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Paste and thickened tailings transportation: flow characterisation

Sadegh Javadi Rudd [a,*], Allan Thomas [b], Behnam Pirouz [a]

[a] *ATC Williams, Australia*

[b] *Slurry System Engineering, Australia*

Abstract

Tailings transport and distribution are integrated elements of any wet tailings storage facility (TSF). Tailings from the process plant are typically thickened to a moderate or relatively high solids concentration, still pumpable, depending on factors such as TSF deposition requirements and strategies, process plant water security, the dewatering technology employed and costs.

The primary author of this paper discussed the tailings transport aspects in a paper published in Paste 2020 (Javadi et al. 2020). The paper provided an overview of various aspects of a tailings transportation system, such as material and flow characteristics, flow regimes, basis of design definition, as well as the environmental considerations for tailings transportation post pipe integrity failure.

This paper focuses on the flow characterisation and hydraulic modelling of paste and thickened tailings transport in the turbulent and laminar regime. In this paper, the predicted flow behaviours of non-Newtonian tailings types (copper, coal and gold) during the design phase are compared and evaluated against actual operational data collected after commissioning. The main objective of the paper is to present the flow characterisation findings from the full-scale operation of the thickened tailings system.

Particle settling in laminar flow is discussed for a hypothetical copper/gold tails application, and flushing scenarios to prevent bed build-up are suggested. Pump pressures in an operating high-density gold tailings pipeline are compared with predicted pump pressures. It is concluded that the pipeline is operating with a fixed bed of solids with turbulent flow above the bed, and good agreement between measured and predicted pressures is obtained.

Keywords: *paste and thickened tailings transport, flow characterisation and hydraulic modelling*

1 Introduction and objectives

Tailings storage facility (TSF) disposals often involve tailings thickening, transport, and distribution. Tailings from the process plant are typically thickened to a moderate or relatively high solids concentration, still pumpable, depending on factors such as TSF deposition requirements and strategies, process plant water availability, the dewatering technology employed, and associated costs.

In *Paste 2020*, the main author of this paper published an overview of various aspects of thickened tailings transport systems. Multiple elements of the transport system, whether pressurised or open channel, were reviewed. Considerations for the design of hydraulic transport systems, including flow regime, material characteristics, flow behaviour assessment (rheological measurement and interpretation), design basis definition, pipeline leakage monitoring, and failure analysis and management, were also discussed (Javadi et al. 2020).

* Corresponding author. Email address: sadeghj@atcwilliams.com.au

This paper continues the findings of the flow characterisation for pipe flow. The primary objectives are to evaluate the effectiveness of commonly used non-Newtonian hydraulic models by comparing model predictions with full-scale data.

2 Turbulent flow

Wilson and Thomas' hydraulic model for turbulent flow of non-Newtonian (e.g. Bingham plastic) slurries is one of the most widely used models for the flow prediction of thickened slurries. Wilson & Thomas (1985, 2006) and Thomas & Wilson (2007), adopting the drag reduction theory (viscous sublayer thickening), proposed an analytical model for turbulent flow of non-Newtonian suspensions in pipes.

The analytical model was based on the viscous sublayer thickening which was proposed by Lumley (1973, 1978) for the flow of aqueous fluid carrying a small quantity of long-chain molecules. Their model assumed that the non-Newtonian characteristics of a slurry material thicken the viscous sublayer in the same way, and therefore the viscous sublayer for non-Newtonian turbulent flows is thicker than for an equivalent Newtonian flow by a factor of α. The thickness of the sublayer should also be multiplied by a factor equal to α and the thickness of the superposed logarithmic layer is reduced by (α-1). The result of these thickness changes is a displacement of the velocity profile beyond the sublayer.

This model assumed that the drag reduction thickens the viscous sublayer and accounts for a large change in velocity. Nevertheless, the velocity profiles in the viscous sublayer and region above the viscous sublayer will remain linear and logarithmic respectively, except the blunting velocity profile of plug flow formation due to the slurry yield stress (Javadi 2017).

2.1 Two large-scale examples of turbulent flow tailings pipelines

The viscous sublayer thickening hydraulic model of Wilson–Thomas has already been found to show reasonable agreement with experimental data and some operational data. However, operational variations such as changing process conditions, variations of the inner diameter of the pipeline along the route, and different discharge points, make it challenging to confirm the slurry flow conditions, such as the presence of a settled bed, and so the overall total pump discharge head can only be approximately compared to predicted total head. However, there is an option of using paired pressure sensors on a straight section of the pipeline with a constant internal diameter (ID) to collect reliable data.

