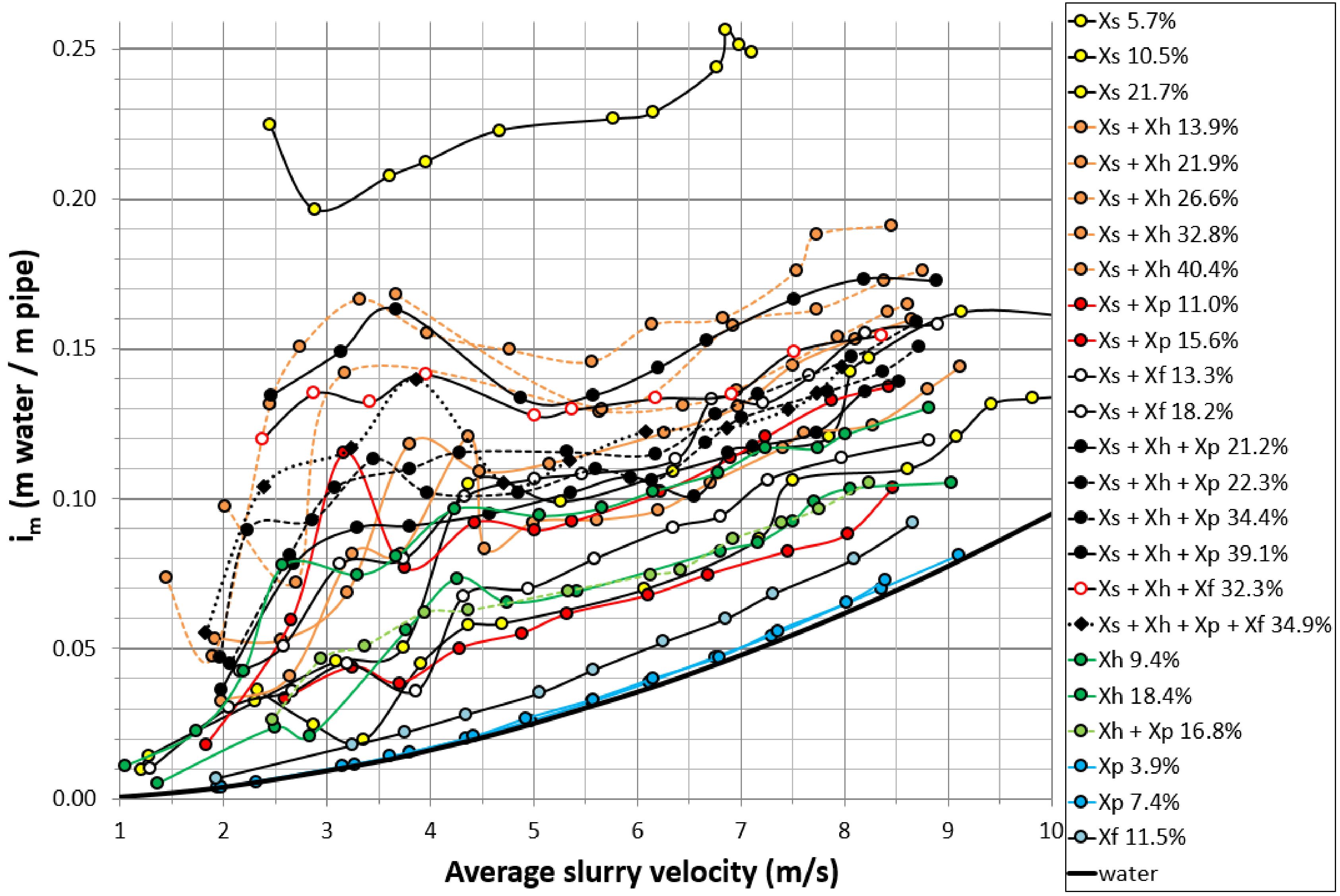
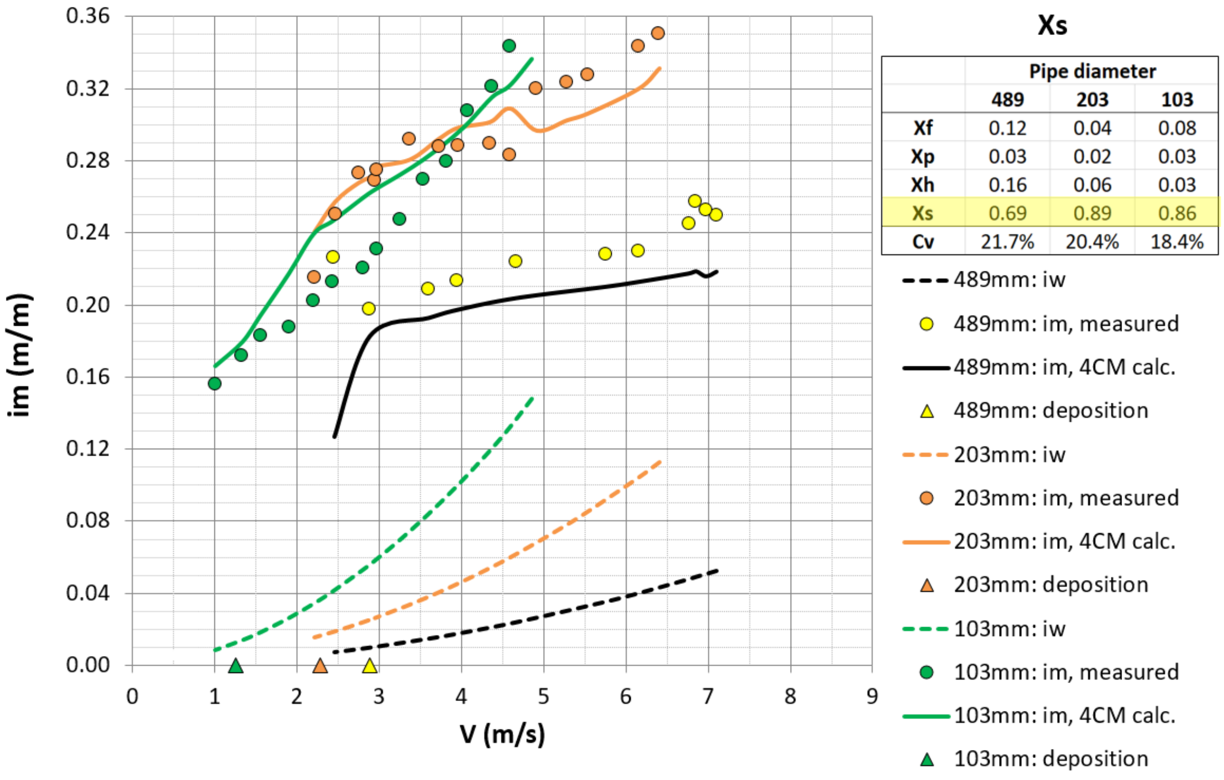
