Laminar Flow Settling: The Potential for Unexpected Problems

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ABSTRACT

It often assumed that low operating velocities are not a problem for high density thickened tailings and paste mixtures as they are inherently stable and pipelines may be started and shutdown without fear of blockage. However, this is not necessarily the case and when an apparently non-settling suspension is subjected to shear in laminar flow, the settling rate of the coarse particles can be increased significantly. For commercial pipelines operating in laminar flow, there is no effective mechanism for re-suspending settled particles and it is possible that the pipeline may block[1].

This paper discusses experiences with operating laminar flow pipelines and reviews the current state of knowledge.

1. INTRODUCTION

It is difficult to imagine that particle settling will be a pipeline design issue for the viscous slurry shown in Figure 1. Yet test work and experience with similar slurries show that coarse particles will settle if the pipeline is operated in laminar flow.

The issue of coarse particle settling under laminar flow conditions was first highlighted when the stabilised slurry concept was advocated in the 1970's for transporting coarse coal. The concept proposed that a viscous vehicle, comprising fine coal particles and water, would support the coarse particles enabling laminar flow pipeline operation. A special preparation circuit would be required to produce the bi-modal particle size distribution and generally an additive would be required to achieve stability. The advantages would be reduced pipeline pressure gradients, larger particle sizes and reduced dewatering costs. However, Thomas (1977) demonstrated that particles would slowly settle as they travel along the pipeline forming a bed and increasing the pressure gradient required to prevent deposition. He concluded that the stabilised slurry concept is not an attractive proposition due to the high pressure gradients required for large pipes.

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[1] Schaflinger *et al* (1990) have reported on a viscous resuspension mechanism but the effect is negligible for most commercial slurry pipelines.

As far as the author is aware, the only coal slurry pipeline that has been designed to operate in laminar flow is the Belovo-Novosibirsk pipeline. The commissioning of the pipeline appears to have been problematic as discussed in Section 4.2 of this paper.

Several recent developments have resulted in a need to design slurry pipelines for laminar flow operation:

(i) The move to higher solids concentration tailings slurries to achieve water savings in arid environments (e.g. kimberlite slurries). This has largely been made possible by recent advances in thickener technology.

(ii) Decreased particle sizes in tailings slurry due to comminution circuit improvements aimed at achieving enhanced recoveries.

(iii) The move to thickened and paste tailings systems driven by environmental concerns.

(iv) Increased use of high concentration paste fill and hydraulic backfill for underground mines.

(v) The requirement for pipelines to transport new types of fine viscous slurries (eg. nickel laterite slurries).

In contrast with the stabilised slurry concept where the mixture would specifically be designed to achieve laminar flow operation, these new laminar flow applications are the result of process requirements. Designing pipelines to operate in laminar flow presents an interesting challenge in dealing with coarse particle settlling and the consequent increase in pipeline pressure gradient.

This paper reviews laminar flow operating experience and test work results with a view to establishing a strategy for the design of slurry pipelines operating in laminar flow.

Figure 1: Viscous heavy mineral tailings slurry

2. SLURRY PIPELINE FLOW REGIMES

Figure 2 illustrates the range of slurry flow behaviour typically encountered for high density tailings applications.

The pressure gradient curve for a solids concentration of 53% by mass has two distinct flow regimes:- laminar and turbulent flow. In laminar flow the slurry rheology dominates the friction loss while the mixture density dominates the friction loss in turbulent flow. Conventional practice is to design the pipeline to operate in turbulent flow to enable coarse particles to be suspended by turbulence.

For a solids concentration of 71% by mass, it is clear that turbulent flow operation will not be feasible due to the high velocity at which the transition from laminar to turbulent flow will occur (not shown on Figure 2 but likely to be greater than 5 m/s).

If the process requirement is such that the slurry must be transported at 71% by mass, the pumping system must be designed to meet this duty and the designer must consider the following issues:

- What is the minimum velocity that the system can be operated at?
- Can the pressure gradients be scaled to larger pipe sizes?
- Will the coarse particles settle?
- Will particle settling cause the pressure gradient to increase?
- Can coarse particles be flushed out of the pipeline if they settle?

