Keynote Address

Tailings Transport – Back to Basics!

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Abstract

The underlying principles of tailings transportation are strongly influenced by the paradigms of conventional Newtonian engineering hydrodynamics. However, fundamental differences exist, and the objective of this presentation is to highlight these, and their practical implications. The Bingham plastic rheological model is accepted as an appropriate point of departure, and the fundamentals of the development of the engineering hydrodynamics of tailings transport are presented. In particular, the meaning, measurement, importance and implications of the yield stress are explored. The exploitation of tailings rheology for pressure gradient prediction is then presented, emphasising the key role that the yield stress plays in turbulent, transitional and laminar pipe flow. Discussion centres around the problems associated with the application of each flow regime, and the case for operation in the transition zone is argued.

1. Introduction

Tailings disposal has undergone fundamental changes in recent years (Jewell et al., 2002), and environmental and economic drivers have pushed tailings transport designers and operators to consider operating at considerably higher concentrations than before (Slatter, 2002). Slatter (*ibid*) makes the point that real engineering is just as much an art as a science, and is by definition a rather grey exercise, with many varying degrees of what constitutes a good design in any particular application. Higher concentration designs will not necessarily reduce environmental contamination, or always ensure significant cost and water savings. It therefore behoves us to re-visit the basics of tailings transport, lest we fall into the trap of believing that the “new” will always be “better”!

Fluid mechanics is arguably the most empirically based engineering science. The main reason for this is that the last unsolved problem of Classical Physics is Fluid Turbulence, and we are probably still a decade away from a solution which is widely acceptable to physicists (McComb, 1990, 2005). It comes as no surprise then that the paradigms of classical Newtonian engineering hydrodynamics education and practice are firmly rooted in dimensional analysis.

The hydraulic transport of tailings material fits broadly under the heading of the flow of non-Newtonian suspensions, and is closely related to, and profoundly influenced by, classical Newtonian engineering hydrodynamics. The essential difference between the two is the presence and influence of solid particles. There are two major consequences of the presence of particles. The smaller particles influence the viscous behaviour (rheology) of the mixture, and the larger particles will tend to settle. Both of these will influence the flow patterns and velocity distributions fundamentally. The objective of this presentation is to highlight these fundamental influences, and their practical implications for tailings transport.

2. Theory and Literature

2.1. Classical Newtonian Engineering Hydrodynamics

Since the work of Osborne Reynolds in the late 19th century, the paradigms of classical Newtonian engineering hydrodynamics have been based on dimensional analysis of the major variables. For pressure gradient and flow behaviour prediction, the relevant dimensionless groups are the Reynolds number, the friction factor and the relative roughness. Flows present as laminar, transitional or turbulent, and the interrelationship between the dimensionless groups in each regime has been summarised classically using the well-known Moody diagram (Moody, 1944). This approach has strongly influenced the development of techniques for pressure gradient and flow behaviour prediction for non-Newtonian flows, and a similar, extended set of dimensionless groups has been developed.

2.2. The Bingham Plastic Rheological Model

Rheology is often best understood as a dynamic property of microstructure. At rest, the attractive forces between particles or agglomerates form a three-dimensional structure, which extends to the walls of the container. The stress required to break this structure and initiate shear, is called the yield stress. Below this stress, the material is envisaged to behave as an elastic, Hookean solid. As shear stresses and shear rates increase, the agglomerates gradually re-orientate and disintegrate, resulting in a decrease in the viscosity of the material. This process is known as shear thinning. At very high shear stresses and shear rates, the re-orientation and disintegration process reaches equilibrium, and the viscosity becomes constant.

Although this portrayal of the relationship between viscosity and microstructure is idealised, it is useful for engineering purposes, and the simplest rheological model which can accommodate this behaviour is the Bingham plastic model, which can be formulated in terms of shear stress τ;

$$\tau = \tau_y + K\dot{\gamma}, \quad [1]$$

or viscosity η;

$$\eta = \frac{\tau_y}{\dot{\gamma}} + K. \quad [2]$$

The two terms on the right-hand side will be equal when

$$\dot{\gamma}_b = \frac{\tau_y}{K} . \quad [3]$$

The importance of the boundary shear rate $\dot{\gamma}_b$ is that it marks the boundary between yield stress and plastic viscosity domination of viscosity. This is shown graphically in Figure 1.