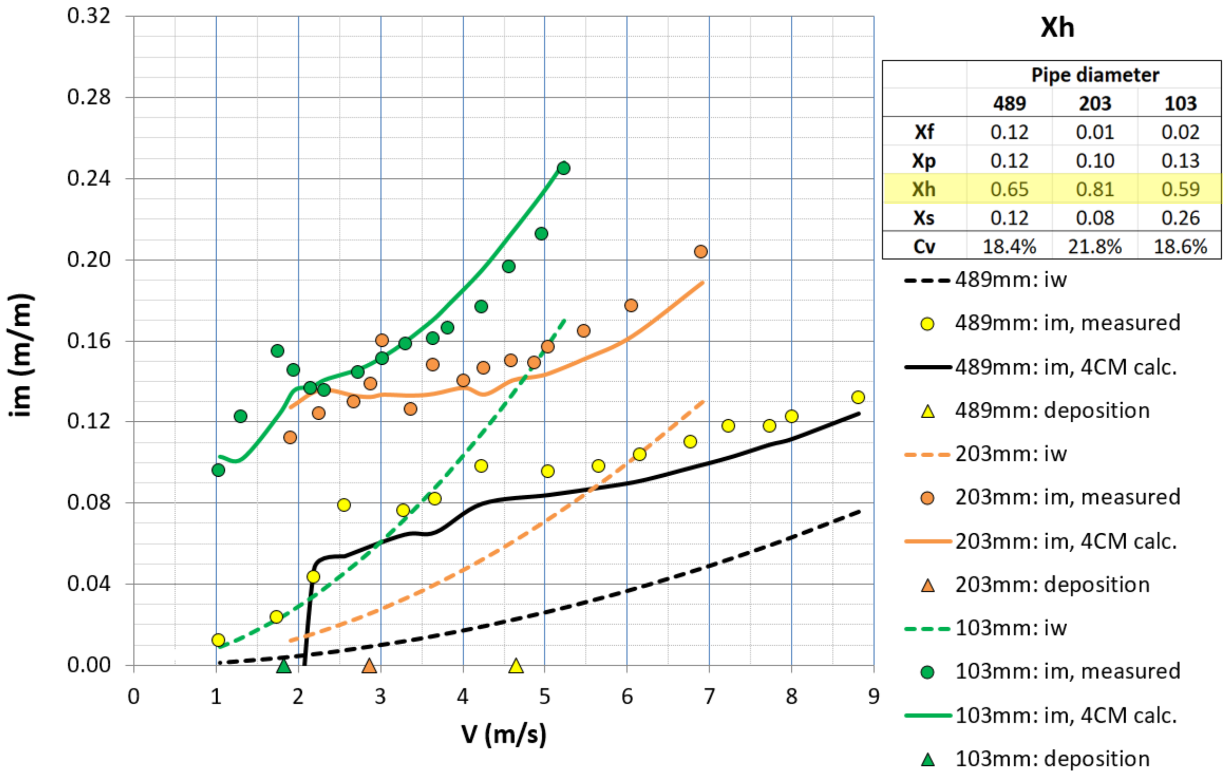