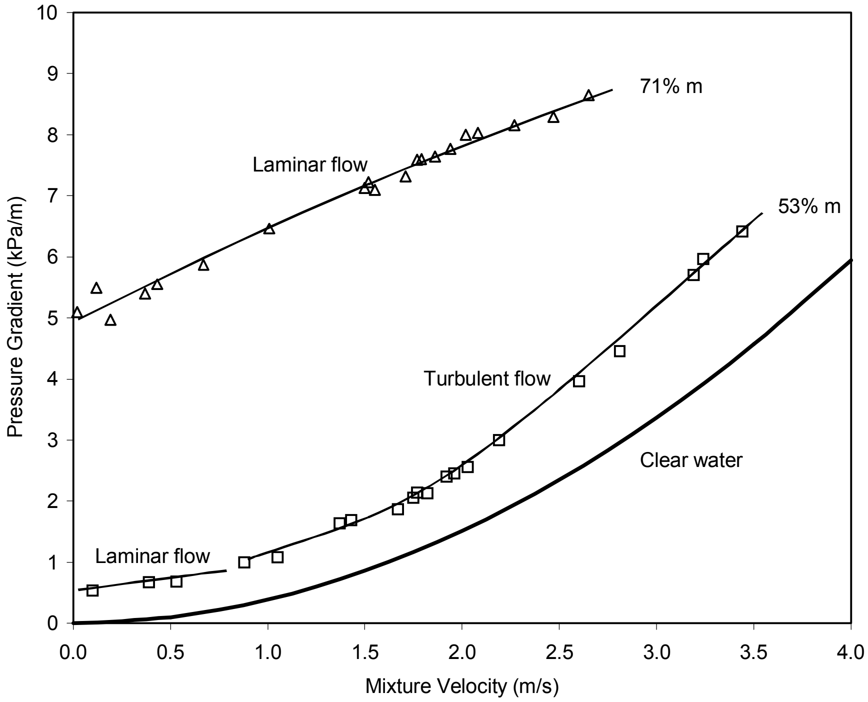

Figure 2: Pipeline flow regimes

3. PARTICLE CLASSIFICATION AND SETTLING

Particles can be classified as settling, non-settling or slow settling:

- Particles with a settling velocity greater than 1 mm/s are considered to be settling (corresponding to a particle size of about 32 µm for sand density particles settling in water). The particles are supported in a slurry flow by turbulent mixing and inter-particle collisions.
- Particles with a settling velocity less than 0.1 mm/s are considered to be effectively non-settling (10 µm for sand density particles). The particles are maintained in suspension by Brownian motion and it is likely that they will form flocs. The slurry mixture can be considered to be homogenous even under laminar flow conditions.
- Particles with intermediate settling velocities are termed slow settling.

For the purposes of this paper, coarse particles are considered to be settling particles that are too large to participate in the flocculation process (Gillies *et al* 1999).

If the concentration of non-settling particles is high enough so that there is significant floc interference, the mixture can be considered to be a homogenous fluid with distinct physical properties including a yield stress (Gillies *et al* 1997). Thomas (1978) has noted that under static conditions the yield stress is capable of supporting coarse particles. He developed the following equation for determining the yield stress required to support a particle:

$$\tau_y \geq k\, g\, d \left(\rho_s - \rho_{mf}\right), \tag{1}$$

where τ_y = slurry yield stress (Pa)
k = constant = 0.10 for typical mineral slurries
g = gravitational constant (m/s^2)
d = particle diameter (m)
ρ_s = particle density (kg/m^3)
ρ_{mf} = density of non-settling particles and water mixture (kg/m^3).

Figure 3 illustrates this concept with 25 mm particles being supported by a viscous kimberlite slurry.

As shown in Figure 4, under flow conditions the applied shear stress (τ_o) due to the pressure gradient exceeds the slurry yield stress in an annular region. Thomas (1978) has noted that the yield stress plays no part in supporting coarse particles in the sheared annulus as the floc structure is broken and so there is little vertical resistance to particles settling. He observed that for a slurry with a Bingham Plastic rheology, particles in the sheared annulus can be considered to be settling in a Newtonian fluid with a viscosity equal to the plastic viscosity.

Stable non-settling slurry behaviour under static conditions is no guarantee that the slurry will be stable under sheared conditions.