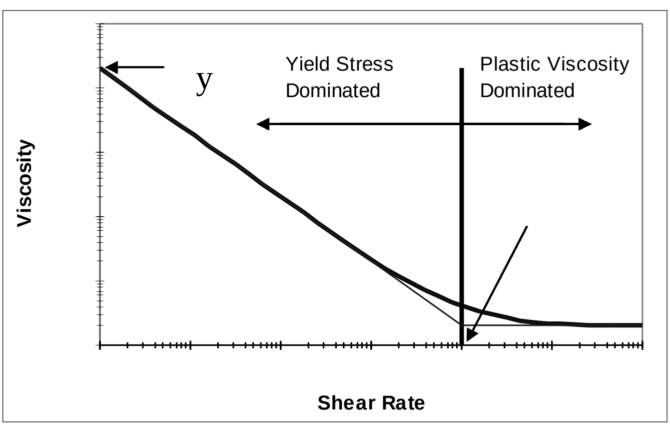

Figure 1: Graphical presentation of Equation [2] showing the boundary shear. rate $\dot{\gamma}_b$.

It is significant to note from Figure 1 that the ordinate intercept of the oblique asymptote is in fact the yield stress value τ_y. This illustrates the fact that – for practical purposes – the viscosity values for shear rates less than the boundary shear rate $\dot{\gamma}_b$ are directly proportional to the yield stress. This serves to emphasise the importance of the yield stress value when operating in the region to the left of the boundary shear rate. The yield stress τ_y is a strong function of particle properties, concentration and solution chemistry, with the plastic viscosity K usually being a weaker function of these.

2.3. Dimensional Analysis

Dimensional analysis of the Bingham plastic model as applied to circular pipe flow will yield three dimensionless groups. Besides the standard friction factor, the other two dimensionless groups are of prime concern here. They are the Reynolds number and the Hedström number:-

$$Re_B = \frac{\rho V D}{K} \ , \quad [4]$$

$$He_B = \frac{D^2 \rho \tau_y}{K^2} \ . \quad [5]$$

One of the problems with dimensional analysis as shown above is that it separates the rheological parameters τ_y and K, and is unable to accommodate the additive relationship of Equation [1]. An alternative approach (Slatter & Lazarus, 1993) is to analyse the viscous stress as a unit, yielding

$$Re_2 = \frac{8 \rho V^2}{\tau_y + K\left(\frac{8V}{D}\right)} \ . \quad [6]$$

2.4. Laminar Flow

Laminar flow is one of the very few areas where a rigorous analytical solution is available, known as the Rabinowitsch-Weissenberg integral;

$$\frac{8V}{D} = \frac{32Q}{\pi D^3} = \frac{4}{\tau_0^3} \int_0^{\tau_0} \tau^2 . \dot{\gamma}(\tau) d\tau . \quad [7]$$

Application to Equation [1] will yield the well known Buckingham equation;

$$\frac{8V}{D} = \frac{\tau_o}{K}\left[1 - \frac{4}{3}\left(\frac{\tau_y}{\tau_o}\right) + \frac{1}{3}\left(\frac{\tau_y}{\tau_o}\right)^4\right], \quad [8]$$

that can be used for design in laminar flow.

2.5. The Laminar/Turbulent Transition

The dimensional analysis presented above can be used to develop an approach for determining the critical velocity V_c for large pipes (Slatter & Wasp, 2000);

$$Re_{Bc} = 26\, He_B^{0.5} \quad \text{for } He > 1.5x10^5. \quad [9]$$

This results in a critical velocity which can be calculated directly from

$$V_c = 26\sqrt{\frac{\tau_y}{\rho}}. \quad [10]$$

2.6. Turbulent Flow

A turbulent flow model appropriate for non-Newtonian slurries is based on a particle roughness turbulence effect (Slatter, 1999). A roughness Reynolds number was formulated to accommodate the larger of either the particle roughness size (usually taken as the d_{85} size) or the standard pipe roughness k (Slatter & van Sittert, 1997) as,

$$Re_r = \frac{8\rho V_*^2}{\tau_y + K\left(\frac{8V_*}{\max:\left(d_{85}, k\right)}\right)} \quad [11]$$

where V* is the classical shear velocity.