Individual results, 100, 200 and 500 mm loops



	Pipe diameter		
	489	203	103
Xf	0.12	0.04	0.08
Xp	0.03	0.02	0.03
Xh	0.16	0.06	0.03
Xs	0.69	0.89	0.86
Cv	21.7%	20.4%	18.4%

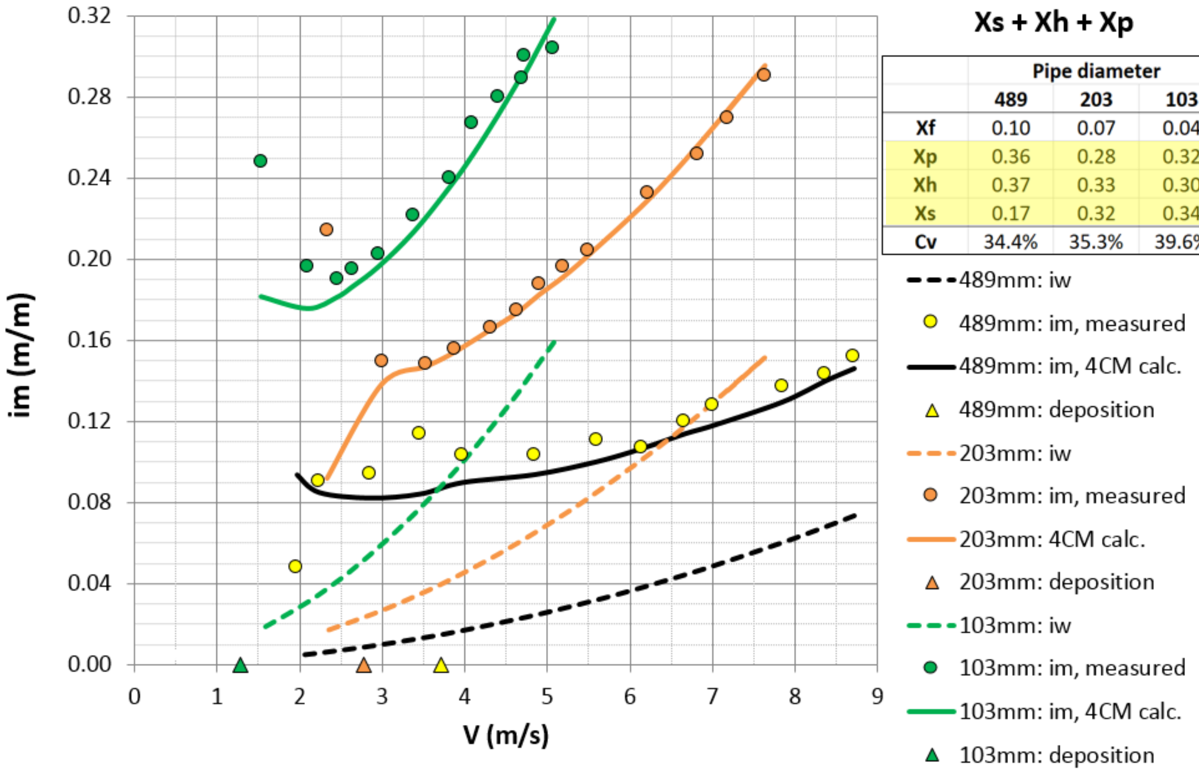


	Pipe diameter		
	489	203	103
Xf	0.12	0.01	0.02
Xp	0.12	0.10	0.13
Xh	0.65	0.81	0.59
Xs	0.12	0.08	0.26
Cv	18.4%	21.8%	18.6%

These figures show slurries where the single X_s or X_h components are dominant, resulting in relatively narrow particle size distributions. Volumetric concentrations are near 20%. Note the very visible effect of particle size and pipe size on the measured pressure gradient.