Figure 3: Particles supported by slurry yield stress (view looking down into a drum)

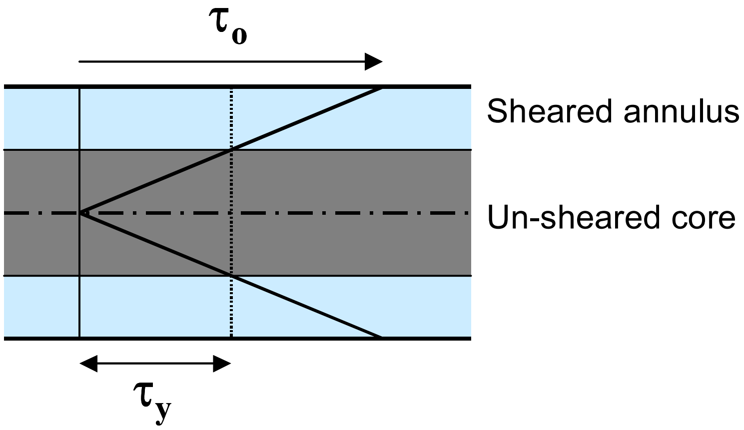

Figure 4: Shear stress distribution and slurry yield stress

4. OPERATING LAMINAR FLOW PIPELINES

4.1 Rugby limestone pipeline (England)

This 92 km long 250 mm diameter pipeline was first operated in 1964. Aude *et al* (1996) and Wasp (1999) have reported on operating conditions when the pipeline was operating at a velocity of 1.12 m/s (close to the estimated transition between laminar and turbulent flow). They made the following observations over a 36 hour period:

- The pressure gradient increased from 0.106 kPa/m to 0.121 kPa/m.
- Slurry entered the pipeline at 56.5% by mass and discharged at 54.5% by mass.
- Nearly 4% of the particles in the slurry feed into the pipeline were larger than 150 μm but there were only trace amounts of particles larger than 150 μm discharging from the pipeline.

Coarse particles were obviously settling during the 36 hour period. Pigs were used for the initial attempts to clear the accumulated particles out of the pipeline. This was not successful as the pigs hung up in the pipeline, resulting in pipeline wear failure due to high velocities around the stuck pigs. At the time, the standard procedure adopted for clearing the pipeline was to introduce a slug of water once the pump station discharge pressure exceeded 10 MPa.

The author visited the pipeline during 2000 and held discussions with the Pipeline Engineer, Mr David Clowes, who was unaware of the instabilities reported by Aude and Wasp (he has about 20 years operational experience with the pipeline). Additives are added to the slurry to reduce the viscosity and it is possible that the pipeline is now operated in turbulent flow.

4.2 Belovo-Novosibirsk pipeline (Siberia)

Aude et al (1996) noted that this 262 km long 530 mm diameter pipeline is the first and only pipeline designed to transport a stabilised coal-water mixture (CWM). Yunnan (1995) reported that the pipeline was forced to shut down during the system start up trials due to a blockage.

Slurry from the preparation plant was pumped through a 1 km test loop before being introduced into the main line. The following test results were obtained from the test loop:

- The pressure gradient increased with time when the system was operated at low shear rates (0.5 to 2.0 s^{-1}).
- At the maximum shear rates of 9.0 to 11.0 s^{-1}, the pressure gradient was independent of time.
- A stationary deposit was observed on the pipe invert with a highly viscous layer above the bed.

Yunnan notes that the same phenomena were observed in the main pipeline causing the pump station discharge pressure to rise and states that the blockage was caused by the unstable dynamic properties of the CWM. It is evident that although the CWM may have been statically stable, settlement of coarse particles occurred when the slurry mixture was subject to shear in the pipeline. The blockage was cleared using pigs.

It is worth noting that the above instabilities were not observed during pumping trials conducted for the project. The test were carried out in a 200 m long 200 mm diameter re-circulating pipe loop (Ercolani, 1986).

The author has not been able to obtain any information on the current status of the pipeline.

5. EXPERIMENTAL DATA

5.1 Sand and clay slurry

Song and Chiew (1997) tested fine clay Bingham plastic slurries (d_{50} = 4.5 μm) in a 180 mm by 100 mm high clear rectangular pipeline. Sand (d_{50} = 150 μm) was added to the clay slurry to form a statically stable mixture. The mixture was pumped through the pipeline at high velocity to ensure that all the coarse particles were suspended and then abruptly stopped. The mixture was left for three days to ensure that the coarse particles did not settle. The flow rate through the pipeline was then slowly increased and the thickness of the bed of settled coarse particles measured. Referring to Figure 5, they observed the following:

(a) At zero flow there was no deposition of coarse particles, i.e. the mixture was statically stable.