This roughness Reynolds number was used to correlate the classical roughness function B in the same way as for Newtonian fluids.

If Re_r d»#ð 3.32 then B = 2.5 ln Re_r + 5.5. This is analogous with smooth wall turbulent flow for which the flow behaviour can be predicted from

$$\frac{V}{V_*} = 2.5\ln\left(\frac{R}{k}\right) + 2.5\ln Re_r + 1.75. \quad [12]$$

If $Re_r > 3.32$ then B = 8.5. This is analogous with fully developed or rough wall turbulent flow for which the flow behaviour can be predicted from

$$\frac{V}{V_*} = 2.5\ln\left(\frac{R}{k}\right) + 4.75. \quad [13]$$

3. Yield Stress Domination

While it is clear from cursory examination of Equation [10] that the yield stress has a dominant effect on the laminar/turbulent transition for large pipes, its dominant effect in other areas is more subtle and will be highlighted below.

3.1. Operational Area

We can formulate the critical bulk shear rate Γ_c in a pipe at the laminar/turbulent transition as

$$\Gamma_c = \frac{8V_c}{D}. \quad [14]$$

Combining Equations [3], [5] [10] and [14], we derive that

$$\frac{\dot{\gamma}_b}{\Gamma_c} = \frac{\sqrt{He}}{208}. \quad [15]$$

If we substitute the lower limit value for the large pipe regime ie He = 1.5×10^5, then we get

$$\frac{\dot{\gamma}_b}{\Gamma_c} = 1.86 \approx 2. \quad [16]$$

The important consequence here is that the boundary shear rate is always at least twice the critical bulk shear rate, for large pipes. This situation is shown graphically in Figure 2.

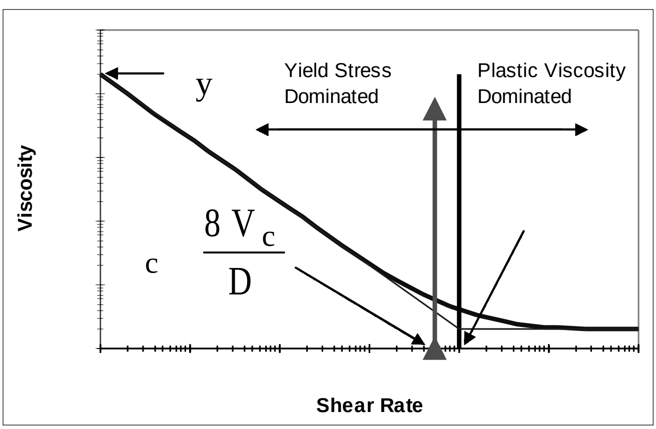

Figure 2: Bingham plastic viscosity diagram showing the maximum transition point for large pipes.

This means that in the laminar, transition and early turbulent region, the behaviour of these flows will be dominated by the yield stress value.

3.2. Yield Stress Measurement (Slatter, 2004)

The determination of yield stress has traditionally been performed using at least three different approaches.

3.2.1. Flow curve extrapolation

Flow curve or rheogram measurements of shear stress vs shear rate are obtained from either tube or rotary rheometry. After competent data reduction, Equation [1] can be fitted to the data points. This results in the yield stress effectively becoming a fitting parameter, rather than a true measure of structural failure. Furthermore, Nguyen & Boger (1992) point out that competent data reduction cannot proceed until the value of the yield stress is independently determined.

3.2.2. The slump test

The slump test has been used by concrete engineers for many years to estimate the workability of fresh concrete. Standard slump tests involve a conical frustum mould, but Clayton et al. (2003) recommend a cylindrical shape, and the reader is referred to this reference for the different analytical approaches relating yield stress to slump height. These authors point out that slump height is an empirical value which is a complex function of both yield stress and density. Since yield stress is a unique material property, it is the more appropriate to use for direct comparisons.