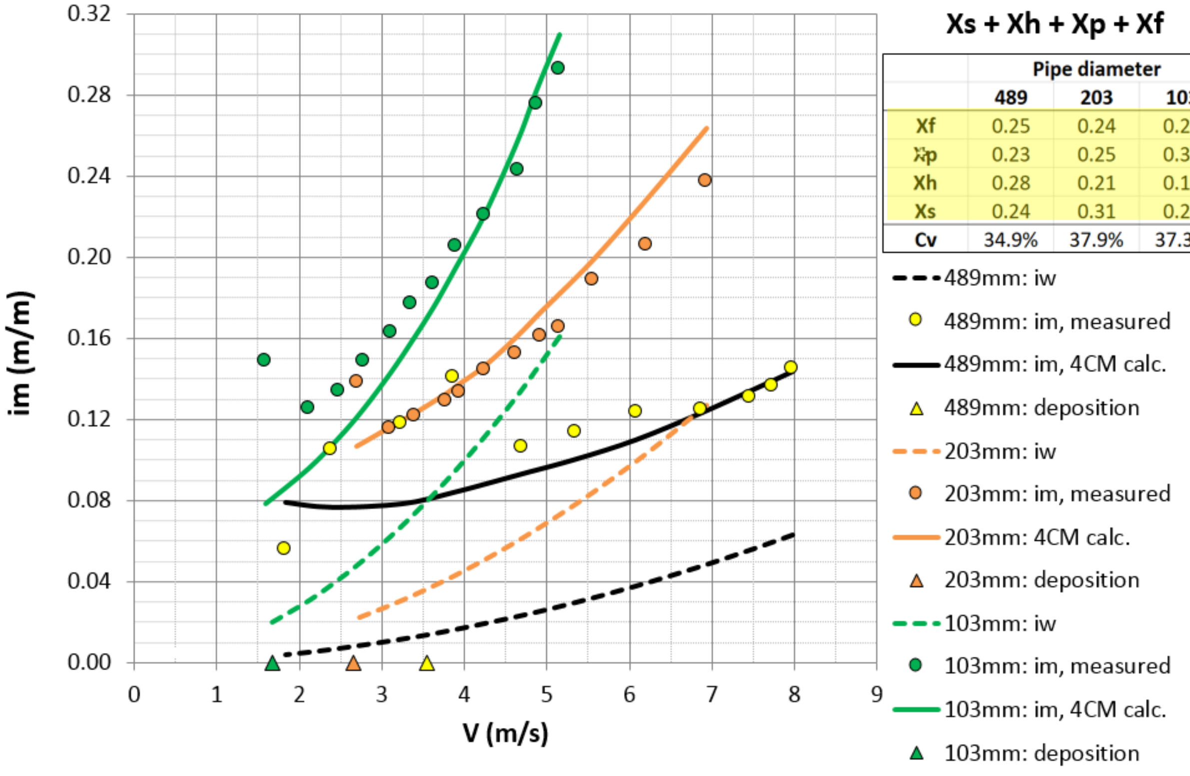
Individual results, 100, 200 and 500 mm loops

Xs + Xh + Xp



	Pipe diameter		
	489	203	103
Xf	0.10	0.07	0.04
Xp	0.36	0.28	0.32
Xh	0.37	0.33	0.30
Xs	0.17	0.32	0.34
Cv	34.4%	35.3%	39.6%

Xs + Xh + Xp + Xf



	Pipe diameter		
	489	203	103
Xf	0.25	0.24	0.26
Xp	0.23	0.25	0.33
Xh	0.28	0.21	0.18
Xs	0.24	0.31	0.23
Cv	34.9%	37.9%	37.3%

These figures show mixtures of three and four components respectively at volumetric concentrations near 35%. These tests represent concentrated slurries with broad particle size distributions. Note that the pressure gradients shown in these figures are comparable to the lower concentration, narrow PSD distributions seen in the previous slide.