(b) Initially each velocity increment resulted in an increase in the bed height. Referring to Figure 4, it can be presumed that the increased bed height corresponds to an increased sheared zone with increasing velocity (and wall shear stress).
(c) Once a critical velocity is reached, the bed height decreased with further increases in velocity. This critical velocity corresponds to the onset of turbulence enabling the coarse particles to be re-suspended.
(d) As the velocity was reduced to the critical velocity, the bed height increased to the values observed while the flow rate was increased.
(e) Unsurprisingly, there was no reduction in bed height with further velocity reductions. In laminar flow there is no mechanism for suspending coarse particles.

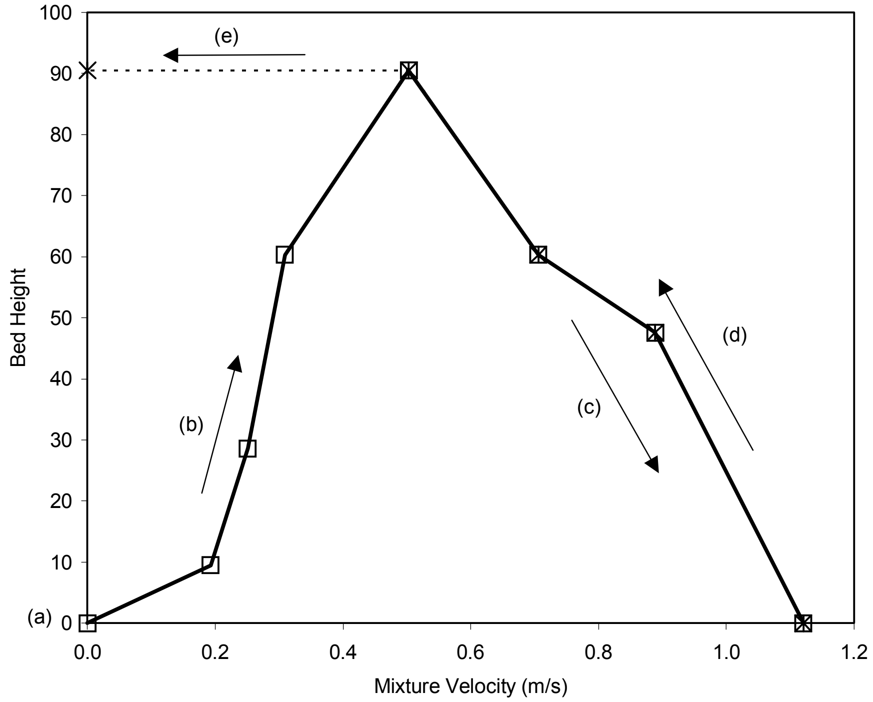

Figure 5: Sand-clay slurry deposition data, Song and Chiew (1997)

5.2 Sand and viscous Newtonian mixtures

Gillies *et al* (1999) have investigated horizontal transport of sand particles in viscous Newtonian mixtures (oil and ethylene glycol) in 50 mm and 100 mm pipelines. They concluded that particle diameter, pipe diameter and fluid viscosity play minor roles in the sand transport process in laminar flow.

They observe that pressure gradients of the order of 2 kPa/m are required to transport sand in an oil carrier fluid. This pressure gradient requirement is reduced for higher density carrier fluids.

Based on this and previous work, Shook (1999) believes that a pressure gradient of between 1 kPa/m and 2 kPa/m is required to transport solids in laminar flow. Thomas (2000) has also stated that a certain critical pressure gradient is required to transport settled particles under laminar flow conditions. Previously he had noted that the deposition occurs at a constant pressure gradient value regardless of pipe size (Thomas 1977).

5.3 Sand and long chain polymer gel mixtures

Pullum and Graham (2000) have reported on an ongoing investigation into the laminar flow of suspensions of coarse particles in pseudo plastic carrier fluids. The investigation has made use of nuclear magnetic resonance imaging (MRI) and video imaging that has provided valuable additional insight into laminar slurry flow behaviour.