Large-scale operational data of a thickened tailings transport system of a 25 Mtpa copper concentrator is presented. The 5.0 km tailings delivery pipeline requires 4 centrifugal pumps in series, each fitted with 870 kW motors. The tailings pipeline is a combination of lined carbon steel pipe and poly pipes. Table 1 summarises this operational system technical specification and tailings properties.

Table 1 25 Mtpa copper plant tailings transport

Item	Description	
Pumps	Weir 20/18 AHPP 870 kW (4 in series)	
Pipeline		
Section (1)	DN650 CS 9.53 mm thick, 38 mm thick PE lined, 2.2 km	
Section (2)	DN710 HDPE PN20, 0.7 km	
Section (3)	DN710 HDPE PN16, 0.8 km	
Section (4)	DN630 HDPE PN10, 1.34 km	
Material properties		
Particle specific gravity	2.80	
D_{max}	0.5 mm	
D_{80}	0.11 mm	
D_{50}	0.023 mm	
D_{25}	0.002 mm	
Rheology	Yield (Pa)	Plastic viscosity (mPas)
54%	12.5	16.0
56%	16.0	30.0
58%	27.5	48.0

The operational range of the tailings delivery is shown in Figures 1 and 2. As seen, the tailings volumetric flow rate range mainly from 3,650–4,050 m^3/h at a typical solids concentration of 54–60% (w/w). The tailings particle D_{80} is 100–120 µm.