Individual results, 100, 200 and 500 mm loops

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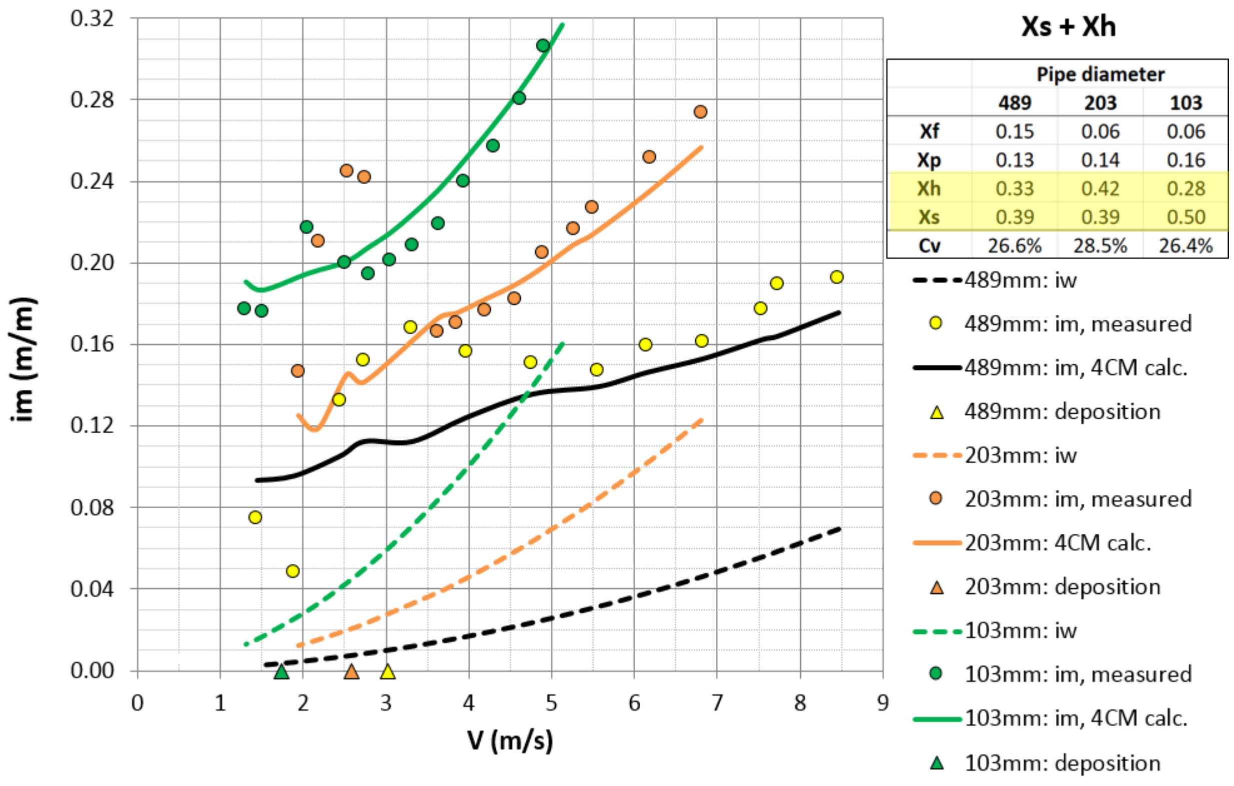
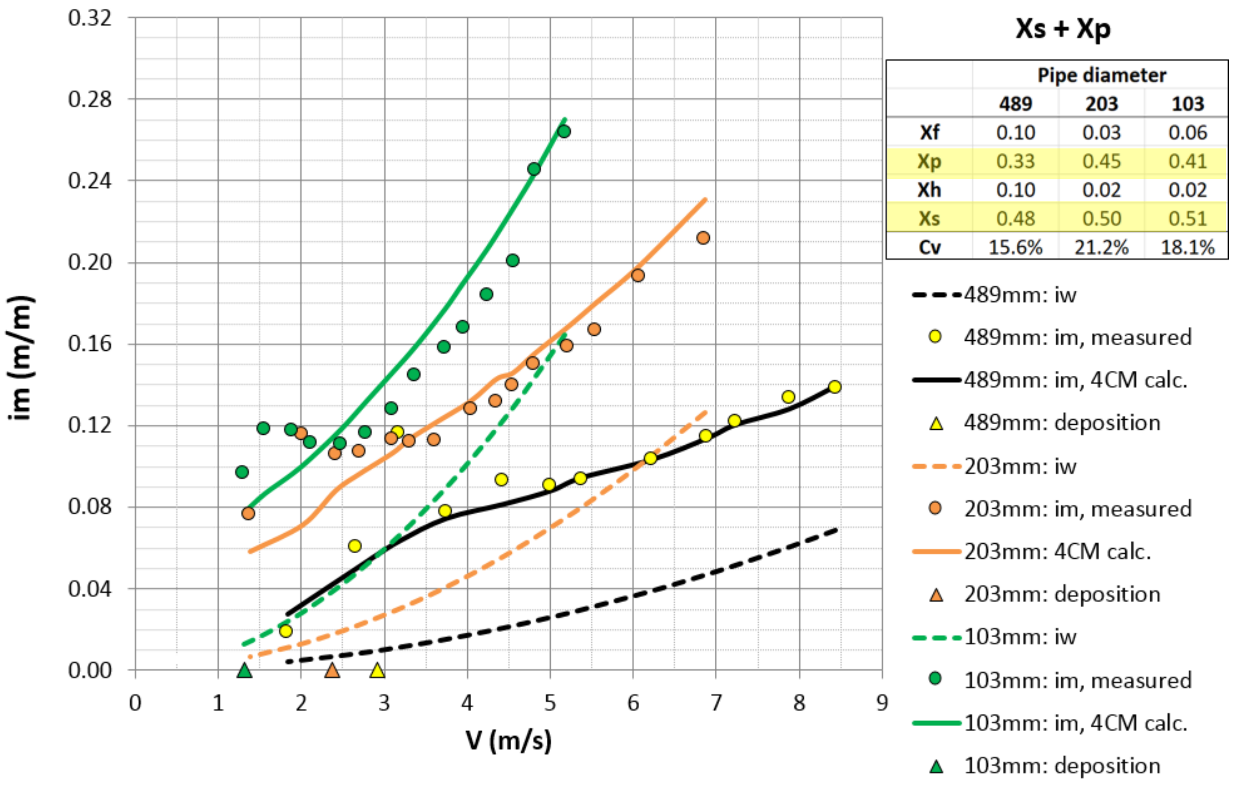