Tests were conducted in a 100 mm horizontal re-circulating pipe loop with a carrier fluid (long chain polymer gel) and 1.5 mm sand particles (5% by volume). The three carrier fluids tested were characterised using the yield pseudo plastic model (yield stress values of 2 Pa, 6 Pa and 10 Pa). The main findings of the tests were:

- Despite being statically stable, the sand particles migrated to the bottom of the pipeline once flow was initiated where they were transported in a sheared and moving bed.
- The mixture with the lowest yield stress (2 Pa) formed a stationary bed at a velocity of 2.4 m/s. No evidence of stationary bed formation was observed for the other two suspensions even when left running at low velocities (less than 0.02 m/s) for prolonged periods.
- The video images demonstrated that under laminar flow conditions the sand particles saltated and formed dunes and slugs similar to turbulent Newtonian flow.

Despite the researchers' conclusion that the suspensions are inherently stable and can be restarted at will, the data may also support the view that laminar flow of this type of suspension is not viable for commercial applications:

- The concentration plots indicate that there is a significant difference between the delivered and in situ concentrations.
- The pressure gradient plots show that the "excess pressure gradient" decreases with increasing carrier fluid viscosity. This indicates that the Coulombic friction component may dominate in large diameter pipelines.
- The 2 Pa yield stress fluid required a pressure gradient greater than 1.8 kPa/m to keep the bed moving (corresponding to the deposition velocity of 2.4 m/s). If Shook and Thomas' contention regarding minimum pressure gradients is correct, significantly higher velocities will be required for larger diameter pipes to avoid a stationary bed. Thomas (1977) has noted that this means that the pressure gradient becomes increasingly uneconomic as the pipe sizes increases.

It will be interesting to test the 6 Pa and 10 Pa suspensions in larger diameter pipes to establish how the minimum pressure gradient requirement varies with pipe diameter and carrier fluid viscosity.

5.4 Copper tailings

Figure 6 shows observed stationary deposit velocities versus solids concentration for a copper tailings slurry (d_{50} = 70 µm, d_{90} = 134 µm) in 50 mm and 150 mm pipelines. The data reveals some interesting points:

- Firstly considering the 150 mm pipeline data, contrary to expectation for a settling slurry, the deposition velocity increases with increased solids concentration. Data point 1 corresponds to typical slurry flow behaviour with the level of turbulence dictating the deposition velocity. As the solids concentration is increased, the mixture exhibits non-Newtonian behaviour with laminar flow at low flow rates and turbulent flow at higher flow rates. The transition velocity between laminar and turbulent flow increases with increasing solids concentration. As demonstrated in Section 5.1, there is no mechanism to suspend particles in laminar flow and so the coarse particles settle until the transition velocity between laminar and turbulent flow is reached. Data points 2, 3 and 4 correspond to the transition velocity between laminar and turbulent flow.

- The 50 mm pipeline data shows a similar trend with data point 5 in turbulent flow and data points 6 and 7 corresponding to the transition velocity between laminar and turbulent flow. However, data point 8 shows a marked decrease in deposition velocity (actually the bed was still sliding at this flow rate, but it was the lowest flow rate tested). The pressure gradients for data points 3 and 8 are 1.16 kPa/m and 2.18 kPa/m respectively. The pressure gradient in the 150 mm pipeline was evidently too low to transport the settled bed of solids in laminar flow. This supports Shook and Thomas' belief that a minimum pressure gradient is required to transport coarse particles in laminar flow.

This data illustrates the danger of using small scale pipe loop data for the design of pipeline systems. If only 50 mm pipe loop tests had been conducted, it may have been concluded that 0.5 m/s was a suitable minimum operating velocity for the system at a solids concentration of 66% by mass. However, if the system was designed with a 150 mm pipeline, the pipeline would block unless the operating velocity was greater than 1.8 m/s.