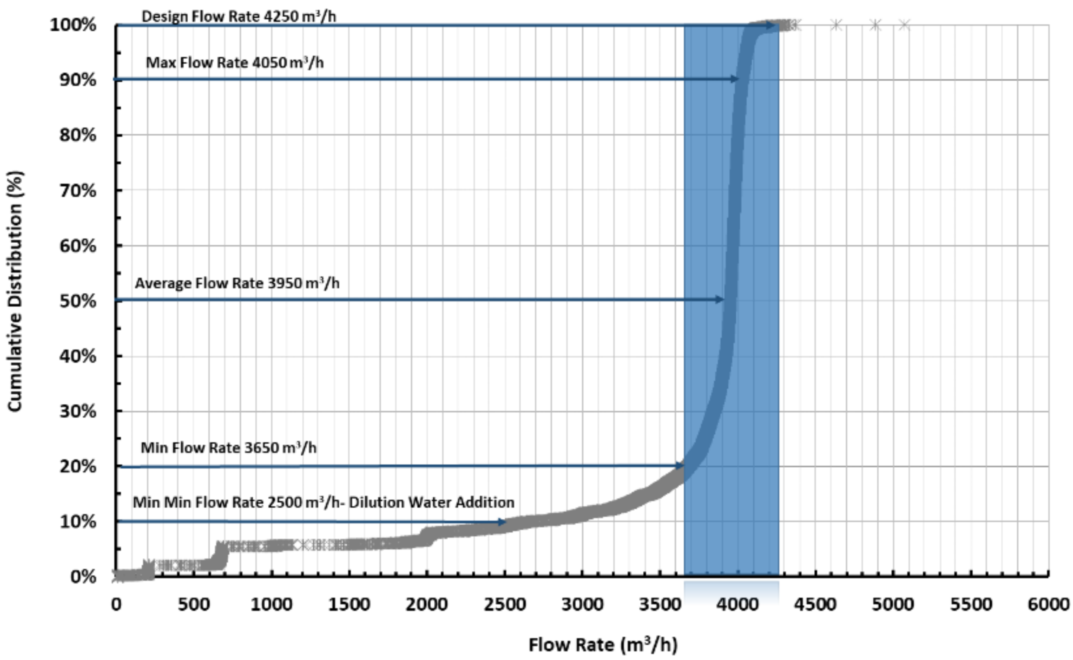

Figure 1 Tailings flow rate range

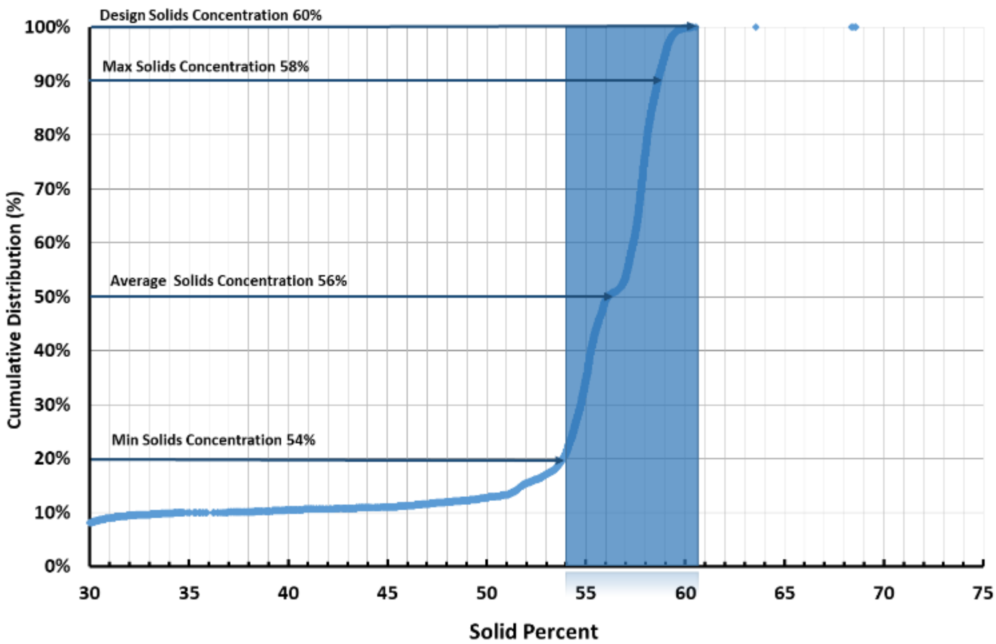

Figure 2 Tailings solids concentration range

Figure 3 compares the total pumping head per pump estimated by a sublayer viscous thickening model at 54 and 58% with the actual recorded operational data. The predicted curve shows an increasing trend of head loss with higher flow rates, consistent with the model expectations for non-Newtonian slurry flow, although the operational data exhibit significant scatter, mainly due to variations in operating condition fluctuation. However, the general operational data trend aligns reasonably well with the model prediction. The shaded region or spread between curves indicates the degree of variation between model prediction and actual performance.

An increase in pumping head is expected at flow rates below 3,000 m^3/h (equivalent to a transitional velocity of 3.28 m/s) for 58% and 2,000 m^3/h (equivalent to a transitional velocity of 2.26 m/s) for 54%, due to running below the transitional velocity and bed formation. There is one operational data point at 2,300 m^3/h which agrees with the predicted 58% upward trend. Apart from 3 very low flow rate outliers below 1,700 m^3/h, all other operational data below 3,000 m^3/h are within the predicted curves suggesting they are for concentrations between 54 and 56%.