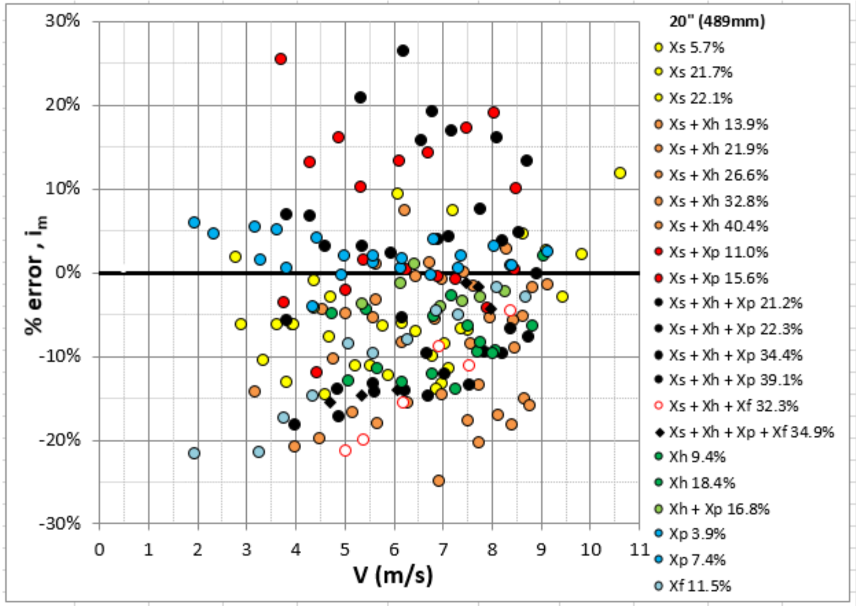
	Pipe diameter		
	489	203	103
Xf	0.15	0.06	0.06
Xp	0.13	0.14	0.16
Xh	0.33	0.42	0.28
Xs	0.39	0.39	0.50
Cv	26.6%	28.5%	26.4%