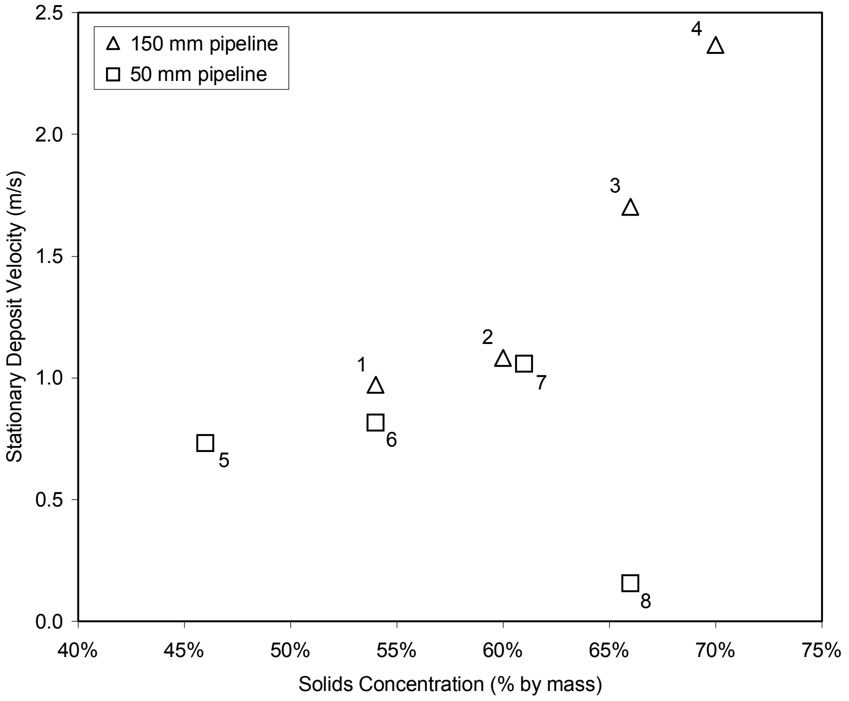

Figure 6: Copper tailings deposition velocity data

5.5 Laminar settling test apparatus

As noted by Aude *et al* (1996) and Wasp (1999), it is not feasible to detect laminar flow settling in a closed pipe loop due to the slow particle settling rates in slurries that may be considered for laminar flow transport. They cite the following example:- it will take more than four hours for a particle settling at 1 mm/minute to settle from the middle to the invert of a 500 mm pipeline. If the transport velocity is 1 m/s, a 15 km long pipeline would be required.

Wilson (1999) has referenced experiments conducted to determine the settling velocity of particles in a non-Newtonian fluid contained in the annulus between two coaxial cylinders having a vertical axis[2].

Paterson & Cooke Consulting Engineers have constructed a similar apparatus to obtain an indication of the tendency of particles to settle in pipelines that may be operated in laminar flow. The laminar flow settling tests are conducted using an apparatus consisting of two concentric cylinders with slurry placed in the annular gap between the two cylinders. The inner cylinder is rotated subjecting the slurry to shear. Provided that secondary flow patterns and turbulence (Taylor vortex formation) are avoided, the shear action is laminar and qualitatively representative of laminar pipeline flow. A major difference is that the shear rate in the annular apparatus is relatively constant in the annular gap, whilst in laminar pipeline flow the shear rate will vary from a maximum at the pipe wall to zero at the pipe centre line. It is therefore appropriate to formulate a bulk shear rate and then ensure that the bulk shear rate is similar in both the proposed pipeline and the annular apparatus. Settling in the annular apparatus will then be qualitatively similar to the pipeline conditions. After subjecting the slurry to shear for a time period similar to the transit time for the proposed pipeline, samples can be collected from different heights in the annular gap and the extent of settling established. The internal diameter of the outer cylinder is 288 mm. The outside diameter of the inner cylinder is varied for the test conditions.

Figure 7 presents data from a laminar settling test conducted for sand particles (between 45 μm and 212 μm) in a fine clay slurry (τ_y = 59 Pa, Bingham plastic viscosity = 0.0084 Pa.s, ρ_{mf} = 1 330 kg/m^3). The mixture was statically stable and the sand particles were uniformly distributed at a concentration of 15% by mass. Equation (1) suggests that the fine clay slurry should be capable of supporting a 46 mm particle under static conditions! Tests were conducted at bulk shear rates of 37.3 s^{-1} and 74.5 s^{-1} for 30 minute periods. After each test, slurry samples were withdrawn from different levels in the sheared annulus and the percentage of particles greater than 45 μm determined. Referring to Figure 7, it is evident that significant settling occurred during the tests as the percentage of sand particles decreased at all levels except at the 0 mm level. The settling rate was faster for the test conducted at the higher shear rate.

Wilson (2000) has reported the same finding from tests conducted using a similar apparatus that had been modified so that the annular gap increased with depth.