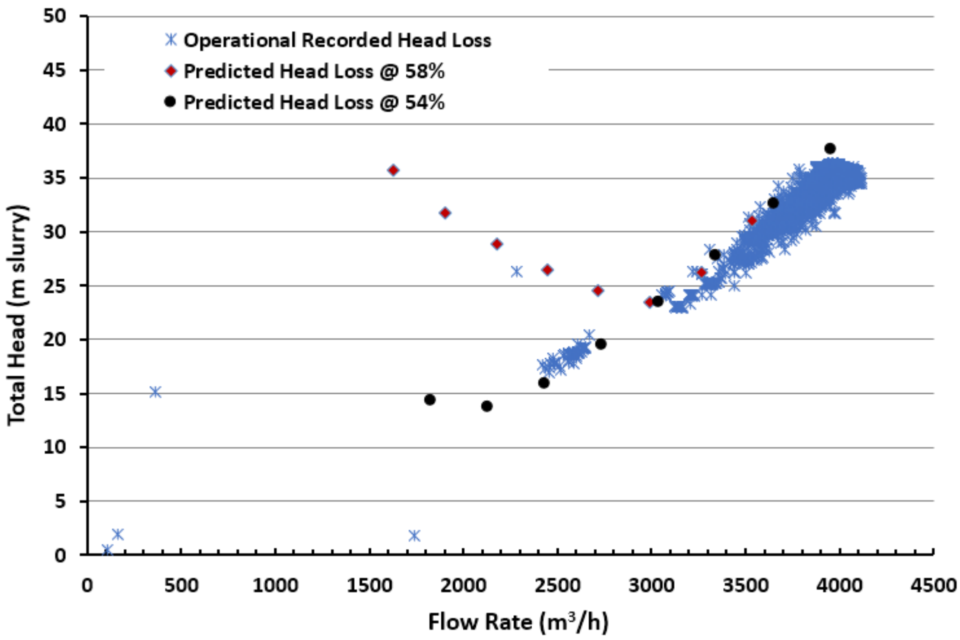

Figure 3 Head loss predicted versus recorded for 54 and 58% copper tailings

A similar analysis is undertaken on a coal tailings delivery, shown in Figure 4. The pumping system is a multistage centrifugal pumping and 4,450 m long pipeline consisting of carbon steel and polyethylene pipes. The operational range is 600–1,200 m^3/h at solids concentration of 28–32%. A summary of operational system technical specification and tailings properties is presented in Table 2.

Table 2 Coal washing plant tailings transport

Item	Description	
Pumps	Warman 12/10 AH (3 stages)	
Pipeline		
Section (1)	DN450 CS 9.53 mm thick, basalt-lined 0.9 km	
Section (2)	DN500 HDPE PN20, 1.4 km	
Section (3)	DN4500 HDPE PN16, 2.15 km	
Material properties		
Particle specific gravity	1.95	
D_{max}	0.6–1 mm	
D_{80}	0.04–0.070 mm	
Rheology	Yield (Pa)	Plastic viscosity (mPas)
30%	2.6	15.0
33%	4.5	16.0
35%	7.0	17.0

For this type of tailings, a hook-shaped relationship between the required pumping head and flowrate is observed, as presented in Figure 4. As shown, the model prediction aligns closely with the operational data in fully turbulent range, whereas in the transitional regime the model under-predicts friction losses. The predicted transitional velocity of 1.24 m/s, equivalent to 500 m^3/h, is in good agreement with the recorded operational data.

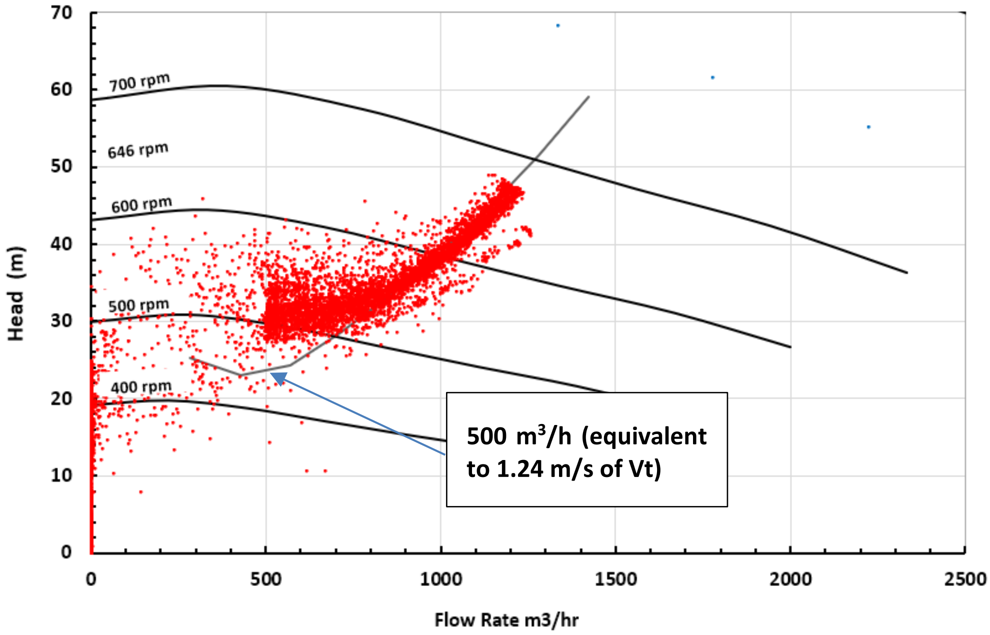

Figure 4 Head loss predicted versus recorded for 30% coal tailings

2.2 Discussion turbulent flow – two large-scale pipelines data

Most tailings pipelines operate in turbulent flow, and operating data from 2 large-scale pipelines have been considered. The Wilson–Thomas theory for pipe flow of non-Newtonian Bingham plastic slurries results in the predicted head loss versus flow rate curve approaching slightly closer to the water curve as the flow rate decreases towards transition. This is a subtle effect which is not easily able to be confirmed in Figures 3 and 4 because of the large amount of data scatter. However, the data do confirm the Wilson–Thomas transition velocity prediction. For example, in Figure 3, at 58% concentration, the predicted transition flow rate is 3,000 m^3/h, and below 3,000 m^3/h the predicted total head increases as laminar flow occurs and a stationary bed builds with turbulent flow above the bed. One of the operational data points (at 2,250 m^3/h) confirms this predicted trend.