3.2.3. The vane test

The vane test involves immersing the vane in the fluid, slowly rotating it, and measuring the time/torque response, from which the maximum torque T_{max} is extracted. The special geometry of the vane causes the material to yield within itself, rather than on the interface between the sample and e.g. a bob. Wall slip is thus excluded. At yield, the sheared surface comprises the cylindrical surface of the vane tip loci.

4. Pressure Gradient Prediction

The predictive models presented above can now be exploited to utilise the slurry rheology for predicting pipe flow behaviour and pressure gradients. Pressure gradient prediction usually begins with rheological characterisation of the material over a range of concentrations. This information can then be used to predict the pressure gradient

4.1. System Curve

The system curves for water and a typical tailings at three concentrations is presented in Figure 3.

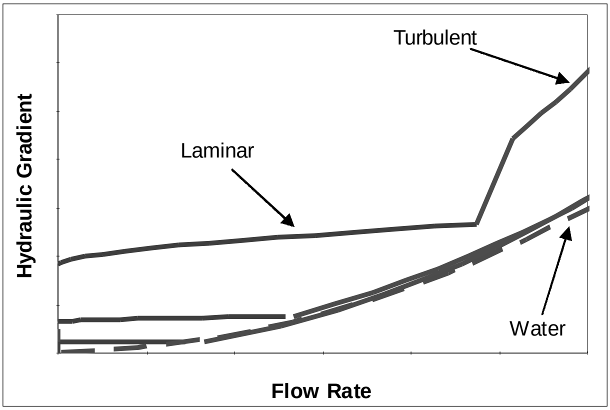

Figure 3: System curves for water and tailings at three concentrations.

Figure 3 shows the general form of the laminar and turbulent regions, and the effect of increasing concentration.

4.2. The Importance of the Yield Stress

In order to reinforce the comments above regarding the importance and influence of the yield stress value, the effect of yield stress on the friction head loss can be investigated. The results of such an exercise are presented in Figure 4. For this exercise, all variables were held constant – only the yield stress has been varied.

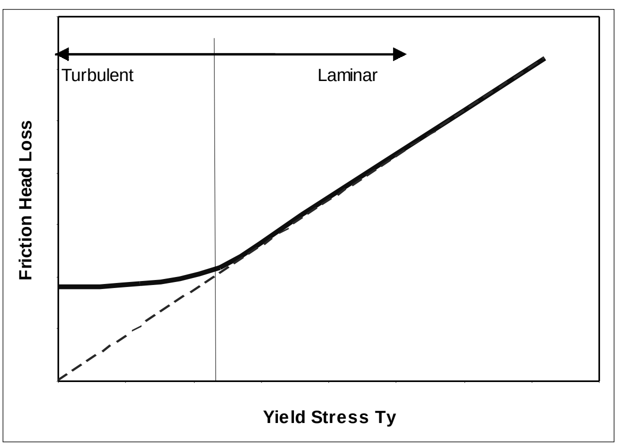

Figure 4: Variation of friction head loss with yield stress for typical tailings slurry.

Figure 4 shows a direct proportionality between friction head loss and yield stress in the laminar regime. A much weaker, but monotonically increasing, relationship is seen in the turbulent regime.

5. Particle Settling

So far, we have dealt with the effect of small, essentially non-settling particles, which modify the viscous characteristics of the carrier fluid. Larger particles, because of their tendency to settle, have quite a different effect on the behaviour of the mixture.

5.1. Settling in Turbulent Flow

In turbulent flow, turbulent eddies are used to suspend and transport settleable solids through the pipe. If there is insufficient turbulence, particles will form a stationary bed, and pipe blockage can occur. Although early research on the deposition velocity was largely empirical, a quantum leap in this area was achieved with the work of Wilson who applied a mechanistic approach based on the two-layer model (Wilson, 1979). This work is presented in the form of nomograms, which are still very much in use. In practical terms, the deposition velocity is the velocity at which, as average pipe velocity is decreased, a stationary bed will begin to form on the pipe invert. It is desirable to operate above this velocity to avoid unstable operation and pipe blockage.