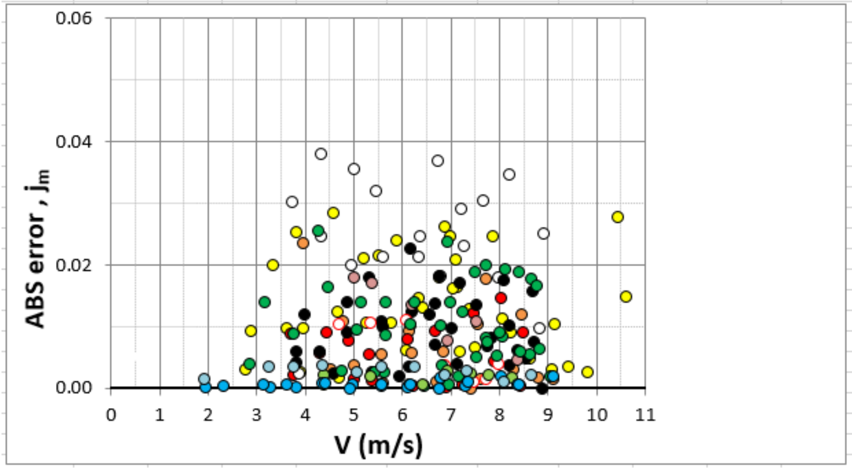


	Pipe diameter		
	489	203	103
Xf	0.10	0.03	0.06
Xp	0.33	0.45	0.41
Xh	0.10	0.02	0.02
Xs	0.48	0.50	0.51
Cv	15.6%	21.2%	18.1%

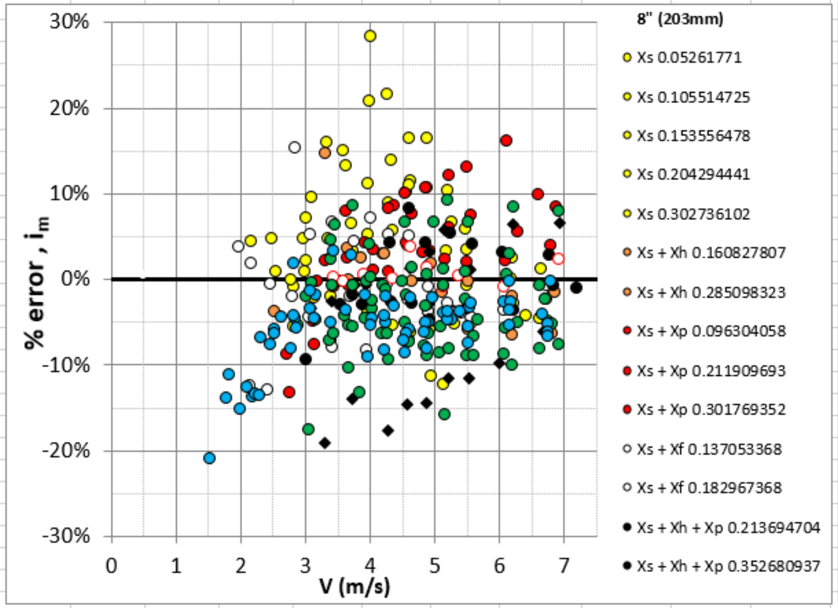
These figures show stratified X_s solids combined with heterogeneous X_h and pseudo-homogeneous X_p solids respectively.
Note that the $X_s + X_p$ mixtures represent bimodal PSDs, having a relatively small fraction of X_h surrounded by larger fractions of X_s and X_p.

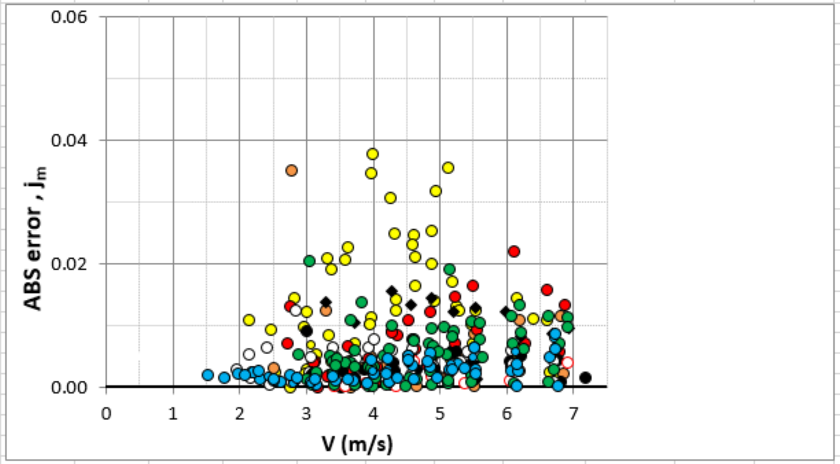
Error summary – 4CM Pipeline pressure gradient