3 Laminar flow

Most tailings pipelines operate in turbulent flow. But increasingly, high-density and paste tailings pipelines, are being considered. In this paper, slurry rheology is assumed described by the Bingham plastic model and 'high density' refers to tailings with a concentration such that the yield stress is 20–30 Pa and 'paste' refers to tailings with a yield stress 40–50 Pa. Disposing of tailings at high density or as paste has environmental advantages including using less water and requiring less ground area for the TSF and less expensive rehabilitation of the mine area at the end of mine life. However, pump pressures are usually higher, and there may be operational issues with settling of coarser particles.

These high-density and paste pipelines are intended to operate in laminar flow. Under laminar flow conditions, there are no turbulent eddies to help support particles and the coarsest particles slowly settle as they travel along the pipeline. If all particles are less than about 10 microns, settling will probably not be a problem, but for the majority of tailings, particle settling is an issue. If a settled bed forms, then the pump pressure will increase over time.

Particles which settle to the bottom of the pipe will eventually accumulate and form a stationary bed. This bed will not normally be able to be slid along the bottom of the pipe unless the laminar flow pressure gradient is very high. The situation is analogous to the extensive work of Ken Wilson and co-workers and other, from 1970 onwards in predicting the deposit velocity of particles in turbulent flow based on sliding of a bed of solids.

Cooke (2002) refers to a 1999 telephone conversation with Cliff Shook in which Shook believed a laminar flow pressure gradient of between 1,000 and 2,000 kPa/km is required to transport solids in laminar flow. These pressure gradients are much higher than in a normal turbulent flowing tailings pipeline.

3.1 Two examples of successful laminar flow pipelines

Aude et al. (1996) described laminar flow pumping in a Trinidad limestone clay pipeline. The clay slurry has a yield stress of 50 Pa and is pumped a distance of 10 kms at 0.76 m/s. The particle size of this slurry is not known exactly but probably has a D_{50} around 10 microns and a top size of perhaps 150 microns. However, even with this fine particle slurry and a yield stress of 50 Pa, there is a slow bed build-up resulting in an increase in discharge pressure with time. Because of this, it is routine operating practice to pig the pipeline every day. The degree of settling of a slurry depends on pipeline length. If the pipeline was only one third the length, pigging might only be required once every 3 days. However, regular pigging is not realistic for a mine site tailings pipeline. On a mine site, the only alternative would be to regularly dilute the slurry when required to remove the bed under turbulent flow conditions.

Houman & Johnson (2002) describe a laminar flow pipeline transporting a kimberlite tailings slurry (D_{100} = 1,000 microns, D_{80} = 300 microns and D_{50} = 100 microns) in a 330 mm ID, 5.5 km steel pipeline. Piston diaphragm pumps are used with discharge pressures ranging from 3–12 MPa (550–2,180 kPa/km). These pressure gradients are in line with the 1,000–2,000 kPa/km suggested by Shook in the previous section.

3.2 Transition velocity

For a Bingham plastic slurry, the transition velocity (Vt) between laminar and turbulent flow is primarily dependent on the yield stress (τ_y) and slurry density (ρ), for example as per Wilson & Thomas (2006).

$$V_t\left(\frac{m}{s}\right) = 25\sqrt{\frac{\tau_y}{\rho}} \qquad (1)$$

3.3 Particle settling in laminar flow

Under static conditions, the yield stress of a Bingham plastic slurry will prevent finer particles from settling. For example, one of the authors (Thomas), has experience of a slurry comprising a mixture of beach sand and kaolin clay which did not segregate, even after 18 months stored in a 200-litre drum. However, once this slurry was pumped in laminar flow in a 105 mm ID test loop, slow settling of the sand occurred (i.e. shearing of the Bingham plastic allowed coarse particles to settle).