5.2. Settling in Laminar Flow

In laminar flow, there are no mechanisms such as turbulent eddies to suspend settleable solids, and they will accumulate in a bed on the pipe invert (Pullum et al. 2004). The only method of transporting these materials is to ensure that the forces acting on the settled bed are sufficient to maintain the sliding motion of the bed. The same mechanistic two layer model approach has been used successfully to model this behaviour (ibid).

Although the deposition velocity in laminar flow is a complex function of particle characteristics and carrier fluid rheology, it has been found that a pressure gradient above 1 kPa/m is usually sufficient to ensure a sliding bed (Cooke, 2002).

6. Operation in the Transition Region

There are at least two practical difficulties emanating from the above discussions, as we attempt to design and operate tailings transport pipelines at higher concentrations. The first is – considering turbulent flow operation – that due to the increased viscous stresses at higher concentration, it may not be possible to achieve enough turbulence to operate above the deposition velocity at realistic velocities. The second is that if we operate in laminar flow, the required minimum operating pressure gradient of at least 1 kPa/m may result in excessive energy and pumping plant costs.

Furthermore, a principal omission from the above topics is any consideration of operating in the transition region.

Figure 5 shows the results of a standard pipe flow test curve for a 6%v/v kaolin suspension in a 5 mm pipe. Superimposed on this is a plot of the standard deviations of the pressure transducer readings taken at the same time (Huq & Slatter, 1999).

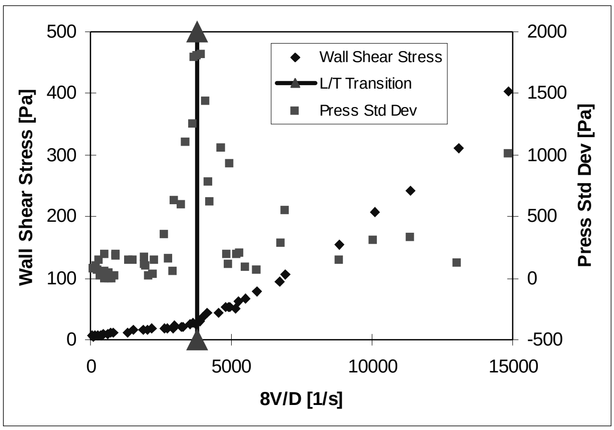

Figure 5: Pipe flow test data showing pressure readings standard deviation.

Figure 5 shows clearly that there is a dramatic spike in the pressure deviations in the transition region. This is a reflection of the regime chaos at transition, which has been reported by several other investigators (eg Park et al., 1989 and Graham et al. 1999).

For our purposes, there are two advantages arising from this. Firstly, the regime chaos indicates that there is a high transport potential for settleable solids. Secondly the extreme nature of the spike shown in Figure 5 indicates that identifying and tracking this region would be possible with an intelligent control system. A tailings transport system operating in this region may well have advantages, and is a region – perhaps exotic, but – well worth investigating.

7. Conclusion

The fundamentals of tailings transport have been developed from the paradigms of conventional Newtonian engineering hydrodynamics, using the Bingham plastic rheological model as the appropriate point of departure. Emphasis has been given to the meaning, measurement, importance and implications of the yield stress, illustrating the key role it plays in turbulent, transitional and laminar pipe flow. The case for operation in the transition zone has been argued against the problems associated with the application of each flow regime.

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Determining the Optimum Location of a High Rate Thickener for a Thickened Tailings System

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Abstract

This paper presents a cost comparison between pumping large volumes of dilute thickener feed to a remote thickener located at the tailings storage facility (TSF), and using high pressure positive displacement pumps pumping thickened tailings from a thickener located at the process plant to the tailings residue facility. The study considers only the pump and pipeline system capital and operating costs, and specifically excludes all costs associated with preparation and placement.

This study shows that for a 2.5 km distance both options have a similar net present cost. As the distance increases to 5 km it is better to locate the thickener at the process plant and pump high density thickened tailings using piston diaphragm pumps. This is mainly due to the differences in annual operating costs over the life of mine as it is not energy efficient to pump large volumes of dilute slurry long distances.

Each site assessment is obviously project specific and this trade-off study shows that it is not immediately obvious as to which pumping solution is the most cost effective.