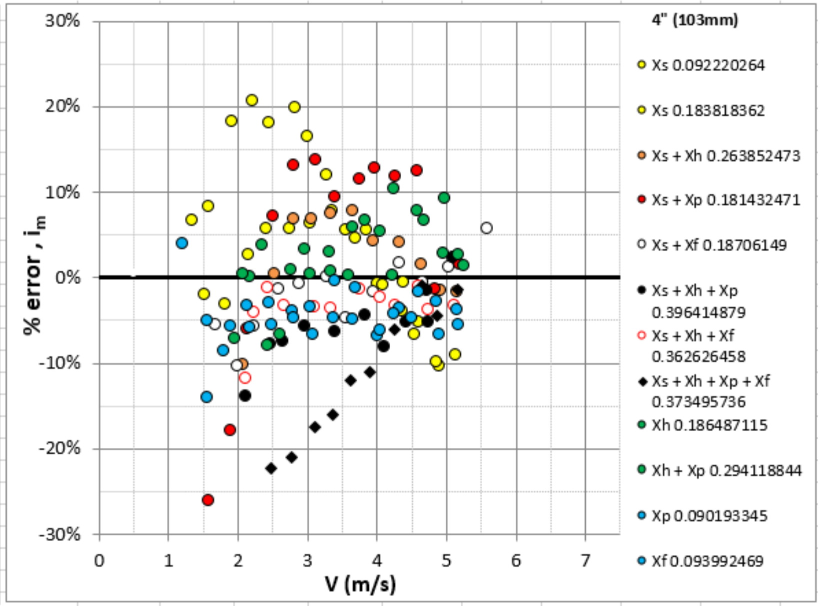


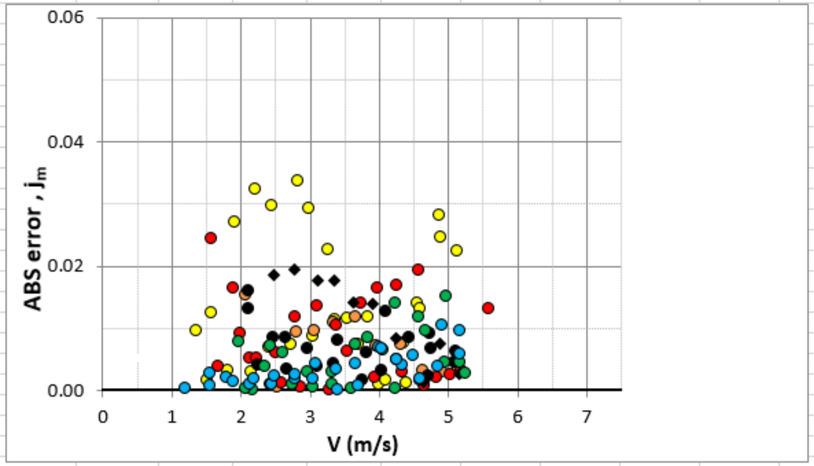
500 mm (20")





200 mm (8")





100 mm (4")

Conclusions

- A comprehensive data set spanning multiple settling slurry flow regimes in pipelines from 103 to 489 mm has been collected to validate the previously described 4-component model for pipeline friction loss. The model provides reasonable predictions across the range of this test program.
- Tests carried out in the 489 mm pipeline experienced higher particle degradation and less operating stability than previous similar tests in smaller pipelines.
- Two bi-modal tests of stratified *Xs* solids in *Xf* fraction carrier exhibited unexpectedly high friction losses. It could not be determined if this was the result of a faulty measurement, or an unexplained behaviour of the mixture in the larger pipe size. Additional tests will be needed to resolve this question.
- Excluding the two tests mentioned above, the average error between measured and calculated values for pressure gradient in the 489 mm pipe loop tests was 8.0%, compared to 5.4% and 5.5% for the previous 203 mm and 103 mm tests.
- However, since the magnitude of the losses are smaller in the larger pipe, the average absolute error was similar to previous tests, in the range of 0.010 m H_2O/m pipe.

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