During laminar pipe flow of a Bingham plastic, much of the core region in the pipe remains essentially unsheared, and the coarse particles in that region may not settle. However, there is a layer near the pipe wall which is sheared, and coarser particles within this sheared layer settle around the inner surface of the pipe towards the bottom of the pipe as flow proceeds along the pipeline. An effective viscosity within the sheared layer can be obtained by equating it to the viscosity of a Newtonian fluid flowing at the same flow rate and wall shear stress as the slurry. Using this effective viscosity and the density of the slurry, the coarse particle settling rate can then be predicted. For present purposes, a spherical shape is assumed.

3.4 Particle settling: high-density tailings example

Consider a copper/gold tailings slurry, solids specific gravity 2.83, D_{99} particle size 0.425 mm, and D_{95} size 0.18 mm, pumped in a 4.75 km, 593 mm ID pipeline. The nominal solids throughput is 2,103 dry tph at a nominal solids concentration, Cw = 60.3% and flow rate is 2,128 m^3/h with the velocity 2.14 m/s. At Cw = 60.3%, yield stress is 0.8 Pa and plastic viscosity = 10 mPas, and Equation 1 gives Vt = 0.55 m/s well below the 2.14 m/s operating velocity, so flow is turbulent. Predicted pressure gradient is 96 kPa/km.

Now, purely as an example, suppose high-density thickeners are installed and the concentration increases to 71% with yield stress 25 Pa and plastic viscosity 85 mPas. At the same nominal 2,103 tph solids, the flow rate has reduced to 1,602 m^3/h with velocity 1.61 m/s. Based on Equation 1, Vt is 2.91 m/s, so flow is laminar. Assuming laminar flow with no settling, the predicted pressure gradient is 207 kPa/km which is well below the 1,000–2,000 kPa/km range required to slide a settled bed along the pipe. This means that any solids which settle to the bottom of the pipe will not be removed by the laminar flow and will accumulate over time.

Let us now calculate the time and distance for a D_{99} (0.425 mm) particle starting at the top of the pipe to settle. The wall shear stress is 30.7 Pa, giving an effective viscosity in the sheared wall zone of 460 mPas. The predicted settling velocity of a 0.425 mm particle is 0.21 mm/s, meaning a 0.425 mm particle will take 4,420 seconds (74 minutes) to settle in the sheared zone near the pipe wall from the top of the pipe, around the inner surface of the pipe, to the bottom, and in this time the slurry will have travelled 7.12 kms (if the pipeline was long enough). Hence, a 0.425 mm particle starting at the top of the pipe will not have settled to the bottom of the pipe before it exits the pipeline. But this applies to a 0.425 mm particle starting at the top of the pipe. A particle starting only halfway up the pipe would reach the bottom in half the time (2,210 seconds) and arrive at the bottom after 3.56 kms, 1.19 kms before the end of the pipeline. A 0.425 mm particle starting near the bottom of the pipe would settle to the bottom almost immediately after it leaves the pump**.**

The plus D_{99} particles represent 1% of the solids, or 21 tph at a solids throughput of 2,103 tph. The above settling calculations suggest about 3 quarters of the 0.425 mm particles reach the bottom, and considering that particles greater than 0.425 mm will settle faster, it is not unreasonable to assume that about 21 tonnes of plus 0.425 mm particles are sitting on the bottom of the pipe after one hour. Assuming a solids packing density of 0.75 with solids specific gravity = 2.83, the 21 tonnes occupies a volume of 10 m^3. After 24 hours' operation, settled solids will be 504 tonnes occupying 240 m^3 representing 18% of the internal volume of the pipeline. The average pressure gradient increases from 207–249 kPa/km or an increase of 20%. However, the increased 249 kPa/km pressure gradient is still well below the minimum 1,000 kPa/km required to slide the solids along the pipe and out the exit of the pipeline. It is obvious that, to prevent continued bed build-up, regular turbulent flushing is required, perhaps on a daily basis.

3.5 Particle settling: paste example

Consider the same copper/gold tailings pipeline as considered in the previous section, but now suppose paste thickeners are installed and the concentration increases to 73% with yield stress 50 Pa and plastic viscosity 230 mPas. At the same nominal 2,103 tph solids, the flow rate has reduced to 1,521 m^3/h with velocity 1.53 m/s. Based on Equation 4, Vt is 4.06 m/s, so flow is laminar. Assuming laminar flow with no settling, the predicted pressure gradient is 426 kPa/km which is still below the 1,000–2,000 kPa/km range required to slide a settled bed along the pipe. This means that any solids which settle to the bottom of the pipe will not be removed by the laminar flow and will accumulate over time.