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[2] Highgate and Whorlow (1967), Thomas (1979)

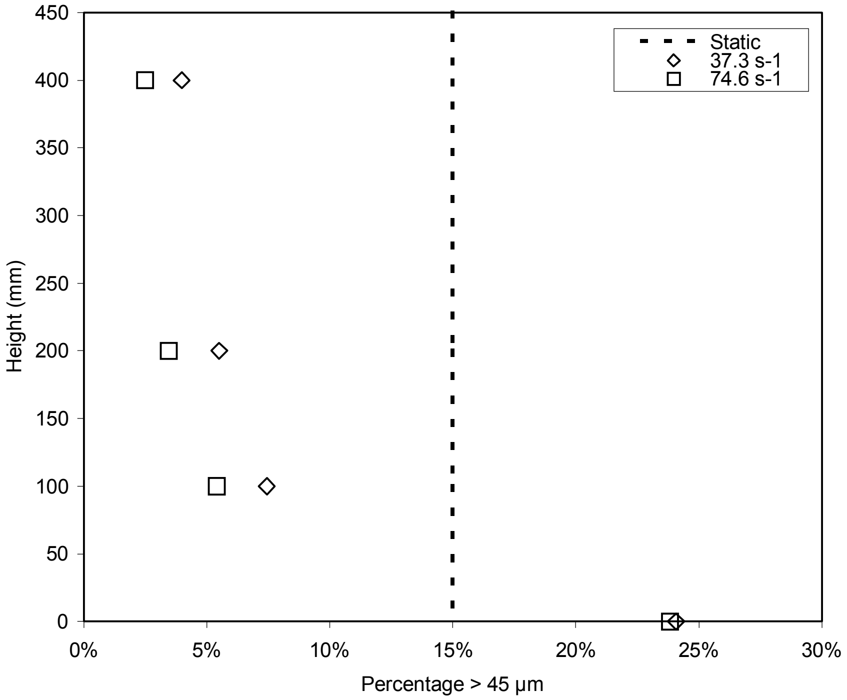

Figure 7: Laminar settling test data (clay sand slurry)

6. SUMMARY

The following points should be considered when designing laminar flow slurry pipelines:

- When statically stable suspensions are sheared, the coarse particles settle. The settling rate may be slow but particles as fine as 100 µm will settle. This has a major design implication for long distance pipelines.
- Settled particles will remain on the pipe invert if the flow remains laminar as there is no mechanism for re-suspending the particles.
- If the pipeline pressure gradient exceeds a certain minimum value (believed to be between 1 kPa/m and 2 kPa/m), the settled bed of particles will be transported through the pipeline as a sliding bed in a similar manner to turbulent Newtonian flow. If the pressure gradient is lower than this value, particles will accumulate on the pipe invert thereby increasing the pipeline pressure gradient until one of the following occurs:
    - (i) The pressure gradient exceeds the minimum value required to transport the bed under laminar flow conditions.
    - (ii) The velocity above the bed increases sufficiently to generate turbulence to suspend the coarse particles and erode the bed.
    - (iii) The pump station discharge pressure rises to a value where preventative action is necessary to avoid pipeline blockage. The accepted strategy is to introduce a slug of flushing water, or alternatively introduce sufficient flushing water to dilute the slurry sufficiently to ensure turbulence. This approach is well suited to systems with positive displacement pumps. Care must be taken with centrifugal pump stations due to the reduction in pressure generated when flushing water is introduced into the pumps.

- An initial estimate of the pipeline pressure gradient may be obtained using standard scale up techniques for laminar non-Newtonian flow. However, an additional allowance must be provided to cater for the increased pressure gradient due to laminar settling. The literature provides little guidance and the system designer must use sound engineering judgement to estimate the required allowance.

It is unlikely that laminar settling will be a concern for underground paste fill systems due to the typically high pipeline pressure gradients (5 to 15 kPa/m).

Laminar settling must however be considered for the design of pipelines conveying fine viscous slurries (e.g. laterites), thickened and paste tailings. These pipelines generally have large diameters and are operated at pressure gradients of less than 1 kPa/m.

ACKNOWLEDGEMENTS

The author would like to thank Dr Paterson, Mr Johnson, Mr van Sittert and Prof Paul Slatter for their comments and suggestions. The test data presented in this paper was collected by Mr van Sittert.

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