Let us now calculate the time and distance for D_{99} (0.425 mm) particles to settle. The wall shear stress is 63 Pa giving an effective viscosity in the sheared wall zone of 1,100 mPas. The predicted settling velocity of a 0.425 mm particle is 0.08 mm/s, meaning a 0.425 mm particle will take 11,200 seconds (187 minutes) to settle in the sheared zone near the pipe wall from the top of the pipe to the bottom. But transit time is only 3,100 seconds, indicating that only about one quarter of 0.425 mm particles will settle in 24 hours' operation compared with the Section 3.5 high-density example. This suggests that a similar settled volume of 504 tonnes might take 4 days to accumulate, and the pressure gradient will have increased to 520 kPa/km, still well below the minimum 1,000 kPa/km required to slide the bed. It is obvious that, to prevent continued bed build-up, regular turbulent flushing is required, perhaps once every 4 days.

3.6 Operational data: paste tailings pipeline

The tailings pipeline at a gold mine in Saudi Arabia consists of 980 m of 250 NB 9.27 mm wall steel pipe with an 8 mm liner followed by 500 m HDPE pipe, PE100, OD355, PN20. The steel pipe ID = 238.6 mm and HDPE pipe ID=273.2 mm. The level at pumps = 906 m and RL end of pipeline = 924 m, and the inlet head to the distribution tank is typically 10 m, giving a total static head of 28 m. The solids specific gravity = 2.83 and particle size distribution is D_{max} = 0.600 mm, D_{80} = 0.087 mm, D_{50} = 0.021 mm, and D_{25} = 0.004 mm.

Some recent measured operating data on 27 July 2025 gave flow rate 450 m^3/h, with density 1,590 kg/m^3, pump pressure 1,437 kPa, and Cw = 58%. From the most recent rheology testing, at Cw = 58%, plastic viscosity = 26.4 mPas and Bingham yield stress = 25.2 Pa, giving Vt = 3.15 m/s from Equation 4.

Assuming homogeneous laminar flow with no settling, then at 450 m^3/h, the velocities and predicted laminar pressure gradients (J) in the steel and HDPE pipes are:

- Steel: ID 238.6 mm, V = 2.80 m/s is < Vt so flow is laminar, J(m/km) = 34.2, J(kPa/km) = 536.
- HDPE: ID 273.2 mm, V = 2.13 m/s is <Vt so flow is laminar, J(m/km) = 28.5, J(kPa/km) = 447.

For homogeneous laminar flow, the total pump head would be:

- 0.98 × 34.2 + 0.5 × 28.5 = 33.5 + 14.2 = 47.7 m + 18 m static head + 10 m tank inlet head = 75.7 m.

This gives predicted pump pressure = 75.7 × 9.81 × 1.59 = 1,180 kPa, significantly lower than the measured 1,437 kPa.

3.6.1 Predicted particle settling rates in laminar flow

3.6.1.1 Predicted settling rate of maximum 0.6 mm particle

The predicted settling rate of a 0.60 mm particle in the sheared zone around the inside of the 238.6 mm ID steel pipe is 1.93 mm/s. The particle settles from the top of the steel pipe in the sheared zone around the inner circumference to the bottom in 194 seconds, during which time it has travelled 540 m.

The above settling predictions apply to the 238.6 mm ID steel pipe. The poly pipe has a larger diameter, which means a lower predicted particle settling rate of 1.60 mm/s. The particle settles from the top of the HDPE pipe in the sheared zone around the inner circumference to the bottom in 268 seconds, during which time it has travelled 570 m compared with the 540 m in the 238.6 mm ID steel pipe. So, the travel distances to settle to the bottom are approximately the same in both pipes. This means that, as regards travel distances to settle to bottom of the pipeline, we can ignore the different types of pipes in the pipeline.

The above applies to a 0.6 mm particle starting at the top of the pipe at the pipeline entrance. A particle starting at the mid-circumference point will reach the bottom of the pipe in half this distance or 270 m from the entrance, and a particle starting near the bottom of the pipe will settle to the bottom almost immediately.

3.6.1.2 Predicted settling of D_{95} size (0.18 mm) particle in laminar flow

The predicted settling rate of a 0.18 mm particle in the sheared zone around the inside of the steel pipe is 0.17 mm/s and in the poly pipe 0.14 mm/s. The distance travelled to settle to the bottom of the steel pipe is 6,000 m and 6,400 m in the poly pipe. These predictions apply to a 0.18 mm particle starting at the top of the pipe at the pipeline entrance. A particle starting 1/4 of the inner circumference up from the bottom will reach the bottom of the pipe after about 1,500 m of travel, at around the end of the pipeline. A particle starting at the bottom of the pipe at the pipeline entrance will reach the bottom immediately.

3.6.2 Predicted pump pressures: turbulent flow over stationary bed

Although these tailings are very fine, the above settling predictions suggest that about 1/4 of the 5% of particles above 0.18 mm will eventually settle in the pipeline length and form a bed. If the pressure gradient is too low to slide the bed along the pipeline, then the bed will build up over time. As the stationary bed height increases under laminar flow conditions, the velocity above the bed will increase until eventually it will reach Vt = 3.14 m/s. Turbulent flow then begins above the bed and the incoming slurry will flow above the bed as a pseudo-homogeneous turbulent slurry without further deposition.

Assume turbulent flow at V = Vt above bed:

- In the 238.6 mm ID steel pipe at 450 m^3/h, the velocity above the bed reaches Vt = 3.14 m/s when the bed height = 40 mm. The equivalent diameter above the bed then equals 219 mm and under turbulent flowing conditions J = 38.2 m/km or 599 kPa/km.
- In the 273.2 mm ID HDPE pipe at 450 m^3/h, the velocity above the bed reaches Vt = 3.14 m/s when the bed height = 98 mm. The equivalent diameter above the bed then equals 207 mm and under turbulent flowing conditions J = 40.8 m/km or 640 kPa/km.
- Total friction loss = 0.98 × 38.2 + 0.5 × 40.8 = 57.8 m.
- Adding 18 m static head plus 10 m tank inlet head gives pump head = 85.8 m or 1,338 kPa.
- This predicted pump pressure is 7% below the of the measured 1,437 kPa pump pressure.

Assume turbulent flow at Vt + 0.2 m/s above bed:

- However, it is probable that the actual velocity above the bed might need to be slightly greater than Vt to maintain a steady bed height. If a velocity of 3.34 m/s is assumed above the bed (0.2 m/s above Vt) then the bed height in the steel pipe is 53 mm and D_{eq} = 209.5, giving J = 42.9 m/km, and the bed height in the HDPE pipe is 107 mm, with D_{eq} = 198 mm, giving J = 46.0 m/km.
- Total friction loss = 0.98 × 42.9 + 0.5 × 46.0 = 65.03 m.
- Adding 18 m static head plus 10 m tank inlet head gives pump head = 93.03 m or 1,451 kPa, which is within 1% of the measured 1,437 kPa. This close agreement suggests that the gold tailings pipeline is operating in turbulent flow above a fixed bed at a velocity 0.2 m/s above Vt.

3.7 Conclusions regarding laminar flow pipelines

It is now well established that settling of even very fine particles will occur in laminar flow. This was shown (Aude et al. 1996) in the 10 km Trinidad limestone pipeline, which with a 50 Pa yield stress and maximum particle size around 150 microns, required daily pigging to remove settled solids. It is now accepted that to slide a settled bed in laminar flow requires a pressure gradient of the order 1,000–2,000 kPa/km, although in the pipeline described by Houman & Johnson (2002), a lower limit around 500 kPa/km was found applicable. Unless the laminar flow pipeline is very short, these pressure gradients mean that pump pressures are too high for centrifugal pumps and positive displacement pumps are required, as in the above 2 cases.

But most high-density and paste pipelines use centrifugal pumps. The previous settling calculations for a typical gold tails example suggested that flushing would be required about every day for the high-density example and perhaps about every 4 days for the paste example. But to the authors' knowledge, most high-density and paste pipelines are not regularly flushed. This is certainly the case with the Saudi Arabia pipeline which, to the authors' knowledge, is not regularly flushed. The particle settling calculations and comparisons with the observed pump pressures suggest that this pipeline operates with permanent fixed beds with turbulent flow above them. The present authors suggest that this may be the case with a lot of (if not all) high-density and paste pipelines which are not regularly flushed.

One possibility to minimise flushing requirements may be to install a venturi at selected chainages or a short length of a smaller-diameter pipe, inducing a transition to turbulent flow. The resulting turbulence enhances mixing and mitigates the risk of bed formation downstream. The laminar section length can be defined as the critical distance beyond which particles initiate settling, leading to bed formation. With this setup, some fixed beds would still exist but the bed heights and lengths would be reduced, resulting in a lower pump pressure.

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